LASTFIRE
Large Atmospheric Storage Tank Fires

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Evaluation of New Generation Firefighting Foams for Storage Tank and Associated Facilities

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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.

There is currently concern regarding the environmental effects of firefighting foam resulting in new foams being introduced to the market. Consequently, LASTFIRE has embarked on a programme involving literature reviews, monitoring of relevant research and development, and a comprehensive series of testing to establish an independently managed snapshot of the fire performance of these "new generation" foams which are claimed to reduce environmental consequences.

The report describes the procedures and results of the test programme which has involved more than 100 fires up to tank fires with 11 m diameter. It is important to recognise that whilst fire performance is obviously a major factor in selecting and using firefighting foam, other issues including physical properties, guaranteed shelf life, compatibility with other firefighting agents and suitability for use with materials of construction of systems must also be taken into account. This report also describes aspects of these issues noted during the test work.

The test programme is undoubtedly the most comprehensive large scale, end user driven and managed practical work related to storage tanks undertaken for more than 30 years.

In addition, LASTFIRE is working with other industry groups to form a true understanding of the environmental effects of the new generation foams.

Overall Objectives

As a critical part of the overall development of best practice "Cradle to Grave" assurance of firefighting foam, the following objectives were established for the current work, recognising the need to maximise returns on the investment being made:

- Developing a snapshot of current capability of a representative selection of the new generation foams, particularly to assess if they can be considered absolute "drop in" replacements with equivalent performance capability and without the need for system or application equipment modifications.
- Forming an overall view on whether or not modifications to current practices of foam application are required with new foam formulations to achieve acceptable performance, or if more efficient usage of resources can be gained with different application techniques.
- Revalidation of the LASTFIRE test protocol. (As part of the original LASTFIRE study a critical foam performance test was developed to simulate tank fire application as part of a batch acceptance test. This was validated against proven foams that had performed well in real incidents at typical standard application rates. No small scale test can ever be perfect in terms of simulating large scale real situations but the protocol had served its purpose very well over many years and LASTFIRE wanted to ensure that it is still a valid representative small scale test given the characteristics of new generation foams.))

- Validating the accepted strategy for large bund fires using a “section by section” approach. (Although a recognised practice described in standards such as NFPA 11, the principle of applying foam to very large full surface bund fires is relatively unproven in real incidents, although it has been applied successfully in some cases. (LASTFIRE has completed a Literature Survey related to such incidents.))
- Using the opportunity to take fire radiation measurements for rectangular fires at different orientations and determine if proprietary programs for fire modelling are suitable for this purpose.
- Assessing the accuracy of typical foam concentrate proportioning devices with the new generation foams. (Carried out as part of the overall goal to determine if new generation foams are true drop in replacements for existing systems.)
- Developing a LASTFIRE Group preferred vendor list for those companies which recognise LASTFIRE requirements and commit to working with the group to gain knowledge and improve tank firefighting efficiency.

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 subsidise the work through a contribution towards the fuel costs. The following suppliers joined the programme:

- Angus International
- Auxquimia
- Bio-Ex
- Dr. Sthamer
- Tyco

All other direct costs were met by LASTFIRE. GESIP, a France based consortium of fuel storage and processing companies developing best practice standards in facility safety provided a test facility, foam application equipment and logistical and manpower support for the large-scale tank application tests. They also assisted in the development of the tank test protocol and carried out initial small-scale tests to establish burning characteristics of the fuel being used and to establish accuracy of one of the proportioner types used during the tests. ACAF Systems Inc. provided specialist Compressed Air Foam hardware in the form of purpose-built small throughput test equipment and proprietary hardware for the larger scale tests. Firedos, a LASTFIRE Associate member provided a water driven proportioning unit for all the test series and incorporated special design features to adjust and measure concentrate flows from it. CTD France provided a metered flow pumped proportioner that was used during the test work at GESIP. It is estimated that the total cost of the tests was in the order of 600,000 Pounds Sterling. LASTFIRE is very grateful to all parties that made a contribution in manpower or resources to this work.

Test Protocols and Locations

The test series was carried out on an anonymous basis with each manufacturer supplying 2m^3 of their foam concentrate. This was used throughout the test series. The samples had all identification markings removed and replaced with a simple reference label. Samples included Fluorine Free and C6 fluorosurfactant based concentrates. These two generic types are described as "New Generation" foams as in the vast majority of cases they represent new formulations that have been introduced following the withdrawal of C8 fluorosurfactant based foams and the introduction of higher purity C6 fluorosurfactants.

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 became part of their product development programme.

Two representative samples of C8 and/or C6 (without same levels of purity) fluorosurfactant foams previously available and used extensively at facilities were included in the test series as proven reference samples for comparison with newer types.

After some initial test protocol development work, the main test programme was initiated. The first series of tests was carried out in Hungary at the facilities of FER, a LASTFIRE member that operates the emergency response capability at the MOL Szazhalombatta refinery. These tests consisted of standard LASTFIRE Tests and "small" (~4.5 m^2) and "large" (~18 m^2) simulated bund spill fires. Application rates consistent with LASTFIRE testing were generally used so typically represented approximately 50-60% of typical NFPA 11 design application rates. (The lower test rate being used to provide a "Safety Factor" in real situations.)

Different devices using small scale non-aspirating, aspirating, Medium Expansion and CAF application were used. (The 3 main LASTFIRE nozzles were designed to provide similar foam quality as would be achieved with typical proprietary equipment but on the small scale so as to represent real situations as closely as possible.)

The second series of tests was carried out at the facilities of GESIP, Vernon, France. These tests involved application of foam using standard rates as per NFPA 11 guidance with proprietary equipment including aspirated and non-aspirated monitors, a fixed system pourer and a compressor driven CAF unit onto a 100 m^2 (~11 m diameter) 10 m high tank fire. Sufficient fuel depth was used to ensure that foam applied forcefully from ground level equipment did not penetrate though to the water substrate.

Thus, these larger scale tests represented true life situations although relatively short preburn times were used due to site environmental conditions.

Drones were used to record the test fires and the resultant records proved extremely useful in analysing the data to a much greater degree than other records would have allowed. It was concluded that such devices could play a critical role in real incidents allowing more efficient application of foam and better monitoring of fire control and extinguishment. It was recognised that environmental conditions (especially wind speed and variation) could have an effect on results but the Working Group developing and managing the test protocols considered that as these tests were a progression from the earlier smaller tests that this "Real World" testing would be the most appropriate and this undoubtedly proved to be the case.

Test Results and Overall Conclusions

The following are the main conclusions drawn from the work, but it should be emphasised that this should be considered as one part of the ongoing work being carried out by LASTFIRE. The comments here should be read in conjunction with those in the main report for greater understanding of their implications and derivations.

- The LASTFIRE test still continues to be relevant to all foam types for assessing the performance of foams using different application devices. However, the scoring system will be reviewed to give even greater emphasis on extinguishment and additional nozzle types will be developed.
- None of the new generation foams should be considered as a straightforward "drop in" replacement for any current foam concentrate being used. Even if appropriate fire performance can be shown for the specific hazard it is still necessary to check that the concentrate is compatible with the proportioning systems and other system components.
- From the samples tested, some concentrates of both C6 and FF formulations demonstrated adequate levels of fire performance for bund spill fires and small tank fires using standard NFPA application rates although generic "foam type" conclusions cannot be drawn from this. The performance capability is very specific to the particular formulation and also to the type of application equipment used.
- There are different levels of performance within each generic type of foam. It is not possible to state, for example, that all C6 foams demonstrate better performance than all FF foams or vice versa. This emphasises the need for batch testing.
- There is no reason to doubt that adequate performance can be achieved for larger tanks than those tested but the flow capability over longer distances still needs to be checked. Strictly speaking this statement applies to all new generation foams but it is recognised that fluorosurfactant based foams are less likely to have an issue with this than FF types.
- The sectional application approach to bund fires can be effective but responders should be made aware of potential edge or hot surface sealing issues and the need for constant monitoring and top up of any areas controlled when the main application is moved to other areas.
- It is important to note that full environmental data for foam types is required prior to developing strategies for application, containment, remediation and disposal. It must be recognised that all foams have some environmental effect. With the current state of development of FF foams in particular it is not possible to be generic in drawing conclusions about what environmental effects a foam has.
- It is considered that current standards do not give sufficient emphasis to the importance of the combination of foam type and the application device performance and consequent foam quality. It is important to get this combination right to optimise overall performance. There is great scope for developing more efficient systems achieving similar performance to those designed in accordance with current standards.
- CAF application, if engineered correctly, can be very forgiving of foam concentrate quality. Given the same foam concentrate, equivalent or better extinguishing performance was gained

with this technique using approximately 30-35% of the flow used with conventional techniques.)
- Detailed performance based specifications are critical to achieving appropriate long-term performance and to managing foam stocks correctly. Such specifications need to request, for example, environmental data and materials compatibility data as well as fire performance standards appropriate to the hazards.

Next Phases of Work

Recognising that there is still considerable work to do to have full confidence in new generation foams for large diameter tanks and some spill situations, and to have sufficient information so that specific sites can make informed decisions on foam selection and management, LASTFIRE intends to carry out the following work:

- Tests to demonstrate the ability of new generation foams to travel over longer distances than have been tested to date.
- Modify the LASTFIRE test to include additional application devices and clarify scoring systems and evaluation criteria.
- Further develop typical performance based specifications that can be modified to suit specific site operating conditions and requirements.
- Carrying out a series of small scale tests to determine effect of properties such as expansion and drainage time with new generation foams and to assess effectiveness on other fuels and effectiveness for post extinguishment vapour suppression.
- Gaining additional knowledge of the environmental effects of new generation foam through other industry bodies such as PERF.
- Work with standard writing authorities, regulators, suppliers and any other stake holders to develop sustainable long-term policies for foam application and management on a Cradle to Grave approach.

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Abbreviations and Definitions

AFFF	-	Aqueous Film-Forming Foam
CAF	-	Compressed Air Foam
NFPA	-	National Fire Protection Association
FF	-	Fluorine Free

Mission Statement

The end goal of current LASTFIRE activities is to provide members with guidance to develop their long term sustainable policy for cradle to grave assurance of firefighting foam, its procurement, management, application and disposal based on proven fire performance and other data, taking into account their own operating circumstances.

Note: The guidance is not intended to be prescriptive but rather to provide sufficient information for end users to develop their own policies on a sound basis. Given the guidance and test data, end users may develop different policies. It is recognised that maintaining fire performance and minimising environmental consequences are the key drivers of this process. The research described in this document is a critical aspect of this work.

1. INTRODUCTION TO LASTFIRE

The LASTFIRE Group, a consortium of international oil storage companies and related associates reviewing and developing best practice guidance in storage tank fire risk reduction, is committed to minimising risk to life safety and the environment whilst also protecting assets and business in a cost effective and efficient manner.

The emphasis of Fire Hazard Management of all oil processing and storage companies is always on incident prevention through the implementation of design standards, process monitoring and control and operating practices. It must be accepted, however, that incidents, including fires, will happen, however infrequently. In the case of atmospheric tank related incidents these can range from small spill fires to multi – tank and full surface bund fires.

For all credible events, it is important to have a response strategy that minimises consequences to as low as is reasonably practicable, particularly to life safety and the environment, but also to company business, public concerns and asset value. One aspect of the work carried out by LASTFIRE is to develop best practice guidance in developing site-specific risk-based incident response strategies.

The response strategy for fires associated with storage tanks will normally include, but is not limited to, identification of the most appropriate foam concentrate and foam solution application rates and application methods appropriate to the fuels involved. Developing a suitable response strategy will also reduce the risk of incident escalation and maximise the effectiveness of the foam and water resources, minimising associated firewater runoff which could contain toxic or harmful components, and minimise collection and disposal costs.

The work described here is part of the ongoing work carried out by LASTFIRE to provide guidance to members and the industry in general on developing optimised response strategies for tank fire incidents but, because of its focus on foam application efficiency, it is also relevant to other firefighting foam applications. It forms part of LASTFIRE commitments to a site specific "Cradle to Grave" Foam Assurance process [1]. Neither the LASTFIRE Group, the Project Coordinator nor any individual member company take any responsibility for the accuracy or use of the information provided. It is provided based on best available experience and knowledge of group members, but specific site/incident conditions must be considered prior to defining any tank fire response strategies or other related policies.

2. INTRODUCTION

2.1 Overview

As mentioned above, LASTFIRE members are committed to minimising the environmental consequences of their operations. The majority of firefighting foams that have been used over the last 40 or more years have contained Fluorosurfactants. These chemicals provide fuel tolerance which allows the foam to be applied more forcefully without being destroyed and provides greater flowability of the foam. In recent years there has been concern regarding the environmental and toxic effects of firefighting foam with certain Fluorosurfactants in them. These have generally been known as C8 Fluorosurfactants because they are based on molecules with eight Carbon atoms. (However longer chain molecules also exist). This situation has resulted in "new generation" foams being produced. These can be broadly categorised into "Fluorine Free" and "High purity (i.e. minimal C8 content) C6 Fluorosurfactant" types. Although some manufacturers have claimed "No C8", this is, in reality, not correct as there is likely to be C8 material as an unintended by-product in the production process. Hence regulatory authorities set purity limits. For an example, the Queensland Department of Environment and Heritage Protection Operational Policy on the Management of Firefighting Foams states that a foam product is C6 purity compliant if it does not have greater than 50 mg/kg of total impurities in the concentrate for any compounds where perfluorinated part of the carbon chain is longer than 6 carbon atoms (e.g. PFOA, PFOA precursors, 7:3 Ft, 8:2 Ft, 10:2 Ft, fluoropolymers, etc. but excluding PFOS which has a separate impurity limit of 10 mg/kg [2]. Although there is currently much debate about the environmental and toxic effects of the C6 Fluorosurfactants they are currently considered in many geographical areas as being acceptable in this regard for firefighting foam application, although in some areas they too are now effectively banned for future use. C6 Fluorosurfactants have been included in many foam formulations for many years but it must be recognised that the majority of foam formulations on the market have been changed in some way, even if only in relatively minor ways, to meet "purity" requirements and minimise environmental consequences. For example in the USA much work was done under a "PFOA Stewardship Program" (see full link in references).

During regular batch acceptance testing to the LASTFIRE test protocol contracted by end users it was noticed that different results were being obtained even though it was claimed, in some cases, that formulations were exactly the same as previously and carried the same trade name or a very similar name with a minor change. This comment does not apply to all manufacturers fortunately. However, although most reputable manufacturers would make it clear when formulations have changed by clearly changing the foam's name or designation, this was not a unique experience. At a LASTFIRE meeting in 2016 where several supplier representatives were present this matter was discussed and it was accepted and admitted that in most cases some formulation changes had occurred. Subsequently, one major supplier, in a Firefighters conference in Poland, confirmed that changing formulations was always a balance between cost and performance and that in order to achieve the same levels of performance shown by previously proven C8 based formulations it would be necessary to increase costs and that this might not be acceptable to end users.

With this background and the increasing importance being placed on the potential environmental effects of firefighting foam, as highlighted by new legislation in some countries including the recently introduced policy in Queensland, Australia where only Fluorine Free foams are considered acceptable unless it can be shown that all foam solution run off can be contained , and the EU based restrictions on PFOA (see full links in references), it is critical to determine long term sustainable policies for selection and use of agents in the future. What firefighting foam types might be available and how to optimise their use and balance environmental effects with efficient extinguishing are issues that face all responders to flammable liquid fires but is particularly of interest to those in the hydrocarbon storage and processing industry. LASTFIRE, therefore embarked on a programme of fire testing at critical application rates with typical application equipment, developing best practice guidance in foam management and constantly monitoring latest regulatory requirements.

It is also important to note that in reality none of the new generation foams are proven in major large diameter tank incidents. (For clarification and emphasis, the term "New Generation" is used to mean those concentrates now complying to the more stringent C6 purity requirements as well as Fluorine Free foams, so, as previously mentioned, they are all to some extent new and unproven.) The LASTFIRE Group was advised by one manufacturer that even the change in levels of "by product" C8 surfactants caused by higher purity requirements in those formulations that previously were based on "C6 only" formulations could have a significant effect on performance. This would be consistent with LASTFIRE findings during routine testing. Previously available foams have been proven in tank fires with greater than 80 m diameter. These foams are no longer available. It is recognised that the change from earlier Fluorosurfactant based foams to newer types might be considered less of a change than the change to Fluorosurfactant Free foams but ultimately they are still different from those that were available previously.

The industry is good at preventing tank fires so gaining true operational experience of new generation foams will take many years.

The following is a summary of the overall phases of the current test programme:

1. Initial work to develop protocols for further phases
2. Phase 1 –Small scale testing related to bund fires and LASTFIRE tests
    i. LASTFIRE tests (heptane), freshwater and saltwater
    ii. LASTFIRE test example with gasoline
    iii. Different sized bund fires (4.7 m^2 and 18.5 m^2)
    iv. Critical application rates (approximately 60% normal design rates)
    v. Section by section approach for bund fires
    vi. Different application techniques (monitors, system pourer, MEX and CAF)
    vii. Evaluation of proportioning systems
3. Phase 2 – ~11 m diameter (100m^2 area), approximately 10 m high tank fire
    i. Normal design rates as per typical standards such as NFPA 11 with allowance for losses in line with best industry practice
    ii. Different application techniques (monitors, system pourer, CAF)

In addition, some small-scale tests were carried out on different fuels and qualitative assessments of dry chemical compatibility were carried out and reported.

It is considered that the test series is the most comprehensive set of large scale storage tank fire tests carried out by end users for more than 35 years.

Note: As the research project, although carried out in complementary phases, was intended as a structured programme, the conclusions drawn from all the work are presented as one section although the report does include some comments resulting from individual phases.

Note: For the purpose of this report, 'C6' means an AFFF based foam that meets the higher purity levels described in Reference 2.

2.2 Current Test Programme Objectives

An ideal fire test for storage tank application would involve a number of large scale tests (30+ m diameter with different foams, different application rates, different application methods and different ambient conditions). In practice the cost of this would be prohibitive and not justified by the actual risk. Therefore, it is necessary to simulate, as far as is reasonably practicable, actual tank fire conditions but on a smaller scale. Hence test protocols were developed on this basis.

In order to maximise return from available funds, the current test programme included several objectives which were, in order of priority:

a. Developing a snapshot of current capability of a representative selection of the new generation formulations of concentrates, particularly to assess if they can be considered absolute "drop in" replacements with equivalent performance capability and without the need for modifications to proportioning systems, application equipment, application rates or application technique.

Much of the currently available data has been developed by suppliers and might not be based on end user requirements, particularly related to specific applications such as tank fires. LASTFIRE, working with suppliers, wished to have tank fire related performance established under independent end-user direction.

b. Forming an overall view on whether or not modifications to current practices of foam application are required with new foam formulations to achieve acceptable performance, or indeed, if more efficient usage of resources can be gained with different application techniques.

Based on the ongoing and increasing pressure related to environmental aspects of foam, LASTFIRE considered it appropriate to initiate work on determining whether other application techniques or strategies might be more effective or more efficient for use with new generation foams, particularly those of Fluorine Free formulation. (For example, are higher application rates required with Fluorine Free foams, or could optimising foam properties through equipment modifications allow lower flow rates.)

c. Revalidation of the LASTFIRE test protocol.

As part of the original LASTFIRE study, following on from work carried out at Mobil (prior to becoming part of Exxon Mobil), it was recognised that there was not a representative small-scale test simulating the particular conditions of a storage tank fire. Consequently, working with end users and foam suppliers including Angus, Chemguard, Ansul, Williams Fire and Hazard Control and Solberg as well as LASTFIRE members, a test (The “LASTFIRE Test”) was developed. This was always intended by LASTFIRE as a batch acceptance test. Specifically, it was decided that it should not be a generic approval test and the current changes introduced in foam concentrate formulations by some manufacturers without changing the end product name have totally vindicated this decision. This test was validated through comparison with incident experience and against foam quality measurements with full scale application equipment with proven foam concentrates. No small-scale test is ever perfect, but the test has served many LASTFIRE members and other companies very well as part of their detailed performance based procurement specifications. The test has proven to be repeatable if carried out within the protocol tolerances for environmental conditions. With new generation foams – both C6 and Fluorine Free based – different performance characteristics such as foam stiffness have been seen and the LASTFIRE Group wished to revalidate the test against larger scale tests for new foams to assess ongoing applicability on issues such as foam flow distance. (e.g. A new formulation foam that can flow over a small pan fire and perform well might be too stiff to flow over a longer distance for example.)

In addition, the opportunity was to be taken to clarify the interpretation of the test performance within the protocol and possibly extend it to other application methods. (Currently there are three test nozzles simulating aspirating and non-aspirating monitor application and fixed pourer application.)

Note for clarification: the LASTFIRE test includes a “semi-aspirating” nozzle. This nozzle is intended to produce foam characteristics similar to a “non-aspirating” proprietary foam application nozzle. In the small-scale nozzle, some air is deliberately added to the foam solution flow to create the semi-aspiration. In a non-aspirating nozzle, air is added as the foam solution travels through the air so hence the resultant foam properties from the two devices will be similar. In general in this document, the term semi-aspirating is maintained when referring to the LASTFIRE test nozzle.

d. Validating the accepted strategy for large bund fires using a “section by section” approach

Although this approach is described in NFPA11 and other industry guidance has been adopted by professional fire responders such as the Rotterdam Europoort Unified Fire Team, in reality there has been very little critical test work or incident experience to validate the approach (see LASTFIRE Bund Fire Literature Review Document in Appendix A).

e. Using the opportunity to take fire radiation measurements for rectangular fires at different orientations and determine if proprietary programs for fire modelling are suitable for this purpose.

Most currently available fire modelling programs assume circular fire areas. It would be useful to confirm whether or not they could be used within acceptable tolerances for bund fires. For example, can the diagonal length of a rectangular fire area be taken for radiant heat levels received by objects directly at right angles to that length. However, it was found that the size of the test pan meant that the diagonal dimension was not sufficiently different from the side dimension to be able to measure any significant differences at right angles to them, especially given the very large change in radiation that occurs in real life fires over short periods. In order to gain meaningful results much larger fire tests would be required.

f. Assessing the accuracy of typical foam concentrate proportioning devices with the new generation foams

As it is recognised that some of the new generation foams have very high viscosity and different physical characteristics than the previously available formulations it is necessary to ensure that the can be proportioned into a water supply to make foam solution with sufficient accuracy to provide appropriate foam properties. (Note: NFPA 11 and EN 13565 Part 2 detail acceptable levels of accuracy)

g. Developing a LASTFIRE Group preferred vendor list for those companies which recognise LASTFIRE requirements and commit to working with the group to gain knowledge and improve tank firefighting efficiency.

The suppliers joining the study clearly showed not only their financial commitment to the work but also clearly demonstrated that they regard these tests as part of their own ongoing development programme. LASTFIRE is very grateful to these companies for their input and working with them has clearly shown the mutual benefits of this approach. These suppliers now have a greater understanding of end user requirements and also of the performance of their foams under different operation and application conditions.

2.3 Additional Aspects

A further objective was the development of a list of additional issues that were highlighted during the tests that might have a bearing on any final foam concentrate procurement specification or selection process. (For example, the identification of additional training needs due to specific performance characteristics of a foam.)

In addition, in order to gain a better understanding of chemical content and potential environmental or toxicity issues a collaboration was formed with a test laboratory to carry out Fluorosurfactant content tests and also with the PERF group (Petroleum Environmental Research Forum, Joint Industry Project on Critical Review of Health and Environmental Hazards of Short-chain PFAS-based and Fluorine Free Firefighting Foams). The ongoing PERF project's stated aims are:

To capture the state of knowledge of the fate, transport, and effects of short-chain PFAS-based AFFFs and fluorine free firefighting foams and identify limitations of and data gaps in the current studies or data sets. This critical review will address uncertainties regarding human health and environmental hazards associated with long-chain PFAS foam alternatives, inform future research opportunities, support advocacy for effective fire response tools, and inform risk-based decision-making on foam replacement and management.

2.4 Safety

At all stages of the testing, risk assessments were carried out to determine appropriate safety and environmental protection measures and procedures required during the tests. In general, these were based on typical industry practices of containment, PPE, ignition source control, etc. For all tests back up extinguishing equipment was made available. Non-essential personnel were not allowed within the operational test area. It is noted that both test sites used are also run as training facilities and that no concurrent training was carried out in the vicinity of the test work.

2.5 Participants

The tests programme was developed and managed by ENRg Consultants Ltd (LASTFIRE Project Coordinators) under the direction of the LASTFIRE Executive Panel. Regular planning meetings were held with the Executive Panel and other participants. At the time of writing, the companies forming the LASTFIRE Executive Panel were BP, Neste, Shell and Total. The following foam manufacturing companies participated in this research by provision of foam concentrates to be used in the tests and part funding of the project. The part funding was based on the suppliers meeting the estimated total fuel costs used, although in practice the amount of fuel used exceeded the initial estimates.

- Angus International
- Auxquimia
- Bio-Ex
- Dr. Sthamer
- Tyco

Proprietarily available AFFF and Fluorine Free foams were used for the initial test to develop protocols to be used in Phase 1 tests.

LASTFIRE Associate, Firedos, assisted with the research by overseeing and analysing the results of the proportioning tests. ACAFS Systems provided the CAF equipment for the testing.

Phase 1 work was carried out at the facilities of FER at Szazhalombatta refinery in Hungary.

A cooperation agreement was entered into with GESIP training centre, Vernon France, to provide the test facility, technical input and logistical support for Phase 2 of the work.

LASTFIRE once again expresses their gratitude to all organisations that took part in this critical work.

2.5.1 Confidentiality Agreements

All participants took part in the work under a strict Confidentiality Agreement. In particular, this report does not identify the performance of any specific foam concentrate. Results of individual foam concentrates were made available to the supplier of that concentrate.

This policy was adopted for the following reasons:

1. LASTFIRE recognise that suppliers are always in a process of continual development of their foam concentrates and this test work gave the opportunity to further develop their products based on the test results. Therefore, it would not be appropriate to imply that the performance seen during the tests was necessarily that of normal production batches in the future.
2. LASTFIRE is strongly of the opinion that a detailed procurement specification should include batch testing of fire performance [3].
3. LASTFIRE recognise that anonymity of samples would more clearly identify the independent nature of the test series and encourage more suppliers to be participants.
4. Although LASTFIRE aim to develop associations with preferred suppliers, it is critical that independence is maintained. LASTFIRE consider their role to be the development of realistic and appropriate performance based requirements to include in procurement specifications. It is then up to end users to dictate these requirements and suppliers to meet the specifications and so commercial evaluation of bids can be based on a rational basis.

2.5.2 Company Representatives

The following LASTFIRE member companies were represented at various stages of the research and were witness to the tests.

- BP
- Caltex
- Chevron
- ExxonMobil
- FER
- Nynas
- Reliance Industries Limited
- Rotterdam Unified Fire Brigade
- Total

3. INITIAL PROTOCOL DEVELOPMENT

Preliminary tests were performed at the facilities of FER Szazhalombatta in Hungary. The purpose of these preliminary tests was to assess and finalise the proposed test protocol using the small and large bund test design for Phase 1 of the overall programme.

Figure 3.1. Test pan used for initial protocol development

Tests were carried out in a purpose built test pan which allowed tests of approximately 4.5 m^2, 9 m^2 and 18 m^2 fire area. The intention was that a direct comparison could be used with the application rates and fire sizes used in the LASTFIRE tests and that the standard LASTFIRE test nozzles could be used. Tests were conducted with proprietarily available samples of a Fluorine Free foam and an AFFF AR foam and all tests were conducted using gasoline as the fuel. (See specification in Appendix B.) Four types of application technique were used for the protocol development, aspirated and non-aspirated monitors; foam pourer system nozzles and a CAF system. For the three standard nozzles, the application rates used were as specified in the LASTFIRE test (discussed in more detail in Section 4). It should be noted that these application rates are critical application rates representing approximately 60% of design rates that would be applicable in NFPA 11 or EN 13565 Part 2. (The intention of the LASTFIRE test is to evaluate foams at critical rates to provide a safety margin over normal design rates.)

A 3 minute preburn in line with the LASTFIRE test was used. Essentially the differences in the fire pan compared to a LASTFIRE test pan were as follows:

1. Lower freeboard of hot metal above the fuel surface
2. Square pan instead of a circular pan
3. Provision of additional obstacles within the fire area

An overall summary of results in provided in Appendix C.

