J. of Fire Prot. Engr., **8** (3), 1997, pp 133–150

MULTIPURPOSE OVERHEAD COMPRESSED-AIR FOAM SYSTEM AND ITS FIRE SUPPRESSION PERFORMANCE

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SUMMARY

The paper describes a newly-developed compressed-air foam (CAF) system, based on an overhead fixed-pipe installation, and presents results showing its fire suppression performance. The CAF system generates foams by injecting compressed air into the flowing foam solution. The resulting foam is characterized by excellent fire-mitigation properties. This is because compressed-air foams, at the expansion ratios of between 1:4 tc 1:10, consist of very small and uniform-in-size air bubbles. The system needs little water to operate and is able to provide effective protection against Class A and B fires.

The system's performance was compared to the performance of water mist and sprinkler-based installations. The experiments confirmed that the CAF system is effective in suppressing Class A and B fires. For the scenarios evaluated, the compressed-air system generated foams with sufficient momentum to penetrate the fire plume and to reach the fuel surface. The experimental results indicate that, in an open space, the foam system performs much better than water mist in extinguishing wood crib and flammable liquid pool fires. In an enclosed space, both water mist and compressed-air foam perform equally well against flammable liquid fires. The suppression performance of the CAF system on large wood crib fires was much better than a sprinkler system.

INTRODUCTION

The widespread application of overhead fixed foam systems[1] in industrial, military, and civilian installations confirms the fire extinction effectiveness of this technology.[2] Typical advantages of fixed foam systems include rapid reaction time, automatic operation, and low maintenance costs (compared to supporting an on-site fire brigade), as well as a low demand for water.[2,3] However, current fixed foam technology has some drawbacks. In the present fixed foam systems, foam solution, which is prepared by proportioning foam concentrate into flowing water, is discharged through air-aspirated nozzles.[4] The nozzles operate as mixing chambers, inducing turbulent interaction between air and foam solution. In the process, the kinetic energy of the liquid stream is partly dissipated, and the foam is characterized by low momentum, non-uniform distribution of bubbles or cells, and low expansion ratio. The expansion ratio (E) is defined as the following equation, at atmospheric pressure:

$$E=\frac{V_a+V_{fs}}{V_{fs}} \tag{1}$$

where (V_a) is the volume of air and (V_{fs}) is the volume of foam solution itself. NFPA 11 provides standard procedures for taking foam samples as well as for constructing foam sample collectors;[5] see also other NFPA, ISO, and UL standards.[6–8]

To effectively suppress fires, it is important to deliver foams with high momentum. This is especially important in the case of high-ceiling storage warehouses and hangars, where the injected foam needs to penetrate fire plumes before reaching

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the seat of a fire. Usually, aspirated foams possess insufficient momentum and are blown away by ascending fire plumes. Another disadvantage of aspirated foams is their propensity to generate a wide distribution of bubble sizes. This promotes inter-bubble diffusion of air through foam films because of the higher pressure in smaller than in larger bubbles. In other words, smaller bubbles get smaller and larger bubbles become even larger with time. This phenomena decreases foam stability since larger bubbles are less stable.

Compressed-air foam suppression systems have been applied to the mitigation of wildland fires,[9,10] and recently to suppression of structural fires.[3,11] The injection of the compressed air into the water line containing the foam solution produces a well-entrained foam that can be projected a considerable distance from the nozzle. It has been shown that a CAF system can provide rapid cooling and fire extinction using less water than would be required for traditional hose-stream techniques.[3]

The fire-suppression performance of overhead fixed foam systems could be greatly improved if compressed-air foams, rather than foam solutions, were distributed through piping networks and delivered to the fire using special overhead nozzles. It was surmised that compressed-air foams distributed from a fixed system would possess better stability with respect to drainage than aspirated foams, since CAFs are characterized by a narrow distribution of bubble sizes. It was thought that less energy would be dissipated in the CAF system because it does not require air entrainment, as in the case of air-aspirated nozzles, and a CAF would penetrate fire plumes better since it has a substantial delivery momentum. It was also suggested that fixed CAF systems would be more flexible than air-aspirated installations since the foam expansion ratios could be easily changed by adjusting the flow rates of foam solution and compressed air.

There is no published account of any previous attempt to design, construct, and operate a fixed overhead CAF system. Technical difficulties related to the degradation of foams during transport at elevated pressures (450-880 kPa abs) through a piping system and manifolds prevented the successful use of CAF technology in fixed systems. Additional problems were associated with the injection of compressed air into flowing foam solution at balanced pressures to promote good mixing, and with the separation of foam into air and foam solution due to the impact of foam on traditional system components such as sprinkler deflectors.

The present paper describes the successful implementation of CAF technology in a fixed piping system. The paper summarizes the salient construction details of the system, including foam generation and delivery, and provides a comprehensive set of results showing the effectiveness of overhead CAF installations. The paper also compares the fire suppression effectiveness and extinction mechanisms of CAF and water mist and sprinkler systems operated in open space and in compartments.

Terms and Definitions

Foam expansion is related to a parameter called air holdup (ε), which is the volume fraction of foam occupied by the gas, according to the following expression:

$$E=\frac{1}{1-\varepsilon} \tag{2}$$

The expansion ratio and the air holdup is determined with respect to standard pressure, *i.e.*, 101.3 kPa. *In situ*, or at pipe pressure, foams are characterized by the so-called quality, which is the fraction of foam occupied by the compressible gas at some elevated pressure. The term quality is useful for describing the rheology and flow of compressed-air foams.[12] At standard pressure, gas holdup and quality convey the same meaning. Throughout this paper, foam expansion will be used exclusively, since this terminology is predominant in the fire suppression literature.

CAF systems produce shaving-cream-like foams which reflect uniform bubble distribution for wet foams, and uniform cell distribution for dry foams. Typically, bubbles in the CAF are less than 50 μm in diameter and differ in size by less than one order of magnitude.[13,14] On the other hand, foams generated by air-aspirated nozzles have a wide distribution of bubble sizes, often spanning two or three orders of magnitude; single bubbles could be up to a few centimeters in diameter.

The difference in size among bubbles in foams generated by air-aspirated systems promotes diffusions from small to large bubbles. (For foams with expansion ratios above 1:4, the diffusion takes place between foam cells.) This is because the rate of diffusion is proportional to the difference in pressures within foam bubbles.[15] Considering two bubbles, one small and one large described by the radii r_s and r_l, submerged in the foam solution, the pressure difference follows from the Laplace and Young law,[16]

$$\Delta P = 2\gamma\left(\frac{1}{r_s} - \frac{1}{r_l}\right) \tag{3}$$

where γ is the surface tension. As shown by Lemlich,[15] the change in size of a single bubble having a radius r depends on the bubble-size distribution function $F(r,t)$,

$$\frac{dr}{dt} = K\left(\frac{1}{r_{12}} - \frac{1}{r}\right) \tag{4}$$

where K is a proportionality constant which incorporates ΔP, and

$$r_{12}(t) = \frac{\int_0^\infty r^2 F(r,t)dr}{\int_0^\infty rF(r,t)dr} \tag{5}$$

This relationship indicates that a large variation in bubble sizes leads to larger pressure differences, more vigorous diffusion, and to coarsening of foam. The coarsening promotes foam decay, by inducing increased drainage of foam solution from thin films and from the so-called Plateau borders (which are triangular in cross-section and are formed at the boundary of three neighboring thin films). A connected network of Plateau borders serves as a drainage system for water to leave a foam blanket due to gravity.[17] A paper by Gururaj *et al.*[18] provides a comprehensive review of recent literature on foam drainage.

The above discussion applies especially to overhead fixed-foam systems. Foams delivered from such installations are used for direct fire suppression, and it is important that water drains slowly and does not run away from the point of initial application.

