Regimes of Fire Spread Across an AFFF-Covered Liquid Pool

Bradley A. Williams, Ronald S. Sheinson and Justin C. Taylor
Navy Technology Center for Safety and Survivability
Naval Research Lab, 4555 Overlook Ave. SW, Washington, DC 20375

Abstract

We have examined the fire suppression performance of AFFF against three fuels that cover a wide range of flash point temperatures. For qualification testing of aqueous film-forming foams under the U.S. Military Specification MIL-F-24385, the fuel used for the test is gasoline, which typically has a flash point of approximately -40^{o}C. In a recent series of tests we compared JP-5 jet fuel (minimum flash point 60^{o}C) with biodiesel (flash point >130^{o}C) under a slightly modified protocol based on the MIL-F-24385 testing. A significant observation is that the mode of flame advancement across a foam blanket differs between the fuels with different flash point ranges. For gasoline, which has a flash point below ambient temperature, transient or steady flames appear at a substantial distance from the reignition source. For the higher flash point fuels, by contrast, the foam has a well-defined lateral boundary which gradually erodes due to heat from the fire, and the burning region is confined to the uncovered fuel surface. For JP-5 (flash point <100^{o}C), essentially the entire fuel surfaces which is uncovered by foam is involved with fire. For biodiesel, which has a flash point significantly above the boiling point of water, there is a lateral "standoff" distance of several inches from the foam boundary to the limit of the fire. These observations indicate that for low flash point fuels, the ability of the foam to act as a vapor barrier to the fuel is a critical factor in burn back, but for high flash point fuels, the progression rate is governed by the heat capacity and resistance to thermal radiation of the foam.

Introduction

Aqueous Film Forming Foam (AFFF) has been used in the past few decades as an effective method to suppress fuel fires for both military and civilian use. This fire suppression technique is unique in that once it is applied, AFFF forms both an aqueous film layer and a foam layer on top of the fuel. These layers smother the fire and significantly decreases the vapor allowed to be exposed to possible reignition, ultimately extinguishing the fire.

"MilSpec" AFFF is tested against the MIL-F-24385 qualification test [1], which specifies a number of physical and performance properties. The majority of MIL-F-24385 fire suppression testing is performed in a 28-ft^2 round pan, with a 6-ft diameter, using unleaded gasoline not containing ethanol. AFFF solution is applied at a rate of 2 gallons/minute after a ten second "pre-burn" time, which is defined as the time interval between lighting the fuel and applying the AFFF. The pre-burn interval allows the fire to spread across the entire pan, and the fuel to heat up, reaching an equilibrium temperature.

Once the pre-burn is complete (10 seconds), AFFF mixed at its typical proportion must extinguish the fire in no more than 30 seconds.

In addition to the extinguishment, MIL-F-24385 involves a "burn back" test, which occurs after applying foam for a total of 90 seconds (including the extinguish time). The burn back test is a way to determine how well the foam will prevent the fire from reigniting. A round 1 ft diameter pan containing burning fuel is placed in the middle of the foam filled 28-ft^2 pan and is left in place until the fire spreads and sustains itself outside the 1 ft diameter pan. The starter pan is then removed. The burn back test measures the amount of time required from the initial placing of the 1 ft diameter pan until 25% of the 28-ft^2 pan is re-engulfed in flames, which for Milspec AFFF must be at least six minutes.

In addition to practical studies validating AFFF performance according to the MilSpec and other standards, a number of studies have looked at different properties of AFFF, to understand their contribution to fire extinguishment. These have included the effect of both the foam and film to act as a vapor barrier [2,3], rheological properties [4] and spreading [5,6] and drainage [7,8]. All of these properties, as well as many others, influence fire suppression and inhibition of reignition, but their relative importance is likely to vary with the particular fire scenario and especially properties of the fuel. Thus, test data under various conditions may help to assess the importance of different properties in influencing foam effectiveness.

The present study compares extinguishment, and particularly burn back test results, among three fuels with very different flash points: gasoline, JP-5, and biodiesel. In addition to quantitative differences in the extinguishment and burn back times at different AFFF application rates, we find that the phenomenology of burn back is different between the fuels. This trend can be explained based on the flash point of the fuel relative to ambient temperature and the boiling point of water. This finding has significant implications for the mechanism and critical parameter governing AFFF effectiveness as a function of fuel type.