3.1 Analysis/Observations of Results from Protocol Development

Whilst the main intention was to develop protocols for following phases, some qualitative results and observations were noted. These can be summarised as follows:

1. Lower application rates than are typically used in design standards can be effective with good quality foam and application techniques. This is in line with earlier work published by GESIP.
2. A section by section approach to bund fires can be carried out provided responders are aware of the potential need of moving application to critical areas such as obstructions and tight

corners and continuing to top up any initial fire area secured with foam whist moving the main application to other areas.

3. The combination of foam solution application rate, foam quality (expansion rate, flowability and drainage time) and application method is critical to effective and efficient fire control an extinguishment. It is considered that current design standards do not take this into consideration sufficiently as they tend to only specify foam solution application rates and minimum run time rather than optimising the foam concentrate/application equipment/application rate.
4. In CAF application, it is critical to optimise the air/foam solution mixing process. It can produce a very stable foam with characteristics allowing it to flow over the fuel surface and extinguish fires at lower application rates with foams that had failed to achieve this with other application techniques and higher rates of application.
5. It was noted that forceful application (monitor nozzles) of the Fluorine Free foam tested was not effective at the low application rates used in the tests.

Figure 3.2. Sequence of fire test using monitor application. Note two nozzles being used for full bund fire (very low application rate)

4. PHASE 1 – BUND FIRE TESTING, LASTFIRE TESTS AND PROPORTIONING TESTS

4.1 Objectives

Phase 1, carried out in June 2017, contributed to all the objectives as listed in Section 2.2 in relation to the LASTFIRE test and bund tests. In addition, the proportioning efficiency tests were carried out.

Overall the intention was also to address the following areas:

1. Investigation into application rate versus extinguishing time for bund fires. For this testing, a minimum of two foams were analysed including at least one Fluorine Free Foam.
2. Relative effectiveness of different foam applications – aspirated monitor, semi-aspirated monitor, system pourers, CAF nozzles.
3. Stability of foam and effectiveness of foam blanket.
4. A qualitative assessment of how far foam can travel and travel rates (times and distances that can actually be achieved for different foam characteristics (expansions/low/medium, etc.)
5. Ability for foam to move round obstacles and seal against hot metal surfaces
6. Effect of fuel type using small scale tests

4.2 Test Protocols

The tests were undertaken at the FER facilities in Szazhalombatta in Hungary in June 2017. This facility had been used previously for LASTFIRE testing and other LASTFIRE research work. It has access to a full time professional specialist hydrocarbon industry firefighting team (FER).

The bund was located within an area where a long duration fire could proceed without causing any interruption to business at the refinery. These tests were performed outside.

Six current foam samples were used during the testing. These consisted of two AFFF-AR type foams and four Fluorine Free type foams. These foams were anonymously given codes Foam A-F (the actual foams were only known by the LASTFIRE Coordinator). For the purpose of comparison, two reference samples, which were C8 Fluorosurfactant based foams, were included in the test programme. These were named Reference 1 and Reference 2.

Table 4.1. Foam Types

Foam Code	Generic Foam Type
A	FF
B	C6
C	FF
D	C6
E	FF
F	FF

It should be noted that for all tests in Phase 1, the foam solution was a premix to ensure accurate proportioning with all foams. All concentrates were used at the manufacturer's recommended proportioning rate for hydrocarbon application. This is in line with the LASTFIRE Test protocol. The protocol for mixing the premix used in all Phase 1 tests was as follows in order to ensure a homogenous solution:

1. Take required volume of foam concentrate
2. Add half water quantity to IBC, add the concentrate and mix for 5 minutes with an electric stirrer
3. Add extra water to correct quantity and mix for a further 5 minutes
4. Circulate solution for 10 minutes with positive displacement pump (discharge below surface of liquid)

Figure 4.1. General Photographs of Test Site used in Phase 1

4.2.1 LASTFIRE Test validation

The LASTFIRE Foam Test Protocol, as outlined in LASTFIRE Document *LASTFIRE Test Specification 2015* [4] was used for the LASTFIRE tests undertaken (both with fresh water and salt water). The fuel used for all LASTFIRE tests was heptane. A further test was undertaken with gasoline for comparison as part of the ongoing revalidation of the LASTFIRE test protocol.

The application rates used were those stated in the LASTFIRE Test Specification, as follows (noting that these are approximately 50-60 % of the application rate recommended in standards such as NFPA 11 and EN 13565 Part 2):

- Semi aspirated (non-aspirated) - 3.68lpm/m^2
- Aspirated - 3.68lpm/m^2
- System - 2.53lpm/m^2

All LASTFIRE Tests were undertaken using official nozzles and witnessed by approved LASTFIRE Testers. FER personnel participated in the torch and burnback tests overseen by the LASTFIRE Tester.

The simulated seawater used for the saltwater LASTFIRE tests was based on the EN 1568 specification for artificial seawater, see Figure 4.2.

% by weight	Component	
2,50	Sodium Chloride	($NaCl$)
1,10	Magnesium Chloride	($MgCl_2$. $6H_2O$)
0,16	Calcium Chloride	($CaCl_2$. $2H_2O$)
0,40	Sodium Sulphate	(Na_2SO_4)
95,84	Potable water	

Figure 4.2. Artificial seawater specification from EN 1568

4.2.2 Small Bund testing

The small bund test pan was of metal construction with dimensions 2.15 m x 2.15 m. This size of bund allowed the current LASTFIRE nozzles to be used for foam application at the same application rate as the LASTFIRE test itself. This also allowed for comparison between the LASTFIRE tests and the small bund tests. The depth of the test pan was designed such that a freeboard of approximately 200 mm of hot metal remained above the fuel level. The fuel layer depth was defined to ensure that foam application did not penetrate through it. Obstacles were installed in the test pan to evaluate the capability of foam to travel round objects of different configurations that would generally be found in real large-scale bunds such as pipes and their supports etc. Two obstacles were used in the small bund tests, one with the opening facing towards foam application and the other obstacle with the opening facing away – see Figure 4.3.

Figure 4.3. Small bund test pan with obstacles

In line with the LASTFIRE Foam Test Protocol, a three minute preburn was used on all tests in the small bund. All foams were tested with the following nozzles at the nett application rates stated, noting that these are approximately 50-60% of the application rate recommended in standards such as NFPA 11 and EN13565.

- Semi aspirated (non-aspirated) - 3.68 lpm/m^2
- Aspirated - 3.68 lpm/m^2
- System - 2.53 lpm/m^2
- Medium Expansion - 3.68 lpm/m^2
- CAF - 2.16 lpm/m^2

The following process was followed for all tests:

1. Record ambient conditions (temperature, wind speed)
2. Record temperature of fuel and water
3. Add fuel to quarter bund test pan. Initial fuel depth 100 mm (50 mm of water).
4. Set up and position relevant nozzle to be used for test
5. Ignite fuel and allow 3 minute preburn (to coincide with the established LASTFIRE test protocol)
6. Application of foam to relevant section with one nozzle/foam combination at a continuous application rate appropriate to the nozzle being used
7. Record time to virtual extinguishment (edge flickers over less than 2 m (total) of edge and no ghosting)
8. Record time to full extinguishment
9. Stop foam application at 7 minutes (in accordance with LASTFIRE Test)
10. Take a sample of the foam
    a. Measure foam expansion (in accordance with NFPA 11)
    b. Measure drainage time of foam (in accordance with NFPA 11)

11. If applicable, 2 minutes post extinguishment, perform vapour suppression (torch test) using a gas lance. Gas lance will be held at corners and half way along each edge for 10 seconds each at a distance of 75 mm
12. 5 minutes after extinguishment, perform a burnback test
13. Following each nozzle test, 25 mm of fuel will be added to the test pan.

4.2.3 Large Bund Testing

The large bund test pan was of metal construction with dimensions 4.3 m x 4.3 m (four times the area of the small bund test pan). The obstacles used in the small bund testing were also used in the large bund testing. However, for the large bund test, four obstacles were used, all with opening facing in different directions, see Figure 4.4 below. It is recognised that most bund walls are not of metal construction, so these tests probably represented worst case situations but nevertheless there will always be pipework and other metal structures within the bund that the foam will have to seal against

Figure 4.4. Large bund test pan with obstacles

The protocol for the large bund test was similar to the small bund test as follows, but the types of nozzles used were dictated by the results of the small bund tests.

1. Take a sample of the foam
    a. Measure foam expansion (in accordance with NFPA 11)
    b. Measure drainage time of foam (in accordance with NFPA 11)
2. Take required quantity of foam concentrate
3. Add half water quantity to IBC, add the concentrate and mix for 5 minutes
4. Add extra water to correct quantity and mix for a further 5 minutes
5. Circulate solution for 10 minutes with positive displacement pump (discharge below surface of liquid)
6. Record ambient conditions (temperature, wind speed)
7. Record temperature of fuel
8. Add fuel to quarter bund test pan. Initial fuel depth 100 mm litres (50 mm of water).
9. Set up and position relevant nozzle to be used for test
10. Ignite fuel and allow a 3 minute preburn (to coincide with the established LASTFIRE test protocol)

11. Application of foam to relevant section with one nozzle/foam combination at a continuous application rate appropriate to the nozzle being used
12. Record time to virtual extinguishment (edge flickers over less than 2 m (total) of edge and no ghosting
13. Record time to full extinguishment

4.2.4 Proportioning Tests

A series of proportioning tests was conducted at the same time as the Phase 1 tests. These tests used two proportioning devices, a standard venturi inductor type and a water turbine/pump proportioner. The purpose of these tests was to evaluate suction capability and mixing rate of the foam concentrates used in this research.

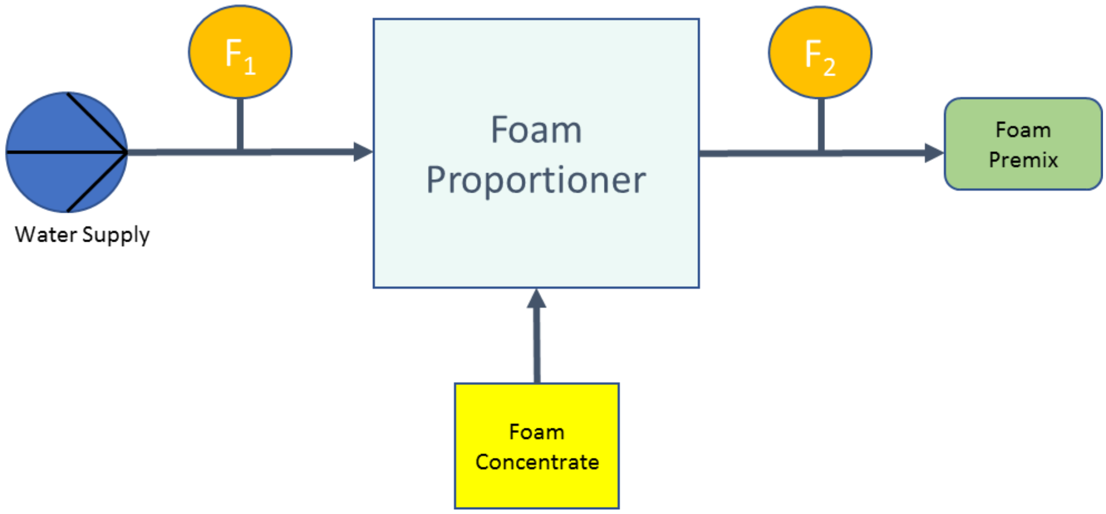

Figure 4.5. Setup for Proportioning Tests, testing suction capability and mixing rate of foam concentrates

The following test protocol was used for these tests for each foam concentrate:

1. Note of which foam proportioner to be tested (venturi/water driven turbine proportioner)
2. Note nominal mixing rate
3. Note nominal flow rate
4. Measure temperature of foam concentrate
5. Measure sucking time (time to reach mixer)
6. Note flow rate of premix (F_1, lpm)
7. Note flow rate of foam concentrate (F_2, lpm)
8. Calculate the real mixing rate from measured flow rates (%)
9. Measure real mixing rate using refractometer (%)

The detailed report of the results from the proportioning tests is included in Appendix D.

4.3 Analysis of Results

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

- The ambient temperature was high during the LASTFIRE and bund tests carried out in Hungary. The temperatures experienced were at the extreme of or above the LASTFIRE test protocol conditions limit. Therefore, this is a relatively severe test due to the volatility of the fuel.

Although wind speed did vary in the tests, the direction remained generally constant throughout each individual test. Application devices were adjusted, as they would be in real incidents, to maximise foam application into the test pan or tank.

- The bund test fire should not strictly be classified as a "spill fire" as per the definition in most standards which quote a 25 mm maximum depth as a spill fire, but instead as "fuel in depth" fire and so a more onerous application than a spill fire because of greater plunging and consequent fuel pick up potential. (Note: As an example of one standard's approach to bund fires, EN13565 Part 2, specifies an application rate of 4 lpm/m^2 to a hydrocarbon spill fire of less than 400 m^2 using handlines and the same rate for fuel in depth fires but a longer run time (30 minutes instead of 15 minutes).

The tests highlighted in Table 4.2 were carried out as part of Phase 1. Note that these were carried out in a random order.

Table 4.2 Test Matrix for Phase 1

Sample	**LASTFIRE Fresh - Heptane**				**LASTFIRE Salt - Heptane**			**Small Bund - Gasoline standard LASTFIRE App Rate**					**Small Bund extra**	**Large Bund - Gasoline 50% LASTFIRE App Rate (with exceptions)**				
	Non-Asp	**Asp**	**Sys**	**MEX**	**Non-Asp**	**Asp**	**Sys**	**Non-Asp**	**Asp**	**Sys**	**MEX**	**CAF**	**Non-Asp 2 nozzles**	**Non-Asp**	**Asp**	**CAF**	**Non-Asp 4 nozzles**	**CAF 25lpm**
Reference 1	✓	✓	✓	✓				✓	✓	✓	✓	✓						
Reference 2	✓	✓	✓	✓				✓	✓	✓	✓	✓						
A	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓
B	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
C	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓
D	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
E	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
F	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓

4.3.1 LASTFIRE Tests

The LASTFIRE test was undertaken for all foams, including the two reference samples using fresh water. Salt water tests were carried out for the test samples only, not the two reference samples.

It was noted that with the semi aspirated and the aspirated nozzle in the fresh water tests, the two C6 based foams tested scored similarly on all counts. However, one C6 based foam performed better than the other with the system nozzle. The construction of the system nozzle is such as to create a relatively forceful application especially if the foam has lower expansion. The later large scale tests using a proprietary foam pourer showed exactly the same characteristics.

The torch test and burnback resistance test results/scores have been analysed. These show that for fresh water, aspirated nozzle C6 and Fluorine Free foams tested performed in a similar way with very similar results classification. Semi aspirated nozzle results were slightly more varied, with the C6 foams tested performing very similarly. However, the Fluorine Free foams were of mixed results, with the majority performing worse than the C6 foams, but one foam performing better. For the system nozzle, only one C6 and one Fluorine Free achieved an "Acceptable" or higher rating. The two foams that did, performed well and both obtained the maximum possible score.

For the fresh water tests, All foams apart from one AFFF and one Fluorine Free failed on the system nozzle. The two foams that did pass the system nozzle test both obtained a 'GOOD' rating. The aspirating nozzle was the best performing nozzle across all foams tested.

For the LASTFIRE salt water tests the majority of the foams did not score well in the torch tests or the burnback test. Three foams scored above zero marks with the aspirated nozzle, with one C6 and one Fluorine Free both scoring the maximum possible.

As a one-off test, Foam D was tested with heptane and gasoline (using fresh water) with semi aspirated and aspirated nozzles. This foam performed better on control time and extinguishment time with the semi aspirated nozzle on gasoline but performed better on control and extinguishment time with the aspirated nozzle on the heptane. However, the times to control and extinguishment were very similar with both fuels and could be seen to correlate.

Foam E showed similar extinguishment times with aspirated and system nozzles in LASTFIRE fresh water and saltwater tests. Foam D showed similar extinguishing times with semi and aspirated nozzles in LASTFIRE fresh and salt tests.

Good correlation was observed between the MEX and aspirated nozzles in both LASTFIRE tests for those foams which could expand to medium expansion. Therefore, it was not considered a major priority to develop this further. (Note: some foams were unable to expand to medium expansion, and if low and medium expansion is needed from a single product, then this should be identified clearly within the procurement specification as not all products are formulated to do this.)

It should be noted that in the past, 'traditional' good quality C8 based products would routinely achieve scores between 90 and 100, hence the LASTFIRE Typical Foam Specification recommends a 'GOOD' for all three nozzles using fresh water and 'ACCEPTABLE' for some nozzles on salt water. Using this approach, only a limited number of the foams tested would be able to reach these criteria and so cannot be considered to have the same performance even though the performance is still acceptable.

As mentioned previously, it should also be noted that some manufacturers taking part in these tests noted the benefit to themselves and the development of their foam products. It is recognised that many 'new generation' foams, especially the Fluorine Free foams are currently at development stage and participating in research such as this provides valuable learning points which can be used to further develop and improve the foam formulations and performance.

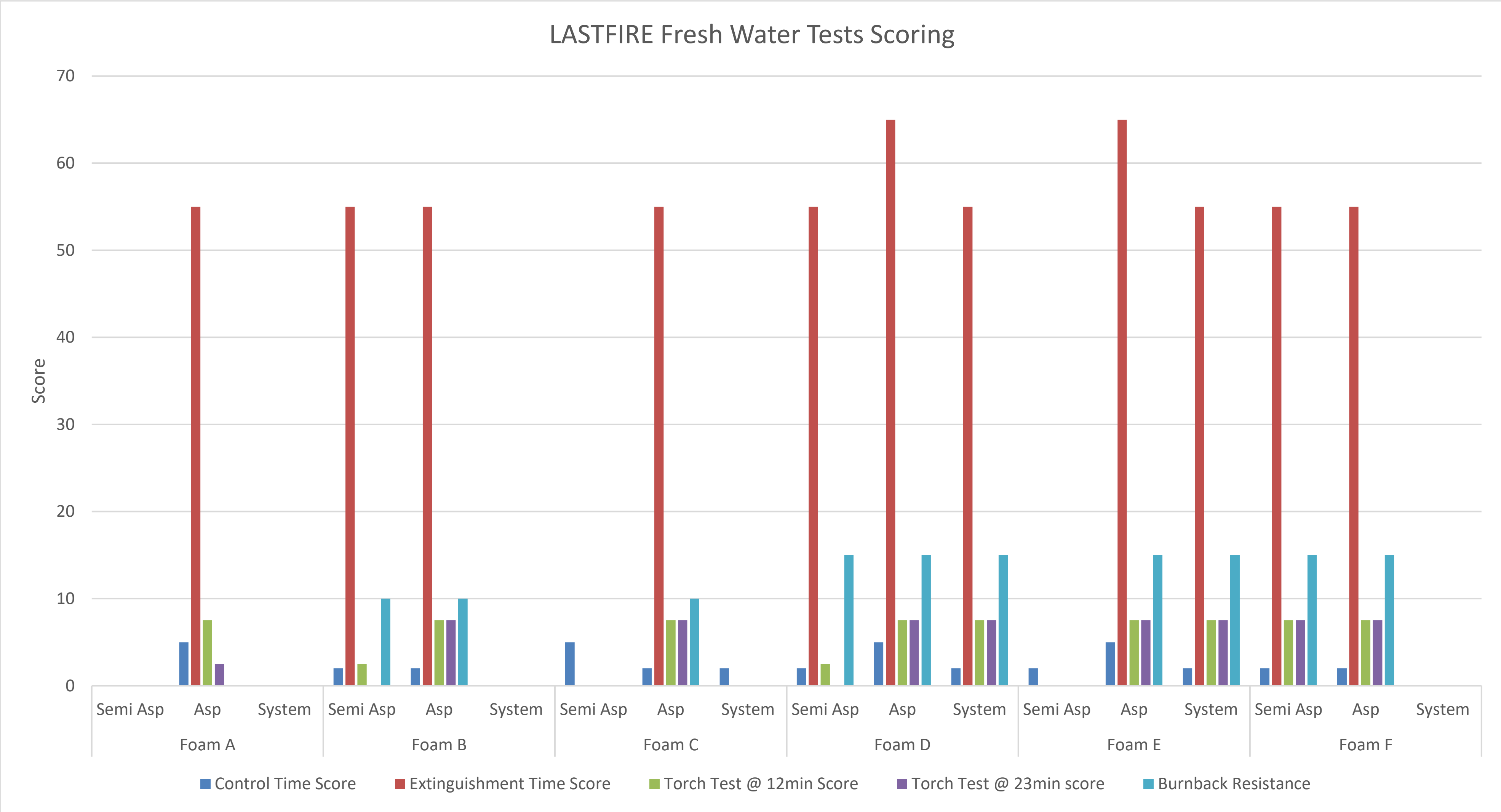

Figure 4.6. Scoring results for the LASTFIRE fresh water tests

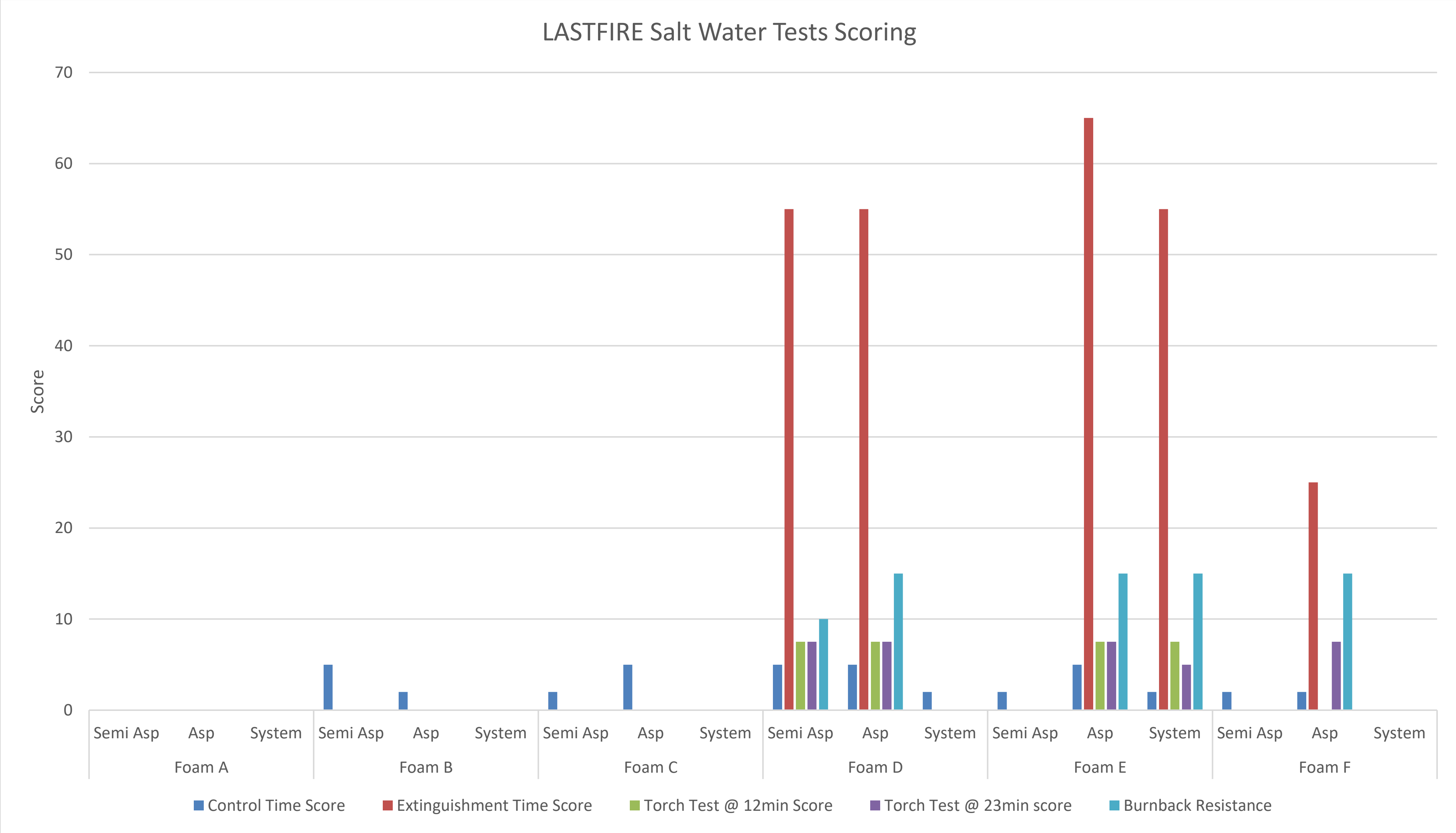

Figure 4.7. Scoring results for the LASTFIRE salt water tests

4.3.2 Small Bund

The small bund tests were carried out for all foams including the two reference samples. All foams were tested using the five nozzles outlined in the test protocol in Section 3.2.2.

As in the LASTFIRE tests, there was good correlation shown for control time between MEX and aspirated nozzles in the small bund tests for those foams which could expand to medium expansion, noting again that one foams was unable to expand to this level. It should be noted that Foam A was the only foam to not expand to medium expansion and did not reach control with this nozzle. However, for all foams tested the virtual extinguishment time for the MEX nozzle was less when compared to the aspirating nozzle across all foams. In fact, for foam samples B, C, E and Reference 2 the virtual extinguishment time using the MEX nozzle was similar to that for the system nozzle. Note that as discussed previously, this might have been due to the design application of the product such that they are not intended to work at medium expansion.

Control times observed using the system nozzle in the small bund tests were noticeably higher than all other nozzles tested, except for Foams D and E. This correlates with the LASTFIRE test results where Foams D and E were the only foams to perform well with the system nozzle. It should be noted that the system nozzle has a lower application rate than all other nozzles used and does not provide significant forward momentum of foam so it is expected that the time to control would be longer than that obtained using other nozzles at a higher application rate. It should be noted that all foams except Reference 1 reached control and virtual extinguishment with the system nozzle. In fact, all nozzles apart from Reference 1 and Foam Sample A reached control and virtual extinguishment with all nozzles (foam A reach virtual extinguishment with all nozzles apart from the medium expansion nozzle). Foams D was the only nozzle to reach extinguishment with all nozzles, noting that these extinguishment times were comparable to those achieved by other foams with certain nozzles, thus showing that certain foams are better suited for certain nozzles over other nozzles.

Despite all foams performing well to control and virtual extinguishment, only one foam was able to extinguish with all nozzles tested. However, all foams reached extinguishment with the CAF nozzles, and all apart from Reference 1 reached extinguishment with the aspirated nozzle. Two foams (one C6 and one Fluorine Free) were able to extinguish with the system nozzle. Interestingly, although the C6 was the same one as that which extinguished with the system nozzle in the LASTFIRE test, the Fluorine Free foam was different. Foam E, which performed well with the system nozzle in the LASTFIRE test did not extinguish with the system nozzle in the small bund test, and despite not extinguishing with the semi aspirated nozzle in the LASTFIRE test, this foam/nozzle combination did extinguish in the small bund, although it is noted that this was at 21:22 minutes after start of foam application, past the cut off time for the LASTFIRE test of 20 minutes and was the longest extinguishment time observed in these tests. Also, foam F, which did extinguish with the semi-aspirated nozzle in the LASTFIRE test did not manage to reach extinguishment in the small bund test. However, it did extinguish the small bund with the system nozzle which it did not achieve in the LASTFIRE test. These differences may be the result of travel issues around the obstacles or the ability of the foam produced with the nozzle to seal in the corners of the square small bund pan compared to the round edges of the LASTFIRE pan. (It should be noted that the baffles in the LASTFIRE test pan do provide corners which need to be sealed by the foam, two corners forward flowing and two backwards flowing. This aspect is different to other tests and often causes foams to have difficulty obtaining top scores in the tests, especially with the system nozzle used at the low flow rate specified. However, this is an important aspect of tank fires and as such is a relevant feature of the test.)

Ad hoc burnback tests were carried out with foam/nozzle combinations that reached extinguishment and no flaming continued from torch test. Foams E and F generally performed well at burnback. Foam B performed well with the semi aspirated nozzle. In all other cases where burnback test was conducted, there was some degree of continued flaming which required extinguishment with dry chemical extinguisher or further cooling to pan edge.

As a one off test to establish a principle, Foam E was tested on the small bund with double the application rate for semi asp nozzle (from a net rate of approximately 3.7 lpm/m^2 to 7.4 lpm/m^2). When two nozzles were used, the extinguishment time was reduced significantly, but the doubling of application rate did not make any significant difference to the control time or the virtual extinguishment time for this foam. The result, admittedly a "one off", also showed that in practice higher application rates are not necessarily efficient in terms of reducing control times and this observation enhances the opinion that the "sectional" approach using lower application rates can be effective and practical with the proviso that responders should recognise that it is more likely critical areas such as hot metal contact might require additional application to gain full extinguishment. This can easily be covered in training.

