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Evaluation of the fire protection effectiveness of fluorine free firefighting foams

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January 2020

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FOREWORD

Fire incidents with catastrophic consequences have historically resulted from flammable liquids, and this remains an important fire protection hazard. These fire incidents can occur in aircraft hangars, shipboard spaces, flammable liquids fueling facilities, large fuel storage tanks, etc. Class B firefighting foams are often used in both manual and fixed system applications for vapor suppression and extinguishment of flammable liquid fires. Foams form a film and/or a blanket of bubbles on the surface of flammable liquids, which prevent the fuel vapors and oxygen from interacting and creating a flammable mixture.

Fire protection foams have changed composition in recent years, due to increasing concerns regarding the environmental and health effects of some of the legacy constituents (i.e., fluorosurfactants). New formulations known as "Fluorine Free Foams (FFFs)" have been introduced and marketed as environmentally acceptable alternatives for legacy fluorinated foams. Industrial end users have anecdotally reported unexpected variability in the fire performance of these reformulated foams, thus meriting further investigation of their capabilities and limitations.

Fire Protection Research Foundation (FPRF) facilitated this program to evaluate the fire protection performance and effectiveness of fluorine free, Class B firefighting foams on fires involving hydrocarbon and alcohol fuels. The deliverables from this project are intended to provide guidance for foam system application standards (e.g., NFPA 11: Standard for Low−, Medium−, and High− Expansion Foam) and to identify any additional research needed to better understand the capabilities and limitations of Fluorine Free Foams (FFFs).

The objectives of this study were to determine the firefighting capabilities (i.e., control, extinguishment and burnback times) for four FFFs and one short chain C6 AFFF formulation (for baseline) as a function of application rate (gpm/ft^2) and discharge density (gal/ft^2) for a range of test parameters including fuel type, water type and fuel temperature.

The Fire Protection Research Foundation expresses gratitude to the report authors Gerard G. Back, who is with Jensen Hughes located in Baltimore, Maryland, USA, and John P. Farley, who is with the Naval Research Laboratory, Washington, DC, USA. The Research Foundation appreciates the guidance provided by the project technical panelists, sponsor representatives and the funding provided by the project sponsors.

About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

Keywords: foams, fluorine free foams, extinguishment, control, burnback, discharge density, AFFF, foam quality, aspiration, NFPA 11.

Report number: FPRF-2020-01

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EVALUATION OF THE FIRE PROTECTION EFFECTIVENESS OF FLUORINE FREE FIREFIGHTING FOAMS

SUMMARY REPORT

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EXECUTIVE SUMMARY

The Fire Protection Research Foundation (FPRF) contracted Jensen Hughes and the Naval Research Laboratory (NRL) to conduct an experimental program to assess the firefighting capabilities of fluorine free, Class B firefighting foams on fires involving hydrocarbon and alcohol-based fuels. The objectives of this study were to determine the fire extinguishment and burnback times for five fluorine free foams (FFFs) and one short chain C6 Aqueous Film Forming Foam (AFFF) formulation (for baseline) as a function of application rate (gpm/ft^2) and foam discharge density (gal/ft^2) for a range of test parameters including foam quality/aspiration, fuel type, water type and fuel temperature. The data provides a general characterization of the firefighting capabilities of FFFs as a "Technology" or a "Class" of foams for use in standards making decisions. The deliverables from this project were used to provide guidance for foam system application standards (e.g., NFPA 11: Standard for Low−, Medium−, and High− Expansion Foam) and to identify any future research needed to further understand their capabilities and limitations.

The assessment was conducted as a blind study where the foams were given generic names and the manufactures of the foams are not identified. The experimental approach consisted of conducting a parametric assessment of the critical variables that could affect the fire protection performance of new foam formulations using the Underwriters Laboratories UL 162 – Standard Foam Equipment and Liquid Concentrates as basis for the investigation. Per UL 162, FFFs fall under the broad category of "Synthetic (S)" Foams. UL 162 defines a "Synthetic" foam as one that has a chemical base other than a fluorinated surfactant or hydrolyzed protein. Since UL 162 was used as the basis of this assessment, the test parameters for "Synthetic" foams were used throughout this assessment. It should be noted that UL does not verify the composition of the foam concentrate, nor does it assess the fluorine content of the foam (at least not at the time that this report was written).

During the current revision cycle of NFPA 11, a new category of foams was proposed to address these new formulations (i.e., SFFF; Synthetic Fluorine Free Foams). Since this category / NFPA 11 was still in draft at the time this report was written, the fluorine free foams included in this assessment were still referred to as FFFs but would fall under the SFFF category if adopted by NFPA 11.

The variables assessed during this program included the following:

- Two Discharge Types: UL Type II with polar solvents and UL Type III with other fuels;
- Six Foam Types (all UL Listed): one Alcohol Resistant C6 AFFF (AR-AFFF), three Alcohol Resistant FFFs (AR-FFF1, AR-FFF2 and AR-FFF3) and 2 hydrocarbon listed FFFs (H-FFF1 & H-FFF2);
- Four Fuel Types: Heptane, Gasoline (MIL SPEC and E10) and Isopropyl Alcohol (IPA);
- Fuel Temperature: Ambient Temp. 60ºF and High Temp. 85ºF;
- Discharge densities: Up to three discharge densities;
- Two Water Types: Freshwater and Saltwater; and
- Two Foam Qualities: Lower Aspiration (3-4 expansion) and Higher Aspiration (7-8 expansion)

The tests were conducted in two series. The first test series (Series I) focused on assessing the capabilities of these foams at a representative lower foam quality/aspiration (foam quality representative of a non-aspirating discharge device). The second series (Series II) was added to re-assess the foams at a representative higher foam quality/aspiration (foam quality representative of an aspirating discharge device).

One hundred sixty-five tests were conducted during this assessment. As a general observation, the results of these tests were consistent with UL listed values with a limited number of exceptions.

To summarize the results, the baseline C6 AR-AFFF demonstrated consistent/superior firefighting capabilities through the entire test program under all test conditions. For the FFFs in general, the firefighting capabilities of the foams varied from manufacturer to manufacturer making it difficult to develop “generic” design requirements. This may also be the case with AFFFs but only one was tested during this program (i.e., no data to assess variability).

The AR-AFFF performed well against all test fuels included in this assessment (IPA, Heptane, and Gasoline (MILSPEC and E10). The FFFs did well against heptane but struggled against some of the scenarios conducted with IPA and gasoline (both MILSPEC and E10), especially when the foam was discharged with a lower foam quality/aspiration.

The FFFs required between 2-4 times both the rates and the densities of the AR-AFFF to produce similar results against the IPA fires conducted in with the Type II test configuration. During the Type III tests, the FFFs required between 3-4 times the extinguishment density of the AR-AFFF for the tests conducted with MILSPEC gasoline and between 6-7 times the density of the AR-AFFF for the tests conducted with E10 gasoline.

From an application rate perspective, the FFFs typically required between 1.5 to 3 times the application rates to produce comparable performance as the baseline AFFF for the range of parameters included in this assessment.

When comparing the capabilities of the AR-FFFs and the H-FFFs, the H-FFFs typically demonstrated better capabilities. In general, for the tests conducted with the lower aspiration, the extinguishment densities for the AR-FFFs were about twice that of the H-FFFs. This difference was reduced through the use of the higher aspirated foams during Series II. For the tests conducted with the higher aspirated foams, the extinguishment densities for the AR-FFFs were, on average about 1.5 times that of the H-FFFs. However, the AR-FFFs required a higher flow/application rate than the H-FFFs against the E10 fires to achieve those results.

When comparing capabilities of the AR-FFFs to the H-FFFs, the AR-FFFs required about twice the application rate to produced similar capabilities as the H-FFFs for the lower expanded foam and about 1.5 times the rate for the higher expanded foam. Consequently, the use of higher aspirated foams reduced the differences in capabilities between the two types of FFFs (i.e., alcohol resistant and hydrocarbon FFFs).

With respect to FFF types, the original two AR-FFFs (AR-FFF1 and AR-FFF2) demonstrated similar firefighting capabilities and typically required about three times the application rates of AR-AFFF to produce comparable performance for the lower aspirated foams. For higher aspirated foams, the AR-FFFs required about twice the application rates of AR-AFFF to produce comparable performance. The third AR-FFF (AR-FFF3) added at the start of Series II did about

25% better than the original two AR-FFFs but could not be included in every comparison due to a limited data set.

There was some variation in capabilities between the two hydrocarbon FFFs with H-FFF2 requiring between 25%-50% more agent (application rate) than the AR-AFFF for the lower aspirated foams and about 15%-30% more agent (application rate) than the AR-AFFF for the higher aspirated foams. H-FFF1 required between 50%-100% more agent (application rate) than the AR-AFFF for the lower aspirated foams and about 30-40% more agent (application rate) than the AR-AFFF for the higher aspirated foams.

With respect to elevated fuel temperatures, the results were consistent over the range in ambient/fuel temperatures included in this assessment. With that said, it is understood that fires involving boiling flammable liquids are much harder to extinguish than fires that are combatted prior to the transition into boiling.

The type of water (i.e., freshwater versus saltwater) had minimal effect on the firefighting capabilities of the FFFs and varied between foams.

In summary, the results demonstrate that FFFs have come a long way but there is still a lot more to learn about their capabilities and limitations (although there is a lot of promising data). As of today, FFFs are not a “drop in” replacement for AFFF. However, some can be made to perform effectively as an AFFF alternative with proper testing and design (i.e., with higher application rates/densities).

Due to its oleophobic properties, AFFF has two separate mechanisms that combine to aid in the extinguishment of a flammable liquid fire; a water/surfactant film that forms on the fuel surface and a foam blanket (i.e., matrix of bubbles) which both serve to seal-in the flammable vapors resulting in extinguishment (i.e., shutting off the fuel vapors that are burning above the fuel surface). FFFs have only the foam blanket to seal-in the vapors. As a result, the capabilities of FFFs will be highly dependent on the characteristics of the foam blanket (which depend on the associated discharge devices as well as the foam type itself). The film produced by AFFF has provided an additional level of protection for systems and discharge devices that do not produce aspirated foam. Additional attention will need to be given to the discharge devices identified as part of the UL listing when fielding these foams. Additional discussions on aspiration and foam quality in general are being added to NFPA 11. It was recommended that the tested/listed foam qualities (i.e., expansion and 25% drainage) be included on UL listing data sheet(s). Additional research is currently being conducted by other organizations to identify a range of optimal foam properties (which may be manufacturer specific).

The results also show that the legacy fuel (heptane) used to list/approve foams, may not be a good surrogate for all hydrocarbon-based fuels. Specially, some foams struggled against other fuels (like gasoline) as compared to heptane. Going forward, it was recommended that FFFs be tested and listed for a variety of hydrocarbon fuels (e.g., gasoline, E10, Jet A, etc), similar to approach currently used for polar solvent listings/approvals.

Ultimately, end users will need to design and install within the listed parameters in order to ensure a high probability of success during an actual event. This applies to the not only to the discharge devices but also to the proportioning systems as well (due to the highly viscous nature of some of the FFF concentrates).

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LIST OF ACRONYMS AND ABBREVIATIONS

AFFF	Aqueous Film-Forming Foam
AR-FFF	Alcohol Resistant - Fluorine Free Foam
BBT	Burnback Time
C6	Short Chain Surfactants
C8	Long Chain Surfactants
CBD	Chesapeake Bay Detachment
Cont	Control
dec	decrease
E10	Gasoline with 10% Alcohol
EPA	Environmental Protection Agency
ET	Extinguishment Time
Exp	Expansion
Ext	Extinguishment
F	Fail
FAA	Federal Aviation Administration
FFF	Fluorine Free Foam
FPRF	Fire Protection Research Foundation
ft	feet
ft^2	square feet
gal	gallons
gal/ft^2	gallon per square foot
gpm	gallon per minute
gpm/ft^2	gallon per minute per square foot
H-FFF	Hydrocarbon - Fluorine Free Foam
inc	increase
IPA	Isopropyl Alcohol
in	inch
Lbs	pounds
MILSPEC	Military Specification Mil-F-24385 F
ml	milliliters
NFPA	National Fire Protection Association
NRL	Naval Research Laboratory
P	Pass
psi	pounds per square inch
S	Synthetic
SFFF	Synthetic Fluorine Free Foam
sec	seconds
UL	Underwriters Laboratory
USN	United States Navy
WC	Worst Case

1. BACKGROUND

The National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF) sponsored this program to evaluate the fire protection performance and effectiveness of fluorine free, Class B firefighting foams on fires involving hydrocarbon and alcohol fuels. The deliverables from this project provided guidance for foam system application standards (e.g., NFPA 11: Standard for Low−, Medium−, and High− Expansion Foam) [1] and identified some additional research needed to better understand the capabilities and limitations of Fluorine Free Foams (FFFs).

Per Underwriters Laboratories UL 162 – Standard for Foam Equipment and Liquid Concentrates [2], FFFs fall under the broad category of "Synthetic (S)" Foams. UL 162 defines a "Synthetic" foam as one that has a chemical base other than a fluorinated surfactant or hydrolyzed protein. Since UL 162 was used as the basis of this assessment, the test parameters for "Synthetic" foams were used throughout this test program. It should be noted that UL does not verify the composition of the foam concentrate, nor does it assess the fluorine content of the foam (at least not at the time that this report was written).

During the current revision cycle of NFPA 11, a new category of foams was proposed to address these new formulations (i.e., SFFF; Synthetic Fluorine Free Foams). Since this category / NFPA 11 was still in draft at the time this report was written, the fluorine free foams included in this assessment were still referred to as FFFs but would fall under the SFFF category if adopted by NFPA 11.

2. TEST OBJECTIVES

The objectives of this study were to determine the firefighting capabilities (i.e., control, extinguishment and burnback times) of five FFFs and one C6 AFFF formulation (for baseline) as a function of application rate (gpm/ft^2) and discharge density (gal/ft^2) for a range of test parameters including water type, fuel type and fuel temperature.

3. APPROACH

3.1. PARAMETRIC ASSESSMENT

The approach consisted of conducting a parametric assessment of the critical variables that may affect the firefighting performance of the new FFF formulations using the UL 162 [2] as basis for the investigation. The assessment was conducted as a blind study where the foams were given generic names and the manufactures of the foams were not identified.

The variables included the following:

1. Two Discharge Types / Fire Scenarios:
   a. UL Type II with polar solvents
   b. UL Type III with other fuels

2. Six Foam Types:
   a. One AR−AFFF C6

b. Three UL listed alcohol resistant FFFs (AR-FFF1, AR-FFF2 and AR-FFF3)
c. Two UL listed hydrocarbon FFFs (H-FFF1 and H-FFF2)

3. Four Fuel Types:
   a. Heptane
   b. Gasoline (MILSPEC and E10)
   c. Isopropyl Alcohol (IPA)

4. Fuel Temperature:
   a. Temp 60º F (+/- 10ºF)
   b. Temp 85ºF (+/- 5ºF)

5. Discharge densities: Up to three discharge densities

6. Two Water Types:
   a. Freshwater
   b. Saltwater

7. Foam Quality/Aspiration:
   a. Lower Aspiration (3-4 Exp. Ratio)
   b. Higher Aspiration (7-8 Exp. Ratio)

3.2. Foam Quality/Aspiration

Foam quality is a term used to characterize the foam blanket produced by the various combinations of foam concentrates/solutions and discharge equipment/devices. Foam quality consists of two parameters; expansion ratio and 25% drainage time. The equipment and procedures used to measure these parameters are described in Section 10 of UL 162 [2].

Based on input from the Technical Panel, two representative foam qualities were assessed during this program. These consisted of foam solutions with expansion ratios between 3-4 to represent the discharge from non-aspirating discharge devices and foam solutions with expansion ratios between 7-8 to represent the discharge from aspirating discharge devices. These qualities were achieved by varying the aspiration of the foam that was discharged from the test nozzle. Tests were conducted in the lab at JENSEN HUGHES to identify the appropriate nozzle configurations to produce these foam qualities for the range of foam concentrates and flow rates assessed during this program.

With respect to the 25% drainage times, the measured values for the higher aspirated foam solutions were consistent with the values included in some of the manufacturer's literature. In general, the AR-FFFs typically produced extremely long drainage times on the order of an hour. The H-FFFs exhibited drainage times round 30 minutes. The drainage times for both types of foams (i.e., AR-FFFs and H-FFFs) were typically reduced by about 30% for the lower aspirated foam solutions (i.e., 3-4 expansion ratios). All of these values are significantly longer than the drainage times for AFFF which typically reside in the 5-10 minute range.

It needs to be noted that the characteristics of the lower aspirated foam solutions (i.e., expansion ratio and drainage times) could be outside of the listed parameters for some of these foams.

3.3. TEST SERIES DESCRIPTION AND LOGIC

The test program consisted of two test series (Series I and Series II). The test variables were modified slightly between Series I and Series II. In short, Series I included only four FFFs and focused on worst-case foam quality (lower aspirated foams / lower expansion ratios). Series II included a third AR-FFF (AR-FFF3) and assessed the capabilities of higher aspirated foams. An assessment of E10 gasoline was also added as part of Series II.

The test logic was developed to determine the failure point for each foam concentrate/solution by either increasing or decreasing the application rates based on the results of the previous test. This logic was developed by the FPRF based on inputs from the Foam Task Group in support of NFPA 11 and is shown in the flow chart provided as Figure 3.0-1. In short, the assessment started at the listed/recommended application rate. If the foam solution failed for a given set of conditions, the flow rate was increased by 25%, if the solution passed, the flow rate was decreased by 25%. The ultimate object was to bound the critical value for each set of conditions (i.e., identify the failure point).

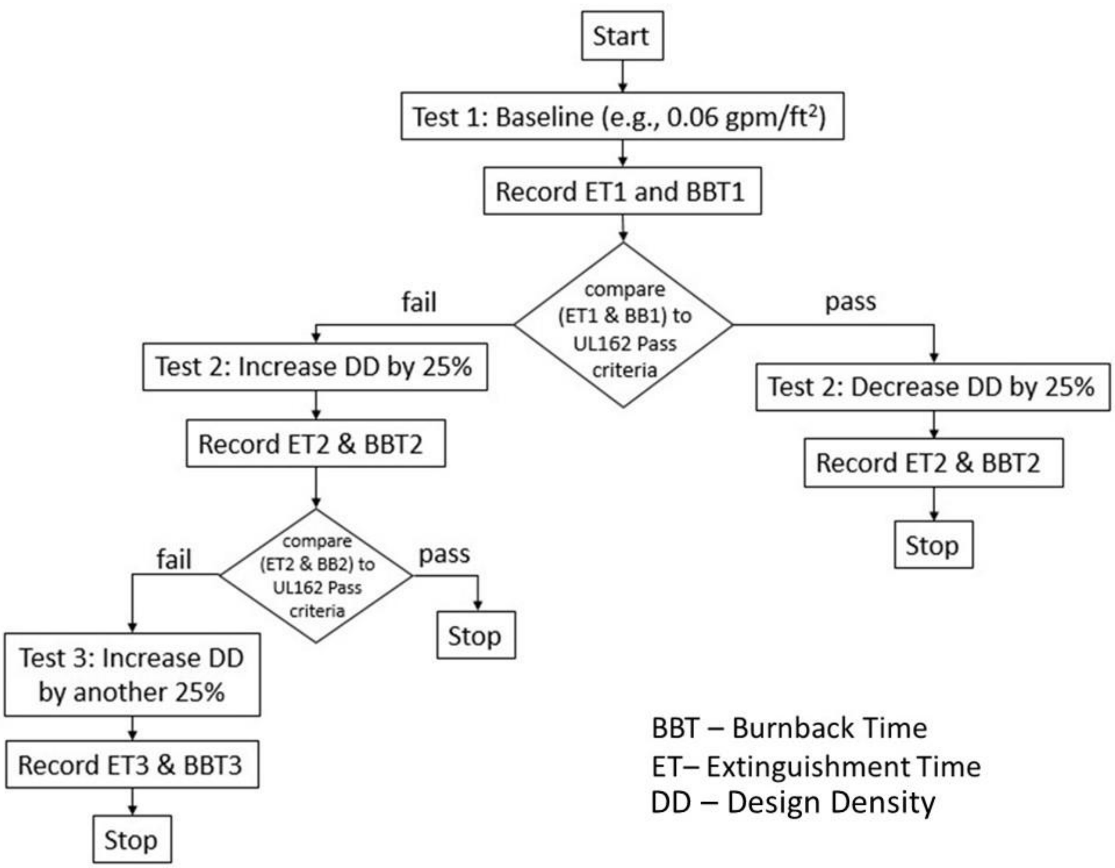


Figure 3.3-1 Test Sequence / Assess Logic

During Series II, the same logic was applied except, the starting point was the critical application rate identified in Series I (i.e., the lowest application rate that resulted in extinguishment for each scenario in Series I) and only one increase/decrease step was tested (during Series II).

4. SERIES I TEST MATRICES

The test matrix for the Series I, Type II tests is shown in Table 4.0-1. The tests were initially conducted with three alcohol resistant foams (AR-AFFF, AR-FFF1 and AR-FFF2). Towards the end of Series I, a limited number of tests were also conducted with a third AR-FFF (AR-FFF3). All tests were conducted using Isopropyl Alcohol (IPA) as the fuel with no water substrate in the pan. During this series, each foam was assessed using both freshwater and saltwater (where applicable) to make the foam solution and were discharged as higher aspirated foam. Higher aspiration was selected to ensure the foam impacted the backboard on the opposite side of the pan. In addition, a few tests were also conducted with heptane and gasoline to provide additional data on the overall capabilities of FFFs.

Table 4.0-1 Series I – Type II IPA Test Matrix

Test #	Type of Discharge (a)	Foam Concentrate (b)	Fuel Type (c)	Fuel Temperature (d)	Discharge Density (e)	Water Type (f)	Exp. Ratio (g)
1	Type II	Concentrate	IPA	Standard	Recommended	Fresh	7-8
2	Type II	Concentrate	IPA	Standard	1st inc/dec	Fresh	7-8
3	Type II	Concentrate	IPA	Standard	2nd increase	Fresh	7-8
4	Type II	Concentrate	IPA	Standard	Recommended	Salt	7-8
5	Type II	Concentrate	IPA	Standard	1st inc/dec	Salt	7-8
6	Type II	Concentrate	IPA	Standard	2nd increase	Salt	7-8

The test matrix for the Series I, Type III tests is shown in Table 4.0-2. Each of the four initially selected FFFs (AR-AFFF, AR-FFF1, AR-FFF2, H-FFF1, and H-FFF2) and the baseline C6 AR-AFFF were tested using the tests shown in Table 4.0-2.

Table 4.0-2 Series I - Type III Test Matrix

Test #	Type of Discharge (a)	Foam Concentrate (b)	Fuel Type (c)	Fuel Temperature (d)	Discharge Density (e)	Water Type (f)	Exp. Ratio (g)
1	Type III	Concentrate	Heptane	Standard	Recommended	Fresh	7-8
2	Type III	Concentrate	Heptane	Standard	Recommended	Fresh	3-4
above	Type III	Concentrate	Heptane	Standard	Recommended	Fresh	WC (3-4)
3	Type III	Concentrate	Heptane	Standard	1st inc/dec	Fresh	WC (3-4)
4	Type III	Concentrate	Heptane	Standard	2nd increase	Fresh	WC (3-4)
5	Type III	Concentrate	Heptane	Standard	Recommended	Salt	WC (3-4)
6	Type III	Concentrate	Heptane	Standard	1st inc/dec	Salt	WC (3-4)
7	Type III	Concentrate	Heptane	Standard	2nd increase	Salt	WC (3-4)
8	Type III	Concentrate	Gasoline	Standard	Recommended	Fresh	WC (3-4)
9	Type III	Concentrate	Gasoline	Standard	1st inc/dec	Fresh	WC (3-4)
10	Type III	Concentrate	Gasoline	Standard	2nd increase	Fresh	WC (3-4)
12	Type III	Concentrate	Gasoline	Standard	Recommended	Salt	WC (3-4)
13	Type III	Concentrate	Gasoline	Standard	1st inc/dec	Salt	WC (3-4)
14	Type III	Concentrate	Gasoline	Standard	2nd increase	Salt	WC (3-4)

As shown in the matrix, the first two tests identified the worst-case foam quality/aspiration that was used for the duration of the Type III tests during Series I. These initial two tests were conducted using the baseline scenario (Type III test configuration, heptane as the fuel, freshwater to make the foam solution and the manufacturer's recommended/listed discharge density) against the higher and lower aspirated foam solutions.

Once the worst-case foam quality/aspiration was identified (the lower aspirated foam), the foam concentrate was then assessed using the logic defined in Section 3 in the following sequence; heptane fuel - freshwater solution, heptane fuel- saltwater solution, gasoline fuel – freshwater solution and gasoline fuel – saltwater solution.

The original statement of work for Series I included 10 tests conducted at higher temperatures (i.e., high fuel temperatures using MILSPEC gasoline as the fuel). These tests were originally intended to be conducted with the worst-case foam quality/aspiration. However, due to the difficultly in extinguishing the MILSPEC gasoline observed during the initial tests with the lower aspirated foam, the elevated temperature tests were conducted with each agent using higher aspirated foam. These tests were conducted in early fall at ambient temperatures ranging from 82°F-93°F (in between Series I which was conducted in April and Series II which was conducted in October).

5. SERIES II TEST MATRICES

At the start of the overall effort, only one series of tests was scheduled (i.e., Series I). During Series I, questions were identified associated with foam quality/aspiration and fuel type that demonstrated the need for additional testing. This testing was conducted during the second series (Series II) and included a more detailed assessment of foam quality/aspiration and fuel type. In addition, the Type II tests conducted in Series I with IPA were repeated at much higher flow rates/ discharge densities.

The test matrix for the Series II, Type II tests is shown in Table 5.0-1. The tests were conducted with all three AR-FFFs (AR-FFF1, AR-FFF2 and AR-FFF3). Consistent with Series I, all tests were conducted using IPA as the fuel with no water substrate in the pan. During this series, each foam was assessed using both freshwater and saltwater to make the foam solution (where applicable) and were discharged at the higher aspirated foam. As stated above, the flow rates were dramatically increased between Series I and Series II.