EXPERIMENTAL SET-UP AND PROCEDURES

Suppression Chambers

The aim of the experimental program entailed testing the performance of the fixed CAF system in open space and in compartments. Open and enclosed spaces induce different combustion regimes in fires, which affect fire extinguishment. Fires in open spaces have unconstrained access to oxygen and are only limited by the amount of available fuel. From the mitigation perspective, these fires are more difficult to extinguish than fires in compartments. This is because, in the compartment fire case, the air may be depleted of oxygen, and the initial application of water-based suppressants, especially in the case of large fires, may lead to the rapid evolution of water vapor and subsequently to fire suffocation.

The first series of experiments was conducted in a mobile test unit measuring 3.5 m x 3.1 m x 3.3 m. The chamber's walls were constructured from perforated steel to break up the convective air currents without limiting the ventilation rate, as illustrated in Figure 1. The chamber simulated open-space condition with unlimited ventilation. A thermocouple tree, containing 6 thermocouples at 0.3 m intervals, was placed above the center of the fuel with the lowest thermocouple 1.5 m above the floor. The thermocouples provided an indication of fire control for experiments in which full flame extinction was not achieved. In order to estimate the mitigating effect of fire suppression systems on the thermal radiation hazards, three heat flux meters were placed around the enclosure, as shown in Figure 1 (see also Reference 19). Two heat flux meters were located 1.7 m away from the centerline of the fuel (Figure 1): Heat Flux Meter #1 (HF1) at 1.7 m, and Heat Flux Meter #2 (HF2) at 2.5 m above the floor. Both HF1 and HF2 were mounted horizontally to view the fire. Heat Flux Meter #3 (HF3) was located directly above the fuel facing downward. It was 2.5 m above the floor.

The second series of tests was conducted in a compartment whose geometry in plan and side views is illustrated in Figures 2 and 3, respectively. The compartment was 6.1 m x 6.1 m x 3.2 m in size and had two window openings, each 1.5 x 1.2 m and separated by 0.25 m. The windows, located 1.5 m above the floor, allowed air to enter the compartment by natural convection, and no forced ventilation was provided. The windows were instrumented with bi-directional probes and thermocouples, to measure the gas velocity and temperature profiles in the window. These data were useful in understanding the flow and temperature fields which were established during the pre-burn portions of the experiments before the activation of the suppression systems. The compartment also had a 0.8 m by 1.9 m door opening. The door was opened during the pre-burn period, but was closed before the discharge of suppression systems. The compartment was instrumented with three thermocouple trees, each containing four thermocouples. The locations of the thermocouple trees are shown in Figures 2 and 3.

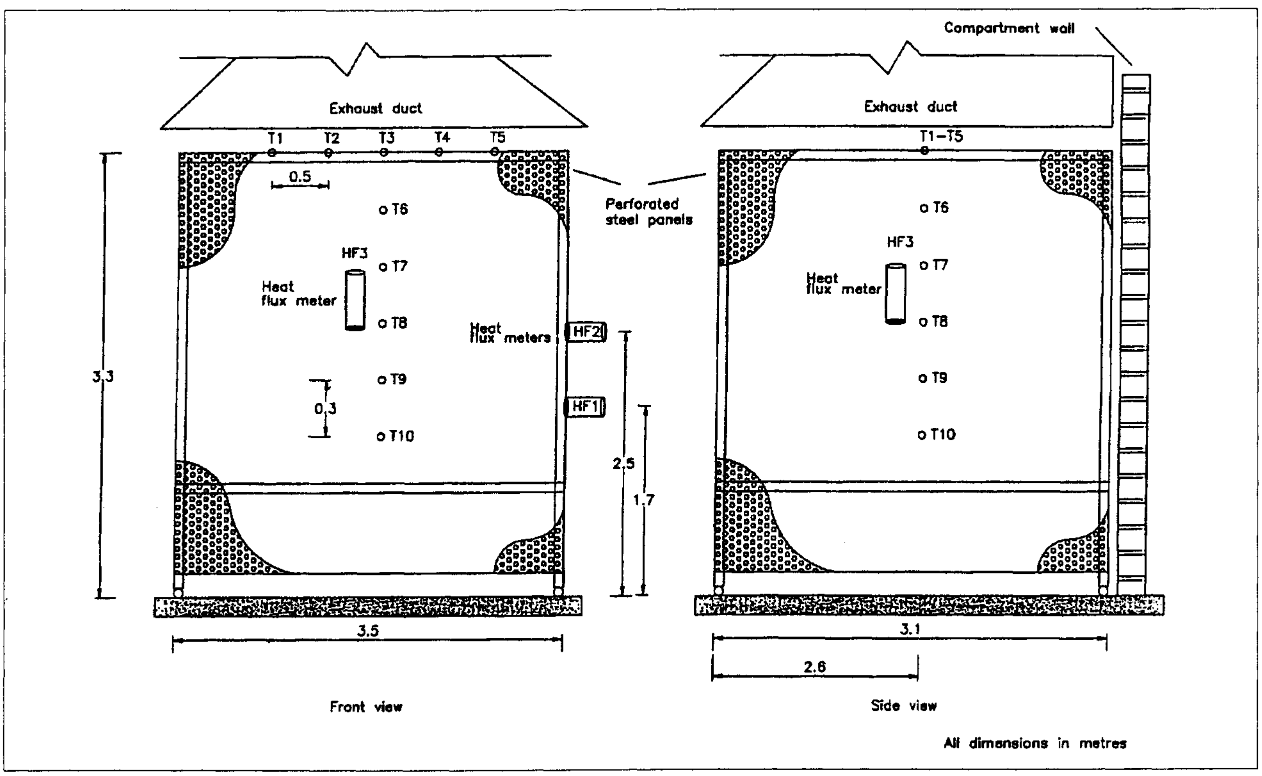

Figure 1. Instrumentation Used in Experiments Performed in an Open-Space Type Suppression Chamber.

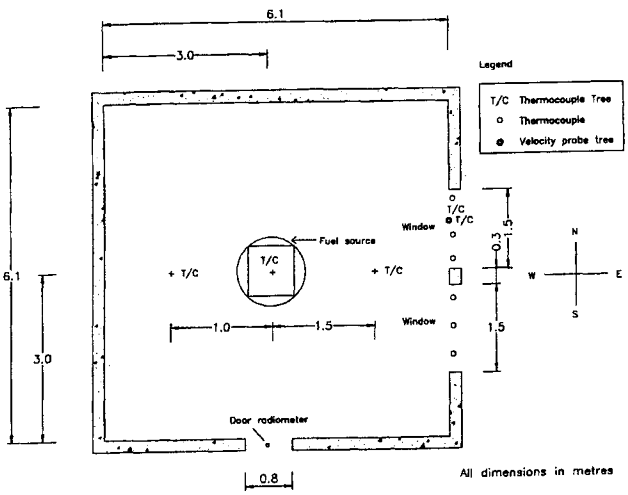

Figure 2. Geometry and Instrumentation of the Compartment-Type Suppression Chamber; Plan View.

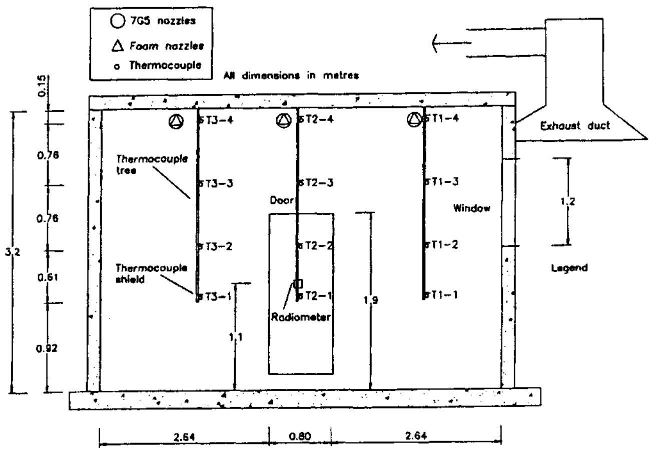

Figure 3. Side View of the Compartment Chamber, with Instrumentation Locations.