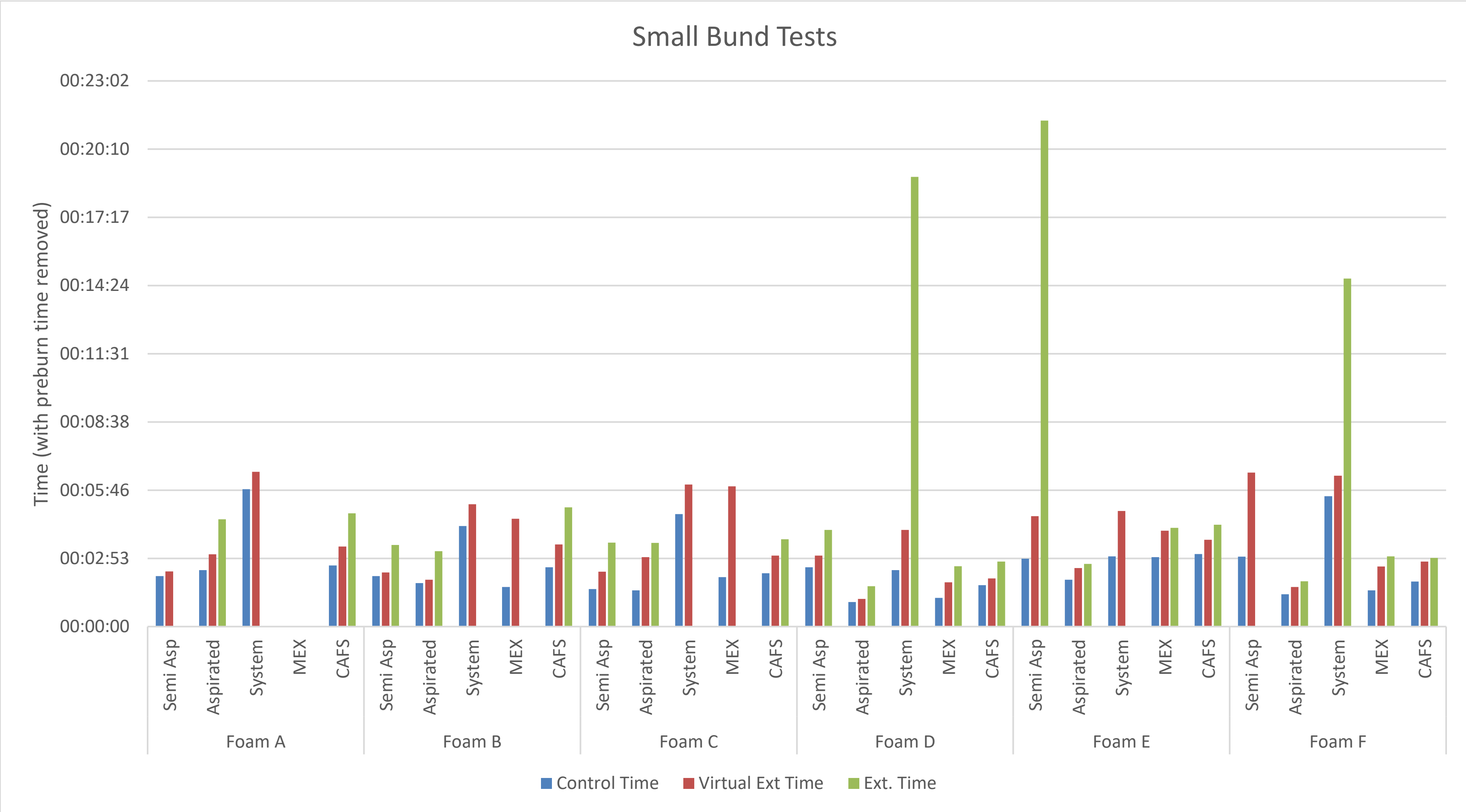

Figure 4.8. Results for the small bund tests carried out – time to control, virtual extinguishment and extinguishment with preburn time removed. Application rates as follows: Semi aspirated, 3.68 lpm/m²; Aspirated, 3.68 lpm/m²; System, 2.53 lpm/m²; MEX, 3.68 lpm/m²; CAF, 2.16 lpm/m²

4.3.3 Large Bund

The results of the large bund tests are shown in two graphs, one with the lower application rates from the small bund (Figure 4.10) and one with the tests carried out at higher application rates that were comparable to those used in the small bund (Figure 4.11). Note that the application rate was increased by using 4 (semi aspirated) or 2 (CAF) nozzles rather than increasing the flow. The first large bund tests were conducted using foams B, D, E and F which includes representation from both foam types tested and these were critical test with lower application rates (effectively half that used on the small bund tests and the LASTFIRE tests). Following an analysis and discussion of the results obtained in the small bund, it was decided that to start, the four best performing foams would be tested with the semi aspirated nozzle, the aspirated nozzle and the CAF nozzle all at an application rate of 1.84 lpm/m^2.

All foams tested reached control with the semi aspirated nozzle at an application rate of 1.84 lpm/m^2 (effectively half that used on the small bund tests). There was a noticeable difference in the time to control between the C6 foams and the Fluorine Free foams tested. Also, all four foams tested with CAF at an application rate of 1.84 lpm/m^2 were able to reach control. Only one foam managed to extinguish with the semi aspirated nozzle although this required a very long time (although this was comparable to the same foam performance in the small bund). It should be noted that three out of the four foams reached virtual extinguishment but two were unable to extinguish the fire with this application rate and nozzle combination.

For the aspirated nozzle at 1.84 lpm/m^2 Foams B, D both C6 foams were able to reach control relatively quickly. However, one Fluorine Free foam was not able to control the fire and the other took significantly longer than the C6 samples. However, for the particular Fluorine Free foam the control time with the aspirated nozzle was only marginally longer than that achieved with both the semi aspirated and CAF nozzles at the same application rate.

Only one foam reached virtual extinguishment with the aspirated nozzle at an application rate of 1.84 lpm/m^2. However, this did not reach full extinguishment. Therefore, no specific conclusions can be drawn from this result, although it does highlight in the difference in foam properties such that different foams appear to be better suited to certain nozzle/application rates and that it is the combination of foam, nozzle, application rate that should be considered.

Only one foam out of the four tested with the CAF at 1.84 lpm/m^2 did not reach virtual extinguishment. Foams B and F achieved extinguishment within an acceptable time, whilst foam E achieved extinguishment but took significantly longer, but this was comparable, but slightly less (approximately 3 minutes) to the extinguishment time achieved using Foam E with the semi aspirated nozzle.

All foam samples (not including the reference foams) were then also all tested using the semi aspirated nozzle at an application rate of 3.68 lpm/m^2 (the same application rate as used in the small bund test) and using the CAF nozzle at an application rate of 2.70 lpm/m^2.

All foams reached control with the semi aspirated nozzle at the 3.68 lpm/m^2 application rate. There was not a big spread in the difference of times to control for all foams, although the C6 foams both recorded slightly quicker control time. Note that foam D reached control with this higher application rate at a similar time to that achieved with the lower application rate. Virtual extinguishment times show the difference in performance of the foams between the smaller bund pan and the large bund pan. Only the C6 foams were able to reach virtual extinguishment with the semi aspirated nozzle. For both of these foams, this was within 15 seconds of achieving control. None of the foams tested were able to extinguish the large bund test with the semi aspirated nozzle at an application rate of 3.68 lpm/m^2.

As with the semi aspirated nozzle, all foams reached control with the CAF nozzle at the 2.70 lpm/m^2 application rate. There was less spread in control times between the foams with the CAF than the semi aspirated nozzle. The C6 foams did perform better in terms of time to control with the CAF nozzle, but this was only marginal.

All foams reached virtual extinguishment using the CAF nozzle at the application rate used. There was no discernible difference between the types of foam in times to achieve virtual extinguishment. All foams reached virtual extinguishment within approximately 50 – 70 seconds after reaching control and reached extinguishment with a similar spread following virtual extinguishment.

Additional Note - Dry chemical compatibility

For several tests where the foam was unable to reach extinguishment, dry chemical was used to attempt to extinguish the fire, noting that where this was applied only flickers remained at the perimeter of the test and thus is was deemed readily accessible for this type of approach. On several occasions following application of dry chemical and extinguishment of the fire it was noted that the foam blanket had been destroyed by the application of the dry chemical. A previous standard *Ministry of Defence Specification DEF-1420, Dry Powder, Extinguishing, Foam compatible* was used prior to the commercialisation of AFFF foams to test the dry chemical compatibility of foams. Alos MIL F 24385 contains requirements for this. It is suggested that these standards are reviewed and potentially used to assess the compatibility of the new emerging foam types.

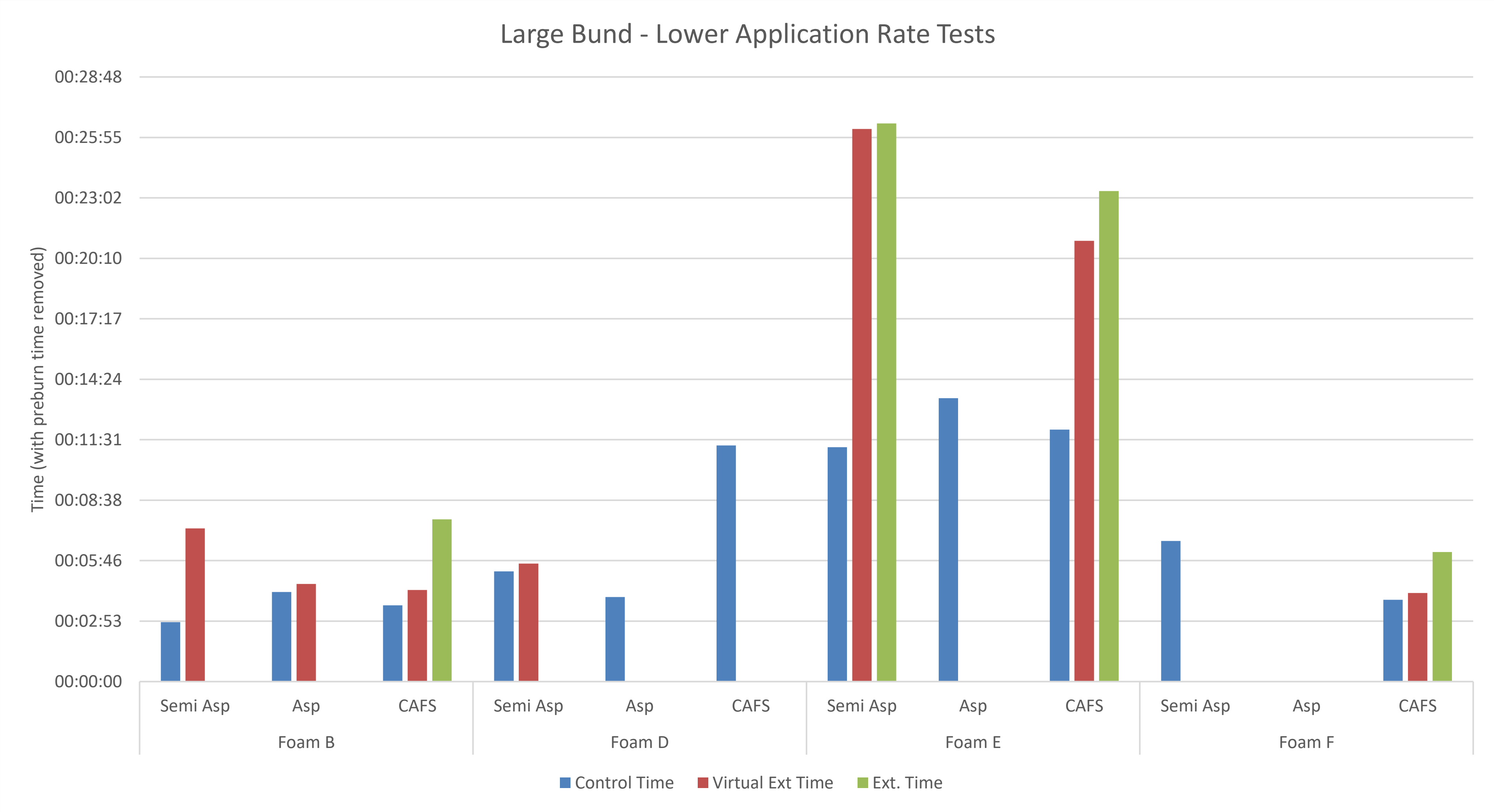

Figure 4.9. Results for the large bund tests carried out using lower application rates – time to control, virtual extinguishment and extinguishment with preburn time removed. Application rates as follows: Semi aspirated, 1.84 lpm/m²; Aspirated, 1.84 lpm/m²; CAF, 1.84 lpm/m²

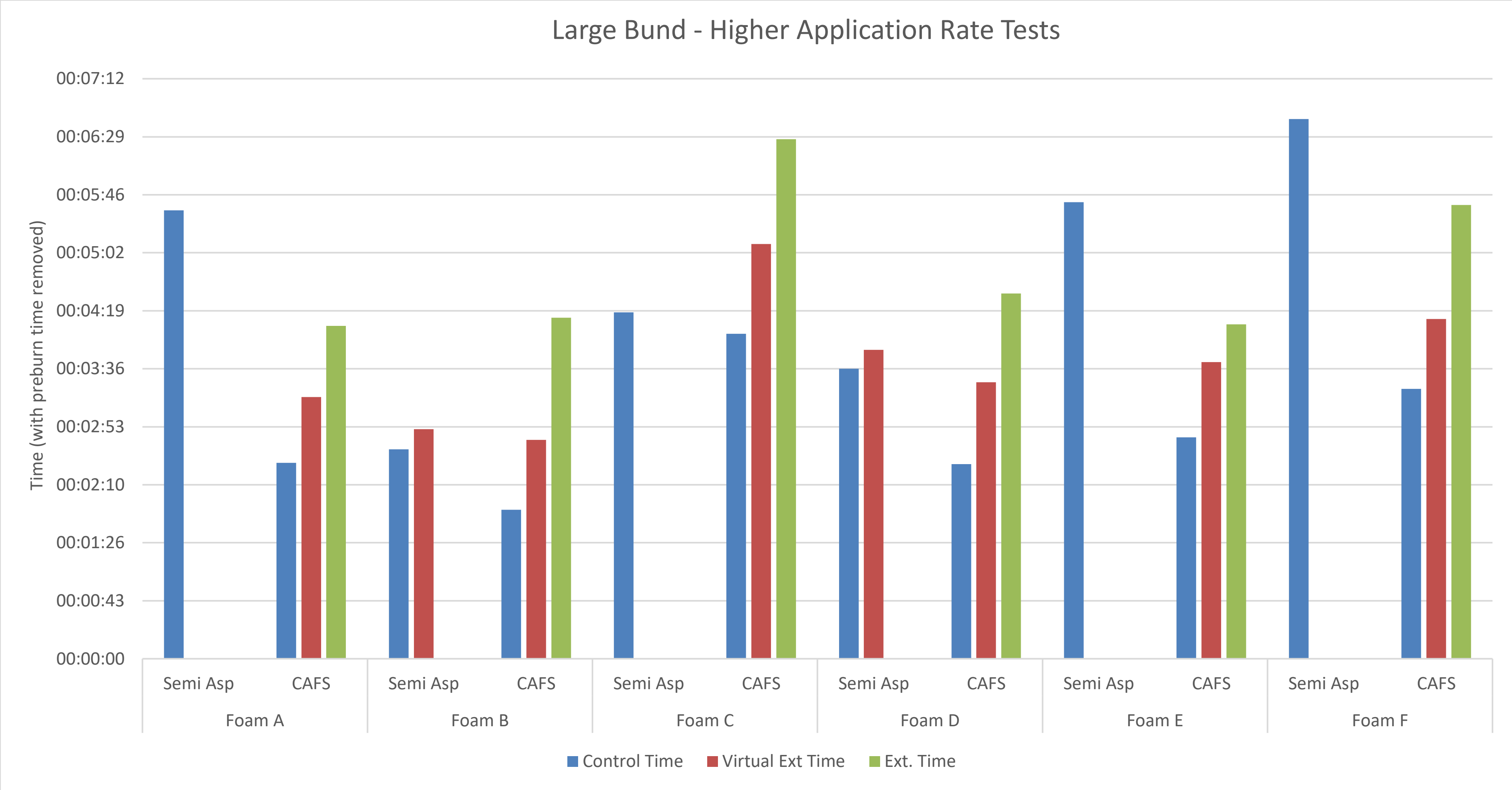

Figure 4.10. Results for the large bund tests carried out using higher application rates – time to control, virtual extinguishment and extinguishment with preburn time removed. Application rates as follows: Semi aspirated, 3.68 lpm/m^2; CAF, 2.70 lpm/m^2

4.4 Phase 1 Comment

Following conclusion of Phase 1, various initial conclusions were drawn. The results also were used to optimise and focus the test required in the following phase.

The phases of the overall test programme were intended as a complete package and whilst specific conclusions could be drawn, related to bund fires, etc. it was not considered appropriate to finalise any conclusions before completion of the next phase. Conclusions from the overall programme are provided in Section 8.

5. PHASE 2 – TANK TESTS

5.1 Objectives

Although many of the overall objectives described earlier apply to all phases of the test programme, the primary objectives of Phase 2 (Tank Tests), were as follows:

- Carry out tank fire tests based on “real life” foam application practices
- Gain a snapshot of current foam performance (C6 and Fluorine Free) on a larger scale test tank in terms of time to control, virtual extinguishment and extinguishment. Note that no specific pass/fail test criteria were intended, the purpose was to establish current capability and to determine if changes in application practices were required to achieve appropriate performance with the new formulations
- Develop understanding of flow characteristics of new foams with various application types.
- Establish whether earlier results obtained in smaller tests could be extrapolated to larger scale (in particular establish whether foam can travel further distances than it does in small scale tests)
- Perform tests that are closer to reality in terms of tank size, height and ambient conditions.

5.2 Tank Test Protocol

As part of the development of the test protocol an international review of potential test locations was carried out. In particular, consideration was given to the following options:

1. A low level tank allowing easier observation of foam flows and possibly foam application less subject to foam losses due to wind conditions. A low level tank could also facilitate removal of any remaining foam blanket between tests
2. A higher tank giving more realistic application conditions but possibly higher impact of wind conditions

After considerable debate, it was concluded by the project Working Group that the preferred option of end users was option 2 because as near realistic conditions as possible was required, especially as the smaller scale test had already established efficiency at lower rates. This was considered more applicable because foam losses have to be accounted for within recognised standards and depend on foam properties as well as environmental factors. (The higher the expansion, the more likely higher losses will be.)

However, limitations were imposed on maximum wind speed during tests (3 m/s). In addition, it was decided that drones would be used to record every test to provide a better visual record of the extinguishing process and to allow confirmation of ground level recordings of control and extinguishing times.

Therefore, NFPA 11 guidance and design parameters were used for the tests as follows:

- Monitor application: 6.5 lpm/m^2 plus allowance for losses (industry practice being approximately 60% additional foam solution resulting in a produced foam solution requirement of 10 lpm/m^2). For information this is exactly in line with NFPA11 taking into account losses. NFPA 11 (2016) Paragraph 5.2.4.2.1 and associated Annex material clearly states that the standard application rates quoted assume that all the foam reaches the fire area and it is necessary to add allowances for losses. General industry practice is to apply a factor of 1.6 giving a total produced foam solution flow rate requirement of 6.5 x 1.6 = 10.4 lpm/m^2. (This gives a loss factor equal to 0.6/1.6 = 37.5% which is considered to be realistic and is used in many recognised industry guidance notes.)

System application: 4 lpm/m^2 (no allowance for loss required as all foam pours into tank)

Prior to the tank tests, repeated burn tests were carried out with the specific gasoline being used to investigate the required volume of gasoline to be added following each test and to determine if significant changes in burning characteristics occurred after initial burning. These were carried out using a square pan, 0.6 m x 0.6 m (surface area of 0.36 m^2) and depth 200 mm. The following protocol was used:

1. Fill test pan with 22 mm water and 125 mm gasoline.
2. Perform five consecutive tests of the 3 minute preburn duration
3. After each 3 minute preburn, extinguish fire using a metallic plate.

Additional tests were also carried out on effect of multiple burns using the same fuel in order to assess the requirement to top up the fuel after each burn rather than replace all the fuel which would not have been feasible from an economic point of view. The gasoline used (see Appendix E) was a relatively narrow band gasoline, mainly consisting of C7 components.

Following these tests and site safety and environmental concerns, it was determined that due to the scale of the tests, a 2 minute preburn and a 250 mm freeboard would be sufficient and that a top up equivalent to approximately 25 mm depth of fuel would be sufficient to maximum repeatability of burn characteristics based on a total burn time in the order of 5 minutes being anticipated.

The large scale tank testing was carried out at GESIP in Vernon, France and used a tank with a fuel surface area of 100 m^2. The tank was approximately 10 m in height.

Only one application rate for each nozzle was used during these tests as follows:

- Application rate of 1000 lpm (10 lpm/m^2) for aspirated and non-aspirated nozzle (referencing NFPA 11 rates, including a factor to allow for drop out from monitor application)
- Application rate of 400 lpm (4 lpm/m^2) for system nozzle (referencing NFPA 11 rates)
- Application rate of 325 lpm (3.25 lpm/m^2) for CAF

Proprietary equipment was used for application.

Note, the application rates were determined on the following basis:-

Monitor application rate conforms to the NFPA 11 standard including the recognised best industry practice of applying a 60% increase in foam solution production to allow for losses.

Figure 5.1. Aspirated POK monitor used during Phase 2 tests

Figure 5.2. Non-aspirated POK monitor used during Phase 2 tests

System application rate complies with the NFPA 11 recommendation of 4 lpm/m^2 and thus both application rates represent real life designs for this size tank.

CAF application rate based on CAF generator constraint and proportioning system. The minimum application rate for CAF for spill fires in NFPA would be approximately 1.6 lpm/m^2. Applying the same principle of a 1.6 factor to allow for losses gives a flow rate of 2.6 lpm/m^2, this would result in 260 lpm for the tank tests, but the minimum flow rate of the CAF generator was approximately 300 lpm. It should be noted that although the applied rate was higher than the NFPA design rate it was approximately 30% of the traditional monitor application rate (300lpm).

Figure 5.3. CAF Unit used during Phase 2 tests

The following test sequence was used for the tank testing:

1. Set up and test proportioning system to be used. It was noted that proprietary proportioners of different types were used during the tests in Phase 2 to be in line with real world incident situations. These were of water driven positive displacement (see Firedos procedure below) and metered flow/controlled pump types.
2. For monitor application tests, position monitor upwind of tank as far as is reasonably practicable and adjust so that foam application into the tank is optimised (during the test this was normally done by checking application into the tank prior to fuel ignition, in which case any foam on the fuel surface was removed prior to the subsequent test)
3. Add fuel to the tank to ensure fuel depth of 150 mm minimum
4. Adjust volume of water in the tank to provide 250 mm freeboard at the start of each test
5. Record ambient conditions (temperature, wind speed)
6. Record temperature of foam concentrate
7. Set up and position relevant nozzle to be used for the test. (Note that aspirated and non-aspirated nozzle application will be from the ground)
8. Start flow to correct rate, take sample if possible and check foam quality (expansion and 25% drainage time) (note not possible for system nozzle tests)
9. Commence filming of tank
10. Ignite fuel and allow 2 minute preburn
11. Apply foam to tank with one nozzle/foam combination at a continuous application rate appropriate to the nozzle being used (see above). Adjust nozzle to maximise foam application on to tank as far is reasonably practicable
12. Record times to control and virtual extinguishment as per definition in previous phase of testing. Use video and drone footage where necessary
13. Record time to full extinguishment if achieved. Note, if based on visual observation only minor edge flickers and/or minor impact zone fires remain and have reached a steady state condition without further control, consider movement of foam nozzle to bring about full extinguishment

14. Abort foam application at 7 minutes maximum, or before if it is obvious if no control is being achieved. If extinguishment is reached before this time, foam application will be stopped on confirmation of extinguishment.
15. Take a sample of the foam to measure foam expansion and drainage time where possible (note not possible for system nozzle tests)
16. Remove any remaining foam on fuel surface prior to next test by application of water spray/jets
17. New fuel to be added in between each test to ensure fresh fuel in tank and to ensure sufficient fuel depth at the start of the next test.

The following procedure was used for the Firedos Proportioning system which was used in the first six tests.

1. Start the water supply, discharge of water through the selected discharging unit only
2. Venting of the suction line and piston pump of the *FireDos* in foam return mode (this is always necessary after changing the foam concentrate)
3. Check the pressure in the water line after the *FireDos* water motor and adjusting of the back pressure in the foam return line to the same value
4. Reading of water volume flow and foam concentrate volume flow, calculation of the real mixing rate
5. Start of the extinguishing test by putting the *FireDos* in operation mode (one 3-way ball valve)

For tests with the same foam concentrate, start with point 3 from the second test onwards.

Figure 5.4. Firedos unit used during Phase 2 Tests

Figure 5.5. Setup of Firedos proportioner with flow meters used during Phase 2 tests

From Test seven onwards, the CTD proportioner from GESIP was used.

Figure 5.6. CTD "metered flow/controlled pump" proportioner unit used during Phase 2 Tests

5.3 Analysis of Results

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

- Due to the application rates and the amount of foam required for these tests, a proportioning system was used rather than premix solution as was used in Phase 1.
- Ambient conditions (air temperature, maximum wind speed and precipitation) throughout the Phase 2 tests were relatively steady. All tests were carried out within ambient conditions dictated within the LASTFIRE protocol.
- It was found that a steady wind in one direction can be accommodated easily by monitor placement, but difficulties would arise if the wind direction was variable during application. It was noted that the consistency of the foam was found to have larger impact on throw capability of the foam through a proportioner. (One foam concentrate appeared to give "lumps" of foam concentrate into the water supply which did not result in a homogenous foam solution prior to the application device, thus causing variations in foam quality produced over time.)

- The two C8 reference foams that were tested in Phase 1 were not tested in Phase 2. The tests in Phase 1 proved that newer formulations were able to provide equivalent performance and as such it was not deemed necessary to further test these foam concentrates. One further foam concentrate was added to the test schedule for Phase 2. This was named Foam G, but with hindsight it would have more appropriately been called Reference 3 as it was selected as a standard proprietary foam sample. The results for this foam are not detailed because it was not provided direct from a manufacturer under the same contractual conditions as the other foams tested or indeed in such a controlled way. However, some useful additional learning points were noted during these tests and these are described in the report.
- Due to perceived concerns regarding the accuracy of continuous proportioning with one particularly viscous foam concentrate the proportioner type was changed to a metered pump type system. It was noted from visual observation of the foam that the same issue seemed to occur. (It is considered that this might be because there was insufficient transit time between the proportioner and the foam application device to achieve a homogenous mix of solution due to the high viscous globular nature of the foam concentrate.)
- If it became obvious that the foam was not gaining control of the fire after a reasonable period, further foam was applied either from the system nozzle or an additional monitor stream. The foam concentrate used as back up in most cases was a Fluorine Free foam and it was noted that where this was necessary, it did not appear to affect the integrity of the foam blanket that had been established with either other Fluorine Free or C6 foams.
- Long term stability of foam concentrate must be proven in some way. It was noted that one foam sample had appeared to from a "skin" during the two main tests series and concern was expressed as to whether or not this was an early indication of degradation. There are some concerns regarding whether the normal approach of using accelerated aging at elevated temperatures is really applicable. However, currently there no other alternative methods known.

Fig 5.7. Foam in IBC seeming to form a 'glossy skin' during storage between test phases

The tests identified in Table 5.1 were carried out as part of Phase 2. Note that these were undertaken in a random order.

Fig 5.8. Tank used for testing at GESIP, France, Fire before foam application

Fig 5.9. Cooling of adjacent tank during tests (note different wind conditions affecting flame drag)

Table 5.1 Test Matrix for Phase 2

Sample	Tank - Gasoline NFPA Application Rates incl. Safety Factor			
	Non-Asp	Asp	Sys	CAF
A		✓	✓	
B		✓	✓	✓
C		✓		✓
D	✓	✓	✓	
E		✓		✓
F	✓	✓	✓	
G		✓	✓	✓

All foams were tested using the aspirated nozzle. The results for these tests are provided in Figure 5.10.

Foams B, C and D all showed similar performance in the tests in terms of time to control, virtual extinguishment and extinguishment. Three of the Fluorine Free foams tested were able to extinguish the fire in the 11 m diameter tank using the aspirated monitor at a generated rate of 10 lpm/m^2.

