
A Qualitative Review of Performance Parameters of Aqueous Film Forming Foam

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Abstract : Aqueous Film Forming Foam (AFFF) has become a critical component within the aviation industry. However, relatively few reports address the possible causes of the poor performance of AFFF during fire conditions due to the rarity of air crashes. In this review, the factors that commonly affect the performance of AFFF during the firefighting circumstances are reviewed and discussed. This paper is based on the existing literature of AFFF and other firefighting foams, however, it is limited to the following performance parameters; foam generation devices and processes, foaming ability, mechanical stability, drainage time, critical application rates and effect of degradability. The paper further reviews and discusses the role of each parameter and how it influences the capabilities of AFFF during firefighting and thus its performance.

Keywords: Aqueous film forming foam, foaming ability, mechanical stability, drainage time, critical application rate, degradability.

1 Introduction

Within the aviation industry, fire protection is a crucial sector, which has given rise to differing perspectives regarding compliance standards [1]. Due to the inevitable loss of life and expensive equipment, aircraft accidents are catastrophic. In the aviation industry, firefighting foam, particularly aqueous film-forming foam (AFFF), is the only optimal extinguishing agent for the suppression of combustible or flammable liquids. The number of aviation accidents involving aircraft has decreased significantly over the past several decades and is therefore no longer a concern [2]. Nevertheless, the aviation industry must adhere to all applicable compliance standards and be well-prepared for any unanticipated events.

Mandatory periodic training is required for all aspects of aviation fire protection to ensure that firefighting skills and resources within the sector adhere to Federal Aviation Administration (FAA), National Aviation Authority (NAA), and National Fire Protection Association (NFPA) compliance standards, in order to respond promptly in the event of an incident [3]. Consequently, periodic inspection to evaluate the performance parameters of fire-extinguishing foam is essential. During periodic testing, AFFF is frequently unable to perform as expected due to unforeseen events. The primary objective of AFFF is to extinguish the fire and give potential victims more time to escape the accident scene. All of this, however, must be completed within one minute of arrival at the accident scene in accordance with applicable compliance standards [4].

Numerous and diverse factors contribute to the poor performance of AFFF, making it difficult to determine where the problem originates. There have been fatal fire accidents in the aviation industry (globally) over the past several decades, prompting researchers to investigate the fire protection industry further. However, there are still significant voids in previous research, with few studies on the impact of the materials used to construct the storage tank for AFFF concentrate storage [5]. This is due to the complexity and variety of these issues, due to the intricate engineering disciplines involved, such as material sciences, fire engineering and thermal engineering, the complexity of augmenting the firefighting foam in the storage tank construction materials has always been a concern.

2 A brief overview of Class B fires

In the aviation industry, fire is of great concern due to the incidence of fires that are usually devastating to both human lives and properties. Since fire is of great significance in this research paper, it is beneficial to understand the various classes of fire. Fire is usually classified into five classes. In fire science, fire is classified by the type of fuel it burns, namely: Class A, B, C, D, and K [6]. The classes are discussed in detail in Table 1. However, the present research work will only focus on Class B fire since firefighting foams are used to suppress this Class of fire.

It is essential to comprehend that Class B fires are an exothermic reaction as any other type of fire that relies significantly upon four (4) elements: fuel, air or oxygen, heat, and a chemical chain reaction [7]. However, this fire is normally caused by low-viscosity liquids. Removing one element will effectively halt the fire. The following four (4) suppression mechanisms are required for knockdown and burn-back resistance in Class B fires:

- The foam blankets the fuel surface, smothering the fire.
- The foam blanket separates the flames or ignition source from the fuel surface.
- The foam cools the fuel and any adjacent metal surfaces.
- The foam blanket suppresses the release of combustible fumes that can mix with air [7].

Table 1: Various classes of fire [6].

Class of fire	Type of fire	Commonly encountered
A	Common combustibles such as wood, paper, and rubber materials.	General places.
B	Flammable liquids such as fuel, petroleum greases, and flammable gases.	Airports and petroleum industries.
C	Energized electrical equipment and conductors.	Electrical distribution industries.
D	Combustible metals such as magnesium, titanium, and sodium.	Metal manufacturers.
K	Cooking oils, normal grease, and animal fat.	Production and FMCG industries.

In general, there are two different basic flammable or combustible fuel groups that yield to Class B fires [8]. It is essential to identify which group you are exposed to, as it greatly assists in selecting the suitable extinguishing agent (type of firefighting foam). The two groups are divided as follows:

- Standard hydrocarbon fuels such as gasoline, diesel, kerosene, jet fuel, etc. do not blend with water or are not miscible in water, they usually float on top of the water, and, for the most part, they do not intermix.
- Polar solvents, or alcohol-type fuels, are fuels that mix readily with water or are miscible in water [7].

3 Evolution of AFFF for effective extinguishment of Class B fires

Originally, five types of firefighting foams were commonly used: fluoroprotein foams (FPs), aqueous film-forming foams (AFFFs), film-forming fluoroprotein foams (FFFPs), alcohol-resistant aqueous film-forming foams (AR-AFFFs), and alcohol-resistant film-forming fluoroprotein foams (AR-AFFFPs) [8]. All of them were designed to be effective in handling precise fire conditions and contain one or more fluorinated surfactants as key ingredients.

