Fire Test Performance of Eleven PFAS-Free Class B Firefighting Foams Varying Fuels, Admixture, Water Types and Foam Generation Techniques

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Abstract. The firefighting performance of eleven PFAS-free firefighting foams was evaluated using different fuels (Jet A1, commercial heptane and diesel) and types of water (freshwater and synthetic sea water). Moreover, different firefighting foam generation techniques and application methods were evaluated. The firefighting foams were generated as aspirated foams or as compressed air foams (CAFs). The results for CAF showed a higher performance, with respect to extinction time and burn-back resistance, compared to the foam generated using a UNI 86 nozzle. The CAF was not optimised, indicating a further potential of this foam generation technique. The results indicate that the time to fire knockdown decreases with decreasing foam viscosity. The heat flux was shown to be small, although the entire fuel surface was involved in the fire. The tests showed a dependence on fuel type; different products performed differently depending on the fuel. Tests using sea water showed that addition of salt to the foam solution generally prolonged the extinction time, although for one of the firefighting foams a shorter extinction time was observed. Out of the eleven evaluated PFAS-free products there was no product that outperformed the rest. None of the products in the study met the fire test performance requirements in all the referenced standards. Instead, the products seem to have different niches where they perform best e.g., with different types of fuel or water.

Keywords: Firefighting foam, PFAS-free, Class B foam, Fire test, FFF, Liquid fire

1. Introduction

Firefighting foam is the most common agent to fight large pool fires, involving one or many flammable liquids (class B fires). Firefighting foam has even been described as the only practicable method to extinguish large scale tank fires [1]. A firefighting foam works by preventing fuel vaporization, separating oxygen from the fuel and cooling the fuel surface and surroundings [2]. In general, the aqueous film-forming foams (AFFFs) contain per- and polyfluorinated alkyl substances (PFAS) which give them the ability to form a film on the fuel. PFAS are chemi-

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cals of environmental and health concern, often referred to as “forever chemicals”, due to their persistent and bioaccumulative properties in combination with their wide spread to the environment and humans [3]. The two most extensively studied PFAS, PFOA and PFOS, are classified as reproductive toxicants and are suspected carcinogens. In addition, some PFAS have been shown to cause reproductive and developmental, liver and kidney, and immunological effects as well as tumours in animal studies [3]. These environmental and health concerns of PFAS highlight the need for substitution to novel, PFAS-free, firefighting agents and methods and evaluation of the performance of these alternatives.

Firefighting foams without fluorine are often referred to as fluorine free foams (FFFs or F3s). The process to substitute PFAS-containing firefighting foams requires both a development of the alternatives as well as an evaluation of their performance to extinguish fires. For class B fires, there is a need for highly efficient PFAS-free firefighting foams or a highly efficient combination of PFAS-free firefighting foams and equipment, e.g. firefighting foam generated as compressed air foam (CAF). CAF is a technique that was especially used during the 1930's, – 40's and – 50's. When PFAS-containing film-forming foams were invented in the 1960's, CAF faced a reduced interest due to the easier use of AFFF (CAF requires a compressor to be operated) and superior firefighting properties [4, 5].

To understand differences between PFAS-containing and PFAS-free firefighting foams, several studies have focused on comparisons between AFFFs and FFF [4, 6–11]. The performance of PFAS-free firefighting foams in standard scale tests has previously not received significant attention. In this study, eleven firefighting foams have been evaluated with respect to their firefighting performance. Nine of the eleven firefighting foams were commercially available products while two firefighting foams were in a late stage of product development.

In order to evaluate and compare firefighting foams, a wide range of test standards are being used. Many of the test standards are similar with respect to e.g., the size of the fire tray, the application rate, wind conditions, fuel temperature and type of foam nozzle. On the other hand, the test standards differ in the way that they are developed to cover different areas of usage. As examples, the ICAO test standard [12] is focused on aviation, the IMO standard [13] is focused on the maritime sector, while the EN standard [14] and the LASTFIRE fire test [15] are more focused towards the petrochemical industry. The tests in this study are based on the international test standards EN 1568–3:2018 [14], ICAO Level B [12], and IMO MSC.1/Circ.1312 [13]. From previous studies it is known that type of fuel [7, 9, 16], type of water [17] and the principle of foam generation [18–20] may impact the properties (and thereby performance) of a firefighting foam. Therefore, these parameters were also included in the evaluation of the eleven fluorine-free firefighting foams.

Table 1
Specification of the Fuels Used in the Tests

Parameter	Commercial heptane	Jet A1	Diesel
Aromatics	≤ 20 mg/kg	≤ 26.5% (V/V)	≤ 5.0% (V/V)
Benzene	≤ 10 mg/kg	—	—
Boiling point (initial)	≈ 94Fire Test Performance of Eleven PFAS-Free	≈ 70°C	≈ 180°C
Boiling point (final)	≤ 100°C	≤ 300°C	≤ 340°C
Density at 15°C	0.705–0.725 kg/l	0.775–0.840 kg/l	0.800–0.830 kg/l
Flashpoint	–5°C	38°C	70°C
Sulphur compounds	≤ 1.0 mg/kg	≤ 1.0 mg/kg	≤ 10.0 mg/kg
Methylcyclohexane	≤ 25 wt-%	—	—
n-heptane	≥ 32 wt-%	—	—
Lower explosion limit (LEL)	0.6%	0.6%	0.6%
Upper explosion limit (UEL)	7.0%	6.0%	7.5%

2. Methodology

The fire suppression tests were based on the international test standards EN 1568–3:2018 [14]; ICAO Level B [12]; and IMO MSC.1/Circ.1312 [13]. Together, these standards cover a wide field of application and make it possible to relate the results of the fire suppression tests to not only other tests, but also to already established and accepted requirements for extinction time and burn-back resistance. The test standards have several parameters in common, e.g. the size of fire tray (4.5 m²) and the fixed horizontal foam nozzle. Extra tests were added to the test series to also evaluate the burn-back resistance of a cold fuel (a fuel never ignited) and the impact of foam generation techniques. Heat radiation measurement were included to further improve the analysis.

2.1. Fuels and Foam Concentrates

The three fuels used in the tests were: Jet A1, commercial heptane and diesel. Specifications of the fuels are given in Table 1. The commercial heptane met fuel properties prescribed in EN 1568–3 [14] while the properties of Jet A1 were in accordance with ASTM D1655-15 [21]. The diesel was provided by OKQ8, was free from rape methyl ester (RME), contained a maximum of 20% hydrated vegetable oils (HVO) and fulfilled the requirements in SS 15 54 35 (environmental class 1) [22] and SS-EN 590 [23].