For foam F, the monitor had to be moved at the start of foam generation because it was noted that foam was not reaching the tank. Following study of the relevant video the control time, virtual extinguishing time and extinguishing time were modified to compensate for this. No oscillation of the monitor was required to extinguish edge flickers around the perimeter of the tank. However, it did take longer to reach control, virtual extinguishment and extinguishment than Foams B, C and D. Foam A was also able to extinguish the fire with the aspirated nozzle. However, since experience of the pattern of control and virtual extinguishment for Fluorine Free foams (from Phase 1 bund tests and the LASTFIRE tests) had been established, where edge flickers can remain for some time after virtual extinguishment, the monitor was oscillated at the end of the test to extinguish the remain edge flickers. This technique worked effectively, and the remaining flickers were extinguished successfully and efficiently. (Note, it is considered that if it is known that this effect is likely to occur then it is easy to preplan noting that oscillation of the monitor is required at the end of the fire to ensure that any remaining edge flickers are extinguished.)

It was noted that Foam A actually reached control before either foam B or F, but then was unable to reach virtual extinguishment as quickly. Foam G gained control after a longer period of foam application than all other foams. However, the nozzle was also moved after 3 minutes 40 seconds of foam application to reduce losses. Foam G was unable to reach virtual extinguishment as it had difficulty extinguishing the foam impact area. This test was eventually brought close to full extinguishment when the monitor stream was moved away from the tank, but remaining edge flickers then lead to reignition of old foam. Full extinguishment was only gained after additional application with other equipment including foam pourer application, which was being fed from a supply of foam solution of a different generic type. The test suggested that the accepted practice of being able to apply separate streams of foam solution of different generic types without significant breakdown of the foam from either stream was still applicable when one of the foams was fluorine free.

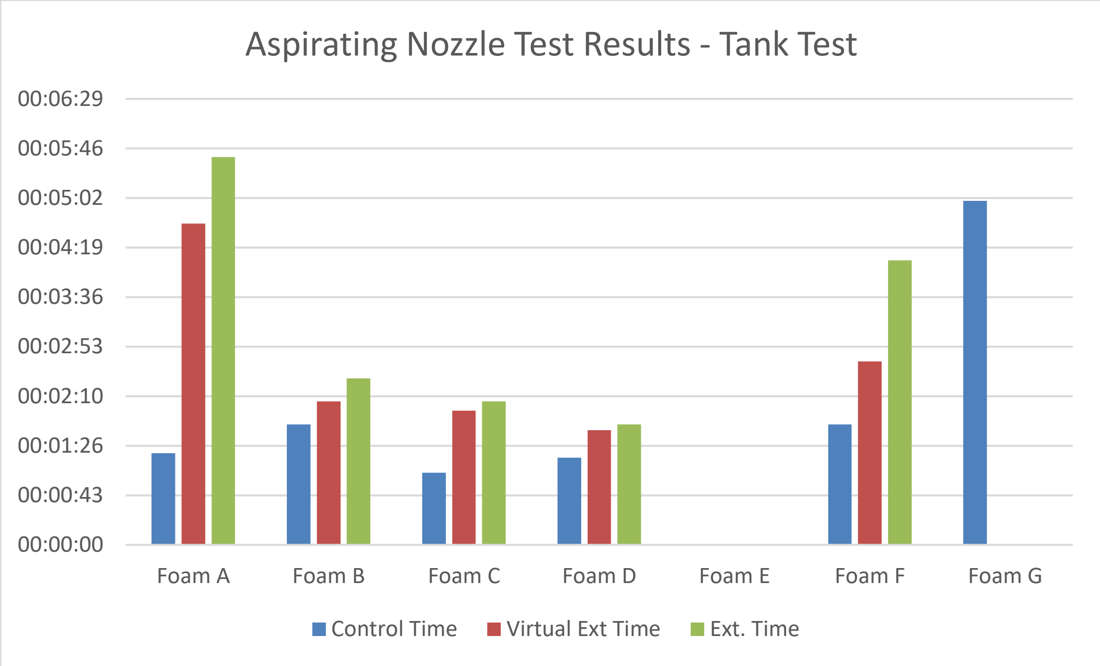

Figure 5.10. Phase 2 Tank test aspirated nozzle test results. Foam Production rate of 10 lpm/m ^{2}

Foam D and Foam F were both tested using the non-aspirated nozzle at an application rate of 10 lpm/m^2, representing both types of foam concentrate being tested. The results for these tests are provided in Figure 5.11. Both foams were able to extinguish the fire with this nozzle. Foam D reached control only 30 seconds faster than foam F. However, the time to virtual extinguishment had a greater variation with foam D reaching virtual extinguishment only 17 seconds after control and foam F taking 2 minutes 5 seconds after control to reach virtual extinguishment. The time for foam F to reach extinguishment was double that of Foam D. These results showed good comparison with those obtained in Phase 1. It was also noted that although foam F took longer to reach control with the aspirated nozzle than with the non-aspirated nozzle, it was able to reach virtual extinguishment and extinguishment quicker with the former. Foam D performed better all round with the aspirated nozzle, in fact extinguishment was reached quicker with the aspirated nozzle than the time to reach control with the non-aspirated nozzle.

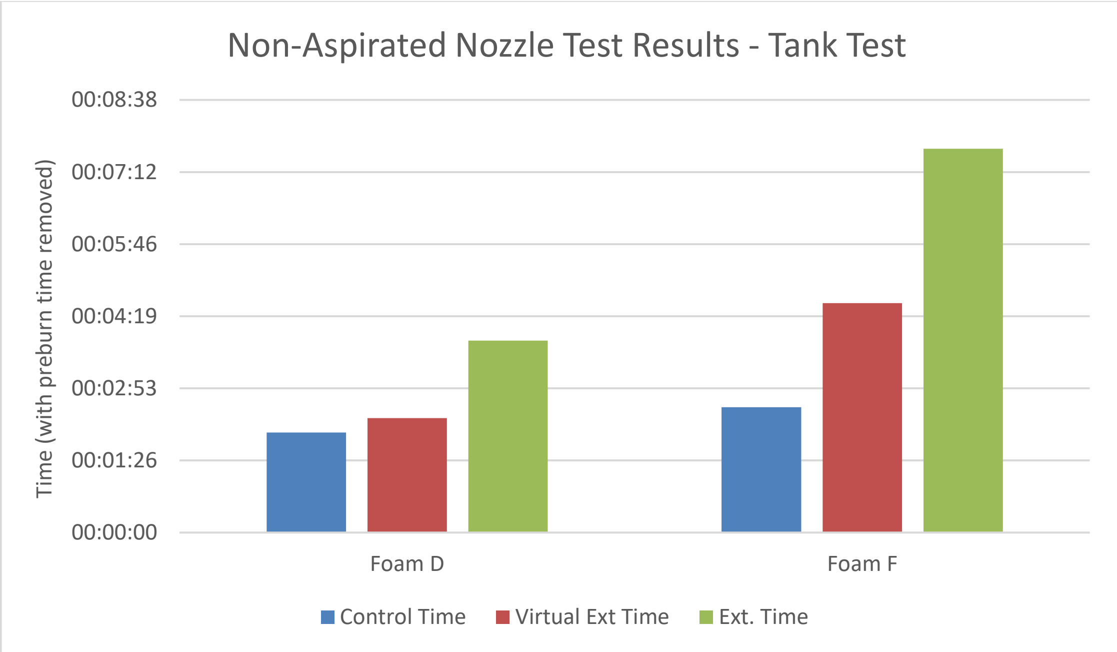

Figure 5.11. Phase 2 Tank test non-aspirated nozzle test results. Application rate of 10 lpm/m^2

Foams A, B, D, F and G were all tested using the system nozzle at an application rate of 4 lpm/m^2. The results for these tests are provided in Figure 5.12. Foams D and F performed better than foams A and B using the system nozzle and were both able to extinguish the fire within 3 minutes of foam application. All foams apart from foam G were able to reach control. For all the foams that were able to reach control, the fire was controlled within 2 minutes 20 seconds or less.

Foam A reached virtual extinguishment soon after control. However, it then took longer to reach full extinguishment from this stage. Foam D and Foam F both took longer to reach virtual extinguishment from control than reaching full extinguishment from virtual extinguishment, i.e. once virtual extinguishment was reached, extinguishment was relatively quick. Foam B (tested at 1% nominal concentration) took slightly longer than foam A to reach control, but then took a further 3 minutes 25 seconds to reach virtual extinguishment and a further 1 minute 5 seconds to extinguish the fire. This was due to the foam struggling to seal at the edges of the tank and unable to control the fire at the impact area. Virtual extinguishment and full extinguishment was only achieved after the foam application ceased, which allowed the impact area to seal (virtual extinguishment) and then extinguishment. This result was very much in line with the results obtained in the LASTFIRE tests with the system nozzle in Phase 1. This demonstrated that the LASTFIRE test is valid, especially when considering the sequence of control, virtual extinguishment and extinguishment.

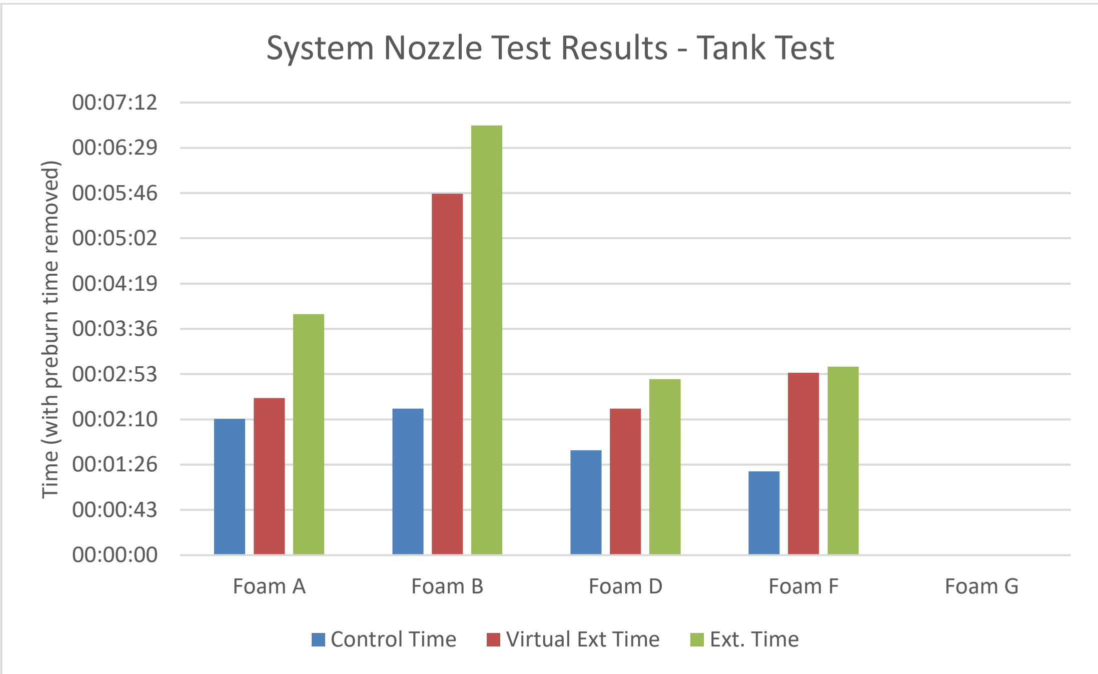

Figure 5.12. Phase 2 Tank test system nozzle test results. Application rate of 4 lpm/m^2

Four foams were tested using the CAF system, foams B, C, E and G. The results for these tests are provided in Figure 5.13. Three of the foams tested reached control in similar times, within 2 minutes 20 seconds or less. For those tested with the semi aspirated nozzle as well as the CAF, times to control, virtual extinguishment and extinguishment was lower with the CAF. Foams B and C performed better with the aspirated nozzle rather than the CAF. However, it should be noted that the CAF tests were performed at a much lower application rate (3.25 lpm/m^2) than that used during the aspirated nozzle tests. Foam E and Foam G performed better with the CAF than the aspirated nozzle. Foam E was unable to reach extinguishment with the aspirated nozzle but did achieve this with CAF. Foam G only managed to reach control with the aspirated nozzle but reached extinguishment with CAF. Foams B and G were both tested with the system nozzle and the CAF, and both performed significantly better with the CAF than the system nozzle. It should also be noted that some difficulty was experienced in ensuring that the foam was able to reach the tank with the CAF. Further work may be required to ensure that a CAF system would be able to achieve the required throw to enable the foam to reach the fuel surface. Note that one foam was tested at a slightly lower flow rate of 300 lpm.

These tests proved similar to those carried out in Phase 1 with CAF that this is a very 'forgiving' system. Foams that did not perform well with other nozzle types were able to extinguish the fire using the CAF.

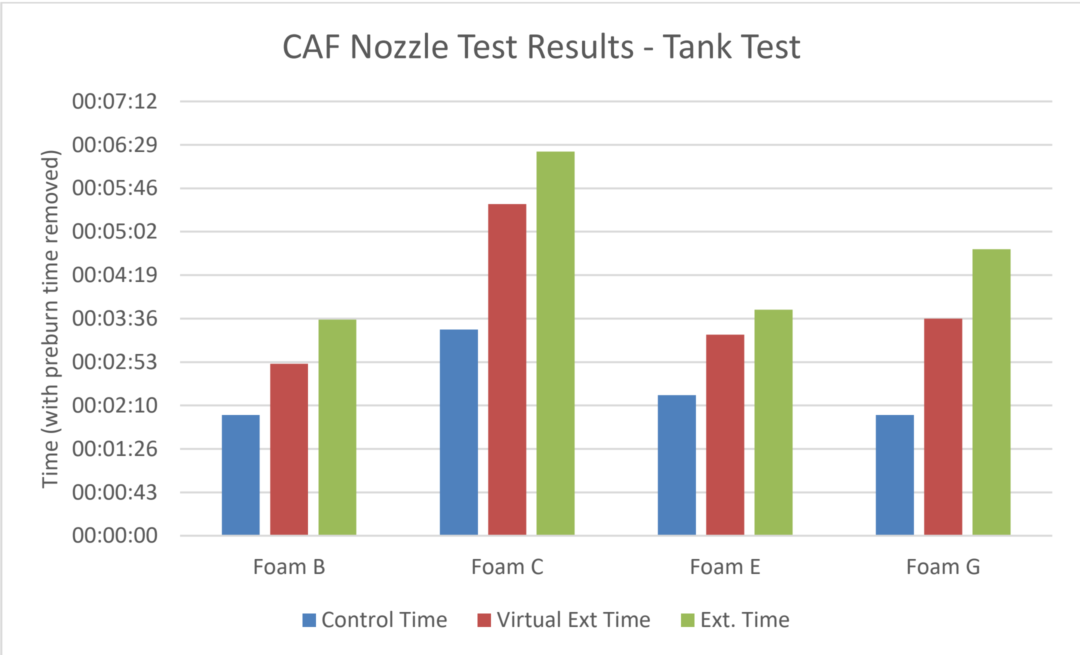

Figure 5.13. Phase 2 Tank test CAF test results.

Many lessons were learnt from the testing, especially as this phase of testing was mimicking the "real world" by use of actual equipment at design flowrates. The conditions of the tests were monitored throughout the testing and these have been taken into account in all conclusions drawn from the research.

It was noted with all Fluorine Free foams when using the monitor application, the foam blanket disappeared quite quickly following the tests, despite the foams measuring a long drainage time when tested. When using the system nozzle application, the Fluorine Free foam blanket was significantly harder to break down when water was applied.

The first CAF test that was carried out was aborted due to the fire extinguishing very quickly despite the observation that the CAF monitor was located too far from the tank to achieve sufficient throw.

5.4 Phase 2 Comment

It should be noted that visual observations with new formulation foams on the tank included "ghosting" and "tunnelling" in exactly the same way as has been observed in small scale LASTFIRE tests. These are critical issues noted with both generic types and emphasise the point that performance was not the same as that observed previously with other formulations.

Another observation with the C6 formulations was the apparent curling away of the foam from the hot tank shell. In some cases this prevented full extinguishment or clearly allowed vapours to escape after extinguishment. Such observations had been noticed in the smaller scale testing including the LASTFIRE test. It is noted that whilst these issues might be readily observed and controllable in bund firefighting, they might be more difficult to manage in tank fire situations.

Example sequences for monitor and system application during Phase 2 tests are provided in Appendix F.

The use of a drone was found be very helpful, indeed essential, to the overall analysis of the tests and provided good vision to the top of the tank during the fire. The Infrared imaging camera used on a drone was also useful and provided some interesting images. However, it was found that this was not as useful as the visual drone camera. Due to the resolution of the image, hot spots (for example, the foam pourer on the side of the tank and the tank rim itself) obscured the location of the fire, especially once only edge flickers remained. It may be that the resolution used would be more effective on a larger tank fire but in general higher resolution cameras and larger viewing screens should be used.

Figure 5.14. Live screen setup for drone footage throughout Phase 2 tests

Figure 5.15. Live streaming of visual drone footage throughout Phase 2 tests

Figure 5.16. Live streaming of Infra-red drone footage throughout Phase 2 tests

6. SMALL SCALE TESTS AND CHEMICAL ANALYSIS

6.1 Small Scale Tests

A series of small scale tests were conducted which raised various interesting points which may be relevant to developing overall polices. The tests were conducted on 0.41 m^2 area pan using forceful application and fresh water with different fuels. Application rate was 2.4 lpm/m^2. These should not be considered as being a standard test but rather some initial work assessing the performance of new generation foams on different fuels. The results using heptane as a fuel generally correlate with the LASTFIRE test results.

However, it was noted that some foams that performed satisfactorily on heptane did not do so on Jet A1. This is of concern as it suggests that the performance of new generation foams, and particularly fluorine free types, might not be as consistent over a range of hydrocarbons as was the case with previous foams.

Some tests were also carried out with water soluble fuels which raised the same issues.

This requires additional testing on a larger scale as part of the next phase of work to establish whether or not it is a critical issue.

Table 6.1 Small Scale Tests Results

	A	B	C	D	E	F	R1	R2
	3%	**1%**	**3%**	**3%**	**3%**	**3%**	**3%**	**1%**
0.41m², Heptane, 2.4l/min.m²								
C90%	0:46	0:28	0:25	0:30	0:26	0:25	0:30	0:30
Ext.	2:05	1:07	2:00	1:54	2:03	2:08	NO	1:10
BB100%	7:00	12:55	15:47	18:35	18:24	27:02		11:40
0.41m², Gasoline, 2.4l/min.m²	**3%**	**1%**	**3%**	**3%**	**3%**	**3%**	**3%**	**1%**
C90%	NO	0:32	1:15	0:46	1:17	0:58	0:31	0:33
Ext.	NO	1:14	1:47	1:29	2:10	1:30	1:12	1:02
BB100%		8:57	7:48	10:10	17:48	26:57	10:42	7:36
0.41m², Jet A1, 2.4l/min.m²	**3%**	**1%**	**3%**	**3%**	**3%**	**3%**	**3%**	**1%**
C90%	0:42	0:20	0:52	0:20	1:40	1:36	0:30	0:29
Ext.	NO	0:26	NO	0:56	NO	NO	0:35	0:31
BB100%		13:32		17:14			15:34	11:40

6.2 Chemical Analysis

LASTFIRE has made an agreement with PERF (Petroleum Environmental Research Forum). PERF, whose members include several LASTFIRE members, is carrying out a project to develop a better understanding of the potential human health and environmental risks of new generation foams. The stated objectives are to:

- Support Risk Based decision making on replacement management of older foams
- Identify gaps and research opportunities
- Support advocacy for effective firefighting solutions and tools.

The samples of foam that have been performance tested by LASTFIRE will be analysed under this PERF contract and the results will be made available to LASTFIRE members at a later date.

7. OTHER OBSERVATIONS

During the tests through visual observations and discussions with suppliers and observers, other points were highlighted that should be taken into account when developing long term sustainable policies for foam application. These include:

- Dry chemical compatibility.
  It was noted that application of dry chemical to extinguish minor residual fires appeared to accelerate degradation of the foam blanket in some cases, but particularly with some Fluorine Free foams.
- Premix stability.
  Some suppliers expressed concern about degradation of performance of premix foam even after only overnight storage. This would not be a problem with most systems for storage tank application but might be in extinguishers or other premix situations.
- Foam Concentrate Stability
  There was a period of approximately six months between Phase 1 and Phase 2. During this period, the foam samples were kept in secure locations prior to transport to GESIP. In some cases it was noted that there appeared to be some separation of the foam concentrate or development of a skin on the foam concentrate surface. This raises the importance of assessing the long-term stability of foam concentrates.
- Air Entrainment
  It should be noted that air can be entrained within viscous foams during production or transport and this can have a significant impact on proportioning accuracy using conventional equipment. The vast majority of equipment is based on a volume ratio as per the official definition of Expansion. This should be addressed in procurement specifications to ensure maximum permissible air entrainment levels.
- Concentrate Viscosity
  It was apparent that some constituents of a foam concentrate that improve fire performance have a major effect on viscosity. In extreme cases the viscosity could be such that emptying of containers manually or by proportioners would be difficult if not impossible. In less extreme cases it might still be necessary to review all storage and logistics policies to ensure a continuous supply of foam concentrate. (For example, it might be the case that when IBCs

are manifolded together to form a bulk storage unit preferential suction from the nearest container will occur and prime will be lost when that container empties.)

- Stability of Foam Blanket
  It was noted that in some cases although a foam blanket looked very stable initially and gave long drainage times in fact it collapsed relatively quickly on the fuel surface.
- Application of different foams simultaneously
  In some cases when a foam failed to extinguish a fire an additional foam of a different generic type was applied through a separate stream. It was noted that this did not cause any significant breakdown of the foam blanket that had been achieved. It is not known whether this would be generally true for all foam concentrates.
- Seawater usage
  Tests involving seawater were limited to the LASTFIRE standard test. There were significant differences in performance noted between fresh and seawater application. Therefore, for seawater applications it is critical that the foam concentrate is specifically tested with a relevant standard saltwater solution.
- Foam performance standards
  It was noted that some of the foams tested claim to have EN or UL certification. However, significant differences in tank fire performance were noted. This confirms that whilst these standards are very useful and relevant to general purpose application, the LASTFIRE test is more critical in terms of the specific requirements of tank fire application.

8. GENERAL FINDINGS AND CONCLUSIONS FROM RESEARCH

The following is a list of the general conclusions made from all phases of the test programme. Section 9 below provides the key findings which have a major impact on current knowledge and the development on longer term policies.

- No new generation foam should be considered to be an absolute drop in replacement for any existing foam stock. Even if appropriate fire performance is achieved, compatibility with existing equipment, particularly proportioning equipment, and potential issues such as greater difficulty in sealing against hot surfaces must be considered by responders.
- Some C6 formulations have similar if not better performance that some of the earlier proven C8 formulations based on small scale testing (but it should be emphasised that the C8 types tested were relatively old samples).
- Although in Phase 2 it was shown that it is possible to extinguish a 11 m diameter tank fire with C6 and Fluorine Free foam, the need to optimise the combination of application hardware, proportioning equipment, foam concentrate and application rate was highlighted. (i.e. an “engineered package” approach should be taken.)
- Undoubtedly more attention should be paid to optimising the combination of foam type, application rate and application method. Testing of specific combinations is critical to effective performance. Unfortunately, recognised system design standards do not emphasise this issue.
- The application of CAF is very “forgiving” of different foam performance capabilities in the sense that it creates a levelling of all foam types, thus further demonstrating application technique and foam properties are as important, if not more so, than the foam concentrate type itself. It should be noted that this improvement in performance was obtained at approximately 30% of the application rate using conventional techniques.
- The “recognised” large bund section by section application approach can be (and has been) successful but responders need to be fully aware of potential issues regarding edge/obstruction fires and topping up foam blankets.
- Premix stability of foams must be assessed for those applications where premix storage or transit time is more than a few minutes.
- The application of dry chemical needs to be considered as part of overall performance testing and procurement as it was shown that some formulations have poor compatibility.
- Physical properties must also be taken into account during any procurement process as the changeover to any new foam might require changes to equipment, especially proportioning systems. In reality this has always applied when changing foam concentrates but has not always been done. This work has highlighted that it is particularly important when changing to a new generation foam.
- Virtual extinguishment may be a better measure than full extinguishment for bund fires as It is considered that in reality virtual extinguishment would be extended to full extinguishment by the further application of foam in specific areas which were still ignited such as tight corners depending on the equipment being used, the bund layout, physical properties, depth to fuel level in the bund and access to those areas that need additional foam.

- Overall the LASTFIRE test does correlate with other tests using gasoline and the bund fires, so it is considered to still be valid. However, there are some developments that could be made to improve and widen the applicability of the test.
  1. Inclusion of a CAF nozzle into the test protocol
  2. Further development of the Medium Expansion nozzle for use with those products that are specifically identified as suitable for use as low or medium expansion foams. However, this is not seen as a major priority (see bullet point below)
  3. Development of additional foam system nozzles so that those types which specifically push a foam against the tank wall as well as those which direct the foam down the wall into the fuel are evaluated in the test.
  4. Consideration of a change from 'control' evaluation to 'virtual extinguishment' evaluation, or the addition of the latter with improved definition and clarification of criteria
  5. Revision of scoring system to reflect greater emphasis on virtual extinguishment and full extinguishment.
  6. Modifications to the test protocol, mainly regarding the burnback test. It was noted that removal of the burnback pot can be difficult (cleaning out remaining foam, dripping fuel as it is removed, foam expansion tends to be higher with new foam formulations and burnback pot might be too short). Older formulations of foam tended to dry out during the test period, thus allowing relatively easy removal of the foam from inside the burnback pot. With many new formulations this drying out does not occur, but the foam becomes much more fluid, thus any foam above the level of the burnback pot no longer stands up but falls freely into the pot. A burnback pot should be developed (with a bottom) with same diameter as LASTFIRE test burnback pot (0.6 m high).
  7. A standardised design and methodology for torch test should be developed. E.g. rather than moving the torch around the whole circumference of the test pan and across the surface, hold the torch in specific pre-defined locations for a certain period of time. The design of the torch should also be considered to ensure that there is sufficient flame but not too much such that it is difficult to control.
- Good correlation between the Medium Expansion nozzle and the aspirated nozzle was observed in both the LASTFIRE test and the small bund tests for those foams which could expand to medium expansion. Therefore, it is not considered a major priority to develop this further. Note that some foams tested were unable to expand to medium expansion.
- There was good correlation between the LASTFIRE test results and the bund test results, especially with the semi aspirated (non-aspirated) nozzle in general for the C6 foams. There was not such a good correlation for the FFs (but note comments after Phase 2 tests).
- It should be noted that in all tests, some foams did extinguish finally after a considerable time following the end of foam application. In reality this is not what is required so, although these times have been noted so that effects can be observed, these times were not considered any further in comparison to those which extinguished during the application of the foam. For example, an anomalous result was obtained using Foam E in the large bund tests with semi aspirated nozzle at an application rate of 1.84 lpm/m^2. This result is unreliable as this foam did not extinguish in further tests on the large bund with 4 semi aspirated nozzles (application rate of 3.68 lpm/m^2). This extinguishment may have been achieved with the help of external conditions such as wind gusts.

- Drainage times were measured for all tests. Many foams showed very long drainage times in the test (note cut off time is 30 minutes, which many foams went beyond) which did not actually correspond to those observed during the actual test and once the test was completed, i.e. the foam disappeared quicker than expected in the test pan if comparing to the drainage time achieved in the test measurement.
- It was noted that when the application rate in the Phase 1 tests using CAF was increased this had a greater effect on reducing extinguishing time for Fluorine Free Foams than it did with C6 based foam. This suggests that the higher rate was already in the "overkill" region for the C6 based foams in the earlier tests with this type of application where increasing application would result in much greater extinguishing efficiency.
- It was proved during the larger tank tests that Fluorine Free foams were able to extinguish an 11m diameter tank fire using NFPA 11 application rates (including a standard industry factor increase for dropout rates).
- It was found that certain foams were difficult to proportion correctly with various types of proportioning equipment due to their viscosity and potential air entrainment. This proved that it is not a straightforward exercise to simply proportion any foam at a given concentration with equipment and be confident that it is correct.
- Although CAF application demonstrated efficiency in these tests further consideration should be given to ensuring that a CAF system can achieve the required throw and flow capability across the fuel surface.
- The patterns observed during the LASTFIRE tests mimicked that observed in the larger scale tank test which proves that the LASTFIRE test is valid for the purpose of storage tank fires. The characteristics observed in both the LASTFIRE test and the tank test included:
  1. Time to control and extinguishment correlations
  2. Foam flow around the tank
- The issue identified in the small-scale tests of some foams performing poorly on higher flash point fuels than on lower flash point fuels was not observed on earlier foams and needs to be assessed in more detail to see if it is observed in larger scale tests.
- It was also noted that the foam pourer used in these tests was in place on the side of the tank throughout the test programme. This was still able to perform well despite being in situ during several fires prior to use and demonstrates the potential survivability of such equipment in real situations.