It is well known that water has long been a universal agent for the suppression of fires; however, it is not exceptional in all instances [9]. For instance, water is regularly incapable of suppressing combustible fluids and can be perilous. Protein-based foams, which presented a drastic improvement over water for combating liquid fuel fires, were initially developed and used. These protein-based foams are thick and form a heavy, heat-resistant covering over a burning liquid surface [10]. These properties made protein-based foams constrained, as they were not able to spread rapidly over the fuel surface. This was a concern for a long time, as protein-based foams were not very effective in low-viscosity fuels such as kerosene, which is commonly used in the aviation industry.

In general, foam is made by first mixing foam concentrate with water to create a foam solution. This aqueous concentrate is then blended with air using standard aspirating nozzles to generate foam [10-12]. Fire-fighting foam is an extinguishing agent composed of numerous bubbles formed mechanically or chemically from the liquid, as shown in Figure 1. These are commonly used to reduce the spread and extinguishing of Class B fires and to prevent re-ignition, while in certain situations they may be implemented to extinguish Class A fires [2]. AFFF is a low-viscosity foam, consequently, it spreads easily on the surface of the flammable liquid. This enables the formation of a dense and stable foam layer that acts as a physical boundary against heat and mass transfer, thus exhibiting excellent cooling and covering effects in hydrocarbon fires [7].

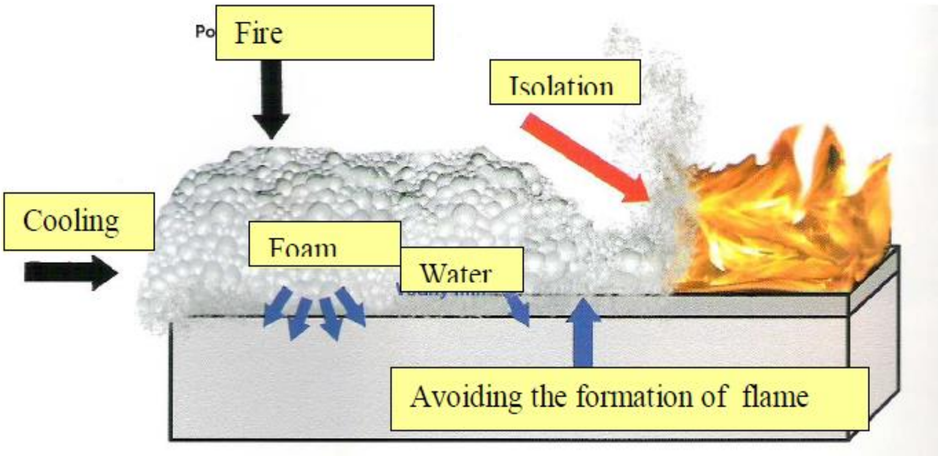

Figure 1: Scheme of the extinguishing mechanism by using firefighting foam [13]

Synthetic-based foams were developed and introduced in the mid-1960s to optimize protein-based foams [14]. These firefighting foams included AFFF and AR-AFFF. AFFF concentrates are made by blending fluoro-and hydrocarbon-surfactants; modest quantities of salts and foam stabilizers are regularly included [15]. The AFFF concentrate is then mixed with a specific level of water to form a foam solution. The proportioning rate is usually 1%, 3%, or 6% of foam concentrate to water. Furthermore, an additional feature of 'aqueous film' is formed on the surface of a flammable liquid by the foam concentrate as it drains from the foam blanket [3]. This film is very fluid and floats on the surface of most hydrocarbon fuels, hence providing AFFF with tremendous speed during extinguishing conditions. This made AFFF further developed and predominant in most firefighting foams. Moreover, the introduction of AFFF represented a significant increase in firefighting performance in terms of more rapid control and extinguishment of fuel fires, especially in industries that are involved with low-viscosity fuels [16].

All firefighting foams were developed for the suppression of specific combustible fuels. It is vital to identify which fuel group is involved when flammable fire conditions occur. This is to ensure timely and effective extinguishment during fire conditions. As a consequence, firefighting foam may be ineffective when used on unsuitable fuel, which may yield unexpected or unfavorable outcomes [17].

To date, AFFF has been widely used in aviation fire protection for the suppression of hydrocarbon fuels (a part of Class B fires) [17-18]. This synthetic-based foam has a low viscosity and spreads quickly across the surface of most hydrocarbon fuels. Initially, AFFF was developed for the aviation industry due to the fuel (kerosene) they are involved with, and it has proven to be effective in several cases [13]. However, they can also be relatively utilized for extinguishing Class A fires. During firefighting, a water film forms underneath the foam, which cools the liquid fuel, halting the formation of combustible fumes [6]. Consequently, this gives a sensational fire knockdown, which is a critical aspect of crash rescue firefighting.

4 Foam generating devices and processes

Foam, in general, is created by mechanical action (dispensing equipment); hence, the generation of firefighting foam is a mechanical process that comprises numerous prior steps [19-22]. There are various methods of generating firefighting foam; each method relies on the type of fire involved and the foam concentrate used. To date, there are three methods of generating firefighting foam from a foam concentrate, namely: aspirated nozzle, compressed air foam (CAF), and chemical reaction method [23-24]. The distinctions in these methods yield unique characteristics of the foam produced, with noticeable contrasts in the size and uniformity of the bubbles produced using each method [23]. Such differences may lead to significant variations in foam performance during fire conditions. However, the aspirated nozzle is a traditional and widely used method of generating firefighting foam, particularly in aviation fire protection.

