ETANKFIRE - Fire extinguishing tests of ethanol tank fires in reduced scale

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ETANKFIRE

SP Technical Research Institute of Sweden

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Abstract

The ETANKFIRE project is focused on tank fires involving ethanol; the work conducted in this part of the ETANKFIRE project (WP1 and WP2) has been focused on tank firefighting operations.

Two series of fire extinguishing tests in reduced scale have been conducted. Both test series simulated tank fire conditions by using a large amount of fuel and long preburn times. The influence of foam application techniques, foam characteristics, and application rates have been investigated. Some tests have also included alternative extinguishing media such as cellular glass, liquid nitrogen and aqueous vermiculite dispersion (AVD).

In total 29 extinguishing tests were conducted in the first test series using a 0,41 m^2 fire tray and 14 tests were conducted in the second test series using a 3,14 m^2 fire tray. Prior to the experimental work a literature review was conducted to gain experience, both from real tank fire incidents and from various test and system design standards for the use of foam on water-miscible fuel fires.

The results showed the importance of the characteristics of the finished foam. Higher foam expansion ratios and longer drainage times resulted in significantly improved fire performance. These improved foam characteristics are dependent on the foam application hardware as well as the foam concentrate formulation. To obtain these improved characteristics the foam concentration was increased to 6 % from a nominal value of 3 % On the other hand, the improved foam characteristics allowed the application rate to be reduced by 50 % without compromising extinguishing performance. This shows that the performance requirements in existing test standards for foam (e.g. UL 162, EN 1568) do not provide an incentive for manufacturers to formulate their foam to handle more severe fire conditions, such as a tank fire scenario.

The tests also indicated that gentle application of the foam is not guaranteed by the use of foam pourers (Type II discharge outlet according to NFPA 11) as the foam was not able to flow gently along the tank wall due to high steel temperatures.

With respect to alternative media, applying a layer of cellular glass followed by foam application made the extinguishing operation even more robust.

The overall conclusion is that fighting ethanol tank fires would very likely result in a failure to extinguish if standard firefighting operations are used. However, the test results also indicate important parameters that would improve the possibilities for a successful extinguishment. Further validation of these results in larger scale could also provide possibilities to improve foam system standards, e.g. NFPA11 and EN 13565-2 for extinguishment of water-miscible fuels as well as test standards for foam concentrates (e.g. UL 162, EN 1568-4).

Key words: ethanol, fire extinguishment, fire suppression, tank fire, tactics, foam, foam concentrate, CAF, liquid nitrogen, vermiculite, cellular glass.

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Preface

The use of ethanol has increased significantly as a means to fulfil climate goals by replacing fossil fuels with renewable fuels, but the introduction of ethanol fuels creates new risks and challenges from a fire protection point of view. SP Fire Research, together with the Swedish Petroleum and Biofuel Institute (SPBI), took the initiative to develop a proposal for a joint industry research project on ethanol tank firefighting – ETANKFIRE. This project provides a platform of knowledge that assists in the selection and installation of fire protection relevant to the risk at ethanol storage facilities. The goals of the project are to develop and validate a methodology for fire protection and suppression of storage tank fires containing ethanol fuels and to determine the large scale burning behaviour of ethanol fuels.

The ETANKFIRE project is structured into seven work packages (WP0 to WP6) as shown in Figure 1 below. The work in WP1 to WP4 is related to the extinguishment of ethanol storage tank fires while work related to the burning behaviour has been handled in WP5. The project is divided into two phases: Phase 1 includes WP1, WP2 and WP5; Phase 2, focusing on WP3 and WP4, will be launched upon completion of Phase 1 when necessary funding has been obtained.

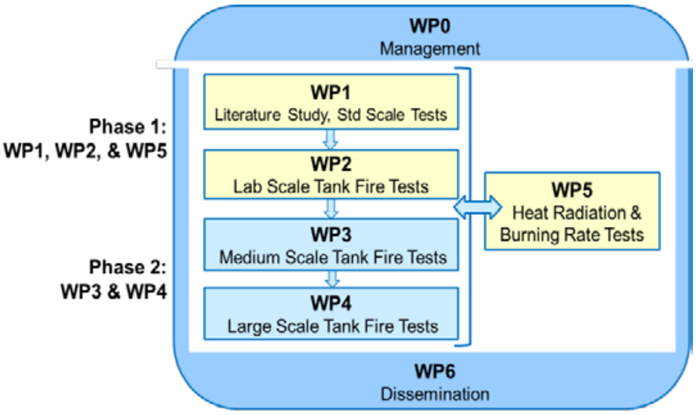


Figure 1 **ETANKFIRE project structure. Phase 1 involved WP1, WP2 and WP5 and Phase 2 will include WP3 and WP4. The activities in WP0 and WP6 will be included in both Phase 1 and Phase 2.**

The large scale free-burning fire tests in WP5 were completed in 2012 [1]. This report presents the results from the fire extinguishing tests in WP1 and WP2 completed in 2015. The following members of the ETANKFIRE consortium are gratefully acknowledged for their contribution to the work.

- BRANDFORSK (Swedish Fire Research Board) (project 603-111)
- Släckmedelscentralen SMC AB, subsidiary company to the Swedish Petroleum and Biofuel Institute (SPBI)
- Lantmännen ek. för. (Swedish ethanol producer)
- Shell Research Limited (Observer Member)
- Alert Inc./The Solberg Company Partnership
- Tryg Forsikring A/S
- LASTFIRE representatives, UK (part of the testing and research group)

We would also like to acknowledge ACAF Systems for providing the CAF test unit, Hasopor AB for providing the cellular glass, and Dupré Minerals LTD for supplying the AVD solution.

Summary

The ETANKFIRE project is focused on tank fires involving ethanol; the work conducted in this part of the ETANKFIRE project (WP1 and WP2) has been focused on tank firefighting operations. The goal has been to evaluate the potential of both traditional and unconventional extinguishing media and application techniques to provide important experience in firefighting tactics which could be of direct use for various stakeholders.

The work in WP1 includes a literature review and a series of small scale experiments. The literature review has primarily been focused on finding experience from real tank fires involving ethanol or other water-miscible fuels. It also includes an evaluation of some test experiences based on various test standards for foam on water-miscible liquids and foam system design standards for water-miscible liquids.

The experimental part of WP1 consisted of 29 extinguishing tests conducted in a 0,41 m^2 fire tray designed to simulate a storage tank. The intention was to provide a better understanding of the various parameters that might influence the extinguishing process, such as the amount of fuel, preburn time, type of application and application rate. Alcohol resistant foam was the main extinguishing media used in the tests, but some tests were also conducted with other media, such as cellular glass, liquid nitrogen and aqueous vermiculite dispersion (AVD).

The work in WP2 involved in total 14 extinguishing tests in a 3,14 m^2 fire tray of similar design as used in WP1. The tests were focused on verifying the extinguishing performance of the most promising tests in WP1 on a larger scale. The results from WP1 were used for the selection of the test conditions, e.g. amount of fuel, preburn time, application rate, foam characteristics and type of application. The tests were focused on the use of firefighting foam as this was considered to be the main firefighting option at the present time. AFFF-AR 3x3 was used in most of the tests but some tests were also conducted using a 3F-AR 3x3 (fluorine free foam). One test also involved the use of cellular glass with a subsequent application of foam.

The results showed that, compared with pool fires, tank fire conditions having increased depth of fuel, prolonged preburn time and a more severe foam application (a slightly higher impact position of the foam on the tank wall was used) might have a negative influence on foam extinguishing performance. In several tests the fire could not be controlled at all, or controlled only when the fire was significantly influenced by dilution.

However, the results also showed the importance of improving the characteristics of the finished foam (i.e. higher foam expansion ratio and longer drainage time) resulting in significantly improved fire performance. Improvements in foam characteristics are dependent on both the foam application hardware and the foam concentrate formulation. To obtain these improved characteristics during the tests, the foam concentration was increased to 6 % from a nominal value of 3 %. Foam nozzles generating aspirated low expansion foam were used in most tests but in some tests the foam was generated as medium expansion foam and compressed air foam (CAF).

The improved foam characteristics allowed the foam application rate to be reduced by 50 % without significantly compromising the level of extinguishing performance. This indicates that the most common test standards for foam concentrates (e.g. EN1568, UL 162) do not adequately simulate a tank fire situation and do not provide an incentive for the manufacturers to formulate and test their foam concentrates to handle more severe fire conditions, such as a tank fire scenario.

The tests also indicated that gentle application of the foam is not guaranteed by the use of foam pourers (Type II discharge outlet according to NFPA 11) as the foam was not able to flow gently along the tank wall due to high steel temperatures. During cold conditions, the foam flowed gently along the wall down to the fuel surface (according to the definition). However, after the 15 min preburn time, the steel tank wall temperature was in the range of 550 °C (about 650 °C in the WP2 scale) that caused an immediate evaporation of the foam at the wall surface and formed a steam layer that pushed the foam stream away from the wall, resulting in a free fall down to the fuel surface. Some foam was also blown outside the test tray due to the thermal updraft from the fire.

The test in which a combination of cellular glass and foam application was used made the extinguishing operation even more robust. The layer of cellular glass protected the foam from direct contact with the fuel and made it possible to use the nominal foam concentration of 3 %, a reduced application rate, and direct foam application (Type III).

The overall conclusion is that fighting ethanol tank fires would very likely result in a failure to extinguish if standard firefighting operations are used. However, the test results also indicate important parameters that would improve the possibilities for a successful extinguishment.

The test scales used in the WP1 and WP2 tests (Phase 1 of the ETANKFIRE project) were very limited compared to real tank fires. It would be of great importance to verify the most promising results at a larger scale as suggested for Phase 2 of the ETANKFIRE project. Such validation of the results could provide unique possibilities to improve foam system standards, e.g. NFPA11 and EN 13565-2 for extinguishment of water-miscible fuels as well as test standards for foam concentrates (e.g. UL 162, EN 1568-4).

The Phase 2 fire tests will preferably be conducted in a facility having a diameter in the range of 10-15 m with a significant fuel depth and extended preburn time. In order to mimic a real tank fire situation at least part of the test facility perimeter should have an extended tank wall construction. A minimum of four tests would be sufficient to confirm the findings of Phase 1.

To realize Phase 2 of the ETANKFIRE project additional partners are required to obtain necessary funding.

1 Introduction and background

1.1 Ethanol use and storage hazards

The use of ethanol has increased significantly as a means to fulfill climate goals by replacing fossil fuels with renewable fuels. In the 2007 Spring Council, the EU agreed on targets to cut greenhouse gas emissions by at least 20 % by 2020. To have a real impact on the green economy and reach the emission targets it is essential to successfully introduce a broad biobased economy, including ethanol fuels as one component.

The main use of ethanol is for low percentage (typically up to 15 %) blending in gasoline, but it is also used as E85 and “diesel ethanol”. In 2011, the acceptable proportion of ethanol in low blended fuels was increased from 5 % to 10 % in Europe. Similarly, in the US the use of ethanol fuels has increased dramatically during the last decade. In 2012 the ethanol content in the gasoline sold in the US was nominally 10 % but in some states the ethanol content has been increased to 15 %. It is also becoming more common to use blender pumps making it possible for the customer to choose a blend, e.g. E20, E30 or E40.

An obvious consequence of increasing the volume of low percentage blended ethanol, both in Europe and the US is that the volume of bulk ethanol transported, handled and stored has increased dramatically in recent years. The diameter/volume of the storage tanks is also increasing, making fire and ensuing firefighting operations a significant challenge in case of a full surface tank fire.

One important issue causing concern was that the burning behaviour of a large scale ethanol fire might be significantly different from that of a petroleum fire. This concern was confirmed by large scale (254 m^2) fire tests conducted in 2012 in WP5 of the ETANKFIRE project using both E85 and E97 as fuel [1]. The results showed that the heat radiation incident upon the nearby surroundings was 2-3 times higher for both E85 and E97 compared to calculated and experimental data for gasoline. This will increase the risk for fire escalation to nearby storage tanks and equipment and also affect firefighting operations due to the increased access issues and heat exposure to firefighting personnel and equipment.

Although tank fires in general are rare, extensive fire protection measures are normally required based on various national laws and regulations or a site specific risk based assessment of business risk. Typically this translates into significant investments, both in preventative measures and risk mitigation measures, including extinguishment in the case of a full scale fire.

However, as practical experience is very limited and the standards for fire protection often lack specific information concerning ethanol and similar fuels, there is a significant risk that such investments will not provide the fire protection level expected by e.g. tank owners and regulators.

This is also confirmed by the existing experience from firefighting operations of tank fires involving ethanol or other water-miscible fuels. The number of tank fires is limited but those tank fires that have occurred have all resulted in controlled burn out rather than extinguishment, see chapter 2.2.

Therefore, the main goal of the ETANKFIRE project has been to provide a platform of knowledge that helps to ensure proper investment in the fire protection of ethanol storage facilities.

This report focusses on ETANKFIRE WP1 and WP2, which aim to develop and validate a methodology for fighting full surface tank fires containing ethanol fuels.

1.2 Goal for WP1 and WP2

The main goal for the work and test programs in WP 1 and WP2 was to evaluate the potential of various traditional as well as unconventional extinguishing media and application techniques for ethanol tank firefighting. This will provide important knowledge for firefighting tactics that could be of direct use for various stakeholders, such as tank terminal operators and the fire and rescue services.

The results will also form an important platform of knowledge for proposing relevant verification tests on a larger scale as planned for WP 3 and WP 4 of the ETANKFIRE project. This work is defined as **Phase 2** of the ETANKFIRE project and is planned to be launched when necessary funding has been obtained.

The work in WP1 includes a literature review and a series of small scale experiments. The scope of work for the literature review was limited to a summary of the open literature that has become available on the internet during the time since the project started, including some reports from real tank fire incidents and some test experiences, e.g. based on various standards for testing of water-miscible fuels. This part of the WP1 work is presented in chapter 2.

The experimental part of WP1 was intended to provide a better understanding of the various parameters that might influence the extinguishing process. As further described in chapter 2, the amount of fuel, preburn time, type of application and application rate might have a considerable influence on extinguishing efficiency due to dilution of the fuel when using firefighting foams. In order to investigate these parameters in an economical and systematic way, a series of small scale fire tests was conducted. The test setup and the test programme is further described in chapter 3.1 and 4.1, respectively.

The main intention of the tests in WP2 was to verify the performance of the most promising tests in WP1 in a larger, “laboratory” scale. The results from WP1 were used for the selection of the basic test conditions (amount of fuel and preburn time) and the specific test conditions, e.g. application rate, foam properties and type of application. The test setup and the test programme for the work in WP2 is further described in chapter 3.2 and 4.2, respectively.