9. KEY CONCLUSIONS

The notes below list the key conclusions from the research project to date which have a significant impact on the future development of sustainable long-term policies for foam application. Note, whilst this list includes some specific comments for policies that could be implemented, these should not be seen as prescriptive. Ultimately LASTFIRE is providing information that assists end users in developing their own site-specific policies.

- Although there is a tendency to be generic in comments regarding foam types, realistically this is a too simplistic approach because there are good and bad example for every foam type. What is critical is to assess actual performance related to specific applications, whatever the generic type of foam. *i.e. the results show that you cannot make statements such as "all AFFFs are better than all Fluorine Free foams" or vice versa.*
- A detailed performance-based procurement specification is critical to assuring efficient foam application. *(LASTFIRE has produced a typical procurement specification and will revise it in accordance with the results of this research.)*
- New generation foams, of both C6 and Fluorine Free formulations at standard rates can provide satisfactory fire performance for bund spill application provided responders are made aware of any potential limitations identified in critical tests *(e.g. difficulties in sealing against tight corners or edges with some foams).*
- The tank fire tests have shown that new generation foams of both C6 and Fluorine Free types can be used at NFPA 11 application rates for these limited sized tanks, but additional work is required to validate for larger incidents, including work on optimising foam properties and application techniques.
- An optimum combination of the application system and the foam is key to efficient foam application as some foams clearly work better with certain nozzle types. *(It is not necessarily the case that a foam that works better with one nozzle will work better than another foam with a different nozzle.)* It was also apparent, from visual observation of the foam stream, that given the same atmospheric conditions and equipment, the dropout rate for monitor application also varied with foam concentrate. This was considered to be due partly to different expansion and stability achieved with the different foams through the same equipment but highlights the need to optimise equipment and foam concentrate combination.
- Current standards do not sufficiently take into account the combined effect of foam concentrate, finished foam properties, application rate and application method as a total engineered package. *In reality it is the combination that determines performance, but standards tend to suggest that the most critical issue is application rate by itself provided a foam is of reasonable quality such as having UL listing. In practice this is far too simplistic and more efficient foam application can be achieved by greater emphasis on the overall "package" of these features. This is true for all application methods such as semi-aspirating and aspirating but is most obvious when considering CAF application – the results have clearly shown that a "good" CAF system application can be very forgiving of foam quality in the sense that even though major differences were observed with some nozzle types, CAF provided very similar virtual extinguishing times and extinguishing times across all foams tested in the large*

bund tests. CAF was also found to be forgiving on foams that had not performed very well with other nozzles, even at a low application rate in the tank tests.

- There should be a recognition that there are options – simplistically a higher quality foam at one rate or a lower quality foam at a higher rate! *There is an opportunity with the advent of new generation foams to revise standards to recognise this. Potentially there is a benefit in terms of pipe sizing, logistics, pump sizing and storage capacities.*
- It should be accepted that whereas manufactures were generally at the same level of development for earlier generation Fluorosurfactant based foams, they are not all at the same level for new generation foams, in particular Fluorine Free foams. This might be because different manufactures have placed different emphasis on this subject. *It is obvious based on ad hoc comparison with earlier test that new generation foams have improved in performance as developments are taking place.*
- Based on the long-term experience of LASTFIRE testing it should be realised that manufacturers are able to modify formulation to optimise performance with particular application techniques. For example, a foam that shows "Good" performance with a semi-aspirating nozzle might only demonstrate "Acceptable" performance with an aspirating nozzle and vice versa. This is not intended to suggest that manufacturers deliberately create formulations for specific tests. It demonstrates though that end users should be very clear on what performance characteristics they require based on the equipment they will be using and select a foam that meets these requirements. For example, if a site only uses aspirating foam nozzles then a test result with a semi-aspirating nozzle is not relevant.
- It has to be recognised that some manufacturers market similarly named products but with different formulations and the difference might not be obvious. For example, some manufactures will develop a special formulation to pass MIL F 24385 with a very similar trade name as another grade and it is only when the small print is read that the difference becomes obvious.
- It is the LASTFIRE opinion that the tests have clearly shown the ongoing need for batch testing especially as new formulations are developed and refined – and the batch testing ideally should include physical properties and proportioning tests.
- The procurement has to take into account a combination of factors (fire performance, physical properties and environmental performance), possibly including larger tests to demonstrate flow at this stage.
- Although it has been shown that with good quality foams and optimised application equipment FF foams can be used with forceful application.

10. FOAM APPLICATION STRATEGIES

It has been noted that in some areas where there has been strong pressure to move towards fluorine free foams that facilities have adopted a policy of using fluorine free foam in rapid response spill fire situations such as limited size bund spills but maintaining stocks of other foams with proven performance for larger incidents – and ensuring that plans are in place to contain as much firewater and foam effluent as possible and have formal plans in place for its proper disposal.

The test results vindicate this approach provided a good quality fluorine free foam is selected. However, it is considered that this should not yet be recommended as a universal approach until more data is available from further testing as the ideal situation is to have a single foam on site in order to minimise the possibility of cross contamination or other logistical issues. That being said the plans to contain as much effluent as possible and dispose of it in a suitable way should always be in place whatever foam is used.

11. PROPOSED FURTHER RESEARCH WORK

Much has been achieved with the current work, but it is emphasised that further work is required prior to full acceptance of new generation foams and, in particular, fluorine free foams. This should be seen as an opportunity to develop new standards and protocols on a realistic and rational basis.

In order to obtain a full picture of the current performance requirements for tank applications, it is considered that the following work needs to be carried out. It should be recognised that other aspects such as corrosion data, environmental concerns also require further work.

- Revision of LASTFIRE test specifications to take account of conclusions
- Revise the LASTFIRE typical procurement specification to take account of research conclusions
- Undertaking tests of new generation foams in a larger test facility to establish flow capability (ideally up to at least 50 m)
- Small scale testing of tolerances in proportioning rates (1% up to 1.3%, 3% up to 3.9% and 6% up to 7%) to see if there is any difference in performance (control and extinguishment times)
- Development of a test for the compatibility of dry chemical with current foams on the market (using the Ministry of Defence Specification DEF-1420, Dry Powder, Extinguishing, Foam compatible as basis for development of a test procedure)
- Small scale testing mixing the foam with fuel to see the effect/fuel tolerance of the foam.
- Testing using different fuels, particularly alcohol type fuels/crude, etc.
- Development of a LASTFIRE small scale test to provide a cost effective initial analysis of foam performance on different fuels and the effect of different preburns, proportioning rates, etc (some test facilities and some manufacturers use such procedures and these could be reviewed as the basis for the small scale LASTFIRE tests)
- Testing using subsurface systems
- Review of optimisation of properties, including throw characteristics (including CAF and different application techniques)
- Further saltwater compatibility testing
- Develop specification for testing of vapour suppression capabilities for new generation foams

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Appendix A – Bund Fire Literature Review

BUND FIRE TESTING LITERATURE REVIEW

Contents

1. Introduction

Bunds (Dikes) are used extensively in the process industries as a safety structure to provide secondary or tertiary containment for the prevention of release/spread of hazardous liquids to the environment should the primary containment, the tank, fail [1]. Bunds are also often used to segregate and group tanks according to their contents classification [2]. As an example of other possible design considerations, in the UK it is required that a bund be constructed if the oil storage tank falls within 10m of a watercourse, or if within 50m of a potable water supply or where spillages could run into drains or reach controlled waters [3].

All tank operators conforming to best practice guidelines will implement spill prevention measures such as tank design specifications, regular tank inspections, corrosion monitoring, operating procedures, tank contents monitoring and minimising pipework connections. However, losses of containment can still happen and the spill can be ignited. (LASTFIRE data showed that of 180 reported spills into the bund, 5 bund fires occurred.) However, large area bund fires are relatively rare events due to these measures being put in place and thus there is very limited experience gained related to managing such incidents.

There is an extensive volume of literature widely available regarding bunds, their use, construction and purpose. It is the aim of this literature review to provide a brief overview of these areas, and to focus on the data available on previous bund fire incidents, how they were managed and the severity of their consequences. Typically, the term "large bund fire" would be considered as referring to an incident in the order of 2000m^2 or more. (The Large Bund Fires Best Practice in Emergency Response Report by the International Forum for Industrial Fire-Fighting (IFIF) [4] qualifies a large bund as having a net bund surface greater than 1900 m^2.)

As mentioned above, minimal data exists on large bund fires from actual incidents and, because of the cost of large scale tests and the recognition of the relatively low risk, there has only been limited test work carried out. [4]. The majority of testing in this area of research has focussed on small bund fires, highlighting the need to understand how these differ from other fire types or establishing appropriate foam application rates and how they should be managed. Thus, there is little proven data on which to develop best practice standards for large bund fire response.

A spill/leak into a bund can occur following a number of events, including:

- Failure of primary containment/pipework causing a leak into the bund area (local weather conditions or equipment/instrumentation failure, or corrosion in the tank bottom (Crude oil spills from tanks at a Kaohsiung, Taiwan refinery in 2002 and at Fawley, Hampshire in 2002 were the result of corrosion of tank bottom [5]).
- Overfilling of the tank (overfill ground fires are common to fixed-cone roof, internal floating roof, external floating roof and domed roof tanks [2])
- Boilover of tank contents
- Poor firefighting techniques for a tank fire - overfilling, splashing of contents or possibly causing tank damage through inappropriate cooling actions

Ignition of a fire in a bund following a spill or leak could result from a number of ignition sources, including hot work in the vicinity of the bund, static electricity, hot surfaces, lightning/weather effects, or vehicles. Ignition of a fire in a bund can have significant consequences, including the spread of fire to tanks within the bund area, and additional radiant heat to adjacent tanks or other equipment.

It should be noted that a bund fire, if badly managed may result in the discharge of the flammable liquid and firewater that is being used to control the fire, with potentially significant environmental effects.

2. Good practice on bund construction/integrity

There are several different types of bund construction; the choice of design depends on requirement for access, space and type of facility amongst others. Designs of bunds include ramp type, humped or square bund [6]. A bund can also be divided into smaller areas using walls of a lower height. These walls can minimise spread of liquid in the case of a limited quantity leak/spill. A further option for secondary containment is the use of double shell tanks, which are similar in principle to a bund but have a smaller surface area but are much higher.

When designing a bund, the following should be considered:

- Location of pipework into and out of bund
- Pipework transits through bund walls.
- Level detection methods
- Access requirements
- Access/Egress for firefighters
- Collection sump/drainage requirements

There are a number of key design considerations for bund construction/integrity which are discussed here in further detail [7]:

1. *Bunds should be impermeable*

    The impermeability of the bund is also of concern when considering the integrity of the bund. Typically local regulations demand that secondary containment must be ‘liquid-tight’, i.e. impermeable to oil and water with no direct outlet [3]. Some bunds are designed to include impermeable liners [1], although currently there are no universally agreed European or International Standards, materials classifications or performance requirements for bund linings [8].

    The Energy Institute has published guidance [9] providing a framework for facilities where lined bunds are expected as the principal type of secondary containment. Also under development is a project aiming to test the fire resistance properties of commercially available sealants, for bund wall pipe penetration and construction joints, against a suitable performance standard. (LASTFIRE coordinators have been partially involved in this work.) This is in part due to the range of requirements and applications, including materials compatibility, environmental concerns and operating temperatures, which have to be considered when designing a secondary containment system.

2. *Bunds should be designed to have adequate strength and durability*

It is currently accepted good practice that a bund should have a durability life of 50 years or more unless specified otherwise [7, 10]. If a tank within a bund catastrophically fails, the bund construction will be subject to large impingement forces, so it is necessary that the structure is capable of withstanding these. The following typical industry standards provide additional guidance:

API 650 *Welded Tanks for Oil Storage*

BS EN 1992-3:2006 *Design of concrete structures. Liquid retaining and containing structures*

3. *The minimum number of tanks as far as is practicable should be contained within the bund*

The number of tanks that are contained within a bund should comply with standards which detail best practice in regard to separation distances between tanks. (e.g. Energy Institute Model Code of Safe Practice, Part 19 *Fire precautions at petroleum refineries and bulk storage installations* and UK Health & safety Executive Guidance HSG176 *storage of flammable liquids in* tanks for additional guidance.)

4. *Bunds should be designed to contain the minimum capacity as defined within relevant guidance (see section on bund sizing issues below)*

5. *Bunds should be designed to include a method for removal of rainwater*

A bund should contain a mechanism for drainage of rainwater. A sump or drain at a low point in a sloping floor is usually integrated into the design. This should typically have a manual valve (normally kept closed to ensure that any spill/leakage is not discharged to the drain). It is normally the case that any rainwater is directed to an oil separation unit prior to eventual discharge. The valve is a critical element as it might fail or be left open due to human error/not maintained correctly. The capacity of the bund will be reduced if rainwater is not removed from the bund. If intermediate walls are used, then drainage between sections should be considered to ensure that full drainage of the bund is possible depending on the location of the drain.

6. *Pipework should not penetrate bund walls or floor where practicable*

Pipework to/from the storage tank should ideally pass over the bund wall rather than through the wall or floor. If this does occur, then the joint between the pipe and the bund construction should be sealed with an oil resistant and fire resistant material to ensure that the bund remains leak-proof [3].

7. *Bunds should have adequate fire resistance and corrosion resistance where necessary*

All parts of bund construction and joints should be resistant to corrosion by water and the contained liquids. Fire resistant sealants should be used on bund joints to provide protection of bund integrity in a bund fire situation.

8. *Bunds should be inspected/maintained regularly*

It should be noted that maintenance of bunds is also of high concern when discussing the integrity of a bund. An inspection regime should be in place to ensure the continued integrity of a bund. Inspection of the bund area should also consider the mechanism for drainage of any rainwater (testing valves).

It is also typical practice to include some type of leak detection system in a bund to enable detection of a spill into the bund. A number of different detectors are available which can be used in a bund, including sensors based on changes in refractive index, conductivity and flow. Point type Infra-red absorption detectors (detection flammable gas) at strategic points around the bund (e.g. valves and drain line outlet) would provide detection of major spills of volatile fuels into the bund.

The failure of a bund and/or secondary containment may occur as the result of the following:

1. Bund unable to contain volume of liquid from tank

An incorrectly designed bund may result in the inability to contain required capacity in the result of an accident. Note that the bund may have been originally designed correctly, but if alterations are made to the tanks contained within the bund without consideration of the bund capacity this situation may also arise. A number of incidents where this has occurred are reported in literature (Umm Said, 1977; Australia, 1986)

A sudden primary containment failure resulting in a surge of liquid may cause failure of the bund structure, either due to the dynamic pressure associated with the impact of the liquid or the impact of the tank structure itself [15].

This scenario may also result in the overtopping of a bund wall. Therefore, although the bund may retain its integrity, secondary containment will fail to contain the spread and discharge of the stored liquid. A number of examples of incidents where this has occurred are reported (Ponca City, 1924; Floreffe, 1988; Long Beach, 1992) [11].

If two or more tanks in a common bund fail, it is likely that the bund will be unable to contain all liquid spilled, even if designed correctly to best practice guidelines.

2. Release from bund due to bund valves open

Valves in the bund construction are a potential single point failure of the secondary containment. These may fail due to lack of sufficient maintenance, incorrect design, etc. It is good practice in maintenance and operation for any valves in a bund to be left closed at all times (not to be left open).

3. Poor bund design/maintenance

An example of poor bunding design or maintenance is that seen at Buncefield, where the bunds were not impermeable and not fire resistant. This resulted in the inability of the bunding to handle large volumes of firewater used during the incident [12].

It is possible even if the bund wall remains intact in the event of a tank failure, that some material will be lost due to the energy of the wave of fuel from the tank in such a situation. Estimates from incidents have calculated that losses range on average from 25% to 50% of the original contents [13], with losses from earthen bunds or constructed embankments often higher than a vertical bund wall. Some experimental work has been carried out [14] to examine the flow of liquids over existing bund designs. This work had the objective to investigate if mechanisms could be retrofitted to existing bunds/tanks to minimise the overtopping potential. This included investigating the usefulness of a horizontal 'lip' on the top of the bund, as well as modifications to the primary containment to limit the magnitude of the dynamic pressures resulting from a surge of liquid.

When constructing a bund some thought should be given to the location of emergency response equipment (in relation to potential radiant heat flux and accessibility) and fire fighter access, both to the required equipment and also staging of fire response resources. This includes road access, height of bund wall and distance between bund wall and the tanks in contains.

3. Bund sizing issues (fire water)

Although in some cases bunds might be sized to take only 100% of the volume of the largest tank within the bund, typical industry guidance and regulations state that the volume of the bund should be equal to 110% of the tank volume (or 110% of the largest tank volume or 25% of the total capacity, whichever is greater if more than one tank is located within the bund) [3, 15]. The extra capacity is intended to allow for the addition of cooling water and foam solution discharged into the bund during response to an emergency. The USA based code NFPA 30, Flammable and Combustible Liquids Code, states that Class I – Class IIIA liquids shall be contained in the event of a spill or rupture, and that the containment system be large enough to hold the contents of the largest tank, i.e. 100% volume ratio. It is also typical practice to limit the number of tanks in a single bund to a 60,000 m^3 total capacity [15].

It should be noted that rainfall contained within a bund is normally controlled by regular inspection (especially after periods of heavy rainfall) and should be removed/drained from the bund as soon as possible so that it does not compromise the bund capacity.

The height of the bund wall can vary and there are no set rules prescribing the ratio between bund wall height and bund floor area. A bund wall with a height of 1-1.5m is often used so that application of firefighting agents is relatively straightforward. [15]. A high bund wall (greater than 3 m) will make firefighting response much harder as it will be difficult to observe the progress of fire extinguishment in the bund [4]. However, a low wall height would not necessarily provide a defence against overflow from catastrophic failure of a tank. The height of the bund wall should also consider the distance between the tank and the bund wall – the closer the bund wall to the tank, the higher the wall will be to provide the required volume. The height of the bund wall will also impact on the application of firefighting foam, it has been recommended that a freeboard of not less than 100mm [7] is provided for this, and this should be considered when designing the bund wall height when assessing potential spills/leakages. However, in reality such a small freeboard is unlikely to be sufficient in very large bunds as foam depth will vary considerably from place to place.

Figure 1. Example of a bund following a fire event with product and foam

4. Bund Fire Modelling

Modelling can be used to determine the geometry of the liquid pool spread, vapour dispersion and pool fires (height and temperature of the flame) and these models can be used to calculate the hazardous consequences of a bund fire or overtopping event, such as radiant heat impacts [16]. Obviously in a large spill the geometry of the spill will be that of the bund. However if the spill is insufficient to cover the full bund surface then it is often the case that the geometry of the fire is divided into the constant geometry of a pool fire initially and the geometry of change of the pool over time [17]. The most important combustion parameters to determine are the flame height and radiation intensity, as these can be further analysed to determine the consequences of the fire. Other parameters include rate of combustion and radiation intensity. It should be noted that the majority of modelling assumes a circular spill which may not be an accurate description of a bund fire, which means that the modelling results may differ from that in a real fire situation.

One study which used modelling to identify the risks associated with a pool fire in a bund at a petrochemical tank storage area found that the resultant thermal radiation from a potential fire could destroy tanks, equipment and cause serious casualties with a radius of approximately 28.5 m [17]. Modelling has also been used to determine the heat exposure of responders, identifying heat flux contours around the bund fire. 1kW/m^2, 3kW/m^2 greater than/equal to 10kW/m^2 [4].

There are two main types of software used for the assessment of pool fires. These are Semi-empirical models and field (Computational fluid dynamics (CFD)) models. Although semi-empirical models are easier to use, CFD models will provide a more accurate representation. A number of each type are discussed further in the IFIF Report [4] in relation to emergency response planning, including EFFECTS (developed and owned by TNO); FRED (Shell); Cirrus (BP); PHAST (DNV); ALOHA (for the generation of threat zone estimates for various types of hazards) and POOLFIRE6 (Developed by Atkins). An example of fire modelling software is a widely used code, Fire Dynamics Simulator (FDS). This is free software developed by the National Institute of Standards and Technology and is a CFD model of fire-driven flow. This software was developed to solve practical fire related issues, with an emphasis on smoke and heat transport from fires and has been used for a number of industrial fire situations Note that CFD models not only provide a more accurate representation of the pool fire, they offer a much more flexible framework for solving combustion problems [4].

Consequence modelling has been carried out [11] to determine the difference in consequence between a bunded and unbunded release in terms of individual risk level. Pool size, radiant heat intensities (using PFIRE2), size and shape of unignited vapour clouds (using DRIFT) and overpressures from vapour cloud explosions were examined. This research showed that the risk to individuals was similar in each scenario close to facility, but in the unbunded case, the risk was much higher further away.

Although a number of models exist and are being used to generate estimates of fire spread, threat zones and individual risk levels, there is no one model that is specifically related to bunds and bund fire scenarios.

5. Response tactics

Note – As emphasised previously, bund fires are rare events so there is little validated test or incident results for response tactics for firefighting of large bund fires

There are three key areas of response strategy for the treatment of a bund fire. These are passive (controlled burn), defensive and active emergency response strategy [4]. A passive approach includes the decision to allow a controlled burn. This is discussed in further detail below. A defensive approach includes a first response aimed at stabilising the situation by preventing fire spread and reducing potential for escalation (e.g. preventing further loss of containment from failing structures). An active approach would consist of full emergency response to the incident, including cooling of structures which are exposed to the radiant heat of the fire.

Literature [2, 18], highlights that a bund fire can be treated as a large pool fire, which is described as a static, confined spill, often deeper than 25 mm. A pool fire can cover a large area, such as a large bund, and depending on the depth of the bund/pool this type of fire can burn for a long period of time. It is probable that foam applied to the fire will be plunged directly into the fuel during application unless care is taken to minimise this effect. It is better to apply the foam to a solid surface and allow the foam to run on to the fire. However, this is only possible if such a surface exists, and may depend on the volume of liquid in the bund, the relative bund wall height and the performance of the application equipment. If treated like a pool fire, it is preferable that a foam with a high fuel tolerance and heat resistance as well as fast flowing characteristics is used [18].

As the size of the bund increases, and often, consequentially, the number of tanks contained within the bund increases, the complexities associated with firefighting also increase. Response strategies, of course, depend on the scale of the fire. A small spill fire may require the application of foam but no tank cooling but use of water spray to allow access to isolation valves, etc. as necessary.

A full bund fire, although significantly less frequent, may occur following a major spillage/tank rupture, or boilover event. Where a bund contains more than one tank, cooling of the second tank can be critical. However, if cooling water is applied at the same time as foam attack, the foam blanket can be damaged or destroyed. Therefore the cooling might only be used whilst the foam response is being prepared [18]. In the case of a bund containing more than one tank, the foam should be directed simultaneously at the tank(s) which have not ruptured, using the tank wall to allow the foam to run on to the liquid, and at the bund wall.

For bund firefighting NFPA 11 recommends fixed foam pourers are installed for common bunds surrounding multiple tanks where there is less than 0.5 tank diameter spacing or where there is poor access. NFPA recommends an application rate of 4.1 lpm/m^2 for low-level foam discharge outlets. For foam monitors, the recommended foam application rate increases to 6.5 lpm/m^2. BS5306 states a minimum application rate of 4 lpm/m^2 and a minimum of one 2600 lpm discharge device (low or medium expansion foam) for every 450 m^2 of bund area. The minimum discharge time stated in BS5306 is 60 minutes. This is one area where the guidance in the two standards differs considerably. It was noted in one incident reviewed, the fixed bund pourer system installed was of poor design and was inoperable during the fire following damage to the system by the fire.

A tactic proposed by IFIF is to use a [4] “sectional approach” to fight the fire in a bund. This entails dividing the bund into discrete areas such that the surface area of each is a ‘small bund’ size (less than 1900m^2). Initial foam application can be by use of a spray to secure the area near to the monitors being used. This would then allow each area to be extinguished using jet/spray monitors (each with an application rate of 6000 l/min), in approximately 30 minutes according to the referenced document. Once one area has been extinguished, firefighting should be focussed on the next adjacent section. If using this approach, it is suggested that the foam blanket in extinguished sections should be replenished every 15 minutes for 5 minutes to avoid burnback. A sectional approach to extinguishing a bund fire means that not all the water and foam solution flow required for the full fire area is needed from the beginning. Firefighting can begin as soon as there is a reasonable amount of these available. It is emphasised that this is recommended practice from one organisation and validation of it through large incident experience is limited.

During one incident reviewed for this document, foam attack was initiated a few hours into the incident. Foam attack was started from the front corner of the bund, working towards the back of the bund. The fire in this case was under control within 30 minutes from the start of foam attack (4 hours into the incident). At this point, the fire truck could be repositioned closer to the bund for continued attack.

As mentioned above run off from a fixed water cooling system on a tank in the same bund as the fire is likely to destroy a foam blanket on the bund if used. It is also suggested by Williams Fire & Hazard Control that if possible, any other tanks in the bund should be cooled using foam (especially if this can be added to fixed cooling systems) [4]. The application of foam to cool tanks in the bund also supports the development of a well distributed foam blanket in the bund. During one incident reviewed it was noted that the foam blanket was maintained in the bunded area after the fire was extinguished to prevent reigntion.

The passive response option to employ a controlled burn may be appropriate in the following situations [4]:

- Insufficient firewater/foam concentrate available to fully fight the fire
- Minimal fuel such that the fire is likely to self-extinguish within a relatively short period
- Low likelihood of successfully extinguishing the fire for whatever reason
- Insufficient volume available in the bund to contain fuel and required amount of firewater/foam (bund likely to be overtopped)

Ultimately, current best practice is to establish an adequate water and foam supply and begin to supress the fire once sufficient resources are available [2].

For any facility with a potential for a bund fire scenario to take place, formal preplanning should include firefighting response strategies for such a scenario. This formal preplanning ensures that responders are aware of materials/equipment available, resources and communication strategies. Preplanning should also consider the dimensions, shape, obstructions and access to the bund itself, as this may have practical impact on safe access to the bund for responders and the application of foam to the complete bund. As well as the fire scenario itself, the control of firewater run off – perhaps to remote containment or to other bunds – must be part of the preplanning process.

Site specific planning of firewater management and control measures should also be undertaken with active participation of the local fire and rescue service. For this, the following should be considered:

- Bund design factors (firewater removal pipework, controlled overflow to remote secondary or tertiary containment (e.g. aqueous layer controlled overflow for immiscible flammable hydrocarbons)
- Recommended firewater/foam application rates and firewater flow and volumes at worst-case credible scenario.
- Controlled burn options appraisals. Planning of emergency response measures/tactics likely to reduce potential duration and extent of fire scenarios, therefore reducing firewater demand requiring containment/management. Requires site specific assessment.

Note that some previous test works has been carried out to attempt to validate response tactics guidelines. Test work carried out in Hungary by FER with assistance from LASTFIRE achieved foam flow of 60m with standard NFPA application design rates and an application technique not involving significant forward momentum of the foam application (i.e. simulating foam pourer application). 60m was the extent of the pool fire so greater travel distance would be possible. Most standards assume only 30m flow is possible, but this test work showed that a much higher flow distance can be achieved. Work was carried out by GESIP [19] to identify the minimum extinguishing rates for different class foam concentrates (Class I film-forming, Class I non-film-forming and Class II) on a 45 m^2 bund. This work was then validated on a 200 m^2 bund area. The trial conditions set in this testing was 99% extinguishment of the fire surface area in less than 600 seconds. The results of this work included identification of the following minimum extinguishing rates on the lowest performance foam concentrates:

- Class I film-forming foam: 2 lpm/m^2
- Class I non-film-forming foam: 2.5 lpm/m^2
- Class II foam: accepted at 2.5 lpm/m^2 on 45m^2 bund, confirmed at 3 lpm/m^2 on 200m^2 bund.

It should be noted the difference between these application rates determined from experimental testing and the recommendations from NFPA and EN detailed previously. These application rates are significantly less than those recommended.

6. Incidents

This section lists some typical incidents where fires have occurred in bunds for various reasons.

Although good practice suggests designing bunds to contain 110% of the contents of the largest tank in the bund, in practice, there have been several incidents where bunds have not been able to contain spillages from the primary containment. This may be due to a number of reasons, including bund overtopping due to momentum of release, poor maintenance or poor design. Examples of incidents are provided in subsections below.