Aviation fire protection has adopted the technique of an aspirated nozzle when generating foam. Due to the type of environment and aviation standards that the National Fire Protection Association (NFPA) developed and oversaw, this technique is more useful for aviation fire protection [25]. Technically and according to the research, the aspirated nozzle is suitable for low-expansion foams such as AFFF and AR-AFFF [26-27]. Aviation fire protection utilizes AFFF for fire suppression due to the class of fuel (Jet A-1) they are involved with. Subsequently, the aspirated nozzle technique has been compatible with AFFF. However, during the periodic tests in aviation, the functionality of this technique is tested, and according to the reports, there are still concerns when using it [23]. Moreover, gaps exist in the optimization of this foam generation.

Comprehending various foam generation methods is essential in the present research work to evaluate and deduce if any other method can yield any benefits. Most of the research has been focused on the aspirated nozzle and CAF generation methods, aiming to optimize or implement new methods [26,28]. Optimization of these methods requires complex mathematical analysis as there are numerous parameters involved. Besides, the complexity further relies on the variation of chemicals involved in the chemical reaction technique. The experimental work conducted by Laundess et al. [23] shows that foam generated by the CAF technique displays uniformly small bubbles; the aspirated nozzle produces a greater spread of bubble sizes; and the chemical (nitrogen) reaction displays the most uniform size distribution of bubbles, as shown in Figure 2. In addition, the CAF method has the advantage of being environmentally friendly [23, 28, 29, 30]. With the aspirated nozzle technique having environmental concerns, a new technique or optimization has emerged as an alternative in aviation fire protection.

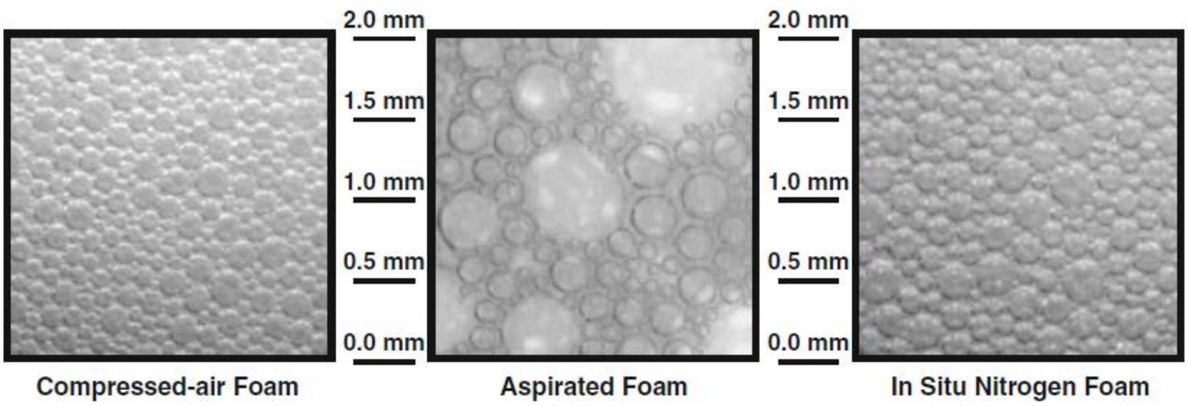

Figure 1: Bubble characteristics for different generation methods [23].

4.1 Aspirated nozzle

The technique has been extensively used and is the traditional way of generating firefighting foam. In this method, foam is generated by extracting air into a jet of foam concentrate inside a nozzle [24, 26, 31]. Most firefighting foam nozzles are specially designed with convergent geometry. In this way, parameters such as pressure, velocity, and flow rate are carefully controlled. As shown in Figure 3, foam solution at high pressure and low velocity enters the orifice at 1 and exits as finished foam at low pressure and high velocity at 5, at a constant flow rate. During stages 2, 3, and 4, air is drawn by a jet and blended with foam concentrate, resulting in strong mixing and agitation [32].

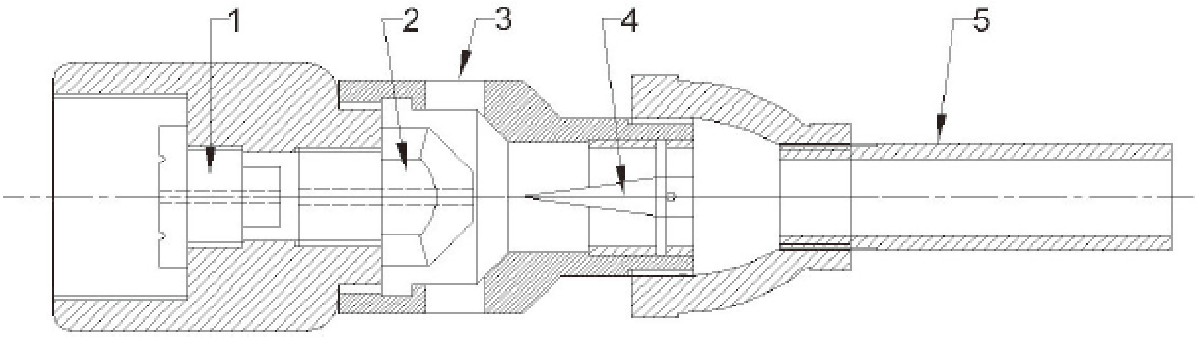

Figure 2: Nozzle for generating foam [32].