Table 5.0-1 Series II - Type II IPA Test Matrix

Test #	Type of Discharge (a)	Foam Concentrate (b)	Fuel Type (c)	Fuel Temperature (d)	Discharge Density (e)	Water Type (f)	Exp. Ratio (g)
1	Type II	Concentrate	IPA	Standard	Listed	Fresh	7-8
2	Type II	Concentrate	IPA	Standard	1st inc/dec	Fresh	7-8
3	Type II	Concentrate	IPA	Standard	Listed	Salt	7-8
4	Type II	Concentrate	IPA	Standard	1st inc/dec	Salt	7-8

In addition to the Type II tests conducted with IPA, a limited number of tests were conducted with IPA against the Type III scenario (manual firefighting/foam application). The tests were conducted using the two best AR-FFFs (AR-FFF1 and AR-FFF3) identified during the Type II tests and were conducted at the same flow rates and equipment (i.e., straight stream nozzle configuration) used to extinguish the fire during the Type II tests listed in Table 5.0-1. The Type III tests conducted with each of the two selected AR-FFFs using IPA as the fuel are listed in Table 5.0-2

Table 5.0-2 Series II Type III – IPA Test Matrix

Test #	Type of Discharge (a)	Foam Concentrate (b)	Fuel Type (c)	Fuel Temperature (d)	Discharge Density (e)	Water Type (f)	Exp. Ratio (g)
1	Type III	Concentrate	IPA	Standard	Listed	Fresh	7-8
2	Type III	Concentrate	IPA	Standard	1st inc/dec	Fresh	7-8

The next set of tests were conducted to provide a direct comparison of the effects of foam quality/aspiration on the firefighting capabilities of the FFFs. These tests were conducted with MILSPEC gasoline in the Type III test configuration. The MILSPEC gasoline was selected since it was observed to be the most challenging hydrocarbon fuel to extinguish during Series I. For consistency, the MILSPEC gasoline was floated on a one-inch water substrate as was used in Series I. All five FFFs (AR-FFF1, AR-FFF2, AR-FFF3, H-FFF1, and H-FFF2) were tested against the fires listed in Table 5.0-3.

Table 5.0-3 Series II Type III MILSPEC Gasoline Test Matrix

Test #	Type of Discharge (a)	Foam Concentrate (b)	Fuel Type (c)	Fuel Temperature (d)	Discharge Density (e)	Water Type (f)	Exp. Ratio (g)
1	Type III	Concentrate	MILSPEC	Standard	Listed	Fresh	7-8
2	Type III	Concentrate	MILSPEC	Standard	1st inc/dec	Fresh	7-8
3	Type III	Concentrate	MILSPEC	Standard	Listed	Salt	7-8
4	Type III	Concentrate	MILSPEC	Standard	1st inc/dec	Salt	7-8

The final set of tests provided a comparison of the extinguishment difficulty between MILSPEC gasoline and E10 gasoline and are listed in Table 5.0-4. These tests were conducted using the Type III test configuration with no water substrate. The decision to eliminate the water substrate is provided/described later in the report. All five FFFs (AR-FFF1, AR-FFF2, AR-FFF3, H-FFF1, and H-FFF2) were tested against the fires listed in Table 5.0-4.

Table 5.0-4 Series II Type III MILSPEC / E10 Test Matrix

Test #	Type of Discharge (a)	Foam Concentrate (b)	Fuel Type (c)	Fuel Temperature (d)	Discharge Density (e)	Water Type (f)	Exp. Ratio (g)
1	Type III	Concentrate	MILSPEC	Standard	Listed	Fresh	7-8
2	Type III	Concentrate	MILSPEC	Standard	1st inc/dec	Fresh	7-8
3	Type III	Concentrate	MILSPEC	Standard	Listed	Salt	7-8
4	Type III	Concentrate	MILSPEC	Standard	1st inc/dec	Salt	7-8
5	Type III	Concentrate	E10	Standard	Listed	Fresh	7-8
6	Type III	Concentrate	E10	Standard	1st inc/dec	Fresh	7-8
7	Type III	Concentrate	E10	Standard	Listed	Salt	7-8
8	Type III	Concentrate	E10	Standard	1st inc/dec	Salt	7-8

6. TEST DESCRIPTION

The tests were based on the requirements stated in UL 162 – Standard Foam Equipment and Liquid Concentrates [2] and incorporated the same equipment and procedures (with a limited number of exceptions). A high-level description of the equipment and procedures is provided in the following sections. Additional detail can be found in the UL Test Standard [2].

6.1. TEST FACILITY

The fire tests were conducted at the Chesapeake Bay Detachment (CBD) of the Navy Research Laboratory (NRL) located in Chesapeake Beach, MD. The tests were conducted outdoors on a 100 ft by 100 ft concrete pad referred to as the Flight Deck. The Series I tests were conducted in April 2019 and the Series II tests were conducted in October 2019.

6.2. FIRE PAN

A 50 ft^2 (4.65 m^2) square stainless-steel pan with 12 in (30.5 cm) high sides was constructed for this test series. The pan was located on the concrete slab near the center of the Flight Deck. The pan was placed on concrete cinder-blocks and was shirted on the three sides during each test.

6.3. TEST SETUP

During Type II tests, the nozzle was fixed and positioned/aimed such that the spray impacted a backboard located on the opposite side the pan. The nozzle remained fixed for the duration of the test. Most of the Type II tests were conducted using IPA as the test fuel with no water substrate.

During the Type III tests, the foam nozzle was initially fixed/held still such that the spray impacted the fuel near the center of the fire pan until the intensity of the fire was reduced by approximately 90% (defined as control). Once the fire had been knocked-down/controlled, the firefighter then manually directed the spray at the remaining fire in the pan while simultaneously cooling the sides. The firefighter was limited to two sides of the pan and the nozzle was never allowed to extend over the edge of the pan as per the requirements stated in UL 162.

Photographs of the two types of tests are provided as Figure 6.3-1.

Type II Configuration

Type III Configuration

Figure 6.3-1 Test Configurations

6.4. TEST SEQUENCE / TIMING

As short description of the test sequence/timing, after the pan was ignited, the fire was allowed to free-burn for a period of one minute prior to foam application. The foam was then applied at the prescribed rate and duration as stated in UL 162 Table 12.1 [2]. One minute after the end of discharge (after the flow was secured secured), a flaming torch was passed above the foam blanket (approximately two inches above) for one minute to confirm the fuel vapors were being contained below the foam blanket. After the delay specified in UL 162, a second torch pass was then performed. Immediately after the second torch pass, a stove pipe was placed in the corner of the pan, the foam in the stove pipe removed, the fuel beneath the foam ignited and allowed to burn for one minute and then the stove pipe was removed marking the start of the burnback portion of the test. After the fire had spread over an area of 10 ft^2 or self-extinguished upon removal of the stove pipe, the test was terminated, and the fire was extinguished (where applicable). Photographs showing a torch pass and the stove pipe insertion are provided as Figure 6.4-1. Check lists showing the sequence and the timing of the tasks for the two scenarios (i.e., Type II and Type III) are shown on Figure 6.4-2. The recommended agent flow rates are shown at the top of the figure for each type of foam and test configuration (i.e., test type).

Torch Pass

Stove Pipe Insertion and Foam Removal

Figure 6.4-1 Post Extinguishment Tasks

As a point worth noting, many people are not aware that for the Type III tests, AFFFs are tested at 2 gpm using a 3 minute discharge time (6 gallons of foam total) while FFFs (i.e., “Synthetic” Foams) are tested at 3 gpm with a 5 minute discharge time (15 gallons of foam total). Both are required to extinguish the fire by the end of agent discharge (i.e., 3 minutes max for AFFF and 5 minutes max for FFFs).

All Type II and Type III – FFFs (3 gpm flow rate)		Type III – AFFF (2 gpm flow rate)	
	____ Spray backboard for foam quality test		____ Spray backboard for foam quality test
	____ Dump Fuel (62 gal)		____ Dump Fuel (62 gal)
0:00	____ Ignite Pan – Start Stop Watch	0:00	____ Ignite Pan – Start Stop Watch
1:00	____ Begin Attack – One minute after ignition	1:00	____ Begin Attack – One minute after ignition
	____ Record Results Above		____ Record Results Above
	____ Record Control Time ______________		____ Record Control Time ______________
	____ Record Extinguishment Time ____________		____ Record Extinguishment Time ____________
6:00	____ Stop AFFF Application	4:00	____ Stop AFFF Application
7/8	____ First Torch Pass	5/6	____ First Torch Pass
18/19	____ Second Torch Pass	9/10	____ Second Torch Pass
19:00	____ Insert Stovepipe and clear foam	10:00	____ Insert Stovepipe and clear foam
20:00	____ Ignite fuel in stove pipe	12:00	____ Ignite fuel in stove pipe
21:00	____ Remove stove pipe	13:00	____ Remove stove pipe
	____ Record Results Above (time to 10 ft^2)		____ Record Results Above (time to 10 ft^2)
	____ Extinguish the Fire		____ Extinguish the Fire

Figure 6.4-2 Test Sequence and Timing

6.5. Test Fuels

The firefighting capabilities of the foams were assessed using four different fuels; gasoline (MILSPEC and E10), heptane and IPA. Approximately 55 gallons of fuel was used during each test.

During the tests conducted with IPA, the fuel was poured directly into the pan (i.e., no water substrate was used). This is consistent with the UL test requirements for polar solvents.

During the Series I tests conducted with MILSPEC gasoline and heptane (Series I), the fuel was floated on a one-inch water substrate. This is consistent with the UL test requirements for hydrocarbon fuels.

The addition of the E10 in Series II raised the question of whether to use a water substrate or not. There does not appear to be a definition of a “polar solvent” or “hydrocarbon fuel” that directly applies to a mixture of the two such as E10. As a result, a limited number of tests were conducted with E10, with and without a water substrate. The results showed that using a water substrate made the E10 much easier to extinguish and produced consistent results as the MILSPEC gasoline with a water substrate. This was attributed to the alcohol in the fuel reacting with the water substrate. As a result, the tests conducted with E10 gasoline were conducted without a water substrate.

Then, the question arose pertaining to the difference in extinguishment difficultly associated with the use of a water substrate for the MILSPEC gasoline. Although the test data showed only a minimal difference in extinguishment difficulty for MILSPEC gasoline, with and without a water substrate, the foam quality/aspiration comparison was conducted with MILSPEC gasoline on a water substrate (consistent with Series I) and the fuel type comparison (MILSPEC versus E10) was conducted with MILSPEC gasoline with no water substrate.

Samples of both the E10 and MILSPEC gasoline were collected and sent to a lab for chemical analysis. The results will be added to this report as an addendum once the results become available.

6.6. Foam Solution and Discharge System

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 required to ensure that the foam concentrate and salt during the tests conducted with saltwater were well mixed prior to the start of the test (allowed visual observation of the mixing and final solution). Various size pressure vessels were used during the program including 10, 20 and 80 gallon vessels.

The foam concentrate was measured using a 1000 ml plastic graduated cylinder. Approximately 1135 ml of concentrate (0.3 gal) was required for each 10 gallon increment/batch of 3% foam solution. The solution was prepared by senior technicians from both Jensen Hughes and NRL.

During testing, the pressure vessel was located about 50 ft from the fire pan (upwind side) and was pressurized with air to just over 100 psi using a high flow rate air compressor.

A photograph of the mixing container and the 80-gallon pressure vessel is provided as Figure 6.6-1.

Figure 6.6-1 Foam Mixing and Discharge System

Most of the tests were conducted using the UNI 86 nozzle in a variety of configurations to produce the required flow rates and foam qualities/aspiration. The aspiration was varied by changing the barrel length as well as through the addition (and blocking) of the aspirating holes built into the nozzle. Specifically, adding holes or increasing the hole size increased the aspiration/expansion ratio of the foam while partially blocking the existing holes decreased the aspiration/expansion ratio of the foam.

During the UL listing process, the foam quality used during the fire tests is selected to cover the range of the foam qualities produced by the listed discharged devices. Manufacturers are allowed to bring their own nozzles that have been adjusted to produce their desired foam qualities to expedite the process (i.e., negate the need to continually adjust the nozzles to produce the desired characteristics).

In addition to varying the flow rate and the foam quality/aspiration, the nozzle was also configured with either a straight bore or fan-tip spray pattern adapter. An illustration and a photograph of the nozzle is provided in Figure 6.6-2.

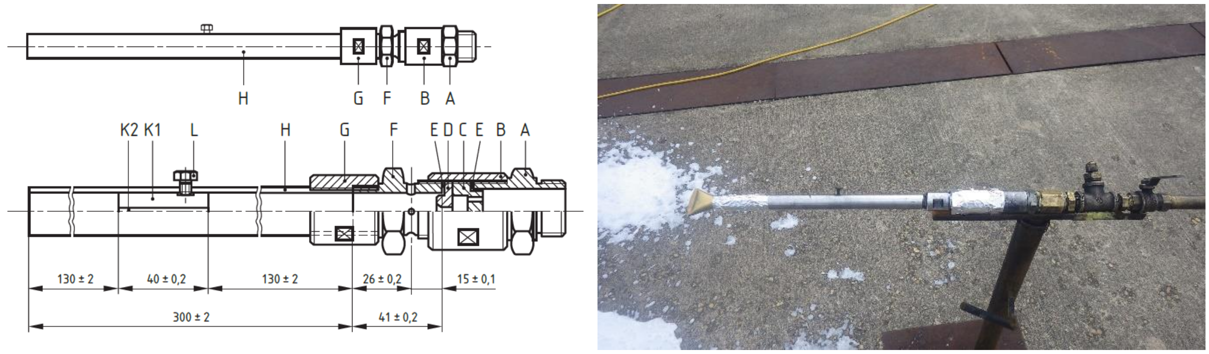


Figure 6.6-2 UNI 86 Nozzle Schematic and Photograph (with fan tip installed)

For the Type II fixed nozzle tests, the nozzle was placed at a height of 3.1 ft (approximately 1 m) above the upper edge of the pan. The nozzle was installed horizontally at a distance which ensured that the foam impacted the center of the backboard. This distance was established prior to testing for the various flow rates.

For the Type III tests, the nozzle was held at the same height above the upper edge of the pan and aimed to ensure the foam impacts the center of the pan. Once the fire had been knocked-down and control had been achieved, the firefighter then moved around the pan (limited to only two sides of the pan) and manually applied the foam to the fire.

6.7. Saltwater Solution

The saltwater solutions were prepared using ASTM salt crystals. Approximately 3.5 lbs (5.5 ounces/gallon) of salt was used for each 10 gallon batch of foam solution made with saltwater. During these tests, the saltwater solution was first prepared in the clear/white, open top mixing container prior to the addition of the foam concentrate (refer to Figure 6.6-1).

6.8. Waste Collection

There was approximately 100 gallons of effluent collected, stored and disposed of from each test. The waste collection and storage systems were provided by Clean Harbors Environmental Services, Inc. The waste was stored in a 10,000 gallon tanker parked on the northwest corner of the Flight Deck. The waste was transferred to the tanker after each test using a pump and hoses provided by Clean Harbors.

On completion of the test program, the waste storage tanker, the empty 55 gallon heptane and IPA drums and the empty 5 gallon plastic foam containers were removed by Clean Harbors and the waste disposed of in accordance with local requirements.

7. General Observations And Points Worth Noting

7.1. Foam Quality/Aspiration Artifacts

The initial two tests conducted with each agent identified the “worst case” foam quality/aspiration to be used during the remainder of the tests conducted during Series I. As expected, higher aspirated foams provided superior capabilities resulting in the majority of the Series I tests being conducted with lower aspirated foam solutions. During Series I, questions were identified associated with foam quality/aspiration and fuel type that demonstrated the need for additional testing. These were the genesis of the Series II test program which included a more detailed assessment of foam quality/aspiration and fuel type.

One of the first observations made during testing was a reduction in stream reach associated with the lower aspirated foams. Specifically, the nozzles used during testing were air-aspirated nozzles (i.e., the UNI 86 nozzle) designed to produce aspirated foam. When the aspirating holes in the nozzle were blocked (or partially blocked), the stream reach was typically reduced from 5-6 ft to 3-4 ft. As a result, it was extremely challenging to cool the opposite sides of the pan and to discharge foam into the far corner of the pan during the tests conducted with the lower aspirated foams.

In addition, the solution behaved more like a liquid than a stream of bubbles resulting in some plunging/mixing where the foam impacted the fuel surface. This apparently resulted in some degree of fuel pickup in the foam blanket which tended to re-ignite when the torch was passed over the blanket during the post extinguishment portion of the test.

7.2. Manual Firefighting Techniques

During the Type III tests (which involve manual firefighting), the firefighter applied agent from one location into the center of the pan until the fire was controlled (90% reduction in intensity). Once controlled, the firefighter was allowed to approach the pan and fight the fire from two sides; the one in which he/she started and one of the two adjacent sides. During this period (post control period), the firefighter needed to simultaneously cool the pan sides while extinguishing the fire. As a result, the firefighters applied the foam against the inside walls of the pan to cool the sides while trying to extinguish the fire. Cooling was required to prevent reignition during suppression as well as to minimize the degradation of the foam blanket in contact with the pan sides during the post-extinguishment test period.

7.3. Pass/Fail

The test logic/sequence was established to bound the capabilities of the FFFs by identifying the line between failure and success as described in Section 3.3. However, there are numerous failure points that could occur during the test as shown in Table 7.3-1

Table 7.3-1 Potential Failure Points

Fire Performance					
Control	**Extinguishment**	**1st Torch Pass**	**2nd Torch Pass**	**Burnback**	**UL 162**
Pass/Fail	Pass/Fail	Pass/Fail	Pass/Fail	Pass/Fail	Pass/Fail
Pass/Fail	Pass/Fail	Pass/Fail	Pass/Fail	Pass/Fail	Pass/Fail

To simplify the logic/assessment (and to account for the stream reach and plunging issues mentioned previously), the foams were initially assessed during Series I based on both extinguishment and on successful completion of the entire test (i.e., UL 162 compliant). During Series II, the focus was placed strictly on fire extinguishment.

With this said, using the UL 162 test protocol as the basis of this assessment, adds a level of confusion due to the limitations on how the tests are to be conducted. As an example, many of the test fires could have been extinguished with a lower application/flow rate if the firefighter was allowed to walk around the entire pan during agent application (as opposed to just two sides as prescribed in UL 162). There is also a concern about the variations in flow rates, discharge times and test sequence/timing between the different types of foams. Specifically, AFFFs are tested at 2 gpm while FFFs are tested at 3 gpm with different discharge times and burnback requirements. This needed to be accounted for when comparing the capabilities of the new FFFs to the legacy AR-AFFF (C6 formulation).

7.4. Wind and Weather

During this program, all the tests were conducted outdoors. As a result, the tests were conducted at ambient conditions and wind may have affected some of the results of these tests. However, the GO/NO-GO criteria for these tests was a wind speed of 10 mph. Specifically, the test was postponed if the wind was 10 mph or greater. In addition, no tests were conducted in the rain.

With this said, the average wind speed during this test program was approximately 4-7 mph. In all cases, the tests were conducted with the wind at the back of the firefighter and/or discharge nozzle to aid in the stream reach. In addition, the tests were conducted in an order such that most foams were conducted against the same fire scenario, on the same day which should have had the same effect on each foam.

8. Type II and IPA Test Results and Discussion

8.1. Type II IPA Test Results

The Type II IPA test results (both Series I and Series II) are shown in Table 8.1-1.

Table 8.1-1 Type II Test Results (IPA)

Foam	Type of Discharge	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont. min:sec	Cont. sec	Ext. min:sec	Ext. sec
AR-AFFF	Type II	IPA	Fresh	2.25 gpm	7-8	2:40	160	4:30	270
AR-AFFF	Type II	IPA	Fresh	3.0 gpm	7-8	2:30	150	4:10	250
AR-AFFF	Type II	IPA	Salt	2.25 gpm	7-8	2:20	140	4:30	270
AR-AFFF	Type II	IPA	Salt	3.0 gpm	7-8	2:15	135	3:45	225
AR-FFF1*	Type II	IPA	Fresh	3-4.5 gpm	7-8	No	No	No	No
AR-FFF1	Type II	IPA	Fresh	7.0 gpm	7-8	4:30	270	No	No
AR-FFF1	Type II	IPA	Fresh	8.0 gpm	7-8	2:15	135	4:35	275
AR-FFF1*	Type II	IPA	Salt	3-4.5 gpm	7-8	No	No	No	No
AR-FFF1	Type II	IPA	Salt	7.0 gpm	7-8	No	No	No	No
AR-FFF1	Type II	IPA	Salt	8.0 gpm	7-8	1:35	95	3:35	215

Foam	Type of Discharge	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont. min:sec	Cont. sec	Ext. min:sec	Ext. sec
AR-FFF2*	Type II	IPA	Fresh	3-4.5 gpm	7-8	No	No	No	No
AR-FFF2	Type II	IPA	Fresh	7.0 gpm	7-8	3:15	195	No	No
AR-FFF2	Type II	IPA	Fresh	8.0 gpm	7-8	2:00	120	4:55	295
AR-FFF2*	Type II	IPA	Salt	3-4.5 gpm	7-8	No	No	No	No
AR-FFF2	Type II	IPA	Salt	7.0 gpm	7-8	No	No	No	No
AR-FFF2	Type II	IPA	Salt	8.0 gpm	7-8	1:55	115	4:15	255
AR-FFF3*	Type II	IPA	Fresh	3-3.75 gpm	7-8	4:15	255	No	No
AR-FFF3	Type II	IPA	Fresh	4.5 gpm	7-8	3:25	205	No	No
AR-FFF3	Type II	IPA	Fresh	5.0 gpm	7-8	1:40	100	4:30	270
AR-FFF3	Type II	IPA	Fresh	6.0 gpm	7-8	1:10	70	3:00	180

* Tests conducted during Series I at lower than listed values

During Series I, the AR-AFFF met the UL 162 Type II requirements at the recommended/listed rate (3 gpm). The AR-AFFF did extremely well during the two tests conducted at a reduced flow rate (i.e., 2.25 gpm), with both test fires being extinguished and one of two successfully passing the UL 162 requirements. For the test that did not pass the UL requirements (2.25 gpm freshwater solution), the fire reached the 20% burnback criteria in about 4-minutes (5-minutes is the pass/fail criteria) which is only a marginal failure.

During the Type II tests conducted with AR-AFFF, a foam blanket was observed to quickly develop at the base of the backboard and flow back across the fuel surface toward the discharge nozzle as the foam accumulated in the pan. Once the foam blanket reached the opposite side, the foam began to expand causing a "pillow" effect around the edges. A photograph of the foam blanket produced by the AR-AFFF during the Type II tests is shown in Figure 8.1-1.

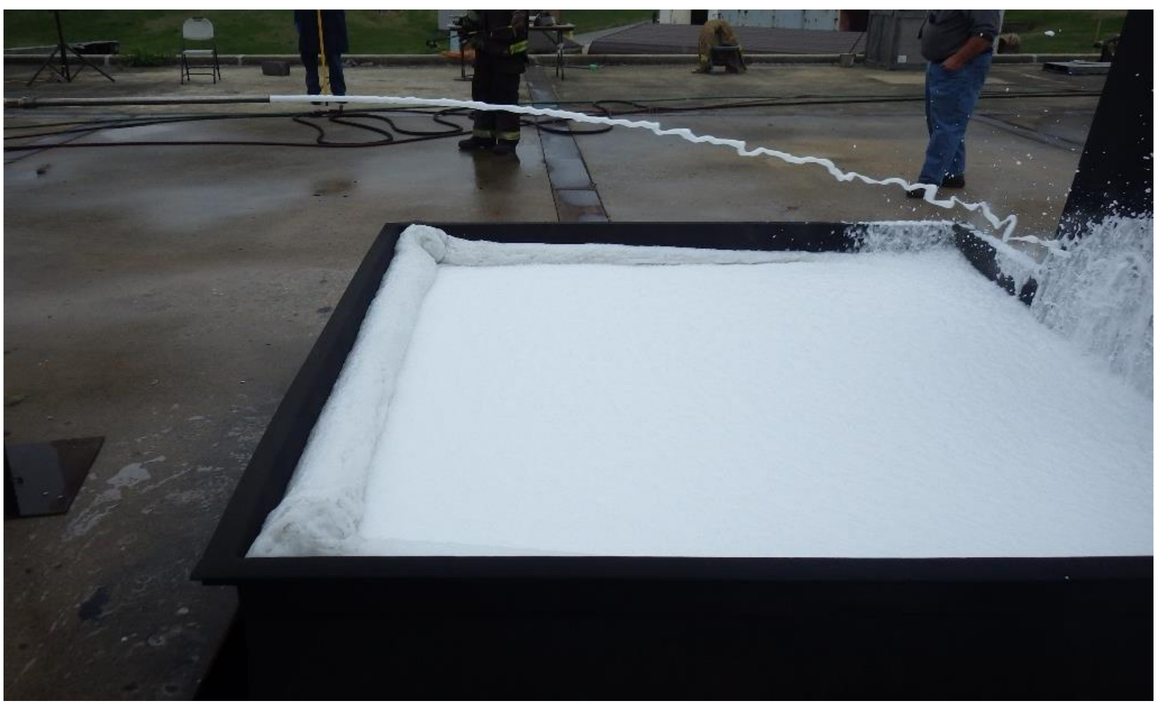


Figure 8.1-1 AR-AFFF Foam Blanket Produced During Type II Tests

During Series I, the original two AR-FFFs were unable to extinguish the IPA fires using either freshwater or saltwater to make the solutions and flow rates up to 4.5 gpm. In a majority of these tests, a foam blanket began to form below the backboard and began to spread across the fuel surface toward the nozzle as the foam accumulated in the pan (similar to the AR-AFFF). However, in all tests, an equilibrium condition occurred at which point, the foam blanket was being held back and/or consumed by the fire. The size/width of the foam blanket appeared to be proportional to the flow rate of the nozzle, but in most cases, the foam blanket never grew to cover more that 70% of the fuel surface. During the one of the tests conducted at 4.5 gpm, the foam blanket was able to reach the opposite side of the pan but could not extinguish the fire along the base of the wall. Photographs showing tests conducted with 3.75 gpm and 4.5 gpm are provided as Figure 8.1-2.

3.75 gpm **4.5 gpm**

Figure 8.1-2 Foam Blanket Formation During Type II Tests with AR-FFF(s)

The previously described observations suggest that the foam blankets produced by the AR-FFFs are not as robust and do not flow as well as that produced with the baseline AR-AFFF and may need to be pushed into obstructed areas in actual fire scenarios. More research is required to further assess/quantify these flow characteristics.

Discouraged by the performance of the original two AR-FFFs (AR-FFF1 and AR-FFF2), a third AR-FFF (AR-FFF3) was obtained and assessed using a limited number of tests (3.0 gpm and 3.75 gpm) toward the end of Series I. In general, AR-FFF3 produced a thicker, more stable foam blanket and was able to control the fire at a flow rate of 3.75 gpm but could not extinguish the fire against the wall directly below the nozzle. However, the foam showed superior capabilities as compared to the original two AR-FFFs and was selected to further testing during Series II. As an interesting observation, after the test conducted with AR-FFF3 at 3.75 gpm was complete (and the fire continued to burn along the edge of the pan), the backside wall of the pan directly below the nozzle was manually cooled and the foam was able to extinguish the fire.

