SMALL-SCALE TEST PROTOCOL FOR FIREFIGHTING FOAMS DEF(AUST)5706: EFFECT OF BUBBLE SIZE DISTRIBUTION AND EXPANSION RATIO

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ABSTRACT

The experimental program described in this paper sought to assess the suitability of the small scale DEF(AUST)5706 standard for measuring the suppression and burnback performance of Class B foams on pool fires. The test protocol required the measurement of the 3/4 control, extinguishment and 1/3 burnback times for a circular pan of aviation gasoline (AVGAS 100/130), 0.28 m^2 in surface area. The test program involved compressed-air foams (CAF) and aspirated foams of two expansion ratios, and employed two AFFF formulations: a 6% telomer concentrate and, to obtain base-line measurements, 3% PFOS FC-600 concentrate which was manufactured by the 3M company prior to the PFOS phase out. At lower expansion (7:1), the aspirated and compressed-air foams demonstrated similar fire control performance, whilst more expanded (9:1) CAF was generally more efficient at extinguishing, but less efficient in controlling the fire. CAF formed a better seal over the fuel surface and at the hot pan walls, and these foams performed noticeably better than aspirated foam against fuel re-ignition. The paper links these observations with the underlying distributions of bubble sizes, which were measured and fitted to modified Rosin/Rammler cumulative volume distribution functions. We propose that a modified version of DEF(AUST)5706 be adopted as a universal small-scale test protocol.

INTRODUCTION

Firefighting foams serve widely as a means of fire suppression, particularly for extinguishing flammable liquid (Class B) fires, in both civilian (e.g., refineries, airports) and military applications. Fluorosurfactant foams are particularly efficient at achieving control and extinguishment of such fires as they form a film on the surface of the fuel, with each successive bubble layer consisting of multiple films. These films act as a physical barrier between the fuel and the oxygen in the air, preventing the diffusion of flammable vapours. The sealing property of the barrier and the spreading of the foam are perhaps more important than spreading of single films on fuel surfaces owing to a negative spreading coefficient [1, 2].

When developing a new firefighting foam technology, or gauging the performance of a foam formulation, it is necessary to perform suppression and burnback tests; the latter require a liquid fuel covered with a foam, usually shortly after a fire extinguishment, to be reignited and the rate of fire spread recorded. Several large scale standards exist for testing Class B firefighting foams, including ICAO, MIL-F-24385F, Lastfire, IMO, UL162 and ISO 7203/EN 1568, reviewed in reference [3]. These standard tests provide reliable information on the performance of Class B foams, however they are expensive to perform.

The experimental program described in this paper sought to assess a small scale fire suppression test standard, DEF(AUST)5706 [4], in order to determine the relevance of the results it provided. We were particularly interested to determine whether the results of DEF(AUST)5706 could serve to estimate foam performance in large scale tests and whether DEF(AUST)5706 could provide an inexpensive test method for developing new foam formulations. DEF(AUST)5706 determines the time taken by a foam to control and extinguish a fuel fire 0.28 m^2 in area. It also evaluates foam performance in resisting re-ignition of the fire.

Our approach was to compare the effect of bubble size and foam expansion on the fire suppression and burnback performance of a number of firefighting foams under various test conditions. The foam expansion ratio is defined as the ratio of the volume of the foam to the volume of foam solution present in the foam. We have investigated two types of foam formulations: (i) a 6% telomer AFFF (aqueous film forming foam) obtained from an Australian supplier and (ii) a 3% PFOS-based AFFF previously manufactured by 3M and denoted as FC-600. The suppression and burnback performance of FC-600 foams as well as the physical properties of the FC-600 concentrates are well known, providing one with a useful reference evaluation.

In the experiments, we employed AVGAS 100/130 fuel, an aviation gasoline used in aircraft with piston or Wankel engines, as well as in some racing cars. We tested both compressed-air (CAF) and aspirated foams at an expansion ratio of 7:1 in order to compare the suppression and burnback results for the two different foam generation systems. CAF were obtained by injecting compressed-air into a flowing solution of surfactants, whereas aspirated foams were produced when air was drawn and mixed into the aqueous phase directly inside a nozzle. The second approach avoids the need for a compressor but relies on the energy of mixing to be derived from that of the flowing foam solution. The compressed-air foam system was also run at an expansion ratio of 9:1 in order to investigate the effect of foam expansion on the results.

FOAM CHARACTERISATION

The foams were characterised in terms of drainage time and bubble size distribution. Table 1 displays the 25% drainage times for each foam studied in this paper. The 25% drainage time is the time at which 25% of the liquid originally in the foam has drained out. The compressed-air foams exhibited considerably slower drainage rates than the aspirated foams. These results may be explained by the bubble size distributions discussed below.