The governing equation for critical parameters during the foam generation is usually Bernoulli's equation, which is given as:

$$P_1 + \frac{1}{2}\rho {v_1}^2 + \rho g h_1 = P_5 + \frac{1}{2}\rho {v_5}^2 + \rho g h_5 \qquad (1)$$

As seen in Equation 2.1, in case where the potential energy at the elevation 1 ($\rho g h_1$) equals the potential energy at elevation 2 ($\rho g h_5$), then the equation can be simplified and written as:

$$P_1 + \frac{1}{2}\rho {v_1}^2 \quad P_5 + \frac{1}{2}\rho {v_5}^2 \qquad (2)$$

Where,

p_1 *is the pressure at elevation* 1 *in Pa*

v_1 *is the velocity at elevation* 1 *in* $^m/_s$

h_1 *is the height at elevation* 1 *in m*

P_5 *is the pressure at elevation* 2 *in Pa*

v_5 *is the velocity at elevation* 2 *in* $^m/_s$

h_5 *is the height at elevation* 2 *in m*

v_5 *is the velocity at elevation* 2 *in* $^m/_s$

g is the acceleration due gravity in $^m/_{s^2}$

ρ *is the density offuid in* $^{kg}/_{m^3}$

Since convergent nozzles are used to increase the outlet velocity (v_5 *in Equation* 2.3) due to the conservation of mass, while critically maintaining the inlet flowrate during firefighting. Therefore, the following assumptions can be made:

$$A_1 > A_5$$

$$V_1 < V_5$$

$$P_1 > P_5$$

When the areas of the inlet and outlet are known and the flow rate that must be achieved is also known, then velocities can be calculated using the following equation:

$$Q = VA \tag{3}$$

Where,

$Q\ is\ the\ flowrate\ in\ {}^{m^3}/_{s}$

$V\ isthe\ velocity\ offoam\ solution\ is\ {}^{m}/_{s}$

$A\ is\ the\ area\ of\ the\ nozzle\ at\ aparticular\ point\ in\ m^2$

4.2 Compressed air foam (CAF)

The CAF method is commonly used for generating any kind of firefighting foam and was initially developed by the National Research Centre of Canada (NRCC) in the late 1990s [13]. The technique has offered several benefits in fire protection since the prohibition of halogen-based agents due to some environmental impacts. This technique is similar to the aspirated nozzle method in that it also consists of a divergent nozzle for discharging foam. The distinction is that, in the CAF system, the air is pressurized using an air compressor and then fed or injected into an aqueous foam solution [31-33]. As the foam expands, it discharges and is guided through a nozzle.

4.3 Chemical reaction

Laundess et al. [23] discovered the chemical reaction technique, aiming to eliminate the foam generation problems. The method has not yet been recognized in fire protection standards but certainly has several benefits. With other generation methods extensively used to produce much heavier carbon dioxide bubbles, it was of great practical significance to evaluate other methods that would produce lighter, uniform bubbles. Consequently, nitrogen gas bubbles were the empirical and realistic alternative [34-36]. In this way, the chemical reaction between foam solution and nitrogen creates numerous, uniformly sized bubbles of nitrogen gas within the foam.

The method has been reviewed by many researchers. The only concern is the need to optimize foam formulations to prevent surfactants from being affected by nitrogen generation and the presence of salts formed during chemical reactions [23, 37, 38, 39]. For this reason, aviation fire protection will need to examine this as an alternative to possibly eliminating the aspirated nozzle method.

5 Foaming ability and Mechanical stability

Foams are typically described in terms of their foamability and stability. Foamability is defined as the capacity of the surfactants to form foam regardless of the special foam properties, while foam stability describes the variations in foam height or volume with time, immediately after foam generation [29, 40]. The two concepts are interrelated; the greater the stability of the foam films, the greater the foamability of the solution. Modern firefighting foams are primarily of the mechanical type [41]. This means that before being utilized, they should be proportioned (mixed with water) and aerated (blended with air). Four elements are necessary to produce a quality and stable foam blanket, and they include foam concentrate, water, air, and aeration (mechanical agitation) [2].

In recent years, mechanical stability has been a concern for most firefighting foams. Many researchers have approached this challenge with the aim of optimization. Foaming ability is a key factor in advancing the mechanical stability of firefighting foams [42-44]. The rate at which air bubbles are produced during the foaming process is essential for evaluating the mechanical stability of the foam [45]. Stability properties, as well as the effectiveness of firefighting foams, are determined by their physical and chemical properties, as described by Turekova and Balog [13]. These properties may include: viscosity, foam frost resistance, the content of the sediment, foam stability, half-life of foam, pH, foaming concentrate, spreading factor, etc. [13].

The mechanical stability of AFFF depends upon the structure of the surface films from the so-called foaming agents [23, 46, 47, 48]. During firefighting conditions, the foams are continuously disrupted by the influence of the heat of ignition, the internal force of the foam, and the hot surface of burning liquid [5, 49]. Foaming ability is thus a fundamental procedure as it directly affects the quality, hence the performance, of the foam. The important parameters affecting a foam's ability to extinguish hydrocarbon fuel fires were addressed by Snow et al. [50] with theoretical modelling to further evaluate the challenges and limitations of the current methods used. Figure 4 shows the parameters that affect the foaming ability of AFFF under firefighting circumstances.

Xiaoyang Yu et al. [51] studied the formation of stable aqueous foams. They experimentally demonstrated that the presence of sodium and sulphur within the aqueous solution is responsible for the stable foam formation. As a matter of fact, for stable foam formation, there must be less surface tension in the water. This is mostly accomplished by increasing the sodium alkyl sulphate concentration [51-53]. As a consequence, sodium and sulphur are the primary elements of interest when optimizing the AFFF concentrate.