2 Literature review

2.1 Overview of recommendations for design and testing

Storage tank fire protection is based on the use of firefighting foams where the foam is either applied by mobile equipment or via fixed foam systems mounted on the storage tank. There are various existing guidance documents and standards; two of the most commonly used international standards are NFPA 11 “Standard for Low-, Medium-, and High-Expansion foam” [2] and EN 13565-2 “Fixed firefighting systems-Foam systems-Part 2: Design, construction and maintenance” [3].

There are also numerous standardized test methods for evaluating the quality of various foam concentrates. The most common standard for the US market is UL 162 “Foam equipment and liquid concentrates” [4] and for the European market EN 1568 “Fire extinguishing media-Foam concentrates”. The EN1568 standard consists of four parts covering specifications: medium expansion foam, (Part 1) [5], high expansion foam (Part 2) [6], low expansion foam (Part 3) [7] and low expansion foam for water miscible liquids (Part 4) [8]. Both the UL 162 and the EN 1568 standards are quite generic. They are intended to evaluate the most important properties of a foam concentrate to ensure its performance in most pool fire situations. The development of the UL standard goes back to 1960 and the EN 1568 standard goes back to the end of 1980, when a common European standard was developed based on input from a number of national standards and ongoing standardisation work within ISO. Since then, there have been a number of revisions of both standards but the basic principles are still the same.

A group of oil storage and processing companies has developed a fire test protocol called the LASTFIRE foam test protocol, which is primarily intended for batch controls, and includes one protocol for hydrocarbon fuels [9] and one protocol for water-miscible fuels[10]. The LASTFIRE method was developed in the beginning of 2000 on the initiative of the LASTFIRE group, where most of the members are oil companies. The intention of the LASTFIRE method was to better mimic the conditions in a tank fire situation and thereby also stress the performance requirements of the foam concentrates, e.g. by using a fire test tray with thicker steel walls and a slightly longer preburn time.

It is important to understand that the development of a specific test method is always a compromise between many factors. For example, testing costs, among other factors, must be balanced with the fidelity of the testing scenario to real conditions in terms of scale, amount of fuel, preburn time, etc. Increasing environmental concerns and the need for more fuel continue to drive changes in firefighting tactics as well as storage tank size and number, which in turn change the nature of the fire threat. Many test methods are based on previous test methods for which the original justification for the methodology has been lost over time. The test performance criteria could be tied to reference tests of “high quality” foam concentrates available on the market in an earlier era, and possibly developed for a different fuel application.

The downfall of prescribed testing is that it is very difficult for standard test methods to provide incentive for suppression media manufacturers to develop products that perform well in conditions that simulate the current fire threat. The prescription based system is set up for manufacturers to design their products to achieve the specified performance requirements, which may or may not be adequate, while further improvements for certain applications, e.g. tank fires, are not encouraged.

2.1.1 Foam application rates in tests and specified design application rates

The application rate is one of the most important design parameters and as previously mentioned, recommendations are given in e.g. EN 13565-2 and NFPA 11. Both standards are to a large extent focussed on hydrocarbon fuels. In some cases the recommended design figures are linked to test results. However, when evaluating foam in small scale testing, one must consider the effects of the reduced scale and the need for a “safety factor” for real life situations. The test application rate is therefore lower than the design application rate, and a “scaling factor” is often used to compensate for the difference.

When considering water-miscible fuels (e.g. ethanol), NFPA 11 only specifies the use of fixed foam discharge outlet, Type II (while Type I discharge outlets are considered obsolete). The specified minimum discharge time is 55 min, while there are no specified application rates given. Instead, the reader is instructed to “Consult manufacturer for listings of specific products”. In the US, such listings are normally made according to UL 162 using a square fire tray with an area of 4.67 m^2 (50 ft^2). Water-miscible fuels (polar fuels) are tested using a Type II (backboard) application and the test application rate may vary depending on the type of fuel. It is up to the foam manufacturer to suggest the test application rate. However it must not be less than 2.4 l/m^2 min (0.06 gpm/ft^2). The stipulated scaling factor is 1.67, i.e. the minimum design application rate should be 1.67 x test application rate, but not be less than 4.1 l/m^2 min (0.10 gpm/ft^2) according to UL 162.

The design application rates specified in EN 13565-2 are linked to the performance of the specific foam concentrate tested according to EN 1568-3 and 1568-4. The minimum (basic) design application rate is 4.0 l/m^2 min, which is then multiplied by a foam concentrate correction factor (defined as factor f_c) depending on the performance classification obtained as a result of the EN1568-tests and, for hydrocarbon fuels, other factors dependent on the method of foam application.

Design application rates for water-miscible fuels in EN13565-2 are only given for fixed top pouring systems while application via monitors is not considered suitable (similar to NFPA 11). For “fuel in depth” situations (e.g. storage tanks), the foam concentrate correction factor (f_c) varies from f_c=2.0 to f_c=3.0 according to the classification obtained from EN 1568-4. This means that a design application rate for a fixed foam system is in the range of 8.0 - 12.0 l/m^2 min for water-miscible fuels. It should be noted that these figures are considered relevant for fuels such as ethanol, methanol, isopropyl alcohol (IPA) and acetone while more destructive fuels may require higher correction factors if this is indicated by tests of the specific fuel.

In the EN 1568-4 standard, a smaller fire tray (1.73 m^2) is used for water-miscible fuels compared to hydrocarbons (4.5 m^2), but the same test nozzle (11.4 l/min) is used. This results in a test application rate of 6.6 l/m^2 min corresponding to a scaling factor of 1.21 - 1.82 (8.0/6.6 and 12.0/6.6). Using the “UL162 scaling factor” (1.67) would result in a minimum design rate of 11.0 l/m^2 min.

Based on the results from the EU-project “FAIRFIRE” [11], a small scale method has been developed for product development tests, production control, quality control of foam concentrates stored at a facility, etc.. The test method is intended to reflect the classification obtained by EN 1568. The test procedure suggested in the FAIRFIRE project has been published as SP Method 2580 [12]. A smaller version of the foam nozzle used in EN 1568 (parts 3 and 4) (“UNI 86”) was developed in the FAIRFIRE project and gives a flow rate of 2.5 l/min (designated “UNI 86R”) For testing of water-miscible fuels, a tray area of 0.41 m^2 is used, corresponding to a test application rate 6.1 l/m^2 min.

The test method developed for water-miscible fuels (e.g. ethanol) by the LASTFIRE group is based on a circular fire tray of 4.67 m^2 (50 ft^2) and, depending on the type of application, two types of test nozzles and application rates are used. The lowest application rate, using a nozzle simulating foam application through a fixed foam pouring system. Intended to simulate a relatively gentle application (replicate of Type I discharge outlet according to NFPA 11) is 2.5 l/m^2 min (nozzle flow rate 11.7 l/min) while the application rate using the aspirated “monitor” nozzle is 3.63 l/m^2 min (nozzle flow rate 17.0 l/min). Using the monitor nozzle, the foam is applied using the backboard technique (Type II), which is similar to the application technique used in UL 162 and EN1568-4.

The LASTFIRE group has not suggested any scaling factor or design values, but test rates are generally in the order of 50 % of NFPA design application rates. For water-miscible fuels, the scaling factor is 2.2 in relation to the minimum design value specified in EN 13565-2 (8.0 l/m^2 min) assuming the monitor nozzle (3.63 l/m^2 min) is used during the test.

2.1.2 The influence of application method and fuel depth

It is a known fact that the application technique used during testing of water-miscible fuels has a very strong influence on the results and that the degree of fuel agitation caused by application of fire suppression media is very critical. This is also reflected in the existing test standards/methods; none of which specify the use of direct foam application during the test, recognising the deficiencies of current foam concentrates using this technique. An indirect application is necessary to minimize fuel agitation and allow a foam build-up on the burning fuel surface. The most common type of application during testing is backboard application (defined as Type II in UL 162 and considered to replicate a Type II discharge outlet according to NFPA 11). However, the relevance of the Type II application is uncertain in real scale as fuel agitation can be expected to increase due to much higher flowrates and higher drop heights to the fuel, even if a fixed over-the-top system is used. General industry guidance includes advice such as “apply foam to the inner tank side wall to swirl the foam on the fuel surface”. In reality it is doubtful if this would be possible in real situations.

Another concern is that all existing standardized tests are based on using a relatively limited amount of fuel (low fuel depth) compared to the situation in a real scale storage tank, see Table 1. Even though the fuel agitation is reduced during testing by using Type II application, there is in many cases a considerable foam breakdown before a layer is formed. The degraded foam dissolves and mixes with the fuel and will within minutes generate an increasing concentration of water in the fuel as the foam application continues, as shown in Figure 2. This condition might influence and improve the extinguishment considerably. However, in a real tank fire situation, this dilution effect will only occur very slowly and the test data could therefore be very misleading.

The dilution effect presented in Figure 2 is based on the test conditions in Table 1 and assumes that the burning rate is 3 mm/min during the preburn time and an average of 1.5 mm/min during the extinguishing phase. The 3 mm/min is based on the measurements in a 2 m^2 tray in the WP5 test series [1]. It is also assumed that 100 % of the applied foam is mixed with the fuel during application. The diagram therefore represents the estimated maximum water concentration in the fuel.

Table 1 **Summary of test conditions according to UL 162, EN 1568-4 and LASTFIRE. For comparison, a corresponding figure for the ETANKFIRE test conditions are also given, assuming an maximum application rate of 8 l/m^2 min.**

Standard/ Method	Initial fuel layer (mm)	Preburn time (min)	Foam application time (min)	Foam application rate (l/m^2 min)
UL 162	39[1]	1	5	2.4[2]
EN 1568-4	72.5	2	3 (Class I) 5 (Class II)	6.6 6.6
LASTFIRE	64[3]	3	7	3.63
ETANKFIRE	450[4]	15	Until extinguishment (or about 15 min)	4 - 8[5]

1) Minimum fuel depth.
2) Minimum application rate.
3) Average fuel depth, test tray has a conical bottom area.
4) Fuel layer used in most of the WP1 and WP2 tests.
5) Highest expected application rate during the planning of the tests, i.e. the “worst case” considering the water dilution. (Finally used application rates varied from 3.63-12.4 l/m^2 min, see chapter 5).

During testing of a weak foam (e.g. some Class II foams according to 1568-4), such situations can occur during the first minutes where all foam is destroyed upon application. After some minutes (usually 2.5 - 3 min) a foam build up is achieved which could be an effect of the increasing water concentration in the fuel, which then could be around 15 - 20 %. The requirement for complete extinguishment for a Class II foam is 5 minutes, which corresponds to a maximum water content of about 35 %. Although the water content in the fuel will not be 35 % if a foam layer is established and the fire is extinguished within 5 minutes, it indicates that the dilution effect could be of significant importance. As shown in Figure 2, the dilution effect is in the same order as the LASTFIRE test method at the end of foam application/maximum extinguishing time (7 min) while it is just below 30 % in UL162 (5 min) and about 25 % for Class I foams in EN 1568-4 (3 min). This also indicates that it is important to consider this effect when increasing the application rate (e.g. in UL 162) as the water content in the fuel will increase even faster and be higher at the maximum stipulated extinguishing time.

It should be noted that it has been claimed in some cases that application of water to an fuel containing a percentage of ethanol would cause preferential solution of the ethanol with the ethanol content then descending to the bottom of the tank with the water, thus leaving only hydrocarbon at the fuel surface and so allowing conventional forceful application techniques to be used. This theory has not been validated in large scale tests or through incident experience.

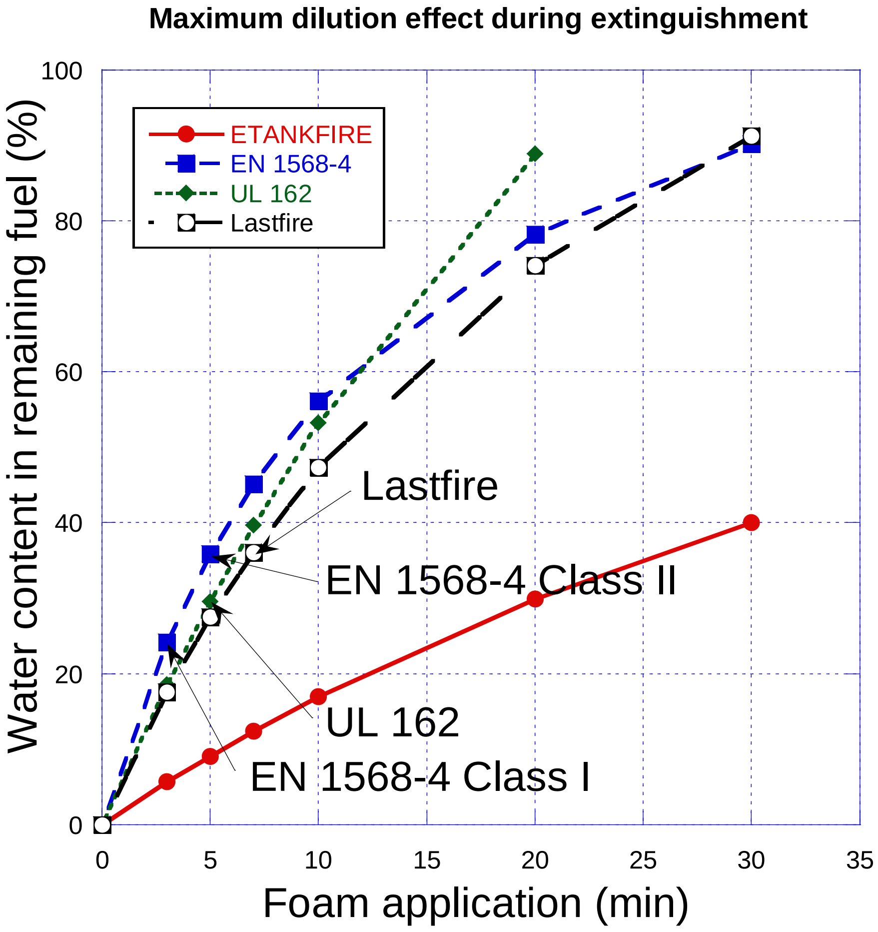


Figure 2 Estimated water concentration in the remaining fuel as function of time from start of foam application during "worst conditions" (100 % foam destruction) with the maximum allowed time to extinction indicated by arrows for each test standard. The assumed burning rate is 3 mm/min during the preburn time and 1.5 mm/min during the extinguishing phase and a foam application rate as specified in Table 1.