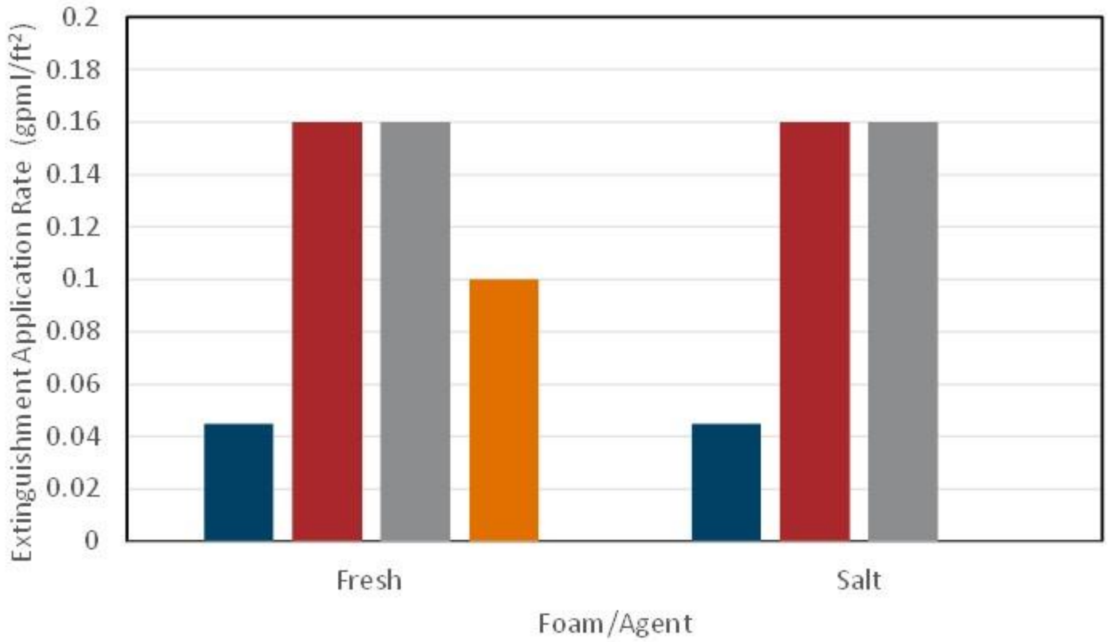
After socializing the Series I test results with the technical panel, it was decided that there may have been a misunderstanding of the “recommended rates” that were selected for testing. After a more detailed review of the UL listings/listed parameters for each foam, it was concluded that the rates used during the Series I Type II tests were about a factor of two low. Specifically, the AR-FFF1 and AR-FFF2 should have been tested at a rate of about 8.5 gpm and AR-FFF3 at a rate of about 6.5 gpm. Based on this information, AR-FFF1 and AR-FFF2 were retested during Series II over a flow rates range of 7-8 gpm and AR-FFF3 between 4.5 and 6 gpm. The slightly lower rates were selected since the performance metrics shifted between Series I and Series II from meeting the UL 162 requires to extinguishing the fire.

During the Series II tests, all three AR-FFFs successfully extinguished the fires at rates slightly below (10%-20% below) the UL listed parameters. The successful tests are summarized in Table 8.1-2 and are shown graphically in Figures 8.1-3.

Table 8.1-2 Successful Type II Test Results (IPA)

Foam	Type of Discharge	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont. sec	Cont. gal/ft^2	Ext. sec	Ext. gal/ft^2
AR-AFFF	Type II	IPA	Fresh	2.25 gpm	7-8	160	0.120	270	0.203
AR-AFFF	Type II	IPA	Salt	2.25 gpm	7-8	140	0.105	270	0.203
AR-FFF1	Type II	IPA	Fresh	8.0 gpm	7-8	135	0.360	275	0.733
AR-FFF1	Type II	IPA	Salt	8.0 gpm	7-8	96	0.256	215	0.573
AR-FFF2	Type II	IPA	Fresh	8.0 gpm	7-8	120	0.320	295	0.787
AR-FFF2	Type II	IPA	Salt	8.0 gpm	7-8	115	0.307	255	0.680
AR-FFF3	Type II	IPA	Fresh	5.0 gpm	7-8	100	0.167	270	0.450

Application Rate



Extinguishment Density

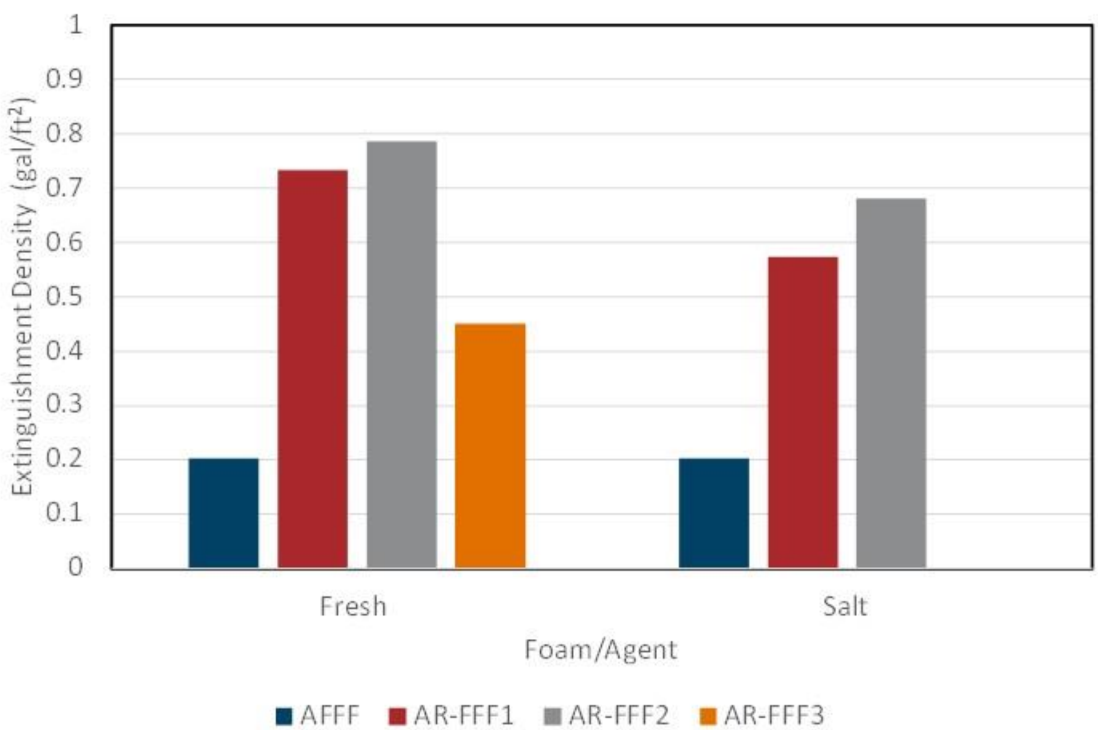


Figure 8.1-3 Type II IPA Foam Comparison

As shown in Figure 8.1-3, AR-FFF1 and AR-FFF2 required 8 gpm to extinguish the IPA fires which is 3.5 times the 2.25 gpm required using AFFF. AR- FFF3 required 5 gpm which is 2.2 times the 2.25 gpm required using AFFF. Extinguishment densities followed roughly the same trends as shown in the bottom plot in Figure 8.1-3.

8.2. Additional Type II Tests (Hydrocarbons)

Eight additional Type II tests were conducted to provide a comparison of the firefighting capabilities of the various foams in the Type II configuration using heptane and gasoline as the fuel. The pass/fail results of these tests are shown in Table 8.2-1 and the time/density results are shown in Table 8.2-2.

Table 8.2-1 Type II Test Results (Gasoline and Heptane – Pass/Fail)

Foam	Type of Discharge	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont.	Ext.	1st Pass	2nd Pass	Burnback	Total
AR-AFFF	Type II	Heptane	Fresh	3 gpm	7-8	P	P	P	F*	P	F
AR-FFF2	Type II	Heptane	Fresh	3 gpm	7-8	P	F	-	-	-	F
AR-FFF3	Type II	Heptane	Fresh	3 gpm	7-8	P	P	P	F	-	F
FFF2	Type II	Heptane	Fresh	3 gpm	7-8	P	F**	-	-	-	F
AR-AFFF	Type II	MILSPEC	Fresh	3 gpm	7-8	P	P	F*	F*	P	F
AR-FFF2	Type II	MILSPEC	Fresh	3 gpm	7-8	P	F	-	-	-	F
AR-FFF3	Type II	MILSPEC	Fresh	3 gpm	7-8	P	F	-	-	-	F
FFF2	Type II	MILSPEC	Fresh	3 gpm	7-8	P	P	F	-	-	F

* self extinguished shortly after the 30 second limit
** small flames on pillow top near front edge

As shown in Table 8.2-1, all of the foams were able to control the test fires at a discharge rate of 3 gpm but only half of the fires were extinguished. As shown in Table 8.2-2, the AR-AFFF typically required less agent (about half that of the FFFs) to control the fires but the extinguishment quantities were fairly similar for the FFFs that passed the test. With that said, two of the FFFs were unable to extinguish the fire in both sets of tests (a set is the group conducted with the same test fuel).

Table 8-2-2 Type II Test Results (Gasoline and Heptane – Time/Density)

Foam	Type of Discharge	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont.	Cont. Time sec	Cont. Den gal/ft^2	Ext.	Ext. Time sec	Ext. Den gal/ft^2
AR-AFFF	Type II	Heptane	Fresh	3 gpm	7-8	P	28	0.028	P	110	0.110
AR-FFF2	Type II	Heptane	Fresh	3 gpm	7-8	P	65	0.065	F		
AR-FFF3	Type II	Heptane	Fresh	3 gpm	7-8	P	46	0.046	P	80	0.080
FFF2	Type II	Heptane	Fresh	3 gpm	7-8	P	42	0.042	F*		
AR-AFFF	Type II	MILSPEC	Fresh	3 gpm	7-8	P	38	0.038	P	210	0.210
AR-FFF2	Type II	MILSPEC	Fresh	3 gpm	7-8	P	60	0.060	F		
AR-FFF3	Type II	MILSPEC	Fresh	3 gpm	7-8	P	57	0.057	F		
FFF2	Type II	MILSPEC	Fresh	3 gpm	7-8	P	51	0.051	P	285	0.285

* small flames on pillow top near front edge

8.3. TYPE III IPA TEST RESULTS

In addition to the Type II tests conducted with IPA, a limited number of tests were conducted with IPA using the Type III scenario (manual firefighting/foam application). The tests were conducted with the two best AR-FFFs (AR-FFF1 and AR-FFF3) identified during the Type II tests and were tested at the same flow rates and equipment (i.e., straight stream nozzle configuration) used to extinguish the fires during the Type II tests. The results of the test are shown in Table 8.3-1.

Table 8.3-1 IPA Type III Test Results

Foam	Type of Discharge	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont. min:sec	Ext. min:sec
AR-FFF1	Type II	IPA	Fresh	8.0 gpm	7-8	2:15	4:35
AR-FFF1	Type III – Straight Bore	IPA	Fresh	8.0 gpm	7-8	No	No
AR-FFF1	Type III– Fan Tip	IPA	Fresh	8.0 gpm	7-8	No	No
AR-FFF3	Type II	IPA	Fresh	5.0 gpm	7-8	1:40	4:30
AR-FFF3	Type III– Straight Bore	IPA	Fresh	5.0 gpm	7-8	No	No
AR-FFF3	Type III– Fan Tip	IPA	Fresh	5.0 gpm	7-8	No	No
AR-FFF3	Type III– Fan Tip	IPA	Fresh	8.0 gpm	7-8	4:15	No

During the first test conducted with each foam (i.e., straight bore nozzle), the foam tended to disappear on impact with the fuel surface. As a result, the foams had no effect on the fire and there was no visible expanded foam on the burning fuel surface, even at the end of the tests (i.e., after the 5-minute discharge). Concerned that the straight stream application was adversely affecting the development of the foam blanket on the fuel surface (i.e., causing the foam to plunge into the fuel), the tests were then repeated with the spreader tip installed at the end of the nozzle (produces a fan shaped spray pattern).

The results of the tests conducted with the spreader tip were slightly better than the tests conducted with the straight bore nozzle but the foams still had only a minimal effect on the fire. The final test was conducted using the best performer from the Type II test series (i.e., AR-FFF3) at a higher flow rate than the one required to pass the Type II tests (8 gpm versus the 5 gpm required to pass the test). Even at this higher flow rate, it took over four minutes of discharge to control the fire and extinguishment was never achieved.

An interesting observation was made by the firefighters during the manual suppression of the fire after the test was terminated. If the firefighter directed the foam against the side/wall of the pan (versus discharging into the center of the pan), it had the same effect as hitting the back wall during the Type II tests. Hitting the side of the pan appears to dry the foam and gently applies it to the fuel surface allowing the development of a foam blanket which ultimately leads to extinguishments.

The results demonstrate that IPA is extremely difficult to extinguish with direct spray impingement on the fuel surface and requires an indirect attack to be effective. A series of photographs showing the difference between applying the foam to the center of the pan versus hitting the side/wall are provided in Figure 8.3-1.

AR-FFF1 discharged into the center at 8 gpm

2:00 **3:00** **4:00** **5:00**

AR-FFF1 discharged against the back side/wall at 8 gpm

2:00 **3:00** **4:00** **5:00**

Figure 8.3-1 Direct and Indirect Attacks on Type III IPA Fires

9. Type III Test Results And Discussion

9.1. Type III Test Results

The results of the Type III tests are discussed in the following sections.

As expected (since these are tests used in the listing process), all five foams met the UL 162 requirements for heptane, at the design/recommended discharge rates (i.e., 2 or 3 gpm) using higher aspirated foam. However, only three of the foams met the requirements with lower aspirated foam. The foams that did not meet the requirements were able to extinguish the heptane fires but failed some part of the post extinguishment assessment (reignition during a torch pass or burnback resistance – refer to Section 6.4). There were also significant variations in capabilities of the foams for the fires conducted with gasoline. A comparison of fuel types will be discussed later in the report.

The tables shown in the following sections have been highlighted (in yellow) to show the lowest flow/application rate required to meet the following criteria; control, extinguishment and meeting the full UL 162 requirements for each set of conditions (i.e., fuel type, water type and foam quality/aspiration).

9.1.1. Type III AR-AFFF Results

The pass/fail results of the Type III tests conducted with AR-AFFF are shown in Table 9.1.1-1 and the time/density results are shown in Table 9.1.1-2.

Table 9.1.1-1 AR-AFFF Type III Test Results (Pass/Fail)

Foam	Series	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont.	Ext.	1st Pass	2nd Pass	Burnback	UL 162
AR-AFFF	Series I	Heptane	Fresh	2 gpm	7-8	P	P	P	P	Self Ext	P
AR-AFFF	Series I	Heptane	Fresh	2 gpm	3-4	P	P	P	P	Self Ext	P
AR-AFFF	Series I	Heptane	Fresh	1.5 gpm	3-4	P	P	P	F	-	F
AR-AFFF	Series I	Heptane	Salt	2 gpm	3-4	P	P	P	P	Self Ext	P
AR-AFFF	Series I	Heptane	Salt	1.5 gpm	3-4	P	P	F	-	-	F
AR-AFFF	Series I	MILSPEC	Fresh	2 gpm	3-4	P	P	P	P	Self Ext	P
AR-AFFF	Series I	MILSPEC	Fresh	1.5 gpm	3-4	P	F	-	-	-	F
AR-AFFF	Series I	MILSPEC	Salt	2 gpm	3-4	P	P	P	F	-	F
AR-AFFF	Series I	MILSPEC	Salt	2.5 gpm	3-4	P	P	P	P	+5:00	P
AR-AFFF	Series II	MILSPEC	Fresh	3 gpm	7-8	P	P	P	P	Self Ext	P
AR-AFFF	Series II	E10	Fresh	3 gpm	7-8	P	P	P	P	Self Ext	P

Tests conducted without a water substrate

As shown in Table 9.1.1-1, the AR-AFFF met the UL 162 requirements at the design/recommended discharge rate (i.e., 2 gpm) with the lower aspirated foam in all tests with the exception of the test conducted using saltwater to make the foam solution and with MILSPEC gasoline as the fuel. During this test, the fuel reignited on the second torch pass and continued to burn along the edges of the pan.

The AR-AFFF was also capable of extinguishing the heptane fires with the lower aspirated foam at a 25% reduction in flow rate (i.e., 1.5 gpm) but was unable to extinguish the MILSPEC gasoline using the same flow rate (and using freshwater to make the foam). During the test conducted with MILSPEC gasoline at the lower flow rate, the AR-AFFF was able to quickly control the fire, but the fire continued to burn in the far corner of the pan away from the firefighter location (possibly related to stream reach).

During Series II, the AR-AFFF was also able to quickly extinguish both the MILSPEC and E10 gasoline fires at a foam flow rate of 3 gpm and successfully completed the two torch passes and burnback portions of the test.

The time/density results will be discussed later in the report.

Table 9.1.1-2 AR-AFFF Type III Test Results (Time/Density)

Foam	Series	Fuel Type	Water Type	Flow Rate	App Rate gpm/ft^2	Exp. Ratio	Cont.	Cont. Time sec	Cont. Den gal/ft^2	Ext.	Ext. Time sec	Ext. Den gal/ft^2
AR-AFFF	Series I	Heptane	Fresh	2 gpm	0.04	7-8	P	33	0.022	P	77	0.051
AR-AFFF	Series I	Heptane	Fresh	2 gpm	0.04	3-4	P	40	0.027	P	127	0.085
AR-AFFF	Series I	Heptane	Fresh	1.5 gpm	0.03	3-4	P	53	0.026	P	172	0.086
AR-AFFF	Series I	Heptane	Salt	2 gpm	0.04	3-4	P	35	0.023	P	152	0.100
AR-AFFF	Series I	Heptane	Salt	1.5 gpm	0.03	3-4	P	60	0.030	P	196	0.098
AR-AFFF	Series I	MILSPEC	Fresh	2 gpm	0.04	3-4	P	52	0.035	P	115	0.077
AR-AFFF	Series I	MILSPEC	Fresh	1.5 gpm	0.03	3-4	P	58	0.029	F		
AR-AFFF	Series I	MILSPEC	Salt	2 gpm	0.04	3-4	P	46	0.031	P	142	0.095
AR-AFFF	Series I	MILSPEC	Salt	2.5 gpm	0.05	3-4	P	38	0.032	P	112	0.093
AR-AFFF	Series II	MILSPEC	Fresh	3 gpm	0.06	7-8	P	45	0.045	P	65	0.065
AR-AFFF	Series II	E10	Fresh	3 gpm	0.06	7-8	P	45	0.045	P	60	0.060

Tests conducted without a water substrate

9.1.2. Type III AR-FFF1 Results

The pass/fail results of the Type III tests conducted with AR-FFF1 are shown in Table 9.1.2-1 and the time/density results are shown in Table 9.1.2-2.

Table 9.1.2-1 AR-FFF1 Type III Test Results (Pass/Fail)

Foam	Series	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont.	Ext.	1st Pass	2nd Pass	Burnback	UL 162
AR-FFF1	Series I	Heptane	Fresh	3 gpm	7-8	P	P	P	P	Self Ext	P
AR-FFF1	Series I	Heptane	Fresh	3 gpm	3-4	P	P	P	P	Self Ext	P
AR-FFF1	Series I	Heptane	Fresh	2.25	3-4	P	P	P	F	-	F
AR-FFF1	Series I	Heptane	Salt	3 gpm	3-4	P	P	P	P	Self Ext	P
AR-FFF1	Series I	Heptane	Salt	2.25 gpm	3-4	P	F	-	-	-	F
AR-FFF1	Series I	MILSPEC	Fresh	3 gpm	3-4	P	F	-	-	-	F
AR-FFF1	Series I	MILSPEC	Fresh	3.75 gpm	3-4	P	P	F	-	-	F
AR-FFF1	Series I	MILSPEC	Fresh	4.5 gpm	3-4	P	P	F	-	-	F
AR-FFF1	Series I	MILSPEC	Salt	3 gpm	3-4	P	F	-	-	-	F
AR-FFF1	Series I	MILSPEC	Salt	3.75 gpm	3-4	P	F	-	-	-	F
AR-FFF1	Series I	MILSPEC	Salt	4.5 gpm	3-4	P	P	F	-	-	F
AR-FFF1	Series I	IPA	Fresh	3.75 gpm	3-4	F	F	-	-	-	F
AR-FFF1	Series II	MILSPEC	Fresh	3 gpm	7-8	P	P	P	F	-	F
AR-FFF1	Series II	MILSPEC	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
AR-FFF1	Series II	MILSPEC	Salt	3 gpm	7-8	P	P	P	F	-	F
AR-FFF1	Series II	MILSPEC	Salt	3.75 gpm	7-8	P	P	P	F	-	F
AR-FFF1	Series II	MILSPEC	Fresh	3 gpm	7-8	P	P	P	F	-	F
AR-FFF1	Series II	MILSPEC	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
AR-FFF1	Series II	MILSPEC	Salt	3 gpm	7-8	P	P	P	F	-	F
AR-FFF1	Series II	MILSPEC	Salt	3.75 gpm	7-8	P	P	P	F	-	F
AR-FFF1	Series II	E10	Fresh	3.75 gpm	7-8	P	F	-	-	-	F
AR-FFF1	Series II	E10	Fresh	4.5 gpm	7-8	P	P	P	F	-	F
AR-FFF1	Series II	E10	Salt	3.75 gpm	7-8	P	F	-	-	-	F
AR-FFF1	Series II	E10	Salt	4.5 gpm	7-8	P	P	P	F	-	F

Tests conducted without a water substrate

As shown in Table 9.1.2-1, the AR-FFF1 met the UL 162 requirements with the lower aspirated foam at the design/recommended discharge rate (i.e., 3 gpm) using the lower aspirated foam for the fires conducted with heptane. When mixed with freshwater, AR-FFF1 was also able to extinguish the heptane fire at a 25% reduced rate (i.e., 2.25 gpm) with the lower aspirated foam. When mixed with saltwater, AR-FFF1 was only able to control the heptane fire at the reduced rate.

During the test conducted using the lower aspirated foam with MILSPEC gasoline as the fuel, AR-FFF1 was unable to meet the UL 162 requirements even at the higher flow rates (i.e., 50% above design – 4.5 gpm). When mixed with freshwater, AR-FFF1 was able to extinguish the MILSPEC gasoline at a 25% increased rate (i.e., 3.75 gpm) but failed the first torch pass. When mixed with saltwater, AR-FFF1 required a 50% increased rate (i.e., 4.5 gpm) to extinguish the MILSPEC gasoline but also failed the first torch test.

During the Series II assessment conducted with higher aspirated foams, AR-FFF1 extinguished the MILSPEC gasoline with 3 gpm for all scenarios (freshwater, saltwater, and with and without a water substrate for the fuel). AR-FFF1 required a 50% increase in flow rate (4.5 gpm) to extinguish the E10 fires (no water substrate) with both freshwater and saltwater solutions.

The time/density results will be discussed later in the report.

Table 9.1.2-2 AR-FFF1 Type III Test Results (Time/Density)

Foam	Series	Fuel Type	Water Type	Flow Rate	App Rate gpm/ft^2	Exp. Ratio	Cont.	Cont. Time sec	Cont. Den gal/ft^2	Ext.	Ext. Time sec	Ext. Den gal/ft^2
AR-FFF1	Series I	Heptane	Fresh	3 gpm	0.06	7-8	P	45	0.045	P	105	0.105
AR-FFF1	Series I	Heptane	Fresh	3 gpm	0.06	3-4	P	65	0.065	P	180	0.180
AR-FFF1	Series I	Heptane	Fresh	2.25	0.045	3-4	P	81	0.061	P	264	0.198
AR-FFF1	Series I	Heptane	Salt	3 gpm	0.06	3-4	P	45	0.045	P	185	0.185
AR-FFF1	Series I	Heptane	Salt	2.25 gpm	0.045	3-4	P	53	0.047	F	-	-
AR-FFF1	Series I	MILSPEC	Fresh	3 gpm	0.06	3-4	P	80	0.080	F	-	-
AR-FFF1	Series I	MILSPEC	Fresh	3.75 gpm	0.075	3-4	P	64	0.080	F	-	-
AR-FFF1	Series I	MILSPEC	Fresh	4.5 gpm	0.09	3-4	P	55	0.082	P	300	0.375
AR-FFF1	Series I	MILSPEC	Salt	3 gpm	0.06	3-4	P	50	0.050	F	-	-
AR-FFF1	Series I	MILSPEC	Salt	3.75 gpm	0.075	3-4	P	72	0.090	F	-	-
AR-FFF1	Series I	MILSPEC	Salt	4.5 gpm	0.09	3-4	P	60	0.090	P	250	0.375
AR-FFF1	Series I	IPA	Fresh	3.75 gpm	0.075	3-4	F	-	-	F	-	-
AR-FFF1	Series II	MILSPEC	Fresh	3 gpm	0.06	7-8	P	70	0.070	P	220	0.220
AR-FFF1	Series II	MILSPEC	Fresh	3.75 gpm	0.075	7-8	P	50	0.063	P	210	0.263
AR-FFF1	Series II	MILSPEC	Salt	3 gpm	0.06	7-8	P	85	0.085	P	230	0.230
AR-FFF1	Series II	MILSPEC	Salt	3.75 gpm	0.075	7-8	P	60	0.075	P	195	0.244
AR-FFF1	Series II	MILSPEC	Fresh	3 gpm	0.06	7-8	P	70	0.070	P	220	0.220
AR-FFF1	Series II	MILSPEC	Fresh	3.75 gpm	0.075	7-8	P	60	0.075	P	150	0.188
AR-FFF1	Series II	MILSPEC	Salt	3 gpm	0.06	7-8	P	85	0.085	P	230	0.230
AR-FFF1	Series II	MILSPEC	Salt	3.75 gpm	0.075	7-8	P	60	0.075	P	160	0.200
AR-FFF1	Series II	E10	Fresh	3.75 gpm	0.075	7-8	P	110	0.138	F	-	-
AR-FFF1	Series II	E10	Fresh	4.5 gpm	0.09	7-8	P	95	0.143	P	275	0.413
AR-FFF1	Series II	E10	Salt	3.75 gpm	0.075	7-8	P	140	0.175	F	-	-
AR-FFF1	Series II	E10	Salt	4.5 gpm	0.09	7-8	P	110	0.165	P	260	0.390

Tests conducted without a water substrate

9.1.3. Type III AR-FFF2 Results

The pass/fail results of the Type III tests conducted with AR-FFF2 are shown in Table 9.1.3-1 and the time/density results are shown in Table 9.1.3-2.

