LASTFIRE Research 2021

Large Scale Testing

June/July & November 2021

March 2022

In association with GESIP

REVISION RECORD				
ISSUE	**DATE**	**ORIGINATOR**	**REVIEWED**	**DESCRIPTION**
DRAFT	February 2022	Dr E Lister	Dr N Ramsden	Issued for Comment
ISSUE 1	June 2022	Dr E Lister	Dr N Ramsden	Issued including additional tests carried out in March 2022

Contents

Executive Summary

The LASTFIRE Project, a group of international storage tank operators working together to develop best practice guidance in storage tank Fire Hazard Management, is committed to minimising environmental consequences of their activities.

As with previous recent LASTFIRE research campaigns since 2016 [1,2], this series of tests has focused on the evaluation of the effectiveness of "new generation" firefighting foams, with a focus on those that are Fluorine Free. Although LASTFIRE developed and managed the test protocols at all times, these tests were carried out in association with GESIP as part of their ongoing mutual agreement. in three separate test periods in June/July 2021, November 2021 and March/April 2022 at the GESIP facility in Vernon, France.

Overall Objectives

The objective of this research phase was to provide data demonstrating the performance of typical application techniques including forceful application of fluorine free foams (FFF) to hydrocarbon storage tank fires or other deep fuel events (50+ m diameter tank fires, full surface bund fires, etc.), or foam pourer application (for 100+ m diameter tank fires, full surface bund fires, etc.).

Funding and Supplier Involvement

LASTFIRE research is funded from the annual subscriptions of members. Suppliers were requested to take part in the test series and make a contribution to the fuel costs. Many suppliers, worldwide, were approached and asked if they wished to take part in these end-user managed test. The following suppliers joined the programme, and LASTFIRE thanks them for their assistance and participation in these tests:

- Angus International
- Bio-Ex
- Dr. Sthamer
- Perimeter Solutions

It should be noted that some of these companies made it clear that the products being submitted were development products and not necessarily currently available commercially. Some LASTFIRE member organisations kindly contributed extra funding for the construction of the test pit, which was constructed in association with GESIP, a France based consortium of fuel storage and processing companies developing best practice standards in facility safety.

ACAF provided the CAF (compressed air foam) application equipment and FireDos the proportioning unit.

Test Protocols and Locations

The test series was carried out on an anonymous basis with each foam manufacturer providing 4 m^3 of their foam concentrate. The samples had all identification markings removed and replaced with a simple reference label. Samples included Fluorine Free and C6 fluorosurfactant based concentrates, noting that the C6 fluorosurfactant sample was only used for initial commissioning of the test pit and thus acted as a reference point. It is noted that no PFAS based foams are allowed to be used anymore on the site.

LASTFIRE recognised that some of the manufacturers saw this as a unique opportunity to test their formulations at a larger scale and as such it has assisted their product development programme.

Test Results and Overall Conclusions

The following are the main conclusions drawn from this testing. Recommendations are also provided for future testing.

- This research has further identified that the combination of foam and application technique is of key importance.
- Compatibility with existing equipment, particularly proportioning equipment is important.
- All the FFF/application technique combinations tested during this phase of tests were able to travel the 50 m length of the test pit and were able to either reach total extinguishment or were very close to extinguishing the fire at the end of the test with only minor flickers remaining at the edge of the pit (classed as "virtual extinguishment" in this research).
- The application of CAF is very "forgiving" of different foam performance capabilities in the sense that it results in a levelled set of results across all the foams tested (as previously observed in smaller scale testing). This further demonstrates that application technique and foam properties are very important and need to be considered alongside application rates.
- "Virtual Extinguishment" has been used in this phase of research as well as previous studies and it is found to be a good measure of the capability of a foam as it is considered that in most real situations, virtual extinguishment would be extended to full extinguishment by the further application of foam in a specific area which is still ignited, as is often done in practice,
- There is evidence from these tests that foam properties other than only expansion and drainage time are critical for different aspects of fighting a fire. For example, flowability over the surface and sealing against an edge, where it has been observed that different foam/application type combinations perform differently.
- The opportunity was taken during these tests to take radiant heat measurements to compare with modelled values and these are discussed in a separate report. Vapour dispersion measurements were also taken during pit refuelling in the November test period.

Abbreviations

AFFF	Aqueous Film Forming Foam
CAF	Compressed Air Foam
FFF	Fluorine Free Foam
PFAS	Per- and polyfluoroalkyl substances

1 Introduction and Scope of Work

Per- and polyfluoroalkyl substances (PFAS) have been used in firefighting foam at facilities handling flammable liquids for more than 50 years. There have been increasing concerns regarding their environmental and occupational health effects. They exhibit persistence, mobility, potential for long range transport, observed adverse effects, and bioavailability for uptake via drinking water. They have very high potential for irreversible effects. Therefore, these chemicals are facing increasing controls and restrictions internationally.

The LASTFIRE Group carried out, as part of their ongoing efforts to evaluate the effectiveness of "new generation" fire fighting foams, especially those that are fluorine free, a series of large scale tests.

From previous research [1,2] it has been identified that it is not possible to have a straightforward "drop in" replacement foam and that although the quality of the foam is important, it is also the combination of the application method and foam together that have to be considered. Thus it is always necessary to review issues such physical properties and flow characteristics before any change in foam type or brand. Previous research work has included various phases including testing with different foams; application methods; application rates; fuels and preburn times. Work has also investigated the effect of fresh and salt water. Figure 1.1 provides an overview of the previous test work that has been carried out prior to this current work. As such, following on from previous research, this test programme aims to investigate effectiveness of a number of different fluorine free foams (FFF) on a larger scale with a number of different application techniques

Figure 1.1 Summary of LASTFIRE Research conducted prior to this test period

Although LASTFIRE developed and managed the test protocols at all times, these tests were carried out in association with GESIP as part of their ongoing mutual agreement.

This document describes the tests which were carried out to a protocol developed with a working group involving LASTFIRE and GESIP representatives and foam suppliers who had agreed to participate in this research programme.

The tests outlined in this report should be considered as one part of the overall LASTFIRE research programme, not as "stand alone". It should also be recognised that the procedures outlined here may need to be revised, or additional work may be needed when carrying out further tests depending on the conditions at the time. It is not the intention that the results of these tests should give any one product or system any commercial advantage by testing and publishing results. The primary aim is to furnish potential end users, and the industry as a whole, with independently assessed information relating to fire fighting strategies using FFF.

LASTFIRE is taking the pragmatic approach that all PFAS compounds in firefighting foams will be banned at some time. Thus, the overall objective of the research programme is not to compare new generation foams with PFAS based foams, but to determine whether or not they can be effective and if so, to optimise their application through the combination of foam concentrate, equipment and tactics to provide end users with sufficient data to minimise transition costs and to prevent "regret spend".

2 Test Programme Aims and Objectives

The main aim of this research was to carry out a series of large scale tests with a number of FFF to provide data for assessing different application types for hydrocarbon storage tank fires or other deep fuel events (50+ m diameter tank fires, full surface bund fires, etc.), or foam pourer application (for 100+ m diameter tank fires, full surface bund fires, etc.).

Further sub-objectives of the test series were identified as:

- Effect of alternative application methods
- Assessment and determination of safety factors in application rates
- Large scale validation of previous small scale work
- Validation of radiant heat flux modelling*
- Vapour dispersion monitoring**

* This work was carried out in order to gain the most benefit from the test series. Consequence modelling programs are used extensively in the industry during Quantitative Risk Assessments and preplanning exercises, yet there is very limited validation of the results from large scale testing. This work is the subject of a separate report *Radiant Heat Measurement vs Model Predictions* being developed by LASTFIRE in association with academic institutions and software suppliers.

** This work was carried out during the November test period. Vapour detectors were used to monitor changes in vapour levels around the test pit during refuelling. This work will be reviewed and described on in a separate report.

3 Test Programme

The test work was planned, as far as is practicable, to address the objectives stated above in Section 2. A number of large scale tests were carried out to gather sufficient data to enable comparisons to be made and also validate findings from previous smaller scale testing.

The test pit was constructed under a joint venture agreement with GESIP during 2019 and an initial fire test was conducted, within an end 10 m section, that confirmed ignition method and principles of containing fuel within one section of the pit.