The eleven firefighting foam concentrates were supplied by eight manufacturers. Not all manufacturers agreed to publish the tradenames of their product(s), for those who did, the tradenames are (manufacturer given within brackets): Ecopol F3 (Bioex), Enviro USP (Fomtec), FFF-AR (Solberg), Freegen SF-LV (3F), Sil-

vara K3 (VS Focum), Skum NFF 3 × 3 UL201 (Tyco), Unifoam Bio Yellow (Kempartner) and Versagard AS-100 (Solberg). The two development products were provided by Bioex and Solberg.

The test programme was shared in advance with the manufacturers to give them the opportunity to choose the optimal firefighting foam concentrate for the tests based on their product portfolio. All concentrates were delivered in plastic containers and stored indoor, at ambient conditions, prior to the tests. All the foam concentrates were claimed by the manufacturers to be free from intentionally added PFAS.

3. Experiments

3.1. Fire Suppression Tests

The fire suppression tests were based on the test procedures described in EN 1568–3 [14], ICAO Doc. 9137 (level B) [12] and IMO Circ. 1312 [13]. The fire suppression tests were carried out using different types of fuels, fire trays, application types, water types and firefighting foam generation techniques. A summary of the fire suppression tests is given in Table 2. All tests were conducted using 4.5 m² stainless steel fire trays; the fire tray was circular.

($D = 2.4$ m) in test F1.0–F4.2 and quadratic (2.1×2.1 m) in test F5.0 and F5.1. Table 2 also highlights deviations from the test standards. The preburn time was 60 s from the time the entire surface of the burning fuel was involved in the fire. The flow rate of foam solution was 11.4 L/min (application rate 2.5 L/min/m²). All tests were conducted in a controlled environment indoors. The fuel was placed on a waterbed of 90 L in all the tests except test F1.0, F1.1 and test F1.2 where the water volume was 100 L. The difference in water volumes is due to the different test standards.

The foam nozzle was installed horizontally at a height of 1.0 m above the top of the fire tray wall. The horizontal distance from the nozzle to the fire tray was adjusted so that the central part of the foam discharge fell directly on the fuel surface at a point 1.2 m (in test F1.0–F1.2) or 1.0 m (in test F2.0–F4.2) from the edge of the tray furthest away from the nozzle, this according to the ICAO and the EN standard, respectively. Gentle application (test F5.0 and F5.1) was achieved by using a vertical stainless-steel backboard (1.0 m high and 1.0 m wide). The backboard was fitted closely along the top of the fire tray wall and the central part of the foam discharge was aimed at the centre axis of the backboard, 0.35 m above the rim of the tray (0.5 m above the fuel surface).

The time from start of foam application to 90 and 99% control, respectively, of the fire was visually judged by an experienced person. These times may not be exact values; however, this method to extract information from fire tests and real tank fires has previously been reported [16, 24, 25] and is also defined in test standards as a method to be used e.g., in EN 1568–3 [14] and the LASTFIRE foam test protocol [15]. The 90% and 99% fire control times correspond to the time that 10% and 1%, respectively, of the surface is involved in the fire. Due to fuel

Table 2
Summary of the Fire Performance Test Parameters, Nom. = Nominal

Test ID	Based on standard	Fuel type	Fuel/water volume [L]	Fire tray	Flow rate [L/min]	Application type	Water type	UNI 86/CAF	Admixture
F1.0	ICA0 Doc. 9137	Jet A1	100/100	Circular, D = 2.4 m	11.4	Forceful	Fresh	UNI 86 CAF ^a	Nom
F1.1									
F1.2								UNI 86	1.5 × Nom. ^a
F2.0	EN 1568-3	Commercial heptane	144/90	Circular, D = 2.4 m	11.4	Forceful	Fresh	UNI 86 CAF ^b	Nom
F2.1									
F2.2								UNI 86	1.5 × Nom. ^b
F3.0	EN 1568-3	Diesel ^b	144/90	Circular, D = 2.4 m	11.4	Forceful	Sea	UNI 86	Nom
F4.0	EN 1568-3	Commercial heptane	144/90	Circular, D = 2.4 m	11.4	Forceful	Sea	UNI 86 CAF ^b	Nom
F4.1									
F4.2								UNI 86	1.5 × Nom. ^b
F5.0	IMO Circ. 1312	Commercial heptane	144/90	Square, L = 2.1 m	11.4	Gentle	Sea	UNI 86 CAF ^c	Nom
F5.1									

^aDeviation from test standard ICAO Doc. 9137

^bDeviation from test standard EN 1568-3

^cDeviation from test standard IMO Circ. 1312

Table 3
Summary of the Burn-back Test Parameters

Test ID	B1.0	B1.1	B1.2	B2.0	B2.1	B2.2
Proceeded by test	F2.0	F2.1	F2.2	N/A	N/A	N/A
Hot/Cold	Hot	Hot	Hot	Cold	Cold	Cold
UNI 86/ CAF	UNI 86	CAF	UNI 86	UNI 86	CAF	UNI 86
Fuel type	Commercial heptane	Commercial heptane	Commercial heptane	Commercial heptane	Commercial heptane	Commercial heptane

pick-up, flames may exist on the established firefighting foam layer. These flames are normally rather small, but do contribute to the surface involved in the fire.

Firefighting foam was applied until extinction or for a maximum of 5 min (F1.0–F1.2), 6 min (F2.0–F4.2) or 8 min (F5.0–F5.1). Since test F2.0 and F2.1 were followed by burn-back tests, a special procedure was followed, outlined in the next section.

The fire performance tests were carried out in two steps, in the first step, all products were evaluated using nominal admixture and the UNI 86 nozzle (tests F1.0, F2.0, F3.0, F4.0 and F5.0); in the second step, some products and parameters were selected for further testing (cf. the results section).

3.2. Burn-back Tests

In total, six burn-back tests were performed: three as hot burn-back tests and three as cold burn-back tests. A summary of the burn-back tests is given in Table 3. The hot burn-back tests, designated B1.0, B1.1 and B1.2, were performed in connection to the fire suppression tests F2.0, F2.1 and F2.2. The cold burn-back tests, designated B2.0, B2.1 and B2.2, were performed as tests separate from any of the fire suppression tests, i.e. the fuel temperature was equal to the ambient temperature. In B1.0–B1.2, the foam application time depended on the extinction time in the previous fire suppression tests (F2.0–F2.2). If the fire was extinguished in less than 2:30 min:s, foam was applied until 3:00 min:s; if the fire was extinguished after 2:30 min:s, foam was applied for another 30 s. In B2.0–B2.2, foam was applied for 1:00 min:s. The firefighting foam application was followed by a 5:00 min:s wait. The fuel in the burn-back pot (circular, diameter 0.3 m, height 0.25 m, filled with 2 L of commercial heptane) was then ignited and the burn-back pot was placed in the centre of the fire tray (circular, diameter 2.4 m, initially filled with 144 L of commercial heptane and 90 L of water). The times to reach 25% involvement of the fuel surface in the fire were recorded. The firefighting foam was generated by the UNI 86 nozzle (in tests B1.0, B1.2, B2.0 and B2.2) and as CAF (in tests B1.1 and B2.1) and. In all tests, the foam solution flow rates were 11.4 L/min.