Methodology

Although the qualification testing for Milspec AFFF is done using gasoline, which has a flashpoint of approximately -40° C, most fire threats against which AFFF is used for protection involve fuels with much higher flash points. The major fuels used at military air bases (on land) and civilian airports are JP-8 and Jet-A/A1, respectively. These fuels all have minimum flash points of 38° C. JP-5 (used for aviation aboard Navy aircraft carriers) and F-76 Military diesel have minimum flash points of 60° C.

In addition, alternative (non-petroleum derived) fuels are likely to be of increasing importance in the future. Up to the present there has been little study of AFFF's effectiveness on alternative fuels. We conducted a series of tests of AFFF extinguishment and burn back on JP-5, a higher flashpoint fuel in widespread shipboard use, and biodiesel, a current generation alternative fuel with a very high flashpoint (typically above 130°C).

Since JP-5 and biodiesel have flashpoints substantially above ambient temperature, we added a small amount (650 ml) of n-heptane to the fuel just before the beginning of the test to facilitate ignition. Also, the preburn time (interval between ignition and application of AFFF) was increased to 30 seconds for JP-5 and 40 seconds for biodiesel in order for the fire to spread across the entire surface of the pan and reach a steady state. National Foam Type 3 MilSpec AFFF was used for the extinguishment tests of JP-5 and biodiesel; results were compared to a large body of data of this and other AFFF formulations on gasoline.

Results

For JP-5, we found that if the standard AFFF application rate from the MIL-F-24385 test was used, the fire extinguishment time was under 20 seconds, compared to the 30 seconds requirement on gasoline (actual extinction times for qualified AFFFs on gasoline are typically 25-30 seconds). The short extinguishment time meant that the test was not very challenging to the foam. Therefore a variety of tests were performed at different AFFF application rates, to find a test condition for JP-5 which was sufficiently challenging to determine foam performance. Table 1 shows the results of the experimental tests for a Type 3 AFFF in fresh water at its design concentration of 3% for a JP-5 fire.

Table 1: Extinguishment and burn back times using JP-5 fuel as a function of pre-burn time and flow rate

Pre-Burn Time (sec)	Extinguishment (sec)	25% Burn back (min:sec)	Nozzle Pressure (psi)	Approx. Flow Rate (gpm)
30	18	N/A	70	1.8
30	19	11:03	50	1.6
30	21	8:02	30	1.2
30	26	5:00	20	1.1

It was found that an application rate reduced by about 40% was needed to produce comparable extinction and burn back times for JP-5 which were similar to those for gasoline under the standard test conditions. The higher flash point fuel is much easier to extinguish. For testing JP-5 and biodiesel, it was decided to use a flow rate of 1.24 gallons/minute and half strength AFFF mixture (the Type 3 concentrate was mixed at 1.5%). This half strength mixture is allowed 45 seconds to extinguish the fire in MilSpec qualification testing.

With the parameters set to identify the difference in foam quality of alternative fuels, JP-5, pure biodiesel, and a B-20 blend of the two were tested. It should be noted however that the preburn time for the pure biodiesel was increased again from 30 seconds to 40.

Biodiesel's flash point of >130°C caused the initial flames to spread extremely slowly, needing more time than JP-5 and the B-20 blend to completely light. Table 2 shows the results of these tests.

Table 2: Test Results with "Standard" AFFF Flow Condition of 1.24 gallons/min.

Test #	Fuel	Pre-Burn Time (sec)	Fire Out (sec)	25% Burn (min:sec)
1	JP-5 Drum	30	24	8:31
2	JP-5 Drum	30	20	7:48
3	B-20 (JP-5 Drum/Biodiesel)	30	22	7:12
4	B-20 (JP-5 Drum/Biodiesel)	30	22	7:17
5	B100 Biodiesel	40	15	11:05

In the burn back test used to determine if the foam can keep the fuel from reigniting to 25% of the area of the fuel within six minutes, gasoline, JP-5, and biodiesel showed markedly different phenomenology in the burn back tests. These differences are illustrated in Figs. 1-4.

Fig. 1 shows how gasoline lights on top of the foam and sweeps across it, while Fig. 2 shows the phenomenon of "ghost flames" which transiently sweep across the foam surface in gasoline tests. Fig. 3 shows the end of the burn back portion of a JP-5 (the firefighter is starting to apply foam to re-extinguish the fire). In this case, the fire is confined to a well-defined area which is not covered with foam; in contrast, the area where foam remains is free of fire, unlike the gasoline burn back of Fig. 1.