TABLE 1: 25% Drainage Times.

Foam Concentrate	Generation System	Expansion Ratio	25% Drainage Time (s)
Telomer 6%	Compressed-Air	7:1	502
	Compressed-Air	9:1	516
	Aspirated	7:1	197
FC-600 3%	Compressed-Air	7:1	844
	Aspirated	7:1	485

In this study, foam samples were deposited into a cubical, glass chamber and photographed from the side, with bubbles manually sized and counted in the photographs, as done in [2]. The measurement involved the FC-600 foams as the rapid drainage rate of the telomer aspirated foams made photographic bubble characterisation impractical. Figure 1 illustrates the cumulative volume distributions for both compressed-air and aspirated foams of FC-600 formulation, at an expansion ratio of approximately 7:1, with the measurements replotted in a Rosin/Rammler graph in Figure 2 for both data sets [5]. In the past, we modelled the CAF bubble sizes with the Weibull distribution [6], but on this occasion have found the Rosin/Rammler description of the bubble sizes more suitable. The compressed-air and aspirated foams show the mass median diameters (diameter such that 50% of total volume is in bubbles of smaller diameter) of 163 and 647 μm respectively. The Rosin/Rammler distributions of the FC-600 foams are described by the following equations:

CAF: $$Q(D) = 1 - \exp\left(-\frac{\ln D}{\ln 175.7}\right)^{19.7}$$

Aspirated: $$Q(D) = 1 - \exp\left(-\frac{\ln D}{\ln 730.8}\right)^{12.8}$$

where, Q stands for the cumulative volume distribution and D is the bubble diameter (μm).

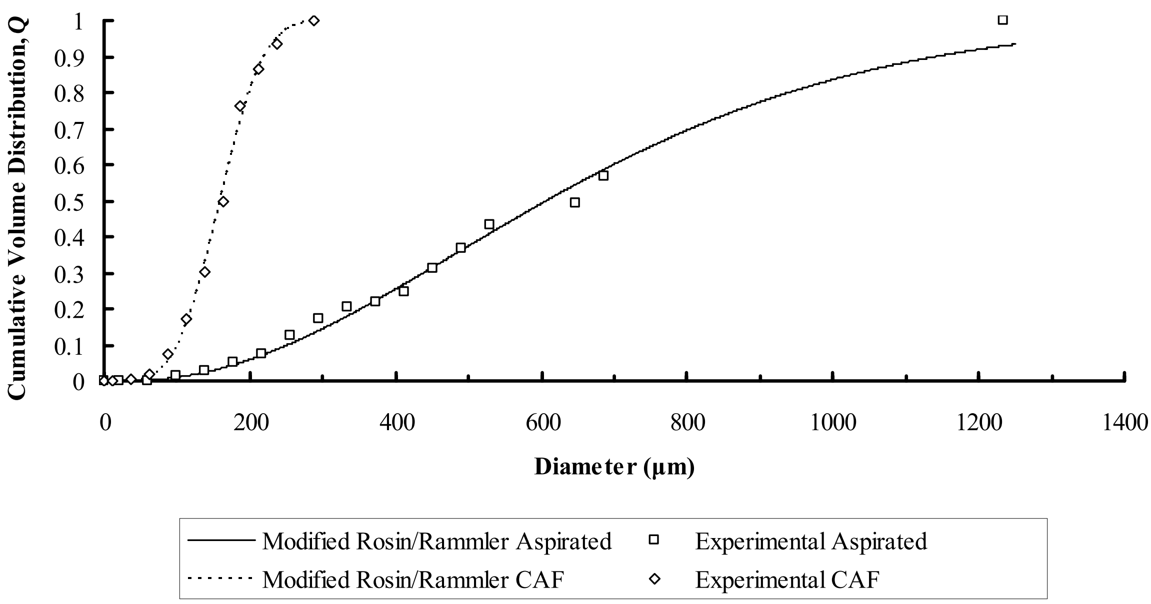

FIGURE 1: Cumulative Bubble Size Distributions for Aspirated and Compressed-Air Foams Generated from 3M FC-600 Formulation.

The bubble sizes for the aspirated foam correspond to a large range of diameters from 10 μm up to 1250 μm. This helps explain the rapid drainage experienced by the aspirated foam in comparison to the compressed-air foam. Larger bubbles engender a structure of interconnected channels (called Plateau borders) of larger cross-sectional areas, promoting a rapid drainage of the foam solution. In contrast, bubbles of the compressed-air foam display diameters ranging from just 12.5 μm to 287 μm, and hence the Plateau borders of this foam allow less flow. This more uniform distribution of smaller bubble sizes is the reason that the compressed-air foam has a much slower drainage rate than the aspirated foam.