Table 9.1.3-1 AR-FFF2 Type III Test Results (Pass/Fail)

Foam	Series	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont.	Ext.	1st Pass	2nd Pass	Burnback	UL 162
AR-FFF2	Series I	Heptane	Fresh	3 gpm	7-8	P	P	P	P	Self Ext	P
AR-FFF2	Series I	Heptane	Fresh	3 gpm	3-4	P	P	P	P	Self Ext	P
AR-FFF2	Series I	Heptane	Fresh	2.25 gpm	3-4	P	P	P	P	Self Ext	P
AR-FFF2	Series I	Heptane	Salt	3 gpm	3-4	P	P	P	P	+5:00	P
AR-FFF2	Series I	Heptane	Salt	2.25 gpm	3-4	P	F	-	-	-	F
AR-FFF2	Series I	MILSPEC	Fresh	3 gpm	3-4	P	F	-	-	-	F
AR-FFF2	Series I	MILSPEC	Fresh	3.75 gpm	3-4	P	F	-	-	-	F
AR-FFF2	Series I	MILSPEC	Fresh	3.75 gpm	7-8	P	P	P	P	Self Ext	P
AR-FFF2	Series I	MILSPEC	Fresh	4.5 gpm	3-4	P	P	F	-	-	F
AR-FFF2	Series I	MILSPEC	Fresh	4.5 gpm	7-8	P	P	P	P	Self Ext	P
AR-FFF2	Series I	MILSPEC	Salt	3 gpm	3-4	P	F	-	-	-	F
AR-FFF2	Series I	MILSPEC	Salt	3.75 gpm	3-4	P	F	-	-	-	F
AR-FFF2	Series I	MILSPEC	Salt	3.75 gpm	7-8	P	P	P	P	Self Ext	P
AR-FFF2	Series I	MILSPEC	Salt	4.5 gpm	3-4	P	P	F	-	-	F
AR-FFF2	Series II	MILSPEC	Fresh	3 gpm	7-8	P	P	P	F	-	F
AR-FFF2	Series II	MILSPEC	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
AR-FFF2	Series II	MILSPEC	Salt	3 gpm	7-8	P	P	P	F	-	F
AR-FFF2	Series II	MILSPEC	Salt	3.75 gpm	7-8	P	P	P	F	-	F
AR-FFF2	Series II	MILSPEC	Fresh	3 gpm	7-8	P	P	P	F	-	F
AR-FFF2	Series II	MILSPEC	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
AR-FFF2	Series II	MILSPEC	Salt	3 gpm	7-8	P	P	P	F	-	F
AR-FFF2	Series II	MILSPEC	Salt	3.75 gpm	7-8	P	P	P	F	-	F
AR-FFF2	Series II	E10	Fresh	3.75 gpm	7-8	P	F	-	-	-	F
AR-FFF2	Series II	E10	Fresh	4.5 gpm	7-8	P	P	P	F	-	F
AR-FFF2	Series II	E10	Salt	3.75 gpm	7-8	P	F	-	-	-	F
AR-FFF2	Series II	E10	Salt	4.5 gpm	7-8	P	P	P	F	-	F

Tests conducted without a water substrate

As shown in Table 9.1.3-1, the AR-FFF2 met the UL 162 requirements at the design/recommended discharge rate (i.e., 3 gpm) using the lower aspirated foam for the fires conducted with heptane. When mixed with freshwater, AR-FFF2 was also able to extinguish the heptane fire at a 25% reduced rate (i.e., 2.25 gpm) with the lower aspirated foam. When mixed with saltwater, AR-FFF2 was able to control the heptane fire but was not able to extinguish the fire at the reduced rate.

During the test conducted using the lower aspirated foam with MILSPEC gasoline as the fuel, AR-FFF2 was unable to meet the UL 162 requirements even at the higher flow rates (i.e., 50% above design – 4.5 gpm). AR-FFF2 was able to extinguish the MILSPEC gasoline at the higher rate (i.e., 4.5 gpm) for both water solutions (freshwater and saltwater) but failed the first torch pass in both tests.

However, during Series I, AR-FFF2 was able to meet the UL 162 requirements at 3.75 gpm (25% above recommended) with higher aspirated foam for MILSPEC gasoline (with a water substrate) for both water solutions.

During the Series II assessment conducted with higher aspirated foams, AR-FFF2 extinguished the MILSPEC gasoline with 3 gpm for all scenarios (freshwater, saltwater, and with and without a water substrate for the fuel). AR-FFF2 required a 50% increase in flow rate (4.5 gpm) to extinguish the E10 fires (no water substrate) with both freshwater and saltwater solutions.

The time/density results will be discussed later in the report.

Table 9.1.3-2 AR-FFF2 Type III Test Results (Time/Density)

Foam	Series	Fuel Type	Water Type	Flow Rate	App Rate gpm/ft^2	Exp. Ratio	Cont.	Cont. Time sec	Cont. Den gal/ft^2	Ext.	Ext. Time sec	Ext. Den gal/ft^2
AR-FFF2	Series I	Heptane	Fresh	3 gpm	0.06	7-8	P	45	0.045	P	107	0.107
AR-FFF2	Series I	Heptane	Fresh	3 gpm	0.06	3-4	P	50	0.050	P	165	0.165
AR-FFF2	Series I	Heptane	Fresh	2.25 gpm	0.045	3-4	P	76	0.057	P	255	0.191
AR-FFF2	Series I	Heptane	Salt	3 gpm	0.06	3-4	P	60	0.060	P	155	0.155
AR-FFF2	Series I	Heptane	Salt	2.25 gpm	0.045	3-4	P	69	0.052	F	-	-
AR-FFF2	Series I	MILSPEC	Fresh	3 gpm	0.06	3-4	P	75	0.075	F	-	-
AR-FFF2	Series I	MILSPEC	Fresh	3.75 gpm	0.075	3-4	P	95	0.119	F	-	-
AR-FFF2	Series I	MILSPEC	Fresh	3.75 gpm	0.075	7-8	P	60	0.075	P	300	0.375
AR-FFF2	Series I	MILSPEC	Fresh	4.5 gpm	0.09	3-4	P	60	0.095	P	260	0.390
AR-FFF2	Series I	MILSPEC	Fresh	4.5 gpm	0.09	7-8	P	60	0.095	P	180	0.270
AR-FFF2	Series I	MILSPEC	Salt	3 gpm	0.06	3-4	P	72	0.072	F	-	-
AR-FFF2	Series I	MILSPEC	Salt	3.75 gpm	0.075	3-4	P	90	0.113	F	-	-
AR-FFF2	Series I	MILSPEC	Salt	3.75 gpm	0.075	7-8	P	60	0.075	P	280	0.350
AR-FFF2	Series I	MILSPEC	Salt	4.5 gpm	0.09	3-4	P	75	0.113	P	250	0.375
AR-FFF2	Series II	MILSPEC	Fresh	3 gpm	0.06	7-8	P	60	0.060	P	255	0.255
AR-FFF2	Series II	MILSPEC	Fresh	3.75 gpm	0.075	7-8	P	75	0.094	P	225	0.281
AR-FFF2	Series II	MILSPEC	Salt	3 gpm	0.06	7-8	P	65	0.065	P	270	0.270
AR-FFF2	Series II	MILSPEC	Salt	3.75 gpm	0.075	7-8	P	70	0.088	P	220	0.275
AR-FFF2	Series II	MILSPEC	Fresh	3 gpm	0.06	7-8	P	60	0.060	P	210	0.210
AR-FFF2	Series II	MILSPEC	Fresh	3.75 gpm	0.075	7-8	P	60	0.075	P	165	0.206
AR-FFF2	Series II	MILSPEC	Salt	3 gpm	0.06	7-8	P	80	0.080	P	200	0.200
AR-FFF2	Series II	MILSPEC	Salt	3.75 gpm	0.075	7-8	P	65	0.081	P	145	0.181
AR-FFF2	Series II	E10	Fresh	3.75 gpm	0.075	7-8	P	270	0.338	F	-	-
AR-FFF2	Series II	E10	Fresh	4.5 gpm	0.09	7-8	P	150	0.225	P	255	0.383
AR-FFF2	Series II	E10	Salt	3.75 gpm	0.075	7-8	P	180	0.225	F	-	-
AR-FFF2	Series II	E10	Salt	4.5 gpm	0.09	7-8	P	140	0.210	P	295	0.443

Tests conducted without a water substrate

9.1.4. Type III AR-FFF3 Results

The pass/fail results of the Type III tests conducted with AR-FFF3 are shown in Table 9.1.4-1 and the time/density results are shown in Table 9.1.4-2. Since AR-FFF3 is only listed/approved for freshwater, no saltwater tests were conducted with this agent.

Table 9.1.4-1 AR-FFF3 Type III Test Results (Pass/Fail)

Foam	Series	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont.	Ext.	1st Pass	2nd Pass	Burnback	UL 162
AR-FFF3	Series II	MILSPEC	Fresh	3 gpm	7-8	P	P	P	F	-	F
AR-FFF3	Series II	MILSPEC	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
AR-FFF3	Series II	E10	Fresh	3.75 gpm	7-8	P	F	-	-	-	F
AR-FFF3	Series II	E10	Fresh	4.5 gpm	7-8	P	P	P	F	-	F

Tests conducted without a water substrate

AR-FFF3 was added to the assessment after Series I was complete and prior to the start of Series II. During Series II, the assessment was focused primarily on fire extinguishment as opposed to meeting the UL 162 requirements. As a reminder, AR-FFF3 is not listed for use with saltwater and as a result, was not tested using saltwater.

Using the higher aspirated foam during Series II, AR-FFF3 was capable of extinguishing the MILSPEC gasoline with 3 gpm but required a 50% increase in flow rate (4.5 gpm) to extinguish the E10 fires (both with no water substrate).

The time/density results will be discussed later in the report.

Table 9.1.3-2 AR-FFF3 Type III Test Results (Time/Density)

Foam	Series	Fuel Type	Water Type	Flow Rate	App Rate gpm/ft^2	Exp. Ratio	Cont.	Cont. Time sec	Cont. Den gal/ft^2	Ext.	Ext. Time sec	Ext. Den gal/ft^2
AR-FFF3	Series II	MILSPEC	Fresh	3 gpm	0.06	7-8	P	70	0.070	P	230	0.230
AR-FFF3	Series II	MILSPEC	Fresh	3.75 gpm	0.075	7-8	P	65	0.081	P	220	0.275
AR-FFF3	Series II	E10	Fresh	3.75 gpm	0.075	7-8	P	85	0.106	F	-	-
AR-FFF3	Series II	E10	Fresh	4.5 gpm	0.09	7-8	P	75	0.113	P	235	0.353

Tests conducted without a water substrate

9.1.5. Type III H-FFF1 Results

The pass/fail results of the Type III tests conducted with H-FFF1 are shown in Table 9.1.5-1 and the time/density results are shown in Table 9.1.5-2.

Table 9.1.5-1 H-FFF1 Type III Test Results (Pass/Fail)

Foam	Series	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont.	Ext.	1st Pass	2nd Pass	Burnback	UL 162
H-FFF1	Series I	Heptane	Fresh	3 gpm	7-8	P	P	P	P	Self Ext	P
H-FFF1	Series I	Heptane	Fresh	3 gpm	3-4	P	P	P	F	-	F
H-FFF1	Series I	Heptane	Fresh	3.75 gpm	3-4	P	P	P	P	Self Ext	P
H-FFF1	Series I	Heptane	Fresh	2.25 gpm	3-4	P	P	P	F	-	F
H-FFF1	Series I	Heptane	Salt	3 gpm	3-4	P	P	P	F*	Self Ext	F
H-FFF1	Series I	Heptane	Salt	2.25 gpm	3-4	P	P	F*	F	-	F
H-FFF1	Series I	Heptane	Salt	3.75 gpm	3-4	P	P	P	F*	Self Ext	F
H-FFF1	Series I	Heptane	Salt	4.5 gpm	3-4	P	P	P	P	Self Ext	P
H-FFF1	Series I	MILSPEC	Fresh	3 gpm	3-4	P	P	P	F	-	F
H-FFF1	Series I	MILSPEC	Fresh	3 gpm	7-8	P	P	P	P	Self Ext	P
H-FFF1	Series I	MILSPEC	Fresh	3.75 gpm	3-4	P	P	P	F	-	F
H-FFF1	Series I	MILSPEC	Fresh	4.5 gpm	3-4	P	P	P	P	Self Ext	P
H-FFF1	Series I	MILSPEC	Salt	3 gpm	3-4	P	P	F	-	-	F
H-FFF1	Series I	MILSPEC	Salt	3.75 gpm	3-4	P	P	P	F	-	F
H-FFF1	Series I	MILSPEC	Salt	4.5 gpm	3-4	P	P	P	P	Self Ext	P
H-FFF1	Series II	MILSPEC	Fresh	3 gpm	7-8	P	P	P	F	-	F
H-FFF1	Series II	MILSPEC	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
H-FFF1	Series II	MILSPEC	Salt	3 gpm	7-8	P	P	P	F	-	F
H-FFF1	Series II	MILSPEC	Salt	3.75 gpm	7-8	P	P	P	F	-	F
H-FFF1	Series II	MILSPEC	Fresh	3 gpm	7-8	P	P	P	F	-	F
H-FFF1	Series II	MILSPEC	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
H-FFF1	Series II	MILSPEC	Salt	3 gpm	7-8	P	P	P	F	-	F
H-FFF1	Series II	MILSPEC	Salt	3.75 gpm	7-8	P	P	P	F	-	F
H-FFF1	Series II	E10	Fresh	3.0 gpm	7-8	P	F	-	-	-	F
H-FFF1	Series II	E10	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
H-FFF1	Series II	E10	Salt	3.0 gpm	7-8	P	F	-	-	-	F
H-FFF1	Series II	E10	Salt	3.75 gpm	7-8	P	P	P	F	-	F
H-FFF1	Series II	E10	Salt	4.5 gpm	7-8	P	P	P	F	-	F

* self-extinguished shortly after the 30 second limit

Tests conducted without a water substrate

As shown in Table 9.1.5-1, H-FFF1 was capable of controlling and extinguishing all of the fires conducted during the Series I assessment using the lower aspirated foam. Even with the lower aspirated foam, H-FFF1 extinguished the heptane fires at a 25% reduced flow rate (i.e., 2.25 gpm) when mixed with either freshwater or saltwater. H-FFF1 also extinguished the MILSPEC fires with the lower aspirated foam at the design/recommended discharge rate (i.e., 3 gpm) when mixed with either freshwater or saltwater.

The variations in test results occurred during the post extinguishment assessments (reignition during a torch pass or burnback resistance). For the most part, H-FFF1 successfully completed the first torch pass but typically failed the second one, except for the highest flow rate (i.e., 50% above design – 4.5 gpm). However, in most cases, there appeared to be "some" fuel pickup associated with the lower aspirated foams.

During the Series II assessment conducted with higher aspirated foams, H-FFF1 extinguished the MILSPEC gasoline with 3 gpm for all scenarios (freshwater, saltwater, and with and without a water substrate for the fuel). However, H-FFF1 required a 25% increase in flow rate (3.75 gpm) to extinguish the E10 fires (no water substrate) with both freshwater and saltwater solutions.

The time/density results will be discussed later in the report.

Table 9.1.5-2 H-FFF1 Type III Test Results (Time/Density)

Foam	Series	Fuel Type	Water Type	Flow Rate	App Rate gpm/ft²	Exp. Ratio	Cont.	Cont. Time sec	Cont. Den gal/ft²	Ext.	Ext. Time sec	Ext. Den gal/ft²
H-FFF1	Series I	Heptane	Fresh	3 gpm	0.06	7-8	P	35	0.035	P	92	0.092
H-FFF1	Series I	Heptane	Fresh	3 gpm	0.06	3-4	P	36	0.036	P	102	0.102
H-FFF1	Series I	Heptane	Fresh	3.75 gpm	0.075	3-4	P	32	0.040	P	95	0.119
H-FFF1	Series I	Heptane	Fresh	2.25 gpm	0.045	3-4	P	45	0.034	P	220	0.165
H-FFF1	Series I	Heptane	Salt	3 gpm	0.06	3-4	P	35	0.035	P	150	0.150
H-FFF1	Series I	Heptane	Salt	2.25 gpm	0.045	3-4	P	48	0.036	P	280	0.210
H-FFF1	Series I	Heptane	Salt	3.75 gpm	0.075	3-4	P	35	0.044	P	150	0.188
H-FFF1	Series I	Heptane	Salt	4.5 gpm	0.09	3-4	P	30	0.045	P	120	0.180
H-FFF1	Series I	MILSPEC	Fresh	3 gpm	0.06	3-4	P	37	0.037	P	165	0.165
H-FFF1	Series I	MILSPEC	Fresh	3 gpm	0.06	7-8	P	25	0.025	P	132	0.132
H-FFF1	Series I	MILSPEC	Fresh	3.75 gpm	0.075	3-4	P	32	0.040	P	165	0.206
H-FFF1	Series I	MILSPEC	Fresh	4.5 gpm	0.09	3-4	P	30	0.045	P	150	0.225
H-FFF1	Series I	MILSPEC	Salt	3 gpm	0.06	3-4	P	50	0.050	P	290	0.290
H-FFF1	Series I	MILSPEC	Salt	3.75 gpm	0.075	3-4	P	35	0.044	P	210	0.263
H-FFF1	Series I	MILSPEC	Salt	4.5 gpm	0.09	3-4	P	36	0.054	P	195	0.293
H-FFF1	Series II	MILSPEC	Fresh	3 gpm	0.06	7-8	P	45	0.045	P	150	0.150
H-FFF1	Series II	MILSPEC	Fresh	3.75 gpm	0.075	7-8	P	35	0.044	P	120	0.150
H-FFF1	Series II	MILSPEC	Salt	3 gpm	0.06	7-8	P	65	0.065	P	210	0.210
H-FFF1	Series II	MILSPEC	Salt	3.75 gpm	0.075	7-8	P	40	0.050	P	130	0.163
H-FFF1	Series II	MILSPEC	Fresh	3 gpm	0.06	7-8	P	60	0.060	P	185	0.185
H-FFF1	Series II	MILSPEC	Fresh	3.75 gpm	0.075	7-8	P	55	0.069	P	150	0.188
H-FFF1	Series II	MILSPEC	Salt	3 gpm	0.06	7-8	P	60	0.060	P	175	0.175
H-FFF1	Series II	MILSPEC	Salt	3.75 gpm	0.075	7-8	P	60	0.075	P	155	0.194
H-FFF1	Series II	E10	Fresh	3.0 gpm	0.06	7-8	P	210	0.210	F	-	-
H-FFF1	Series II	E10	Fresh	3.75 gpm	0.075	7-8	P	160	0.200	P	285	0.356
H-FFF1	Series II	E10	Salt	3.0 gpm	0.06	7-8	P	175	0.175	F	-	-
H-FFF1	Series II	E10	Salt	3.75 gpm	0.075	7-8	P	105	0.131	P	260	0.325
H-FFF1	Series II	E10	Salt	4.5 gpm	0.09	7-8	P	100	0.150	P	205	0.308

Tests conducted without a water substrate

9.1.6. Type III H-FFF2 Results

The pass/fail results of the Type III tests conducted withH-FFF2 are shown in Table 9.1.6-1 and the time/density results are shown in Table 9.1.6-2. SinceH-FFF2 is only listed/approved for freshwater, no saltwater tests were conducted with this foam.

Table 9.1.6-1 H-FFF2 Type III Test Results (Pass/Fail)

Foam	Series	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont.	Ext.	1st Pass	2nd Pass	Burnback	UL 162
H-FFF2	Series I	Heptane	Fresh	3 gpm	7-8	P	P	P	P	Self Ext	P
H-FFF2	Series I	Heptane	Fresh	3 gpm	3-4	P	P	P	F	-	F
H-FFF2	Series I	Heptane	Fresh	2.25 gpm	3-4	P	P	F	-	-	F
H-FFF2	Series I	Heptane	Fresh	3.75 gpm	3-4	P	P	P	P	Self Ext	P
H-FFF2	Series I	MILSPEC	Fresh	3 gpm	3-4	P	P	P	F	-	F
H-FFF2	Series I	MILSPEC	Fresh	3.75 gpm	3-4	P	P	P	P	Self Ext	P
H-FFF2	Series II	MILSPEC	Fresh	3 gpm	7-8	P	P	P	F	-	F
H-FFF2	Series II	MILSPEC	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
H-FFF2	Series II	MILSPEC	Fresh	3 gpm	7-8	P	P	P	F	-	F
H-FFF2	Series II	MILSPEC	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
H-FFF2	Series II	E10	Fresh	3.0 gpm	7-8	P	F	-	-	-	F
H-FFF2	Series II	E10	Fresh	3.75 gpm	7-8	P	P	P	F	-	F
H-FFF2	Series II	E10	Fresh	4.5 gpm	7-8	P	P	P	F	-	F

Tests conducted without a water substrate

As shown in Table 9.1.6-1, H-FFF2 was capable of controlling and extinguishing all of the fires conducted during the Series I assessment with the lower aspirated foam. When mixed with freshwater, H-FFF2 extinguished the heptane fire at a 25% reduced flow rate (i.e., 2.25 gpm) and was capable of extinguishing the MILSPEC fire at the design/recommended discharge rate (i.e., 3 gpm).

The variations in test results occurred during the post extinguishment assessments (reignition during a torch pass or burnback resistance). For the design/recommended flow rate and lower aspirated foam, H-FFF2 successfully completed the first torch pass but typically failed the second one. As observed with H-FFF1, there appeared to be "some" fuel pickup associated with the lower aspirated foams. However, H-FFF2 met the UL 162 requirements with lower aspirated foam at a 25% increase rate (i.e., 3.75 gpm) for both heptane and MILSPEC.

During the Series II tests conducted with the higher aspirated foams, H-FFF2 extinguished the MILSPEC gasoline with 3 gpm (with and without a water substrate) but required a 25% increase in flow rate (3.75 gpm) to extinguish the E10 fires (conducted without a water substrate).

The time/density results and analysis will be discussed later in the report.

Table 9.1.6-1 H-FFF2 Type III Test Results (Time/Density)

Foam	Series	Fuel Type	Water Type	Flow Rate	App Rate gpm/ft^2	Exp. Ratio	Cont.	Cont. Time sec	Cont. Den gal/ft^2	Ext.	Ext. Time sec	Ext. Den gal/ft^2
H-FFF2	Series I	Heptane	Fresh	3 gpm	0.06	7-8	P	28	0.028	P	55	0.055
H-FFF2	Series I	Heptane	Fresh	3 gpm	0.06	3-4	P	45	0.045	P	123	0.123
H-FFF2	Series I	Heptane	Fresh	2.25 gpm	0.045	3-4	P	55	0.041	P	300	0.225
H-FFF2	Series I	Heptane	Fresh	3.75 gpm	0.075	3-4	P	30	0.038	P	102	0.128
H-FFF2	Series I	MILSPEC	Fresh	3 gpm	0.06	3-4	P	45	0.045	P	187	0.187
H-FFF2	Series I	MILSPEC	Fresh	3.75 gpm	0.075	3-4	P	30	0.038	P	120	0.150
H-FFF2	Series II	MILSPEC	Fresh	3 gpm	0.06	7-8	P	45	0.045	P	160	0.160
H-FFF2	Series II	MILSPEC	Fresh	3.75 gpm	0.075	7-8	P	40	0.050	P	125	0.156
H-FFF2	Series II	MILSPEC	Fresh	3 gpm	0.06	7-8	P	70	0.070	P	170	0.170
H-FFF2	Series II	MILSPEC	Fresh	3.75 gpm	0.075	7-8	P	60	0.075	P	130	0.163
H-FFF2	Series II	E10	Fresh	3.0 gpm	0.06	7-8	P	195	0.195	F	-	-
H-FFF2	Series II	E10	Fresh	3.75 gpm	0.075	7-8	P	160	0.200	P	290	0.363
H-FFF2	Series II	E10	Fresh	4.5 gpm	0.09	7-8	P	65	0.098	P	185	0.278

Tests conducted without a water substrate

9.2. FOAM QUALITY/ASPIRATION EFFECTS

Due to its oleophobic properties, AFFF has two separate mechanisms that combine to aid in the extinguishment of a flammable liquid fire; a water/surfactant film that forms on the fuel surface and a foam blanket (i.e., a matrix of bubbles), which both serve to seal-in the flammable vapors resulting in extinguishment (i.e., shutting off the fuel vapors that are burning above the fuel surface). FFFs have only the foam blanket to seal-in the vapors. As a result, the capabilities of FFFs will be highly dependent on the characteristics of the foam blanket (and the associated hardware and discharge devices). The film produced by AFFF has provided an additional level of protection for legacy systems and discharge devices that do not produce good foam quality. Additional attention will need to be given to the discharge devices identified as part of the UL listing when fielding these FFFs.

The first two tests conducted with each foam during Series I were conducted to identify the "worst case" foam quality/aspiration to be used in the subsequent tests. The tests were conducted using the Type III configuration, with heptane as the fuel, and freshwater to produce the foam solutions. The tests were conducted with expansion ratios representative of both aspirated discharge devices (7-8 expansion ratios) and non-aspirated discharge devices (3-4 expansion ratios). The control and extinguishment time results for these tests are summarized in Table 9.2-1.

Table 9.2-1 Foam Quality/Aspiration Test Results (Heptane Series I)

	Higher Aspirated Foam (7-8 Exp. Ratio)				Lower Aspirated Foam (3-4 Exp. Ratio)			
Foam	Control Time (sec)	Density (gal/ft^2)	Ext. Time (sec)	Density (gal/ft^2)	Control Time (sec)	Density (gal/ft^2)	Ext. Time (sec)	Density (gal/ft^2)
AR-AFFF	33	0.022	67	0.045	40	0.027	127	0.085
AR-FFF1	45	0.045	105	0.105	65	0.065	180	0.180
AR-FFF2	45	0.045	107	0.107	50	0.050	165	0.165
H-FFF1	35	0.035	92	0.092	36	0.036	102	0.102
H-FFF2	28	0.028	55	0.055	45	0.045	123	0.123

As shown in this table, the use of lower aspirated foam had only a limited effect on the control times, but, in most cases, typically doubled the extinguishment times (even for the AR-AFFF). As a result, the lower aspirated foam solutions were used as "worst case" during most of the Type III tests conducted during Series I.

As Series I progressed, and the non-aspirated foams were having difficulty extinguishing some of the test fires, three additional tests were conducted with the higher aspiration to better understand the effects of foam quality/aspiration on agent performance and to provide a better understanding of the firefighting capabilities of these foams, in general. These tests are summarized in Table 9.2-2

As shown in all three cases, the higher aspirated foam produces a thicker foam blanket and provided better firefighting capabilities than the non-aspirated foam, even at a 25% lower application rate.

Table 9.2-2 Selected Tests Conducted with Higher Aspirated Foams (yellow)

Foam	Type of Discharge	Fuel Type	Water Type	Flow Rate	Exp. Ratio	Cont.	Ext.	1st Pass	2nd Pass	Burnback	UL 162
AR-FFF2	Type III	Gasoline	Fresh	3.75 gpm	3-4	P	F	-	-	-	F
AR-FFF2	Type III	Gasoline	Fresh	3.75 gpm	7-8	P	P	P	P	Self Ext	P
AR-FFF2	Type III	Gasoline	Fresh	4.5 gpm	3-4	P	P	F	-	-	F
AR-FFF2	Type III	Gasoline	Salt	3.75 gpm	3-4	P	F	-	-	-	F
AR-FFF2	Type III	Gasoline	Salt	3.75 gpm	7-8	P	P	P	P	Self Ext	P
AR-FFF2	Type III	Gasoline	Salt	4.5 gpm	3-4	P	P	F	-	-	F
H-FFF1	Type III	Gasoline	Fresh	3 gpm	3-4	P	P	P	F	-	F
H-FFF1	Type III	Gasoline	Fresh	3 gpm	7-8	P	P	P	P	Self Ext	P
H-FFF1	Type III	Gasoline	Fresh	3.75 gpm	3-4	P	P	P	F	-	F

All of the tests conducted during Series II were conducted with the higher aspirated foam. The data provides a detailed comparison of foam quality/aspiration effects for the tests conducted with MILSPEC gasoline (on a water substrate). The results of this comparison are shown in Table 9.2-3 and 9.2-4 and are plotted in Figure 9.2-1 to provide a visual comparison.