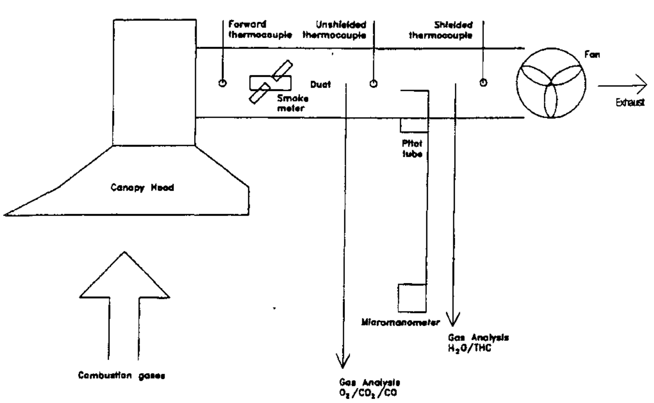

Figure 4. Schematic Diagram of the NFL's Oxygen Consumption Calorimeter.

Oxygen Consumption Calorimetry

The combustion products generated in the experiments were collected by a 2.4 x 3 m canopy hood connected to a 15 m long, 0.56 m diameter exhaust duct. The canopy hood was positioned either directly above the perforated-steel suppression chamber (Figure 1) or above the compartment windows (Figure 3). Gas samples were withdrawn continuously from the duct through two sampling lines (Figure 4). Gas from the first line was desiccated prior to analysis using paramagnetic oxygen and infrared carbon dioxide/carbon monoxide analyzers. Gas from the second heated line was analyzed using water vapor and total hydrocarbon analyzers. The exhaust duct was equipped with a pitot tube, thermocouples, and optical smoke meters. No clogging of the pitot tube by soot from the fires was observed.

The pitot tube and thermocouple readings in conjunction with the gas concentrations were used to determine the rate of heat release.[20-22]

Fuel Type

Three types of fires were used in the tests: heptane pool, diesel pool, and wood crib fires. A 0.9 m diameter pan with a lip height of 100 mm was used for the pool fires. Wood cribs weighed 9.5 kg, had outside dimensions of 0.6 m by 0.6 m and 0.3 m, and were constructed from 40 mm by 40 mm pine sticks. Pans and cribs were placed either on the floor or on the top of a 0.7 m high support platform in the open space fire tests. The nozzles were located 3 m above the floor. In the compartment fire tests, the fuel was always placed on the floor at the center of the compartment, 3 m below the nozzles.

For the crib and the diesel pool fire tests, the fires were allowed to burn for approximately 2 min before activation of the suppression system, to allow the fire to reach the fully-developed stage. This was verified by the heat release rate data. For the heptane pool fires, a 1 min pre-burn was selected since the heptane pool fire reached steady burning conditions more rapidly than diesel fuel and wood cribs.

Generation of Compressed-Air Foam

Figure 5 shows a schematic diagram of the compressed-air foam system. A distribution module contained control valves (for adjusting water flow rates and air pressures), flow meters, and an air-liquid mixing chamber for foam production. The module was connected to water and air supplies on one side, and to a pipe leading to the nozzles on the other side. Foam concentrate and water were mixed in a vessel, which was then pressurized to 680 kPa (gauge) with air. The vessel was weighed before and after the tests to determine the total quantity of foam solution supplied to the nozzles.

A series of experiments was carried out to gain an understanding of the role of different parameters and their effect on the development and breakdown of the foam. Based on these tests, it was determined that the quantity and quality of foams were affected by the geometry of the mixer (type of air injection, length of mixing zone), by the piping system (number of bends and manifolds), and by the construction details of the foam-distribution nozzles.

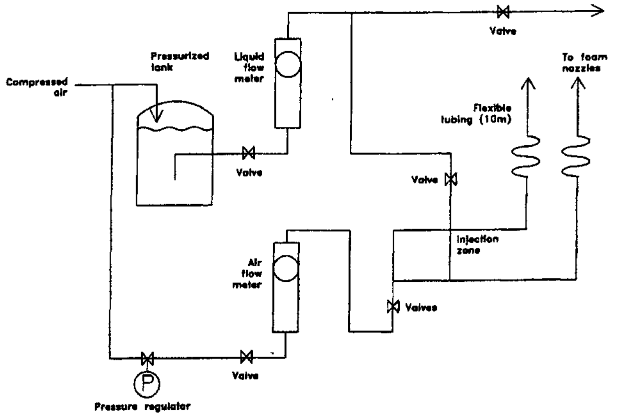

Figure 5. Schematic Diagram of Compressed-Air-Foam System.

An effective CAF system produces foam consisting of similar-in-size bubbles, delivers the foam to nozzles without changes in foam properties, and provides a means of uniformly distributing foams over a prescribed area. With respect to Figure 5, a CAF system consists of three zones:

1. *Air injection zone*: Air is injected through a small orifice into a larger diameter stream of water, ensuring that the air pressure can be maintained higher than the water pressure, so that water does not back up into the air line. This eliminates the pulsations occurring in a large diameter pipe if air and water pressures are not balanced.

2. *Development zone*: After injection of air into the stream of foam solution in the mixer, foam flows through a segment of flexible tubing, which acts as a foam improver. The improver consists of a 10 m long section of 25 mm diameter polypropylene tubing. The non-regular but smooth tube walls generate instabilities which accelerate buildup of uniform foams. After passing through the improver, the foam is directed to the distribution piping. Abrupt bends in the piping, as well as flow contractions and manifolds, promote redistribution of foam into separate gas and liquid phases. The present system can produce uniform foams with expansion ratios ranging from 1:4 to 1:20. Foam solutions with expansion ratios in excess of 1:10 were found to be too dry to effectively suppress the fires.

3. *Discharge zone*: A special nozzle was designed to permit the smooth discharge of foam. This nozzle consists of three orifices spaced at 120° intervals. The jet reaction of the discharging foam rotates the nozzle distributing the foam in a continuous arc to uniformly cover a circular area about 2 m in diameter. The CAF nozzles have no sharp bends and contain no impact points, which are normally present in sprinklers and in fixed aspirated nozzles.

Foam Concentrates

The effectiveness of the fixed-piping CAF system was investigated in conjunction with Class A and B foams. A Silvex solution**, manufactured to be diluted at 1percent in air-aspirated systems, was selected for the Class A foam. This type of foam is primarily applied against fires involving Class A combustibles and is made from hydrocarbon-based surfactants. It lacks film-forming properties, but possesses excellent wetting capacity. In the present experimental program, the Silvex foam concentrate was mixed with water at 0.3 percent concentration.

The Class B foam was an aqueous film-forming foam (AFFF) concentrate, recommended for application at 6 percent concentration in air-aspirated systems, for use in suppressing flammable liquid fires. AFFF is made from fluorocarbon-based surfactants and has strong film-forming characteristics. The quantity of AFFF concentrate used in the present experimental program was between 1 percent and 3 percent of the water flow rate.

Foam Flux Density

The foam flux density from each nozzle configuration was obtained by measuring the rate at which the foam fell on a collecting surface. For these measurements, 169 collecting cups of 0.1 m diameter were laid on the floor at a grid spacing of 0.18 m, covering the whole area of the nozzle spray. Application densities on the floor from single and twin foam nozzles, located 3 m above the floor, were obtained by weighing each collecting cup and calculating the equivalent solution flow rate per unit area per unit time. The foam application density values used in the tests, therefore, indicate the delivery flow rate of the foam solution per unit area.

Figures 6 and 7 show the foam application density measurement from a single foam nozzle, with expansion ratios of 1:10 and 1:4, respectively. The nozzle was placed at the center of the enclosure, and is denoted by a cross (X) in the figures. The plots show that the foam application density was higher near the center, and decreased toward the outer edge of the spray zone.