To investigate the influence of type of application, application rate, foam properties, etc. without a significant influence of dilution effects, the ETANKFIRE tests were conducted with considerably more fuel. However, the selection of fuel depth in the tests was a compromise between real scale conditions with several meters of fuel and economic/practical aspects that must be considered in a testing situation.

This compromise resulted in a proposed fuel depth of 450 mm. This depth corresponds to 6 times the fuel depth used in EN1568-4 and, as shown in Figure 2, this indicates that the water concentration does not exceed about 23.5 % during 15 minutes of foam application at 8 l/m^2 min, assuming "worst case" foam destruction.

2.2 Experience from identified tank fire incidents

A comprehensive literature review on tank fire incidents, covering the time span from 1951 to 2003 was made by Persson and Lönnermark in 2004 [13]. The aim was to gather information related to the extinguishment of actual tank fires to provide data that could be used for validation of foam spread models developed in the FOAMSPEX project [14].

The information was collected through various reports and proceedings, fire magazines, internet and through personal communications. The available information for each of the incidents varied from just a short notice in a newspaper to very detailed information regarding the cause of the fire and the firefighting response. The extent of each identified fire incident varied considerably, from a small rim seal fire, being extinguished without difficulty, to fires involving a complete tank storage facility with 30 to 40 burning tanks.

In total, 480 tank fire incidents were identified worldwide but out of these incidents, only about 30 fire reports provided enough detailed information to be used for a more technical evaluation and model validation (e.g. type and size of tank, fuel, preburn time, foam application method, application rate, time to control and extinguishment, total consumption of foam).

The available information showed that practical firefighting experience was generally limited to tanks having a diameter of 40 m to 50 m or less and the largest full surface tank fire ever successfully extinguished was 82 m in diameter (which, according to our knowledge, still is true). Over-the-top application using mobile equipment seemed to be the dominating suppression methodology while there were no fire incidents providing detailed information on extinguishment of full surface fires using fixed or semi-fixed over-the top foam pouring systems. However, it should be recognised that the vast majority of large diameter tanks containing more volatile fuels with a higher ignition possibility do not have fixed systems for full surface fires installed on them, so this might not be surprising. In general floating roof tanks are used for such fuels and most tank operators only install fixed systems for rim seal incidents, or no systems at all in the case of some internal floating roof tanks.

The study also indicated that the number of tank fire incidents during the 1990s and 2000s that were serious enough to be reported by news media was in the range of 15 to 20 fires per year. It should also be noted that of all the identified fires, lightning was declared to be the cause for ignition in about 150 of the 480 fires.

The majority of the fire incidents involved petroleum products. Of the 30 fires with some form of detailed information, only two were identified to involve water-miscible fuels (see 2.2.1).

Since the study was completed in 2004, no update has been made and, according to our knowledge, no similar work has been presented in the open literature. However, during the planning and work with the ETANKFIRE project, a part of the work has also been to identify and collect information on tank fires involving ethanol. The results are discussed below.

2.2.1 Tank fires involving ethanol/alcohols

The summary of tank fire incidents involving ethanol is primarily based on information that has been identified through the internet, in many cases with help from people having shown interest in the ETANKFIRE project. The available information is very brief and, in most cases, does not allow for any detailed analysis of the firefighting operation.

There appears to be almost no successful extinguishments of these tank fires, even though there is a reported “extinguishment” in some cases. Considering the reported figures on e.g. the amount of fuel, preburn time, consumption of foam, etc., the information indicates that fuel dilution with water and a burn out of the fuel are the main contributors to extinguishment of the fires. The only exception from this may be the Nedalco fire in 1998, which seems to have been extinguished while still having a considerable amount of fuel left in the tank, although it would have been significantly diluted. Most of the identified fires have occurred in Brazil, which perhaps is not surprising since Brazil is one of the world leading ethanol producing countries.

Looking at published photos of some of the fires, they are clearly showing the typical yellow flame, almost free from smoke, that was observed during the ETANKFIRE free burning tests in 2012 [1].

Below is a short summary of the information available for the identified fires. For some fires, an attempt has been made to further evaluate the fire conditions and firefighting operations based on the information available, although it contains a large portion of uncertainty.

2.2.1.1 1984-08-05 Chemischen Werke Huls, Herne, Germany

The fire involved a cone roof tank, 10 000 m^3 (29 m in diameter, height 15 m), containing 4000-5000 m^3 of isopropyl alcohol (IPA) [13]. The ire started as a result of a lightning strike. Initial foam attack started after 1,5 hours, but no control was obtained and the available foam stock was almost consumed after 1 hour so the foam attack was terminated and the tactics were changed to dilute the fuel. The fire was considerably reduced after about 25 hours from ignition and the fire was declared extinguished after 27 hours. In total 54 144 m^3 of water and 57,6 m^3 of foam concentrate (synthetic detergent) were used during the operation.

Evaluation comments: 57,6 m^3 of foam concentrate generates about 1000 m^3 premix solution assuming 6 % foam concentration. The fuel depth at ignition would be about 7 m, and a calculated average burning rate until control (25 hours) would then result in about 5 mm/min. It is also clear that most of the water used during the operation (about 45 000-50 000 m^3) must have been used for heat exposure protection.

2.2.1.2 1998-02-18 Nedalco, Bergen op Zoom, Netherlands

The fire involved a cone roof tank, 1200 m^3 (no info on diameter/height), containing 1000 m^3 of ethanol [13]. The fire spread to the tank from the nearby production facility. After 11 hours of preburn, a foam attack using three foam monitors and Angus Alcoseal foam concentrate was initiated, providing control within 20 min and full extinguishment in 2 hours. The total use of foam concentrate was 11 tons.

Evaluation comments: A tank diameter of 12,5 m and a height of 10 m corresponds roughly to 1200 m^3. Using these tank dimensions, 1000 m^3 of fuel would then correspond to a fuel depth of 8 m at the start of the fire and assuming a burning rate of 6 mm/min during free-burning conditions would correspond to a fuel consumption of about 4 m during the 11 hours preburn time, i.e. 50 % had been consumed. The total consumption of foam was 11 tons (m^3) and assuming a concentration of 6 %, this corresponds to 183 m^3 of premix. Assuming that the total time of application was in the order of 2,5 hours (30 minutes after full extinguishment to secure the fuel surface), the average total discharge rate was about 1200 l/min, i.e. a flow rate of 400 l/min per foam nozzle (monitor). Based on these assumptions, the water content in the could have been about 20 % at extinguishment.

2.2.1.3 2004-01-28 Port Kembla, NSW Australia

The fire involved a cone roof tank, 7000 m^3 (diameter/height estimated to about 32/9 m), containing 4000 m^3 of ethanol ignited, probably due to welding [15, 16], see Figure 3. Foam application was initiated via three monitors using 6 % AFFF-AR, but without controlling the fire. Additional extinguishing attempts were therefore made by dumping foam solution (20 000 liters in each drop) from a large helicopter but this provided only temporary control. After 6 drops, the extinguishing operation reverted to using only the monitor application to provide some control of the fire and successively dilute the remaining fuel. A final foam attack was arranged using a larger foam monitor with a capacity of 5000 l/min about 20 hours after ignition, resulting in extinguishment in about 2 minutes. A fuel analysis after extinguishment showed that the water content was about 95 %, explaining the fast extinguishment. In total 50 000 l of foam concentrate and 45 000 m^3 of water were used during the entire operation.

Evaluation comments: 4000 m^3 of fuel indicates about 60 % filling of the tank which would correspond to a fuel depth of about 5,5 m and an average burning rate of 4,5 mm/min during the 20 h fire duration. The 50 000 l of 6 % foam concentrate is equivalent to 835 m^3 of premix solution. The total use of 45 000 m^3 of water corresponds to an average flow rate of 37 500 l/min.

Figure 3 Photo from the Port Kembla fire in 2004. (Photo: Fire and Rescue NSW).

2.2.1.4 2013-01-06, Ourinhos, San Paulo, Brazil

The fire involved a storage tank, (no information on diameter/height), containing 5000 m^3 of ethanol [17-19], see Figure 4. The fire was caused by a lightning strike. The fire continued for more than 30 hours and the focus of the firefighting operation was to prevent two adjacent tanks, each with a volume of 17 000 m^3, from igniting. The total consumption of cooling water was more than 35 000 m^3.

Evaluation comments: The cooling water corresponds to an average flow rate of 20 000 l/min during 30 hours. A fire duration of more than 30 hours under free burning conditions indicates a fuel depth of at least 10 m at ignition, assuming a burning rate of 5-6 mm/min.

Figure 4 **Photo from the Ourinhos tank fire in Brazil 2013. (Photo: From news media (via George Braga)).**

2.2.1.5 2013-12-17, Raizen ethanol plant, San Paolo, Brazil

The fire involved a storage tank, (no information on diameter/height), containing 3000 m^3 of ethanol [18, 20], see Figure 5. The fire was probably caused by welding, which caused an explosion and the fire. The focus of the firefighting operation was to reduce the intensity of the fire and to protect adjacent tanks and surroundings. The tank was completely destroyed.

Figure 5 **Photo from the Raizen tank fire in Brazil 2013. (Photo: Ricardo Pereira / Rádio Cultura de Dois Córregos).**

2.2.1.6 Ethanol tank fire incidents in Brazil 1989-2007

In addition to the tank fire incidents reported above, a list of identified ethanol tank fires in Brazil has been compiled by FM Global [21] in 2008 and is presented in Table 2. The list is based on media reports. The source of data was mainly taken from local newspaper websites and the companies were not FM Global clients.

Table 2 Media reports of ethanol storage tank fires in Brazil, compiled in November 2008 by FM Global [21]. (Note: The bottom three reports are for the same incident).

Date of loss	Company/location	Available data
12 December 1989	Usina Zanin / Araraquara, SP, Brazil	Lightning strike on a tank farm caused damage to several tanks. Poor water supply (no fixed firefighting system). Estimated damage: US$ 1,321 million.
14 November 1992	Destilaria Pitangueiras / Ribeirão Preto, SP, Brazil	An ethanol tank (4 million liters) was destroyed by fire, reportedly caused by a lightning strike. Estimated damage: US$ 900K.
02 October 2001	Usina Carolo / Pontal, SP, Brazil	A tank containing 450,000 liters of ethanol caught fire as a result of a lightning strike. Fire duration: 21 hours, manual firefighting, not enough foam available. All ethanol was consumed.
23 March 2007	Destilaria Americana / Nova América da Colina, PR, Brazil	Explosion and fire in a 2 million liter tank containing 672,000 liters of ethanol.
28 September 2007	Usina Ponte Preta / Canitar, Ourinhos, SP, Brazil	Three ethanol storage tanks caught fire reportedly due to a lightning strike. Estimated 8 – 9 million liters of ethanol involved in the fire. Firefighting expected to take longer than a day. 26 fire trucks attended. The plant did not have a water supply.
01 October 2007	Unidentified company / Ourinhos, SP, Brazil	Three ethanol storage tanks caught fire reportedly due to a lightning strike. Estimated 9 million liters of ethanol involved in the fire. Firefighting took longer than 12 hours, and did not avoid loss of all fuel. The plant did not have a fire protection system for the tanks.
28 September 2007	Unidentified company / Ourinhos, SP, Brazil	Three ethanol tanks caught fire and exploded as a result of a lightning strike.

3 Test setup and test equipment

Below is a description of the test equipment and test setup used in the small scale tests (WP1) and the laboratory scale tests (WP2).

3.1 WP 1 Small scale

3.1.1 Test equipment and temperature measurements

A fire tray with an area of 0.41 m^2 (0.72 m in diameter) was used for the small scale tests. This tray was selected because it corresponds to the tray size that is used in SP Method 2580 [12], which is a small scale method developed to reflect the results of EN 1568-4 (see chapter 2.1.1).

The intention was to simulate storage tank fire conditions, so a special fire tray (designated "WP1 fire tray") was designed to allow the use of more fuel, a longer preburn time and more severe foam application (see Figure 6). These factors are relevant for the fire scenarios of interest. However, some tests were also made using the standard SP 2580 fire tray (see Figure 7a)) which allowed the possibility to obtain reference data about the expected performance according to EN 1568-4 for the two foam concentrates used during the project.

The WP1 fire tray used was constructed of 6 mm steel and had a depth of 1 m. In order to accommodate a backboard application at longer distances but also have the possibility to observe the fuel surface and the foam coverage during the tests, a 1 m high half spherical extension of the tray wall was used, which was mounted on top of the fire tray, as shown in Figure 6.

Thermocouples were mounted on the tray walls at various positions to record the tests conditions, both during the preburn and the extinguishing phase. Thermocouples were also located inside the fuel to record the fuel temperature during the entire test. The thermocouple position in the centre of the tray was adjusted depending on the amount of fuel used. However, most of the tests were conducted with 450 mm of fuel and in these tests the upper thermocouple (TC 1) was positioned at 450 mm from the bottom of the tray, i.e. at the fuel surface. The other thermocouples (TC 2-6) were then positioned at various depths into the fuel, see Figure 6. Two thermocouples in the fuel (TC 7-8) were located 30 mm from the steel wall to indicate any influence on the fuel temperature through conduction from the heated steel wall. The temperature measurements were recorded every second.

It should be noted that the number of thermocouples in the thermocouple tree varied due to the lower fuel depth in Test #3 and #4. In Test #3, only TC1 and TC2 were installed and in Test #4, TC1 to TC4 were installed. In both cases, TC1 was located at the fuel surface and the remaining TCs were positioned at 50 mm intervals further into the fuel.

Temperature measurements were only conducted in the tests using the WP1 fire tray. There were no temperature measurements when using the SP Method 2580-fire tray (Test #1, #2, #17, #26, #27, #28).

A common method to record extinguishment during fire tests is to use radiometers measuring the heat radiation from the flame. However, this technique was not considered relevant in these tests because a large part of the flame would be shielded by the high freeboard and the heat accumulated in the steel would influence the measurements significantly, therefore they would not truly reflect the suppression sequence.

All test were recorded by photos and a video camera.