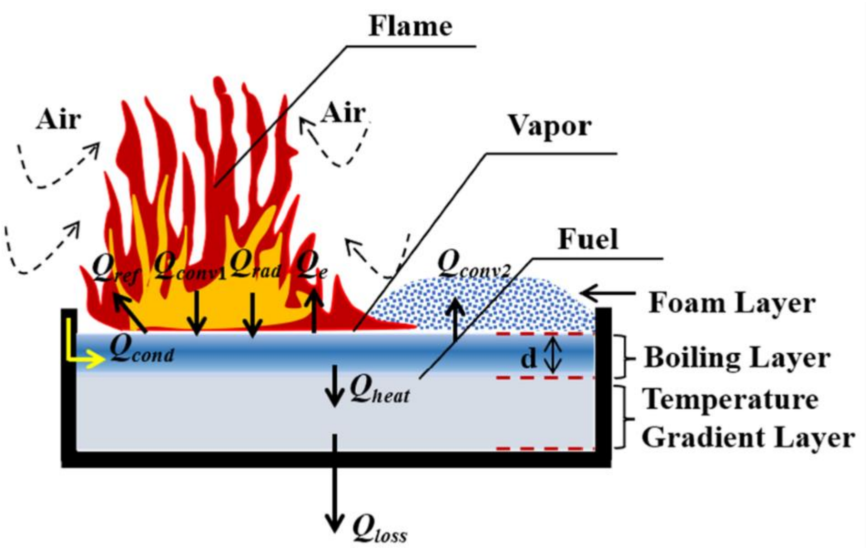

Figure 4: Important parameters affecting a foam's ability to extinguish hydrocarbon fuel fire [51].

Oguike [54] conducted experimental tests intending to assess the foaming ability of various foams. The analysis comprised eight (8) empty bottles that were filled with constant foam concentrate but different volumes of water. The bottles were shaken vigorously at a steady rate in each case, and the foam height was recorded. The foams were left to stand for some time, and their heights were measured again. Foams were left to stand for further days, and height was measured again. Finally, the foams formed were left to stand until they collapsed, and time was recorded for each foam solution. This experiment set a benchmark for most researchers, as most of the other foaming ability experiments have been based on it [55].

The current challenge is to develop small-scale test methods that measure these parameters in such a way that they can be used to predict large-scale foam performance. Persson [56] described optimization techniques and results to investigate foam mass loss by evaporation as a function of radiant heat from a fire. The finding was that foam viscosity and spreading are areas requiring further investigation [56]. In addition, further investigation of mass loss by evaporation must be done in order to develop solutions that will mitigate these foam mass losses by evaporation.

6 AFFF blanket stability/drainage time

Drainage time is a measurement of the rate at which foam concentrate drains out of finished foam and hence indicates the stability of the foam blanket [23, 24, 34, 35]. Drainage time is often used to analyze the stability of various foams; however, according to Mukunda and Dixit [29], it does not provide a reliable indication of the firefighting capability of foams. High expansion foams usually maintain stability and heat resistance due to their long drainage time and, hence, slow loss of water from the finished foam.

In recent years, most researchers have concluded that the drainage times of finished foams do not solely depend on foam concentrate but also on the type of foam generation [32, 57, 58]. In most cases, drainage time for low expansion foams such as AFFF is often expressed as 25% drainage time, while for medium and high, it's usually 50% drainage time. This is the time taken for 25% or 50% of the original foam solution content (by volume) to drain from the finished foam, as shown in Figure 5.

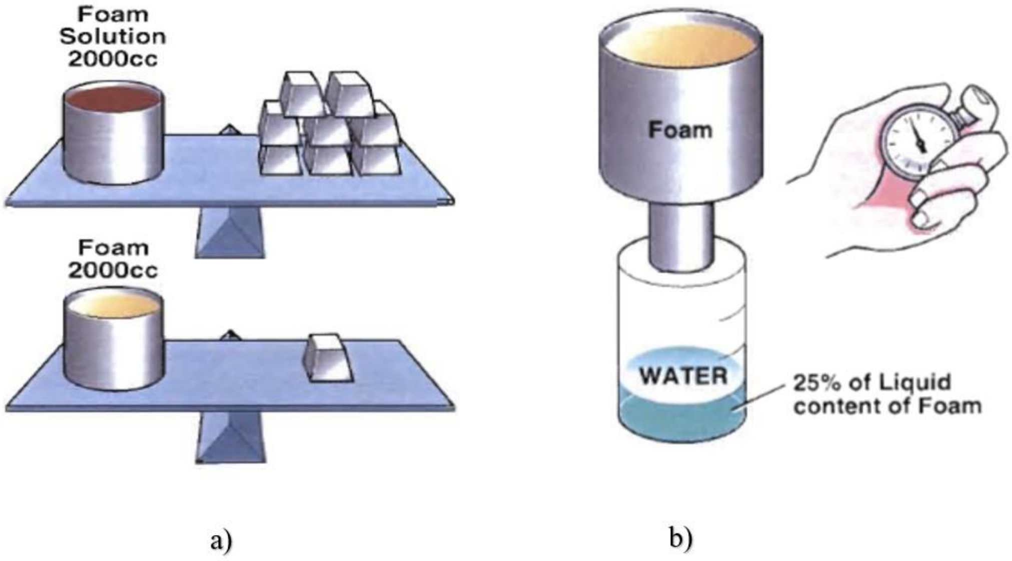

Figure 5: Low expansion test (a) and drainage test (b) [58].