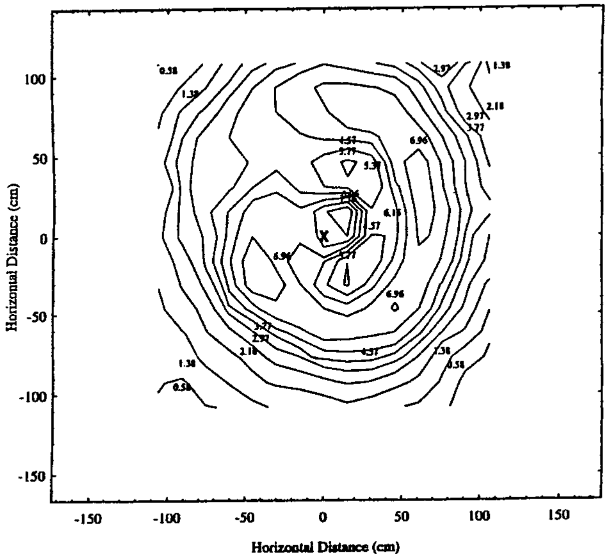

Figure 6. Flux Density of CAF, 1:10 Expansion, Measured below a Single Nozzle, in L/min/m².

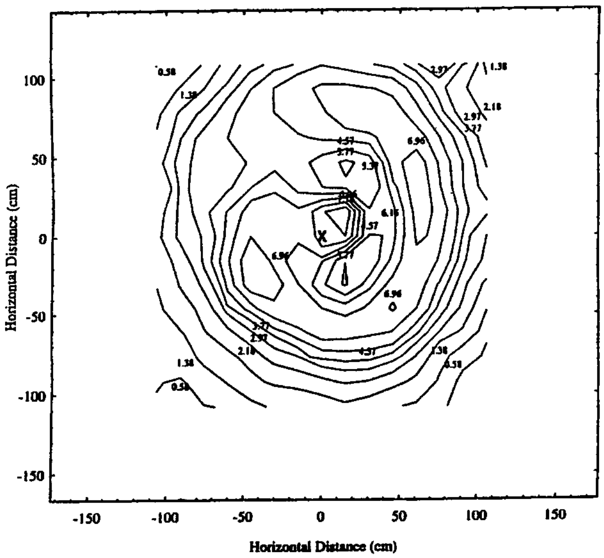

Figure 7. Flux Density of CAF, 1:4 Expansion, Measured below a Single Nozzle, in L/min/m².

** Certain commercial products are identified in this paper to adequately specify the experimental procedure. In no case does such identifiction imply recommendation or endorsement by the National Research Council, or does it imply that the product or material identified is the best available for the purpose.

The application density of the foam solution ranged from 1 L/(min m^2) at the boundary of the spray coverage area to 8 L/(min m^2) at the center, for a foam expansion ratio of 1:10. For an expansion ratio of 1:4, the foam application density ranged from 2 L/(min m^2) at the boundary to 28 L/(min m^2) at the center.

Figure 8 illustrates the foam application density in the coverage area for the case of two nozzles discharging foam with an expansion ratio of 1:10. The nozzles were mounted 2 m apart at the ceiling of the enclosure (3 m above the floor), equal distance from the center. The twin nozzles covered an area of approximately 2.5 m by 2.5 m, and provided a reasonably uniform application density within the coverage area. The values ranged from 2 to 6 L/(min m^2), with the higher value at the center where the fuel was located during the fire experiments.

A typical location where fixed foam systems are used for fire protection is aircraft hangars. NFPA 409 specifies that the minimum application rate for a foam solution in a Group II aircraft hangar should be 6.5 L/(min m^2) for protein-based foam and 4.1 L/(min m^2) for AFFF.[23] The foam application density of the CAF system used in this test series is comparable to NFPA requirements for other foams. Note that other standards relevant to aviation fire protection, as reviewed by Scheffey *et al.*, require similar application densities.[24]

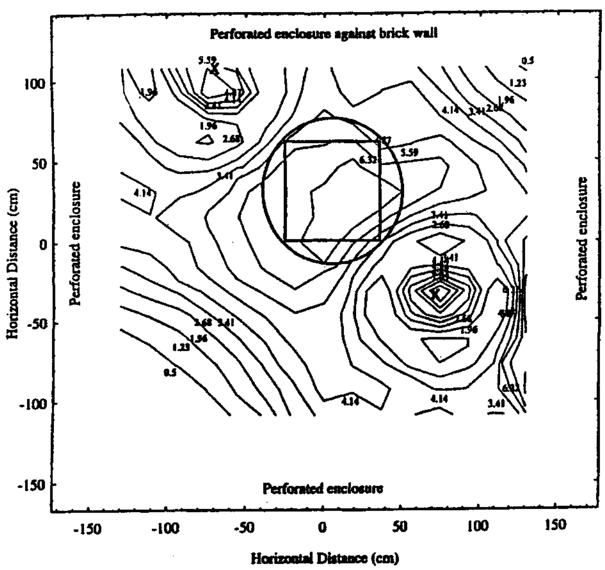

Figure 8. Flux Density of CAF, 1:10 Expansion, Measured below a Two Nozzles, in L/min/m^2.

Even though the drainage time and the burnback time of the foam were not measured, a visual inspection of the foam revealed that the bubbles were smaller and more uniform in size than for foams produced by an air-aspirated AFFF system. Based on previous experience with AFFF-based systems, the CAF system produced more stable and consistent foams. The CAF system generated foams with expansion ratios of between 1:4 and 1:20. The quantity of foam concentrate required in the CAF system was less than half that needed in the air-aspirated installations. For example with AFFF, concentrations of 1 percent and 3 percent were employed with the CAF system, compared to the 6 percent concentration typically used in air-aspirated systems.

Water Mist Tests

Water mist tests were conducted in the test series to compare its fire suppression performance with that of CAF system. In the water mist tests, Spraying Systems Company (SSC)** 3/4 7G-5 single fluid water mist nozzles were used. The 7G-5 nozzle is a swirl type pressure nozzle with a spray angle of 150°. Standard pendant sprinklers were also used for comparison purposes.

The drop-size distributions of the water sprays from the 7G-5 nozzle and the pendant sprinkler were measured using a Greenfield Instruments Model 700A Spray Drop Size Analyzer**. The volumetric mean

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diameter ($D_{v0.5}$) is defined as the droplet size where 50 percent of the volume of the spray is contained in drops whose size is less than the defining term. $D_{v0.9}$ is the droplet size diameter where 90 percent of the volume of the spray is contained in drops less than that diameter. The droplet sizes were measured at the center of the spray, 1 m from the nozzle. The $D_{v0.5}$ for the 7G-5 nozzle at a pressure of 550 kPa (5.43 bar), was 100 microns and the $D_{v0.9}$ was 300 microns. The standard sprinkler had a $D_{v0.5}$ of 440 microns and a $D_{v0.9}$ of 1000 microns at a pressure of 180 kPa (1.77 bar).

Test Results and Discussion

A series of fire suppression experiments was conducted in the mobile test unit and the test compartment described previously in this paper. Several dry (*i.e.*, unsuppressed), experiments were also carried out to provide baseline heat release rate data for the test fire. Fire suppression agents included compressed-air foam, sprinklers, and water mist.

Tables 1 and 2 provide a summary of the experimental conditions and results, for open-space and compartment fire configurations, respectively. The experiments were designed to provide performance comparisons, and to address the following questions:

1. How do Class A and Class B foaming agents compare in a CAF system?
2. What foam expansion ratios are most effective, and most practical?
3. How does increased flux density and foam concentration affect suppression ability?
4. How do fixed CAF systems compare to water mist and sprinkler systems?

Open Space (Unenclosed) Fire Tests

Suppression of heptane pool fires

Class A and B foams: The experimental results with a single foam nozzle, located directly above the fuel, showed that a CAF system, using Class A foam, suppressed a 0.9 m diameter heptane pool fire within one minute of the activation of the system. Class B foam, however, was not as effective as the Class A foam. The CAF with 1 percent Class B foam solution, having an expansion ratio of 1:4, suppressed the heptane pool fire in 1 min 35 sec, whereas 0.3% Class A CAF, with an expansion ratio of 1:4, extinguished the heptane pool fire in less than 40 sec.