Table 9.2-3 Foam Quality/Aspiration Comparison (MILSPEC Gasoline - Times)

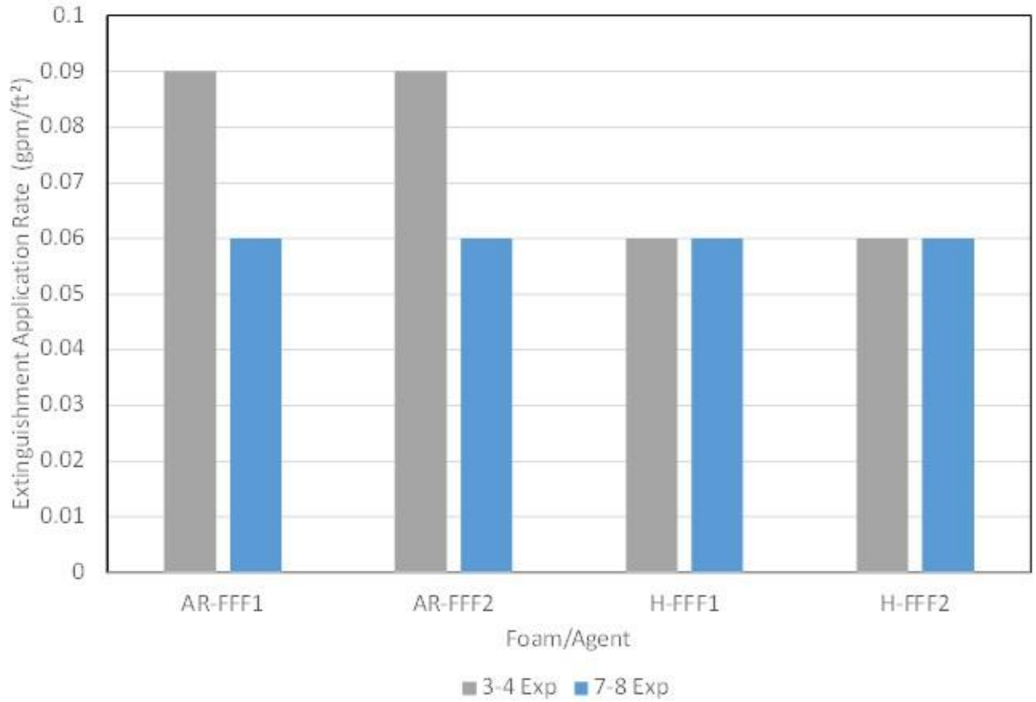
Foam	Type of Discharge	Fuel Type	Water Type	Flow Rate	3-4 Exp. Ratio		7-8 Exp. Ratio	
					Control	Ext	Control	Ext
AR-FFF1	Type III	MILSPEC	Fresh	3.0 gpm	80	No	70	250
AR-FFF1	Type III	MILSPEC	Fresh	3.75 gpm	64	No	50	210
AR-FFF1	Type III	MILSPEC	Fresh	4.5 gpm	55	300		
AR-FFF1	Type III	MILSPEC	Salt	3.0 gpm	50	No	55	260
AR-FFF1	Type III	MILSPEC	Salt	3.75 gpm	72	No	60	195
AR-FFF1	Type III	MILSPEC	Salt	4.5 gpm	60	250		
AR-FFF2	Type III	MILSPEC	Fresh	3.0 gpm	75	No	60	255
AR-FFF2	Type III	MILSPEC	Fresh	3.75 gpm	95	No	75	225
AR-FFF2	Type III	MILSPEC	Fresh	4.5 gpm	60	260		
AR-FFF2	Type III	MILSPEC	Salt	3.0 gpm	72	No	65	270
AR-FFF2	Type III	MILSPEC	Salt	3.75 gpm	90	No	70	220
AR-FFF2	Type III	MILSPEC	Salt	4.5 gpm	75	250		
FFF1	Type III	MILSPEC	Fresh	3.0 gpm	37	165	45	150
FFF1	Type III	MILSPEC	Fresh	3.75 gpm	32	165	35	120
FFF1	Type III	MILSPEC	Fresh	4.5 gpm	30	150		
FFF1	Type III	MILSPEC	Salt	3.0 gpm	50	290	65	210
FFF1	Type III	MILSPEC	Salt	3.75 gpm	35	210	40	130
FFF1	Type III	MILSPEC	Salt	4.5 gpm	36	195		
FFF2	Type III	MILSPEC	Fresh	3.0 gpm	45	187	45	160
FFF2	Type III	MILSPEC	Fresh	3.75 gpm	30	120	40	125

Note: Only one passed entire UL 162 requirements – rest failed on 2nd torch pass

Table 9.2-4 Foam Quality/Aspiration Comparison (MILSPEC Gasoline - Densities)

Foam	Type of Discharge	Fuel Type	Water Type	3-4 Exp. Ratio			7-8 Exp. Ratio		
				Flow Rate	Control gal/ft^2	Ext gal/ft^2	Flow Rate	Control gal/ft^2	Ext gal/ft^2
AR-FFF1	Type III	MILSPEC	Fresh	4.5 gpm	0.083	0.450	3.0 gpm	0.070	0.250
AR-FFF1	Type III	MILSPEC	Salt	4.5 gpm	0.090	0.375	3.0 gpm	0.055	0.260
AR-FFF2	Type III	MILSPEC	Fresh	4.5 gpm	0.090	0.390	3.0 gpm	0.060	0.255
AR-FFF2	Type III	MILSPEC	Salt	4.5 gpm	0.113	0.375	3.0 gpm	0.065	0.270
FFF1	Type III	MILSPEC	Fresh	3.0 gpm	0.037	0.165	3.0 gpm	0.045	0.150
FFF1	Type III	MILSPEC	Salt	3.0 gpm	0.050	0.290	3.0 gpm	0.065	0.210
FFF2	Type III	MILSPEC	Fresh	3.0 gpm	0.045	0.187	3.0 gpm	0.045	0.160

Application Rate



Extinguishment Density

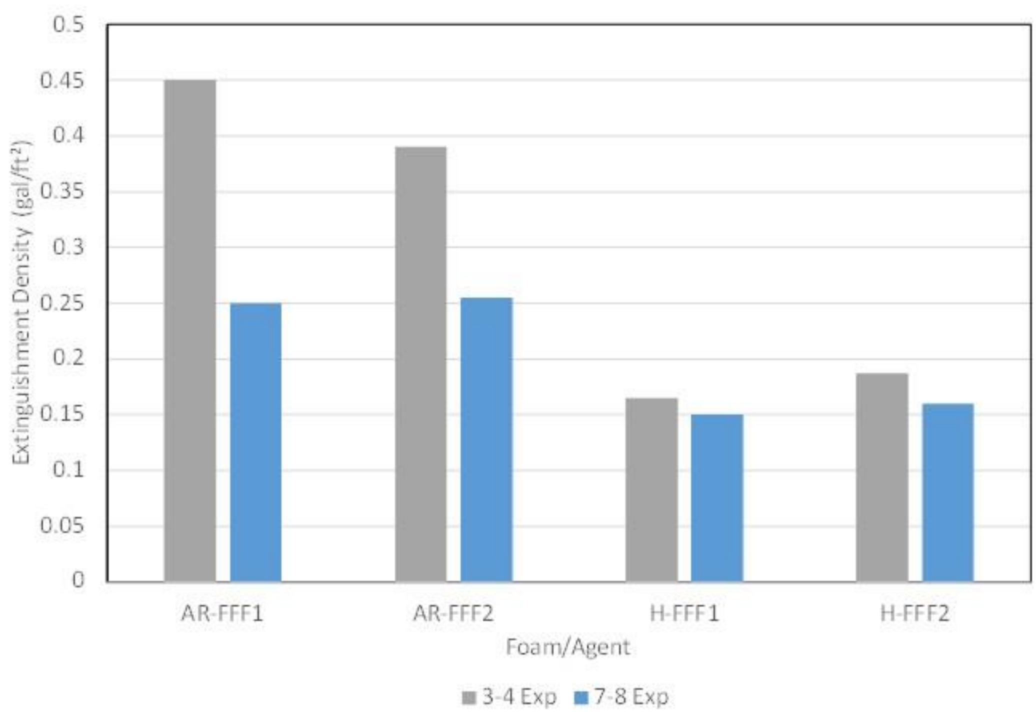


Figure 9.2-1 Foam Quality/Aspiration Comparison – MILSPEC Gasoline and Freshwater

As shown in Figure 9.2-1, reducing the foam quality/aspiration had a significant impact on the AR-FFFs but a lower impact on the H-FFFs. The two AR-FFFs required a 50% higher flow/application rate (i.e., 4.5 gpm versus 3.0 gpm) to extinguish the MILSPEC gasoline fires with the lower aspirated foam when compared to the tests conducted with the higher aspirated foam. The two H-FFFs were able to extinguish the fires at the same rate for both foam qualities but took on average about 20% longer to extinguish the fire with the lower aspirated foam. From an extinguishment density perspective, the higher aspirated foam reduced the extinguishment density of the AR-FFFs by about 50% as compared to the lower aspirated foam. In other words, it took twice as much lower aspirated foam to match the higher aspirated foam capabilities (for the AR-FFFs). For the H-FFFs, the use of higher aspirated foam reduced the extinguishment densities of the H-FFFs between 10%-20% as compared to the lower aspirated foam.

Visual observations of the tests conducted with the AR-FFFs at the lower aspirated foam suggest that the foam blanket was unable to contain the gasoline vapors and/or appeared to react with the foam blanket causing the bubbles to break, making the solution look "milky" rather than "foamy". As a result of this foam breakdown, flames continued to burn along the top of the blanket, even though the fuel was covered with foam. A photograph of this phenomenon is shown in Figure 9.2-3.

Figure 9.2-3 MILSPEC Gasoline Vapor Penetration of the Lower Aspirated Foam Blanket

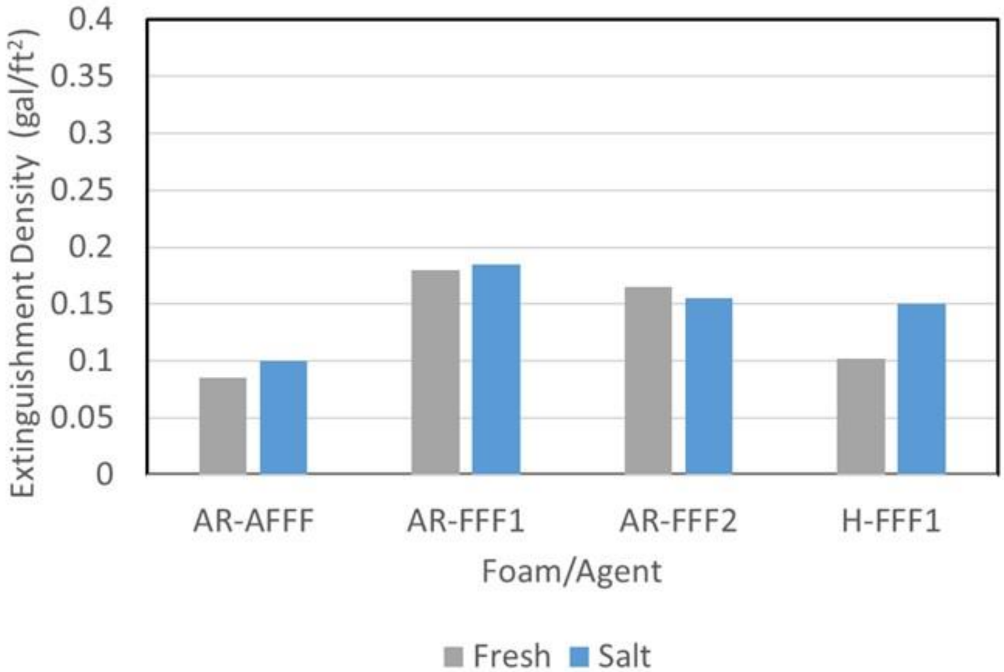
This phenomenon seems to indicate two major issues. First, all FFFs are not equal and their performance appears to be related to both foam quality/aspiration as well as fuel type. In addition, the industry has always used heptane as a surrogate for all hydrocarbon fuels. However, in every instance (agent and water type), the MILSPEC gasoline fires required more agent to control, extinguish to meet the UL test protocol than the tests conducted with heptane.

When discussing this issue with a few chemical engineers/chemists, the general consensus was that heptane “should” be a good surrogate (as the legacy would have it) for MILSPEC gasoline when only considering vapor pressure (light ends/aromatics). However, there appears to be a “chemical compatibility” variable and/or issues with the larger molecules reacting with the foam concentrates and/or foam blankets. This raises the question as to the capabilities of these foams against kerosene-based fuels and/or crude oil. Further testing is recommended to investigate this issue (both chemical analyses and fire performance testing). Additional discussion and comparison of fuel type (including E10 gasoline) is provided later in this report.

9.3. WATER TYPE COMPARISON

The effects of water type on the firefighting capabilities of the foams varied between foams. This is shown in Figure 9.3-1 for the tests conducted using MILSPEC gasoline with a one-inch water substrate.

Heptane



MILSPEC Gasoline

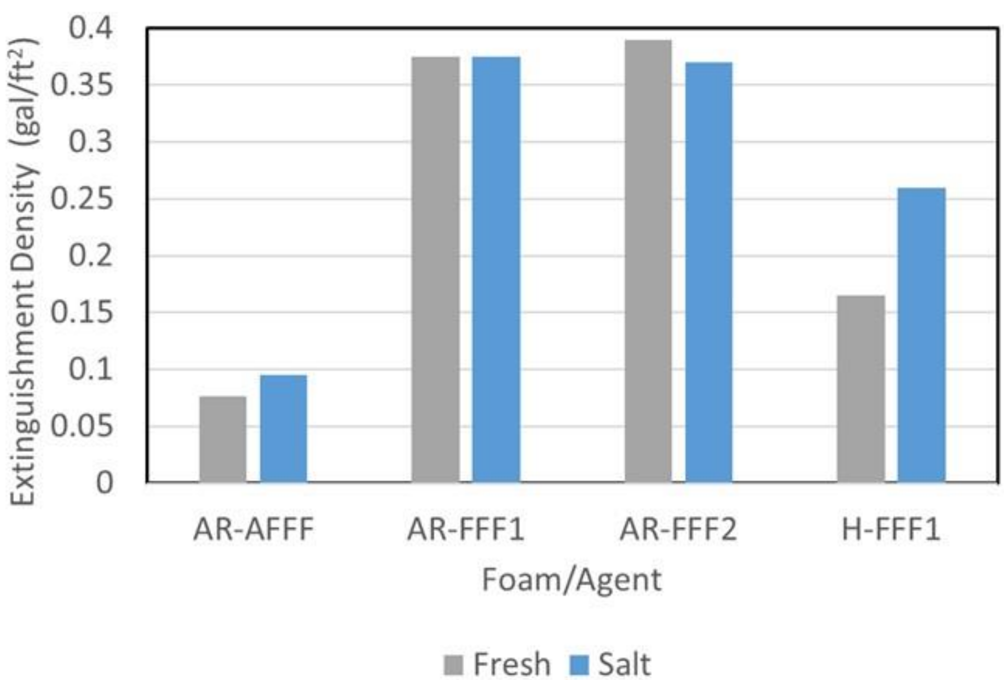


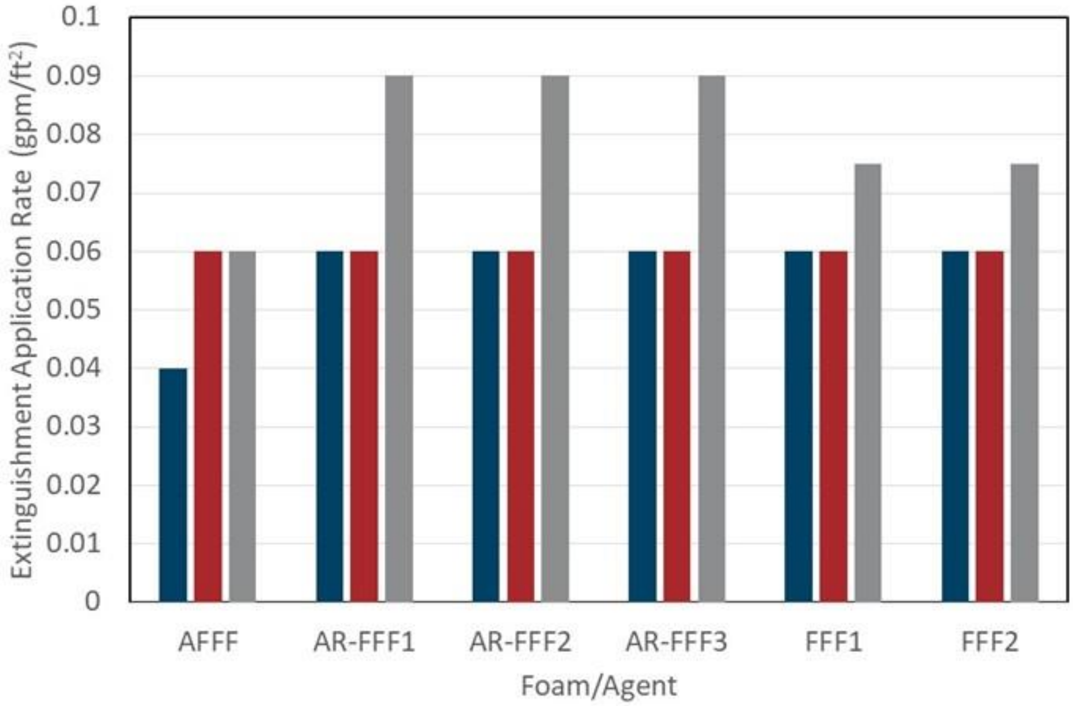
Figure 9.3-1 Water Type Comparison – MILSPEC Gasoline 7-8 Exp. Ratio

As shown in Figure 9.3-1, the use of saltwater to make the foam had only a minimal effect on the AR-FFFs resulting in slight increases in performance (i.e., lower extinguishment densities) but degraded the capabilities of H-FFF1 by as much as 50% (i.e., 50% higher extinguishment densities). These same trends were observed for the tests conducted with heptane and were consistent for both foam qualities included in this assessment.

9.4. Fuel Type and Agent Comparisons

The fuel type and agent comparison discussion will focus on the tests conducted with the higher aspirated foam with the foam solutions made with freshwater. The reason being was that there were no tests conducted with E10 gasoline using lower aspirated foam and that two of the test foams (AR-FFF3 and H-FFF2) were not listed or tested with saltwater. The results of the Type III tests conducted with the higher aspirated foam using freshwater to make the foam are summarized in Figure 9.4-1. Various comparisons of these results will be made in the following sections of this report.

Application Rate



Extinguishment Density

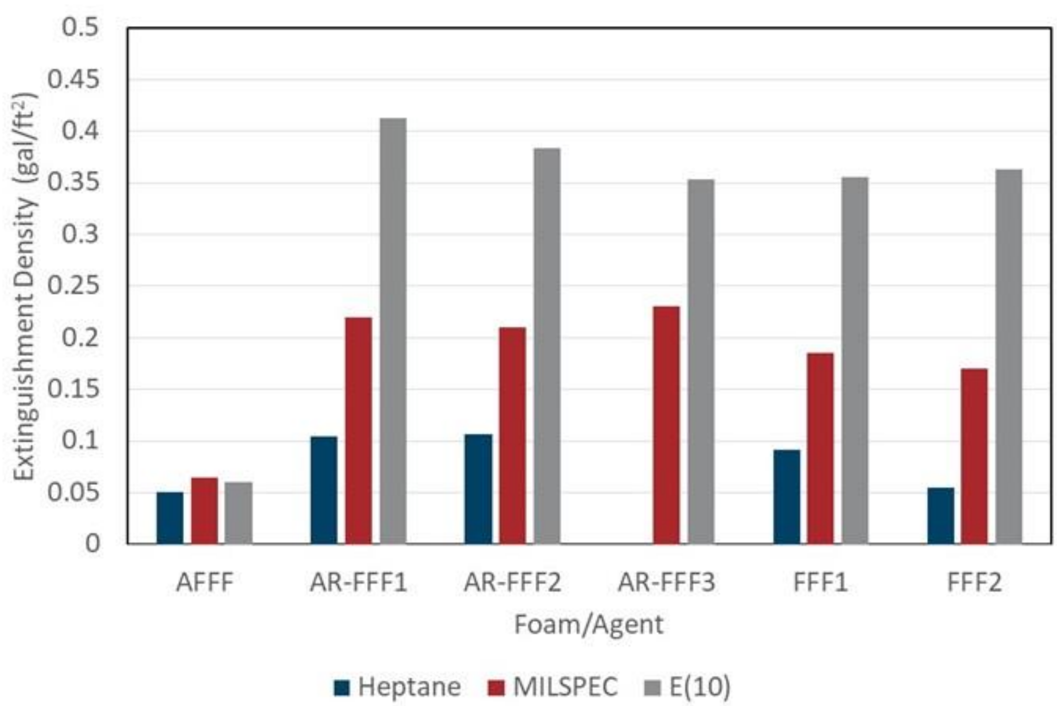


Figure 9.4-1 Fuel Type and Agent Comparison – Higher Aspirated Foam / Freshwater

9.4.1. Fuel Type Comparison (Hydrocarbon Based)

Throughout this test program, heptane was shown to be the easiest of the test fuels to control and extinguish. The original five foams were all able to meet the UL 162 requirements at the design/recommended flow rates with the higher aspirated foam (aspirated foam) using heptane as the fuel. Gasoline was shown to be more difficult to control and extinguish than heptane, with some FFFs requiring as much as a 50% increase in flow rate to extinguish the fire.

The baseline AR-AFFF demonstrated consistent capabilities against all three hydrocarbon test fuels included in this assessment. This is shown as a function of Extinguishment Density in Figure 9.4-1.

The two grades of gasoline (MILSPEC and E10) were more difficult to extinguish than heptane for all of the FFFs included in this assessment. Focusing on the tests conducted with the higher aspirated foam, all of the FFFs were able to extinguish the MILSPEC gasoline fires at 3 gpm (0.06 gpm/ft^2) but typically took about twice as long (and required twice as much agent) to extinguish as heptane fires. The E10 gasoline was even harder to extinguish that the MILSPEC gasoline. The three AR-FFFs required a 50% increase in flow/application rate in order to extinguish the E10 fires. The two H-FFFs also required a 25% increase in flow/application rate in order to extinguish the E10 fires. Surprisingly, the H-FFFs were able to extinguish the E10 fires at a lower rate than the AR-FFFs. In dependent of the flow/application rate, the FFFs typically required about twice as much agent to extinguish the E10 fires as compared to the MILSPEC fires. A detailed comparison of the capabilities of the FFFs against two grades of gasoline is provided in Tables 9.4.1-1 and 9.4.1-2

In general terms and based on the extinguishment densities, it appears that MILSPEC gasoline is twice as hard to extinguish as heptane, and E10 gasoline is twice as hard as MILSPEC gasoline (four times as hard as heptane) for the FFFs.

Table 9.4.1-1 Gasoline Type and Agent Comparison (Times)

Foam	Type of Discharge	Water Type	Exp. Ratio	MILSPEC			E(10)		
				Flow Rate	Cont.	Ext.	Flow Rate	Cont.	Ext.
AR-AFFF	Type III	Fresh	7-8	3.0 gpm	45	65	3.0 gpm	45	60
AR-FFF1	Type III	Fresh	7-8	3.0 gpm	70	220	4.5 gpm	95	275
AR-FFF1	Type III	Salt	7-8	3.0 gpm	85	230	4.5 gpm	110	260
AR-FFF2	Type III	Fresh	7-8	3.0 gpm	60	210	4.5 gpm	150	255
AR-FFF2	Type III	Salt	7-8	3.0 gpm	80	200	4.5 gpm	140	295
AR-FFF3	Type III	Fresh	7-8	3.0 gpm	70	230	4.5 gpm	75	235
FFF1	Type III	Fresh	7-8	3.0 gpm	60	185	3.75 gpm	160	285
FFF1	Type III	Salt	7-8	3.0 gpm	60	175	3.75 gpm	105	260
FFF2	Type III	Fresh	7-8	3.0 gpm	70	170	3.75 gpm	160	290

Table 9.4.1-2 Gasoline Type and Agent Comparison (Densities)

Foam	Type of Discharge	Water Type	Exp. Ratio	MILSPEC			E(10)		
				Flow Rate	Cont. gal/ft^2	Ext. gal/ft^2	Flow Rate	Cont. gal/ft^2	Ext. gal/ft^2
AR-AFFF	Type III	Fresh	7-8	3.0 gpm	0.045	0.065	3.0 gpm	0.045	0.060
AR-FFF1	Type III	Fresh	7-8	3.0 gpm	0.070	0.220	4.5 gpm	0.143	0.413
AR-FFF1	Type III	Salt	7-8	3.0 gpm	0.085	0.230	4.5 gpm	0.165	0.390
AR-FFF2	Type III	Fresh	7-8	3.0 gpm	0.060	0.210	4.5 gpm	0.225	0.383
AR-FFF2	Type III	Salt	7-8	3.0 gpm	0.080	0.200	4.5 gpm	0.210	0.443
AR-FFF3	Type III	Fresh	7-8	3.0 gpm	0.070	0.230	4.5 gpm	0.113	0.353
FFF1	Type III	Fresh	7-8	3.0 gpm	0.060	0.185	3.75 gpm	0.200	0.356
FFF1	Type III	Salt	7-8	3.0 gpm	0.060	0.175	3.75 gpm	0.131	0.325
FFF2	Type III	Fresh	7-8	3.0 gpm	0.070	0.170	3.75 gpm	0.200	0.363

9.4.2. Agent Comparison

In general, the baseline AR-AFFF consistently demonstrated superior capabilities through this entire test program. The AR-AFFF performed well against all of the test fuels included in this assessment (IPA, Heptane, and Gasoline (MILSPEC and E10). The FFFs required between 2-4 times both the rates and the densities of the AR-AFFF to produce similar results against the IPA fires conducted in with the Type II test configuration. From an extinguishment density standpoint, the FFFs required between 3-4 times that of the AR-AFFF for the tests conducted with MILSPEC gasoline and between 6-7 times that of the AR-AFFF for the tests conducted with E10 gasoline.