Researchers have been working on optimizing the foaming ability, hence the stability of foams, particularly for low expansion foams. An experimental work to analyze and compare the drainage time and bubble size distribution of various firefighting foams was described by Kennedy et al. [59]. Table 2 shows the results of [59] comparing the 25% drainage times at an expansion ratio of 7:1 for two different foam concentrates.

Table 1: Comparison of 25% drainage times at 7:1 expansion [59].

		Mean Drainage time (s)			
Foam concentrate	Generation system	Mean	Max	Min	Standard Deviation
Telomet 6%	ISNF	342	450	264	93
	CAF	488	533	430	53
	Aspirated	N/A	N/A	N/A	N/A
FC-600 3%	ISNF	539	725	450	126
	CAF	1060	1281	844	288

Aspirated	N/A	N/A	N/A	N/A

The findings show that the drainage rates for the various foam types were quite different, which may be due to variations in the bubble size distributions as discussed below in Figure 4. To explain the differences in foam drainage rates between the three foam types, they studied the bubble size distributions for each foam type [60-62]. As shown in Figure 6, the drainage time is profoundly dependent upon the type of foam generation. Also, the aspirated foam generation method produced larger bubbles in terms of size. These bubbles contributed to shorter drainage times, as seen in Table 2, hence the reduction of foam quality and stability. This correlation technique was benchmarked by Oguike [54], and most researchers, such as Laundess et al. [23], have concluded the same.

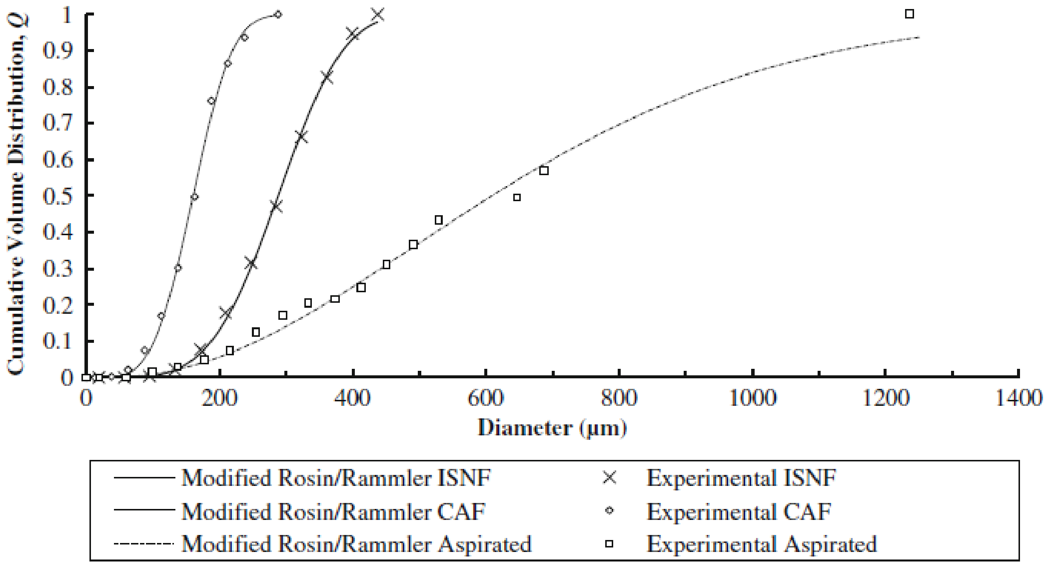

Figure 1: Cumulative bubble size distributions for various foam generation methods [23].

Mukunda and Dixit [29] developed a model of foam drainage based on momentum flux balance and conducted experiments with a device that simulated foam drainage through a fuel layer. According to their theoretical predictions, their findings revealed a linear relationship between 25% drainage time and height. A recommendation made by Laundess et al. [23] indicates that there is a need for further research to develop new surfactant formulations immune to the oxidation reaction that generates nitrogen bubbles. This foam generation method will simultaneously increase the drainage rates and stability of low-expansion foams due to nitrogen bubbles.

7 Critical application rates

In the most recent decade, most researchers have been interested in the application rates of various firefighting foams. The number of studies on effective application rates has increased significantly, and most of these studies have been based on protein- and synthetic-based foams [63-65]. The underlying motivation for considering diverse critical application rates was to identify the compatibility of foams with various classes of fire. With the original motivation behind the development of synthetic-based foams being economic issues, the application rates were thus critical [66].

Most of the research on firefighting foams is based on optimization aiming to provide the necessary effectiveness and efficiency in performance. In 1972, Geyer [67] conducted tests with protein and AFFF concentrates that provided the foundation for the present minimum application rates. These "modelling" tests involved jet propellant (JP-4) pool burns of 21, 30, and 43 meters in diameter. In addition, they comprised large-scale verification experiments with a B-47 aircraft and simulated shielded fires done with a JP-4 pool fire 34 meters in diameter and 43 meters in diameter, with all tests undertaken using the air-aspirating foam generation method. The outcomes by Geyer [67] showed that PF and AFFF have an application rate with a ratio of 1.49:1, respectively, as shown in Figure 7. This difference in application rate acknowledges the intrinsic benefit of utilizing AFFF to extinguish hydrocarbon pool flames and reflects the fact that AFFF has been shown to extinguish pool fires more rapidly than PF at equal application rates. For equivalent extinguishment timeframes, AFFF requires lower rates than PF [10, 12, 15].