The difference in the performance of the two foams (Class A and B) is probably due to the concentrations used in our tests. The Class B foam concentrate (AFFF) was designed for application at a concentration of 6 percent in an air-aspirated nozzle system, and the Class A foam was designed for use at 0.6 percent concentration. This means that, in our study, Class A foam concentrate was used at approximately 50 percent strength, and Class B foam was used at less than 20 percent strength. However, in the CAF system, both foam concentrates performed well even at such low concentrations.

Figure 9 illustrates the heat release rates of the heptane pool fires during suppression using single nozzle systems. It shows a sharp drop in the heat release rate, immediately after the CAF system was activated, with either a 1 percent Class B or 0.3 percent Class A foam, indicating quick knock down, control, and extinguishment of the fire. It clearly indicates that the 0.3 percent Class A foam extinguished the fire quicker than the 1percent Class B foam. This figure also shows that water mist from a 7G-5 nozzle reduced the fire size, but was not successful in extinguishing the heptane pool fire.

Foam expansion ratio: Different expansion ratios for Class A and B foams were compared to determine the impact on the suppressibility of heptane pool fires. Test

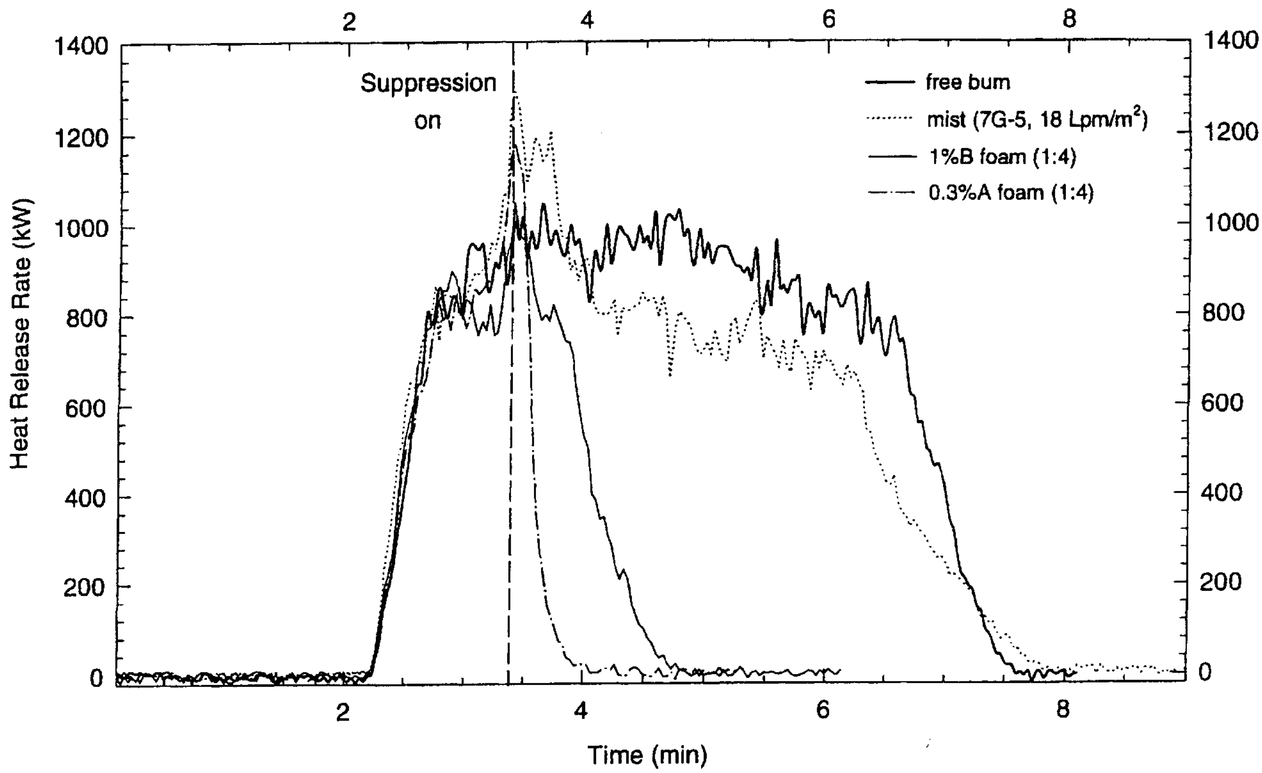

Figure 9. Suppression Effectiveness of Class A and B Compressed-Air Foams and Water Mist on Heptane Pool Fires (*Single* Nozzle).

results showed that a lower expansion ratio foam (1:4) extinguished the fire a little quicker than the higher expansion ratio foam (1:10). A Class A foam with an expansion ratio of 1:4 extinguished the heptane pool fire in 38 sec, compared to 44 sec with an expansion ratio of 1:10. For the Class B foam, the difference was somewhat larger; a foam with a 1:4 expansion ratio extinguished the fire in 1 min 35 sec, compared to 2 min 55 sec with a 1:10 expansion ratio foam.

This does not necessarily mean that a lower expansion ratio foam is more effective than a higher expansion ratio foam. The difference in extinguishment times between the two foam expansion ratios was small, and one should consider that the 1:4 expansion ratio foam required 2.5 times more foam solution than the 1:10 expansion ratio foam. In fact, considering the water requirement, a higher expansion ratio foam may be more efficient in extinguishing a liquid fuel pool fire. If the expansion ratio is too high (above 1:10), however, the foam may be too dry and too light to be able to penetrate the buoyant plume and reach the fuel surface to suppress the fire.

The effect of nozzle height above the fuel in suppressing the fire was also studied. Tests were conducted with the fuel pan located either on the floor or on top of a 0.7 m high platform. The nozzle height above the fire had little effect on suppressibility using the CAF system. The foam nozzle, located 3 m above the fuel pan, extinguished the heptane fire at approximately the same time as the nozzle located 2.3 m above the pan.

Figure 10 shows the heat release rates of heptane pool fires suppressed using dual nozzle systems. The fire was hardly suppressed by the water mist from the two 7G-5 nozzles, whereas the Class A CAF, with a 1:4 expansion ratio, extinguished