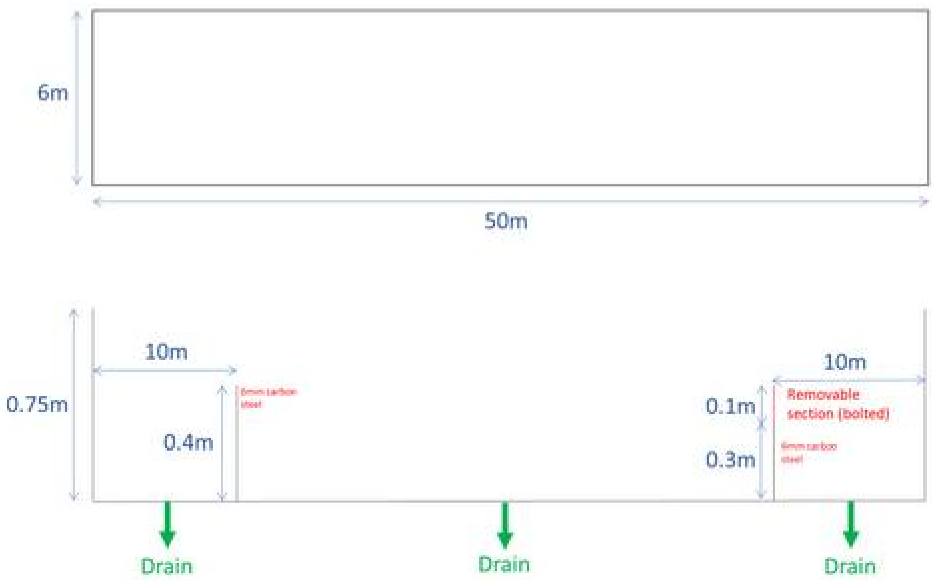
During April 2021 full surface commissioning tests were undertaken using a C6 based AFFF-AR (alcohol resistant aqueous film-forming foam) and proved that the pit could survive a full surface fire and that equipment could extinguish such a fire within an acceptable time (less than 10 minutes). This test also served as a reference point for the current work with FFF.

3.1 Location & Test Pit

The tests were carried out at the GESIP facility in Vernon, France. The test pit is a newly constructed concrete pit, 50 m x 6 m (300 m^2) see Figure 1. The test pit is sectioned off using carbon steel plate to create three sections of lengths, 10 m, 30 m and 10 m. This allows for different lengths to be used and also allows for a lower fuel requirement as the 10 m areas at the ends of the pit where the foam will hit the fuel can have a greater fuel depth than the middle section.

Metal plates are installed at each end of the pit to allow build up of high temperature spots. Markers at 5 m intervals along the length of the test pit were also installed to assist with the analysis of foam progression during the tests.

The test pit has been sectioned at each end so that foam can be applied to either end depending on wind direction.



3.2 Instrumentation and Equipment Required

During these tests, the complete pit was used, so the fire size was 50m x 6m. The analysis of each test included:

- time to 45 m of the pit being extinguished
- time to "virtual extinguishment" where all but minor flickers of the fire were extinguished
- Time to full extinguishment for different foam and application rate and application method combinations.

Expansion and drainage times of the finished foam using different application methods were also measured where possible. It should be noted that expansion and drainage time values are not particularly accurate due to sampling methods, but this will be improved on for future tests following further investigation. It should be noted that during the second test period in November, two methods were used to collect the foam sample for expansion measurements. The normal foam collection pot was used as well as a larger box that was calibrated prior to the tests (weight and volume). In general there was reasonable consistency between the two collection methods, but the larger collection box made the logistics of collecting foam from large application equipment easier.

Below is a list of the equipment (not including the foam application equipment as this is described elsewhere in this report) that was required for the testing:

- Foam Test Kit – pot and stand, measuring cylinder, scales, collection board, collection box (November tests only)
- Pit markings at 5 metre intervals along the pit
- Stop watches
- Vapour monitors (for safety reasons)
- Thermocouple devices for temperature measurements
- Video cameras
- Drones
- Weather station

- Backup fire extinguishing equipment (including foam stock (FFF), standby diesel pump and separate firewater ring main)
- Gas detectors for safety purposes
- Data logging gas detectors for vapour measurements (November tests only)

4 Test Protocol

4.1 Main Tests Protocol

The full test pit length was used for all tests. The fuel used for all tests was a gasoline which was a relatively “clean” C7 based fuel (and contained no ethanol). The fuel was pumped into the test pit using onsite equipment such that there was approximately 150 mm of fuel in the end of the test pit for foam application and 50 -80 mm fuel in the middle section and far end. Between each test the fuel level was topped up as required. It should be noted that although the aim was to have this 150 mm depth of fuel for each test, it was, in some cases, reduced to approximately 100 mm, which was, however, considered sufficient for the foam pourer tests. It would be useful in future tests to gain more knowledge and understanding of the impact of the fuel depth on foam effectiveness. This has now been examined further, based on sponsorship by LASTFIRE member, TotalEnergies (see published article attached as Appendix A) with results to date suggesting that if foam penetrates through a fuel layer to a lower water layer then the extinguishing time is increased as some foam is destroyed.

Figure 4.1 Test pit on completion of construction

A water layer was used in the bottom of the test pit to provide a freeboard of approximately 300 mm.

Eight foams were submitted for these tests. During the first testing period in June/July, five foams were tested. Six foams were tested in November 2021, which included some new samples and also some outstanding foam/application device combinations from the first test period. Different foam/equipment combinations were tested. At the end of each day and between the use of each foam product all equipment was flushed thoroughly with water.

Three monitor application methods were tested – conventional (aspirated), Compressed Air Foam (CAF) and "hybrid" (a combination of low and medium expansion foam). Additionally, for one test, a "non-aspirating" monitor was also used for comparison purposes. Two pourer application methods were tested – conventional and CAF.

4.1.1 Application Rates

The principle for the monitor tests was that the net application rate used was approximately 20% below the official NFPA application rates.

For the pourer tests the standard nominal NFPA rate was used as it was felt that the 50 m flow length compared to the accepted maximum length of 30 m already could be a challenge for the foam.

The CAF application rates were set based on the recommendations of the provider of the equipment and were consistently lower than the test rates for the conventional application techniques.

The NFPA application rate for conventional monitor application is 6.5 lpm/m^2 on to the fuel surface with an allowance to be made for losses from wind (typically using a factor of 1.5-1.6).

Thus, based on a fire area of 300m^2 the design application rate for monitor application would be:

300 x 6.5 = 1950 lpm without allowance for any losses

300 x 6.5 x 1.5 = 2925 lpm with NFPA minimum allowance for losses

In these tests the monitor was located at approximately the same level as the fuel surface so a lower rate of losses would be expected. It was decided to use a nominal flow rate of 2000 lpm representing, effectively zero allowance for losses. From visual observation it was considered that in practice the loss was at least 15% resulting in a nett flow rate of ~1700 lpm representing ~60% of the rate that would be applied to a tank when using NFPA 11 for specifying application rate.

Flow rates were measured during each test using the instrumentation provided for these tests at the FireDos proportioner and are given in the results section below.

During the November test period, two tests were carried out with the CAF pourer at a higher application rate of 1200 lpm for comparison purposes with the previously used rate of approximately 750 lpm. Details of these tests are discussed in the results section of this report.

4.1.2 Foam

The foam manufacturers providing the foam concentrates were:

- Angus
- Bio-Ex
- Dr Sthamer
- Perimeter Solutions (Auxquimia)

A C6 AFFF-AR foam, sourced by LASTFIRE, was used to provide a benchmark of a typical AR foam currently in use. This product was used for the commissioning tests undertaken in April 2021. See Section 5 for further details of the AFFF commissioning tests.

Foam products were delivered to site in large outlet IBCs intended specifically for high viscosity products. At site, prior to the test period, all labels were removed from the IBCs and replaced with anonymous designations A, B, C, D, etc.

For emergency use, a copy of the relevant MSDS information was held by LASTFIRE at the test pit (maintaining the A, B … designations).

4.1.3 Proportioning Equipment

The proportioning equipment used for all tests was a water driven turbine type unit provided by LASTFIRE Associate FireDos. The equipment was specifically set up for the foams to be used that have a higher viscosity than some AFFF products. Flow meters to check foam concentrate and foam solution rates were included on the proportioning skid.

In addition, the use of specific IBCs with a larger outlet ensured that the foam proportioning was as accurate as possible.

Figure 4.2 FireDos Proportioner

4.1.4 Radiant Heat Measurements

Temperature measurements were taken at various locations around the test pit alongside the foam tests. These temperature measurements were taken using specially supplied metal plates that could be converted to radiant heat and could be used to validate existing consequence modelling software. The details of this research can be found in a separate report – *Radiant Heat Measurement vs Model Predictions*.

4.1.5 Vapour Dispersion Measurements

As part of the November test period, the opportunity was taken to record hydrocarbon vapour measurements for the period before, during and after gasoline loading into the test pit prior to igniting the fire. These results are detailed in a separate report – *LASTFIRE Research 2021; Large Scale Testing, Vapour Detection Measurement.*

4.1.6 Test Sequence

Below is the test procedure that was followed for each test:

1. Set up and test proportioning system (FireDos) and confirm correct flow rate and proportioning rate for the test.

2. Set up and position relevant application device to be used for the test. For monitor application this required a range test to ensure that the foam was, as far as was practicable, applied within the 10 m end section.
3. Set up thermocouples for measuring temperature that would later be converted to radiant heat as required for each test.
4. Ensure all designated safety measures in place prior to fuel discharge.
5. Pump in sufficient fuel to ensure fuel level is correct in test pit. Note the freeboard was approximately 300 mm for the tests.
6. Record fuel temperature
7. Record ambient conditions (temperature, wind speed & direction) Wind conditions to be <3 m/s using Davis Vantage Vue weather station (see Figures 4.3 and 4.4)
8. Set radiant heat monitors and thermocouples to record data
9. Ignite fuel and allow agreed preburn to full surface fire
10. Apply foam to test pit with one nozzle/foam combination at a continuous application rate appropriate to the application device being used
11. Record times of foam reaching the markers along test pit, use drone footage where necessary
12. Record time to full extinguishment
13. Take sample of foam to measure and record expansion and drainage time
14. Stop foam application once it is confirmed by GESIP and LASTFIRE personnel that it is appropriate to do so. If foam had not extinguished fire within a reasonable time period, the test was aborted, and back-up systems used to extinguish fire.
15. When safe to do so, clear foam and add appropriate amount of fuel and repeat above sequence for next test.