Figure 2 represents Rosin/Rammler plots both of the compressed-air and aspirated foams. Observe that the straight line for CAF indicates that this distribution could equally well be described by the classical rather than modified Rosin/Rammler cumulative volume distribution. Using the slope of the curve, it is possible to obtain the Rosin/Rammler parameter q, which constitutes a measure of the spread of bubble sizes [5]; the higher the value of q, the more uniform the size distribution. For the FC-600 compressed-air foam this parameter assumes a value of 20, whilst for the aspirated foam it amounts to 13. This means that compressed-air foams exhibit a more uniform distribution of bubble sizes, as is also evident in Figure 1. To further illustrate the differences between the two foams, Figure 3 shows micrographs of bubbles in each foam.

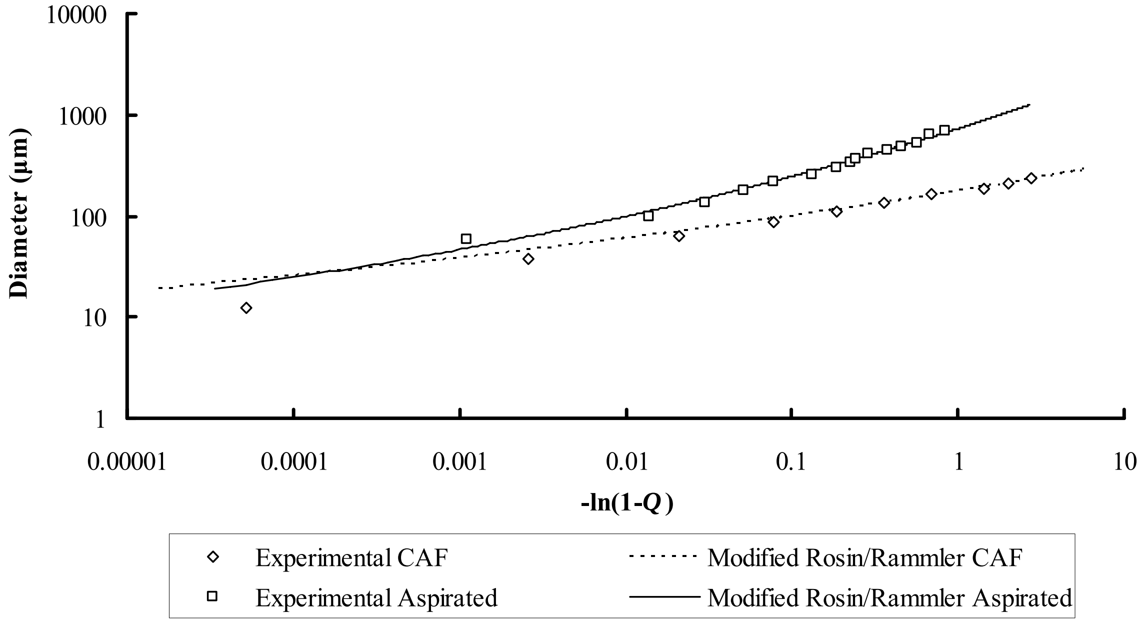

FIGURE 2: Rosin/Rammler Bubble Size Distributions for FC-600 Foams.

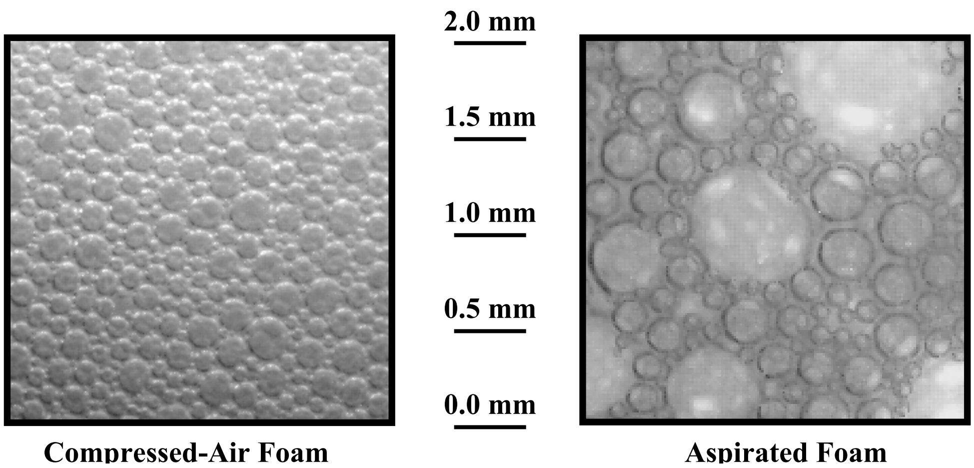

FIGURE 3: FC-600 Compressed-Air and Aspirated Foam.