Figure 1. Burn back test on gasoline, showing spread of flames over the foam-covered region.

Figure 2. Transient "ghost flame" sweeping across foam-covered surface in gasoline burn back test. Such flames occur periodically before sustained ignition

Figure 3. End of burn back test with JP-5. Unlike the gasoline test, the fire is confined to a well-defined foam-free area of the fuel surface. The foam-covered region does not have flames isolated from the main fire.

Figure 4 shows a burn back test with biodiesel. For this fuel the burn back is generally similar to that for JP-5, but with one noteworthy difference. The flames do not cover the entire foam-free region as happens in the JP-5 tests. Rather, there is a "standoff" distance of several inches between the edge of the foam and the flaming region. This is probably due to the flash point being substantially higher than the boiling point of water, so that a flammable concentration of fuel vapor and an aqueous foam cannot coexist. One consequence of the fact that the flame cannot closely approach the foam boundary is that the burn back time for biodiesel is much longer than for JP-5.

Discussion

When analyzing the different means of flame spreading of the fuels, it is important to understand the intrinsic properties of each fuel, specifically flash point and vapor pressure. Since gasoline has such a low flash point (-40^{o}C), it can easily vaporize enough to produce a flammable mixture at ambient temperature, even in the absence of an external heat source.

Figure 4. Burn back test on biodiesel. Unlike the JP-5 burn back, in which the entire foam-free area is covered by flames, in this test there is a "standoff distance" between the flame and the edge of the foam-covered area.

When AFFF is applied to a gasoline pool, it forms an aqueous film layer and a foam layer. These layers act as a vapor barrier which inhibits, but does not completely prevent, formation of a flammable mixture above the foam layer. With gasoline, enough vapor can pass through the foam to produce a flammable mixture even in the absence of an external heat source. This vapor mixture is ignited from the burn back starter pan causing flames to erupt above the foam. These transient “ghost flames” sweep across the top of the pan. As the foam layer erodes, the rate of vapor penetration increases, allowing steady flames to appear even though the pool is still nominally covered with foam.

JP-5 has a flashpoint significantly above room temperature (60^{o}C), thus it cannot form a flammable vapor mixture without an external heat source. In the burn back test, this heat source is the starter pan fire, and flames are never observed a substantial distance away from the main fire, as occurs in gasoline fires.

The flashpoint of JP-5, however, is significantly below the boiling point of water, thus the JP-5 can form a flammable vapor mixture without first boiling away the foam completely. Therefore, the fire in the JP-5 burn back tests extends throughout the entire area of the uncovered pool, up to the foam boundary. The fire advances laterally, eroding the foam horizontally, rather than by vapor penetrating through the foam and causing the foam layer to be eroded vertically.

On the other end of the spectrum, biodiesel has a very high flash point (>130 ^{o}C). The mode of advancement of the flame is similar to that on JP-5, but with one significant difference. For biodiesel, the flash point is not only higher than ambient temperature, it is also higher than the boiling point of water. This means that if the fuel surface is hot enough to support a flammable vapor concentration, there can be no aqueous foam in the vicinity. Thus in the burn back test the flames are separated by about 10 cm from the foam boundary. The foam remains in a concentric circle around the exposed fuel area, even as the flames grow, maintaining the standoff distance between the foam edge and the flames.

Since the flames stay a substantial distance away from the edge of the foam during the biodiesel burn back test, in contrast to the JP-5 burn back test where they are in close proximity, the transfer of fire energy to evaporate the foam is less efficient, leading to a lower rate of foam regression and a longer burn back time.

These tests demonstrate a pattern, illustrated in Fig. 5, that flash point determines how flames spread over AFFF covered fuel. The lower the flash point, the more likely flames are to extend toward the edge of the exposed fuel, and even above the foam itself. Through visual observations and calculated data, it can be concluded that different regimes of flash point react in different ways to the burn back test of AFFF. While lower flash point fuels, such as gasoline, have vapor bubbling through the foam, allowing flames to spark overtop the foam in the form of "ghost flames", in higher flash point fuels that fire is relegated to the exposed fuel area only. Furthermore, when the flash point is above 100 ^{o}C, the flames are separated from the edge of the foam by a "standoff" distance. These methods of flame spreading are based on the intrinsic properties of the fuel and can be used to help determine the key properties by which AFFF suppresses fires of different fuels. It appears that for low flash point fuels such as gasoline, the critical property of AFFF is that of a vapor barrier, while for higher flash point fuels, the critical function of AFFF is to shield the fuel from heat feedback from the fire, since this is required for a flammable mixture to occur.