Figure 4.3 Davis Vantage Vue weather station Weather Station

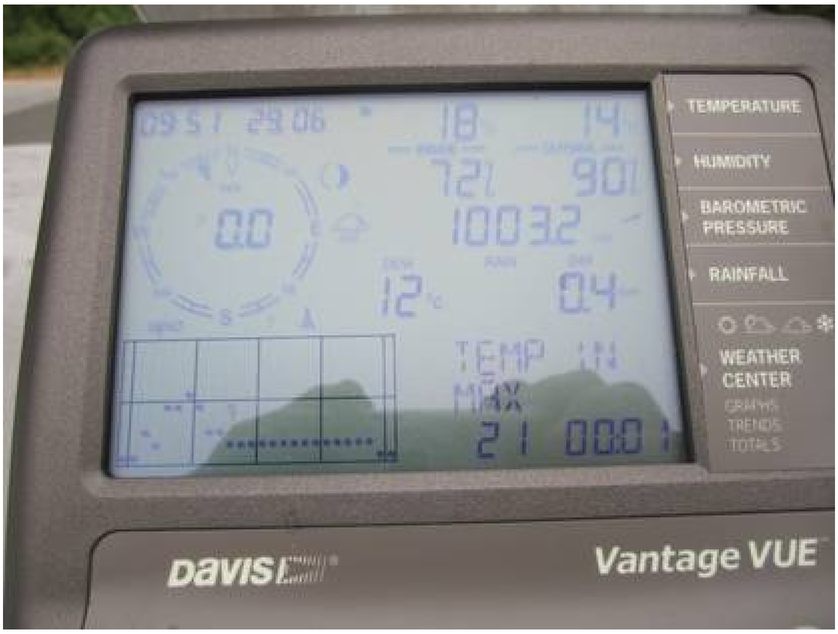


Figure 4.4 weather recoding instrumentation

4.1.7 Summary Tables:

Equipment:

<table>
<tr><td>Test Area</td><td colspan="6">300 m²</td></tr>
<tr><td>Fuel</td><td colspan="6">Gasoline</td></tr>
<tr><td>Freeboard</td><td colspan="6">Approximately 0.3 m</td></tr>
<tr><td>Foams</td><td colspan="6">A - 3% FFF
B - 3% FFF
C - 1% FFF
D - 3% FFF
E - 3% FFF
F - 3% AFFF C6
G - 3% FFF
H – 0.5% FFF
J – 3% FFF
L – 3% FFF</td></tr>
<tr><td>Monitors</td><td colspan="2">Conventional (aspirated)</td><td colspan="2">CAF</td><td colspan="2">Hybrid</td></tr>
<tr><td>Pourers</td><td colspan="3">Conventional</td><td colspan="3">CAF</td></tr>
</table>

Note that the hybrid monitor is a monitor designed to have low expansion foam carry medium expansion foam further. The same application rate as the low expansion monitor was used for this device.

Approximate Fuel Depth for each application type (mm):

Application Method	Area 1	Area 2	Area 3
Conventional Monitor	150	50	50
CAF Monitor	150	50	50
Hybrid Monitor	150	50	50
Conventional Pourer	100	50	50
CAF Pourer	85	35	35
Conventional Non-Aspirated Monitor	150	50	50

Target Approximate Foam Application Rates:

Application Method	Application Rate (lpm/m^2)	Foam Solution Flowrate (lpm)
Conventional Monitor	6.7	2,000
CAF Monitor	4.4	1,325
Hybrid Monitor	6.7	2,000
Conventional Pourer	4.0	1,200
CAF Pourer	2.5	760
Conventional Non-Aspirated Monitor	6.7	2,000

5 AFFF Commissioning Tests

Some initial tests were carried out to test the integrity of the pit and the logistics of application using a C6 foam concentrate. They should not be considered as being carried out in such a rigorous way as the main tests, but still provide a useful comparison of some aspects of the relative effectiveness against the Fluorine Free Foams tested.

5.1 Monitor Application

With the monitor application, using a 2000 lpm application rate, due to a misunderstanding on site the foam was applied gently at the side of the pit and allowed to flow into the tank. The volume was so great that the drainage around the pit overflowed allowing this technique to be used, although towards the end of the fire, foam was applied directly into the fuel, thus it is more difficult to make a direct comparison with the main tests. However, the following points can be noted:

- The foam flow was noticeably quicker but had the same problems with sealing the far edge.
- In some instances, the foam broke up more quickly in some places and the fire flashed back to ignite the exposed surface.
- It was noted that the foam swirled at approximately the 35 m mark and was not able to readily push the foam in front of it.

See images below from the test that highlight the sequence and also show in particular one area of foam break-up.

5.2 Pourer Application

This test with the pourer application at a rate of approximately 1,200 lpm was more readily comparable with the results of the Fluorine Free Foam. The following points were noted:

- Initial foam spread was more rapid than with the Fluorine Free Foam
- Similar problems were experienced with extended times required between virtual extinguishment and full extinguishment (sealing against far edge)
- As with the monitor application, the foam blanket was observed to break up in some places.

See below for images of the pourer application sequence with the C6 foam concentrate:

6 Example Test Sequences

Some examples are provided of the test sequence from the test series.

6.1 Conventional Pourer Application (Test 10)

6.2 Conventional Monitor Application (Test N1)

6.3 CAF Pourer (Test N12)

6.4 CAF Monitor (Test N2)

7 Analysis of Results

The following are key points to note for the analysis of the results obtained in all tests:

- Ten foams were tested during these test periods.
- Tests were observed by experienced professional hydrocarbon industry firefighters and their views taken into account in this report.
- A proportioning system (as opposed to premix) was used for these tests due to the application rates and the amount of foam required for these tests. This was provided by FireDos, a LASTFIRE Associate member company.
- The test pit was constructed such that either end could be used for both monitor and pourer application depending on wind direction. Ambient conditions throughout the tests were recorded and remained relatively steady. It was noted that although wind speed remained relatively constant during the tests, wind direction did change which meant that the end used for foam application changed for some tests so that application was from upwind.
- It was found, as with previous LASTFIRE research studies, that a steady wind could be accommodated easily by monitor placement, but difficulties with ensuring that all foam landed in the test pit would arise if the wind direction was variable during application.
- The "performance" has been assessed by reviewing the time to 45 m extinguishment, virtual extinguishment and full extinguishment.
- Some results show a "DNE" (did not extinguish). However, it should be noted that this effectively meant that the foam was not able to put out the very minor flickers that remained at the end of the test. It should be noted that to conserve fuel, the tests in the second phase (November 2021) were terminated after virtual extinguishment if it was observed that it was taking a significant time while to reach full extinguishment. This decision was taken following the analysis of the results from the first test period where it was agreed that in practice the fire would be easily extinguished through appropriate tactics if it had reached virtual extinguishment.
- On observation of the tests and on review of test footage, it is thought that the far end flickers that remained at the end of most tests were not dependent on the length of the test pit, and would have remained at the end of a smaller length test (e.g. 40 m) or larger as this was found to be due to the fuel pick up in the oldest foam and some edge sealing issues in some cases.
- Every foam/application method combination was able to control the fire at the application rates used.
- Although in footage from some of the monitor tests it appears that foam was "rolling" down the concrete surrounding the test pit into the pit, this did not actually affect the test or make the result invalid as there was a drain all around the pit to stop this. Any foam that did flow over the drain was deemed minimal.
- Outlet size affects the velocity of the foam out of a pourer, noting that the CAF higher flow test exhibited more eddying in its motion due to the velocity at which it was travelling.
- It was noted from visual observation that all the foams tested showed good stability after application. Some tests were carried out measuring drainage time and these confirm the visual observations.
- The ambient conditions were notably different between the two test periods, with an average air temperature of 17.5 °C in June/July and an average of 5 °C in November.

- In Test N7, two foams were inadvertently used at the same time. Foam A was initially put on to the fire from the backup monitor and handline as there was a minor delay with the start of foam C from the CAF pourer. However, using two different foams, and different application techniques together did not appear to impede the performance with foam controlling the fire and virtual extinguishment was reached within 2 minutes 30 seconds.
- Foams D and E were tested with the CAF pourer at two different application rates (approximately 2.6 lpm/m^2 and 4.0 lpm/m^2). It was observed that the higher application rate actually caused greater disturbance in the foam blanket and there was greater eddying motion on the surface, especially close to the pourer, but also extending down the test pit. The higher application rate did not have a major effect on the performance of the foam.
- For Tests N11 and N12 in November, the wind direction had changed, which meant that the fuel was ignited at the opposite end to the foam application. This also meant that water curtains were required to protect the equipment at the foam end see Figure 7.1. The water from these curtains did not enter the test pitas it entered the drain surrounding the pit.