EXPERIMENTAL

Apparatus for Fire Control and Extinguishment

As illustrated in Figure 4, the experimental apparatus for DEF(AUST)5706 consists of a stainless steel fire tray (pan) with an area of 0.28 m^2, a pyrometer on a high stand and a foam nozzle set some distance from the pan. The upper section of the pan is cylindrical, with an external diameter of 595 mm and a depth of 102 mm, whilst the lower section is conical in shape, with an included angle of 90º. The pan incorporates a valve at the base, for convenient emptying after testing.

Two different nozzles delivered the foam to the burning aviation gasoline, depending on the type of foam being tested. A 7 mm brass nozzle, constructed according to Annex A of MOD 42-20 [7], produced aspirated foams. The nozzle drew in air through four inlets located toward the rear of the nozzle, with air flow induced by the pumped foam solution. Approximately one third of the generated foam was directed toward the fire, with the rest ejected downward from holes in the bottom of the nozzle, the split adjusted via a movable collar. A 7 mm stainless steel nozzle, constructed of a straight length of pipe with no air inlets or drains, assisted in delivering the compressed-air foam. A Raytek pyrometer situated on a two metre high stand and connected to a PC-based data acquisition system recorded the radiation intensity from the fires. A video camera filmed each experiment, so that it could be examined at a later date. Figure 4 presents a schematic diagram of the experimental apparatus.

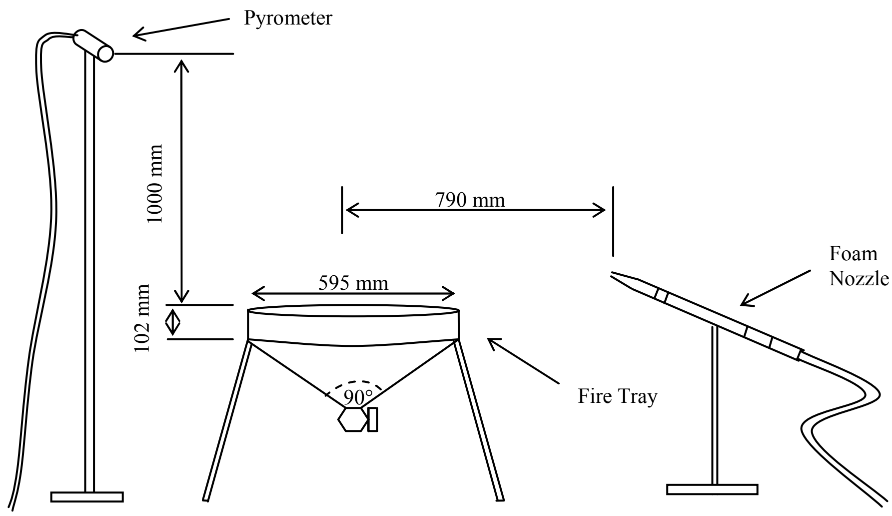

FIGURE 4: Schematic of Fire Control and Extinguishment Experimental Apparatus

As illustrated in Figure 5, a dosing system supplied the foam solution to the nozzle. For aspirated foams, the system consisted of an Alldos Primus 226L dosing pump with a capacity of 190 L/h, a 2 L pulsation dampener and a pressure retention valve. There were also a number of valves in the system so that flow could be shut off or directed to recirculate into the tank whilst the system approached a steady state. The dosing pump provided an accurate flowrate, whilst the pulsation dampener and pressure retention valve served to remove pressure pulsations and provide a constant, smooth, flow through the system. For CAF, a smaller Alldos pump with a capacity of 67 L/h replaced the bigger pump, with air pumped into the system by a GMC air compressor.

Apparatus for Burnback Test

The experimental apparatus for performing the burnback test consisted of the aforementioned circular fire tray and a 1.5 L stainless steel pot which was suspended from an adjustable steel stand; allowing the pot to be raised, lowered and rotated as required. Similarly to the extinguishment experiments, the Raytek pyrometer, connected to a laptop computer, measured the fire radiation intensity, and a video camera recorded footage of each test. A schematic diagram of the experimental apparatus is shown below in Figure 6.