Figure 1. Schematical drawing of the CAF system used in the tests.

3.3. Foam Preparation and Foam Generation

The foam solutions were prepared approximately 30 min prior to the start of each test, using the firefighting foam concentrates at the manufacturers' recommended concentrations (A, B, and E–K: 3%; C: 2%; and D: 6%) with either freshwater poured from the tap (typically 3°dH) or synthetic sea water. The sea water was prepared from: 2.5% sodium chloride, 1.1% magnesium chloride, 0.2% calcium chloride, 0.4% sodium sulphate, and 96% demineralised water, as described in test standard EN 1568–3. The foam solutions were mixed in an open vessel and stirred at approximately 700 rpm until completely mixed. The mixed foam solutions were then kept in a 130 L pressure vessel pressurised by compressed air; this vessel was used as buffer during the tests. The temperature of the foam solutions was in the range of 15°C to 20°C.

As specified in Tables 2 and 3, the firefighting foams were either generated using a UNI 86 nozzle or a CAF generator. When the foams were generated by the aspirating UNI 86 nozzle, the foam solutions were fed through the nozzle with the pressure at the nozzle's inlet kept constant at 6.3 bar(g), thus guaranteeing a constant flow rate. When the foams were generated as CAF, a CAF generator was used. The CAF system is described in Fig. 1. The pressure of the inlet compressed air was adjusted in the range of 3.8 to 4.5 bar(g) to get a constant flow of foam solution. The CAF generator was comprised of two separate inlets, one for compressed air and one for foam solution. The inlets were followed by a mixing chamber designed to cause high turbulence. A flow indicator from GPI meters was used to measure and manually control the flow.

3.4. Heat Flux Measurements

Heat radiation measurements were included to further improve the analysis. Heat flux was measured and recorded in 1 s intervals. The two heat flux meters were Medtherm 64–2–18 Schimdt-Boelter type instruments. They were placed diametri-

cally (90° to the nozzle) at a horizontal distance of 5 m from the tray and at a height of 1.5 m above the rim of tray, angled 10° downwards.

The time (from start of foam application) to reduce the heat flux to 1.5 kW/m² for the firefighting foams was measured. This heat flux level was selected as a parameter because it is considered to be safe for stationary personnel and observers [26].

3.5. Firefighting Foam Characterization

The firefighting foams were characterised with respect to expansion ratio and 25% drainage time. The firefighting foam, discharged at 11.4 L/min, was aimed at a foam collector consisting of a steel plate angled 45° backwards. The firefighting foam was collected in a drainage pot which had a total volume of 1.62 L and was equipped with a discharge at the bottom. The drainage pot was weighed both prior to and after filling it with firefighting foam. The densities of the firefighting foam solutions were assumed to be 1.0 kg/L and the expansion ratios were calculated according to Eq. 1.

$$ER = V/(M_2 - M_1) \quad (1)$$

where ER is expansion ratio, V is the volume of the drainage pot (1.62 L), M₁ and M₂ are the masses of the empty and full drainage pot in kilograms, respectively.

The 25% drainage time, i.e. the time it takes to drain 25% of the mass of the firefighting foam was determined using a scale and a stopwatch.

4. Results

4.1. Fire Test Performance and Burn-back Resistance

Eleven firefighting foams have been tested and evaluated. A summary of the time to reach a heat flux of 1.5 kW/m², 90% and 99% and extinction (100% control) is given in Tables 4, 5, and 6. The times to reach 25% involvement of the fuel surface in the fire in the burn-back tests is given in Tables 7, 8, and 9.

All eleven firefighting foams were tested according to the test procedures in test F1.0, F2.0, F3.0, F4.0 and F5.0. Complementary tests were also made with firefighting foam generated as CAF and with 1.5 × nominal admixture. The selection of firefighting foam concentrates in test F1.1 and F2.1 was based on the performance in test F1.0 (the three best and worst). The selection of firefighting foam concentrates in tests F1.2, F2.2, F4.1 and F4.2 was made to get a wide distribution of performance in test F2.0.

Figure 2 shows heat flux measurements made in test F1.0 and F1.1 using foam concentrate A. With the firefighting foam designated A, 90% control (cf. Table 4) was never achieved in two of the tests (F1.0 and F2.0); however, the heat flux was significantly reduced to approximately 0.2 kW/m².

Table 4
Times (min:s) to 1.5 kW/m², 90%, 99% and 100% (Fire Completely Extinguished) Control of the Fires, UNI 86 Nozzle

Test ID	Control	A	B	C	D	E	F	G	H	I	J	K
F1.0	1.5 kW/m ²	0:37	0:36	0:42	0:39	0:37	0:38	0:39	0:35	0:37	0:35	0:37
	90%	- ^a	1:14	1:02	1:40	1:10	1:52	1:13	1:24	0:41	0:50	0:42
	99%	- ^a	1:57	1:25	2:28	1:37	2:35	1:38	1:58	0:57	1:16	1:21
	100%	- ^a	2:10	1:59	- ^a	1:51	3:10	3:20	- ^a	2:03	2:50	1:40
F2.0	1.5 kW/m ²	0:48	0:50	0:49	0:44	0:43	0:49	0:48	0:46	0:47	0:46	0:47
	90%	- ^a	1:06	1:10	1:19	1:21	1:25	1:31	1:19	1:09	1:54	1:05
	99%	- ^a	3:33	- ^a	2:55	4:27	2:26	4:45	2:20	- ^a	- ^a	- ^a
	100%	- ^a	5:35	- ^a	3:00	5:04	3:03	- ^a	2:30	- ^a	- ^a	- ^a
F3.0	1.5 kW/m ²	0:38	0:37	1:00	0:39	0:35	0:37	0:40	0:36	0:37	1:59	0:40
	90%	0:41	0:40	1:21	0:39	0:40	0:42	0:41	0:38	0:41	3:20	0:45
	99%	1:13	1:09	1:44	0:58	1:01	1:10	0:56	0:50	0:52	5:06	0:58
	100%	1:23	1:26	1:50	1:23	1:27	1:30	1:15	1:17	0:57	5:10	1:03
F4.0	1.5 kW/m ²	0:51	0:46	0:53	0:40	0:47	0:51	0:54	0:47	0:49	- ^a	0:57
	90%	2:50	1:49	1:20	1:15	1:24	1:33	1:40	1:33	2:20	- ^a	2:50
	99%	- ^a	- ^a	- ^a	2:26	- ^a	2:35	- ^a	2:43	- ^a	- ^a	- ^a
	100%	- ^a	- ^a	- ^a	2:47	- ^a	4:11	- ^a	- ^a	- ^a	- ^a	- ^a
F5.0	1.5 kW/m ²	0:46	0:41	0:54	0:45	0:36	0:42	0:37	0:33	0:37	- ^a	0:44
	90%	1:05	1:09	1:05	1:00	1:04	0:57	0:52	0:50	1:10	- ^a	1:05
	99%	6:35	2:58	4:30	2:52	3:16	2:35	3:24	2:42	3:13	- ^a	4:44
	100%	9:15	3:11	5:07	3:33	4:06	2:53	4:35	2:55	3:41	- ^a	5:10