Figure 7.1 Water curtain used during tests N11 and N12 in November 2021

Table 7.1: Overview of tests carried out.

Date of Test	Test Ref:	Foam Ref:	Application Type
23 Jun	1	E	Aspirating monitor
23 Jun	2	E	Aspirating pourer
24 Jun	3	E	CAF monitor
24 Jun	4	E	Hybrid monitor
24 Jun	5	E	CAF pourer
25 Jun	6	D	Aspirating pourer/monitor *abandoned due to hose failure
25 Jun	6A	D	Aspirating pourer
25 Jun	7	D	CAF pourer
28 Jun	8	D	Aspirating monitor
28 Jun	9	D	CAF monitor
28 Jun	10	G	Aspirating pourer
29 Jun	11	G	Aspirating Monitor
29 Jun	12	G	CAF Monitor
29 Jun	13	A	Aspirating Pourer
30 Jun	14	A	CAF Pourer
30 Jun	15	A	Aspirating Monitor
30 Jun	16	A	CAF Monitor (2" tip)
1 Jul	17	B	Hybrid Monitor
1 Jul	18	B	Aspirating Pourer
1 Jul	19	D	Non-Aspirating Monitor
2 Jul	20	G	Hybrid Monitor
2 Jul	21	A	CAF Pourer
2 Jul	22	B	CAF Pourer
23 Nov	N1	C	Aspirating Monitor
23 Nov	N2	C	CAF Monitor
23 Nov	N3	C	Aspirating Pourer
24 Nov	N4	H	Aspirating Monitor
24 Nov	N5	H	CAF Pourer

Date of Test	Test Ref:	Foam Ref:	Application Type
24 Nov	N6	H	Aspirating Pourer
25 Nov	N7	C (and A)	CAF Pourer
25 Nov	N8	D	CAF Pourer
25 Nov	N9	E	CAF Pourer
26 Nov	N10	J	CAF Pourer
26 Nov	N11	J	Aspirating Pourer
26 Nov	N12	G	CAF Pourer
29 Mar	M1	L	Hybrid Monitor
29 Mar	M2	C	Hybrid Monitor

The full raw data tables can be viewed in Appendix B.

7.1 Aspirating Pourer Results

All foams were tested with the aspirating pourer at an approximate application rate of 3.9 lpm/m^2 (slightly below the normal NFPA application rate of 4 lpm/m^2). The results for these tests are provided in Figure 7.2.

All foams were able to travel to 45 m with relative ease and all reached virtual extinguishment. Four foams did not fully extinguish, but at the time of test termination there were only minor flickers remaining and it was considered (by the firefighting experts witnessing these tests) this would be manageable in practice even in a storage tank fire situation.

It was noted that Foam A, D, G and H were relatively rapid to reach 45 m and virtual extinguishment, but Foam G took longer to extinguish, and Foams A, D and H resulted in minor flickers remaining at test termination.

This pattern of control and virtual extinguishment for FFF was also noted in the previous LASTFIRE Research (Phase 1 bund tests, LASTFIRE Tests and the 11 m Tank Tests [1]), where edge flickers have been found to remain for some time after virtual extinguishment.

Foam B took the longest to reach 45 m and virtual extinguishment, but the time between virtual extinguishment and full extinguishment was the shortest. This is opposite to the effect seen with Foam G, for example, where the foam was quick to travel the distance, reaching 45 m in under 4 minutes and virtual extinguishment within 5 minutes, but took a further 12 minutes 40 seconds to extinguish the fire completely. This raises a question whether formulations can be "tweaked" to adjust the balance between speed of control versus security of full extinguishment.

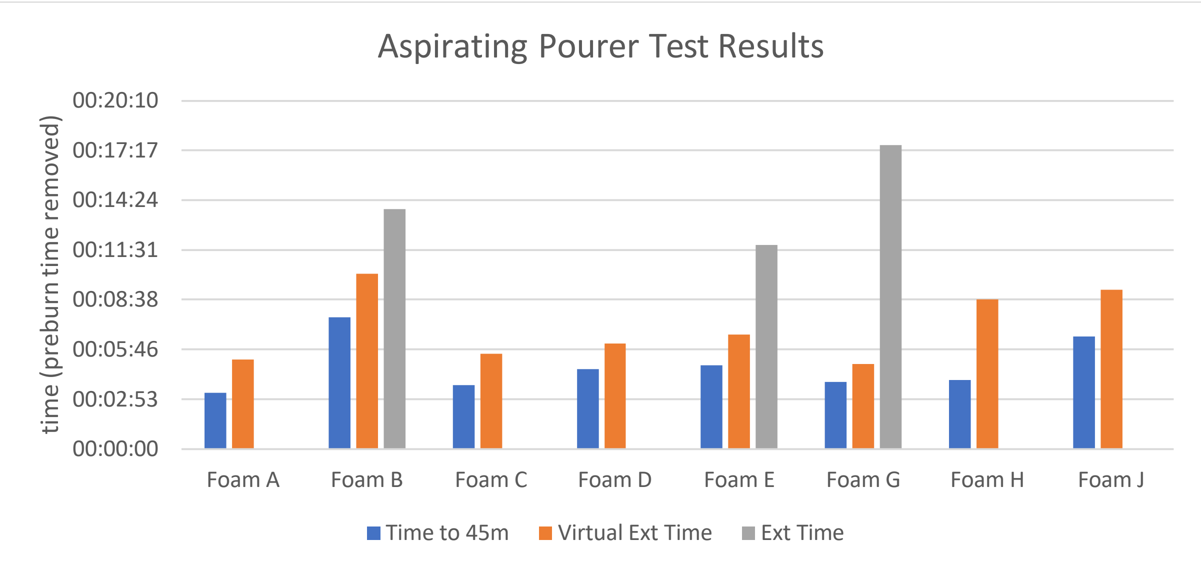


Figure 7.2 Large Scale Test aspirating pourer test results. Foam production rate of approximately 3.9 lpm/m^2

7.2 Aspirating Monitor Results

Six foams were tested using the aspirating monitor (A, C, D, E, G and H) at an approximate application rate of 7.2 lpm/m^2 (note Foam C and H were tested in November at a slightly lower application rate of 6.67 lpm/m^2). This represents a lower rate than would be applicable when designing tank protection systems in accordance with NFPA 11 or EN13565 Part 2. The results for these tests are provided in Figure 7.3. It was found in these tests that it was difficult to ensure that the foam impact point remained the same for all the tests, not only due to variations in ambient conditions, but also due to throw and expansion variations with the different foams using the same equipment. Therefore, this should be recognised in any direct comparison of results from one foam to another.

It should be noted that although there is not an entry for time to 45 m for Foam A, this was not due to the foam not reaching this point (as it did reach extinguishment), but due to camera angles not being able to detect the time to 45 m because of smoke.

Some foams were not able to reach full extinguishment. As with the aspirating pourer results, at the time of test termination there were only minor edge flickers remaining at the “50 m” end and, in some cases, along a short section of the side edges. It was considered this would be manageable in a real world event including a tank fire situation.

In the previous tests carried out by LASTFIRE [1], it was found that when the monitor was moved slightly towards the end of the tests, effective extinguishment was achieved. It is considered that this would also be the case in these large scale tests.

All foams tested with this application type showed relatively similar performance for time to 45 m and virtual extinguishment, and all foams exhibited the same pattern of a very short time between reaching 45 m and virtual extinguishment. As found with the aspirating pourer application, all foams reached virtual extinguishment quickly but then took longer to extinguish the remaining edge flickers, and in some cases these flickers remained at the end of the test.

Foam B was not tested with this application type, but it would be interesting to see if the same differences observed with the aspirating pourer for this foam type (more time to get to virtual extinguishment but less difference between virtual and full extinguishment) apply to monitor application also.