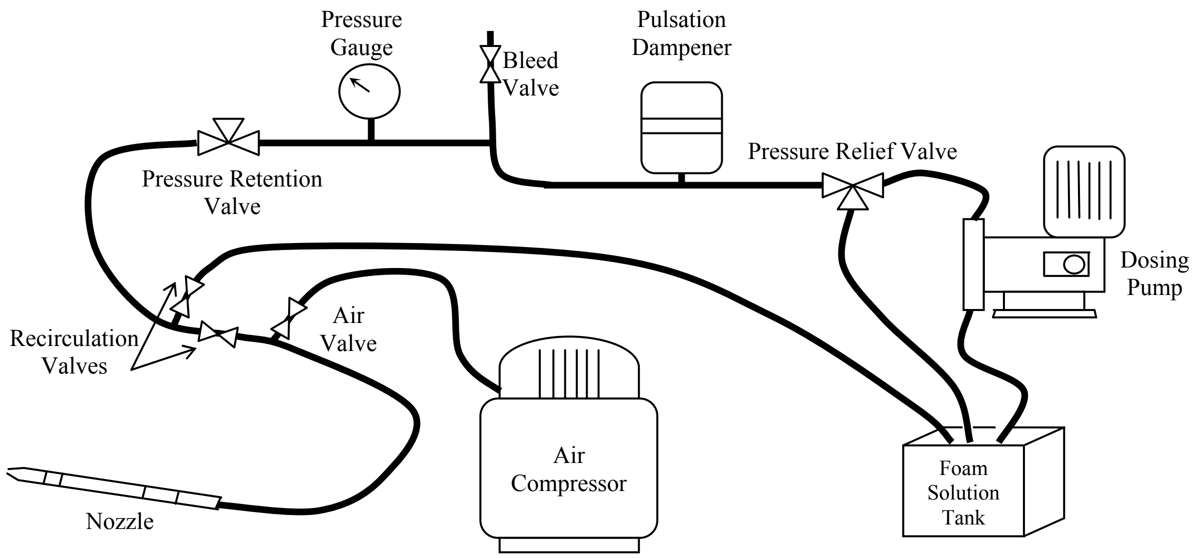

FIGURE 5: Schematic of Foam Solution Dosing System.

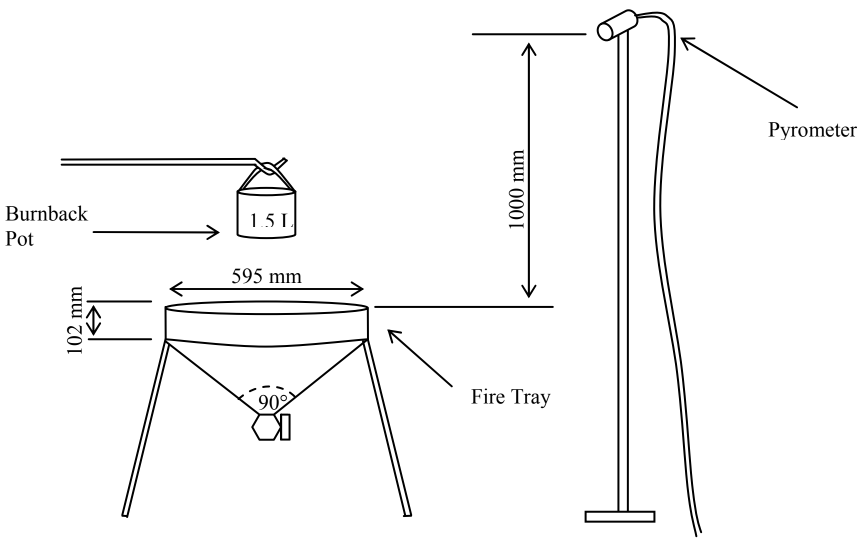

FIGURE 6: Schematic diagram of Burnback Test Apparatus.

Experimental Procedure for Fire Control and Extinguishment

Experiments were performed in open air, with intermittent breeze present throughout the test program. For this reason, we repeated each experiment to find that these conditions did not appear to affect the experimental scatter. The circular fire tray was positioned on a level section of ground and filled with water to the bottom of the cylindrical section. Five litres of the fuel was then added to the tray on top of the water. The relevant nozzle, on its stand, was then positioned so that the nozzle opening was approximately 79 cm from the centre of the fire tray and the nozzle tilted so that the foam would project into the centre of the tray. We then pointed the nozzle away from the tray.

The pyrometer was attached to its stand and situated 80 cm from the edge of the fire tray and the stand adjusted until the pyrometer was one metre above the top of the fire tray. The pyrometer was then angled such that it was directed toward a point 50 cm away from the opposite side of the fire tray. Subsequently, the pyrometer was switched on and connected to the computer so that it could record a zero reading prior to each experiment.

A burning matchstick dropped into the tray then ignited the fuel and a stopwatch was started as soon as the entire fuel surface was alight. The fire was then allowed to burn for a period of 60 s and the radiation intensity noted. During this preburn time, the dosing system was switched on and foam flow directed away from the pan whilst the system was approaching a steady state.