^a intended degree of control of the fire was not reached

Table 5
Control Times (min:s) in Tests with CAF

Test ID	Control	A	B	C	D	E	F	H	K
F1.1	1.5 kW/m ²	1:28	- ^a	0:42	- ^a	0:41	- ^a	- ^a	0:38
	90%	1:55	- ^a	0:54	- ^a	0:52	- ^a	- ^a	0:41
	99%	2:45	- ^a	1:37	- ^a	1:33	- ^a	- ^a	1:04
	100%	3:01	- ^a	1:50	- ^a	1:36	- ^a	- ^a	1:18
F2.1	1.5 kW/m ²	0:56	- ^a	1:11	- ^a	0:33	- ^a	- ^a	0:36
	90%	1:10	- ^a	1:21	- ^a	0:42	- ^a	- ^a	0:51
	99%	2:14	- ^a	3:06	- ^a	1:10	- ^a	- ^a	2:15
	100%	2:32	- ^a	3:26	- ^a	1:21	- ^a	- ^a	2:47
F4.1	1.5 kW/m ²	- ^a	0:56	0:42	0:51	- ^b	0:50	1:19	- ^a
	90%	- ^a	1:20	1:02	1:10	- ^b	0:50	2:00	- ^a
	99%	- ^a	2:35	3:23	2:20	- ^b	2:56	3:17	- ^a
	100%	- ^a	2:52	4:43	2:41	- ^b	3:57	3:28	- ^a

^aNo test was performed

Table 6
Control Times (min:s) in Tests with 1.5 × Nominal Admixture

Test ID	Control	B	C	D	F	H
F1.2	1.5 kW/m ²	0:37	0:38	0:39	0:38	0:35
	90%	1:29	1:03	1:37	1:43	1:18
	99%	1:50	1:25	2:15	2:15	1:50
	100%	2:44	1:59	5:12	3:40	2:12
F2.2	1.5 kW/m ²	0:45	0:42	0:43	0:46	0:49
	90%	1:21	1:35	1:17	1:50	1:22
	99%	5:50	- ^a	2:41	3:01	2:06
	100%	- ^a	- ^a	2:56	4:01	2:16
F4.2	1.5 kW/m ²	0:48	0:53	0:47	0:52	0:49
	90%	2:08	1:23	1:12	1:55	1:23
	99%	- ^a	- ^a	- ^a	3:22	- ^a
	100%	- ^a	- ^a	- ^a	6:16	- ^a

^aIntended degree of control of the fire was not reached

Table 7
Times (min:s) to 25% Involvement of the Fuel Surface in Burn-back Tests

Test ID	A	B	C	D	E	F	G	H	I	J	K
B1.0	- ^a	> 34:57 ^b	- ^a	2:12	25:42	26:52	- ^a	6:58	- ^a	- ^a	- ^a
B2.0	0:13	3:20	0:40	5:30	6:10	6:25	1:40	2:28	0:14	0:02	0:19

^aThe fire was not extinguished – no burn-back test could be performed

^bThe fuel in the burn-back pot burned out

Table 8
Burn-back Times (min:s) in Tests with CAF

Test ID	A	C	E	K
B1.1	9:16	17:27	> 38:08 ^a	14:24
B2.1	13:55	19:15	28:30	17:15

^aThe fuel in the burn-back pot burned out

Table 9
Burn-back Times (min:s) in Tests with 1.5 × Nominal Admixture

Test ID	B	C	D	F	H
B1.2	- ^a	- ^a	7:24	> 38:26 ^b	19:11
B2.2	0:52	0:13	4:16	23:24	3:05

^aThe fire was not extinguished – no burn-back test could be performed

^bThe fuel in the burn-back pot burned out

Figure 2. Comparison of heat fluxes over time in test F1.0 (UNI 86) and F1.1 (CAF) using foam concentrate A.

4.2. Expansion Ratios and Drainage Times

The expansion ratio and time to 25% drainage for the firefighting foams are presented in Table 10. The expansion ratios with CAF are generally high and the firefighting foams should be classified as medium expansion firefighting foams (and not as low expansion firefighting foams).

5. Discussion

The present study investigated eleven firefighting foams. Nine of them were commercially available while the last two were in a late phase of product development. All the firefighting foams were claimed by the manufacturers to be free from intentionally added PFAS. As AFFFs may not be seen as a sustainable alternative for the future, this study has not included a comparison with any PFAS-based AFFF. Instead, the focus has been widened to include impact from different types of fuels and waters, usage concentrations, and firefighting foam generation techniques and application methods. When moving away from using PFAS-containing foams, a more holistic approach to firefighting of class B fires is recommended

Table 10
Expansion Ratios and 25% Drainage Times for Firefighting Foams

Foam ID	Admixture [%]	Water type	UNI 86/ CAF	Expansion ratio []	25% drainage time [min:s]
A	3	Fresh	UNI 86	7.8	4:25
	3	Sea	UNI 86	5.5	3:31
	3	Fresh	CAF	29.6	8:26
B	3	Fresh	UNI 86	7.9	96:00
	3	Sea	UNI 86	7.3	29:27
	3	Sea	CAF	21.7	31:40
	4.5	Fresh	UNI 86	8.7	213:30
	4.5	Sea	UNI 86	8.0	53:05
C	2	Fresh	UNI 86	8.4	18:05
	2	Sea	UNI 86	5.6	5:20
	2	Fresh	CAF	20.6	45:00
	2	Sea	CAF	14.0	13:18
	3	Fresh	UNI 86	8.9	36:07
	3	Sea	UNI 86	6.6	10:17
	6	Fresh	UNI 86	8.0	19:50
D	6	Sea	UNI 86	7.9	11:04
	6	Sea	CAF	15.3	16:17
	9	Fresh	UNI 86	9.2	37:36
	9	Sea	UNI 86	8.9	22:48
	3	Fresh	UNI 86	8.3	121:00
E	3	Sea	UNI 86	6.6	17:35
	3	Fresh	CAF	20.2	205:05
F	3	Fresh	UNI 86	7.1	122:32
	3	Sea	UNI 86	7.4	118:20
	3	Sea	CAF	14.0	90:00 (3.5%) ^a
	4.5	Fresh	UNI 86	8.7	273:20
	4.5	Sea	UNI 86	8.6	228:13
G	3	Fresh	UNI 86	7.4	48:23
	3	Sea	UNI 86	6.5	35:26
H	3	Fresh	UNI 86	7.5	45:55
	3	Sea	UNI 86	8.1	55:10
	3	Sea	CAF	16.6	91:46
	4.5	Fresh	UNI 86	8.2	107:45
	4.5	Sea	UNI 86	8.6	63:44
I	3	Fresh	UNI 86	8.9	4:53
	3	Sea	UNI 86	8.4	3:19
J	3	Fresh	UNI 86	9.9	6:32
	3	Sea	UNI 86	2.0	22:12 ^b
K	3	Fresh	UNI 86	9.4	5:25
	3	Sea	UNI 86	8.8	2:58

^a3.5% drainage in 90:00 min:s^bThe difficulty to distinguish between foam and drained liquid makes this result uncertain

e.g., by inclusion of firefighting techniques, response times and equipment. Since not all products were evaluated in all tests, the results from this study should not be seen as definitive but could constitute a basis for future research.