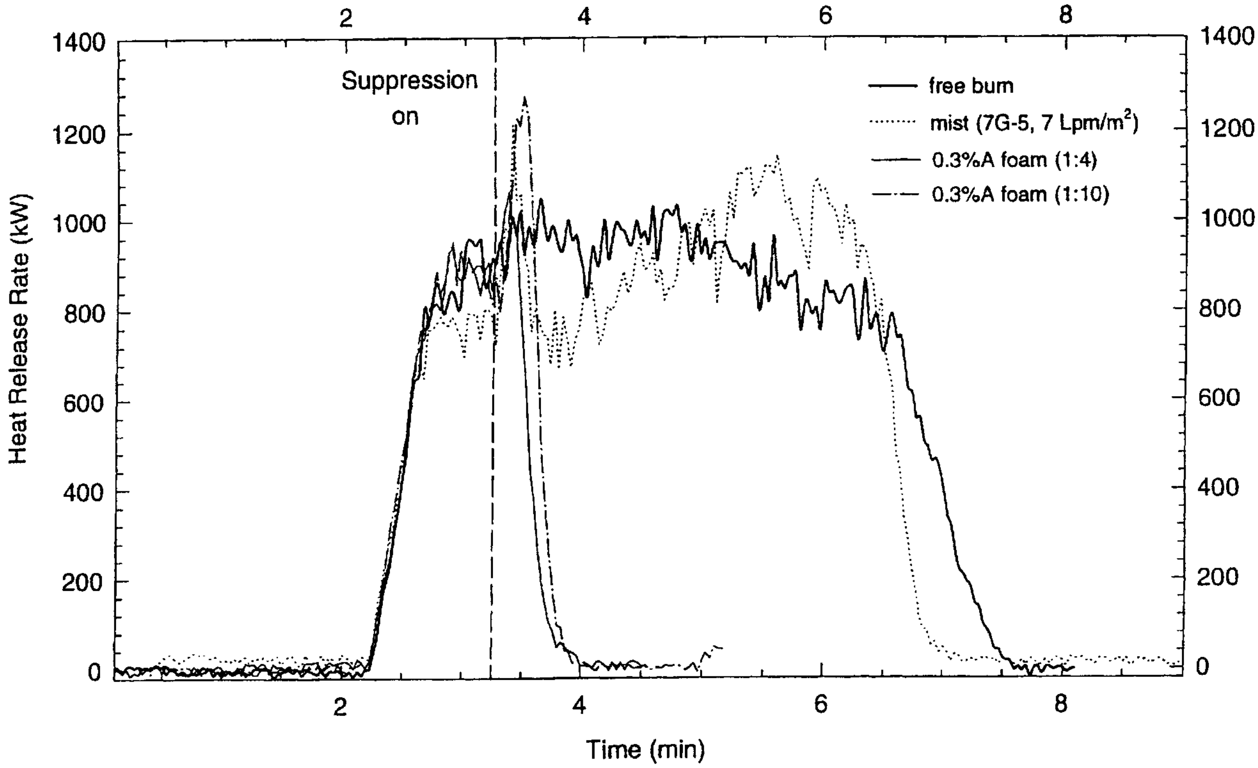

Figure 10. Suppression of Heptane Pool Fire with Water Mist and Class A Compressed-Air Foam in Open Space. The Pool Fire was Placed Midway between *Two* Nozzles.

the fire in 25 sec and, with a 1:10 expansion ratio, foam extinguished the fire in 30 sec. For Class B foam concentrate, extinguishment times were 1 min 11 sec and 2 min 45 sec, respectively, for 1:4 and 1:10 expansion ratios. These extinguishment times are slightly shorter than the ones obtained using a single foam nozzle.

Suppression of diesel pool fires

Using two foam nozzles, the Class A CAF, with an expansion ratio of 1:10, extinguished a 0.9 m diameter diesel pool fire within 35 sec. Foam, with an expansion ratio of 1:4, extinguished the fire in 28 sec. The CAF was equally effective in suppressing the diesel pool fires (high flashpoint liquid) and heptane (low flashpoint liquid).

A CAF system extinguishes pool fires by providing a foam blanket which covers the fuel surface and reduces the thermal feedback to the fuel surface. If the foam blanket is applied rapidly, suppression of the evolving volatile fuel vapors is less important,[25] although some effects are obviously present. It takes slightly longer to extinguish fires of low flashpoint liquids. Compare, for example, the extinguishment times for 1:10 foams, which were 35 sec and 44 sec in the case of high and low flashpoint liquids, respectively. Therefore, the flashpoint temperature of the fuel is not as critical as in the case of extinguishment with water mist. The water mist system could extinguish the diesel fires, but could not extinguish the heptane pool fires (see Table 1).

Suppression of wood crib fires

Foam expansion ratio: The Class A CAF, delivered from a single nozzle above the fire, was not as effective in extinguishing wood crib fires as in extinguishing the liquid fuel fires. The foam, with an expansion ratio of 1:4, controlled the wood crib fire in less than 1 min and extinguished all flames at 3 min 10 sec. The foam blanket covered most of the top surface area of the crib in less than 30 sec; however, due to the orientation of the nozzle, the side of

Table 1. Summary of Results Obtained in Open-Space Experiments.

Test Number	Fuel	Nozzle type	Nozzle number	Nozzle height (m)	Additive	Fire reduced?	Extinguishment time (min : s)
T01	Heptane	7G-5	2	3	None	No	No
T02	Diesel	7G-5	2	3	None	Yes	1 : 09
T06	Crib	7G-5	2	2.3	None	Yes	No
T11	Heptane	Foam	2	3	0.3% A[1]	Yes	0 : 25
T12	Heptane	Foam	2	3	0.3% A[2]	Yes	0 : 30
T13	Crib	Foam	2	2.3	0.3% A[2]	Yes	1 : 42
T14	Crib	Foam	2	2.3	0.3% A[1]	Yes	0 : 37
T15	Heptane	Foam	2	3	1% B[1]	Yes	1 : 11
T16	Heptane	Foam	2	3	1% B[2]	Yes	2 : 45
T17	Heptane	Sprinkler	2	3	None	No	No
T18	Diesel	Sprinkler	2	3	None	Yes	3 : 30
T20	Crib	Sprinkler	2	2.3	None	Yes	4 : 35
T22	Heptane	7G-5	1	3	None	Yes	No
T38	Heptane	Foam	1	3	0.3% A[2]	Yes	0 : 49
T39	Heptane	Foam	1	2.3	0.3% A[2]	Yes	0 : 44
T40	Crib	Foam	1	2.3	0.3% A[2]	Yes	5 : 22
T41	Heptane	Foam	1	2.3	1% B[2]	Yes	2 : 55
T42	Heptane	Foam	1	2.3	1% B[1]	Yes	1 : 35
T43	Heptane	Foam	1	3	1% B[1]	Yes	1 : 33
T44	Heptane	Foam	1	3	0.3% A[1]	Yes	0 : 30
T45	Heptane	Foam	1	2.3	0.3% A[1]	Yes	0 : 38
T48	Crib	Foam	1	2.3	0.3% A[1]	Yes	3 : 10
T70	Diesel	Foam	2	3	0.3% A[2]	Yes	0 : 35
T71	Diesel	Foam	2	3	0.3% A[1]	Yes	0 : 28

[1] Foam expansion ratio of 1:4
[2] Foam expansion ratio of 1:10

the crib was not blanketed by foam. There were persistent flames within the crib which were eventually extinguished as water slowly drained from the foam blanket into the core of the wood crib. The heat release rate shown in Figure 11 indicates a sharp drop with the application of a 1:4 expansion ratio foam.

With a 1:10 expansion ratio foam, the heat release rate was reduced because the foam blanket partially covered the top surface of the crib. However, even after 4 min of foam application, the foam blanket was not contiguous, and flames continued through the top of the crib. Figure 11 confirms these visual observations as a relatively high heat release rate was measured during the initial 4 min, indicating large flames.

It is clear that, at the expansion ratio of 1:10, the foam performed less effectively in extinguishing the fire. The foam reduced the fire size, but required more than 5 min for complete extinguishment. This foam is more viscous than the less-expanded foam and, as a result, has a higher resistance to flow across the solid surface of the fuel. It also contains less water in thin films to drain effectively into the core of the wood crib.