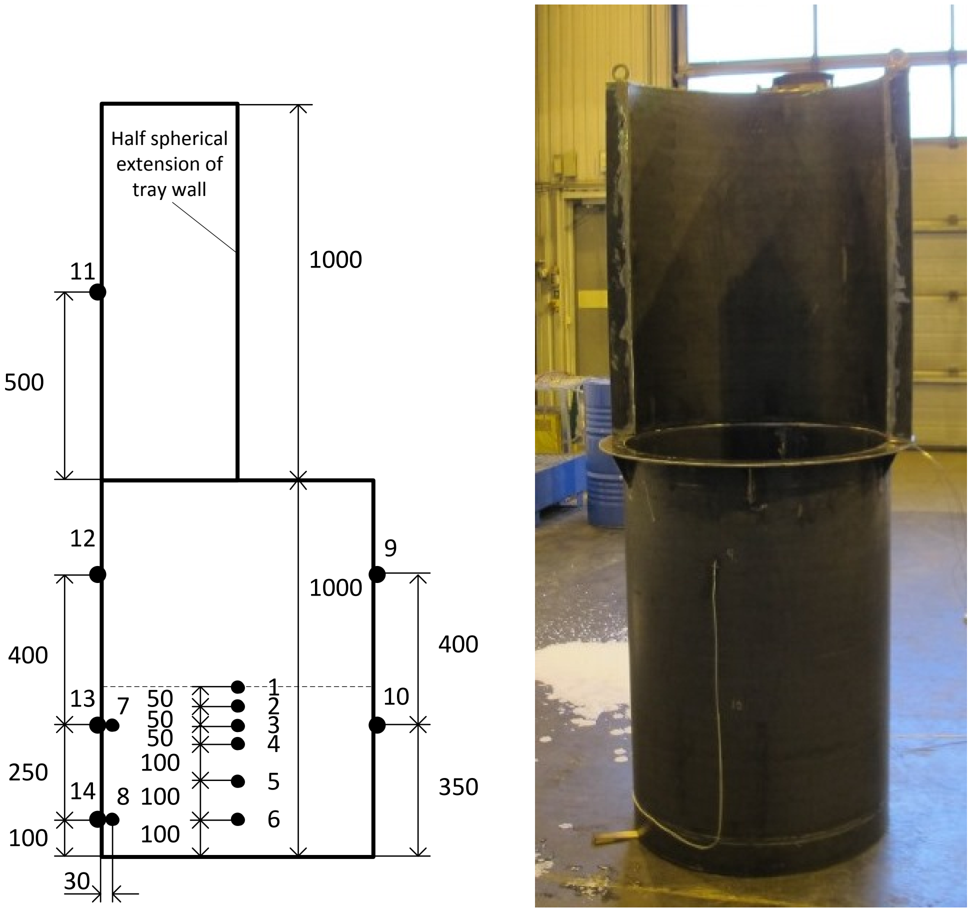


Figure 6 **Sketch of the "WP1 fire tray" and the position of the thermocouples mounted on the tray walls and positioned inside the fuel. The photo shows the tray from the front. All dimensions are in mm.**

For safety reasons relating to the large amount of fuel used in each test, the tray was placed in a second steel tray acting as a bund (not shown in the photo above). A cover for the fire tray was also used, both to eliminate vaporisation of fuel during the fuel filling sequence before the test and during denaturisation and discharge of the waste fuel after the test. The cover was also used to manually extinguish the fire in case the test was not successful.

The ethanol was handled in steel drums which were conditioned prior to the tests to ensure a fuel temperature of about 20 °C at the start of the test.

3.1.2 Foam generation equipment

The foam supply was based on using a pressure vessel filled with a premix solution which was pressurized using compressed air to a pressure giving the correct flow rate through the foam nozzle.

The normal procedure during foam testing at SP is to use a fixed blending system where the water and foam concentrate is thoroughly mixed before being transferred to the pressure vessel. The premix is also prepared just prior to the test to avoid a long premix time. Since the blending equipment was not available in the fire hall where the WP1 tests were performed, the premix was mixed directly in the pressure vessel by adding about 50 % of the water into the pressure vessel, adding the appropriate quantity of foam concentrate while continually stirring and then finally adding the remaining water followed by further stirring.

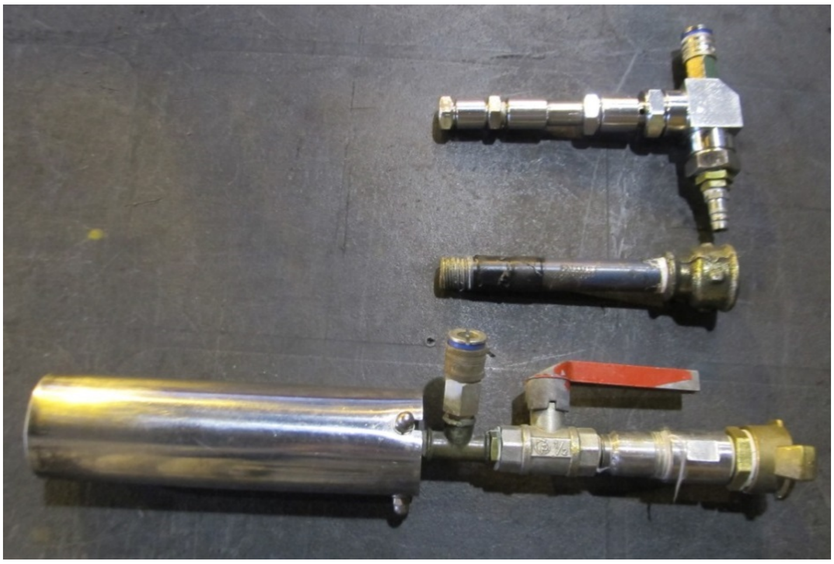
The foam manufacturer stated that a longer premix time would not cause problems so a 150l pressure vessel was used to have enough premix solution for several tests. A change in foam properties was observed between some of the first tests and the premix time was suspected to be the reason. To eliminate this issue, a new premix was prepared for every test in a smaller pressure vessel with a capacity of 30 l premix, using the same procedure for mixing. The foam expansion and drainage were checked before and after subsequent tests, indicating that differences in the foam properties continued to exist so the mixing procedure was changed. As both foam concentrates used in the project had a relatively high viscosity, it was suspected that a certain amount of the foam concentrate did not dissolve into the water in the pressure vessel and a small part of the concentrate may have sunk into the bottom and outlet pipe of the vessel. In this case it would result in a stronger premix just at the start of the foam generation while filling the hoses and sampling foam for expansion and drainage, while the remaining premix concentration in the pressure vessel would be slightly weaker. To ensure that such separation could not occur, the mixing procedure was improved further, beginning at Test #13, by mixing the entire water volume and foam concentrate in a separate container before transferring the premix into the pressure vessel. During the WP1 tests, the concentration was based on volume of water and foam concentrate.

Most of the tests were conducted using aspirated low expansion foam (LEX). The fire area was selected to correspond to SP Method 2580 [12], so the prescribed foam nozzle, UNI 86R, was used (see Figure 7) . As described in chapter 2.1.1, this foam nozzle is a small scale version of the UNI86 foam nozzle used in EN 1568, having a nominal flow rate of 2,5 l/min, corresponding to an application rate of 6,1 l/m^2 min when testing polar solvents.

In the tests using medium expansion foam (MEX), the foam was produced using the medium expansion foam branch specified in EN 1568-1 having a nominal flow rate of 3,1-3,4 l/min at 5 bar. However, in order to obtain the same application rate in all tests, the spray nozzle in the foam branch was replaced with a smaller version (Spraying Systems B1/8GG-2), providing a flow rate of 2,5 l/min at about 7 bar. Comparative tests with the original nozzle using the 3x3 AFFF-AR showed that the expansion ratio was almost the same, about 55 compared to about 50 for the modified nozzle.

a)

b)



c)

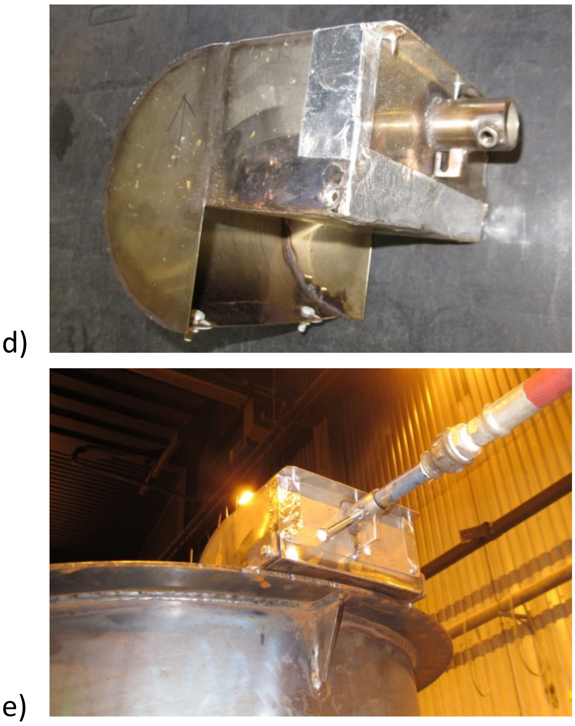


Figure 7 **Photos of foam generation equipment used during the WP1 tests showing: a) 30 l pressure vessel, foam nozzle arrangement and the SP 2580 tray, b) CAFS, c) UNI86R nozzle, CAF-nozzle and MEX nozzle, d) foam pourer, e) foam pourer mounted on the WP1 tray with the CAF-nozzle connected.**

Some tests were also conducted where the foam was generated as CAF. A compressed air foam system (CAFS) designed for the flow rates used in the project was provided by ACAF Inc. The lowest available premix flow rate was about 2 l/min, making it possible to obtain the same flow rate (2,5 l/min) as the other tests. The “foam nozzle” was just a straight steel tube having a length of 150 mm and a diameter of 15 mm.

Two tests were also conducted using a small scale foam pourer mounted on top of the tray wall extension. The foam was generated using the UNI 86R nozzle and the CAFS, respectively, which fed foam into the pourer.

3.1.3 Extinguishing media

The bulk of the tests were conducted using an AFFF-AR 3x3 foam concentrate. This selection was made because it is the type of foam that is most common among the petrochemical industry today for the protection of storage tanks. According to the manufacturer, the selected foam concentrate meets the fire performance requirements according to UL 162.

The environmental aspect of foams containing fluorochemicals is under debate, so it was decided to include some tests with a fluorine free foam to get an indication of the possible performance of such foams compared to traditional AFFF-AR foams. The selected concentrate was a 3x3 AR-foam (designated F3-AR) which, again according to the manufacturer, meets the fire performance requirements of UL 162.

In addition to the use of firefighting foams, some tests were also conducted with some unconventional extinguishing media. These tests included the use of liquid nitrogen, cellular glass and AVD.

Liquid nitrogen was selected as it would provide an extinguishment where the extinguishing media would not contaminate the fuel. Using the nitrogen in liquid form would also allow a reasonable high application rate and provide a cooling of the fuel surface.

AVD is an extinguishing agent based on a dispersion of vermiculite [22, 23]. As AVD can be applied as a foam and has a very high heat resistance, it was identified as a potential alternative to conventional firefighting foams.

Cellular glass is a light weight material based on glass and is already today used for fire protection purposes, e.g. for protection of LNG spills. Due to its low density, the cellular glass will float on the fuel, forming a layer of "solid foam" which will reduce the fire intensity significantly [24, 25]. The cellular glass was identified as an interesting "extinguishing media" for a tank fire situation as the cellular glass can be applied in an early stage of the fire to reduce the fire intensity and, when foam application starts, also reduce the fuel agitation and thereby reduce the foam destruction. The cellular glass used in these tests was in the form of spheres having diameters of 4-8 mm and a bulk density of 150 kg/m^3.

3.2 WP2 Laboratory scale

3.2.1 Test equipment and temperature/HRR measurements

The laboratory scale tests used a fire tray with an area of 3,14 m^2 (2,00 m in diameter). This tray provided a compromise between using the largest possible test area and limiting the amount of fuel (and cost) used in each test. A 3,14 m^2 fire test tray has previously been used in Nordtest method NTFIRE 023 [26], which was used in the Nordic countries before the EN 1568 standard was published. This tray area also allowed the possibility to use a number of different foam nozzles to obtain various flow rates and vary the application rate. Another aspect was also to allow for the longer preburn time used in these tests and to use the Industry Calorimeter system at SP Fire Research to record the heat release rate during the test.

The intention was to simulate storage tank fire conditions, so a special fire tray was designed to allow the use of more fuel, longer preburn and more severe foam application; these factors all are relevant for such fire scenarios. The basic design was the same as used in the WP1 tests, i.e. the tray was constructed of 6 mm steel and had a total depth of 1 m and a 1 m high half-spherical extension of the tray wall mounted on top of the fire tray (see Figure 8 and Figure 9). During the test series, an additional 1 x 1 m extension steel plate was installed to allow an even higher impact position of the foam in Test #6 (see Figure 9 b).

In order to record the tests conditions, both during the preburn and the extinguishing phase, thermocouples were mounted on the tray walls at similar positions as used in the WP1 tests, although with different numbering. Thermocouples were also located inside the fuel to record the fuel temperature during the entire test. However, in the WP2-tests, the location of the thermocouples in the centre of the tray was slightly modified, such that they were positioned closer to the surface. The spacing between the six thermocouples (designated TC 21-26) was only 15 mm, making it possible to get more information about the burning velocity. All tests were made with 450 mm of fuel and the upper thermocouple (TC 21) was positioned 450 mm from the bottom of the tray, i.e. at the fuel surface. Two thermocouples in the fuel (TC 27-28) were located 30 mm from the steel wall to reflect any influence on the fuel temperature through conduction from the heated steel wall. Two plate thermometers were also used to measure the heat exposure from the fire at 1 and 3 m distance (TC 35-36), mounted flush with the rim (see photos in Figure 9). The temperature measurements were recorded every fourth second.

As the tests were conducted in the large fire hall at SP Fire Research, the fire tray was positioned below the Industry Calorimeter [27]. This made it possible to measure the heat release rate (HRR) from the fire, both during the preburn period and also during the extinguishment. By these measurements it was possible to obtain quantitative data on the suppression sequence in each test condition. The HRR was recorded every fourth second.

All test were recorded by photos and a video camera.