Table 11
Maximum Extinction Times in the Referenced Standards

Referenced test standard	Maximum extinction times [min:s]	Comment
EN 1568–3	3:00	Extinguishing performance class I in EN 1568–3 is used as reference
ICAO Doc. 9137 (level B)	2:00	At 1:00 min:s, only flickers not exceeding 25% of circumference of the inner edge of the tray are acceptable
IMO Circ. 1312	5:00	-

Figure 3. Times to 90%, 99% and 100% fire control in test F1.0.

The fire performance tests were based on existing standard test methods: ICAO Doc. 9137 (level B) (test F1.0), IMO Circ. 1312 (test F5.0) and EN 1568–3 (test F2.0 and F4.0). A few minor deviations from these standard test methods have been described, e.g. a different volume of water was used (100 L in F1.0–F.12 and 90 L in the other tests), which equals a 2 mm difference in water depth. The authors argue, however, that the results presented in this study are nonetheless comparable with results of a test performed without any deviations from the standard test methods and may be utilized as a baseline for comparison of different PFAS-free firefighting foams.

None of the products in the study met the fire test performance requirements in all the referenced standards (cf. Table 11). Instead, the products seem to have dif-

ferent niches where they perform best e.g., types of fuel or water. This highlights the importance of testing in an environment as close to reality as possible.

Fire control times are estimated values and should not be used to draw strong conclusions; however, in F1.0, a very large difference between 99% and 100% can be noted for three of the firefighting foams (G, I and J) (cf. Figure 3). The ratio between time to 99% fire control and the time to 100% fire control was found to be typically 0.8 ± 0.1 ; however, with these three foams the ratio was < 0.5 . During the approximately last minute of these (three) fire tests, very few and small flickers (< 20 cm) were observed at the side of the tray closest to the foam nozzle. It is anticipated that these flickers remained due to the foams' flowability properties or due to small differences in the positioning of the foam nozzle between fire tests. Based on this observation, we suggest using 99% fire control as a complementary indicator to 100% fire control, when reporting firefighting foam performance.

No correlation between fire control times and expansion ratio nor drainage time was found; interactions with warm fuel and hot surfaces are not captured in those measurements and further research is needed to establish reasons for this finding.

5.1. Burn-back Resistance

Burn-back resistance was evaluated in both hot (B1.0, B1.1, B1.2) and cold (B2.0, B2.1, B2.2) tests. The hot tests were carried out in connection to the fire suppression tests while the cold tests were made at ambient conditions. The resulting burn-back times are given in Table 7 to Table 9. The main reason to use the cold burn-back test was to get comparable burn-back results, which are independent of the extinguishing process and firefighting foam application time. Another reason was to address only burn-back resistance and not the two-dimensional parameter, including both fire extinction and burn-back resistance. In many situations firefighting foam is used as a preventive measure before a fire actually starts, something that further highlights the need of this type of test.

A flare-up occurred for some of the firefighting foams, which typically lasted for some seconds. In those cases, the time to the first occurrence of a flare-up covering more than 25% of the surface has been reported. This is in line with the definition by Schaefer et al. [11], who argued that the first failure of a foam blanket indicates a loss of adequate protection. Two factors indicating a low transport of fuel vapours through the blanket and the robustness of the firefighting foam when generated as CAF (B1.1, B2.1) can be pointed out: no flare-ups occurred and the burn-back times were significantly improved (longer).

The products designated A, I, J and K did not perform well in the cold burn-back test (B2.0), this correlates to their performance in fire test F2.0. None of these products managed to reach 99% control of the fire in F2.0. This is assumed to be due to interactions with the fuel causing rapid breakdown of the firefighting foam.

No correlation was observed for the times recorded in the hot (B1.0, B1.1, B1.2) and cold (B2.0, B2.1, B2.2) burn-back tests. This may be due to the low number of data points, the differences in application times or the higher fuel and

Table 12
Extinction Times in Different Comparable Tests (F1.0/F1.2; F2.0/F2.2; F4.0/F4.2), min:s

Test	B	C	D	F	H
F1.0	2:10	1:59	- ^a	3:10	- ^a
F1.2	2:44	1:59	5:12	3:40	2:12
F2.0	5:35	—	3:00	3:03	2:30
F2.2	- ^a	- ^a	2:56	4:01	2:16
F4.0	- ^a	- ^a	2:47	4:11	- ^a
F4.2	- ^a	- ^a	- ^a	6:16	- ^a

^a100% control was never achieved

fire tray temperatures caused by the preceding fire (which causes firefighting foam breakdown).

5.2. Admixture

The result (cf. Table 10) illustrate that the expansion ratio and 25% drainage time are parameters that can be affected by changing the admixture. An increase of the admixture by 50% resulted in 6% to 23% (average 13%) higher expansion ratios and 16% to 224% (average 96%) longer drainage times, with both fresh and sea water. According to Andersson [27] the observed increase in drainage times could be due to rheological effects, which tend to have a non-linear dependency on concentrations.

In a previous study [28], where ethanol was used as fuel, it was concluded that “higher foam expansion ratios and longer drainage times resulted in significantly improved fire performance”. In the present study, using the non-polar fuels Jet A1 and commercial heptane, this could, however, not be confirmed. As outlined by Persson et al. [1], several differences exist between cold and hot tests. To explain the total mass loss of the firefighting foam, this study mentions radiation induced drainage and evaporation as additional parameters to ordinary drainage. From other studies [7, 9] it is also known that the fuel impacts the foam degradation. All in all, this means that the expansion ratio and the drainage time measured at ambient conditions should not be used alone to predict the fire performance of a firefighting foam. These parameters can only be used to compare general properties of the firefighting foam and indicate differences between firefighting foam generation principles and equipment.

In Table 12, extinction times in tests with nominal and 1.5 times nominal admixture are compared. From this, no clear trend could be observed. It is instead suggested that the result may depend on the firefighting foam concentrate. It should be noted that in the cases when the product with a higher admixture performed better, the improvement was generally small (4–14 s). In the cases when the product with a higher admixture performed worse, the impairment was generally large (0:30–2:05 min:s). In the cases of impairment, a potential explanation is

that the foam produced with a higher admixture was stiffer and did not spread as well as the foam with lower admixture.