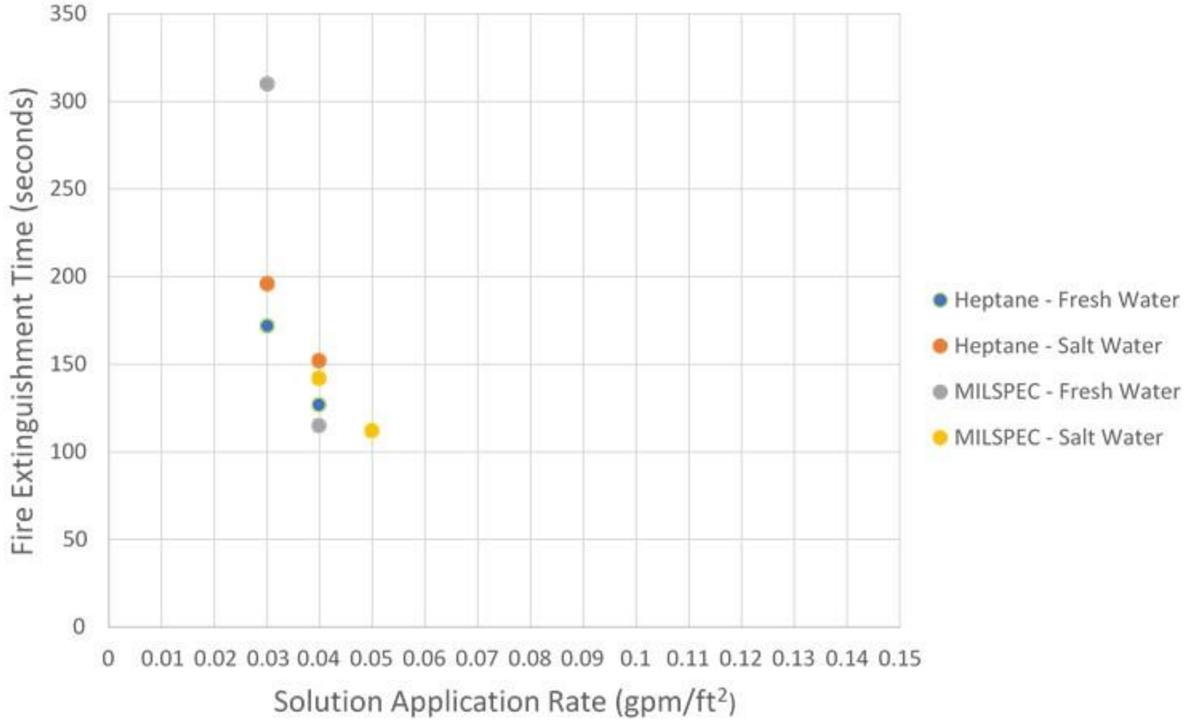
When comparing the capabilities of the AR-FFFs and the H-FFFs, the H-FFFs typically demonstrated better capabilities. For the tests conducted with the lower aspirated foam, the extinguishment densities for the AR-FFFs were, on average about 50% higher for the fires conducted with heptane and about 75% higher for the fires conducted with MILSPEC gasoline. This difference was reduced through the use of the higher aspirated foam during Series II. For the tests conducted with the higher aspirated foam, the extinguishment densities for the AR-FFFs were, on average about 20% higher for the fires conducted with heptane and MILSPEC gasoline and only 10% higher for the fires conducted with E10 gasoline. However, the AR-FFFs required a higher flow/application rate than the H-FFFs against the E10 fires.

9.5. GENERALIZED AGENT CAPABILITIES COMPARISON

9.5.1. Sensitivity to Test Variables

The AR-AFFF produced the most consistent results across the spectrum of test variables (i.e., fuel and water types). However, the test variables had varying degrees of impact on the group of FFFs as a whole. The degree of impact is best illustrated by the scatter in the data shown on the extinguishment time versus application rate plots. An example is provided in Figure 9.5.1-1 which shows the extinguishment times for all the Type III tests conducted with the lower aspirated foam (i.e., Series I) for both AR-AFFF and AR-FFF1 respectively.

AR-AFFF (Lower Expansion)



AR-FFF1 (Lower Expansion)

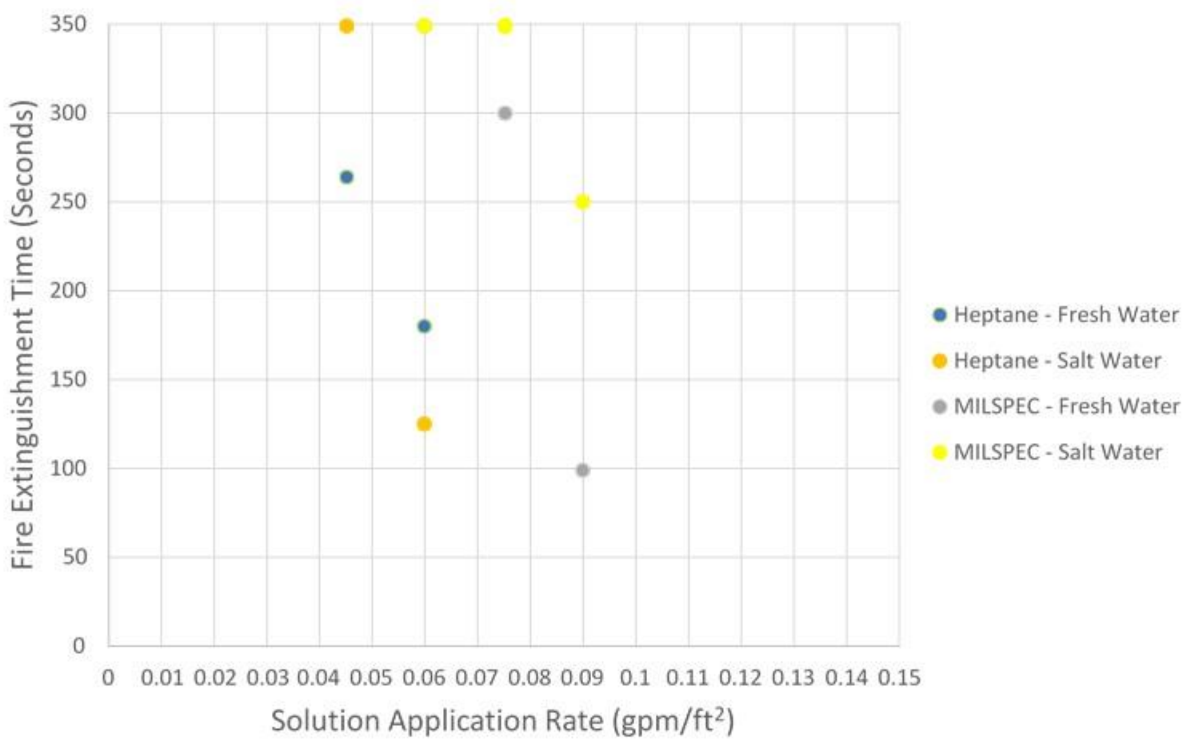


Figure 9.5.1-1 Test Variable Effects Illustrated by Data Scatter

As shown in these plots, the AR-AFFF results are fairly well-grouped while the AR-FFF1 results have a high degree of scatter. Most of this scatter is associated with the difficulty of extinguishing MILSPEC gasoline as discussed previously.

It should be noted that the three points on the AR-FFF1 plot shown with 350 second extinguishment times were fires that were never extinguished.

9.5.2. The L Curve

During a study conducted for the FAA in the mid-90s, the firefighting capabilities (control and extinguishment times) of foam extinguishing agents were typically shown to follow an "L Curve" [4]. An example L curve is shown in Figure 9.5.2-1.

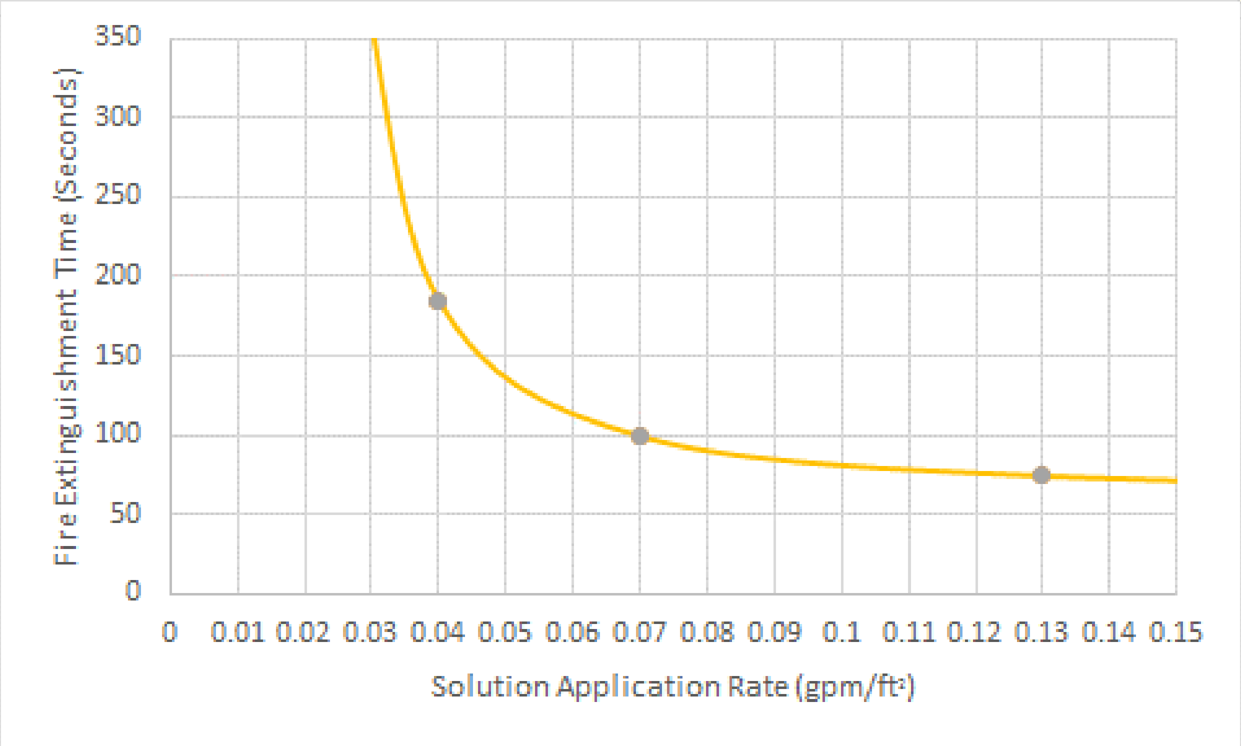


Figure 9.5.2-1 Typical Capabilities L Curve

From a performance standpoint, this curve makes perfect sense. 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 9.5.2-1), this asymptotic value is just below 0.03 gpm/ft^2. These tendencies will be used as the basis for the data analysis provided in the following sections of this report.

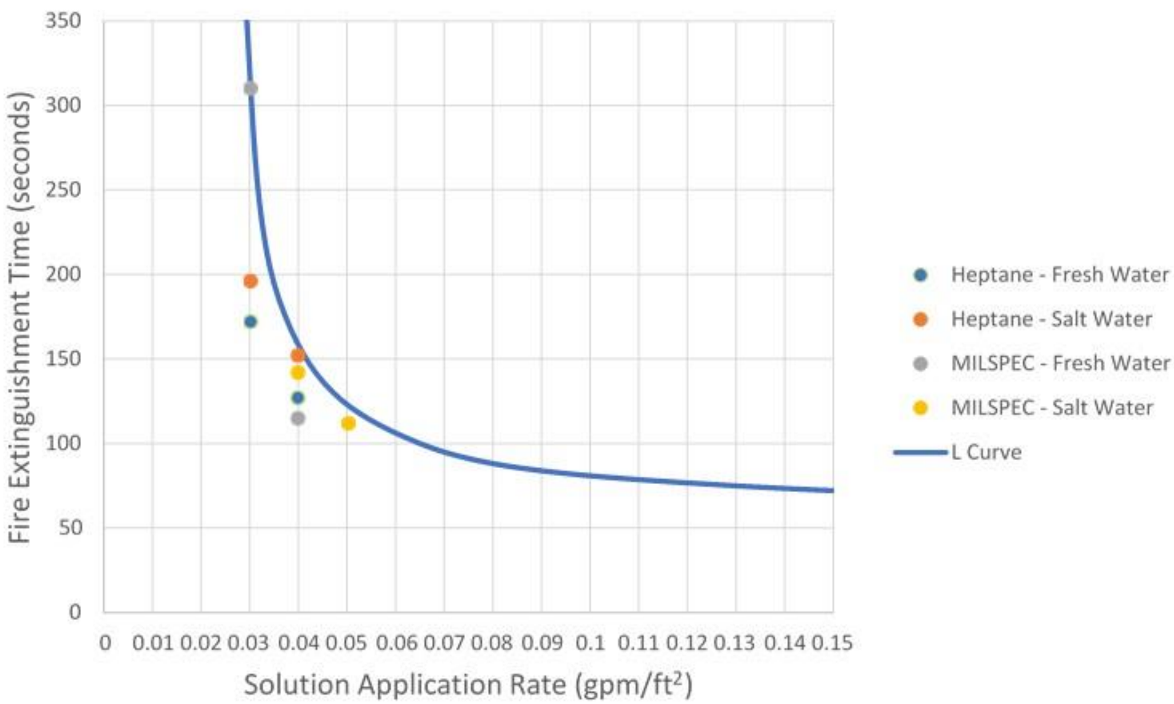
The ”L Curves” developed for each FFF included in this test program (with the exception of AR-FFF3) are provided in the following sections. AR-FFF3 was added in between Series I and Series II and was only tested for a limited number of scenarios providing insufficient data to develop the L curves. For the remaining FFFs, the curves have been shifted to the right to ensure that all of the data falls below the line. In other words, the curves are a “worst case” representation of the firefighting capabilities of a specific foam and are NOT meant to be an actual curve fit of the data. The curves provide a good visual comparison of the differences in capabilities observed between foams as well as a reasonable estimate of the capabilities as a function of application rate.

9.5.3. AR-AFFF Performance Plots

The extinguishment time “L Curves” for the tests conducted with AR-AFFF (i.e., all of the Type III tests conducted with AR-AFFF against heptane and MILSPEC gasoline fires) are provided in Figure 9.5.3-1.

As illustrated by the two plots, the performance data is fairly well grouped indicating that the firefighting capabilities of the AR-AFFF are relatively consistent across all of the parameters included in this assessment. The figures also indicate that the critical application rate for AR-AFFF is on the order of 0.03 gpm/ft^2 for the lower aspirated foam and on the order of 0.025 gpm/ft^2 for the higher aspirated foam.

AR-AFFF (3-4 Expansion)



AR-AFFF (7-8 Expansion)

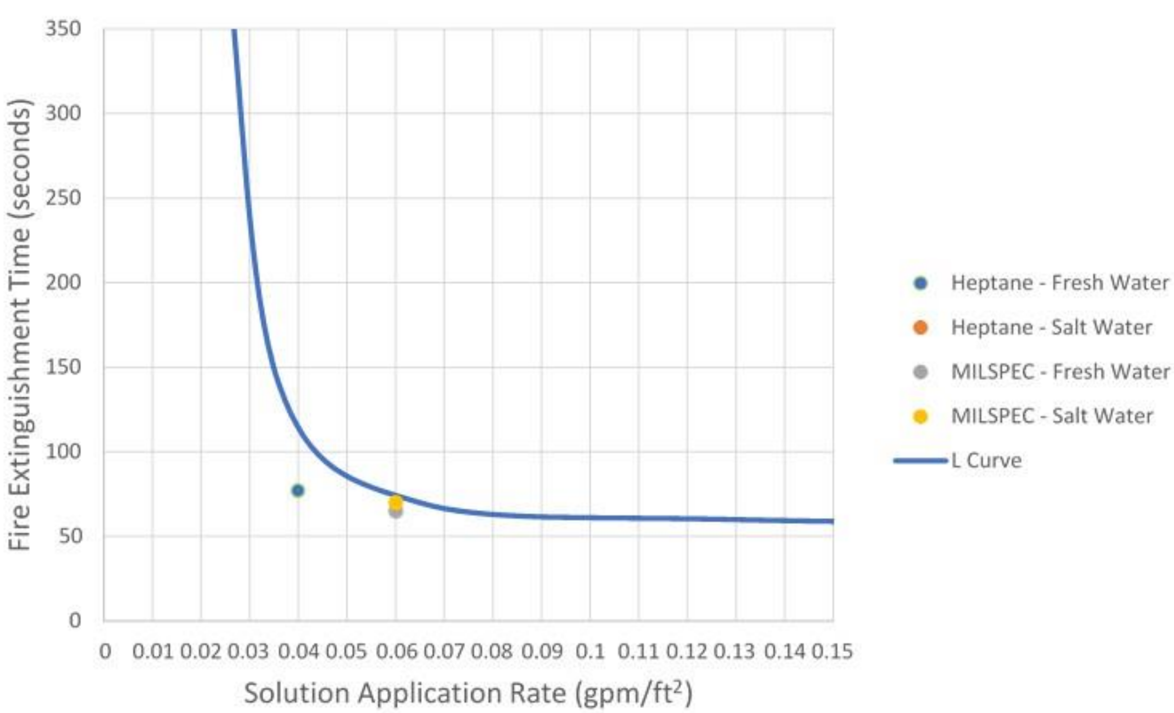
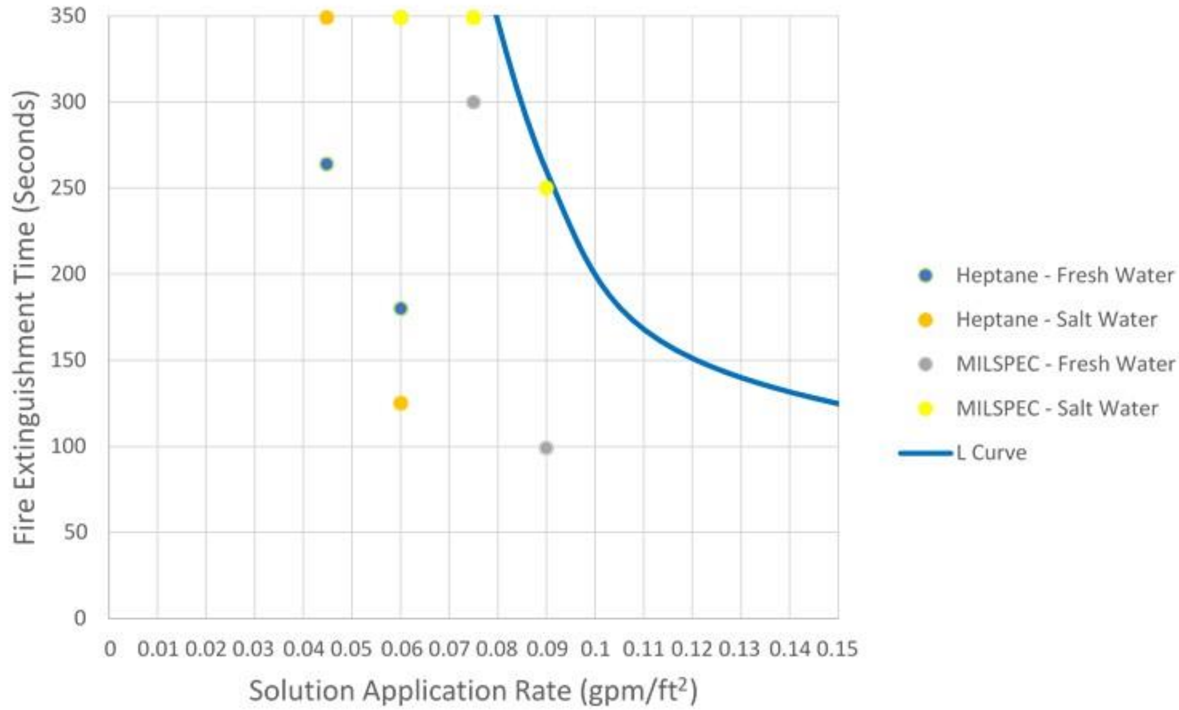


Figure 9.5.3-1 AR-AFFF "L Curves"

9.5.4. AR-FFF1 Performance Plots

The extinguishment time “L Curves” for the tests conducted with AR-FFF1 (i.e., all of the Type III tests conducted with AR-FFF1 against heptane and MILSPEC gasoline fires) are provided in Figure 9.5.4-1. The values above 300 seconds (i.e., 350 seconds) on the extinguishment time plots are fires that were not extinguished.

AR-FFF1 (3-4 Expansion)



AR-FFF1 (7-8 Expansion)

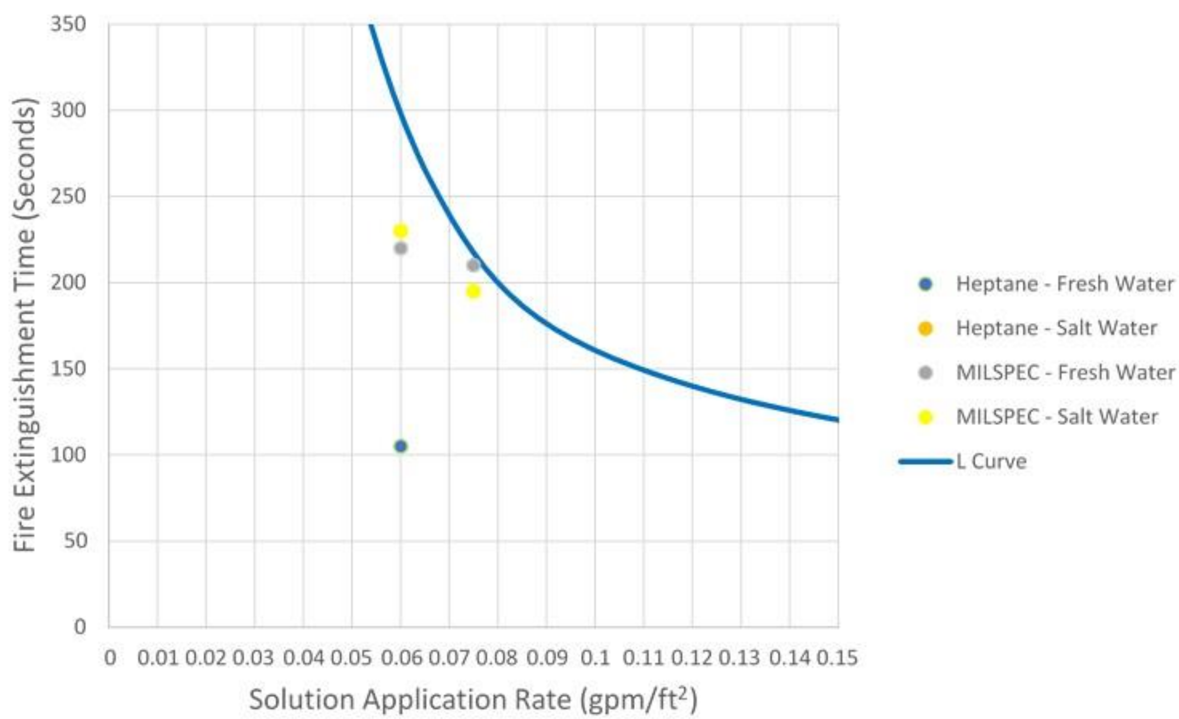


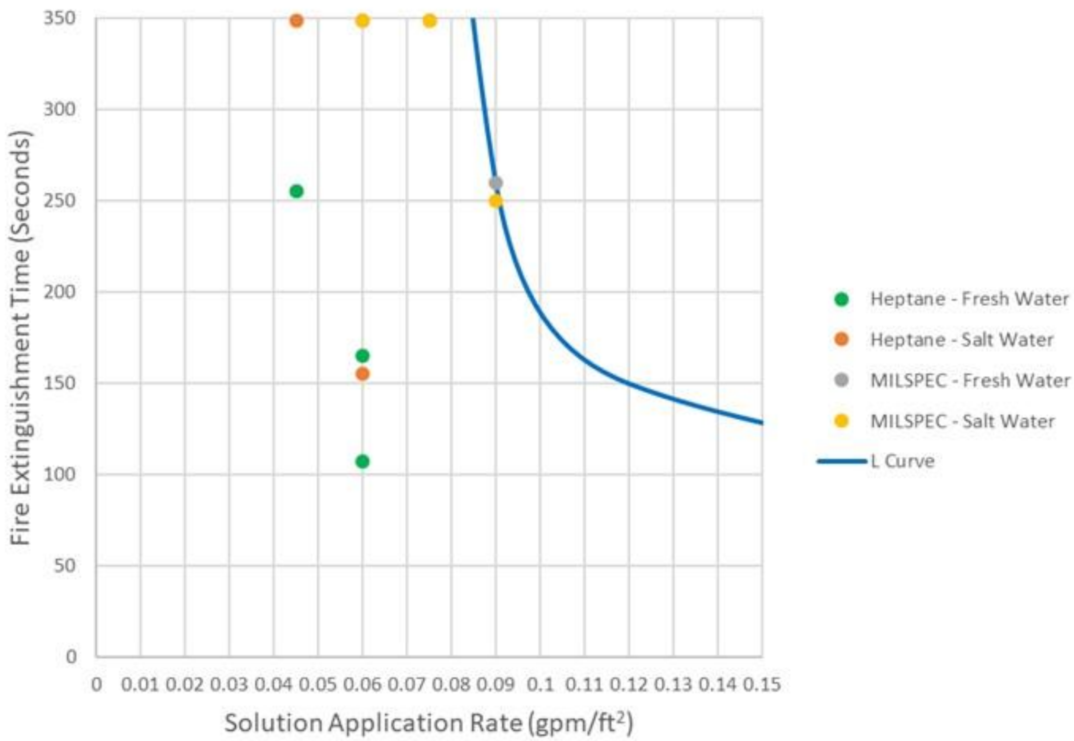
Figure 9.5.4-1 AR-FFF1 "L Curves"

As illustrated by the two plots, the performance data is significantly scattered indicating that the firefighting capabilities AR-FFF1 vary dramatically across the range of parameters included in this assessment, more so for the lower aspirated foam than for the higher aspirated foam. However, most of this scatter is attributed to the difficultly in extinguishing MILSPEC gasoline (i.e., variations in capabilities against different test fuels). The figures also indicate that the critical application rate for AR-FFF1 is on the order of 0.075 gpm/ft^2 for the lower aspirated foam and on the order of 0.05 gpm/ft^2 for the higher aspirated foam.

9.5.5. AR-FFF2 Performance Plots

The extinguishment time “L Curves” for the tests conducted with AR-FFF2 (i.e., all of the Type III tests conducted with AR-FFF2 against heptane and MILSPEC gasoline fires) are provided in Figure 9.5.5-1. The values above 300 seconds (i.e., 350 seconds) on the extinguishment time plots are fires that were not extinguished.