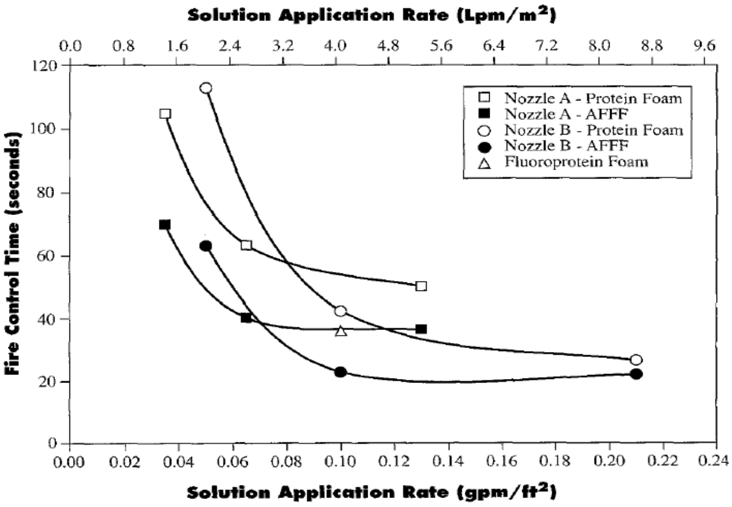

Figure 7: Fire control time as a function of concentrate application rate using protein foam and AFFF on JP-4 pool fires [67].

Many researchers have carried out numerous experimental tests to validate these application rates [37-39]. Geyer et al. [67] further conducted tests on critical application rates for validation. The experimental tests conducted were focused on fire control time as a function of solution application rate for PF, AFF, and FPF for Jet A fuel fires, and the results are shown in Figure 7. These were aimed at employing more foam generation methods and different fire types to make necessary analyses of outcomes and compare with [67]. Based on Figures 7 and 8, the application rate is greatly dependent on the type of foam generation device and the type of foam concentrates used. There have been numerous challenges regarding the critical applications of firefighting foams. The proliferation of performance guidelines and specifications for firefighting foams has created divergent opinions, especially on aviation industry fire protection standards [68].

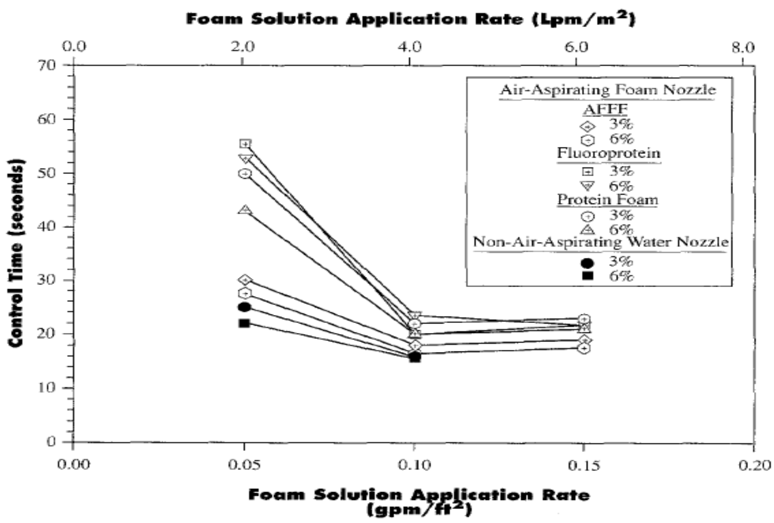

Figure 8: Fire control time as a function of concentrate application rate for AFFF, fluoroprotein, and protein foams for Jet A fuel fires [67].

8 Effect of degradability

Firefighting foams naturally degrade over time due to several factors, such as liquid drainage driven by gravity and coarsening. Firefighting foam degradation is defined by Hinnant et al. [68] as a reduction in foam layer thickness regardless of any changes in foam density or 'quality'. Aviation periodic training is the only platform for testing foam performance parameters, hence foam degradation. Foam degradation can substantially diminish foam's efficacy [40, 45, 46]. Consequently, foam deterioration can be affected by numerous circumstances, including hot fuel, fire, and foam formulations containing surfactants and chemicals necessary for foam generation [69]. Even though these components are recognised, others, such as fuel and fire, are difficult to regulate. During the firefighting process, foam is continuously interacting with fuel and flame. The interaction may immensely destroy the thick layer of foam [68]. In this way, the ability of foam will be reduced, and its performance may be compromised. However, foam degradation may suddenly increase dramatically during this process. The causes of this are not well understood due to a lack of research on foam degradation. Furthermore, the individual effects of fire and fuel on degradation are inseparable due to the presence of fire [68-69]. Previous research on foam degradation has mostly focused on the natural ageing process of foam and the effect of the interaction of hydrocarbon liquids with foam [70-71]. The natural ageing of foam can be mainly influenced by the storage tank utilised. Hinnant et al. [68] studied the influence of fuel on foam degradation for fluorinated and fluorine-free foams. The study outcome showed that the fuel temperature is by far the major factor contributing to foam degradation, followed by the effects of surfactant formulation, type of fuel, and bubble diameter or expansion ratio. Figure 9 shows the percentage change in AFFF thickness versus time at room temperature at 35, 50, 75, and 90 °C.