Comparing the results from the cold burn-back tests with nominal (B2.0) and $1.5 \times$ nominal (B2.2) admixture shows a reduced burn-back performance with the products B, C and D. A possible reason for this could be a more forceful application caused by the stiffer foam. The more forceful application, the greater the fuel pick-up. The results show a slightly improved performance with firefighting foam H. The improvement is rather small and could be explained by natural variations in the test procedure and changes in the properties of the firefighting foams as indicated by the changes in expansion ratios and drainage times. With product F, an improvement of 16:59 min:s (264%) in burn-back resistance was observed. When video recordings of the tests were studied, it was noted that a good share of this improvement may be an effect of the visual judgement (as has already been admitted as an inexact method). Many small flames (< 25 cm), scattered over the whole surface, were observed in test F2.0. It is very difficult to estimate the total area of these flames and this may have produced an error in the time to burn-back in test B2.0. If the small flames are ignored, the time to 25% burn-back was 14:00 min:s (instead of the reported 6:25 min:s). This means that the increase in admixture still would have had a positive impact on burn-back resistance, but at a smaller scale (67%). Based on the measured parameters (expansion ratio and drainage time), it is difficult to explain this improvement. One possible explanation is that the improvement is a result of reduced firefighting foam breakdown. Parameters affecting this breakdown are e.g., solubility of the fuel in the foam and the bubble size distribution [29]. It is important to note, however, that these parameters were not measured during the tests and additional tests are required in the future to validate this assumption.

5.3. Fuel and Water Types

The firefighting performance was evaluated using three different fuels (Jet A1, commercial heptane and diesel) and two types of water (freshwater and synthetic sea water). Referring to the data presented in Table 4, it can be concluded that the fires in test F3.0 (diesel) were extinguished in the shortest times, with all firefighting foams. Furthermore, a comparison between test F3.0 and test F4.0 shows that fires in diesel were easier to suppress and extinguish compared to fires in commercial heptane. This result was expected since diesel has the highest flash and boiling points of all the three fuels used in these tests. Using the aspirated UNI 86 nozzle, firefighting foam A was unable to extinguish Jet A1 (test F1.0) and two of the three commercial heptane fires (tests F2.0 and F4.0). However, when tested using diesel as fuel (test F3.0), foam A put out the fire in 1:23 min:s, which was a relatively good performance. In test F3.0, sea water was used instead of freshwater, it is admitted that this may have affected the result i.e., the effects may not be entirely fuel dependent. A rapid spread of the firefighting foam on the diesel fuel surface was observed in the tests. This, in combination with the relatively low vapour pressure of diesel and potentially also a low fuel pick-up, may explain the short extinction time. The importance of high flowability was discussed in a report

by Altmann et al. [4], the authors concluded a relation between (a low) viscosity of a firefighting foam and (a short) extinction time. This relationship was later elaborated by Persson to also take firefighting foam breakdown and drainage into account [2], i.e. if the firefighting foam drains too quickly, it will not be able to cover the entire surface and extinguish the fire. The authors would like to highlight that the expansion ratio and the drainage time measured at ambient conditions should not be used alone to predict the fire performance of a firefighting foam; parameters measured at ambient conditions may not be applicable at fire conditions.

Referring to the work by Altmann et al. [4], a relation between the fuel's boiling point and extinction time was expected to be observed. According to the data presented in Table 4, times to reach 1.5 kW/m^2 were shorter with all products and a greater number of fires were extinguished in test F1.0, compared to test F2.0. It should be noted that the initial boiling point of Jet A1 is higher than the initial boiling point of commercial heptane. The flashpoint of commercial heptane is, on the other hand, lower than the flashpoint of Jet A1. This indicates fuel flashpoint as a good indicative parameter of firefighting foam performance (also solubility of the fuel needs to be considered). In general terms the results support the conclusion of Altmann et al.; however, the firefighting foams designated D, F and H extinguished the fire in shorter times in F2.0 than in F1.0. In the case of foam F, the difference in time is small and could be due to variations in the test method. In the case of foam D and H, times to 99% control were shorter in F1.0 than in F2.0. An explanation to the fact that the fires were extinguished in F2.0, but not F1.0 could be a lower viscosity of the firefighting foam, which could have been caused by a higher degree of foam breakdown. A higher degree of foam breakdown should be expected due to the differences in the fuel properties. This conclusion is supported by the observations of different flow patterns of the foams in the different tests (similar to what is described in for products G, I and J in Sect. 5). In addition to the study by Altman et al., the impact of fuel on the time to extinction was recently investigated and discussed by Snow et al. [7]. The authors concluded that fluorine free foams display a significant divergence in extinction capability between gasoline and heptane of commercial grade. The current study seconds the conclusion that there is a relationship between fuel type and extinction times. In addition, this addresses the importance of evaluating firefighting foams using the fuel expected to be involved in a fire, especially when it comes to FFFs. An important conclusion from the comparison of different fuels would be that it is important to perform tests in an environment as close as possible to the real situation. For example, if it can be concluded that Jet A1 or diesel will be the only fuels used, there is no need to test the firefighting foam on heptane fires.

The impact of water type (i.e. freshwater or sea water) may be studied by comparing two of the tests where commercial heptane was used as fuel (tests F2.0 and F4.0). A general trend is that sea water, i.e. water containing a strong electrolyte (sodium chloride), negatively impacts fire test performance, which is a general expectation [11]. The impact of sodium chloride on foam drainage was investigated by Burcik [30] and later by Shah et al. [31]. Both studies concluded that the addition of a salt to an aqueous solution of an ionic surfactant decreases the sur-

face tension and enhances the rate of equilibrium surface tension attainment i.e., increases the rate of foam collapse. However, as reported in Table 4, with firefighting foam D the extinction time was shortened by 13 s (7%) when the foam solution was prepared from synthetic sea water compared to freshwater. That some products may perform better with sea water should be expected. It is detailed in reference [32] that there is a relationship between the critical packing parameter, the presence/concentration of an electrolyte and the critical micelle concentration. An addition of salt may therefore change the packing density of ionic surfactant(s), and hence, affect foamability (and change performance of a firefighting foam). This may indicate the existence of an optimum for the salt concentration(s), which is supported by the results from testing of product D. Product J showed in all tests a low compatibility with sea water, this is illustrated both by the expansion ratio (2.0) as well as the results in the fire tests. When the foam concentrate was mixed with sea water, precipitations were immediately formed. Potential reasons for this are discussed in other publications [17]; the current study has not been focused on this matter.