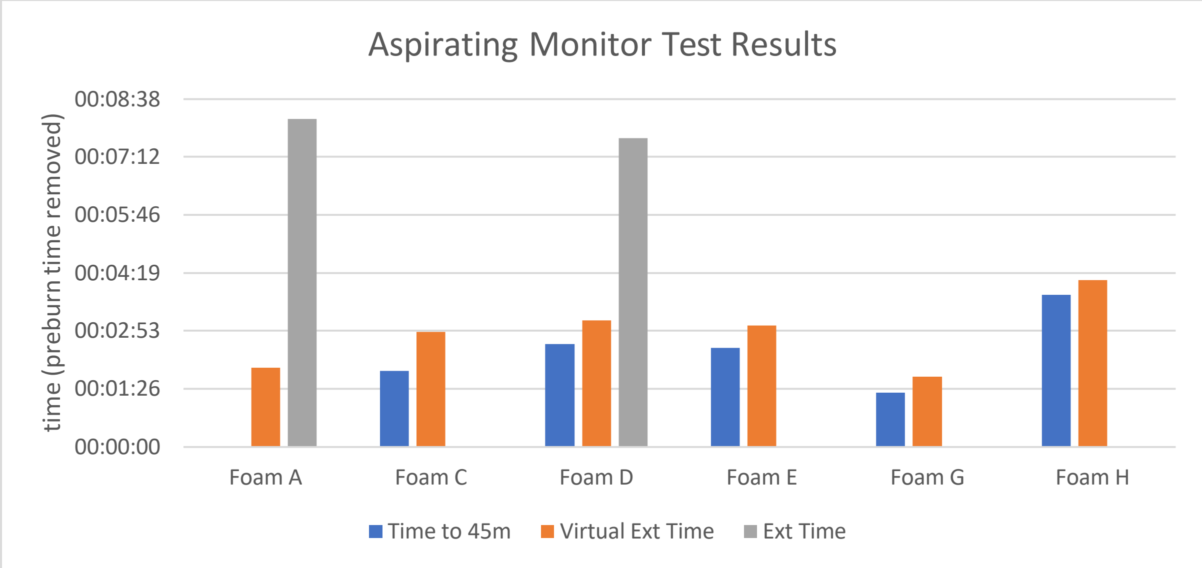


Figure 7.3 Large Scale Test aspirating monitor test results. Foam production rate of approximately 7.2 lpm/m²

7.3 CAF Pourer Results

Seven foams were tested using the CAF pourer system, Foams A, B, D, E (in June/July) and G, H and I (in November). the application rate used in these tests was approximately 2.5-2.7 lpm/m^2. This rate was set by the CAF unit supplier and represents approximately 67% of the standard rate for conventional pourer foam application in NFPA 11. The results for these tests are provided in Figure 7.4.

All seven of the foams reached 45 m and virtual extinguishment in relatively similar times. Foam G took longer to get to virtual extinguishment than other foams tested, but there was a shorter period of time between virtual extinguishment and full extinguishment than with other foams tested. All foams apart from H and J were able to fully extinguish the fire within less than 6 minutes of foam application. However, it should be noted that the tests with Foams H & I in November were stopped when it appeared to observers that minimal flickers remained but that there was no visible reduction in them after ongoing application. All seven foams were also tested with the aspirating pourer, and in each case the times to 45 m, virtual extinguishment, and full extinguishment (if reached) were lower with the CAF pourer application. At the end of the aspirating pourer tests with Foam A and Foam D, some minor flickers remained, but these were extinguished in the CAF pourer tests with these foams. Note that the application rate used for the CAF pourer tests was lower than that used for the aspirating pourer tests (~2.7 lpm/m^2 and ~3.9 lpm/m^2 respectively).

These tests have proved similar to those carried out in both the Phase 1 Bund tests and also the Tank Tests carried out in previous LASTFIRE Research [1]. This extrapolation to larger scale has shown that CAF remains a very "forgiving" system and a leveller for all foams, both in the small scale and larger scale, with similar results achieved for all the foams tested.

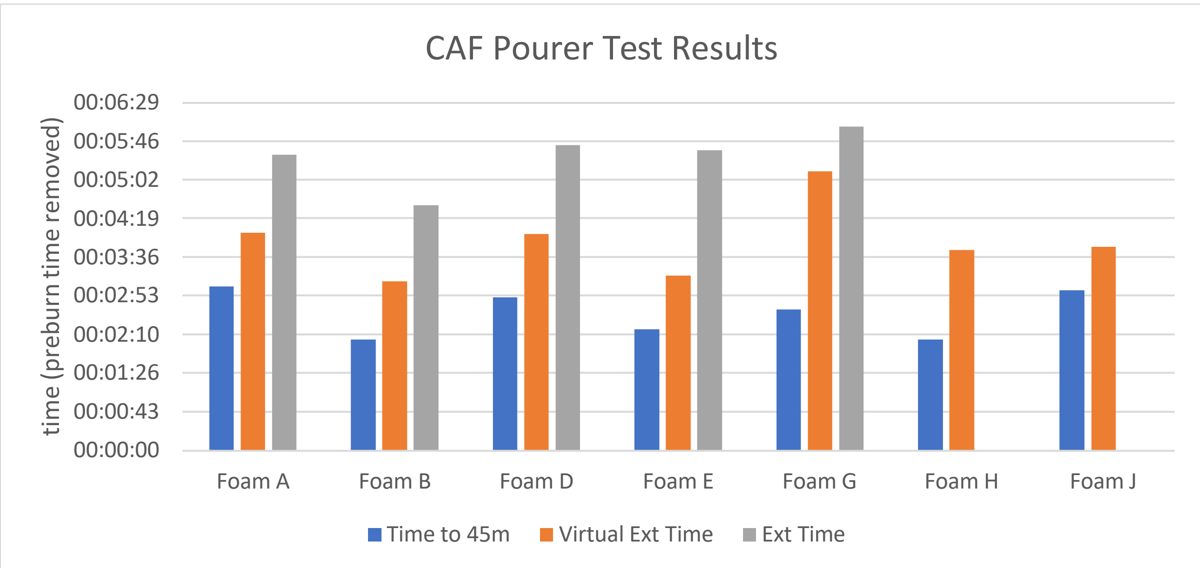


Figure 7.4 Large Scale Test CAF pourer test results. Foam production rate of approximately 2.67 lpm/m^2

7.4 Hybrid Monitor Results

Five foams, B, C, E, G and L, were tested using the hybrid monitor at an application rate between 6.0 and 7.0 lpm/m^2. The results for these tests are provided in Figure 7.5, noting that the two hybrid tests carried out in March 2022 were at the lower application rate, and therefore should not be directly compared with other results.

Foam E showed comparable times for time to 45 m and virtual extinguishment as observed in the aspirating monitor test. However, with the aspirating monitor, the foam was unable to reach complete extinguishment with minor flickers remaining at the end of the test. With the hybrid monitor, this foam was able to achieve full extinguishment in 3 minutes 40 seconds of foam application. This suggests that the higher expansion and consequently gentler application of the foam using this method may have assisted this foam with the extinguishment of the final edge flickers remaining. Foam E with the CAF monitor was slower to reach all three evaluation criteria (time to 45 m, virtual extinguishment and full extinguishment), but with CAF the application rate is significantly lower than that used in the hybrid monitor. Comparisons between the different monitor application types is provided in Section 7.6.2.

Foam B was not tested with either the aspirating monitor or the CAF monitor, so it is not possible to make comparisons of this foam's performance. It still reached 45 m and virtual extinguishment within four and a half minutes of foam application.

Foam G was also tested with both the aspirating monitor and CAF monitor. For this foam, the time to 45 m and virtual extinguishment with the hybrid monitor was comparable to those observed in the aspirating monitor test (2 minutes 21 seconds and 2 minutes 29 seconds; 2 minutes 21 seconds and 2 minutes 44 seconds respectively), but with the hybrid monitor full extinguishment was achieved in 3 minutes 31 seconds (See Appendix B for full raw data from the tests). With the aspirating monitor, minor flickers remained at the end of the test.

Foam C was tested with both the aspirating monitor and CAF monitor as well as the hybrid monitor. For this foam, the times to 45 m and virtual extinguishment with the hybrid monitor were comparable with the other monitor application types (see Appendix B for full results from all tests). Note that the time to full extinguishment for the Foam C hybrid monitor test was not recorded as the final flickers that remained at the end of the test were extinguished with handlines (see note in Section 7).

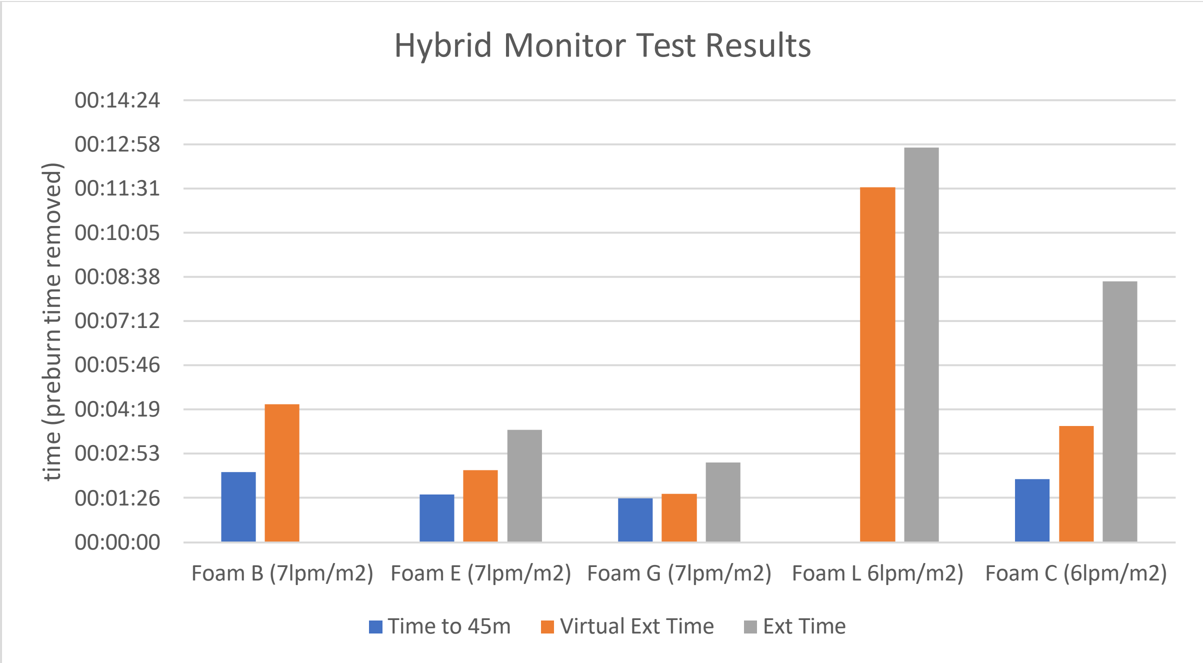


Figure 7.5 Large Scale Test Hybrid Monitor test results. Foam production rate of either 6.0 lpm/m^2 (foams C and L) or 6.97 lpm/m^2 (foams B, E and G)

7.5 CAF Monitor Results

Five foams were tested with the CAF monitor with an approximate application rate of 4-4.5 lpm/m^2. It should be noted however, that different outlet sizes were used on the nozzle, so it is impossible to compare the different foams. As a point to note, three out of the four foams that were tested with an aspirated nozzle tip reached full extinguishment. Foam D was tested with an open-ended tip and did reach 45 m and virtual extinguishment within approximately 3 minutes of foam application, but did not reach full extinguishment.