AR-FFF2 (3-4 Expansion)



AR-FFF2 (7-8 Expansion)

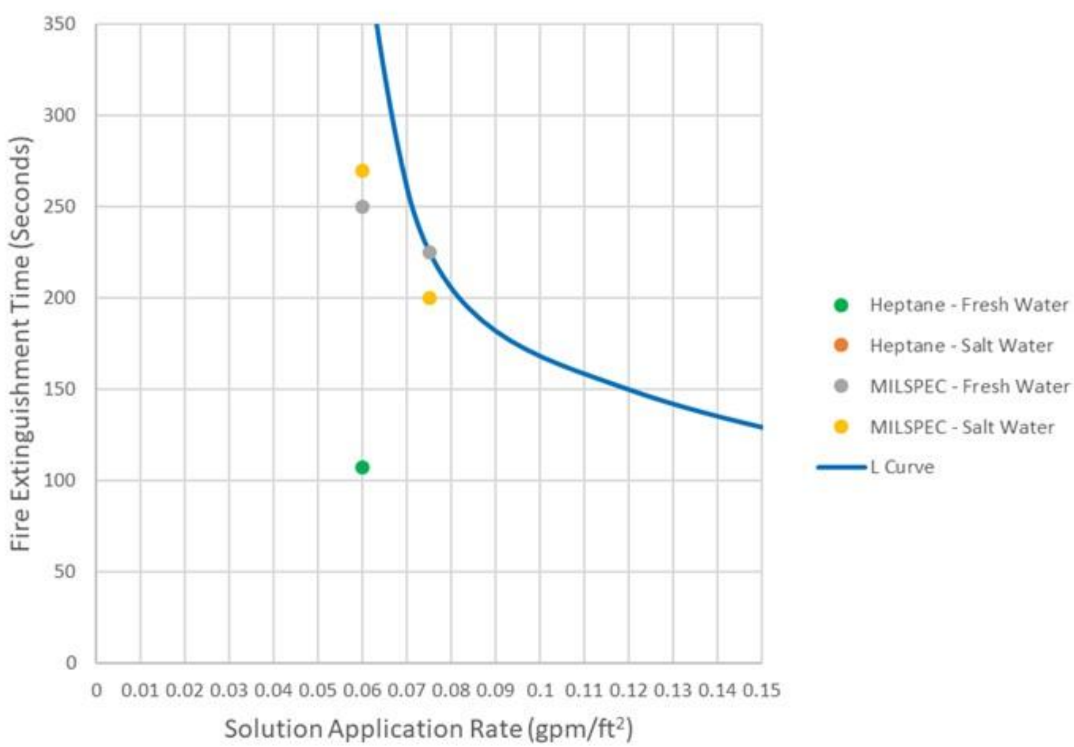


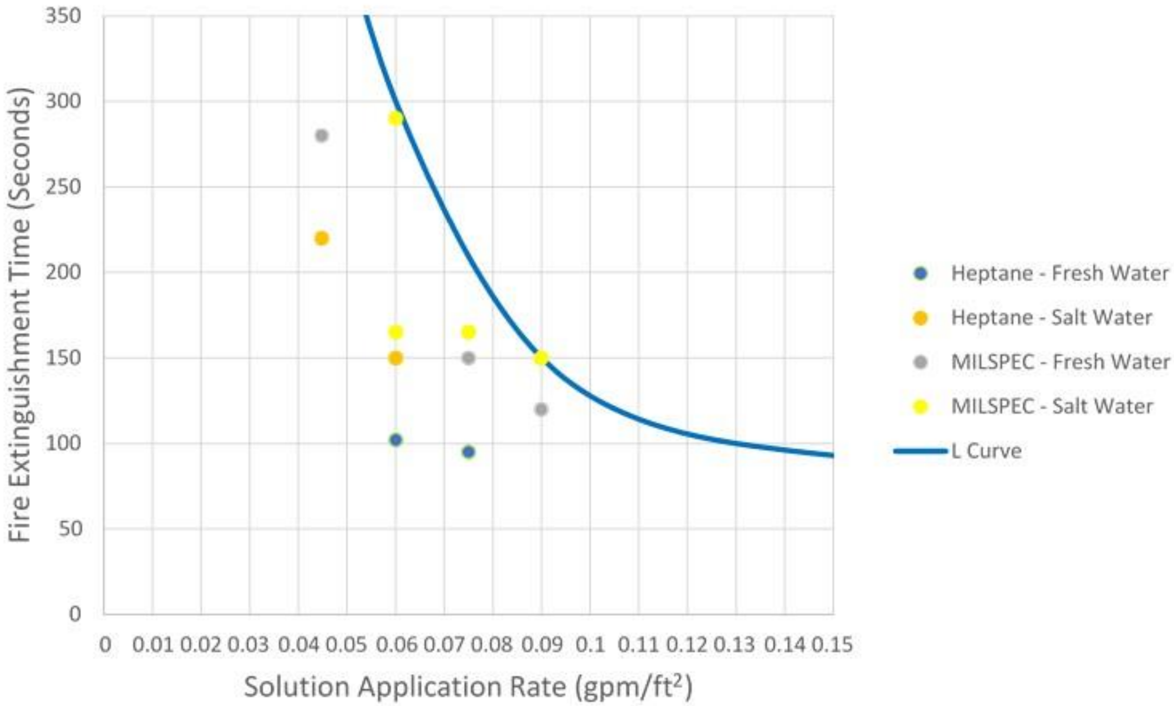
Figure 9.5.5-1 AR-FFF2 "L Curves"

As illustrated by the two plots, the performance data is significantly scattered indicating that the firefighting capabilities AR-FFF1 vary dramatically across the range of parameters included in this assessment, more so for the lower aspirated foam than for the higher aspirated. However, most of this scatter is attributed to the difficultly in extinguishing MILSPEC gasoline (i.e., variations in capabilities against different test fuels). The figures also indicate that the critical application rate for AR-FFF2 is on the order of 0.075 gpm/ft^2 for the lower aspirated foam and on the order of 0.05 gpm/ft^2 for the higher aspirated foam.

9.5.6. H-FFF1 Performance Plots

The extinguishment time “L Curves” for the tests conducted with H-FFF1 (i.e., all of the Type III tests conducted with H-FFF1 against heptane and MILSPEC gasoline fires) are provided in Figure 9.5.6-1.

H-FFF1 (3-4 Expansion)



H-FFF1 (7-8 Expansion)

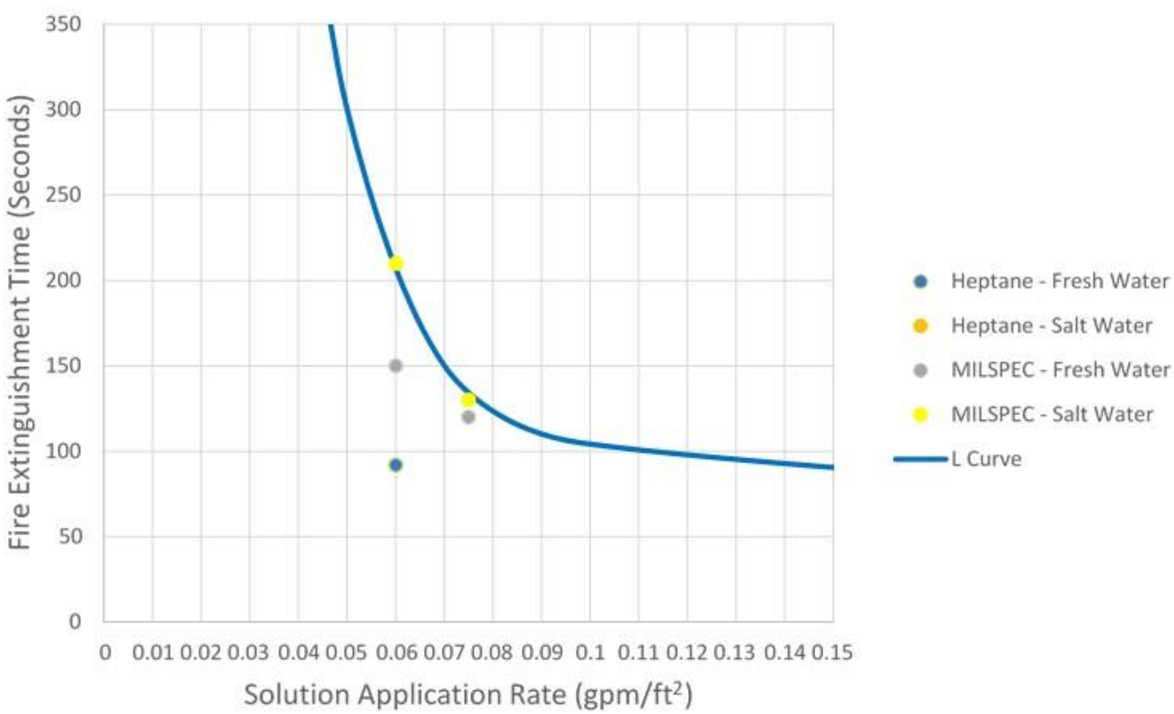


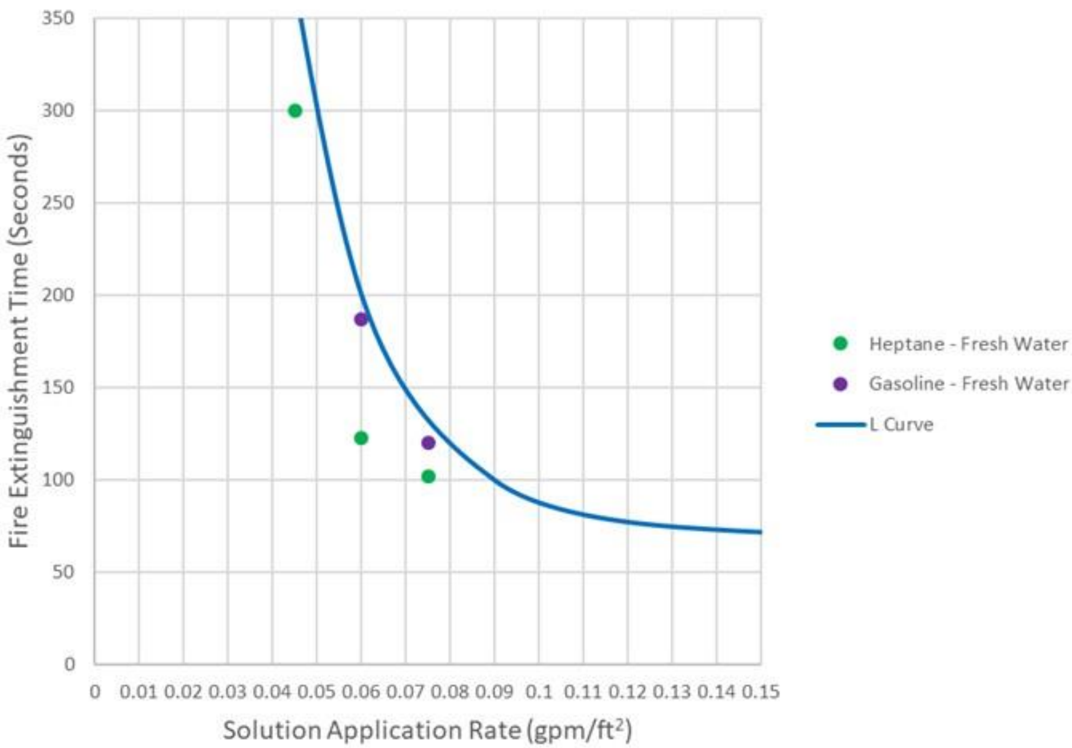
Figure 9.5.6-1 H-FFF1 "L Curves"

As illustrated by the two plots, the performance data is fairly well grouped but there is some degree of scatter, especially on the extinguishment L curve. Most of this scatter is attributed to slightly longer control and extinguishment times for the tests conducted with MILSPEC gasoline (i.e., some variation in capabilities between fuel types). The figures also indicate that the critical application rate for H-FFF1 is on the order of 0.05 gpm/ft^2 for the lower aspirated foam and on the order of 0.045 gpm/ft^2 for the higher aspirated foam.

9.5.7. H-FFF2 Performance Plots

The extinguishment time "L Curves" for the tests conducted with H-FFF2 (i.e., all of the Type III tests conducted with H-FFF2 against heptane and MILSPEC gasoline fires) are provided in Figure 9.5.7-1. It needs to be restated that H-FFF2 is not listed for use with saltwater and as a result, was never tested with saltwater. This explains the reduced number of data points on these plots as compared to the other foams included in this assessment.

H-FFF2 (3-4 Expansion)



H-FFF2 (7-8 Expansion)

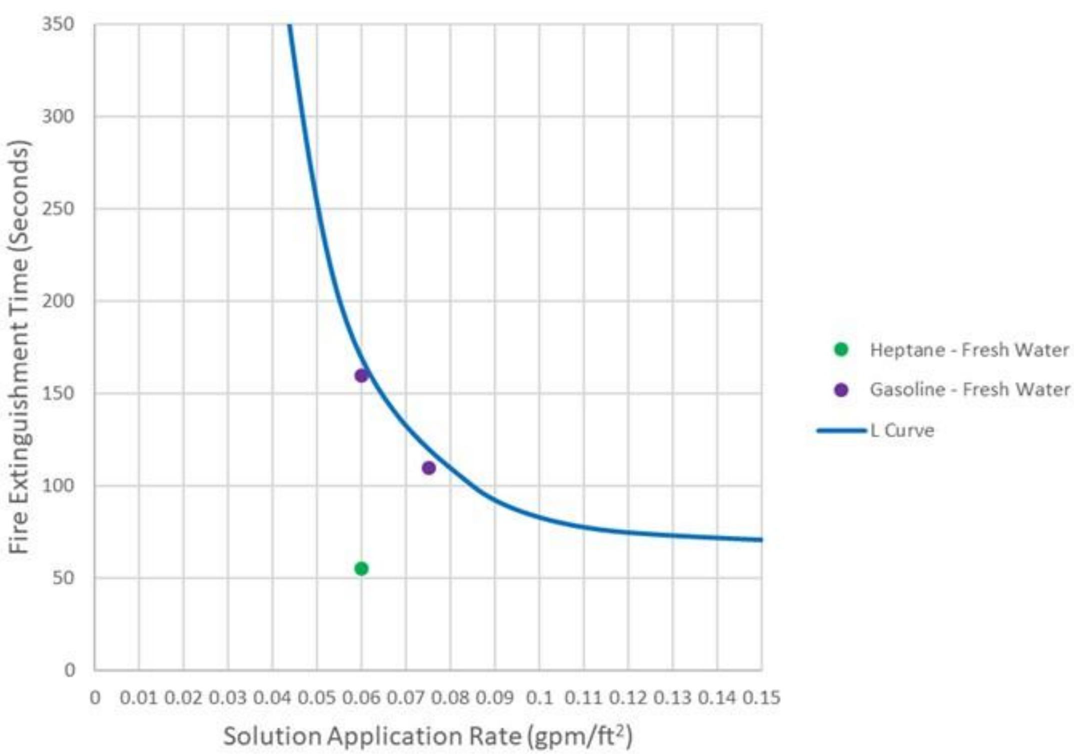


Figure 9.5.7-1 H-FFF2 “L Curves”

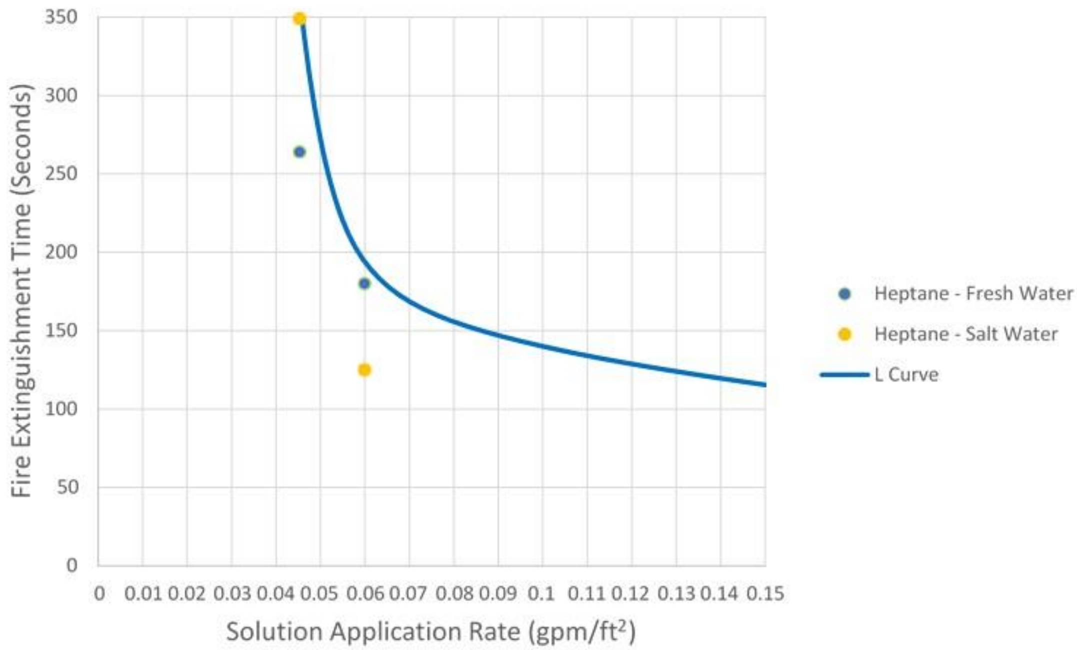
As illustrated by the two plots provided in the figure, the performance data is fairly well grouped indicating that the performance of the H-FFF2 was relatively consistent across all of the parameters included in this assessment. The figures also indicate that the critical application rate for H-FFF2 is on the order of 0.045 gpm/ft^2 for the lower aspirated foam and on the order of 0.04 gpm/ft^2 for the higher aspirated foam.

9.6. Capabilities Comparisons (Various Parameters)

9.6.1. Difficulty Extinguishing Gasoline

As stated previously, the AR-FFFs had difficulty in controlling and extinguishing the MILSPEC gasoline fires when compared to the other foams tested. During the tests conducted with the lower aspirated foam, the gasoline appeared to react with the foam blanket causing the bubbles to break, making the solution look “milky” rather than “foamy”. As a result of this foam breakdown, flames continued to burn along the top of the blanket, even though the fuel was covered with foam. The variations in extinguishment difficulty are shown by a comparison of the L Curves for the two fuels (heptane and MILSPEC gasoline) developed from the AR-FFF1 tests conducted with the lower aspirated foam (i.e., Series I) and are shown in Figure 9.6.1-1. The data shows that the critical application rate for AR-FFF1 is 50% greater for gasoline (0.075 gpm/ft^2) than for heptane (0.50 gpm/ft^2).

AR-FFF1 – Heptane – 3-4 Expansion



AR-FFF1 – MILSPEC Gasoline – 3-4 Expansion

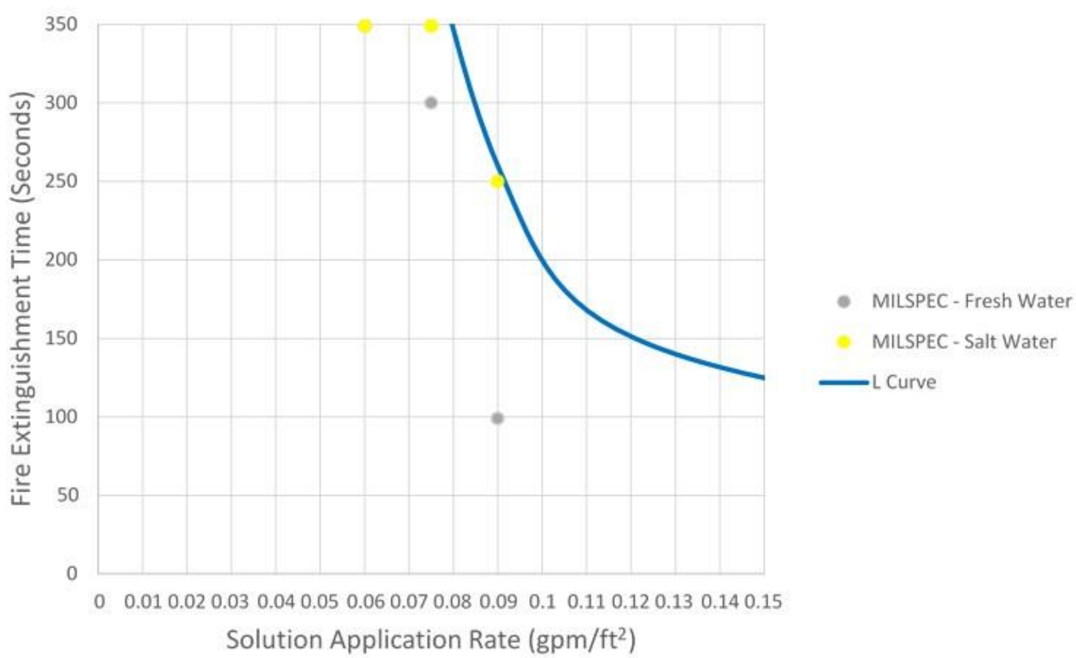
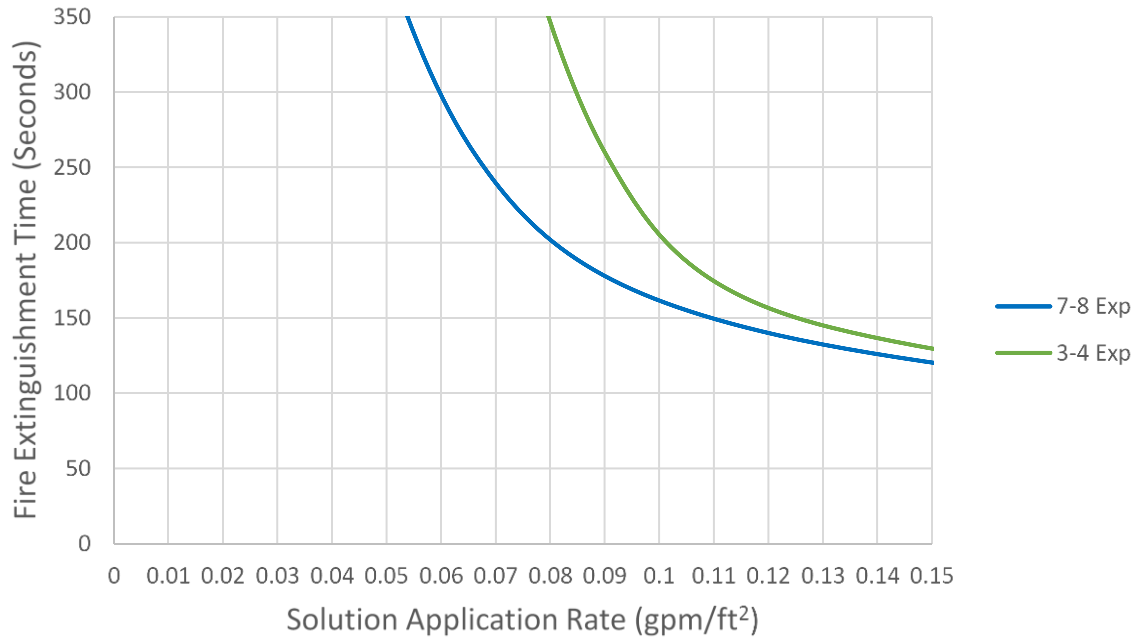


Figure 9.6.1-1 Variations in Capabilities between Test Fuels

The capabilities of the AR-FFFs against MILSPEC gasoline were increased through the use of higher aspirated foam and were observed to reduce the critical application rate from 0.075 gpm/ft^2 for the lower aspirated foam to 0.05 gpm/ft^2 for the higher aspirated foam. The capabilities of the

H-FFFs against MILSPEC gasoline were also increased through the use of higher aspirated foams but to a lesser degree. This is shown in Figure 9.6.1-2

AR-FFFs



H-FFFs

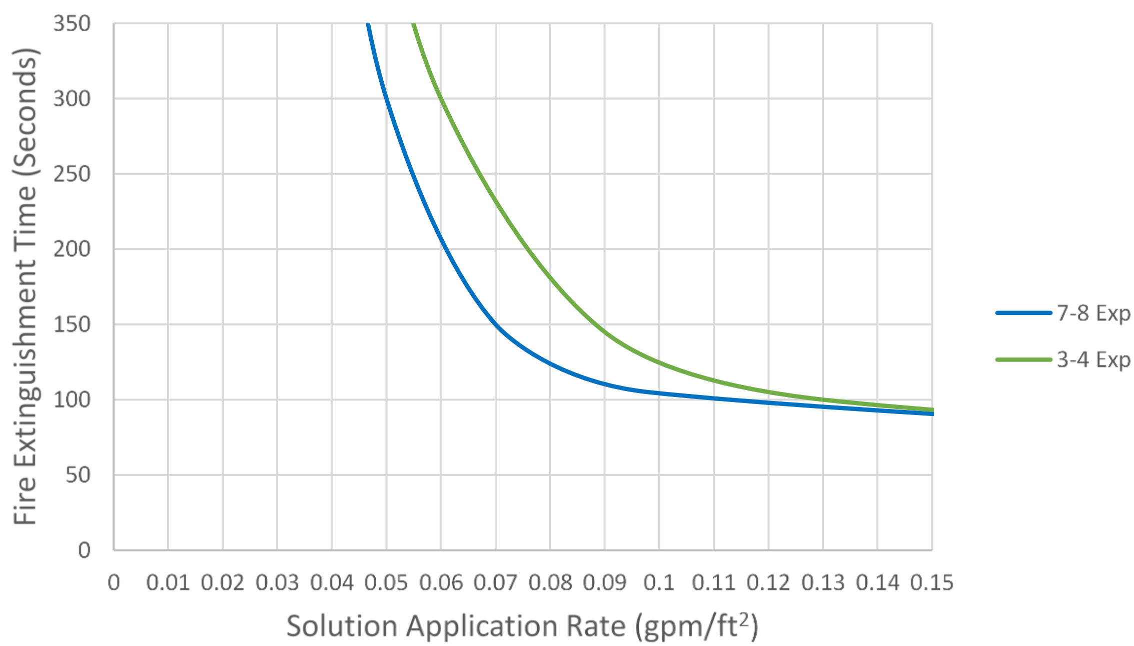
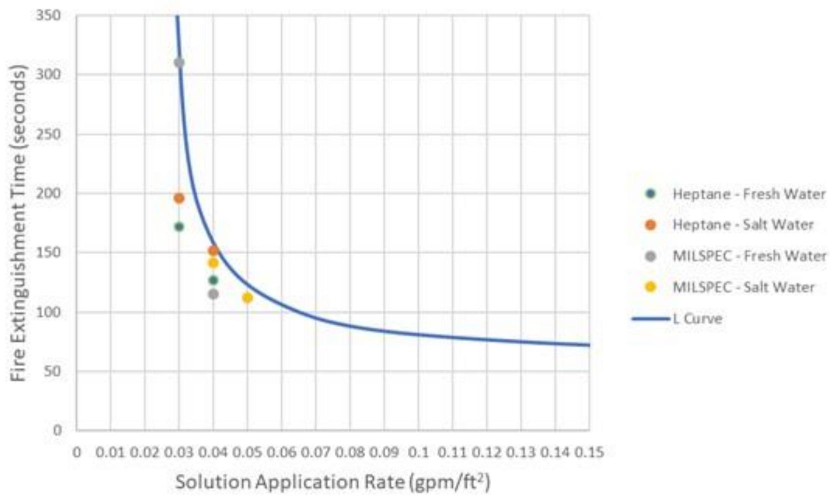


Figure 9.6.1-2 Increased Capabilities Associated with Foam Quality/Aspiration

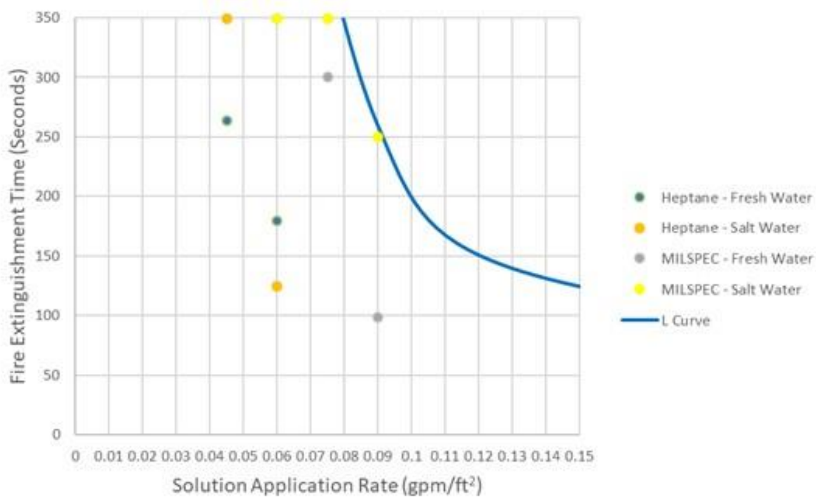
9.6.2. Quantitative Differences in Capabilities between Foam Types

Figures 9.6.2-1 and 9.6.2-2 provide a visual comparison of the L Curves for the general groups of foams (i.e., AR-AFFF, AR-FFFs and H-FFFs). Figure 9.6.2.1 provide the L curves for the lower aspirated foam and Figure 9.6.2-2 for the higher aspirated foam. These figures clearly show a significant difference in the capabilities between the groups of foams with the greatest difference occurring for the lower aspirated foam and with this difference reduced through the use of higher aspirated foam.