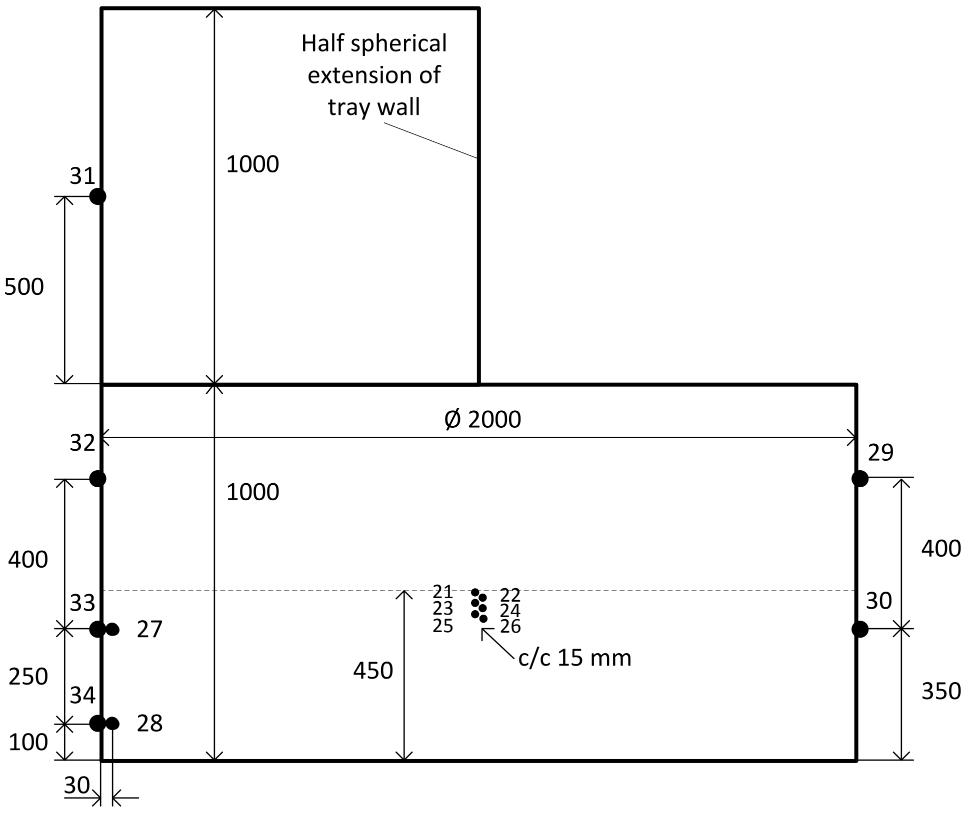


Figure 8 **Sketch of the “WP2 fire tray” and the position of the thermocouples mounted on the tray walls and positioned inside the fuel. Compared to the WP1 test setup, the spacing between the thermocouples in the center of the tray (TC 21-26) was reduced to 15 mm. (The “extra extension” is not shown in the sketch.) All dimensions are in mm.**

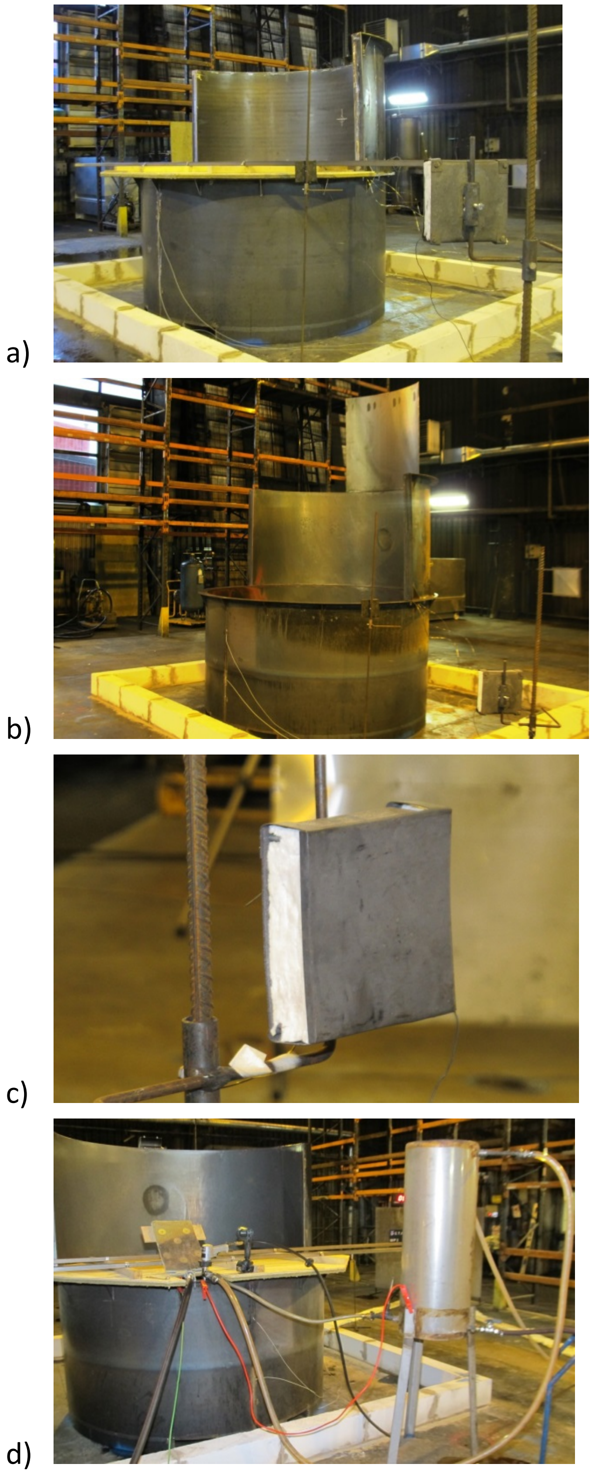


Figure 9 Some photos of the test arrangement during the W2 tests showing: a) the WP2 tray located inside a concrete bund with a cover used during the filling and the denaturisation/discharge sequence and for manual extinguishment, b) the extra extension of the tray wall used in Test #6, c) a plate thermometer used to record the heat exposure from the fire, and d) the heat exchanger equipment used to condition the fuel to the correct temperature.

For safety reasons related to the large amount of fuel used in each test, the tray was surrounded by a concrete bund. A cover to the fire tray was also used, both to eliminate the vaporisation of fuel during the fuel filling sequence before the test and during denaturisation and discharge of the waste fuel after the test. The cover was also used to extinguish the fire in case the test was not successful.

As the ethanol was stored in a 12 m^3 outdoor storage tank, the fuel temperature was only about 10-12 °C. After filling, the fuel was therefore circulated through a heat exchanger until the fuel temperature reached about 20 °C.

3.2.2 Foam generation equipment

The foam supply was based on using a plastic open top intermediate bulk container (IBC) with a maximum volume of 1 m^3 for the premix solution. The premix was then pressurized using a centrifugal pump with a by-pass arrangement to adjust the pressure to provide the correct flow rate through the foam nozzle, see Figure 10.

Based on the experience from the WP1 tests, a new premix solution was prepared for every new test. The mixing was made when the filling of the fuel was finished to minimize the premix time (normally about 25-30 min) before starting the foam application.

The premix was prepared by filling up the IBC with the correct amount of water using a calibrated flow meter. The foam concentrate used for each test was normally filled in two 40 l plastic buckets. To avoid influence of air bubbles generated when pouring the foam concentrate, the amount of foam concentrate was measured by using a scale assuming a density of 1,0 for both foam concentrates. The remaining volume of the buckets was filled with water from the IBC and then mixed manually in the bucket to ensure an homogenous mixture of a high concentration of premix. The concentrated premix was then poured back into the water in the IBC-container while stirring. When the premix was considered well mixed in the IBC, the premix was circulated through the pump and the hose system for 5-10 minutes depending on the amount of premix to further guarantee a well-mixed foam solution both in the IBC and the hose to the foam nozzle.

Figure 10 **Foam supply equipment used during the WP2 tests. The IBC (partly visible upper left) was used to hold the premix solution and was connected to a centrifugal pump followed by a flow meter. The pump had a by-pass arrangement between the pressure and suction side, to allow a fine tuning of the delivered pressure and flowrate to the foam nozzle.**

The foam application rate used in WP1 was 6,1 l/m^2 min for most of the tests, corresponding to a premix flow rate of 2,5 l/min. When increasing the fire area, it is also important to increase the application rate to obtain the same fire extinguishing performance. This calculation was based on the application rate specified in EN 1568-4 (6,59 l/m^2 min) and SP method 2580 (6,1 l/m^2 min) to provide an application rate that correlated to the 3,14 m^2 fire area used in WP2. A linear extrapolation of these values would give an application rate of 7,07 l/m^2 min. However, considering the possible use during this test series of low expansion (LEX) foam nozzles (see Figure 11), it was decided to use the slightly higher application rate of 7,26 l/m^2 min, which corresponds to a foam solution flow rate of 22,8 l/min and allowed the use of a National Foam 6 GPM (nominal 22,7 l/min) foam nozzle. This made it possible to achieve a 50 % reduction of the application rate (3,63 l/m^2 min) by using the UNI 86 foam nozzle specified in EN 1568-4. Also a third nozzle was used to obtain an intermediate application rate. Based on the results from the first tests, it was decided to choose a flow rate of 15 l/min corresponding to an application rate of 4,77 l/m^2 min, which could be obtained using a LASTFIRE foam nozzle at a slightly lower than nominal flowrate. Although several foam nozzles were used, the foam properties in terms of expansion and drainage were reasonable similar.

Medium expansion foam (MEX) was used in one test at the intermediate application rate of 4,77 l/min. The foam was produced using a modified medium expansion foam branch from commercial small scale equipment. As the nominal flow rate was higher, a smaller spray nozzle had to be used. In order to keep the expansion ratio, the foam generating net and its position were also modified.

A number of tests were also conducted where the foam was generated as CAF; the same CAFS provided by ACAF Inc. was used (see Figure 7 in chapter 3.1.2). The unit allowed the flow rate to be easily adjusted to obtain the same flow/application rates used in the LEX- and MEX-tests. In most of the tests, the “foam nozzle” was just a straight steel tube and, depending on the application rate, it had a length/diameter of 400 mm / 27 mm at 7,26 l/m^2 min, and 470 mm / 21 mm at 3,63 l/m^2 min. However, in Test #10 a ”spiral jet nozzle arrangement” consisting of four BETE N2W B168 nozzles was used to simulate a “fixed” CAF application system, see Figure 11.

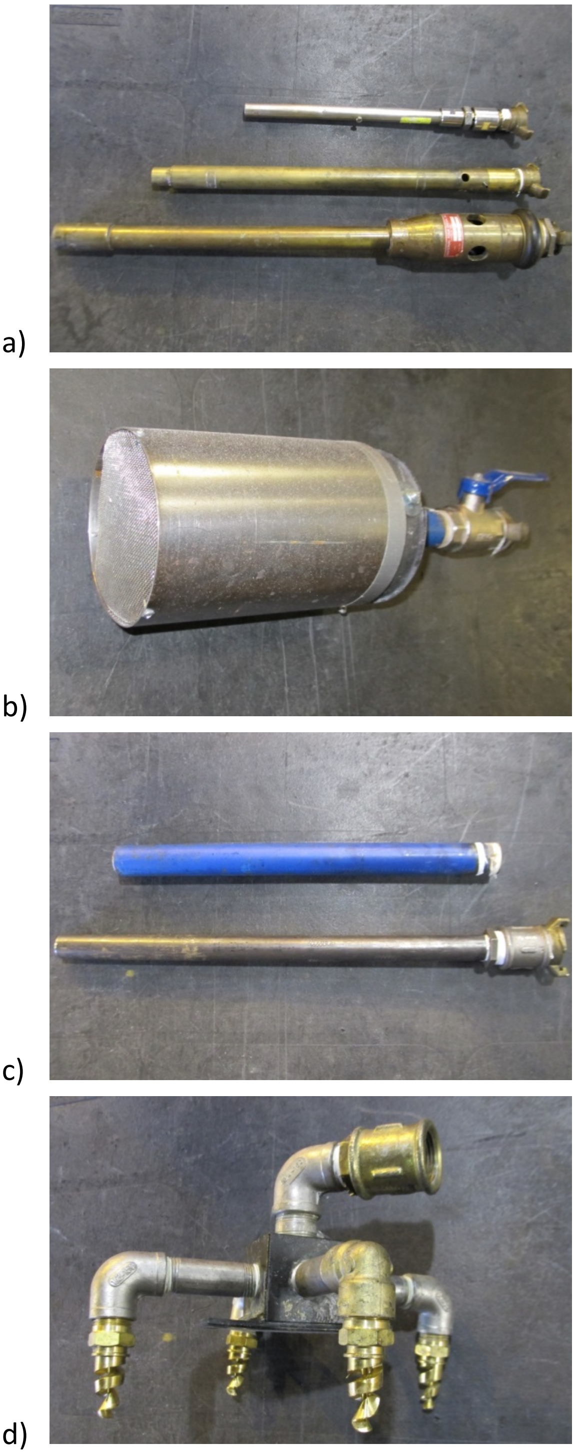


Figure 11 **Foam “nozzles” used during the WP2 tests: a) three low expansion (LEX) foam nozzles (UNI86, LASTFIRE, NF 6GPM), b) Medium expansion (MEX) foam branch, c) outlet pipes when using CAF, d) spiral jet nozzle arrangement used with CAF in test #10.**

3.2.3 Extinguishing media

The WP2 tests were focused on the use of foam as extinguishing media. The foam concentrates used in the WP2 tests were the same as those used in WP1, i.e. the bulk of the tests were conducted with the AFFF-AR 3x3foam and some tests with the fluorine free foam, 3x3 AR-foam (F3-AR) (see chapter 3.1.3). However, one test was also conducted using a combination of the cellular glass used in WP1 and foam application.

4 Test programme and procedures

Below is a general description of the test programme and test procedures used in the WP1 and WP2 tests. As the final test programme for each WP was successively developed on the basis of the obtained results, the final test programme and evaluated parameters are described in chapter 5 along with the results.

The main focus of the tests in both WPs was to study the fire extinguishing performance and influencing parameters, but burnback performance was not evaluated. The main reason for disregarding burnback performance is because it is essentially dependent on the extinguishing methodology, application rate, application time, etc. and many of these parameters were varied between the tests; therefore burnback tests would not provide comparable data.

4.1 WP1 Small scale

4.1.1 Test programme

The experimental work in WP1 was intended to provide a better understanding of the various parameters that might influence the extinguishing process. As previously described in chapter 2.1, the amount of fuel, preburn time, type of application and application rate might have a considerable influence on the extinguishing efficiency due to dilution of the fuel when using firefighting foams. The aim of WP1 was therefore to investigate these parameters in an economical and systematic way using the small scale (0,41 m^2) fire test configuration.

A draft test plan was developed based on the available budget, which corresponded to about 25 fire tests. The first tests were focused on providing reference data using the SP 2580 method to obtain an indication of the probable classification according to EN 1568-4. The next step was to investigate the influence of the fuel depth followed by the influence of an increased preburn time. Based on these initial tests, the fuel depth and preburn time were selected: 450 mm fuel depth and 15 min preburn time. This fuel depth is about 6 times deeper and the preburn time is 7,5 times longer than the standard testing conditions in EN 1568-4. The main parameters that were varied during the tests were related to foam application, such as impact position in relation to the fuel surface when using backboard (Type II) application, foam concentration, foam properties (LEX, MEX and CAF), increased application rate and type of foam concentrate. When testing non-foam extinguishing media (nitrogen, cellular glass, AVD) the main parameters were kept the same as the foam tests as far as possible to provide the best possible comparison.