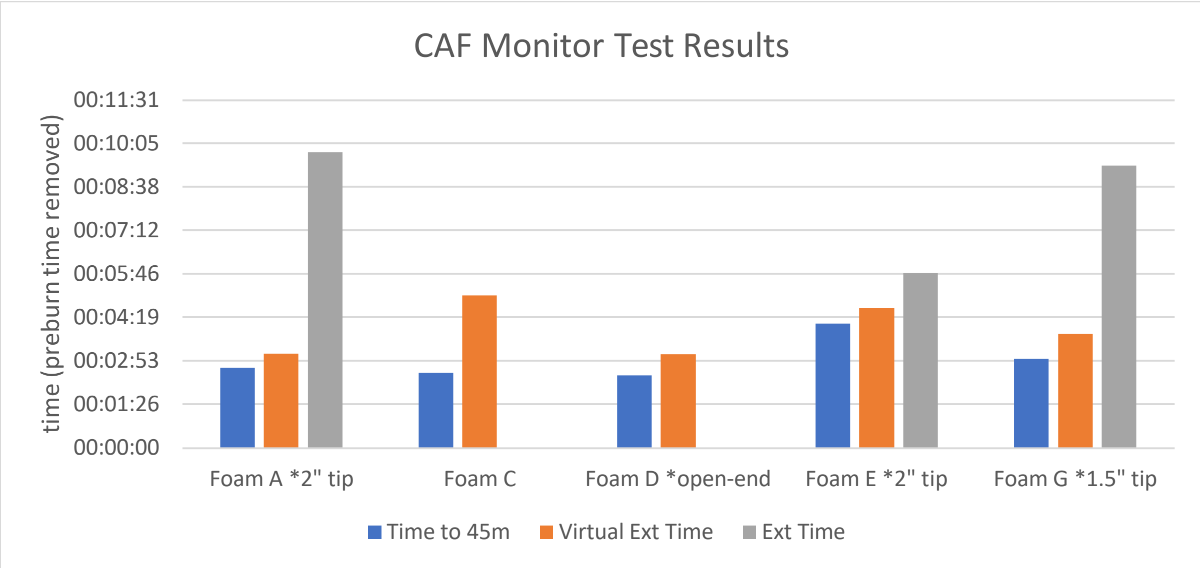


Figure 7.6 Large Scale Test CAF Monitor test results. Foam production rate of approximately 4.00 – 4.50 lpm/m^2

7.6 Comparison Observations

Although it is difficult to make like-for-like comparisons, as different application rates were used for different application devices, the following are some initial observations of the pourer and monitor application methods used.

7.6.1 Pourer Application

Seven foams were tested with both types of pourer (conventional pourer (application rate of approximately 4.0 lpm/m^2) and CAF pourer (application rate of approximately 2.7 lpm/m^2)). The results of these tests can be seen in Figure 7.7. Two foams (A and D) did not reach full extinguishment with the conventional pourer, with minor flickers remaining at the end of the test, but were able to reach full extinguishment with the CAF pourer. Two further foams (H and J) did not reach full extinguishment with the conventional pourer, but also did not reach full extinguishment with the CAF pourer within the timeframe of these tests. All other foams were able to reach full extinguishment with both the conventional pourer and the CAF pourer. All times (time to 45m, virtual extinguishment and full extinguishment), where comparisons could be made, were less with the CAF pourer system. The CAF pourer showed similar results with all foams tested, “levelling” the performance of these as has been observed in previous LASTFIRE research [1,2], i.e., producing similar results with foams that performed differently with the conventional pourer application.

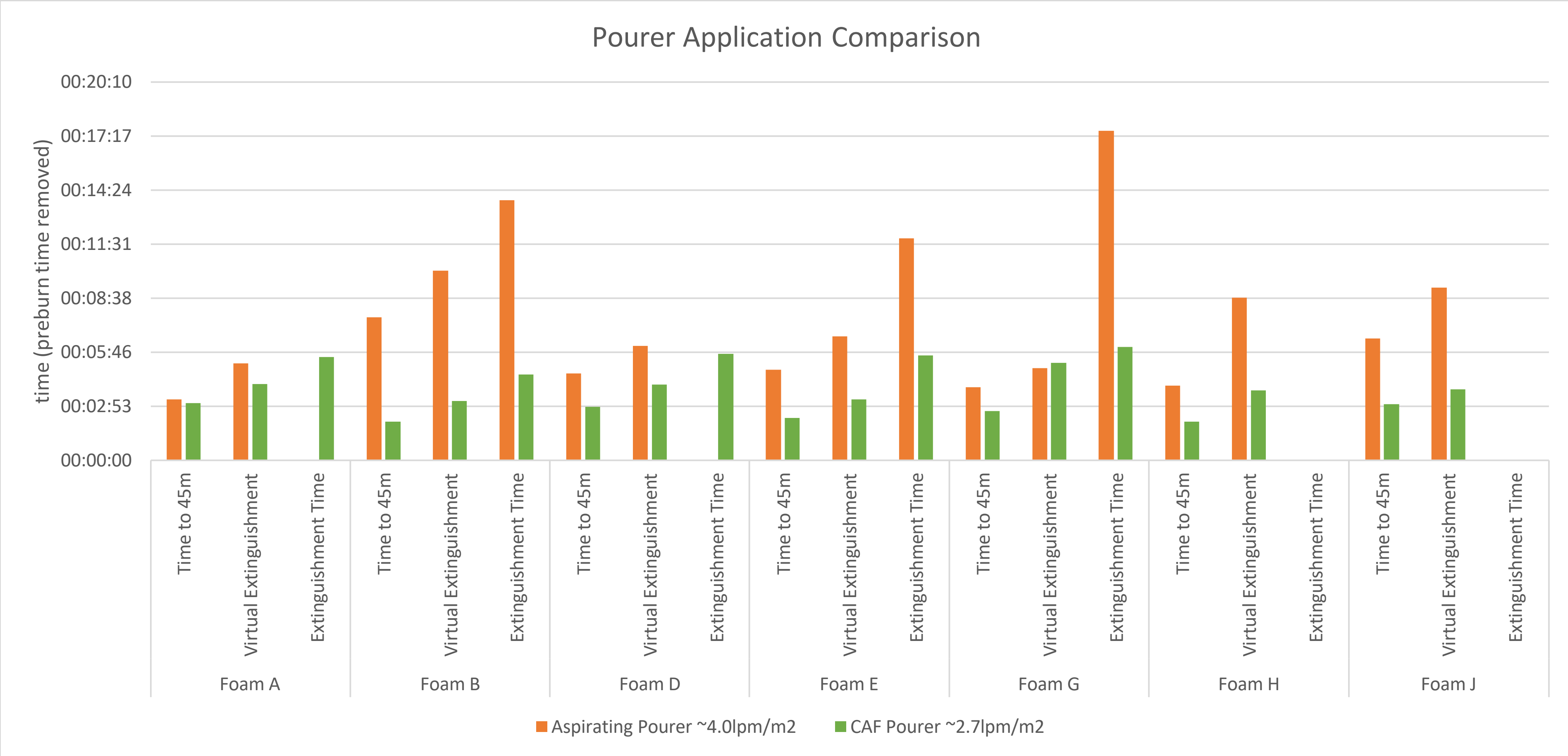


Figure 7.7 Comparison of pourer application technique tests

7.6.2 Monitor Application

Three foams, C, E and G, were tested with all three monitor application types (conventional, CAF and hybrid). The results of these tests can be seen in Figure 7.8. None of these foams reached full extinguishment with the conventional aspirating monitor (note that the other two foams that were tested with this application type did reach full extinguishment, and further note that Foam C was tested in November when it was agreed to extinguish tests via handlines that were not reaching extinguishment). However, with the hybrid monitor at a similar application rate, the foams were able to reach full extinguishment. With both the conventional and hybrid application, all three foams had relatively similar times to 45 m and virtual extinguishment, but the foam produced with the hybrid monitor was able to extinguish the final flickers remaining. Foams E and G were able to reach full extinguishment with the CAF monitor application (noting again that foam C was tested with this application type in November 2021 when tests were extinguished via handlines). The times to 45 m, virtual extinguishment and full extinguishment were all higher with the CAF monitor than the conventional or hybrid monitors. However, it should be noted that this was a lower rate than that used by both the conventional monitor and the hybrid monitor.