After 60 s of preburn, foam was applied to the fire at a rate of approximately 700 g of foam solution per minute for a total of 100 s. During foam application, the time at which the radiation intensity was reduced to 25% of its original value was recorded as the 3/4 control time. Note that for the aspirated foam, the solution flow corresponded to about 2.5 L/min, with the excess of the solution rejected through the holes in the foam nozzle. The elapsed time for complete suppression was also noted as the fire extinguishment time. After the 100 s period of foam application, the dosing system was switched off in preparation for the burnback test. The first section (until 2.7 min) of the record of Figure 7 illustrates typical preburn and suppression sections of each experiment.

Experimental Procedure for Burnback Test

The burnback pot was filled with 1.5 L of the aviation gasoline and carefully lowered into the centre of the fire tray. The stand height was adjusted so that the pot lip was level with the surface of the foam. One minute after the foam application had ceased, the fuel in the burnback pot was ignited using a matchstick and the stopwatch restarted. The height of the burnback pot was adjusted at intervals of three, five and seven minutes after the pot was ignited, so that the pot lip was once again level with the foam surface. The elapsed time corresponding to an increase in the radiation intensity to 1/3 of its original value, as measured by the pyrometer, was recorded as the 1/3 burnback time. Figure 7 provides a sample record of pyrometer measurements, until 1/3 burnback time is observed.

The burnback test relies on the interaction of pot flames with the surrounding foam. In our view, one should allow this interaction to occur by experimenting in large burn halls or in open air, as done in this study. We feel that this interaction should not be artificially minimised by performing experiments in small rooms with fine-tuned exhaust systems, as such an approach may lead to unrealistically long burnback times.

Comparison of DEF(AUST)5706 to MOD 42-40

This paper assessed the performance of the DEF(AUST)5706 standard as a small scale protocol for Class B foams. This standard serves the Australian Department of Defence to facilitate the bidding process for purchasing new foam supplies. DEF(AUST)5706 resembles the UK Ministry of Defence Standard 42-40 (MOD 42-40) [7]. DEF(AUST)5706 refers to MOD 42-40 for details in several areas of the procedure and apparatus design, such as the construction details of the brass aspirating nozzle. There are, however, some minor differences between the two standards as listed in Table 2. Either of the standards could be considered for adoption as a universal small-scale test protocol for Class B foams. Our preference for DEF(AUST)5706 stems from the material of construction and design of the pan, and the more challenging application rate of foam solution.

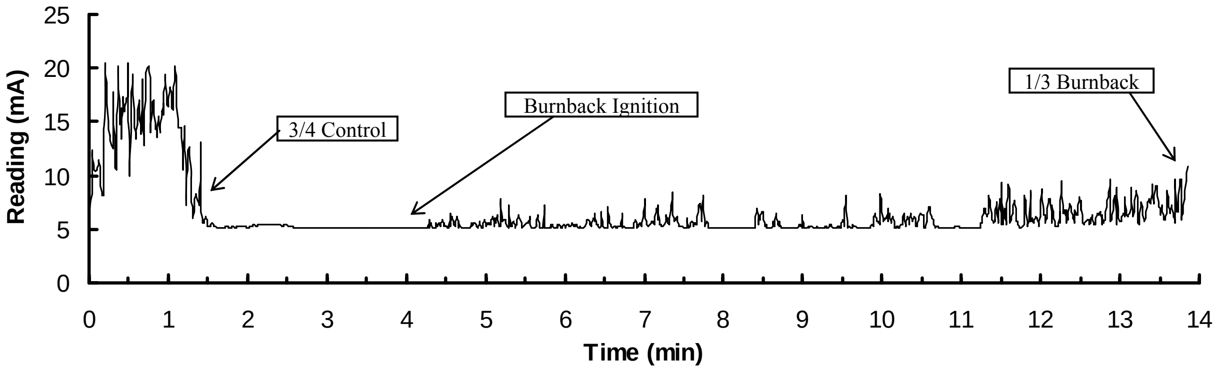

FIGURE 7: Example of Pyrometric Measurements.

TABLE 2: Comparison of DEF(AUST)5706 to MOD 42-40.