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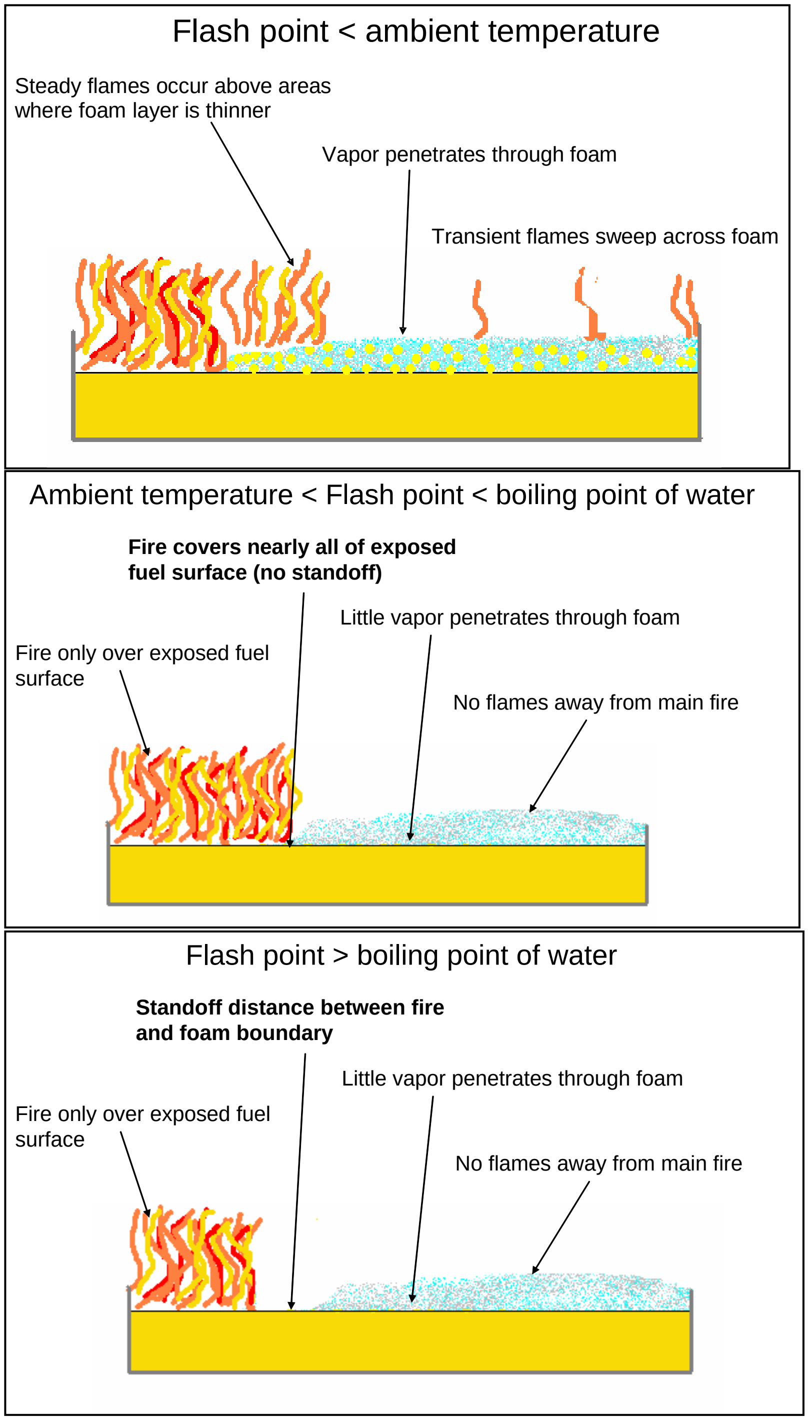

Figure 5: Cartoon illustrations of different burn back regimes. A) When the flashpoint is less than ambient temperature there can be transient or sustained burning over the foam layer. B) When the flashpoint is in between ambient and 100^{o}C, flames occur only above uncovered fuel but covers nearly all of the uncovered area, but not the covered area. C) When the flashpoint is greater than 100^{o}C, flames are only above uncovered region of the fuel but there is also a standoff distance from the foam boundary due to the temperature gradient on the fuel surface from the foam.

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