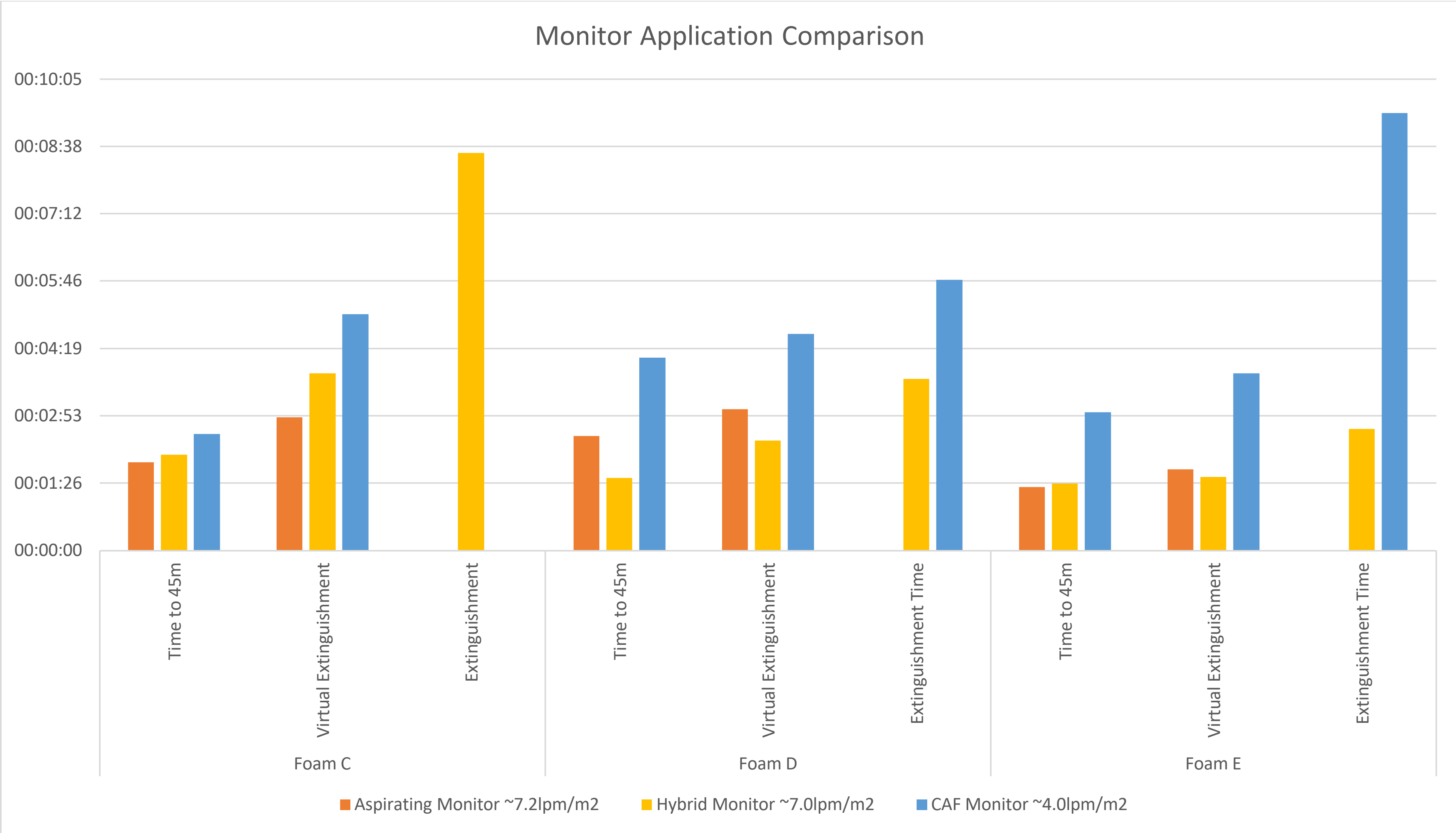


Figure 7.8 Comparison of monitor application technique tests

8 General Findings and Conclusions from Current Work

The following is a list of the general conclusions made from this large scale test programme. They provide key findings which have a major impact on current knowledge and the development of longer term policies and will provide a basis for the next phase of testing using this test pit.

- Some initial tests were carried out to test the integrity of the pit and the logistics of application using a C6 foam concentrate. Although these were not carried out in such a rigorous way as the main tests, they still provide a useful comparison of some aspects of the relative effectiveness against the Fluorine Free Foams tested.
- With both the monitor and pourer application of the C6 based foam flow appeared to be quicker or the same as the Fluorine Free samples used, but also experienced the same issues with sealing against the edges.
- With both application types, the C6 based foam blanket was observed to break-up in some areas which caused flashback.
- Following on from previous LASTFIRE testing, this research has further identified that the combination of foam and application technique is of key importance. A foam that performs well with one application technique may not have as good performance with a different technique.
- Compatibility with existing equipment, particularly proportioning equipment, is important – the higher viscosity fluorine free foams tested here were all checked for compatibility with the system being used prior to the tests but required adjustments to ensure accurate proportioning was achieved.
- All the FFF tested during these tests were able to travel the 50 m length of the test pit and either reach total extinguishment or very close to extinguishing the fire (virtual extinguishment) at the end of the test with minor flickers remaining at the edge of the pit or in some cases over the last section of foam surface. It is considered that this latter phenomenon might have occurred whatever length of pit it was as it had occurred in the first foam to reach the fuel surface. LASTFIRE is carrying out further work at a smaller scale to determine if this effect can be minimised by changing foam properties.
- The application of CAF – observed most significantly in this phase of testing with the CAF Pourer application – is very "forgiving" of different foam performance capabilities in the sense that it results in a levelled set of results across all the foams tested (as previously observed in smaller scale testing). This further demonstrates that application technique and foam properties are very important and need to be considered alongside application rates.
- "Virtual Extinguishment" has been used in this research as well as previous studies and it is found to be a good measure of the capability of a foam as it is considered that in most real situations, virtual extinguishment would be extended to full extinguishment by the further application of foam in a specific area, as often done in practice, which is still ignited.
- Expansion and drainage times were measured where possible in these tests, but it should be recognised that it was very difficult to obtain a truly representative sample of foam, especially for monitor application.
- There is further evidence from these tests that foam properties matter for different aspects of fighting a fire. For example, flow over the surface and sealing against an edge. It is clear from these tests that some foams perform in a different way to others, for example taking longer to flow over the surface but extinguishing the fire quicker.
- During one test in November, two foams were used on the same fire for a short period. This simultaneous use of different foams did not appear to impact the foam's fire suppression

capability. This effect has been investigated, and this topic will be the subject of a different report.

The main conclusion is that these tests proved that FFFs can be effective in extinguishing large hydrocarbon fires using conventional equipment and application rates but additional work to optimise performance through equipment modifications would be useful.

Note: Additional testing related to simultaneous application of different foams by handline were carried out after the test in the main pit. These will be reported separately.

8.1 Other Notable Findings

During the tests, the opportunity was taken to observe other points of interest. The following documents some of these observations that were made during the testing periods.

- The conditions during some of the tests in November provided the opportunity to observe the suction of water vapour into fire – see Figure 7.1 below. This shows the thermal updraught effect of a fire.

Figure 7.1 Suction of water vapour from ground level into fire

- Viscosity measurements were taken of the foam concentrate and the foam solution, these will be the subject of a further test report in the future following further analysis of the results.
- Different flow speeds/characteristics were observed with different application types and different foams. This will be analysed further and reported on in the future.

9 Future Work & Recommendations

The next phase of testing with the large scale test pit is scheduled for April 2022. The following are some recommendations for these upcoming tests, and for future work.

- LASTFIRE is already committed to additional small scale testing including the following:
    - Investigation of foam properties
    - Effect of fuel depth
    - Preburn
    - Fuel pick up
- Further combinations of foam/application type to identify or verify any trends as required will be carried out in the next scheduled test period using the large test pit.

- A number of large “obstacles” have been constructed for use in the test pit. These should be used in some tests to further test foam flow around corners/edges as well as increasing hot surfaces for testing sealing properties.
- Further tests using different foams at same time will be carried out to investigate potential compatibility issues
- The “section by section” approach to manual bund firefighting will be further investigated to see if this can be achieved on the bigger area than previously tested.
- Fuel depth and the impact of this on the tests will be investigated further
- Other fuels, including water soluble types, have been tested at smaller scale, and it is planned that these will be extended to larger scale for comparison purposes.