AR-AFFF



AR-FFF1



H-FFF1

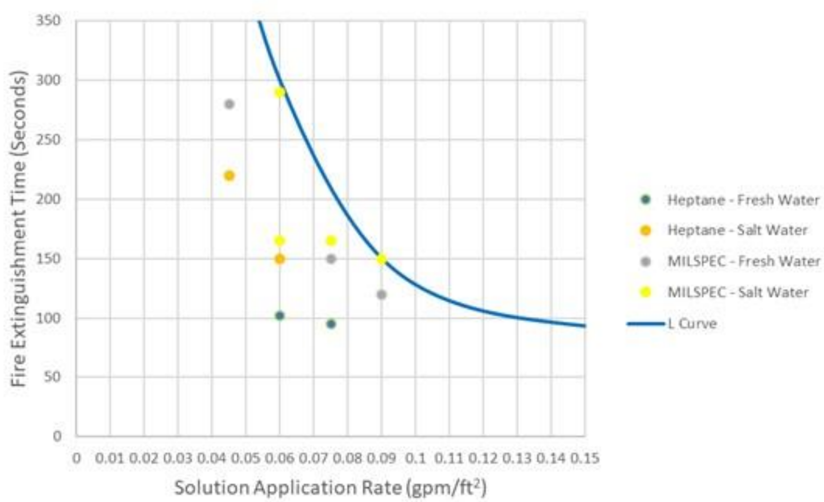
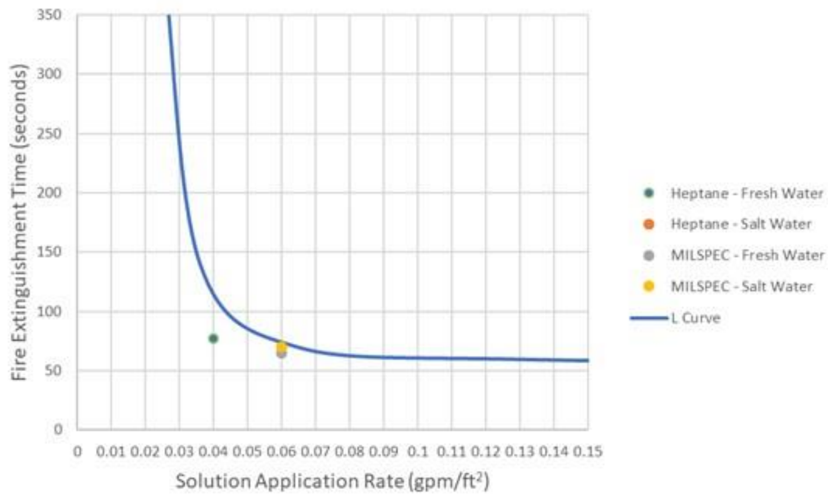
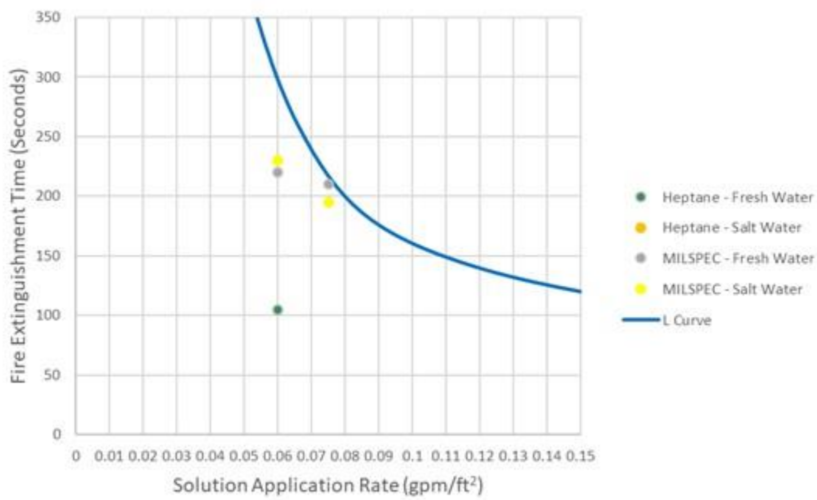


Figure 9.6.2-1 L Curves Illustrating the Extinguishing Capabilities of Lower Aspirated Foams (Agent Comparison)

AR-AFFF



AR-FFF1



H-FFF1

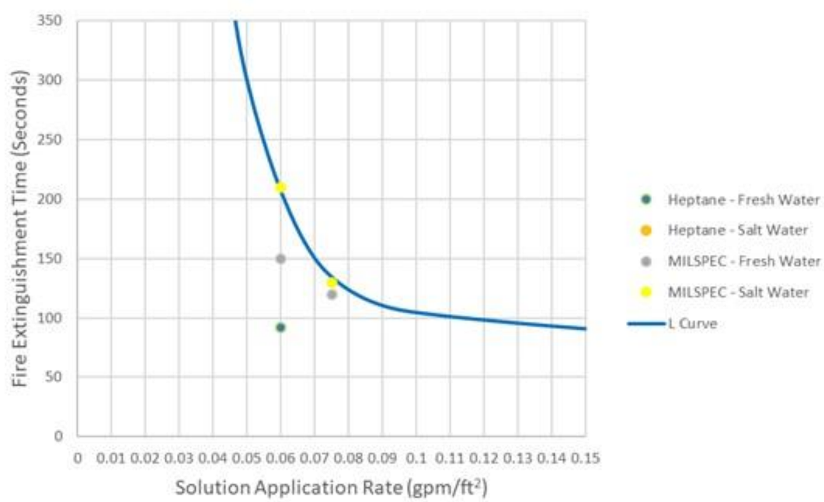


Figure 9.6.2-2 L Curves Illustrating the Extinguishing Capabilities of the Higher Aspirated Foams (Agent Comparison)

To quantify the magnitude of these differences, the critical application rates for extinguishment and the application rates associated a two-minute extinguishment time are summarized in Table 9.6.2-1 for the five foams included in this assessment.

Table 9.6.2-1 L Curve Value Comparisons between Foams

	3-4 Exp. Ratio		**7-8 Exp. Ratio**	
	Asymptote	**2:00**	**Asymptote**	**2:00**
Foam	**gpm/ft^2**	**gpm/ft^2**	**gpm/ft^2**	**gpm/ft^2**
AR-AFFF	0.030	0.050	0.025	0.040
AR-FFF1	0.075	0.130	0.05	0.110
AR-FFF2	0.080	0.140	0.06	0.120
FFF1	0.050	0.110	0.045	0.075
FFF2	0.042	0.075	0.04	0.070

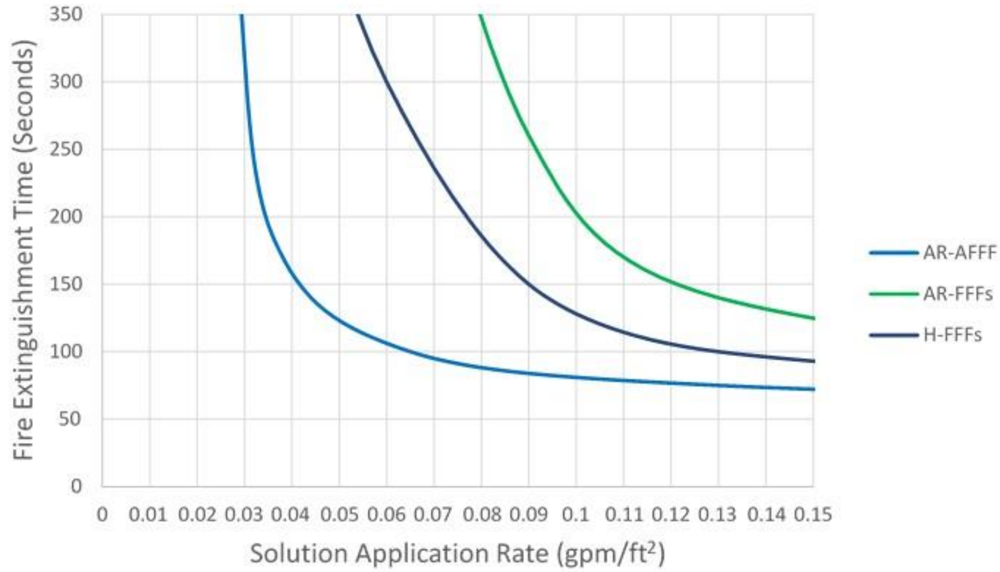
In general, when comparing the capabilities of the FFFs to the baseline AFFF at the same foam quality/aspiration, the FFFs typically required between 1.5 to 3 three times the application rates to produce comparable performance (i.e., 2:00 extinguishment times) for the hydrocarbon fuels (i.e., heptane and MILSPEC gasoline).

The two original AR-FFFs (AR-FFF1 and AR-FFF2) demonstrated similar firefighting capabilities and typically required about three times the application rates of AR-AFFF to produce comparable performance. This assessment could not be performed on AR-FFF3 due to a limited data set.

There was some variation in capabilities between the two H-FFFs with H-FFF2 requiring about 50% more foam (application rate) than the AR-AFFF for the same foam quality/aspiration and H-FFF1 requiring about 75% more foam than the AR-AFFF for the same foam quality/aspiration.

When comparing capabilities of the AR-FFFs to the H-FFFs, the H-FFFs produced similar capabilities as the AR-FFFs at a 40% reduced flow rate for the lower expanded foam and a 30% reduced rate for the higher expanded foam. Consequently, the use of higher aspirated foam reduced the differences in capabilities between the two FFF types (i.e., alcohol resistant and hydrocarbon FFFs). This is illustrated on the plots shown in Figure 9.6.2-3.

3-4 Exp



7-8 Exp

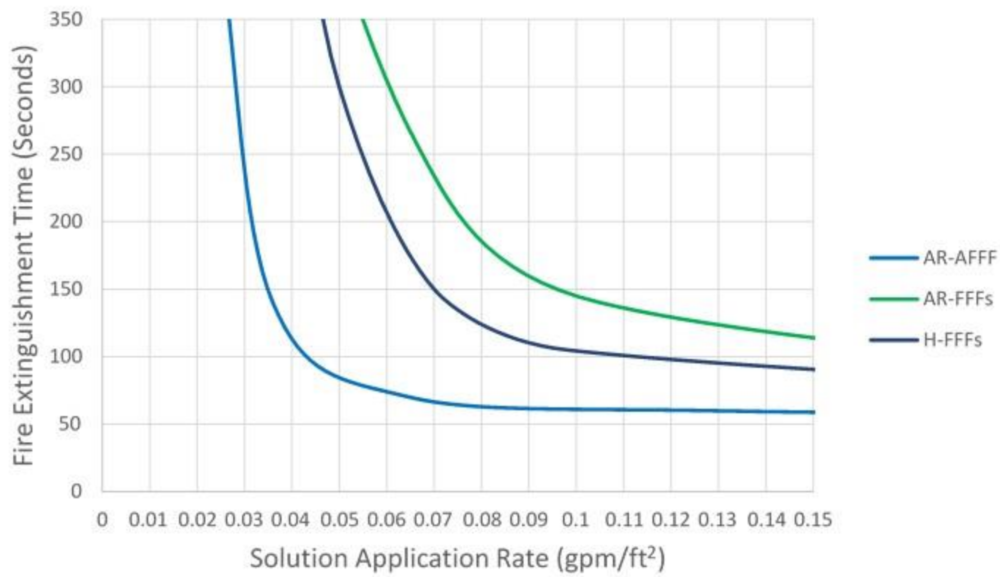


Figure 9.6.2-3 L Curves Illustrating Extinguishment Capabilities (Agent Type Comparison)

In completing the discussion on the development and the use the L Curves, it needs to be noted that the design/installation/deployment requirements begin at the far-right side of the plots providing some level of confidence that the foams may still work in a number of applications. In addition, the L Curves tend to support the notion that reduced firefighting capabilities of specific foams/foam types can be compensated for by increasing the discharge rates/densities.

On a final note, the L Curves provide a sound technical basis for developing design and deployment guidance for future foam standards.

9.7. ELEVATED FUEL TEMPERATURE TESTS

A limited number of tests were conducted to provide a high-level assessment of the effects of fuel temperature on the capabilities of the FFFs. It needs to be noted that although the intent was to focus was on the effects of fuel temperature, the assessment was conducted at ambient temperatures in the desired temperature ranges (i.e., 50º-70ºF and 80º-90ºF) as opposed to just heating the fuel. The point being, that not only the fuel was at these temperatures but so were the foam solutions, water substrate and ambient air used to aspirate the foam.

These tests were conducted with MILSPEC gasoline floated on a water substrate using the Type III scenario and are summarized in Table 9.7-1. The lower temperature tests were conducted in early April (during Series I) and the higher temperature tests were conducted in late August (a month prior to Series II).

Table 9.7-1 Elevated Temperature Test Results

Foam	Type of Discharge	Fuel Type	Water Type	Flow Rate	Exp. Ratio	48º - 72ºF		82º - 93ºF	
						Cont. Time	Ext. Time	Cont. Time	Ext. Time
AR-FFF1	Type III	MILSPEC	Fresh	3.75 gpm	7-8	0:50	3:30	1:00	2:50
AR-FFF1	Type III	MILSPEC	Salt	3.75 gpm	7-8	1:00	3:15	1:00	2:55
AR-FFF2	Type III	MILSPEC	Fresh	3.75 gpm	7-8	1:15	3:45	1:00	3:45
AR-FFF2	Type III	MILSPEC	Salt	3.75 gpm	7-8	1:10	3:40	1:05	3:25
AR-FFF3	Type III	MILSPEC	Fresh	3.75 gpm	7-8	0:45	3:20	1:05	3:40
FFF1	Type III	MILSPEC	Fresh	3.0 gpm	7-8	0:45	2:30	1:00	3:05
FFF1	Type III	MILSPEC	Salt	3.0 gpm	7-8	1:05	3:30	1:00	2:55
FFF2	Type III	MILSPEC	Fresh	3.0 gpm	7-8	0:45	2:40	1:10	2:50

As shown in Table 9.7-1, the results were consistent over the range in ambient/fuel temperatures included in this assessment. With that said, it is understood that fires involving boiling flammable liquids are much harder to extinguish than fires that are combatted prior to the transition into boiling.

10. SUMMARY

One hundred sixty-five tests were conducted during this assessment. As a general observation, the results of these tests were consistent with UL listed values for the various foams with a limited number of exceptions.

The baseline C6 AR-AFFF included in this assessment demonstrated superior firefight capabilities through the entire test program under all test conditions. AR-AFFF was least affected by the range in variables included in this assessment.

In general, the firefighting capabilities of the FFFs vary from manufacturer to manufacturer making it difficult to develop “generic” design requirements. This may have been, and still could be the case with AFFF as a class of foams.

For the Type II tests conducted with IPA, all of the AR-FFFs were able to extinguish the test fires at 10-20% below the listed values. AR-FFF1 and AR-FFF2 required 8 gpm to extinguish the fires which is 3.5 times greater than the 2.25 gpm required using the AR-AFFF. AR- FFF3 required 5 gpm to extinguish the fires which is 2.2 times greater than 2.25 gpm required using the AR-AFFF. Extinguishment densities followed roughly the same trends.

The Type III tests conducted with IPA demonstrate that IPA is extremely difficult to extinguish with direct spray impingement onto the fuel surface and requires an indirect attack to be effective (e.g. bouncing the foam off the side of the pan increased overall capabilities).

For the remaining Type III tests, all foams did well against heptane (i.e., met the UL 162 performance requirements) at the design application rates with higher aspiration. All foams were capable of extinguishing the heptane fires at the design application rates with the lower aspiration but about half of the foams had reignition/burnback issues preventing them from meeting the UL 162 requirements. This may have been an artifact of the nozzle/test (i.e., plunging issues). All foams eventually met the UL 162 requirements with the lower aspirated foam (heptane fire) but some required an increase in flow rate/discharge density of 25% to 50%.

The results demonstrate the effects of foam quality/aspiration on FFF performance. In many cases, a 25% to 50% increase in the flow rate/discharge density of lower aspirated foam was required to match the capabilities of higher aspirated foam.

With respect to fuel type, the baseline AR-AFFF demonstrated consistent capabilities against all three hydrocarbon test fuels (heptane, MILSPEC gasoline and E10 gasoline) included in this assessment. However, both grades of gasoline (MILSPEC and E10) were much more difficult to extinguish than heptane for all of the FFFs included in this assessment.

Focusing on the tests conducted with the higher aspirated foam, all of the FFFs were able to extinguish the MILSPEC gasoline fires at 3 gpm (0.06 gpm/ft^2) but typically took about twice as long (and required twice as much agent) to extinguish as the heptane fires. The E10 gasoline was even harder to extinguish than the MILSPEC gasoline. The three AR-FFFs required a 50% increase in flow/application rate in order to extinguish the E10 fires. The two H-FFFs also required a 25% increase in flow/application rate in order to extinguish the E10 fires. Surprisingly, the H-FFFs were able to extinguish the E10 fires at a lower rate than the AR-FFFs. In dependent of the flow/application rate, the FFFs typically required about twice as much agent to extinguish the E10 fires as compared to the MILSPEC fires.

For the FFFs, it appears that MILSPEC gasoline is twice as hard to extinguish as heptane, and E10 gasoline is twice as hard as MILSPEC gasoline (four times as hard as heptane).

In general, when comparing the capabilities of the FFFs to the baseline AFFF at the same foam quality/aspiration, the FFFs typically required between 1.5 to 3 three times the application rates to produce comparable performance (i.e., 2:00 extinguishment times) for the hydrocarbon fuels (i.e., heptane and MILSPEC gasoline).

The two original AR-FFFs (AR-FFF1 and AR-FFF2) demonstrated similar firefighting capabilities and typically required about three times the application rates of AR-AFFF to produce comparable performance.

There was some variation in capabilities between the two H-FFFs with H-FFF2 requiring about 50% more foam (application rate) than the AR-AFFF for the same foam quality/aspiration and H-FFF1 requiring about 75% more foam than the AR-AFFF for the same foam quality/aspiration.

When comparing capabilities of the AR-FFFs to the H-FFFs, the H-FFFs produced similar capabilities as the AR-FFFs at a 40% reduced flow rate for the lower aspirated foam and a 30% reduced rate for the higher aspirated foam. Consequently, the use of higher aspirated foam reduced the differences in capabilities between the two FFF types (i.e., alcohol resistant and hydrocarbon FFFs). It is recommended that the tested/listed foam qualities (i.e., expansion ratios and 25% drainage times) be included on UL listing data sheet(s).

With respect to elevated fuel temperatures, the results were consistent over the range in ambient/fuel temperatures included in this assessment. With that said, it is understood that fires involving boiling flammable liquids are much harder to extinguish than fires that are combatted prior to the transition into boiling.

The type of water (i.e., freshwater versus saltwater) had minimal effect on the firefighting capabilities of the FFFs and varied between foams.

11. MAIN TAKE A WAYS AND CONSIDERATIONS

1. FFFs have come along way but we (our industry) are still learning about their capabilities and limitations (a lot of promising data and more research in progress).
2. The capabilities of FFFs vary between manufacturers/formulations making it difficult to generically characterize the capabilities of these foams as a “group” of “class” of foams.
3. FFFs are not a “drop in” replacement for AFFFs. However, some can be made to perform effectively as an AFFF alternative with proper testing and design (i.e., with higher application rates/densities).
4. The results demonstrated the need to deploy these new FFFs strictly within the listed parameters and hardware.
5. Due to its oleophobic properties, AFFF has two separate mechanisms that combine to aid in the extinguishment of a flammable liquid fire; a water/surfactant film that forms on the fuel surface and a foam blanket (matrix of bubbles), which both serve to seal-in the flammable vapors resulting in extinguishment (i.e., shutting off the fuel vapors that are burning above the fuel surface). FFFs have only the foam blanket to seal-in the vapors. As a result, the capabilities of FFFs will be highly dependent on the characteristics of the foam blanket (and the associated discharge devices). The film produced by AFFF has

provided an additional level of protection for legacy systems and discharge devices that do not produce good foam quality. Additional attention will need to be given to the discharge devices identified as part of the UL listing when fielding these foams. Foam quality/aspiration discussions are being added to NFPA 11. It is recommended that the tested/listed foam qualities (i.e., expansion ratios and 25% drainage times) be included on UL listing data sheet(s).

6. Fuel type is a variable that is not covered in our listing/approval test protocol and some foams struggle against other fuels (like gasoline) as compared to heptane.
    a. FFFs need to be listed for various fuels (gasoline, E10, Jet A, etc).
    b. Additional emphasis needs to be placed on the "listed parameters"
    c. FFFs (SFFF) require their own category in UL 162 including Table 12.1
    d. The definition of a "polar solvent" needs to be developed for typical grades of gasoline (i.e., with respect to E(#) values) and fuel mixtures.

12. RECOMMENDATIONS: NFPA 11 INPUT AND THE PATH FORWARD

This research study has been facilitated by the Fire Protection Research Foundation (FPRF), an independent research affiliate of the National Fire Protection Association (NFPA). Definitive next actionable steps, such as changes to applicable NFPA Standards, are the purview of the NFPA Codes & Standards process. All proposed changes to the NFPA Codes & Standards are in the domain of the NFPA consensus process.

NFPA 11 relies heavily on test protocols for approving/listing foams for various applications. These protocols are intended to ensure an adequate level (or known level) of capabilities/performance for representative scenarios. As mentioned numerous times before, a significant finding of this study was that, although the five foams tested during this program had the same approval/pedigree, their capabilities varied significantly over a range of representative conditions and fuels. The variations in capabilities observed during this program make it difficult to develop generic design and deployment guidance for the group of foam as a category. To potentially add to the confusion, FFFs fall under the UL definition of "Synthetic" foams which may also have different capabilities and limitations across the various chemistries.

Although the intent of this research was to provide guidance for standards making authorities and not focused to provide any recommendations or revisions to the existing test protocol (e.g., UL 162), industry standards rely heavily on the pedigree provided by the test protocols and are used as the basis of the design and deployment requirements.

Going forward, the industry should consider defining a new class or group of foams referred to as FFFs (or SFFF as being proposed during the NFPA 11, 2020 revision cycle) or consider developing performance-based criteria regardless of foam type.

Since the industry is shifting away from the use of fluorochemical surfactants for firefighting foams, tests need to be developed to verify the composition of the foams (specifically fluorochemical surfactant content). With that said, it would be advantageous if the environmental community could work hand-in-hand with the fire protection community to help field an environmentally friendly foam that will not be scrutinized in the future due to other unforeseen concerns (i.e., minimize the likelihood for regret of transitioning to a new formulation or class of foams).

Prior to developing the design and deployment guidance of this new class of foams, the approval tests need to be expanded to include some of the issues identified during this program. At a minimum, the protocol needs to revisit using heptane as a surrogate for all hydrocarbon fuels and should consider developing a hydrocarbon fuel list similar to that provided for polar solvents. The ultimate goal is to ensure an adequate level of performance over a wider range of conditions than currently provided using heptane alone. If this can be achieved, then, design and deployment guidance can be developed for the “class” as a whole. If the capabilities cannot be homogenized, then the industry may be forced to consider agent/fuel specific requirements. Reviewing the UL listings for these FFFs suggests that this may end up being the case.

As a side note, there is high degree of confusion associated with firefighting foams in general. There are numerous test standards for approving foams for specific applications. The approval tests vary significantly with respect to the test parameters including, fuel type, foam application method, foam application rate, foam application duration, pass fail/criteria (i.e, control and extinguishment times), vapor sealing and burnback. In addition to the variations in test protocols, UL 162 lists/assesses foams at different application rates for the same listing (e.g., Type III tests are conducted with AFFF at 2 gpm and a 3 minute discharge time as compared to synthetic foams which are tested at 3 gpm with a 5 minute discharge). Since the industry is currently focused on identifying an environmentally friendly AFFF alternative, the foam community should also consider standardizing the approval process and design/deployment requirements for foams used for the same applications.

The next NFPA 11 Technical Committee meeting scheduled for early 2020, the rates listed in UL 162, Table 12.1 for “Synthetic” foams should be discussed with respect to the “typical” factors of safety used when applying test results to actual installations. The NFPA 11 technical committee should work with UL to address the variations in capabilities across fuel types observed during this test program (as well as others). The group should consider adding a new class of foams (i.e., SFFF as currently being considered by the NFPA 11 TC) to the UL 162 document to address the deployment of these foams over a wider range of applications/fuel types and to account for the variations in capabilities between this new group/class of foams.

13. ADDITIONAL RESEARCH

The following list of research topics/areas would further increase the understanding of the capabilities and limitations of FFFs and a whole.

- Foam Quality/Aspiration: parametric study of expansion ratios (0 – 7 by ones) looking at its effect on both extinguishment and vapor suppression/containment. Foam layer depth should also be included in this assessment.
- Fuel types: crude oil, kerosene based, polar solvents (water soluble) as well as others
- General chemical compatibility between surfactants and fuels
- Fielding issues associated with higher viscosity concentrates
- Shelf life and viscosity changes of concentrates as a function of temperature and time
- Larger fire sizes (i.e., assess shifts in L curves associated with scale)

14. ACKNOWLEDGEMENTS

In addition to acknowledging the Technical Panel as a whole, specific recognition needs to go to Bernard Leong and Ed Hawthorne for their constant oversight on the technical aspects of the program. The Authors would also like to acknowledge Clarence Whitehurst (NRL) and Stan Karwoski (Jensen Hughes) for their assistance in performing the 165 fire tests conducted during this program.

15. REFERENCES

1. NFPA 11, “Standard for Low−, Medium−, and High− Expansion Foam”, 2016 Edition
2. UL 162, “Standard Foam Equipment and Liquid Concentrates”, 8^{th} Edition dated Feb 2018
3. MILSPEC, “US Military Specification,” Mil-F-24385 F, Department of the Navy, Washington, DC, January 1992.
4. Scheffey, J.L. and Wright, J.A., "Analysis of Test Criteria for Specifying Foam Firefighting Agents for Aircraft Rescue and Firefighting," FAA Technical Report, DOT/FAA/CT-94/04, Atlantic City, NJ, August 1994.