Data applicable to all types of tank is available from the LASTFIRE study [21], which reports frequencies of 8.8E-05 per tank for a small bund fire and 6.0E-05 for a large bund fire. Failure data has also been collated by OGP in 2010 [20], using data from a number of sources for atmospheric storage tanks. This report states the following statistics for the frequencies of small bund fires and large bund fires for atmospheric storage tanks (note that the frequency of a liquid spill outside tank for an atmospheric storage tank is reported as 2.8E-03 and the frequency for a tank rupture is reported as 3.0E-06):

Table 1: Atmospheric Storage Tank Fire Frequencies

Type of Fire	Floating Roof Tank (per tank year)	Fixed Roof Tank (per tank year)	Fixed plus Internal Floating Roof Tank (per tank year)
Small Bund Fire	9.0E-05	9.0E-05	9.0E-05
Large Bund Fire (full bund area)	6.0E-05	6.0E-05	6.0E-05

The Major Hazard Incident Data Service (MHIDAS) database, reported in [11] shows 61% of bunded vessels that had a release reported in the database ignited. Where the presence of bund was mentioned, there was a probability of 0.4 that the bund was ineffective for one or more of the reasons mentioned above. The probability of fire spread to other vessels was reported as significantly less for bunded vessels (39%) than for unbunded vessels (80%) even though the number of tanks in bund not taken into account. The probability of bund failing to contain the release was reported as greater for tanks in a shared bund than single bunds.

Figure 2. Large bund fire event example

Figure 3. example of bund fire engulfing tanks situated in the bund

6.1 Overfilling

As discussed previously, fuel can enter into the bund during filling operations if overfilling occurs. Overfilling can occur due to gauging, operator or mechanical failure. An example of this occurring and resulting in a bund fire is provided here:

1. Naples, Italy, 1985 – fuel overflowed from a floating roof tank during filling operation. This caused approximately 700 tonnes of fuel to enter the secondary containment bund. The pool of liquid covered the complete bund area of the tank and the adjacent pumping area, connected through a drain duct. The spill was followed by a vapour cloud which ignited. (The source of ignition was the pumping station.) The result of this fire was the destruction of 24 tanks, a number of pipelines and the loss of the main firefighting control centre [13].

2. Buncefield, UK, 2005 – a tank overfilled at an estimated rate of 550 m^3 per hour for several hours. This caused overflow into the bund surrounding the tank and generated a significant aerosol/vapour cloud which subsequently ignited. The overfilling occurred due to instrumentation failure coupled with a number of operational and assurance failures.

6.2 Boilover Events

A number of boilover events have occurred which resulted in the failure of the bund to contain the spread of liquid. Examples of such events are as follows:

1. Milford Haven, UK, boilover 1976 – Ignition of the contents of a bulk storage tank by hot particles from a nearby flare stack. After 12 hours, the tank boiled over causing a large quantity of burning crude oil to discharge into the bund. The fire spread over 16,000 m^2 and two further tanks were involved.

2. Tacoa, Venezuela, 1982 – Explosion and fire occurred in a fixed roof storage tank during gauging operations. The tank boilover resulted in spread of the fire over a large area with a large number of casualties despite the tank only being one third full with 3.5 million gallons (13 million litres) of heavy fuel oil. The tank involved in this accident was situated on top of a hill and surrounded by a 17m high earthen dike.

6.3 Bund Overtopping

Bund overtopping may occur following a release of stored liquid if the momentum of the release is sufficiently high. This is a particular problem when a sloping bund wall of low height is used [14]. Examples of catastrophic failures of bulk storage tanks and subsequent bund overtopping from the AEA Technology Consultancy Services MHIDAS database were summarised in Reference [11], further detail on some of these events is provided here.

1. Long beach, USA, 1969 – explosions in a polypropylene storage tank during unloading of casing head gas into tank. It was suggested that this exercise may have caused a static spark due to hot, dry weather. The tank rocketed which damaged bund and pipework. Fire spread to other tanks.

2. South Africa, 2008 – explosion in a storage tank resulted in all contents lost into a common bund and some release outside the bund. Fire spread to other tanks in the area. Noted that

due to design, the fixed bund pourers system was damaged in the fire and as such was inoperable. Fire resulted in significant damage to tanks within bunded area.

3. Nashville, USA, 1970 - a leak via an open discharge valve in a tank (due to roof drain piping in floating roof petrol tank freezing) at a storage facility coupled with an open valve in the bund meant that the liquid was discharged to storm water sewer and resulted in an explosion at a water treatment plant when a spark ignited the vapours.

4. Floreffe, USA, 1988 – a 4 million gallon (15 million litre) storage tank split apart as it was filled to capacity for the first time [22]. This caused a huge release of diesel oil, and it was estimated that between 40 and 71% of the diesel oil overwhelmed the sloped earthen bund surrounding the tank. This resulted in approximately 750,000 gallons (2.84 million litres) entering the local watercourse.

5. Belgium, 2004 – a storage tank failed catastrophically releasing all 37,000 m^3 of crude oil it was storing. Despite this very large release which was via a jet from the bottom of the tank, it was estimated that only 3 m^3 of crude oil overtopped the bund. This was mainly due to the height of the bund wall which was over 4m [13].

6.4 Other Events

Further examples of incidents where the secondary containment failed to contain the spread of fire are provided here:

1. Thessalonika, Greece, 1986 – Sparks from a flame cutting torch ignited fuel from a tank spill in a bund. The fire in the bund spread via grass and spillages, travelling through pipe channels in the bund and resulted in the destruction of 10 out of 12 crude oil tanks (one boiling over).

2. Umm Said, Qatar, 1977 – A weld failure caused catastrophic failure of a 260,000 barrel refrigerated propane (LPG) tank containing 236,000 barrels. The bund in which it sat in was inadequately designed and did not have sufficient capacity to contain the spill. This resulted in an adjoining refrigerated butane tank and most of the process area also being destroyed by fire [5].

7. Summary

This literature review and the associated commentary has highlighted key areas of bund construction and integrity issues, alongside a detailed explanation of large bund fires, including current modelling techniques, response strategies and historical incidents that have occurred worldwide. It has been shown that there are good proven industry standards for construction, sizing and integrity, but it is recognised that it might be difficult to apply retrospectively. Current best practice is to allow the containment volume to take into consideration an allowance for firewater. As well as this, a plan should be in place for control of run off if the bund size is not adequate. The additional quantity required for the bund should meet required standards but also should be site specific and scenario based.

It is highlighted that large bund fires are rare events. Therefore, although some response tactics have been suggested, there is only limited real incident data which has identified and validated effective techniques for fighting such fires. There is also limited data from test work, which makes it more difficult to develop theories of best response tactics. This current situation justifies the test work which is to be carried out by LASTFIRE into large bund fires and best practice response tactics.

It should be noted that bund fires are generally not necessarily really a life safety or environmental risk. Therefore, provision of firefighting measures for such fires should normally be a commercial risk based decision. However, there is an undoubted trend though to prescriptive requirements.

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Appendix B – Gasoline Specification for Tests at FER facilities in Szazhalombatta in Hungary

Hungarian Oil and Gas Public Limited Company	# Certificate Of Analysis ISO 9001:2008 / SGS HU 94/4326	QC_1_MOL01/ LIMS_06 Page: 1 of 1 **Certificate Number :** 3921430

Customer :

Sampling date: 02.06.2017
Received date: 02.06.2017

Sample name : Ütemezett minta
DP2-060212-DAV2KBENZ/88627

Product: BEN_K

	Analysis	Unit	Method	Specification	Result
0010	Appearance		QC_IHM_003		Tiszta, átlátszó
	Sediment				Mentes
	Water				Mentes
0050	Density at 15 ℃	g/cm3	MSZ EN ISO 12185		0.6590
0080	Initial Boiling Point	℃	MSZ EN ISO 3405	30 - 38	29.8
	5 % Recovery	℃		35.0 - 60.0	39.1
	10 % (V/V) recovered at	℃		37.9 - 59.7	41.2
	30 % (V/V) recovered at	℃		50.1 - 68.7	47.5
	50 % (V/V) recovered at	℃		61.8 - 79.5	54.6
	70 % (V/V) recovered at	℃		74.1 - 94.8	64.6
	90 % (V/V) recovered at	℃		89.8 - 115.6	79.8
	95 % (V/V) recovered at	℃		96.8 - 126.2	87.9
	Final Boiling Point	℃		108.6 - 138.7	101.0
	Recovered %	%(V/V)			98.1
	Distillation residue	%(V/V)			0.6

The uncertainty of measurements meets the requirements of standard test methods.

The CoA can only be copied in full and the results relate to the sample ' 3921430 ' exclusively.

The size of CoA is 1page(s).

Date: Százhalombatta, 15.06.2017

MOL Nyrt.
DS Termelés MOL Minőségellenőrzés MOL
2443 Százhalombatta, Olajmunkás u. 2.
3.
Kovács Andrea

Appendix C – Summary of Results from Initial Protocol Development Tests

Table C-1. Bund Fire Testing - Preliminary Results Summary

Test Number	Bund Size	Foam Type	Nozzle Type	Nett Application Rate (lpm/m²)	Extinguishment Time	Notes
1	Quarter	AFFF AR 3%	Semi aspirated	3.7	7'46"	Long drainage time. Several Ghostings but very good burnback. Foam stopped at 9 minutes
2	Quarter	AFFF AR 3% at 6%	Semi aspirated	3.7	9'00"	Very stiff foam Very long drainage time. Foam stopped at 9 minutes
3	Quarter	AFFF AR 3%	Aspirated	3.7	9'45"	Foam stopped at 10 minutes
4	Quarter	AFFF AR 3%	System	2.5	12'35"	Very hot fuel
5	Quarter	AFFF AR 3%	CAF	2.5	7'19"	Foam stopped at 8' 50". Note concerns re mixing foam and water
6	Quarter	FFF	Semi aspirated	3.7	N/A	Test aborted at 9 mins - no control.
7	Quarter	FFF	Aspirated	3.7	N/A	Test aborted - no control at 8'30".
8	Quarter	FFF	CAF	2.5	8'17"	Very stable blanket formed
9	Half	AFFF 3%	CAF	2.5	9'52"	2 nozzles used
10	Half	FFF	CAF	2.5	11'36"	2 nozzles used after 6'30" (application rate increased to 5.0 lpm/m2). Question re dry chemical compatibility
11	Half	AFFF AR	Semi aspirated	3.7	15' 00"	First half fire extinguished at 9@30" using one nozzle for 7 minutes only (50% application rate). 2 nozzles used at 7 minutes. Final corner flicker at 13@50" After burnback test extinguished by dry chemical. Question re section by section approach
12	Half	AFFF AR	Aspirated	3.7	11'46"	Application times as Test 11
13	Half	AFFF AR	Aspirated	3.7	8'36"	2 nozzles used from start of test. Note improvement in extinguishing time
14	Half	FFF	Aspirated	3.7	N/A	Abandoned at 9 mins - no control
15	Half	AFFF AR 3%	System	2.5	12'28"	2 nozzles used but only 1 worked, one blocked
16	Half	FFF	System	2.5	15'17"	2 nozzles used but both working fully
17	Full	AFFF AR 3%	Aspirated	3.4	7'58"	4 nozzles used
18	Full	AFFF AR 3%	System	2.5	14'03"	4 nozzles used
19	Full	AFFF AR 3%	CAF	2.0	9'23"	2 nozzles used
20	Full	FFF	CAF	2.0	N/A	Test aborted at 12'30"

Appendix D – Results from Proportioning Tests

This report has been prepared by Firedos on behalf of LASTFIRE Coordinator.

PROPORTIONING TESTS WITH HIGHLY VISCOUS FLUORINE-FREE FOAM AGENTS.

Contents

1. Introduction

The test was conducted on 13th June 2017 at the FER training ground of the MOL refinery in Százhalombatta, Hungary.

I would particularly like to thank the staff of FER who organised everything and supported the test in a very professional way. Also, special thanks to Mr. Thierry Moinet, who was of great help to during all the tests.

The aim of these tests was to find out more details about the suction capability of proportioners when working with highly viscous foam agents. Figure 1 below is a brief sketch of the test setup. The tests were conducted by use of a Venturi mixer with adjustable proportioning rates, and a ***FireDos*** proportioner with fixed proportioning rates of 1% and 3%.

2. Description of the test setup

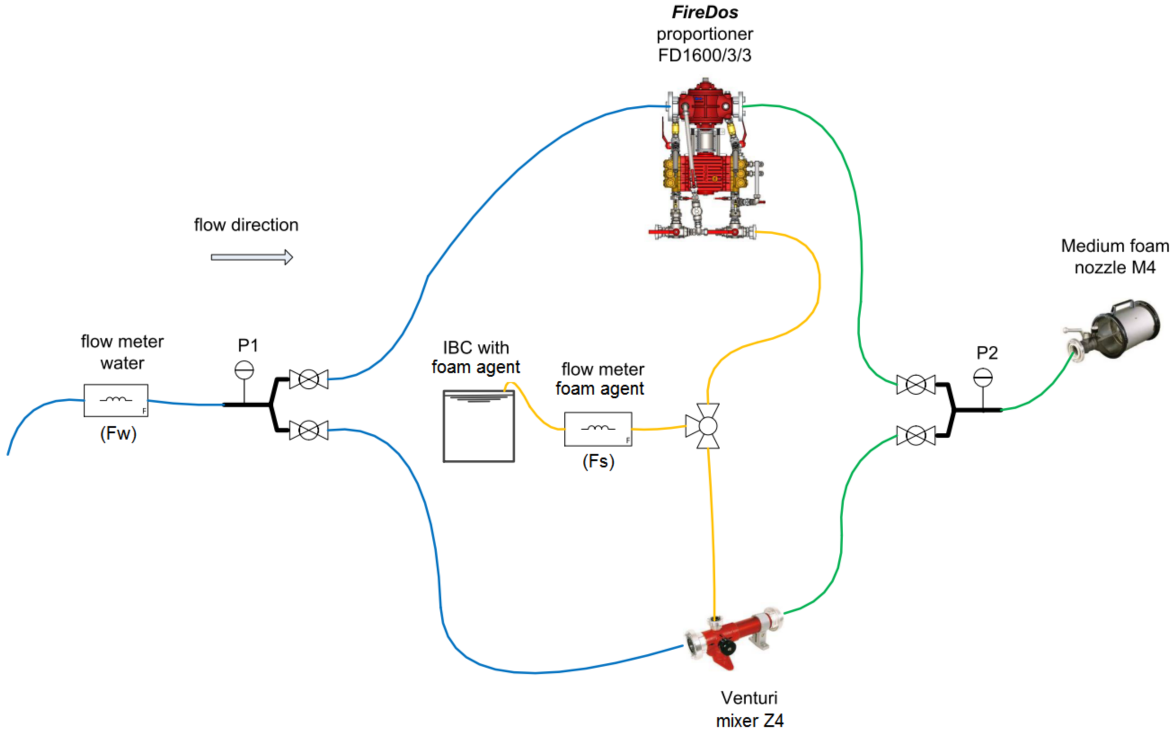

Figure 1: Scheme of test setup

For the water, we installed both test units in parallel with the possibility to open and close each one separately. We installed a magnetic-inductive flow meter (Fw) in the common water line to measure the actual water flow rate and a pressure gauge (P1) to measure the inlet pressure. The hose length in both ways was identical. We installed another pressure gauge (P2) in the common line downstream of both test units to measure the outlet pressure.

We installed another magnetic-inductive flow meter (Fs) in the common part of the foam agent suction line to measure the actual foam agent flow rate. We had to choose this solution because there was no other way with the Venturi mixer to do it. The result was not a perfect design of the suction line, having a flow meter with a lower inner diameter (due to the required low measurement range), a T-piece and a ball valve in the pipework from the foam agent storage tank to the inlet of both test units.

This specific setup was selected to keep the efforts for doing all the tests as low as possible. Still, it is not a usual design for a suction line; it was rather a worst-case scenario for a suction line. However, the test setup was made without knowledge about the viscosity of the foam agents used. Therefore, a calculation of the suction line could not be made in advance.

Figure 2 shows the actual test setup, mainly the water part; and in figure 3, mainly the foam agent suction part. You can also see that both test units where installed at the same level to keep the suction height as equal as possible.

The water supply was ensured by a fire truck. A medium-expansion foam pipe with a nominal flow rate of 400 lpm was used as a discharging unit for all the tests. Also, the Venturi mixer had a nominal flow rate of 400 lpm. For this reason, all tests were conducted at 400 lpm.

Figure 2: Test setup water side

Figure 3: Test setup foam side

3. Testing procedure

Initially, a proportioning test using water instead of foam agent was conducted for both test units. While testing with water, the proportioning rate for the ***FireDos*** proportioner at 1% and 3% was OK and within the limits. In case of the Venturi mixer, we had to adjust the proportioning rate to approx. 4.5% on the scale in order to reach an actual proportioning rate of 3%. This adjustment was kept across all tests with the foam agents. After finishing all the tests with all foam agents, we repeated the water-to-water test in order to verify that no changes had occurred in the meantime. The second water test confirmed the results of the first one.

The procedure of the foam tests was as follows:

- placing an IBC filled with a test foam agent
- connecting the suction hose
- measuring and recording of the height difference between the liquid surface of the foam agent in the IBC and the inlet of both test units
- measuring and recording of the temperature of the foam agent
- closing the suction inlet for the Venturi mixer, opening the suction inlet for the ***FireDos*** proportioner
- closing the water line to/from the Venturi mixer, opening the water line to/from the ***FireDos*** proportioner
- starting the water flow at low pressure, venting the suction line and the ***FireDos*** proportioner

- selecting the proportioning rate at the ***FireDos*** proportioner and adjusting the water flow rate most closely to the nominal figure of 400 lpm
- reading and recording the inlet water pressure (P1) and the outlet water pressure (P2)
- reading and recording the water flow rate (Fw) and the foam agent flow rate (Fs)
- stopping the water flow
- opening the suction inlet for the Venturi mixer, closing the suction inlet for the ***FireDos*** proportioner
- opening the water line to/from the Venturi mixer, closing the water line to/from the ***FireDos*** proportioner
- starting the water flow at low pressure, venting the suction line and the Venturi mixer
- adjusting the water flow most closely to the nominal figure of 400 lpm
- reading and recording the inlet water pressure (P1) and outlet water pressure (P2)
- reading and recording the water flow rate (Fw) and foam agent flow rate (Fs)
- stopping the water flow
- flushing the suction hoses
- starting from the beginning with the next foam agent

4. Test results

The tests focused on the following values:

- water flow rate at the proportioner's inlet
- foam agent flow rate in the suction line
- inlet pressure for the proportioners
- outlet pressure for the proportioners
- difference in height between liquid level in the IBC and the inlets of the proportioners
- temperature of the foam agent

In addition, the following values were measured/calculated from all collected test results:

- the actual proportioning rate
- the pressure drop in the suction line
- the flow velocity in the suction line
- the viscosity of the foam agent at the current flow rate in the suction line
- pressure drop in the water line

The calculation of the actual proportioning rate was made according to different international regulations and always in the same way, by dividing the foam agent flow rate by the sum of water and foam agent flow rate.

The pressure drop calculation for the suction line was made according to the Darcy formula. The flow velocity is simply calculated from the measured flow rate and the inner diameter of the suction hose.

Thanks to the (only afterwards) supplied viscosity data for all the foam agents, it was easily possible to calculate the current viscosity at the present flow rate by approximation with a potential function.

Based on our specific test setup, the pressure drop (P2-P1) in the water line includes not only the pressure drop of the test units, but also the pressure drop for all the hoses, valves and fittings between both pressure gauges.

For the design of a suction line, two limitations exist in general due to physical reasons:

1. Limitation in velocity. Depending on the type of foam agent, there are different maximum permissible velocities. The reason for this limitation is the balance between dynamic and static pressure in flowing liquids. If the velocity is high, the kinematic pressure is high, too. This however means that the static pressure is low. If the static pressure, in turn, is below the vapour pressure of one of the components of the used foam agents, these components start to evaporate and a mixture of gas and liquid enters the proportioner. Inside a pump, this can lead to so-called "liquid-gas pressure hammers," i.e. pressure peaks of more than 1000 bar. For this reason, the velocity limitation is as follows:

   For low-viscosity (Newtonian liquids) foam agents, i.e. AFFF, Class A, Multipurpose Foam Concentrates and so-called "LV" (low-viscosity) AFFF-AR and FFF, the max. velocity in the suction line must not exceed 1.0 – 1.2 m/s.

   For highly viscous, pseudoplastic (non-Newtonian liquids) foam agents, i.e. AFFF-AR and FFF, the max. velocity in the suction line must not exceed 0.6 – 0.8 m/s.

2. Pressure drop limitation. In a suction line, the suction capacity of a pump must always be higher than the pressure drop in the pipework. If the pressure drop becomes higher than the suction capacity of the pump, this will lead to cavitation. Cavitation, in turn, can create pressure peaks of over 1000 bar as well.

These two limitations are not independent from each other because the pressure drop also depends on the velocity. Velocity, in turn, influences the viscosity. The actual challenge for a proper design of a suction line is to find a balance between these two limitations in pressure drop and velocity.

Table 1 below shows a summary of all measured and calculated figures for the different foam agents.

FireDos®

Test protocol

subject: Test of suction capability and mixing rate for foam concentrates

foam concentrate:		A		B		C		D		E		F		Ref 1		Ref2		
foam proportioner:		venturi Z4	FireDos	venturi Z4	FireDos	venturi Z4	FireDos	venturi Z4	FireDos	venturi Z4	FireDos	venturi Z4	FireDos	Venturi Z4	FireDos	Venturi Z4	FireDos	FireDos
nominal mixing rate [%]	measures	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1
nominal flow rate [lpm]:		400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
real flow rate [lpm]:		396	396	404	465	403	392	408	404	404	432	410	408	404	406	400	404	405
inlet pressure [barg]:		9,8	7	10	10	9	6	9	6	9	7	9	6	11	7	9	7,5	6
outlet pressure [barg]:		5,8	5,8	6	8,5	5	5	5	5	5	5,5	5	5	6	6	5	5	5
inner diameter of suction hose [mm]:		36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36
length of suction hose [m]:		6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
differnce in height [cm]:		37	37	34	34	34	34	37	37	37	37	33	33	50	50	40	40	40
temperature of the foam concentrate [°C]:		30,5	30,5	29,8	29,8	34,5	34,5	35,4	35,4	26	26	35,4	35,4	29,8	29,8	27	27	27
density [kg/m³]:		1039	1039	1057	1057	1026	1026	1042	1042	1040	1040	1024	1024	1153	1153	1036	1036	1036
flow rate foam concentrate [lpm]:		8,9	11,8	10,4	14,4	9,3	9,6	9,6	10,2	7,8	4,6	10,6	12,2	11	12,3	3,4	10,5	4,8
real mixing rate [%]:	calculated	2,20	2,89	2,51	3,00	2,26	2,39	2,30	2,46	1,89	1,05	2,52	2,90	2,65	2,94	0,84	2,53	1,17
pressure drop in suction line[bar]:		0,194	0,213	0,226	0,242	0,208	0,209	0,169	0,171	0,258	0,23	0,191	0,199	0,064	0,065	0,15	0,201	0,16
flow velocity [m/s]:		0,146	0,193	0,17	0,236	0,152	0,157	0,157	0,167	0,128	0,075	0,174	0,2	0,18	0,201	0,056	0,172	0,08
viscosity at actual flow [mm²/s]:		515,5	434,5	528,1	414,2	554,5	539,7	398,8	380,2	827,2	1223,2	441,9	404,6	18,2	18,2	947,1	448,4	753,30
pressure drop in water line [bar]:		4	1,2	4	1,5	4	1	4	1	4	1,5	4	1	5	1	4	2,5	1,00

Table 1: Summary of measured and calculated test results

5. Interpretation of the results

The following correlations and results can be taken from table 1.

- Using a Venturi mixer also means that a higher inlet pressure for the water is required because the pressure drop at the Venturi mixer is 3 – 4 times higher than the pressure drop at a ***FireDos*** proportioner (see the last line in table 1).
- The influence of temperature on the viscosity of the fluorine-free foam agents is a very important issue. Referring to the temperature and the corresponding viscosity at the current flow rate, you can see that the lowest temperature will generate the highest viscosity. In turn, the higher the viscosity, the higher is the pressure drop in the suction line.
  The reason for the temperature difference was the use of different types of IBCs. All of them were standing together in the sun. Those with a lower temperature were non-transparent IBCs, as seen in below figure 4. Those with higher temperatures were transparent IBCs, as seen in below figure 5

Figure 4: Non-transparent IBCs

Figure 5: Semi-transparent IBCs

- The pressure drop in the suction line is always too high as the suction line could not be installed in a technically correct manner. Only for the two green fields, the pressure drop is OK. The maximum suction capacity of the ***FireDos*** proportioner used is 0.16 bar. The mistake here was, just as frequently seen in practice, that the suction line had not been calculated in advance due to the missing viscosity figures for all the foam agents.
- Looking at the limitations for the suction line, it is absolutely clear that velocity is not the limitation for fluorine-free foam agents; it is rather the pressure drop due to the high viscosity.

In general, it can be concluded that the proportioning rate was not reached at all with the Venturi mixer. But even with the ***FireDos*** proportioner, the proportioning rate could not be reached in each case. The main reason why the Venturi mixer and even the ***FireDos*** proportioner did not reach the required proportioning rate is the pressure drop in the suction line as well as the impossibility to calculate the suction line in advance due to missing viscosity figures.

The result of all the suction tests is that for pump-based proportioning units using highly viscous pseudoplastic foam agents, proper calculation and installation of the suction line is a must. This is the only way to ensure that the proportioning rate will be reached at the designed water flow rates.

The use of Venturi-based proportioning systems for highly viscous pseudoplastic foam agents is not recommended.

6. Additional information

Beside the suction and proportioning of highly viscous pseudoplastic foam agents, also transportation and handling are an important matter.

Due to the high viscosity, air bubbles will remain in the foam agent and will also influence the proportioning rate due to the share of air inside the liquid. Figure 6 shows a very large amount of air bubbles in the foam agent.

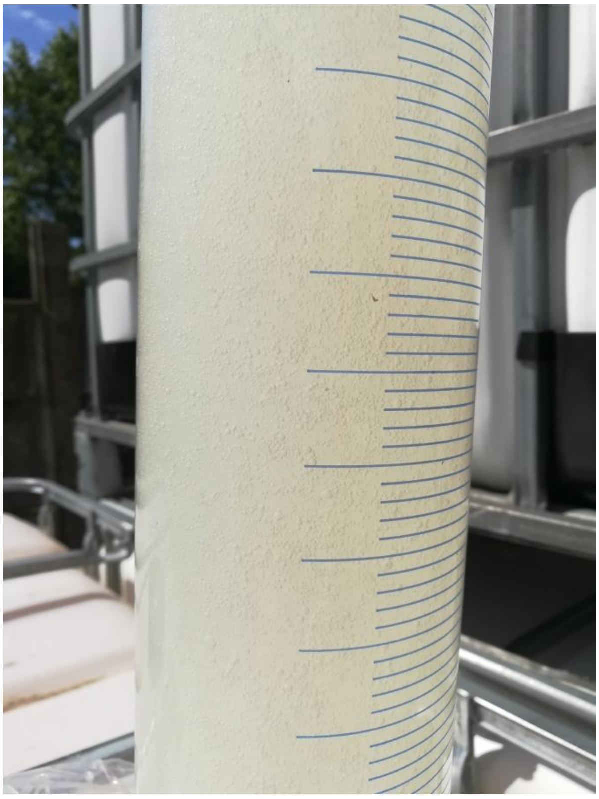

Figure 6: Example of highly viscous foam agent with air bubbles inside

Figure 7: Example of highly viscous foam agent with with air bubbles inside

Figure 8: Example of highly viscous foam agent with air bubbles inside

No foam proportioner can reach the proportioning rate with air bubbles trapped in the foam agent.

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Ingo Weiss

FireDos GmbH

2017-10-13

LASTFIRE
Large Atmospheric Storage Tank Fires

Appendix E – Specification for Gasoline used at GESIP facilities in Vernon, France

ANNEXE 3: FICHE TECHNIQUE ESSENCE C

A3.1 COMPOSITION CHIMIQUE

C'est une combinaison complexe et variable d'hydrocarbures paraffiniques et cycliques, sans aromatiques, dont le nombre de carbones se situe essentiellement dans la gamme C6-C7 et dont le point d'ébullition est compris entre 70 et 100 °C.