4.1.2 Test procedure

The ethanol was transferred to 200 l drums from a 12 m^3 storage tank and was then stored at 20 °C for at least 24 h prior to the test to ensure the same fuel temperature in all tests. The fire tray was filled with ethanol while a cover was placed on the fire tray to reduce evaporation. During the filling procedure the premix-solution was prepared as described in 3.1.2. The premix tank was then connected to the foam nozzle positioned at a predetermined height and the pressure was adjusted to obtain the correct flow rate. For every new combination of foam type, concentration and nozzle, a foam sample was taken to measure the expansion and drainage following the methods described in EN 1568-1 and 1568-3, Annex G.

The cover over the tray was removed and temperature measurements were started 1:00 min prior to ignition. The fuel was then allowed to burn for the selected preburn time, normally 15:00 min. The foam generation was started about 5-10 seconds prior to start of foam application. At the end of the preburn time the nozzle was directed into the tray at the predetermined position.

The foam application continued until the fire was completely extinguished, or for a period of about 15 minutes. In some tests, the foam application was terminated earlier, e.g. due to lack of premix solution.

The extinguishing part of the tests was recorded by a video camera and still photos. Visual observations were recorded during each entire test for the time to 90 % control, 99 % control and 100 % extinguishment.

After the test was completed or if extinguishment was not obtained, the cover was placed on the fire tray and the tray and the fuel were allowed to cool for some time. The fuel was then denaturized with 2 % methyl ethyl ketone (MEK) and 3 % methyl isobutyl ketone (MIBK) before it was transferred to a 5 m^3 waste fuel tank.

In some tests, an additional foam sample was also collected directly after the test to measure the expansion and drainage again.

4.2 WP2 Laboratory scale

4.2.1 Test programme

The experimental work in WP2 was based on the results obtained in WP1 and intended to verify these small scale results in larger scale. A fuel depth of 450 mm and a preburn time of 15 min was used in all tests while the application rate, application methods and various foam properties were the main variables. The tests in WP2 were even more focused on the use of foam as the extinguishing medium because this was considered most interesting and relevant among the ETANKFIRE partners. As in WP1, the final test programme was an outcome of a continuous evaluation of the obtained results with the goal to provide results that could be used as a basis for indicative guidelines to the industry and fire & rescue services. The budget for WP2 allowed about 12-14 fire tests.

4.2.2 Test procedure

The ethanol was stored in a 12 m^3 tank outside the fire hall and was transferred directly to the fire tray by a pump and a long hose. As in the WP1 tests, a cover was used during filling to reduce evaporation. As the fuel temperature in the storage tank was about 10-12 °C, the fuel had to be heated to reach a temperature of about 20 °C. This was done by recirculation of the ethanol through a heat exchanger until the correct temperature was achieved. The entire filling procedure took about 40 minutes.

During the heating of the fuel, the premix solution was prepared as described in 3.2.2. The premix pump was then connected to the foam nozzle, which was positioned at the predetermined height and the pressure was adjusted to obtain the correct flow rate. A foam sample was then taken to measure the expansion and drainage following the methods described in EN 1568-1 and 1568-3, Annex G.

The cover over the tray was removed and temperature and HRR measurements were started 2:00 min prior to ignition. The fuel was ignited and allowed to burn for 15:00 min.

The foam generation was started about 5-10 seconds prior to start of foam application. At the end of the preburn time the nozzle was directed into the tray at the predetermined position.

The foam application continued until the fire was completely extinguished, or for a period of about 15 minutes except for Test #8, where the foam application was terminated after about 8 minutes due to lack of premix solution.

The extinguishing part of the tests was recorded by a video camera and still photos. Visual observations were recorded during each entire test for the time to 90 % control, 99 % control and 100 % extinguishment. As a complement to the visual observations, the HRR measurements provided a quantitative picture of the control and extinguishment performance in each test.

After the test was completed or if extinguishment was not obtained, the cover was placed on the fire tray and the tray and the fuel were allowed to cool for some time. The fuel was then denaturized with 2 % MEK and 3 % MIBK before it was transferred to a 5 m^3 waste fuel tank.

5 Test results

The results from the WP1 and WP2 tests have been summarized in the form of tables presenting the results in test order. Some general examples and comparisons from the temperature and HRR measurements are also presented.

A more general discussion of the results is presented in chapter 6 and detailed diagrams from the measurements are presented in Annex A. Photos from the tests are in Annex B.

5.1 Test results WP1

5.1.1 Extinguishing test results

In total 29 tests, including one “repeat test” (#18, #18B), were conducted during the WP1 test series and are summarized in Table 3 below. Detailed measurement data and photos are presented in Annex A and Annex B, respectively.

The results are presented in test order. Since the test conditions varied between most of the tests, the table also includes a short description of the test conditions for each test followed by the extinguishing results and comments as described below.

- Fire tray, fuel depth (mm) and preburn time (min).
- Extinguishing media (AFFF-AR, F3-AR, AVD, cellular glass, nitrogen) and foam concentration (3 % or 6 %)
- Expansion and 25 % drainage (not measured in every test)
- Application rate (l/m^2 min) and corresponding flow rate (l/min). For the tests with cellular glass the volume refers to the actual bulk volume applied and for liquid nitrogen the flow is given in kg/min.
- Type of generated foam (LEX, MEX, CAF), type of application (Type II, Type III, foam pourer) and foam application position above fuel surface. The type of application is based on the application techniques used in various foam standards, e.g. EN 1568, where Type II refers to backboard application via the tray backwall (gentle application), and Type III refers to foam applied directly to the fuel surface (forceful application). “Foam pourer” in these tests describes the foam application from the top of the tray extension (backwall) which is normally considered as “system application” which is defined as a Type II application according to NFPA 11. The position of application refers to the height of the foam application on the backboard (Type II) or the height of the nozzle above the fuel surface (Type III).
- Visually determined time to 90 % control, 99 % control and complete extinguishment (100 %). The time is given from start of media application. In tests using a combination of cellular glass and foam, the time begins at the start of foam application.
- Comments about the test results and conditions. In certain cases, a preliminary evaluation/discussion is also given about selection of test conditions for subsequent tests.

It should be noted that the comments included for each test mainly reflect the test results and experience that were available after the specific test was completed. An overall discussion and comparison of the various tests and results is presented in chapter 6.1.

Table 3 **Summary of test conditions and results from the WP1 fire tests (continues over 7 pages). (NM=Not measured, NR=Not relevant) (See also Annex A and Annex B).**

Test no	• Tray • Fuel depth (mm) • Preburn (min)	• Media type • Concen-tration	• Expansion • 25 % drainage (min)	• Applica-tion rate (l/m^2 min) • Flowrate (l/min)	• Type of foam • Type of applica-tion • Position above fuel	Time to: • 90 % • 99 % • 100 % (min:s)
1	2580 73 2	AFFF-AR 3 %	6,7 14:57	6,1 2,5	LEX Type II 0,3 m	1:07 1:30 1:45
	Comments: Test according to SP Method 2580 to indicate performance according to EN 1568-4. 25 % burnback time was 27:20. Indicate classification IA according to EN1568-4					
2	2580 73 2	F3-AR 3 %	7,8 32:38	6,1 2,5	LEX Type II 0,3 m	1:02 1:43 1:46
	Comments: Test according to SP Method 2580 to indicate performance according to EN 1568-4. 25 % burnback time was 35:56. Indicate classification IA according to EN1568-4					
3	WP1 tray 73 2	AFFF-AR 3 %	NM NM	6,1 2,5	LEX Type II 0,725 m	2:40 3:32 3:36
	Comments: Similar condition to Test #1 but using the ETANKFIRE WP1 fire test tray. Due to the height of the tray, the position of foam application was higher. The test result indicates more severe test conditions.					
4	WP1 tray 225 2	AFFF-AR 3 %	NM NM	6,1 2,5	LEX Type II 0,575 m	3:40 4:30 4:36
	Comments: Similar condition to Test #3 but using 225 mm of fuel. Due to the increased fuel depth, the distance between the fuel and the point of application was less compared to Test #3. The result indicates even more severe test conditions.					
5	WP1 tray 450 2	AFFF-AR 3 %	NM NM	6,1 2,5	LEX Type II 0,35 m	1:00 1:40 1:47
	Comments: Similar condition to Test #3 and #4 but using 450 mm of fuel resulted in even less distance (0,35 m) between the fuel and the point of application. The extinguishing result was surprisingly better, one reason could be reduced fall height for the foam. Another parameter could be the use of a fresh premix solution.					
6	WP1 tray 450 10	AFFF-AR 3 %	NM NM	6,1 2,5	LEX Type II 0,35 m	4:25 5:15 5:22
	Comments: Identical to Test #5 but using a preburn time of 10 min. The test result indicates again more severe test conditions.					

<table>
<tr><th>Test no</th><th>• Tray
• Fuel depth (mm)
• Preburn (min)</th><th>• Media type
• Concen-tration</th><th>• Expansion
• 25 % drainage (min)</th><th>• Applica-tion rate (l/m² min)
• Flowrate (l/min)</th><th>• Type of foam
• Type of applica-tion
• Position above fuel</th><th>Time to:
• 90 %
• 99 %
• 100 %
(min:s)</th></tr>
<tr><td rowspan="2">7</td><td>WP1 tray
450
15</td><td>AFFF-AR
3 %</td><td>6,4
11:45
(after test)</td><td>6,1
2,5</td><td>LEX
Type II
0,35 m</td><td>3:00
3:47
3:59</td></tr>
<tr><td colspan="6">Comments: Identical to Test #5 and #6 but using a preburn time of 15 min.
The extinguishing result indicated better performance compared to Test #6, although the longer preburn time which was expected to give more severe conditions. The same premix solution was used in Test #5 and #6 while the remaining premix (about 10 l) was “topped up” with 20 l fresh premix before Test #7. From this test, it was decided to use a new premix in every test and ensure a premix time less than 30 min.</td></tr>
<tr><td rowspan="2">8</td><td>WP1 tray
450
15</td><td>AFFF-AR
3 %</td><td>NM
NM</td><td>6,1
2,5</td><td>LEX
Type II
1,05 m</td><td>No
No
No</td></tr>
<tr><td colspan="6">Comments: Similar to Test #7 but with a higher foam application position, 1,05 m above the fuel surface.
The test results indicated a dramatic change due to the higher position of application. Just before the premix solution ran out (11:30), a creamy foam was generated during the last 10 seconds which resulted in a very fast foam coverage and about 80 % control of the fire. The fire was manually extinguished with the cover at 13:03. The water content in the fuel was estimated to about 19 %.</td></tr>
<tr><td rowspan="2">9</td><td>WP1 tray
450
15</td><td>AFFF-AR
3 %</td><td>NM
NM</td><td>6,1
2,5</td><td>LEX
Foam pourer
1,55 m</td><td>No
No
No</td></tr>
<tr><td colspan="6">Comments: Similar to Test #8 but application via a “foam pourer” on top of the tray wall to obtain a more gentle application along the back wall.
Due to the heated steel, the foam did not stick to the wall, instead the foam fell in a single stream onto the fuel, in practice a direct application. At start of the foam application, the foam was also heavily influenced by the thermal updraft. Foam application continued for 18:30 min:s until the premix solution ran out. At this time the water concentration in the fuel was estimated to about 25 %.</td></tr>
<tr><td rowspan="2">10</td><td>WP1 tray
450
15</td><td>AFFF-AR
3 %</td><td>54*
NM</td><td>6,1
2,5</td><td>MEX
Type III
0,55 m
(nozzle height)</td><td>15:30
15:40
15:45**</td></tr>
<tr><td colspan="6">Comments: Foam applied via a medium expansion foam nozzle located at the lower rim of the test tray. Due to the short throw length, the foam landed directly onto the fuel surface almost in the middle of the tray.
* Expansion measured in a 5,8 l plastic vessel.
** No sign of control was obtained during the first 15 minutes and it was therefore decided to move the foam nozzle towards one side. When the foam landed on the formed gel layer, a foam formation was achieved immediately and the fire was completely extinguished in 45 seconds.</td></tr>
</table>

<table>
<tr><th>Test no</th><th>• Tray
• Fuel depth (mm)
• Preburn (min)</th><th>• Media type
• Concentration</th><th>• Expansion
• 25 % drainage (min)</th><th>• Application rate (l/m^2 min)
• Flowrate (l/min)</th><th>• Type of foam
• Type of application
• Position above fuel</th><th>Time to:
• 90 %
• 99 %
• 100 % (min:s)</th></tr>
<tr><td rowspan="2">11</td><td>WP1 tray
450
15</td><td>AFFF-AR
3 %</td><td>NM
NM</td><td>6,1
2,5</td><td>LEX
Type II
1,05 m</td><td>No
No
No</td></tr>
<tr><td colspan="6">Comments: Similar to Test #8 but moving the foam nozzle every 3 minute (center, right, left, center, etc.) to see if the formed gel layer could make the foam to survive the impact better as indicated in Test #8 and #10.
No extinguishing effect was noted when the premix ran out at 18:35.</td></tr>
<tr><td rowspan="2">12</td><td>WP1 tray
450
15</td><td>AFFF-AR
3 %</td><td>NM
NM</td><td>12,4
2,5+2,6</td><td>LEX
Type II
1,05 m</td><td>9:45
10:00
10:30</td></tr>
<tr><td colspan="6">Comments: Similar to Test # 8 but using double the application rate (using two UNI86R foam nozzles).
A small area of foam was established after about 6:45, 50 % of the fuel area was covered at about 8:15 and the fire was extinguished at 10:30, most likely due to fuel dilution. The water content has been estimated to about 21 % at the time for extinction.</td></tr>
<tr><td rowspan="2">13</td><td>WP1 tray
450
15</td><td>AFFF-AR
3 %</td><td>15,8
19:44</td><td>6,2
2,6</td><td>CAF
Type II
1,05 m</td><td>2:30
3:30
3:35</td></tr>
<tr><td colspan="6">Comments: Similar to Test #8 but using CAF.
A foam layer started to establish on the fuel after 1 minute and the fire was extinguished in 3:35, although some of the foam did not hit the tray as the foam stream was not fully coherent. This test indicates that improved foam characteristics (expansion, drainage) is more important than a high application rate to obtain an effective extinguishment.</td></tr>
<tr><td rowspan="2">14</td><td>WP1 tray
450
15</td><td>AFFF-AR
3 %</td><td>NM
NM</td><td>6,2
2,6/2,1*</td><td>CAF
Foam pourer
1,55 m</td><td>4:24
5:00
5:08</td></tr>
<tr><td colspan="6">Comments: Similar to Test #9 but using CAF. Also in this test the foam did not stick to the wall, instead the foam fell in a single stream onto the fuel, in practice a direct application. At start of the foam application, the foam was also heavily influenced by the thermal updraft and some of the foam was blown out of the tray. Despite of this, a foam layer started to establish after about 2 min and resulting in complete extinguishment at 5:08. Once again, improved foam characteristics resulted in extinguishment.
* Measured before and after the test.</td></tr>
<tr><td rowspan="2">15</td><td>WP1 tray
450
15</td><td>AFFF-AR
3 %</td><td>NM
NM</td><td>6,1
2,5</td><td>LEX
Type II
0,35 m</td><td>1:41
2:35
2:40</td></tr>
<tr><td colspan="6">Repeat of Test #7 to confirm the extinguishing performance and provide a comparison for a similar test with the F3-AR concentrate.
The results indicate an improved performance compared to Test #7 which support the possible effect of premix time and an improved mixing procedure.</td></tr>
</table>