	DEF(AUST)5706	**MOD 42-40**
TEST APPARATUS		
Fire Pan		
Material	Stainless steel	Brass
Diameter	OD 595 mm	ID 565 mm
Straight wall height	102 mm	150 mm
Conical section height	300 mm	30 mm
Burnback Pot		
Diameter (ID)	140 mm	120 mm
Height	110 mm	110 mm
TEST PARAMATERS		
Application rate	672 g/min	750 g/min
Fuel	5 L on ~ 35 L water	9 L
TEST PROCEDURE		
Preburn	60 s	110 s
Application	100 s	180 s
Burnback ignition (after extinguishment)	60 s	60 s

RESULTS AND DISCUSSION

Fire Control and Extinguishment

Table 3 compares 3/4 fire control times of CAF and aspirated foams at an expansion ratio of 7:1 ± 0.2. Each value corresponds to an average of two or three measurements obtained in replicated experiments. The measurements indicate that for this expansion, the method of foam generation (and hence the bubble size distribution) has little effect on the suppression performance. Although there is as small difference between the telomer and PFOS formulations, in both cases the results for CAF and aspirated foams lie within 2.5 s of each other. It appears that, at an expansion of 7:1, both foams spread equally fast on the surface of burning gasoline.

Table 4 compares the performance of the telomer AFFF for two expansions 9:1 ± 0.2 and 7:1 ± 0.2. Evidently, less expanded foams perform better, with a significant difference of around 8 s. More expanded foams tend to display higher yield stress [8]. Yield stress signifies a resistance to flow for viscoplastic materials and depends on the bubble size distribution. Uniform distributions allow bubbles to form jammed structures which prevent bubble rearrangements and offer initial resistance to flow [9]. We observed that the 9:1 CAF could spread only after enough foam accumulated at the point of foam application for the gravity to overcome the yield stress. We believe that this is the reason for the slower 3/4 control time observed for 9:1 CAF foams. The performance of foams in standards requiring fast extinguishment, such as the US Mil Spec and ICAO depends in part on the foam's ability to spread rapidly. From this perspective, we argue that for the same formulation, less expanded foams with a broader distribution of bubble sizes would perform better when tested according to US Mil Spec and ICAO protocols.

TABLE 3: Measurements of 3/4 Control Time for CAF and Aspirated Foams.

Foam	Generation System	Time Achieved (s)
Telomer 6%	Compressed-Air	21.0
	Aspirated	23.5
FC-600 3%	Compressed-Air	26.5
	Aspirated	25.0

TABLE 4: Comparison of CAF Performance in 3/4 Control Times for Expansion Ratios of 7:1 and 9:1.

Foam	Expansion Ratio	Time Achieved (s)
Telomer 6%	7:1	21.0
	9:1	29.3

Table 5 explores the relative performance of the two AFFF formulations, in terms of compressed-air and aspirated foams at an expansion ratio of 7:1 ± 0.2. It appears that the foam generation system has little effect on fire extinguishment performance of the FC-600 formulation, and that the performance of FC-600 exceeds that of the telomer-based AFFF. FC-600 has been recognised as a truly outstanding firefighting foam, with high fluorine content, in the form of PFOS surfactants. Unfortunately, this characteristic made it environmentally unacceptable in spite of its superior performance. The application of the telomer-based AFFF in the form of CAF rather than as aspirated foam significantly increases the performance of this formulation. This is an important observation. If one were to adopt DEF(AUST)5706 as a universal small-scale test protocol, CAF and aspirated foams should be allocated different performance criteria.

In Table 6, we further investigate improvements in the extinguishment performance of foams as a function of foam expansion. The effect of foam expansion is substantial, and is likely due to slower drainage under the fire conditions (as opposed to similar 25% drainage times exhibited in the absence of fires, listed in Table 1) and hence a better physical barrier offered by more expanded CAF against diffusion of flammable vapours, especially at hot rims. (The drainage from foam under irradiance has been measured by other researchers [2, 10] but has not been attempted in the present study.) This indicates that foam expansion should be a required parameter to be reported for suppression experiments. Measurements presented in Tables 5 and 6 clearly demonstrate gains in the suppression performance that can be achieved by merely optimising the bubble size (i.e., CAF versus aspirated foam) and the foam expansion (i.e., 9:1 versus 7:1), for a given foam formulation. This finding seems to disagree with that of Tuve and Peterson who reported no change in extinguishing time for foam expansion above five; as interpolated in Figure 25 of reference [11], for the present flux of foam solution. Although, Tuve and Peterson used compressed air to generate the foam, the air was injected into the nozzle, and hence their foam was probably similar to the air aspirated foam, rather than CAF, of the current study.

TABLE 5: Extinguishment Results for Compressed-Air and Aspirated Foams.

Foam	Generation System	Time Achieved (s)
Telomer 6%	Compressed-Air	65.5
	Aspirated	74.0
FC-600 3%	Compressed-Air	48.0
	Aspirated	44.5

TABLE 6: Extinguishment Results for CAF at Expansion Ratios of 7:1 and 9:1.