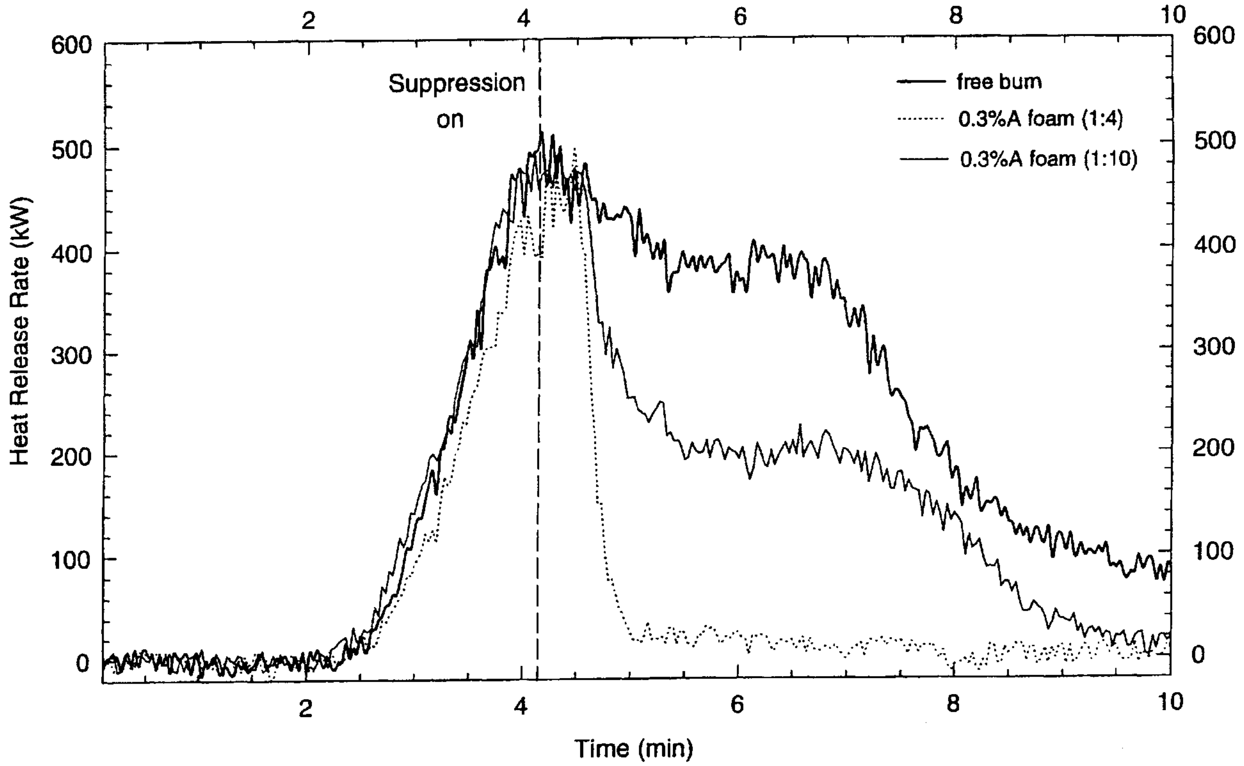

Figure 11. Effect of the Foam Expansion Ratio on the Extinguishment of Wood Crib Fires with Class A CAFs in Open Space (*Single* Nozzle).

Comparison of crib and liquid fuel fires: Comparing the wood crib results to the liquid fuel results (see Table 1) indicates that the Class A CAF performed better on liquid fuel fires. With liquid fuel pool fires, the foam expands to completely cover the fuel surface. This blocks the heat transfer from the flame to the fuel surface and decreases the vaporization of the fuel. In the crib fires, foams cannot reach all of the interior burning surfaces; however, the water draining from the foam eventually penetrates the crib and may indeed extinguish the fire.

Foam distribution: The importance of a uniform distribution of foam was illustrated by the relative performance of the dual nozzle configuration compared to a single nozzle. Two foam nozzles, located 2.3 m above the crib and 2 m apart, provided sufficient foam to cover the top and side of the wood crib, resulting in fire extinguishment. Figure 12 shows the heat release rates measured during suppression with two different expansion ratio foams. The low expansion ratio foam (1:4) suppressed the fire in 37 sec. The foam with an expansion ratio of 1:10 extinguished the fire in 1 min 42 sec.

As shown in Figure 13, two sprinklers took 4 min 35 sec to extinguish the fire, whereas water mist from two nozzles could not extinguish the wood crib fire. The experimental results show that a fixed CAF system is very effective in extinguishing wood crib fires, provided that it is distributed uniformly and is able to cover all surfaces of the crib.

Compartment (Enclosed) Fire Tests

Suppression of heptane pool fires

Results for tests conducted with the CAF system, water mist, and sprinklers are given in Table 2. There was little difference in the performance of the CAF system in extinguishing open-space and enclosed fires. Class A foam with an expansion ratio

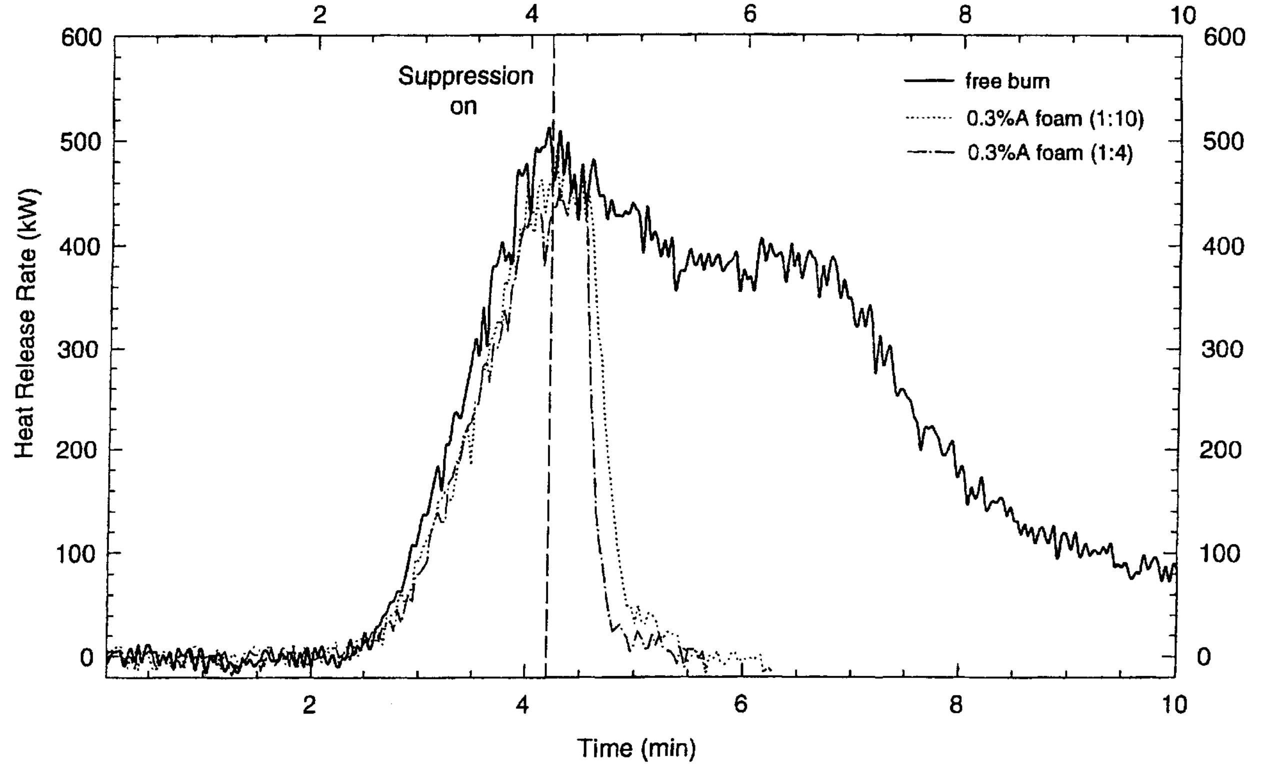

Figure 12. Effect of the Foam Expansion Ratio on the Extinguishment of Wood Crib Fires with Class A CAFs in Open Space (*Two* Nozzles).