Test no	**• Tray** **• Fuel depth (mm)** **• Preburn (min)**	**• Media type** **• Concen-tration**	**• Expansion** **• 25 % drainage (min)**	**• Applica-tion rate (l/m^2 min)** **• Flowrate (l/min)**	**• Type of foam** **• Type of applica-tion** **• Position above fuel**	**Time to:** **• 90 %** **• 99 %** **• 100 % (min:s)**
16	WP1 tray 450 15	F3-AR 3 %	NM NM	6,1 2,5	LEX Type II 0,35 m	1:00 1:31 1:43
	Comments: Similar to Test #15 but using F3-AR concentrate. The performance was even better compared to the AFFF-AR foam.					
17	2580 73 2	AVD 100 %	About 2 No draining	6,1 2,5	“LEX” Type II 0,1 m	3:30 No No
	Comments: Tested according to SP Method 2580 to indicate performance of AVD compared to foam. The UNI86R nozzle was used also for AVD which explains the low expansion. AVD should be used as CAF but the use of a foam nozzle provided the best possible comparison. The impact position was lower (0,1 m above the fuel surface) due to a shorter throw length using AVD. The AVD foam was very stable and seemed not to be destroyed by the ethanol fuel or by the fire. The foam was stiff and did not manage to cover the fuel along the entire rim of the tray. 90 % control was achieved after the position of the foam nozzle had been slightly changed at 3:00. The supply of AVD ran out at 3:35 and complete extinction was therefore not obtained. It is likely that AVD had survived direct application onto the fuel. The AVD layer seemed also to have an extremely good burn back resistance.					
18	WP1 tray 450 15	F3-AR 3 %	54* 13:20	6,3 2,6	MEX Type III 0,55 m (nozzle height)	1:20 NR 1:45
	Comments: Similar to Test #10 but using F3-AR concentrate. The fire performance was very good and completely different to Test #10. It was observed that the foam stream was divided in two parts during the application, and one part had a better throw length resulting in a Type II application against the back wall of the tray. As this could have a major impact it was decided to repeat the test (#18B) using the same fuel because the dilution effect was considered negligible (estimated to 1,4 %). * Measured in a 200 l vessel acc. to EN 1568-1.					
18B	WP1 tray 450 10	F3-AR 3 %	55* NM	5,4 2,2	MEX Type III 0,55 m (nozzle height)	2:40 2:50 2:55
	Comments: Continuation of Test #18 after cleaning the fuel surface from foam and gel. The nozzle pressure was reduced which resulted in one foam stream out of the nozzle but with the same expansion ratio. The flow rate was reduced from 2,6 to 2,2 l/min. As the tray and fuel was still hot, a preburn time of 10 min was used. In this test there was a true Type III application and despite of this and the lower application rate, the fire was extinguished at 2:55. Also in this test the F3-AR foam performed significantly better than the AFFF-AR. * Measured in a 40 l vessel.					

Test no	**• Tray • Fuel depth (mm) • Preburn (min)**	**• Media type • Concentration**	**• Expansion • 25 % drainage (min)**	**• Application rate (l/m^2 min) • Flowrate (l/min)**	**• Type of foam • Type of application • Position above fuel**	**Time to: • 90 % • 99 % • 100 % (min:s)**
19	WP1 tray 450 15	F3-AR 3 %	NM NM	6,1 2,5	LEX Type II 1,05 m	1:35 2:10 2:17
	Comments: Similar to Test #8 but using F3-AR concentrate to compare the performance with the AFFF-AR. As in Test #18 and #18B, the F3-AR foam showed a significantly better performance than the AFFF-AR.					
20	WP1 tray 450 15	AFFF-AR 6 %	7,4 55:57	6,1 2,5	LEX Type II 1,05 m	1:10 1:40 1:43
	Comments: Similar to Test #8, #11 and #19 but using AFFF-AR with 6 % concentration. The intention was to see if the AFFF-AR with improved foam characteristics would give equal results as CAF and the F3-AR foam. The fire performance was completely different, resulting in the best results for this test scenario. The increased concentration increased the expansion slightly but made the foam extremely stable with a 25 % drainage of almost 1 hour.					
21	WP1 tray 450 15	AFFF-AR 3 %	7,6 38:38	6,1 2,5	LEX Type II 1,05 m	No No No
	Comments: Repeat of Test #8 to verify the difference between 3 % and 6 % concentration. The result confirmed the previous results achieved in Test #8 and similar test conditions.					
22	WP1 tray 450 15	Liquid Nitrogen NR	NR NR	2,9 kg/m^2 min 1,2 kg/min	Type III 0,55 m	No No No
	Comments: Test with liquid nitrogen applied directly onto the fuel surface. The discharge of N_2 started 15 sec prior to application on the fuel surface to obtain stable liquid phase application. After about 30 seconds of application, the flames were reduced significantly to a flame height of about 0,5 m and had a blue color. Some small “islands” of liquid N_2 were observed on the fuel surface but the gas seemed to disappear because of the thermal updraft. No further reduction of the fire intensity could be noted visually and the application into the tray was stopped at 3:22 and the fire manually extinguished by the cover at about 3:30. Without stopping the discharge, the nitrogen was then collected in a container during 1 minute and weighed to confirm the discharge rate.					
23	WP1 tray 450* 15	Cellular glass NR	NR NR	NR 25**	Type III 0,55 m	No No No
	Comments: The cellular glass initially spread quickly over the fuel surface and covered the surface at 0:30. The cellular glass, in total 75 liters, was applied during 3 minutes which corresponded to an average cellular glass layer of 183 mm. A reduction in fire intensity could be noticed but there were still a lot of fuel vapors generated due to the variation in depth of the cellular glass layer. The fire intensity slowly continued to decrease and when the test was manually extinguished using the cover at 20:25, it was mainly flames along the “front” rim					

<table>
<tr><th>Test no</th><th>• Tray
• Fuel depth (mm)
• Preburn (min)</th><th>• Media type
• Concen-tration</th><th>• Expansion
• 25 % drainage (min)</th><th>• Applica-tion rate (l/m^2 min)
• Flowrate (l/min)</th><th>• Type of foam
• Type of applica-tion
• Position above fuel</th><th>Time to:
• 90 %
• 99 %
• 100 %
(min:s)</th></tr>
<tr><td>23 cont</td><td colspan="6">of the tray. After the test, it was confirmed that there was a difference in the cellular glass layer thickness over the tray area of about 150 mm, and along the front rim the cellular glass was wetted by fuel due to the thin layer.
* 17,5 l of E97 added to the fuel as used in Test #22 to obtain 450 mm fuel depth.
** The flowrate of 25 l/min of cellular glass would correspond to the application of expanded firefighting foam using a premix flowrate of 2,5 l/min and an expansion ratio of 10.</td></tr>
<tr><td rowspan="2">24</td><td>WP1 tray
450*
15</td><td>Cellular glass +
AFFF-AR
3 %</td><td>NR/NM
NR/NM</td><td>NR**
+
6,1
2,5</td><td>Type III
0,55 m
+
LEX
Type II
1,05 m</td><td>1:10***
2:00
2:13</td></tr>
<tr><td colspan="6">**Comments:**
The cellular glass, in total 8,2 l, was applied during 20 seconds and spread evenly over the fuel surface. When the foam application started (0:45), a layer of foam was formed immediately and 90 % control was obtained after 1:10 of foam application and the fire was completely extinguished in 2:13. This showed that the layer of cellular glass provided an efficient barrier between the fuel and firefighting foam improving the overall performance from no control at all (Test #8, #21) to a quick extinguishment.
* 45 l of E97 added to the fuel as used in Test #22 and Test #23 to obtain 450 mm fuel depth.
** 8,2 l of cellular glass corresponds to an average cellular glass layer of 20 mm. The cellular glass was applied after 15 min preburn time (0:00) and foam application started 45 seconds later.
*** Time to control and extinguishment is given from start of foam application.</td></tr>
<tr><td rowspan="2">25</td><td>WP1 tray
350
15</td><td>AFFF-AR
3 %</td><td>NM
NM</td><td>6,1
2,5</td><td>LEX
Type II
1,05 m</td><td>11:30
12:00
12:22</td></tr>
<tr><td colspan="6">**Comments:** Similar to Test #8 and #21 but using 350 mm to investigate the influence of dilution (and the possibility to reduce the fuel depth in the WP2 tests).
The result was initially identical to the previous tests and 100 % of the foam was destroyed on the impact on the fuel. However, at 7:40 some initial foam formation could be noticed on the fuel surface and at 9 min, about 50 % of the surface was covered by foam. Complete extinguishment was obtained at 12:22, which was faster than in previous tests and indicated that the dilution effect became significant. The water content in the fuel was estimated to about 18 % at extinguishment. To avoid dilution a fuel depth of 450 mm was used for the WP2 tests.</td></tr>
</table>

<table>
<tr><th>Test no</th><th>• Tray
• Fuel depth (mm)
• Preburn (min)</th><th>• Media type
• Concentration</th><th>• Expansion
• 25 % drainage (min)</th><th>• Application rate (l/m^{2} min)
• Flowrate (l/min)</th><th>• Type of foam
• Type of application
• Position above fuel</th><th>Time to:
• 90 %
• 99 %
• 100 %
(min:s)</th></tr>
<tr><td rowspan="2">26</td><td>2580
73
2</td><td>Cellular glass +
AFFF-AR
3 %</td><td>NR/NM
NR/NM</td><td>NR*
+
6,1
2,5</td><td>Typ III
0,10 m
+
LEX
Type III
0,5 m</td><td>7:20**
No
No</td></tr>
<tr><td colspan="6">**Comments:** The cellular glass (4,1 l) was applied manually over the entire fuel surface after 2 min preburn time and foam application started 2:30 from ignition. The test was conducted in the 2580 fire tray to allow direct (Type III) foam application. The intention was to see if a 10 mm cellular glass layer could provide a barrier function between the fuel and firefighting foam also during direct application.
The foam stream pushed away the cellular glass layer resulting in direct contact with the fuel which resulted in an immediate destruction of the foam. After 5:00 of application, some foam formed on top of the cellular glass beyond the impact point and the fire intensity was slightly reduced. At 7:20 the premix solution ran out allowing the foam to close the impact area and 90 % control was achieved. The water content was estimated to about 40 % at end of foam application.
* 4,1 l of cellular glass corresponded to an average cellular glass layer of 10 mm.
** Time to control and extinguishment given from start of foam application.</td></tr>
<tr><td rowspan="2">27</td><td>2580
73
2</td><td>Cellular glass +
AFFF-AR
3 %</td><td>NR/ NM
NR /NM</td><td>NR*
+
6,1
2,5</td><td>Typ III
0,10 m
+
LEX
Type III
0,5 m</td><td>0:30**
1:23
1:28</td></tr>
<tr><td colspan="6">**Comments:** Similar to Test #26 but applying 3 times more cellular glass. The cellular glass (12,3 l) was applied manually over the entire fuel surface after 2 min preburn time and foam application started 2:30 from ignition.
In this test the cellular glass layer was thick enough to protect the foam stream from direct contact with the fuel improving the overall extinguishing performance from a failure in Test #26 to a quick extinguishment.
* 12,3 l of cellular glass corresponded to an average cellular glass layer of 30 mm.
** Time to control and extinguishment given from start of foam application.</td></tr>
<tr><td rowspan="2">28</td><td>2580
73
2</td><td>AFFF-AR
3 %</td><td>29*
NM</td><td>6,6
2,7</td><td>CAF
Type III
0,5 m**</td><td>1:15
1:38
1:48</td></tr>
<tr><td colspan="6">**Comments:** Test similar to Test #26 and #27 using direct foam application, but this test used CAF without a protecting cellular glass layer.
A foam layer was visible already after 0:10 min along the back wall in front of the main impact point and at 0:50 min, 50 % of the fuel area was covered with foam. The fire was extinguished in 1:48 min which was surprisingly fast considering direct application of the foam and a significant dropout of foam not landing in the tray. Once again, a high extinguishing performance is achieved by use of improved characteristics of the expanded foam.
* Expansion significant higher and foam even stiffer than in previous CAF-tests.
** Nozzle directed 10° downwards to minimize the dropout of foam on the floor.</td></tr>
</table>

5.1.2 Temperature measurements

The measurements in the steel tank and fuel temperature provided a possibility to confirm the test conditions during the preburn period and to a certain extent also the influence of various test conditions during the extinguishing phase.

The measurements of the steel temperature very clearly showed the influence of a longer preburn time compared to the “standard preburn conditions” of 2 minutes. As shown in Figure 12, the steel temperature increases rapidly during the first 10 minutes, and then begins to stabilize. After 15 min of preburn time the temperature had reached an almost steady state condition and, based on this, a preburn time of 15 minutes was selected for the bulk of the tests. The highest steel temperature was in most tests recorded by TC 12 and reached about 550 °C after 15 minutes (Test #7). Comparing the steel temperature from all the tests during the preburn period (see Annex A) shows also that the repeatability was very good.