5.4. CAF vs. UNI 86

In this study, firefighting foam was generated using two different techniques, as aspirated foams using a UNI 86 nozzle or as CAF. The expansion ratios of CAF and firefighting foam generated by the UNI 86 nozzle were typically 15–30 and 6–9, respectively (cf. Table 10). With the flow rate of foam solution kept constant, the volume of generated firefighting foam differed between the (comparable) tests. This is of importance when evaluating the results, since both the distribution of bubble size [20, 29, 33] and the total volume of firefighting foam were varied simultaneously. However, the results from these tests are still considered to be of interest since the flow rate of foam solutions was kept constant. Due to the pattern of the CAF jet, it was difficult to direct the full jet of firefighting foam to the fire tray and approximately 5% to 10% of the firefighting foam came down outside of the fire tray. For this reason, the reported flow rate of 11.4 L/min should be seen as conservative.

No characterisation of bubble size distribution was made in the present study. This has been investigated in previous studies [20, 29, 33] with results indicating a lower mass median diameter and a narrower bubble size distribution for CAF compared to aspirated firefighting foam. Smaller bubbles and an a more even size distribution has in the previous studies been shown to contribute to improved drainage properties (i.e. increased drainage times) and to a more robust firefighting foam. A general difference in behaviour observed between firefighting foam generated by the UNI 86 nozzle and as CAF is demonstrated by measured heat flux (Fig. 2) and visualized in Fig. 4. The heat fluxes measured at 0:45 and 1:30 min:s were 2.8 and 1.4 kW/m² with CAF and 0.4 and 0.3 kW/m² with foam generated by the UNI 86 nozzle, respectively. The firefighting foam generated by the UNI 86 nozzle spreads more easily and suppressed the fire quicker than CAF. On the other hand, CAF is a more robust firefighting foam having superior drainage properties, resulting in shorter extinction times. The robustness of CAF is

Figure 4. Photo of the fire tray at two firefighting foam application times in test F1.0 (a, b) and test F1.1 (c, d) using firefighting foam A. The dashed line shows the spread of the CAF.

illustrated in Fig. 4. It is shown how the CAF spreads from one side of the tray to the other without any fuel vapour penetrating the foam layer.

The results (cf. Table 13) show that the extinction times were shortened in the tests with CAF (F1.1, F2.1 and F4.1). In some of the cases, the improvement is minor and is likely only an effect of the increased volume of firefighting foam. In the tests based on EN 1568–3 with commercial heptane and sea water (F2.0, F2.1) the improvement becomes more evident. With the four compared products (A, C, F, K), only one (F) extinguished the fire when the firefighting foam was generated by the UNI 86 nozzle. In the tests with CAF, all products extinguished the fire and the extinction time with product F was shortened by 1:42 min:s (44%). The authors believe that this improvement is heavily affected by the change in the firefighting foam properties caused by smaller bubbles and a narrower size distribution, as has been shown to be the case with CAF [20, 29, 33]. Based on the current investigation, the effect of the increased expansion ratio cannot be excluded and may therefore interfere with the result. On the other hand, the generation of CAF was not optimised, indicating an additional potential of this foam generation technique.

In previous work, a relationship between firefighting foam viscosity and extinction time has been established [4]. This relationship was also investigated in a publication by Laundess et al. [20] where the impact of expansion ratios was compared. A conclusion was that the less expanded foams with a broader distribution of bubble sizes (i.e. foams generated by e.g. an aspirated nozzle) perform better when tested according to test standards requiring short extinction times. The results of the study presented in this paper support these conclusions but adds

Table 13
**Extinction Times (min:s) in Different Comparable Tests (F1.0/F1.1;
F2.0/F2.1; F4.0/F4.1)**

Test	A	B	C	D	F	H	K
F1.0	^a	02:10	01:59	^b	^b	^b	01:40
F1.1	03:01	01:50	01:50	^b	^b	^b	01:18
F2.0	^a	^b	^a	^b	03:03	^b	^a
F2.1	02:32	^b	03:26	^b	01:21	^b	02:47
F4.0	^b	^a	^a	02:47	04:11	^a	^b
F4.1	^b	02:52	04:43	02:41	03:57	03:28	^b

^a100% control was never achieved

^bNo test with CAF was made

foam breakdown and fuel pick-up as important parameters to also take into consideration. If the foam breakdown or fuel pick-up is too large, extinction times may instead be longer. In addition to the study by Laundess et al., Persson et al. [1] concluded that the ability of a firefighting foam to spread on a burning fuel surface depends partly on the flowability of the foam and partly on how the foam is affected by the fire. In the cold burn-back tests with CAF (B1.1, B2.1, B4.1), it was clear that the foam had difficulties to cover the entire surface due to its stiffness (higher viscosity). In the corresponding test using the UNI 86 nozzle (B1.0, B2.0, B4.0), the foam covered the entire surface much faster. In the tests with fire, there was still a difference in spread on the fuel surface between firefighting foam generated as CAF and firefighting foam generated by the UNI 86 nozzle; however, the difference was not as significant as without a fire.

Taking the different expansion ratios into account, the results indicate decreasing foam viscosity leads to shorter fire knockdown times, but longer extinction times. Further research is needed to investigate the impact from a controlled, dynamically changed foam expansion ratio e.g., by generating firefighting foam as CAF, starting with a rather wet foam (low expansion ratio) and ending with a dryer firefighting foam with a higher expansion ratio.

In all the burn-back tests, the performance of CAF was superior to the performance of firefighting foam generated by the UNI 86 nozzle. An improved burn-back performance could to some extent be explained by the higher expansion ratio (which gives a greater volume of firefighting foam), especially in the cold burn-back tests which were not impacted by heat or fire; however, the observed improvement in some cases is great (up to 64 times longer burn-back time) and cannot only be explained by the change in expansion ratio.

5.5. Fire Tray and Application Type

Since both the shape of fire tray and the application type were changed simultaneously, the two parameters cannot be evaluated separately. When control and extinction times in test F4.0 were compared with the times in test F5.0, it was

concluded that the foam performance in general is more successful in test F5.0 (except for foam D). This may be explained by the gentle application [34] which led to less fuel pick-up and firefighting foam degradation; but it may also be a result of the shape of the fire tray, or a combination of both. It was observed that all foams in test F5.0, except for foam D, poured along the backboard and smoothly hit the fuel surface i.e., gentle application. In the case of foam D, the jet was closer than with the rest of the foams and once the jet hit the backboard it scattered and bounced off. This resulted in a more forceful application than expected and a sustained fire at the spot where the firefighting foam hit the fuel surface. The observed drainage time of foam D was very long, potentially indicating a foam with higher viscosity [27]. Rheological properties may have an impact both on the foam jet and the firefighting foam's ability to stick to, and pour along, the backboard.