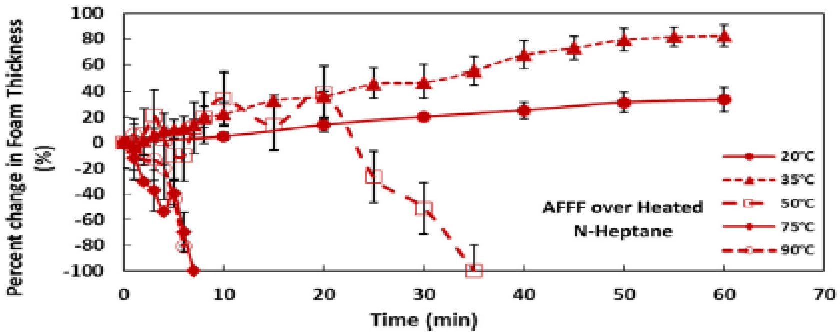

Figure 9: AFFF foam degradation versus time over n-heptane fuel at different temperatures [39].

Parameters such as bubble diameter or expansion ratio are highly dependent on the foam generation method. Larger bubbles cause a faster drainage rate than smaller bubbles, and according to [66, 70, 72], the increased drainage rate can cause the foam to degrade rapidly. In this way, the storage facility may indirectly affect foam degradation. This is due to the sediments or sludge that may accumulate in the storage facility during the ageing process. Consequently, sediments may affect foam characteristics, particularly bubble distribution, during the foam generation process; this is shown by employing a flow process in Figure 10. The optimization of a storage facility by reducing the accumulation of sediments will prove to extensively reduce foam degradation.

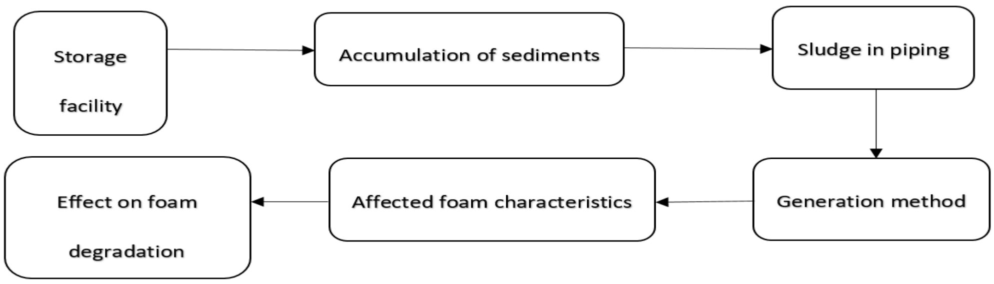

Figure 10: Effect of AFFF degradation.

There have been fewer studies on the effect of surfactant formulation on degradation, further research should be conducted to detect the effect of this parameter on foam degradation. Furthermore, other parameters that may affect foam degradation should be extensively investigated in the future, as foam degradation may regularly affect the performance of the foam.

9 Conclusion

This review article has provided a qualitative evaluation of the factors affecting the performance of AFFF. The review was based on five (5) performance parameters, which are foam generation devices and processes, foaming ability and mechanical stability, drainage time, critical application rates, and the effect of degradability, and how these parameters may or may not affect the performance of AFFF during firefighting. Based on this literature review, the following conclusion can be drawn:

(i) The performance of AFFF can be affected by the type of foam-generating method. There are distinguishable differences in the size and uniformity of the bubbles produced by the various varieties of foam-generating techniques. To be precise, the CAF technique produces foam with uniformly small bubbles; the aspirated nozzle produces a wider range of bubble sizes; and the chemical (nitrogen) reaction produces foam with the most uniform bubble size distribution. In addition, the CAF method has the advantage of being environmentally friendly.

(ii) Stability properties, as well as the effectiveness of firefighting foams, are determined by their physical and chemical properties, particularly the structure of the surface films from the so-called foaming agents. In addition, the presence of sodium and sulphur within the aqueous solution is responsible for the stable foam formation. Thus, it is vital to maintain the chemical properties of AFFF concentrate. This is mostly accomplished by increasing the sodium alkyl sulfate concentration. As a consequence, sodium and sulphur have been reported to be the primary elements of interest when optimizing the AFFF concentrate.

(iii) According to reports, foam stability is also related to drainage time. Despite the fact that numerous reports have suggested that drainage time is not a reliable indicator of foam stability, it can still provide an indication of what to anticipate. Due to the different bubble size distributions produced, the majority of researchers have concluded that the drainage times of finished foams are not solely dependent on foam concentrate but also on the form of foam generation. This implies that the stability of AFFF depends on the type of foam generation as well.

(iv) It has been reported that the critical application rates of AFFF are 0.49 percent lower than those of PFs. This difference in application rate recognises the inherent advantage of using AFFF to extinguish hydrocarbon pool flames and reflects the fact that AFFF has been demonstrated to extinguish pool fires more quickly than PF at equal application rates. In addition, this implies that AFFF requires lower rates than PF for equivalent extinguishment times.

(v) Foam degradation can significantly reduce foam's effectiveness. This review of the literature showed that a variety of factors, including hot fuel, fire, and foam formulations containing surfactants and compounds necessary for foam generation, can affect foam deterioration. Even though these components are recognized, research indicates that others, such as fuel and fire, are difficult to regulate. Nonetheless, foam degradation is an area that requires additional study, as there are significant gaps and a dearth of research validating its impact on the performance of AFFF.

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