A3.2 SPECIFICATIONS

Les spécifications de cette essence C sont les suivantes :

- Aspect clair et limpide,
- Couleur Saybolt : 30 minimum,
- Densité à 15°C : comprise entre 0,690 et 0,710
- Indice de réfraction : compris entre 1,390 et 1,394
- Teneur en aromatiques : 100 ppm maxi,
- Point initial de distillation : 70 °C minimum
- Point final de distillation : 105°C maximum

A3.3 EXEMPLE DE FICHE FOURNISSEUR

SPECIFICATIONS

MESURES	UNITES	METHODES DE MESURE	VALEURS GARANTIES MINI	VALEURS GARANTIES MAXI
Masse volumique à 15 °C	kg/m³	EN ISO 12185	680	712
Aspect à 15°C		VISUEL	Clair & Limpide	
Couleur Saybolt		AFNOR M 07-003	30	
Teneur en aromatiques	ppm (m/m)	UV		100
Indice de brome	mgBr/100g	ASTM D 2710		50
Teneur en n-hexane	% masse	CPG	7	
Teneur en Benzène	ppm (m/m)	ASTM D 6229		30
Viscosité à 20°C	mm²/s	ISO 3104	.5	
Point initial	°C	ISO 3405	65	75
Point sec	°C	ISO 3405		100

VALEURS TYPIQUES

MESURES	UNITES	METHODES DE MESURE	VALEURS TYPIQUES
Indice de réfraction à 20°C		ASTM D 1218	1.392
Point à 10 %	°C	ISO 3405	74
Point à 50 %	°C	ISO 3405	76
Point à 90 %	°C	ISO 3405	86

N° spec mise à jour le / SP1001474 / 11/09/2015 11:37:21

Appendix F – Example Sequences for Monitor, System and CAF Application during Phase 2 Tests

Sequence 1 – Monitor Application

Fig. 1. Start of application

Fig. 2. Note control beginning at "far" side of tank

Fig. 3. Foam blanket building up from far edge

Fig. 4. Further build-up of foam blanket

Fig. 5. "Near" edge only still ignited with some flickers around circumference

Fig. 6. Minor flickers only remaining

Fig. 7. Full extinguishment achieved.

Sequence 2 – System Application

Good fire control with system application. (For infornation – this was a Fluorine Free foam but performance should not be considered as generic to all foams of the same generic type.)

Fig. 1 Note system pourer in smoke/flame
Smoke ingress can have severe effect on foam production

Fig. 2 Control beginning as foam flows across tank from pourer

Fig. 3 Better quality foam seals edges as it travels across tank
Extinguishment also achieved at impact area

Fig. 4 Approximately 50% of fuel surface extinguished

Fig. 5 Note edge sealing as foam progresses

Fig. 6 "Far" edge only still ignited

Fig. 7 "Far" edge flickers only

Fig. 8 Minor flickers only

Fig. 9 Fire now limited to one small flicker area

Fig. 10 Fire extinguished. Note steam from edges

Fig. 11 Steam reduced as tank edge cools

Sequence 3 – System Application

Poorer quality foam – fails to extinguish fully. (For infornation – this was an AFFF but issues should not be considered as generic to all foams of the same generic type.)

Fig. 12 Note impact area still ignited and edge flickers

c

Fig 13. Edge flickers reduced in size but impact area continues to burn
Note also "old foam" swirl

Fig 14. Tunnelling and Ghosting destroying layers of foam bubbles and impact area still ignited.
Note impact area would probably be extinguished if foam application stopped but this is not a preferred policy. It is much better if full extinguishment is achieved with foam application still running.

Sequence 4 – CAF Application

Fig. 1 CAF application into tank

Fig. 2 CAF application into tank

Fig. 3 Control beginning as foam blanket starts to form

Fig. 4 Further foam build up

Fig. 5 Approximately 75% of fuel surface extinguished

4

Fig. 6 Note edge sealing on edge near application device as new foam pushes foam against edge

Fig. 7 edge flickers remaining

Fig. 8 minor edge flickers on far edge near impact area

Fig. 9 Extinguishment

Appendix G – Results Data Tables for all Tests

Phase 1 - Bund Test Results Data Tables

Test Reference	Foam Reference	Type	Proportioning Rate	Nominal Proportioning Rate	Wind Speed (m/s)	Air Temp	Fuel Temp	Solution Temp	Bund Dimension	Nozzle Type	Water Type	Fuel Type	Preburn Time	Nett Application Rate (lpm)	Number of Nozzles	Nett Total Application (lpm/m2)	Foam Expansion	Drainage Time	Control Time	Time to Virtual Extinguishment	Extinguishment Time	Torch Test	Burnback	Notes
SB1	Reference 1	C8	3%	3%	gusts to 2m/s	29.0	39.7	37.3	4.6225	semi	fresh	Gasoline	3 mins	17	1	3.68	4.15	3'32"	6'17"	N/A	N/A	N/A	N/A	Control @ 6'17", virtual extinguishment was not achieved Still flaming at on edge behind nozzle @ 10mins Obstacles reignited at 12 mins Test stopped at 15 mins, approx 10% still burning
SB2	Reference 1	C8	3%	3%	gusts to 2m/s	23.7	36.5	37.3	4.6225	asp	fresh	Gasoline	3 mins	17	1	3.68	7.45	3'30"	6'00"	N/A	N/A	N/A	N/A	Control except one edge @ 6mins Foam stopped at 8'20" due to pump failure, started again at 10'30" Noticeably better performance than with semi-asp nozzle
SB3	Reference 1	C8	3%	3%	gusts to 1.5m/s	28.0	38.2	37.3	4.6225	sys	fresh	Gasoline	3 mins	11.7	1	2.53	4.9	<3 mins		N/A	N/A	N/A	N/A	Still significant flames around edge and in obstructions @ 7'30" and 9'30" @ 10'00" 80% of edges still burning fiercely and flames in both pots
SB4	Reference 1	C8	3%	3%	gusts to 3.5 m/s	18.7	19.1	24.1	4.6225	MEX	fresh	Gasoline	3 mins	17	1	3.68	12	<2 mins	4'09"	N/A	N/A	N/A	N/A	Control @ 4'09" 1 corner edge flickers only @ 5'00", spreading to edge flickers around bund @ 5'30" Noticeably better than low expansion nozzles but same problems occurring Fire went out in obstructions quite quickly Test aborted @ 12'00" (minor flickers remaining only)
SB5	Reference 1	C8	3%	3%	1-2 m/s	21	23.3	24.1	4.6225	CAFS	fresh	Gasoline	3 mins	10	1	2.16	27.45	9'58"	4'32"	7'30"	7'42"	N/A	16'00" - no reduction in surface coverage	Control @ 4'32" Burnback @ 16'00" (using old style burnback pot), did not effect foam blanket, no reduction in surface coverage.
SB6	Reference 2	C8	1%	1%	gusts to 3.5m/s	21.7	20.6	21.4	4.6225	semi	fresh	Gasoline	3 mins	17	1	3.68	3.82	4'36"	4'13"	4'36"	5'17"	@15 mins - flash in 2 obstacles & approx 60% circumference. Self extinguished @ 20'40"	@25mins, single flash & ghosting, edge flickers remaining at 29'00" in far corner. Pot removed @ 30'00", some flickers but held.	only minor corner flickers @ 5'13"
SB7	Reference 2	C8	1%	1%	1 m/s	24.1	27.1	21.4	4.6225	asp	fresh	Gasoline	3 mins	17	1	3.68	4.97	3'36"	5'10"	5'30"	8'14"	@15 mins - no reignition	@26mins - flash @28'50", edges only with some ghosting & in obstacles	several layers of foam gone after burnback flash, minor corner flickers remaining, some fuel exposed due to wind which ignited. Test stopped @ 30'00"
SB8	Reference 2	C8	1%	1%	1 m/s	20	33	22	4.6225	sys	fresh	Gasoline	3 mins	11.7	1	2.53	3.13	1'50"	6'50"	11'06"	N/A	N/A	@28'30" After 1.5mins, ghosting flash, @ 31'00" corners but then self extinguished. Held well when pot was removed.	Note virtual extinguishment after foam stopped (@ 10'00") 9'30" 50% perimeter flaming & flickers in 1 obstruction 10'0H10:X100" 45% perimeter 11'00" some ghosting, 5% area, 30% perimeter 12'00" 20% perimeter 13'00" <10% perimeter, some burning in middle. Test stopped @ 16'00"
SB9	Reference 2	C8	1%	1%	1.5 m/s	22.5	33.9	22	4.6225	MEX	fresh	Gasoline	3 mins	17	1	3.68	11.06	1'28"	5'59"	8'54"	N/A	N/A	N/A	Objects flame out @ 5'20", impact zone @ 5'59" 7'05 small patched on perimeter 8'10" corners and small patches 10'00" 25-30% perimeter. Test stopped @ 15'00", note held for whole period and flames did decrease in height.
SB10	Reference 2	C8	1%	1%	gusts to 2.5 m/s	20	32.7	22	4.6225	CAFS	fresh	Gasoline	3 mins	10	1	2.16	15.2	4'36"	4'29"	6'10"	7'30"	Flame touched foam - minor flickers only & self-extinguished	@15mins, minor edge flickers, sealed when pot removed @ 20mins	@4'33", only back edge and 1 obstacle @5'25", 25% back edge and 1 obstacle note @ 6'00", foam directly applied to obstacle due to nozzle misdirection - extinguished flame 7'10" small flickers remaining Fuel exposed by edge @7mins post burnback <3% fire area @ 23mins, 24'57", self extinguished
SB11	D	AFFF	3%	3%	2.5m/s	19	26	21	4.6225	semi	fresh	Gasoline	3 mins	17	1	3.68	4.06	9'03"	5'30"	6'00"	7'05"	@15 mins - 1 corner led to 50% edge flame & 2 obstacles, some ghosting	N/A	@17'00", ghosting @20'00", both obstacles, 45% edge & 5 % surface @25'00", 25% edge only @27'00" <10% edge flickers only @28'00" self extinguished
SB12	D	AFFF	3%	3%	1 m/s	20	27.5	21	4.6225	asp	fresh	Gasoline	3 mins	17	1	3.68	9.9	10'35"	4'02"	4'10"	4'42"	@15mins, no reignition	@20mins, flash to 25% perimieter, 1 corner only after 54secs. @ 24'22" all extinguished, @25'00" flame contained in burnback pot, @30'00" minor ghosting <1% edge flickers, @32'00" minor flickers only and in pot	Test stopped @32'00"
SB13	D	AFFF	3%	3%	1.5 m/s (gusts to 5 m/s)	23.5	34	22	4.6225	sys	fresh	Gasoline	3 mins	11.7	1	2.53	6.4	7'10"	5'23"	7'05"	21'59"	N/A	N/A	Note minor flickers at impact zone at time of virtual extinguishment @15'00" 55% edge, <2% surface burning, some flashes @17'00" @19'48" self extinguished @21'16" flash (full surface), died down @ 21'30" to minor flickers Note: Very good hold
SB14	D	AFFF	3%	3%	1.5 m/s	29	34	22	4.6225	MEX	fresh	Gasoline	3 mins	17	1	3.68	7.8	6'20"	4'13"	4'52"	5'33"	No reignition	@20mins, full perimeter flash & obstacles (flash went underneath foam), rapid reduction in foam blanket height	Note minor flickers at impact point at control time Note: foam stopped @ 7'00" due to pan overload 22'00", minor flickers only, some fuel exposed. Some foam collapsed on to burnback pot, so reignited @ 23'00" 25'00" some surface ghosting, exposed area only with sustained burning, held well 26'00" burning around pot, fuel exposed 27'00", >25% fuel area burning fiercely 27'30", full area burning, test terminated Note: very rapid destruction of foam blanket & full surface burning.
SB15	D	AFFF	3%	3%	2	30	39	22	4.6225	CAFS	fresh	Gasoline	3 mins	10	1	2.16	>20	17'00"	4'45"	5'02"	5'45"	full pass @ all six points	Some edge @ 22'00", minor flickers, self-extinguished, reignited cycle	Pan only @ 25'00", some reignition @ 28'56" approx 20% edge 30'00" - approx 5% edges some at burnback pot edge
SB16	A	FF	3%	3%	1	30	24	25	4.6225	semi	fresh	Gasoline	3 mins	17	1	3.68	3.3	5'35"	5'08"	5'20"	N/A	N/A	N/A	@8'00" - 25% perimeter @9'00" - 25% perimeter @10'00" - 25% perimeter and 15% surface and both obstructions @13'00" - 50% perimeter 15'00" - 60% perimeter and 15% surface Extinguished with DP - noticeable reduction in foam depth
SB17	A	FF	3%	3%	gusts to 2.2m/s	28	33	25	4.6225	asp	fresh	Gasoline	3 mins	17	1	3.68	2.7	4'40"	5'23"	6'03"	7'32"	Ignition @ 1 corner - 40% perimeter & 1 obstruction		Note: no residual foam at all. Noticeably different jet from conventional foam single corner only @ 7'22" 17'30" - one corner, 1 obstruction and exposed fuel 20'00" - 25% fuel area ignited DP used, foam blanket destroyed very quickly, extinguished with foam

Phase 1 - Bund Test Results Data Tables

Test Reference	Foam Reference	Type	Proportioning Rate	Nominal Proportioning Rate	Wind Speed (m/s)	Air Temp	Fuel Temp	Solution Temp	Bund Dimension	Nozzle Type	Water Type	Fuel Type	Preburn Time	Nett Application Rate (lpm)	Number of Nozzles	Nett Total Application (lpm/m2)	Foam Expansion	Drainage Time	Control Time	Time to Virtual Extinguishment	Extinguishment Time	Torch Test	Burnback	Notes
SB18	A	FF	3%	3%	Gusts to 1.0m/s	25	33	25	4.6225	sys	fresh	Gasoline	3 mins	11.7	1	2.53	3.11	3'45"	8'48"	9'32"	N/A	N/A	N/A	Note: problem with one obstacle @ control time @ 10'00 - 25% perimeter after 10'00", some ghosting, sustained flaming at edges (40%), but moving and ongoing ghosting 12'40" reignition of one obstacle 14'30" one corner only but continuous 16'00 - increasing area - test aborted Note DP used - destroyed foam blanket, foam used to extinguish
SB19	A	FF	3%	3%	1.0m/s	20	20	22	4.6225	MEX	fresh	Gasoline	3 mins	17	1	3.68	3.1	2'00"	Failed	N/A	N/A	N/A	N/A	Note: Expansion seems low Difficulty getting control at impact point Failed to control @ 10'00" - impact point extinguished, but 80% perimeter and some in centre, typically 30% flickering Flames getting worse, so test stopped at 12'00" - Full involvement @ 12'50" - foam used to extinguish
SB20	A	FF	3%	3%	0.2 m/s	21	30	22	4.6225	CAFS	fresh	Gasoline	3 mins	10	1	2.16	17	12'00"	5'35"	6'23"	7'47"	No reignition	@ 19 mins	Note: Slower flow over fuel with CAF of this characteristics @ 7'00" only 1 obstacle - real problem going into the obstacle @24'00" (after burnback pot ignited) slight flicker - self extinguished @ 25'00" - some edges @ 26'00" large area >50% @27'00" 100% - extinguished by foam
SB21	E	FF	3%	3%	0.2 m/s	23	22	18	4.6225	semi	fresh	Gasoline	3 mins	17	1	3.68	4.1	>30mins	5'52	7'40"	24'22"	@25'00" - no reignition	@28'00" no ignition	Note trouble sealing forward of impact point @ 10 mins - approx 25% perimeter total, some flaming at centre old foam @ 12 mins - holding well but constant flickers @ 16 mins - as 12'00" but approx 25% perimeter and some central @ 18 mins - small ignition @ obstruction - self ext @ 21 min - <10% perimeter @ 23 min - some minor ghosting, self extinguished
SB 21a	E	FF	3%	3%	0.2 m/s				4.6225	semi	fresh	Gasoline	3 mins	17	2	7.36	4.1	>30mins	5'30"	7'18"	9'04"	N/A	N/A	Note: No new fuel foam applied off obstructions so more gentle than previous still issues at worst edge last obstacle out @ 7'30", although 1 whole side (25% perimeter) still flaming Note: no film to give any resistance at all
SB22	E	FF	3%	3%	0.2 m/s	27	30	22	4.6225	asp	fresh	Gasoline	3 mins	17	1	3.68	9.6	>30mins	4'59"	5'28"	5'39"	@15'00" - no reignition	@20'00" nothing until 29'30", some ghosting & minor flickers s. ext	Note: very difficult to clean out foam layer from previous test except by water spray. When burnback pot removed, some ignition but s. ext
SB23	E	FF	3%	3%	0 m/s	29	34	23	4.6225	sys	fresh	Gasoline	3 mins	11.7	1	2.53	5.7	>30mins	5'58"	7'53"	N/A	N/A	@30'00"	@ 10mins - approx 25% edge, ongoing edge burning, soemtimes 50%, sometimes 15% @ 13 mins - very small flames, 80% @ 16'30" - very minor flickers - 10% perim, some surface ghosting @ 20'00" as 16'30" @ 22'00" a few sustained minor flickers @@ 24'00" - minor flicker - one corner Burnback pot in at 26mins, still flickers remaining, ignited at 30mins - pan removed at 34mins, minor burning the s. ext. Note: foam sloppy @ 30' though drainage time long
SB24	E	FF	3%	3%	1.5 m/s	33	28	23	4.6225	MEX	fresh	Gasoline	3 mins	17	1	3.68	17.5	25'00"	5'56"	7'03"	7'10"	@15mins - no reignition	@20mins - full perimeter & some surface flash @ 22'20" - died down & s. ext	@ 25'00" - pan only @ 29'34" - full flash - left with obstructions & ghosting @ 32'00" pot removed, full flash - s. ext
SB25	E	FF	3%	3%	0 m/s	30	35	24	4.6225	CAFS	fresh	Gasoline	3 mins	10	1	2.16	18.3	<30 mins	6'04"	6'40"	7'18"	@15 mins - 2 small 'pops' s. ext	@20mins - some minor pops occuring @28'00" - slight pop at edge of pot @30'00" - pan removed - confined to pot area - s. ext	v. long drainage time (not even a drop at 30mins
SB26	B	C6	1%	1%	0 m/s	28	22.4	25	4.6225	semi	fresh	Gasoline	3 mins	17	1	3.68	4.77	5'39"	5'08"	5'17"	6'27"	@15mins - back corner and both obstructions & 75% perimeter flash	@28mins ignited small edge flickers 15% edge @ 30'00", some surface ghosting 31'00" edge of pot ignited 32'15" minor edge flickers & around pot pot removed @ 32'50" 33'10" everything s.ext apart from central area (pot area)	@18'30" - 25% perim, 200mm from edge @21'00" - approx 30% perim @22'00" - 1 obstruction ignited, rest of foam burnback good - holding well @22'30" - edge flickers only @24'00" - minor flickers & 1 obstacle 24'30" - surface ghosting & small flickers @25'00" - s. ext.
SB27	B	C6	1%	1%	0.5 m/s	28	30.7	25	4.6225	asp	fresh	Gasoline	3 mins	17	1	3.68	6.51	4'59"	4'50"	4'59"	6'11"	@15mins - no reignition	@20mins @22'20" - minor flickers around pot 23'30" - edge flickers around pot only 24'30" - burning around pot, no fuel exposed, foam holding well 26'00" edge flickers 25% dying down to nothing 26'25" some fuel exposed around pot @ 27'00" - burning @27'30" - 15% surface burning @28'30" - 25% surface burning @29'30" sudden escalation to full surface - Test stopped	@21'30" - wind gusts - foam away from edge but no reignition
SB28	B	C6	1%	1%	0.5 m/s	29	40	26	4.6225	sys	fresh	Gasoline	3 mins	11.7	1	2.53	4.7	3'00"	7'15"	8'10"	N/A	N/A - still burning @ 15'00"	N/A	@10'00" - foam stopped - edge flickers 25% @9'50" - some surface ghosting @11'20" - edge flickers, some round 1 obstacle, spreading to 300mm into pan @12'00" - only 2 corners ignited @14'11" - 2 corners & some surface ghosting @16'30" - 1 edge sustained & surface ghosting @18'30" - surface ghosting & 30% edge 24'00" - exposed fuel in 2 corners - burning but holding, 40% edge 25'30" - sustained burning but still holding 28'00" - more surface exposed - (800mm in each direction) @28'50" - increased area burning - test stopped
SB29	B	C6	1%	1%	0.5 m/s	29	40.5	27	4.6225	MEX	fresh	Gasoline	3 mins	17	1	3.68	18.52	2'34"	4'40"	7'33"	N/A	N/A	N/A	@7'00" - still <50 - >25% perimeter flaming @8'45" - foam stopped due to overtopping pan @14'00" foam blanket collapsed significantly @18'25" - more sustained burning, no sign of extinguishing @19'00" - cooling applied - water applied into tank - made foam more fluid, flames reduced & extinguished.

Phase 1 - Bund Test Results Data Tables

Test Reference	Foam Reference	Type	Proportioning Rate	Nominal Proportioning Rate	Wind Speed (m/s)	Air Temp	Fuel Temp	Solution Temp	Bund Dimension	Nozzle Type	Water Type	Fuel Type	Preburn Time	Nett Application Rate (lpm)	Number of Nozzles	Nett Total Application (lpm/m2)	Foam Expansion	Drainage Time	Control Time	Time to Virtual Extinguishment	Extinguishment Time	Torch Test	Burnback	Notes
SB30	B	C6	1%	1%	gusts to 2.5 m/s	30.5	40	27	4.6225	CAFS	fresh	Gasoline	3 mins	10	1	2.16	21.1	18'20"	5'30"	6'28"	8'02"	@15'00" - 2nd top corner flame just touched foam, minor flash, s.ext straight away	@20mins @23'52" - minor ghosting around pot @24'38" - edge flickers around full perimeter @25'45" - flickers around 1 obstacle @26'00" - 3 corners, surface around pot @27'00" - 20% fuel surface ignited & 1 edge	@7'00" two corners & 1 obstacle remaining @27'30" - test stopped
SB31	C	FF	3%	3%	1 m/s	29	40	27	4.6225	semi	fresh	Gasoline	3 mins	17	1	3.68	4.48	10'48"	4'35"	5'19"	6'33"	@15mins - virtually full flash from one corner, & both obstructions	N/A - note foam held well following torch test ignition until 30'00"	@5'48" - one corner remaining only note: noticeably more sloped build up behinf nozzle @16'30" - 35% surface, 75% perimeter @18'00" - 35% perimeter, 20% surface @20'00" - 50% perimeter, small patches in centre @21'00" - 2 corners & some flashing in spots @23'00" - 2 obstacles & 40% perimeter - small flames @24'00" - some ghosting & 2 corners @25'00" - 35% perim @27'00" - minor flickers, 25% perim @28'00" - surface burning beginning to increase @29'00" - surface spots & 2 corners @29'40" - fuel exposed, tank cooled, test stopped
SB32	C	FF	3%	3%	0.5 m/s	32	35	27	4.6225	asp	fresh	Gasoline	3 mins	17	1	3.68	6.8	13'10"	4'32"	5'56"	6'32"	@15mins - no reignition	@21'00" - 75% perimeter & 20% surface flash	@22'00" - 50% perimeter & 10% area @22'46" - large areas of ghosting @24'00" - ongoing flames across surface, minor flames around edges, 1 obstacle flaming @25'00" - sustained burning & breakdown of foam Test stopped @ 26'00" due to escalation
SB33	C	FF	3%	3%	gusts to 1.6m/s	36	35	27	4.6225	sys	fresh	Gasoline	3 mins	11.7	1	2.53	4.14	8'31"	7'45"	9'00"	N/A	N/A	N/A	@11'27" - 50% perimeter, 30% surface flames @12'15" - 50% perimeter, some surface flickers @13'15" - continuous ghosting >50% surface @15'30" - continuous ghosting >50% surface, edge flickers @17'00" - continuous ghosting over surface @18'00" - 100% circumference & 20% surface flickers @20'00" - continuous ghosting on surface (50%) and sustained burning 1 corner extinguished with DP - increased burning so foam used to extinguish
SB34	C	FF	3%	3%	0 m/s	32	35	27	4.6225	MEX	fresh	Gasoline	3 mins	17	1	3.68	15.15	4'20"	5'05" (note only impact zone remaining	8'55"	N/A	@15mins - reignition immediately to 100% perim, rapid collapse of foam	N/A	@6'11" - flashes on surface & perimeter @6'27" - impact zone control @7'45" - virtually 100% perimeter flaming @8'30" - flames approx 50% perim @9'09" - pan full of foam @10'00" - foam stopped - 10% edge still burning, pan full @10'56" - s.ext (note foam overtopped bund, still had vapour alight on ground for short period) @16'00" - surface burning & edge flickers @20'00" - sustained burning, 70% perimeter, 2 obstacles, regular bubbles Test aborted @ 22'00" - no change
SB35	C	FF	3%	3%	0 m/s	31	37	27	4.6225	CAFS	fresh	Gasoline	3 mins	10	1	2.16	17.47	9'41"	5'15"	6'00"	6'41"	@15mins - no reignition	@20mins @26'40" - some surface flickers @27'00" - edge ignition 100% perim & obstacles @28'00" - 25% surface also, 50% foam collapse exposing fuel @28'50" - 50% surface burning	@5'00" - obstacle facing away from nozzle out @6'00" 2 corners & 1 obstacle @6'20" - 1 obstacle only DP used to extinguish - caused escalation so extinguished with foam
SB36	F	FF	3%	3%	2.5 m/s	25	23	22	4.6225	semi	fresh	Gasoline	3 mins	17	1	3.68	4	>30mins	5'57"	9'30"	N/A	N/A	N/A	Note: long time needed to finish last areas of burning @10'00" - foam stopped, still burning 40% perimeter & 30% surface @12'00" - continuous ghosting, keeps dying down and restarting @13"10 - 60% perimeter & surface & 1 obstacle @14'15" - 50% perimeter & regular surface ghosting @18'30" - 30% surface, 50% perimeter burning Test stopped @ 20mins - DP & cooling used - good DP resistance
SB37	F	FF	3%	3%	1.5m/s	26	27	22	4.6225	asp	fresh	Gasoline	3 mins	17	1	3.68	6.3	>30mins	4'22"	4'40"	4'55"	@15mins - no reignition	@20mins @22'01" - reignition, 50% perim 150mm strip, s.ext @25'00" - no further reignition @26'28" - further reignition, ghosting approx 75% surface, 150mm in, s.ext pot removed @30mins - flash 50% surface, 75% perim, s.ext after 5 secs	
SB38	F	FF	3%	3%	1.5m/s	34	31.9	22	4.6225	sys	fresh	Gasoline	3 mins	11.7	1	2.53	3.5	>30mins	8'30"	9'22" (small flame @ impact point)	17'42"	@19'30" - no reignition	@22'00" - virtually impossible to maintain burning in pot pot removed @ 25mins - edge ignition s.ext after 15secs	@6'34" - impact zone & far edge @10'00" - foam stopped, 60% perimeter burning @10'32" - 25% edge @11'00" - regular ghosting & perimeter burning, dying down to edge flickers @13'44" - persistent small flames around perimeter, cycle of dying down and then flashing again @15'09 - tiny flame then flashed again
SB39	F	FF	3%	3%	0.5m/s	32	36	23	4.6225	MEX	fresh	Gasoline	3 mins	17	1	3.68	9.32	25'24"	4'32"	5'32"	5'58"	@15'00" - flame touched one corner - flash 80% perim, s.ext @ 16'59"	@20mins - immediate flash full circumference, ongoing surface burning, small sections @22'50" @25'00" - surface burning, 1 obstacle, some edge burning. Pot removed, ongoing flickers all over surface - more surface than edge burning	foam stopped @8'00" due to pan overflowing @14'00" - vapour bubbles through surface - no ignition though extinguished with DP - removed a lot of the foam