5.6. Heat Flux

When the heat fluxes are compared, all the firefighting foams clearly had a suppressive effect on the fire; this conclusion applies also to the firefighting foams that did not extinguish the fire. Times to reach a heat flux of 1.5 kW/m^2 (considered to be safe for stationary personnel and observers) for the firefighting foams are given in Tables 4, 5, and 6. In most of the tests, when the firefighting foam was generated using the UNI 86 nozzle, the variations were relatively small, often less than 10–15 s. When including detection and response times (which are on the minute scale), a difference of less than 15 s to control of the fire is minor and may not be significant. On the other hand, due to the drainage of firefighting foam, this time may be the difference between success and failure i.e., an uncontrolled fire will eventually break down the firefighting foam and again involve the entire fuel surface.

In the case with product A, 90% control (cf. Table 4) was never achieved in two of the tests (F1.0, F2.0). However, the heat flux was significantly reduced, which indicates a suppressive impact of the firefighting foam on the fire. In test F1.0, the heat flux was reduced to approximately 0.2 kW/m^2 (as shown in Fig. 2); however, almost the entire fuel surface was still involved in the fire, cf. Figure 4. This may be due to fuel pick-up and poor foam stability. During test F1.0, a steady state was achieved; foam was applied at the same rate as it was consumed (as indicated by the constant heat flux after 50 s, cf. Figure 2). With the current set up and application rate it would therefore be possible to control the fire, but not extinguish it.

A suggestion is to replace the rather uncertain visually judged performance requirement of “time to 90% control”, with heat flux measurements and record the time to a heat flux smaller than 1.5 kW/m^2 . As can be concluded when comparing Fig. 2 with Fig. 4b, the heat flux can be small even though the entire fuel surface is involved in the fire.

It was found that the maximum heat fluxes were on average 7.6, 7.9 and 10.6 kW/m^2 with diesel, Jet A1 and commercial heptane, respectively. This could, in addition to such parameters as the fuel's vapour pressure and viscosity, explain

why the most difficult fuel to extinguish was commercial heptane, as a higher heat flux increases the firefighting foam breakdown.

5.7. Summary of Different Properties Potential Impact on the Fire Test Performance

This section is intended to summarize some of the previously discussed properties and their potential impact on the fire test performance. Bubble size and bubble size distribution has been discussed. Based on result shown in previous studies [20, 29, 33], CAF tend to have a narrower bubble size distribution and a smaller average size of the bubbles. These properties have been said to improve firefighting properties [20], which is supported by the current study. The observations in the current study indicate the need for a foam to be viscous enough to quickly spread over the fuel surface and control the fire, but also rigid enough not to drain and break down. If the foam is too viscous, a situation where flickers remain for up to circa one minute at the side of the tray closest to the foam nozzle may occur. This was observed with products G, I and J in test F1.0 and products D and H in test F2.0. Expansion ratio and drainage times have been discussed, the authors suggest that these parameters are too dependent on temperature and surrounding environment to be used to predict firefighting performance and should only be used to compare firefighting foams and foam generation equipment at ambient conditions. Impact of salts in the water used for the admixture was investigated, in general terms sea water reduces firefighting performance. However, this was not valid with all foam concentrates and highlights the need to evaluate the foam at as realistic conditions as possible. Finally, the impact of different fuels was addressed. It is proposed that the fuel flashpoint could be an indicator of the complexity of firefighting.

5.8. Ranking of the Firefighting Foams

Based on the results presented in Table 4 there is no single product that outperforms the rest. Products D and F perform well in all tests with commercial heptane, but show rather low performance when tested with Jet A1. Products C, E and K perform well with Jet A1 but not as well with commercial heptane. Except for product J (which did not perform well in any of the tests), all products showed an acceptable performance when tested with diesel. Therefore, it could be anticipated that fires in diesel are easily controlled and extinguished with most foam concentrates showing a medium-good performance when evaluated with commercial heptane as the fuel. When the admixture was increased by 50% (F1.2, F2.2, F4.2), the ranking of the products (cf. Table 14) changed. This indicates that different products show different dependency on the admixture concentration, something that should be expected (this should also be applicable to change in water type, even though it is not shown in the ranking) because the products are made of different constituents. When the firefighting foam generation principle was changed (F1.1, F2.1, F4.1), the ranking of the tested products remained almost unchanged. A potential explanation for this is that a change in the foam

Table 14
Ranking of Times to Extinction with the Different Firefighting Foam Concentrates

Test	Ranking of time to extinction	Fire was not extinguished	Not tested
F1.0	K < E < C < I < B < J < F < G	A / D / H	–
F1.1	K < E < C < A	–	B / D / F / G / H / I / J
F1.2	C < H < B < F < D	–	A / E / G / I / J / K
F2.0	H < D < F < E < B	A / C / G / I / J / K	–
F2.1	E < A < K < C	–	B / D / F / G / H / I / J
F2.2	H < D < F	B / C	A / E / G / I / J / K
F3.0	I < K < G < H < D / A < B < E < F < C	J	–
F4.0	D < F	A / B / C / E / G / H / I / J / K	–
F4.1	D < B < H < C	–	A / E / F / G / I / J / K
F4.2	F	B / C / D / H	A / E / G / I / J / K
F5.0	F < H < B < D < I < E < G < C < K < A	J	–

structure affects all foams similarly and thus does not necessarily change the ranking of the foams.

6. Conclusions

The aim of this investigation was to evaluate PFAS-free firefighting foams by varying fuels, admixture, water types and foam generation techniques in 4.5 m² scale. It may be concluded that the properties of the firefighting foam must be such that the firefighting foam can rapidly spread over the surface and thereby suppress the fire but retain enough stability to prevent foam degradation caused by the fuel's vapour and radiation from the fire. As demonstrated, CAF shortens the extinction times, but does not reduce the heat flux as quickly as the foam generated using the UNI 86 nozzle. The investigation has also shown a significant dependence on fuel type; different products perform differently depending on the fuel. Also, a foam solution prepared from sea water most often showed longer extinction times.¹

A method for conducting cold burn-back tests was successfully developed and applied in this study. This method is especially suitable when the focus is on evaluation of fire prevention i.e., in the case of a fuel leakage which has not yet ignited; however, no correlation between hot and cold burn-back tests was found.

Out of the eleven tested products there was no product that outperformed the rest. None of the products in the study met the fire test performance requirements

¹ <https://www.ri.se/en/what-we-do/projects/testbed-pfas>

in all the referenced standards. Instead, the products seem to have different niches where they perform best e.g., with different types of fuel or water.

All the findings and conclusions point out the importance to perform tests as close to the real fire hazard situation as possible.

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Authors' contribution

All authors contributed to the study conception and design. Material preparation and data collection were performed by Magnus Bobert who also coordinated the tests. Data analysis was performed by Sixten Dahlbom and Magnus Bobert. All authors contributed to the article draft, performed critical reviews and approved the final manuscript.

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Availability of data and material

All data that will not reveal the identity of the firefighting foam concentrate manufacturers identities are available on request.

Code availability

Not applicable.

Declarations

Conflict of interest Firefighting foam concentrate manufacturers are supposed to be anonymous and are therefore not mentioned in the manuscript.

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