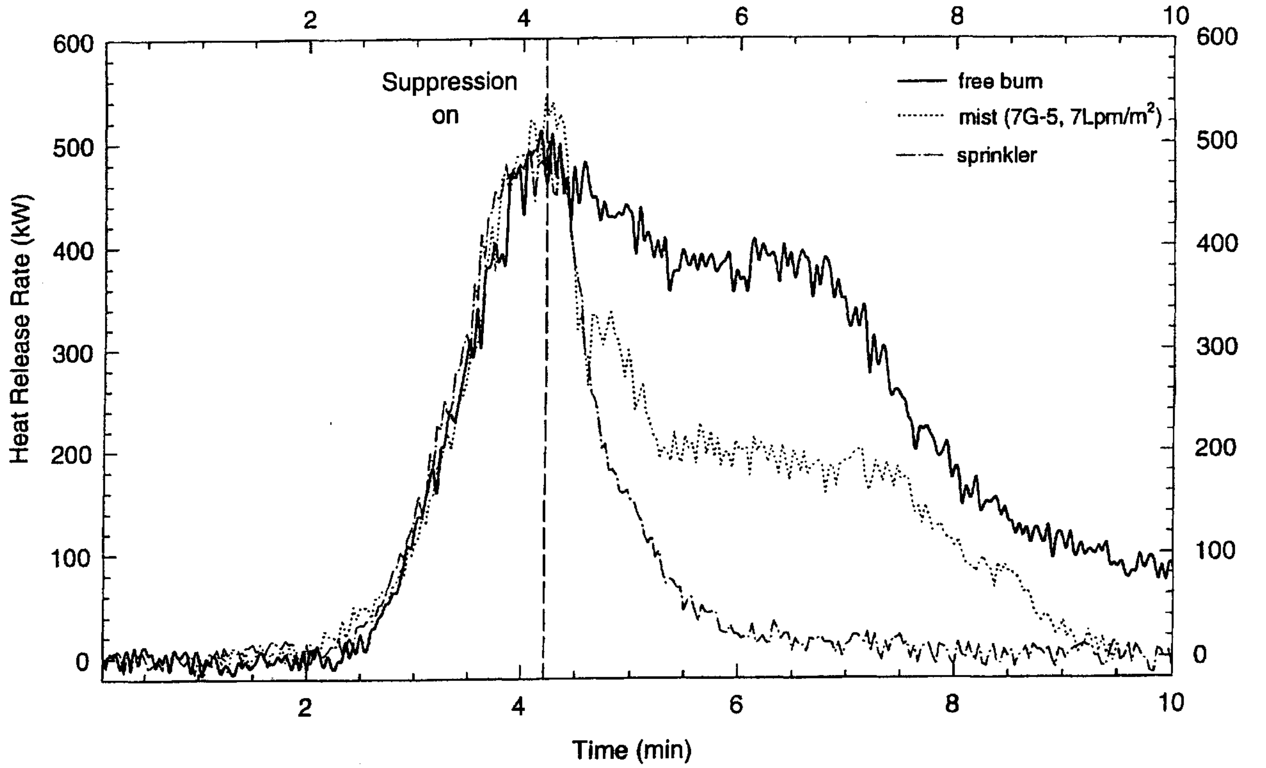

Figure 13. Heat Release Rate during Suppression of Wood Crib Fires with *Two* Water Mist Nozzles and *Two* Pendant Sprinklers.

Table 2. Summary of Results Obtained in Compartment Fire Tests.

Test No.	Fuel Type	Pan Size (m)	Pre-burn Time (min)	Nozzle type	Nozzle number	Additive	Fire reduced ?	Extinguishment time (min : s)
R04	Heptane	0.9	2	7G-5	4	None	Yes	0 : 38
R06	Crib	Large	2	7G-5	2	None	No	No
R21	Diesel	0.9	2	7G-5	2	None	Yes	0 : 17
R22	Heptane	0.9	0.5	7G-5	2	None	Yes	2 : 10
R25	Heptane	0.9	2	Sprinkler	2	None	No	No
R26	Crib	Large	2	Sprinkler	2	None	No	No
R27	Diesel	0.9	2	Sprinkler	2	None	Yes	7 : 00
R32*	Heptane	0.9	1	Foam	4	0.3% A	Yes	0 : 24
R33	Heptane	0.9	1	Foam	4	0.3% A	Yes	0 : 25
R34	Diesel	0.9	1.5	Foam	4	0.3% A	Yes	0 : 35
R35	Crib	Large	2	Foam	4	0.3% A	Yes	7 : 16
R36	Crib	Large	2	Foam	4	0.3% A	Yes	5 : 56
R37[1]	Heptane	0.9	1	Foam	4	0.3%A	Yes	0 : 30
R38[2]	Heptane	0.9	1	Foam	4	0.3% A	Yes	0 : 32
R39[3]	Heptane	0.9	1	Foam	4	0.3% A	Yes	0 : 40

* Flow rate was accidently reduced by 15 percent

[1] The fuel had 25% area obstruction at 0.6 m above the surface

[2] The fuel had 50% area obstruction at 0.6 m above the surface

[3] The fuel had 75% area obstruction at 0.6 m above the surface

N.B. All foam tests were conducted with a foam expansion ratio of 1:10.

of 1:10 immediately controlled the heptane fire in the compartment and extinguished it in 25 sec, compared to 30 sec in the open-space test. There was, however, a considerable improvement in the effectiveness of the water mist system in the compartment tests. The water mist system was able to suppress both the diesel and heptane pool fires.

Unlike water mist, there seems to be no enclosure effect with a CAF system. This is not surprising since the extinguishing mechanism in the compartment remains the same as in the open-space scenario; that is, a foam blanket forms rapidly on the fuel surface reducing the thermal feedback and diminishing the evolution of volatile gases.

Suppression of wood crib fires

In order to determine the effect of deep-seated fires, experiments were carried out with two sizes of cribs. The smaller cribs consisted of 5 layers of pine sticks (0.3 m high and weighing 9.5 kg) and the bigger cribs contained 10 layers of pine sticks. The larger wood crib produced a more challenging fire, because of its size and its shielding by the top layers of sticks.

The CAF system covered the surface of the bigger wood cribs with a foam blanket within 1 min of activation. However, there were persistent flames within the core of the wood crib until almost 6 min. For comparison, water-based systems (sprinklers and water mist) reduced the size of the wood crib fires but could not extinguish the deep-seated flames. The results shown in Table 2 demonstrate a better suppression performance using fixed overhead CAF systems, in comparison to the sprinkler and water mist installations, in extinguishing deep-seated fires in solid fuels.

Conclusions

The results showed that compressed-air foam is an effective suppressant for a wide range of fire scenarios. The CAF performs better than water mist in suppressing flammable-liquid pool fires and wood crib fires in open spaces. In compartments, CAF and water mist perform equally well in extinguishing liquid fuel pool fires, but CAF is much more effective against crib fires.

CAF installations require a smaller amount of foam concentrate, compared to systems based on air-aspirated nozzles, to provide effective suppression. In the present experiments, 0.3 percent Class A and 1 percent Class B foam solutions were used without compromising the extinguishment efficiency of compressed-air foams. This is compared to 1 percent Class A and 6 percent Class B foam solutions which are normally recommended for aspirated systems.

Compressed-air foam systems produce foams characterized by a range of expansion ratios, and by large injection momenta. For the latter reason, CAF easily penetrates strong buoyant plumes. However, a practical application of CAF systems to protect very large spaces still requires further studies to establish good engineering design guidelines and approaches.

Foams achieve suppression by forming a physical barrier on the fuel surface. This barrier blocks the radiation from the flame from reaching the fuel, and contributes to the reduction of the evolution of flammable vapors from liquid and solid surfaces. Because of these effects, there is no difference in the performance of CAF systems in open and enclosed spaces. In other words, the extinguishment does not rely on the enclosure effect, as is often the case with water mist systems.

Acknowledgments

Financial support provided by the Canadian Forces Fire Marshal's Office, National Defence Canada is acknowledged with gratitude. The authors wish to thank George Crampton of the National Fire Laboratory for his involvement in the experimental part of the work, and Daniel Madrzykowski of National Institute of Standards and Technology for informative discussions. The authors would also like to express deep appreciation to Jack Mawhinney, presently of Hughes Associates, Inc., for his assistance throughout the project.

Nomenclature

CAF	compressed-air foam
E	foam expansion, ratio of the foam volume to the volume taken by liquid (-)
$F(r,t)$	bubble distribution function (m^{-1})
K	proportionality constant in Eq 4 (m^2s^{-1})
r	radius of a bubble (m)
r_{12}	ratio of second and first moments of the bubble distribution function (m)
t	time (s)
V	volume (m3)

Subscripts

a	air
fs	foam solution
i	incoming air
l	larger bubble
s	smaller bubble

Greek symbols

ε gas holdup (fraction)

γ surface tension (N/m)

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