Phase 1 - Bund Test Results Data Tables

Test Reference	Foam Reference	Type	Proportioning Rate	Nominal Proportioning Rate	Wind Speed (m/s)	Air Temp	Fuel Temp	Solution Temp	Bund Dimension	Nozzle Type	Water Type	Fuel Type	Preburn Time	Nett Application Rate (lpm)	Number of Nozzles	Nett Total Application (lpm/m2)	Foam Expansion	Drainage Time	Control Time	Time to Virtual Extinguishment	Extinguishment Time	Torch Test	Burnback	Notes
SB40	F	FF	3%	3%	0.5m/s	31	36	23	4.6225	CAFS	fresh	Gasoline	3 mins	10	1	2.16	16.1	>30mins	4'54" (some edge & 1 obstacle)	5'45"	5'54"	@15'00" - one flash in corner - s.ext immediately	@20mins @21'50" - surface flash s.ext @22'06" - 70% perim, 150mm from edge @22'19" - further ignition, s.ext immediately @22'30"- further ignition, s.ext immediately @23'30" - further ignition, s.ext immediately @25'00" - further ignition, s.ext immediately @26'00" - further ignition, s.ext immediately pot area extinguished on removal	
LB1	D	AFFF	3%	3%	1.5m/s	32	32	22	18.49	semi	fresh	Gasoline	3 mins	17	2	1.84	4.1	6'32"	8'15"	8'37"	N/A	N/A	N/A	2 nozzles used for 7 minutes in one half, then 2 nozzles used in other half for further 7 minutes 5'30" 75% blanket. 50% circumference still flames just above pan height. Impact area still aggressive burning 6'15" near quad corner still burning 7'00" two impact points and edges only 10'00" nozzles moved location 11'00" - 2 corners and 50% front edge minor flames just above pan 11'38" 80% front edge only 12'28" 2 corners only 13'30" some flame spread along 1 egde 14'30" 3 corners and 60% of one edge, 90% appears secure 17'00" foam stopped, flames 90% front edge and 2 corners, flames beginning to develop after foam stopped 20'00" flames along right hand and front edges, test stopped
LB2	D	AFFF	3%	3%	1.5m/s	32	33	22	18.49	asp	fresh	Gasoline	3 mins	17	2	1.84	11.1	6'35"	7'02"	N/A	N/A	N/A	N/A	cooling applied to concrete surrounding bund 4'00" blanket reached rear side 6'00" RH front and side flames approx 2m above bund wall 6'36" reduction in flame height and number - mostly at impact points 8'10" some wind blowing across bund. No obstacles alight and 40% edge burning 9'00" 30% edge and 3 corners 10'00" nozzles moved to quad 2 10'27" 3 corners only RH rear out still 13'19" 2 LH corners only 13'40" front LH corner ext 14'10" rear LH corner only with minor reig in nearest obstruction 14'50" minor flickers only rear LH corner 16'35" almost extinguished with minor reig 17'00" foam stopped, flickers to rear LH corner only 18'23" reig rear RH corner and LH rear obstruction 20'00" test stopped
LB3	D	AFFF	3%	3%	2m/s	32	35	23	18.49	CAFS	fresh	Gasoline	3 mins	17	2	1.84	12.5	11'05"	14'15"	N/A	N/A	N/A	N/A	4'10" full blanket, high flame to circumference 5'00" minor flames to back wall. Front edge and corners still very involved 6'30" front still fully involved 8'00" front and RH side very involved, LH side less flame and less involved 10'00" nozzle changeover, rear wall minor flames, rear obstructions out, front still involved, flames >3m 11'30" beginning to gain control 12'00" impact zone out, 2 x front pots and front wall 50% sides 15'30" front edge and rear corners flames approx 400mm above pan 17'00" foam stopped 16'36" rear LH corner out, flickers rear edge and rear RH corner 18'15" minor reig to RH edge, minor flames 19'20 minor reig to rear corners 20'00" 35% perim, 1 corner and 1 obstruction minor flames. Test stopped
LB4	E	FF	3%	3%	gusts to 3m/s	27	22	22	18.49	semi	fresh	Gasoline	3 mins	17	2	1.84	3.8	>30mins	14'10"	29'19"	29'35"	@35'00" - 20 sec direct application to foam surface, forcefull (opening 20mm hole), jet removed, hole closed and s. ext	N/A	Note: Impact zone difficult to control flash again at impact zone after control time 15'00" impact zones extinguished, 100% edge burning 16'35" only edges remaining 17'00" foam stopped - flickers to height of pan 18'00" - 80-100% edge flickers, some reignition @ obstacles @ 18'30" 20'00" - edge flickers 80-100% minor reignition around obstacles, comes and goes 21'00" small surface burning - s. ext 60-80% edge flickers 22'00" small flickers 50-75% edge, some surface reig, obstacles, s. ext 24'00" 10% surface burning, moving around. s. ext. Flickers 50% edge 25'00" 75% surface flash, s. ext 26'00" regular reignition of surface, s. ext. 25% edge 27'00" regular flashes over surface - s.ext, 5% edge ignited, flickers 29'00" one corner only
LB5	E	FF	3%	3%	gusts to 2m/s	38	34	22	18.49	asp	fresh	Gasoline	3 mins	17	2	1.84	12	>30mins	16'30"	N/A	N/A	N/A	N/A	When move the nozzles, get a flare up again, similar effect to when first apply foam 12'00" bund still too hot to approach 13'20" slightly less flame 16'30" control, less surface flame 17'00" foam stopped 18'23" significant edge burning, escalation at 19'30", test aborted

Phase 1 - Bund Test Results Data Tables

Test Reference	Foam Reference	Type	Proportioning Rate	Nominal Proportioning Rate	Wind Speed (m/s)	Air Temp	Fuel Temp	Solution Temp	Bund Dimension	Nozzle Type	Water Type	Fuel Type	Preburn Time	Nett Application Rate (lpm)	Number of Nozzles	Nett Total Application (lpm/m2)	Foam Expansion	Drainage Time	Control Time	Time to Virtual Extinguishment	Extinguishment Time	Torch Test	Burnback	Notes
LB6	E	FF	3%	3%	gusts to 3m/s	27	31	23	18.49	CAFS	fresh	Gasoline	3 mins	17	2	1.84	7.1	>30mins	15'00"	24'00" (but then reig)	26'22"	N/A	N/A	flame height less at approx 4'00", less smoke No flare up when nozzle chnageover at 10'00" 5'00" approachable, blanket visible 5'30" RH side is most involved due to impact zones 8'00" impact zone, surface flame to back half of bund, full circumference involved 10'00" nozzle changeover and RH impact zone sealed, LH impact zone not continuously flaming to begin with, but then ignited, surface flames remain worse at back edge 13'00" surface and edge flames reduced 17'00" foam stopped, surface flames reduced then ext. 75% perimeter flames just above bund wall 19'00" 25% surface burning sporadic, 75% perim 22'00" 90% perim and 10% surface 23'00" 40% perim and 5% surface (moving) 25'00" 15% perim and 5% surface (reignition and subsides continually)
LB7	F	FF	3%	3%	gusts to 0.5m/s	29	27	23	18.49	semi	fresh	Gasoline	3 mins	17	2	1.84	3.96	>30mins	9'42"	N/A	N/A	N/A	N/A	5'00" 80% blanket - impact zones burning and full perim. Back RH more involved and back LH 6'30" mostly impact zones, some surface flames and 75% circ, LH edge no flames 7'30" reig to LH edge, impact zones, surface flames front and RH edge. Back edge often ext, but then minor flames. LH rear corner almost out 10'00" nozzle changeover. RH impact zone ext. RH edge minor flames. LH impact zone flames and RH edge larger flames approx 1.5m above bund wall 12'00" impact areas flames, some surface flames (approx 25%) 12'30" reduced flames and impact areas out wind gusts caused reign of some surface flames 14'00" reig of impact zones and minor flames over blanket then out again 15'00" impact zones out 100% preim flames, mostly minor some to 0.5m above bund wall 16'00" 80% perim, back edge less flames 17'00" foam stopped, 100% perim flames at pan height 19'00" flames diminished but still 100% perim 20'30" appears to be holding quite consistently, minor infrequent surface flames 22'00" rear edge largely out then minor flames reappear 24'00" minor surface flames - no more than 15% at any time, edge flames to corners 25'30" flames over area approx 25% at any time and then reduce 28'00" continues to hold but surface flames continue to move over surface, more than previous, up to 50% at anytime 30'00" test ended, DP to extinguish, mostly out minor edge flames s.ext
LB8	F	FF	3%	3%	2m/s	28	38	23	18.49	asp	fresh	Gasoline	3 mins	17	2	1.84	4.4	28'21"	N/A	N/A	N/A	N/A	N/A	5'00" too hot to approach 6'30" 75% blanket just visible, impact areas still actively flaming to 3 m 8'00" foam beginning to make impact and reducing flame, front RH corner worst as usual 10'00" nozzle changeover, impact zones sealed open slightly LH side 11'00" 50% rear edge minor flames 12'30" flames to front edge still up to 5m RH edge approx 1m, LH edge 0.5m, rear edge 50% out, impact areas appear to have visible fuel areas 15'00" RH edge flames to 1m above bund wall, front edge much reduced. LH edge flames 3m front and 1m beyond, back edge 50% out at times 17'00" foam stopped. Impact zones close and seal. Surface flames to 20% moving over blanket. Edge flames to 100% approx 0.5m above bund wall 20'00" test stopped
LB9	F	FF	3%	3%	0m/s	24	42	24	18.49	CAFS	fresh	Gasoline	3 mins	17	2	1.84	15.15	>30mins	6'54"	7'13"	9'10"	@18'15" - front LH corner minor flickers direct impingement on foam RH corner minor reig - immediately s.ext other corners all ok	N/A (foam too big)	5'00" almost full blanket, front RH corner most involved and RH side 6'30" flames RH corner approx 5m above pan height 6'54" control - impact zones out, no surface flames 50% perim minor flames 8'00" front corners only 8'15" RH corner only 8'55" RH front corner minor flames to pan height 10'00" nozzles changed over 19'40" test complete

Phase 1 - Bund Test Results Data Tables

Test Reference	Foam Reference	Type	Proportioning Rate	Nominal Proportioning Rate	Wind Speed (m/s)	Air Temp	Fuel Temp	Solution Temp	Bund Dimension	Nozzle Type	Water Type	Fuel Type	Preburn Time	Nett Application Rate (lpm)	Number of Nozzles	Nett Total Application (lpm/m2)	Foam Expansion	Drainage Time	Control Time	Time to Virtual Extinguishment	Extinguishment Time	Torch Test	Burnback	Notes
LB10	B	C6	1%	1%	1m/s	24	25	22	18.49	semi	fresh	Gasoline	3 mins	17	2	1.84	4.27	5'03"	5'50"	10'18"	N/A	flash 50% surface 25'00" edges only and 1 obstacle 26'00" 20% perim and 1 obstacle 27'00" surface ghosting and <10% edge	N/A	4'00" controlling well, 75% blanket, impact zone flames and front edge last area for blanket to form 5'00" impact zones and obstacles. Front corners flames to 1.5m, back edge 90% out 5'50" control, both impact points 6'30" both rear obstacles out 7'30" 50% perim - LH edge and front edge, corners and LH front obstacle 9'00" front LH corner and obstacle still involved and flame above obstacle height. Back corner flames approx 0.3m above bund. RH edge out, LH edge 50%, back edge (except corners) out 10'00" nozzle change 11'00" LH front reduced and obstacle out.flames just in corners 12'00" from RH corner minor flames only, some reig to front edge 15'00" holding steady but corner flames starting to grow - 0.6m above bund wall. Back RH corner area growing to obstacle 17'00" foam stopped. Front edge now 50% minor flames and RH edge flame to both pots. LH front corner out, 30% edge 18'30"front and RH edge 100%, flames above pan. Back edge approx 3% and corners, LH edge approx 10% and corners. Blanket holding - no surface flames or flickers 20'00" RH rear obstacle reign and flames to perim front RH obstacle. Test stopped using DP, no destruction of blanket.
LB11	B	C6	1%	1%	0m/s	31	35	23	18.49	asp	fresh	Gasoline	3 mins	17	2	1.84	7.08	6'24"	7'16"	7'39"	N/A	direct impact on foam - virtually s.ext.	N/A	3'45" fire approachable, back edge 80% out. RH and LH edges quickly reduced to minor flames. Front LH corner most involved and obstacle 4'56" impact zones out 6'00" only fron LH corner not controlled 6'38" edges only and LH front obstacle. Wind drifts open up fuel area 8'00" 35% perim and 1 obstacle and corners mostly minor flames/flickers 9'00" holding stable - no surface flames 9'10" LH edge and corners out 10'00" nozzles changed 10'21" 2 corners and 5% perim only and front obstacle out 11'00" 2 small pockets at corners - LHS 11'30" back LH corner out, front LH corner remaining 12'00" very minor flickers in front LH corner 14'30" reig back LH corner, flames above pan height and reducing 17'00" foam stopped. front LH corner out after foam stopped only back LH corner remaining 20'00" minor flickers back LH corner and approx 1m along LH edge
LB12	B	C6	1%	1%	gusts to 2.1m/s	32	36	23	18.49	CAFS	fresh	Gasoline	3 mins	17	2	1.84			6'38"	7'22"	10'44"	LH front slight touch, ok all other ok	N/A	5'00" no impact flame - solid blanket, front edge last to seal 5'40" impact area reig 6'00" 50% perim and 2 obstacles 7'00" minor flames to front edge only and front corners 8'00" 3 areas on rear wall <10% full perim flames approx 0.3m above pan height 8'56" front LH corner only 10'00" nozzles moved over slightly 15'00" foam off as air cylinders empty. 23'00" test end
LB13	C	FF	3%	3%			43		18.49	semi	fresh	Gasoline	3 mins	17	4	3.68			7'18"	N/A	N/A	N/A	N/A	Front sealed first before back with impact area approx 1/4 bund 80% circ and 4 obstacles at 11'00". 2 x DP used - not ext.
LB14	C	FF	3%	3%			43		18.49	CAFS	fresh	Gasoline	3 mins	25	2	2.70			7'02"	8'09"	9'27"	N/A	N/A	impact zone central to bund nozzle movement caused impact zone to move and reignite. Control when 80% perim alight VE - <25% perim - front corners only and 10% front edge 8'48" one LH corner only
LB15	A	FF	3%	3%			43		18.49	semi	fresh	Gasoline	3 mins	17	4	3.68			8'34"	N/A	N/A	N/A	N/A	lots of surface flaming 7'26" impact areas out but then reign. 10'00" foam off, 60% surface flames and 80% perim
LB16	A	FF	3%	3%			43		18.49	CAFS	fresh	Gasoline	3 mins	25	2	2.70			5'26"	6'15"	7'08"	N/A	N/A	4'02" impact areas out 5'00" 35% perim and 3 obstacles alight 5'52" 1 obstacle and 10% perim alight Test stopped at 7'30"
LB17	D	AFFF	3%	3%			44		18.49	semi	fresh	Gasoline	3 mins	17	4	3.68			6'36"	6'50"	N/A	N/A	N/A	5'00" impact areas still alight. 7'30" front corners only 8'47" RH corner out, small area remaining in LH corner - LH corner beginning to roll, foam off front LH corner only - DP applied to corner, out with 1 burst
LB18	D	AFFF	3%	3%			44		18.49	CAFS	fresh	Gasoline	3 mins	25	2	2.70			5'25"	6'26"	7'32"	N/A	N/A	VE front corners minor flickers 6'48" LH corner only
LB19	F	FF	3%	3%			30		18.49	semi	fresh	Gasoline	3 mins	17	4	3.68			9'42"	N/A	N/A	N/A	N/A	After 8'40" flames developed again. Edge flames and surface flames Foam stopped @ 10'00", 100% edges approx 0.3m above pan height, 10% surface flames (old foam) ext with DP - foam blanket survived
LB20	F	FF	3%	3%			30		18.49	CAFS	fresh	Gasoline	3 mins	25	2	2.70			6'21"	7'13"	8'38"	N/A	N/A	Front edge last to ext. large bubbles coming up to surface
LB21	B	C6	1%	1%		25	39		18.49	semi	fresh	Gasoline	3 mins	17	4	3.68			5'36"	5'51"	N/A	N/A	N/A	5'51" impact areas all out, flames to front corners only, LH less than RH 7'04" LH corner out, RH corner still flames on old foam 9'10" RH corner flames increasing in height and areas appears to grow. Foam 'roll' still expanded. Flames moving along front edge as foam stopped 10'00" foam stopped, flames extended to RH obstacle 12'00" reignition in obstacle. extinguish with water spray - some reign in LH corner
LB22	B	C6	1%	1%		25	39		18.49	CAFS	fresh	Gasoline	3 mins	25	2	2.70			4'51"	5'43"	7'14"	N/A	N/A	Control - 2 pots and 25% preim flames to approx 0.4m above VE - all pots out, front RH edge 50% minor flames and LH edge 25% minor flames

Phase 1 - Bund Test Results Data Tables

Test Reference	Foam Reference	Type	Proportioning Rate	Nominal Proportioning Rate	Wind Speed (m/s)	Air Temp	Fuel Temp	Solution Temp	Bund Dimension	Nozzle Type	Water Type	Fuel Type	Preburn Time	Nett Application Rate (lpm)	Number of Nozzles	Nett Total Application (lpm/m2)	Foam Expansion	Drainage Time	Control Time	Time to Virtual Extinguishment	Extinguishment Time	Torch Test	Burnback	Notes
LB23	E	FF	3%	3%	0m/s	23	40		18.49	semi	fresh	Gasoline	3 mins	17	4	3.68			8'40"	N/A	N/A	N/A	N/A	@7'49" minor centre and 100% edge but reestablished @10'00" 100% edge flame and 2 obstacles Test stopped at 13'30" - 80% edge and flickers in centre DP used to extinguish - ok
LB24	E	FF	3%	3%	0m/s	23	40		18.49	CAFS	fresh	Gasoline	3 mins	25	2	2.70			5'45"	6'41"	7'09"	N/A	N/A	@control (5'45") 1 impact zone and 50% edge @6'47" one corner only remaining

Phase 2 - Tank Tests Results Data

Test Ref	Date of Test	Foam Reference	Type	Proportioning Rate	Nominal Proportioning Rate	Wind Speed	Ambient Temperature	Concentrate Temperature	Nozzle Type	Preburn Time	Foam Solution Production Rate (lpm)	Foam Solution Production Rate (lpm/m2)	Foam Expansion	Drainage Time	Control Time	Extinguishment Time	Notes
3	24/10/2017	F	FF	3.70%	3%	to 3.5m/s	20	15	ASP	2 mins	1000	10	8.98	>20min	4'45"	7'08"	2'00" foam application started 3'00" foam monitor moved to optimise foam application 4'30" flames reduced 4'45"good control 5'00" impact area and some edge flames 5'40" impact area out, edge 'flickers' only 6'10" minor flickers only 7'08" extinguished 10'00" foam stopped - confirmation of extinguishment from adjacent tank NOTE: Deduct 60 secs from figures to take account of delayed application
5	25/10/2017	A	FF	3.20%	3%	1.2m/s	18	21.8	ASP	2 mins	1000	10	14	7'50"	03'20"	07'38"	2 minutes preburn – monitor moved to get foam onto fuel surface 03’ 20” gaining control at back 03’ 40” edges only 04’ 10” flickers only at edges 04’ 40” minor flickers 06’ 40” edge flickers; ghosting across blanket 07’ 00” monitor oscillated to extinguish edge flickers 07’ 38 extinguishment – tank full and would have overtopped if more foam required
6	25/10/2017	C	FF	2.80%	3%	0m/s	18	21.8	ASP	2 mins	1000	10	4.1	3'46"	N/A	N/A	04’ 00” monitor moved to get more foam onto fuel 05’ 00” flames reduced but no control yet; monitor movements – elevation & flow 06’ 00” start pourer as no control with monitor 07’ 00” no reduction in fire 07’ 40” backup monitor started; still minimal affect 17’ 00” impact area only 17’ 01” extinguishment TEST TO BE REPEATED DUE TO EQUIPMENT PROBLEM
7	26/10/2017	D	C6		3%	0m/s	15	17.8	ASP	2 mins	1000	10	9.14	4'03"	03'16"	03'45"	2 minutes preburn; zero wind 02’ 50” 50% back area blanket 03’ 16” area at monitor remains 03’ 25” impact area 03’ 40” minor flickers 03’ 45” extinguished (from ground level) 04’ 50” extinguishment confirmed 05’ 30” @ tank top Note: after 30 minutes blanket looks OK but disappears with water spray immediately
8	26/10/2017	B	C6		1%	gusts to 2.5m/s	16	16.3	ASP	2 mins	1000	10	3.35	<2'00"	03'45"	04'25"	03’ 10” approximately 50% blanket 03’ 45” flames to monitor side 04’ 05” flickers only seen from ground level 04’ 25” from ground level fire appears extinguished 16:22” confirmed by drone & at tank top – foam off 06’ 00” foam stopped Obvious signs of vapours at edges and curling away from shell – not noticed on previous foam tests – these observations from tank top at 10 minutes
9	27/10/2017	F	FF		3%	gusts to 1m/s	14	14.4	NON-ASP	2 mins	1000	10	7.44	>10'00"	04'30"	09'40"	03’ 30” some control, flames reduced 04’ 15” areas of control developing 04’ 30” control, rim & edges 05’ 00” impact area & edges 05’ 20” remains the same 05’ 40” reduced flames but still impact area involved 06’ 00” still impact area alight with edge flickers 06’ 35” virtual extinguishment 07’ 00” small impact area only, edge flickers 07’ 30” oscillating monitor starts to extinguish edge flickers 08’ 26” edge flickers persisting 09’ 20” minor flickers at pourer – possible vapours trapped? (VE) 09’ 40” extinguished – check drone 10’ 00” foam application stopped 12’ 00” at tank top no apparent vapour issues, blanket appears secure

Phase 2 - Tank Tests Results Data

Test Ref	Date of Test	Foam Reference	Type	Proportioning Rate	Nominal Proportioning Rate	Wind Speed	Ambient Temperature	Concentrate Temperature	Nozzle Type	Preburn Time	Foam Solution Production Rate (lpm)	Foam Solution Production Rate (lpm/m2)	Foam Expansion	Drainage Time	Control Time	Extinguishment Time	Notes
10	27/10/2017	D	C6	3%	3%	2.7m/s	16	15.8	NON-ASP	2 mins	1000	10	14	4'36"	04'00"	05'50"	02' 00" monitor being moved forward for reach – low throw 02' 50" foam stream now into tank, moved forward again 03' 40" settled foam stream 04' 00" control starting 04. 17" edge flames only visible from ground 04' 37" flickers at edge 05' 33" appeared extinguished at ground level apart from flames at pourer – foam stream moved again 05' 50" complete extinguish 06' 30" foam stopped From tank top curl to blanket at edges
11	27/10/2017	E	FF	3%	3%	2.4m/s	16	14.2	ASP	2 mins	1000	10	4.03	Foam drained rapidly but liquid remained cloudy due to minute air bubbles	see note	see note	Ignition sequence started – virtually immediate full surface fire even following an AFFF foam test 02' 00" foam stream almost straight into tank – minor elevation change 04' 00" definite reduction in flames 04' 50" flames lower 05' 25" flames lower – impact area 06' 00" wind changing – monitor throw moved Front half of tank struggling – blanket over rear half – i.e. flames to impact area 07' 30" oscillation of monitor started 08' 40" system nozzle started – blanket started forming almost straight away – impact area still flaming but much reduced 10' 57" extinguished Visual observation of quantity of concentrate used – proportioner not picking up concentrate continuously– viscosity as before With both systems running flow rate increased to 1,400 lpm
12	27/10/2017	A	FF	3%	3%	2.2m/s	20	18.3	SYS	2 mins	400	4	14	4'36"	see note, VE at 04'30"	5'50"	Wind direction changing – pourer fully involved and smoke going into pourer 03' control starting to move across from pourer – flames at edges 03' 50" blanket to about 50% with flames at edges 04'10" drone footage shows control 04' 30" virtual extinguishment with edge flickers 06' 50" at top of tank – steam still rising at shell, blanket appears secure, foam to top of shell
13	30/10/2017	F	FF	3%	3%	<2m/s	10	9.7	SYS	2 mins	400	4	NM	NM	4'20"	05'00"	03' 00" approximately 50% fire and rim 3' 20" appears to be control 04' 20" approximately 50% circumferential flickers only 04' 54" approx. 1 m of flames to circumference 05' 20" confirmed no fire - checked on drone footage 05' 30" foam stopped Steam at shell & minor curling Short areas of foam charring at shell 08' 30" some heat / vapour haze 10' 00" still very little wind; no obvious blanket breakdown 15' 30 water spray & drone, blanket holding Blanket has slightly glassy appearance 20' 00" still good stable blanket 25' 00" noted movement & ripples on blanket; wind has increased slightly; some foam destruction 26' 45" water on through nozzle to flush then water from monitor as well 38' 00" foam blanket gone
14	30/10/2017	B	C6	3%	3%	<2m/s	12	10	SYS	2 mins	400	4	NM	NM	3'00"	4'20"	Note: test done at 3% not 1% It was apparent during the test that there was an equipment issue preventing proper foam application. This was confirmed by viewing the drone footage. It would seem that insufficient pressure was available at the foam pourer meaning that no aspiration took place and consequently non-aspirated foam solution only was applied. With the higher concentration of solution it was apparent that an aqueous film was formed quite quickly and gave rapid fire control. However, the fire was only extinguished when higher pressures were achieved and aspirated foam was produced. This test, whilst demonstrating the need for correct operating pressures and proportioning, was not considered as a true demonstration of this foams performance and the results have not been included in the report. Test 18 is a repeat test using the foam at 1% - the recommended rate by the manufacturer for hydrocarbon application

Phase 2 - Tank Tests Results Data

Test Ref	Date of Test	Foam Reference	Type	Proportioning Rate	Nominal Proportioning Rate	Wind Speed	Ambient Temperature	Concentrate Temperature	Nozzle Type	Preburn Time	Foam Solution Production Rate (lpm)	Foam Solution Production Rate (lpm/m2)	Foam Expansion	Drainage Time	Control Time	Extinguishment Time	Notes
15	30/10/2017	E	FF	3%	3%	gusts to 2.5m/s	13	19.5	CAFS	2 mins	340 &370		8.6	>30mins	4'20"	5'45"	wind towards pourer 2 minutes preburn CAFS stream being wind affected as wind strengthens, no foam onto fire Rapid control but CAFS skid needs to be moved closer to the fire – subsequently moved 15:12 full surface fire 03' 17" control starting 04' 20" impact area & 70% rim 04' 50" 25% rim, main stream over tank – throw altered 05' 20" minor flickers only at edge 05' 45" extinguished Note foam quality changed during test – continuous proportioning issue CAFS skid at limit of throw
16	30/10/2017	D	C6	3%	3%	gusts to 2m/s	14	15.1	SYS	2 mins	400	4	NM	NM	3'40"	4'58"	02' 45 control starting 03' 03 definite reduction in flames 03' 40" control 04' 20" edge flickers only 04' 40" minor flickers on old foam 04' 58" extinguished; foam stopped; secure blanket but some movement with wind Foam did exhibit some edge difficulties
17	31/10/2017	C	FF	3%	3%	0m/s	8	10.8	ASP	2 mins	1000	10	10.06		3'03"	4'05"	03' 03" good control, approximately 50% 03' 11" small area of flames away from stream 03' 30" appears extinguished but still one small area of flames 03' 57" one minor area and edge 04' 05" extinguished 04' 45" foam off
18	31/10/2017	B	C6	1%	3%	0m/s	9	13.1	SYS	2 mins	400	4	NM	NM	N/A	08'50"	As GESIP proportioner cannot proportion at 1% at 400 lpm a premix was made to compensate therefore test completed at 1% 2 minutes preburn; foam appears to push fire away from pourer 02' 55" 50% opposite pourer very fierce; 50% control at pourer; noticeable increase in radiation 03' 40" high flames to 50% rim, no wind 04' 00" still high flames at rim 04' 10" edge flames reduced height 04' 20" edge flickers 04' 30" foam struggling to seal at edges 04' 50" still edges struggling 06' 30" impact area still struggling & edges 06' 50" full surface ghosting 07' 00" small flickers at edges; impact area involved; tunnelling across blanket 07' 26" no further control at impact area 07' 45" foam stopped - edges reignited but impact area out 08' 50" extinguished Clear areas of charred foam; typical curling of blanket at rim (of AFFF)
20	31/10/2017	B	C6	1%	1%	0m/s	15	14.9	CAFS	2 mins	325	3.25	NM	NM	see notes	5'35"	Stream started close to pourer then moved to be more central 03' 30" some control on side opposite pourer 03' 57" 50% 04' 00" 80% extinguished 04' 16" just pourer area 04' 51" small area of rim upwind still flickers 05' 35" effectively out 06' 20" foam off
21	31/10/2017	C	FF	3%	3%	0m/s	15	14.9	CAFS	2 mins	300	3	NM	NM	5'25"	8'22"	Stream straight onto fuel adjacent to pourer 03' 21" control starting 04' 15" control over 50% area; still big flames at impact area 05' 05" stream / throw increased, better foam quality 05' 25" real control 05' 40" 30% circumference & area at pourer (i.e. impact area) 06' 00" small shell length & pourer 06' 20" pourer & rim opposite flickers again 06' 40" flickers at pourer & shell opposite 07' 30" stream oscillation towards pourer; flickers stubborn at rim 08' 22" extinguished 11' 36" flickers at shell – far side 16: 54 extinguished

n.b Test results excluding aborted tests