10 References

[1] LASTFIRE. *Evaluation of New Generation Firefighting Foams for Storage Tank and Associated Facilities.* Issue 1rev, March 2018

[2] LASTFIRE. *LASTFIRE Ongoing Testing of New Generation Foams: DFW Large Scale Extended Flow Test Report.* Issue 1rev, November 2018

Appendix A - Published Article Regarding Effect of Water Base on Test Results

Appendix B – Test Results Raw Data

Test	Date	Foam	Application type	Total Application Rate (lpm)	Application Rate (lpm/m2)	Proportioning Rate	Nominal Proportioning Rate	Expansion	Drainage Time	Temp Fuel	Temp Air	Temp concentrate	Wind Speed m/s	Preburn	Time to 45 m	Virtual Extinguishment	Extinguishment	Notes (times here include preburn time)
1	23/06/2021	E	Aspirating Monitor	2170	7.23	3.10%	3%	16.6		13.2	13		2	00:00:57	00:03:24	00:03:58		
2	23/06/2021	E	Aspirating Pourer	1235	4.12	3.11%	3%			15	20	21	4	00:00:47	00:05:36	00:07:24	00:12:36	
3	24/06/2021	E	CAF Monitor	1154	3.85	3.10%	3%	9.3		18	15	17	3	00:01:01	00:05:08	00:05:39	00:06:48	
4	24/06/2021	E	Hybrid Monitor	2099	7.00	3.08%	3%	3.7		17	19	20.8	2	00:01:37	00:03:10	00:03:58	00:05:17	
5	24/06/2021	E	CAF Pourer	766	2.55	3.12%	3%	7.3		17.7	20	21.4	1	00:00:30	00:02:45	00:03:45	00:06:05	
6a	25/06/2021	D	Aspirating Pourer	1190	3.97	3.10%	3%			13	15	21.7	1	00:00:42	00:05:19	00:06:47		
7	25/06/2021	D	CAF Pourer	799	2.66	3.03%	3%	11.7		16	20	20.9	0.8	00:00:39	00:03:30	00:04:41	00:06:20	
8	28/06/2021	D	Aspirating Monitor	2176	7.25	3.06%	3%	19		17.5	17	21	0.2	00:01:32	00:04:05	00:04:40	00:09:12	
9	28/06/2021	D	CAF Monitor (non-asp)	1224	4.08	3.16%	3%			21	18	21.6	0.9	00:01:03	00:03:27	00:04:09		at approx 10mins edge flickers remained and nitrogen ran out.
10	28/06/2021	G	Aspirating Pourer	1182	3.94	3.14%	3%	5.2		24	21	18.8	0.9	00:00:51	00:04:44	00:05:45	00:18:25	
11	29/06/2021	G	Aspirating Monitor	2119	7.06	3.07%	3%	6.9		16	14	21.8	0.4	00:01:00	00:02:21	00:02:44		
12	29/06/2021	G	CAF Monitor	1305	4.35	3.05%	3%	7.1		17	16	18.6	0.5	00:01:37	00:04:34	00:05:24	00:10:58	
13	29/06/2021	A	Aspirating Pourer	1156	3.85	3.01%	3%	8.8		14.5	18	20.6	1.5	00:00:38	00:03:52	00:05:48		
14	30/06/2021	A	CAF Pourer	760	2.53	3%	3%	6.9		18.5	20	19	1					NO FIRE*low gasoline level 5m - 26 secs 10m - 33 secs 15m - 43 secs 20m - 51 secs 25m - 1'4" 30m - 1'19" 35m - 1'33" 40m - 1'50" 45m - 2'11" 50m - 2'29"
15	30/06/2021	A	Aspirating Monitor	2146	7.15	3.10%	3%	8.6		11	14	20.1	0.5	00:00:52	Not recorded	00:02:50	00:09:00	Time to 45m was not noted due to patches of flame on impact area
16	30/06/2021	A	CAF Monitor (2" tip)	1378	4.59	3.13%	3%	7.9		18.7	16	20.1	1.3	00:00:44	00:03:23	00:03:51	00:10:31	
17	01/07/2021	B	Hybrid Monitor	2082	6.94	3.02%	3%	17.8		13	17	21.5	3	00:00:43	00:03:00	00:05:13	DNE	
18	01/07/2021	B	Aspirating Pourer	1107	3.69	3.09%	3%	6.9		16	17	22.1	3	00:00:30	00:08:07	00:10:37	00:14:22	
19	01/07/2021	D	Non-Aspirating Monitor	2087	6.96	3.16%	3%	10.8		16	17	20.6	2.5	00:00:46	00:02:45	00:03:14	00:03:56	
20	02/07/2021	G	Hybrid Monitor	2090	6.97	2.33%	3%	17.8		15	18	17.8	1	00:00:55	00:02:21	00:02:29	00:03:31	
21	02/07/2021	A	CAF Pourer	799	2.66	3.15%	3%	10.6		14	19	19.1	0.2	00:00:43	00:03:46	00:04:46	00:06:13	

Test	Date	Foam	Application type	Total Application Rate (lpm)	Application Rate (lpm/m2)	Proportioning Rate	Nominal Proportioning Rate	Expansion	Drainage Time	Temp Fuel	Temp Air	Temp concentrate	Wind Speed m/s	Preburn	Time to 45 m	Virtual Extinguishment	Extinguishment	Notes (times here include preburn time)
22	02/07/2021	B	CAF Pourer	817	2.72	3.07%	3%	13.2		18	21	20.5	1	00:01:14	00:03:18	00:04:23	00:05:48	
N1	23/11/2021	C	Aspirating Monitor	2000	6.67	1%	1%	7.96	00:12:18	7	5.4	not recorded	3	00:00:27	00:02:20	00:03:18	-	5'30" end flames out, just corner areas remaining and far edge still 50% It was noted that individual bubbles were observed blowing off surface
N2	23/11/2021	C	CAF Monitor	1325	4.42	1%	1%	5.56	>30	7	7.4	not recorded	3	00:00:42	00:03:11	00:05:45	-	4'00" far edge minor flames to 45m and at end/corners, edge flames extending to 35m on both sides
N3	23/11/2021	C	Aspirating Pourer	1200	4.00	1%	1%	3.11	00:07:55	11	8.4	not recorded	3	00:00:30	00:04:12	00:06:00	-	
N4	24/11/2021	H	Aspirating Monitor	2000	6.67	0.5%	0.5%	6.43	00:05:07	12.5	3.5	not recorded	1.6	00:00:36	00:04:22	00:04:44	-	6'00" old foam still flames and collecting at far end 6'44" blanket stopped moving, stalled by old foam, some areas smoking 20 m back from far edge and flickers with it
N5	24/11/2021	H	CAF Pourer	760	2.53	0.5%	0.5%	7.96	00:19:11	11	3.8	not recorded	2.3	00:00:25	00:02:29	00:04:09		
N6	24/11/2021	H	Aspirating Pourer	1200	4.00	0.5%	0.5%	4.16	00:04:00	7.5	5.7	not recorded	0.9	00:00:23	00:04:22	00:09:03		
N7	25/11/2021	C (and A)	CAF Pourer	760	2.53	1%	1%	9.2	>30	10	2.3	not recorded	0	00:00:35	Not recorded	00:03:05		Foam A on through monitor at 1'20", and handline at 1'49" Foam C through CAF pourer on at 1'59" and monitor stopped at 2'02"
N8	25/11/2021	D	CAF Pourer	1200	4	3%	3%	6.32	>30	7.5	3.9	not recorded	1.8	00:00:30	00:02:20	00:02:54		
N9	25/11/2021	E	CAF Pourer	1200	4	3%	3%	5.46	>30	7.5	6.0	not recorded	1.7	00:00:29	00:02:17	00:03:12		
N10	26/11/2021	J	CAF Pourer	760	2.53	3%	3%	11.11	>30	6	3.1	not recorded	2.3	00:00:38	00:03:37	00:04:25		
N11	26/11/2021	J	Aspirating Pourer	1200	4	3%	3%	3.96	00:04:18	10	5.0	not recorded	4.2	00:00:25	00:06:55	00:09:37		
N12	26/11/2021	G	CAF Pourer	760	2.53	3%	3%	6.67	>30	10	6.4	not recorded	5.0	00:00:31	00:03:08	00:05:43	00:06:33	
M1	29/03/2022	L	Hybrid Monitor	1800	6	3.28%	3%	6.1	00:10:35	13.5	13	Not recorded	4.0	00:00:35	N/A	00:11:38	00:13:26	Foam off at 9'00", flickers remaining until self-ext. Time to 45m not recorded as flames

Test	Date	Foam	Application type	Total Application Rate (lpm)	Application Rate (lpm/m2)	Proportioning Rate	Nominal Proportioning Rate	Expansion	Drainage Time	Temp Fuel	Temp Air	Temp concentrate	Wind Speed m/s	Preburn	Time to 45 m	Virtual Extinguishment	Extinguishment	Notes (times here include preburn time)
																		remained at monitor end of pit when foam front reached 45m
M2	29/03/2022	C	Hybrid Monitor	1800	6	1%	1%	5.6	11'49"	15	14	Not recorded	6.0	00:00:35	00:02:38	00:04:22	00:09:05	Foam off at 7'45", with a few remaining flickers at the far end until self-ext