Foam	Expansion Ratio	Time Achieved (s)
Telomer 6% AFFF	7:1	65.5
	9:1	43.7

Resistance to Re-Ignition (Burnback Test)

Table 7 below displays the burnback measurements for the foams when generated using the compressed-air and aspirating nozzles at an expansion ratio of 7:1 ± 0.2. The bubble distribution had a significant effect on the results, with this effect being more pronounced for the telomer formulation than for the better performing FC-600. The telomer and FC-600 formulations applied as CAF display longer 1/3 burnback times by 74 and 24% respectively, than the relevant aspirated foams.

Clearly, the burnback test provides a simultaneous assessment of both chemical (i.e., foam formulation) and physical (i.e., bubble size distribution) properties. With respect to the latter, smaller and uniformly sized bubbles exhibit slow drainage and delayed coarsening, providing a lasting barrier for the diffusion of fuel vapours. Foam drainage and foam coarsening are intimately related: More drainage leads to thinner lamellae (i.e., thin films separating the bubbles), and this accelerates diffusion from small (where the pressure is higher) to large bubbles. As large bubbles grow and small bubbles disappear, the Plateau borders hold less foam solution, resulting in additional drainage. This phenomenon is known as coarsening induced drainage [12].

For the same foam chemistry, the burnback performance is only a function of the distribution of bubble sizes, with the 25% drainage time providing a rough assessment of the effect of bubble distribution on the burnback time. Thus, two foams produced from the same concentrate and characterised by similar 25% drainage times yield similar burnback times. This is the reason for the diminutive effect of the expansion ratio on the burnback performance illustrated in Table 8, as these two foams are characterised by similar drainage times (Table 1).

TABLE 7: Burnback Results (1/3 Burnback Time) for Compressed-Air and Aspirated Foams.

Foam	Generation System	Time Achieved (s)
Telomer 6%	Compressed-Air	505.5
	Aspirated	290.0
FC-600 3%	Compressed-Air	628.5
	Aspirated	504.0

TABLE 8: Burnback Results (1/3 Time) for CAF at Expansion Ratios of 9:1 and 7:1.

Foam	Expansion Ratio	Time Achieved (s)
Telomer 6%	7:1	505.5
	9:1	493.3

CONCLUSIONS AND RECOMMENDATIONS

We advocate that a universal small-scale standard be adopted based on a modified version of DEF(AUST)5706. This paper has established that a method of foam generation (i.e., CAF versus aspirated foam), which defines a bubble size distribution, may greatly enhance the suppression effectiveness of a given foam. Furthermore, even small changes in the expansion of compressed-air foam (from 7:1 to 9:1) can make an average foam formulation appear to possess a superior extinguishment performance.

These observations carry important points for adoption of a modified version of DEF(AUST)5706 as a universal small-scale test protocol. Both foam generation and foam expansion must be handled with care in a modified standard. Especially, one must be able to assess the performance of a foam formulation in the presence of confounding factors, such as bubble size distribution and expansion. Perhaps different performance criteria need to be introduced for CAF and aspirated foams, with a requirement that both the foam expansion and the bubble size distribution be reported. We also suggest that a modified version of DEF(AUST)5706 include a requirement for tests to be performed in large burn halls or in open air to allow realistic interaction between pot flames and surrounding foams, during burnback experiments.

The results presented in this contribution differentiated between foam performance due to the chemistry of a formulation and due to the physical foam properties, such as bubble size distributions and foam expansion. For foams generated from the same concentrate, we draw the following conclusions:

- For less expanded foams (i.e., 7:1), the distribution of bubble sizes is not a critical parameter for determining the foam performance for fire *control*. In other words, less expanded foams spread at similar rates regardless of whether the foams have a narrow or broad distribution of bubble sizes. This means that for lower expansions, both CAF and aspirated foams will probably display a similar performance in test protocols requiring fast extinguishment (US Mil Spec and ICAO).

- More expanded foams (i.e., 9:1), especially those characterised by narrow distribution of bubble sizes, such as CAF, exhibit an initial delay to spread, as a consequence of increased yield stress. Such foams are less suitable to achieve fast fire control, however, they are more efficient at fire *extinguishment*. Foams made of uniform bubbles (CAF) drain more slowly and provide a more effective barrier against the diffusion of flammable vapours, especially at hot rims. This means that more expanded CAF will probably outperform aspirated foam in standards requiring good sealing of flammable vapours, especially at hot metal surfaces (Lastfire, IMO).

- Compressed-air foams, because of their uniform bubble sizes, display much greater resistance to fuel re-ignition than aspirated foams. The relative performance of a foam against burnback correlates well with the 25% drainage time. Because of this consideration, the 25% drainage time provides a rough but reasonable assessment of the uniformity of bubble sizes.

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