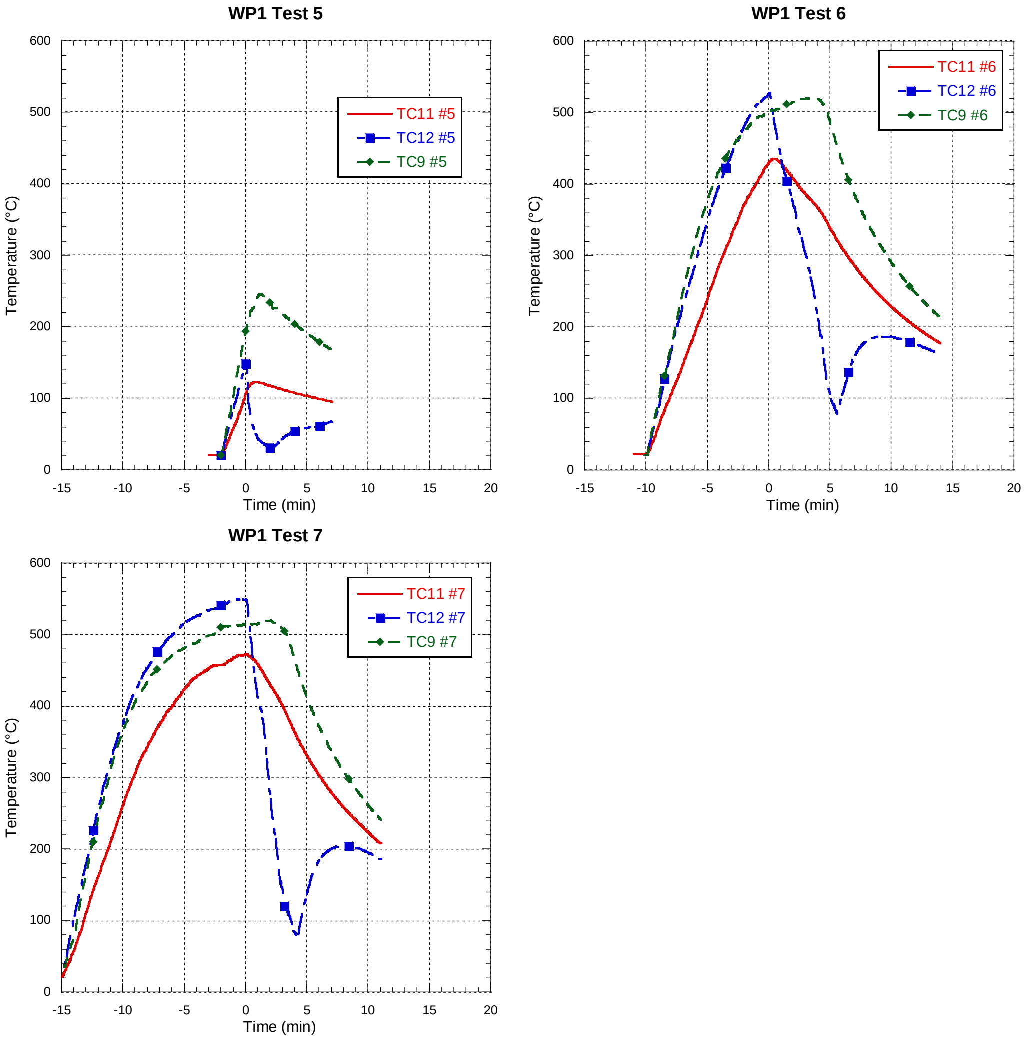


Figure 12 Temperature development of the steel temperature as a function of preburn time during the WP1 tests.

Following the preburn period, the temperature measurements also gave a clear indication how different extinguishing performance also influenced the steel and fuel temperatures, see Figure 13. As the foam was applied towards the extended tray wall (“back wall”) and then spread towards the “front wall”, TC9 was in general the best indicator regarding the control of the fire. TC 11, mounted on the extended tray wall, which in many tests correspond to the point of foam impact (1,05 m above the fuel surface), gave the best indication of the cooling effect from the applied foam. In Figure 13, the measurements are shown for two different tests, Test #9, in which the foam chamber did not extinguish the fire, and Test #20, in which the LEX foam was used at 6 % and Type II application on the extended tray wall 1,05 m above the fuel surface. In Test #9 it is very clear that the foam provides very marginal cooling of the tray wall (TC11 and TC12) and there was no foam layer spreading towards the front wall (TC9). In test 20, the foam impact was directly opposite to TC11, which showed an immediate temperature drop. The foam layer was established very quickly on the fuel surface, confirmed by quickly reduced temperatures at TC12 and TC9. The fire was completely extinguished after 1:43 min:s.

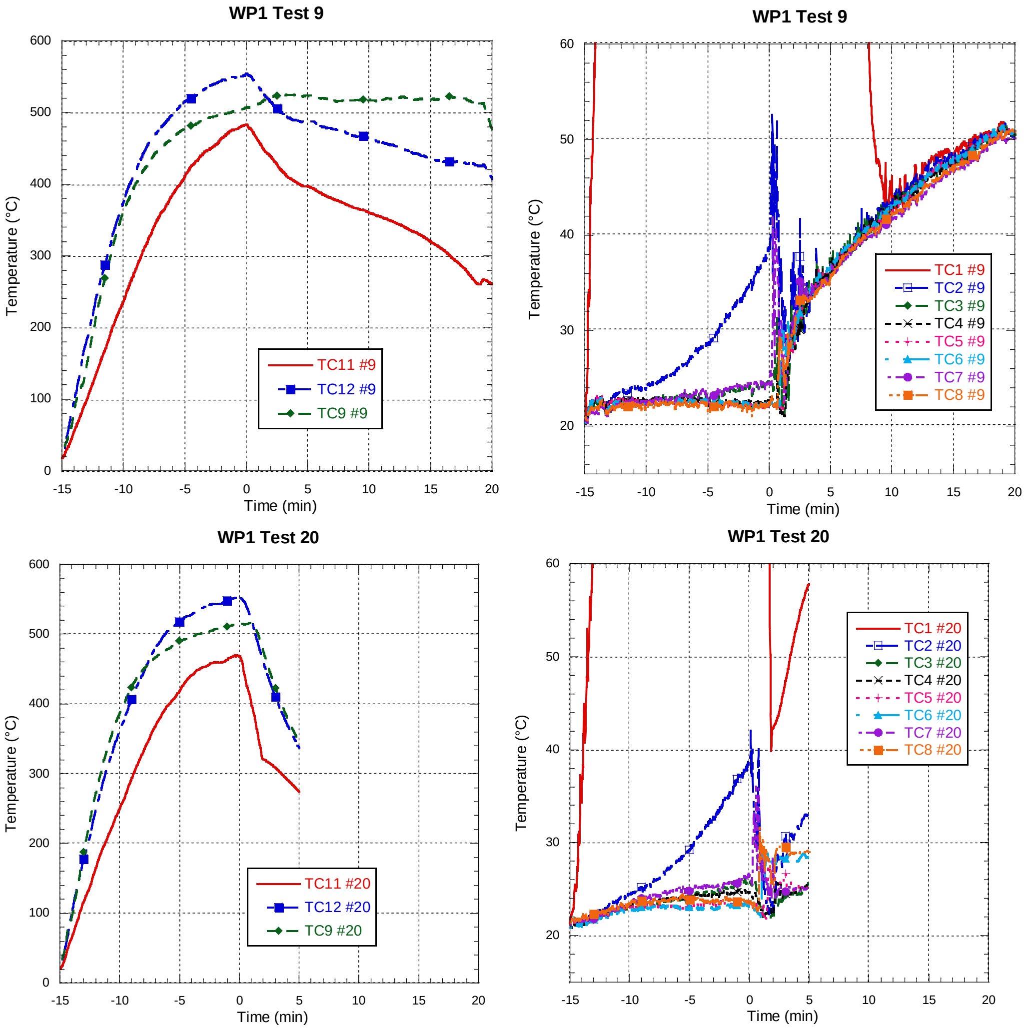


Figure 13 **Examples of steel and fuel temperature development during the preburn time and the foam application from Test #9 (not controlled/extinguished) and Test #20 (extinguished in 1:43).**

The fuel temperature measurements indicate that the temperature in the fuel layer is almost constant except for the position close to the surface, where the temperature increases as the fuel is consumed and the surface slowly recedes toward the next thermocouple. However, at start of foam application, the fuel temperature is increasing in the entire fuel layer, probably due to mixing of the fuel caused by the foam impact. It is also probable that the applied foam will transport heat from the flames and the hot steel, in particular if foam destruction is significant.

In Test #9, where all the foam was destroyed and no foam layer was established, the fuel temperature increased continuously during the foam application (stopped at 18:30) and reached about 50 °C while the temperature in Test #20 only reached about 25°C at the time of complete extinguishment (1:43 min).

The fuel temperature measurements also indicate the ethanol burning rate. The time delay (about 12,5 min) between TC1 and TC2 (positioned 50 mm apart) reaching a fuel temperature of e.g. 35 °C shows that the average burning rate is about 4 mm/min. This is 1 mm/min higher than measured in the 2 m^2 fire tests (3 mm/min) performed in WP5 [1] and used in the planning of the tests, see chapter 2.1.2. The difference is probably related to the design and higher walls of the fire tray.

5.2 Test results WP2

A tentative test programme was based on the results and experience from the WP1 tests. As the number of available tests within the budget for WP2 was significantly less compared to WP1, the decision was to primarily focus on the use of firefighting foams. This is the most likely extinguishing method for tank fires. The main focus was therefore to verify the tests in WP1 that indicated the best fire suppression performance. Further use of liquid nitrogen, AVD, and cellular glass as the sole extinguishing agent was therefore not included in the test programme. As in the WP1-tests, the final test programme was the result of an interactive process, continuously evaluating the results and experience of the previous tests.

Since a gentle application using a fixed foam pourer could not be obtained due to the hot steel in the “tank” wall, further tests in WP2 tests using the foam pourer were considered irrelevant.

5.2.1 WP2 test results

In total 14 tests, including one “repeat test” (#9, #9B), were conducted during the WP2 test series and are summarized in Table 4 below. Detailed measurement data and photos are presented in Annex A and Annex B, respectively. The results are presented in test order and, as the test conditions varied between most of the tests, the table also includes a short description of test conditions for each test followed by the extinguishing results and comments as described below. All tests were conducted with a fuel depth of 450 mm and a preburn time of 15 min (except Test #9B and #13). It should be noted that the comments included to each test reflect the test results and experience available after the specific test was completed. An overall discussion and comparison of the various tests and results is presented in chapter 6.2.

The information and abbreviations used in Table 4 are clarified below. Several parameters are presented in some of the columns, each reported on a separate line.

- Test no (1-13).
- Type of foam concentrate (AFFF-AR and F3-AR) and foam concentration. (In addition, cellular glass was used in combination with foam in Test #13).
- Type of foam generated (LEX, MEX, CAF).
- Expansion and time to 25 % drainage.
- Application rate of foam solution (l/m^2 min) and the corresponding flow rate, (l/min).
- The type of application is based on the NFPA 11 definitions, referring to Type II (backboard application, via the tray back wall) or Type III (applied directly to the

fuel surface). The position of foam application refers to the height above the fuel layer, either from the foam impact position on the backboard (Type II) or the height of the nozzle (Type III).

- Visually determined time to 90 % control, 99 % control and complete extinguishment. The time is given from the start of foam application.
- Comments on the test, both related to the test conditions, observations and the results. In certain cases a preliminary evaluation/discussion relevant for e.g. the selection of test conditions for subsequent tests is included.

Table 4 **Summary of test results from the WP2 fire tests (continues over 3 pages). (See also Annex A and Annex B)**

<table>
<tr><th>Test no</th><th>• Media
• Concen-tration</th><th>• Type of foam</th><th>• Expansion
• 25 % drainage (min)</th><th>• Applica-tion rate (l/m2 min)
• Flowrate (l/min)</th><th>• Applica-tion type
• Position above fuel</th><th>Time to
• 90 %
• 99 %
• 100 % (min:s)</th></tr>
<tr><td rowspan="2">1</td><td>AFFF-AR
3 %</td><td>LEX</td><td>6,0
10:20</td><td>7,26
22,8</td><td>Type II
1,05 m</td><td>No
No
No</td></tr>
<tr><td colspan="6">Comments: The test conditions were similar to Test #8 in WP1. Moved foam nozzle sideways at 10:10 to obtain swirl application but without any noticeable effect. The fire was partly reduced but not under control at 15:00 when foam application was stopped. The dilution effect became significant and the water content was estimated to about 25 % when the test was terminated. As Test #8 in WP1 also failed in a similar way, this confirmed consistency with WP1 results</td></tr>
<tr><td rowspan="2">2</td><td>AFFF-AR
6 %</td><td>LEX</td><td>10,3
35:00</td><td>7,26
22,8</td><td>Type II
1,05 m</td><td>3:20
4:00
4:10</td></tr>
<tr><td colspan="6">Comments: Due to the negative result in Test #1, it was decided to improve foam properties by using 6 % concentration which resulted in a significant better extinguishing performance.</td></tr>
<tr><td rowspan="2">3</td><td>AFFF-AR
6 %</td><td>LEX</td><td>9,7
39:47</td><td>4,77
15,0</td><td>Type II
1,05 m</td><td>2:50
3:40
3:52</td></tr>
<tr><td colspan="6">Comments: Test with lower application rate due to the successful result in Test #2. The result indicated even slightly better performance.</td></tr>
<tr><td rowspan="2">4</td><td>AFFF-AR
6 %</td><td>MEX</td><td>61
18:00</td><td>4,77
15,0</td><td>Type III
1,05 m</td><td>2:20
2:50
2:55</td></tr>
<tr><td colspan="6">Comments: Test with MEX and direct application to compare with Test #3. The fire was effectively controlled and extinguished but the foam layer was destroyed relatively quickly after extinguishment.</td></tr>
<tr><td rowspan="2">5</td><td>AFFF-AR
6 %</td><td>LEX</td><td>9,0
44:30</td><td>3,63
11,4</td><td>Type II
1,05 m</td><td>4:22
5:30
5:34</td></tr>
<tr><td colspan="6">Comments: Test with even lower application due to successful result in Test #3. Even at this application rate, the extinguishing performance was only slightly lower compared to Test #2 and #3.</td></tr>
</table>

Test no	**• Media** **• Concentration**	**• Type of foam**	**• Expansion** **• 25 % drainage (min)**	**• Application rate (l/m2 min)** **• Flowrate (l/min)**	**• Application type** **• Position above fuel**	**Time to** **• 90 %** **• 99 %** **• 100 % (min:s)**
6	AFFF-AR 6 %	LEX	9,7 41:00	4,77 15,0	Type II 2,05 m	2:05 3:15 3:20
	Comments: Test similar to Test #3 but with the point of application 1 m higher (2,05 m) to increase the force of the foam impact on the fuel. The obtained extinguishing performance was even slightly better.					
7	F3-AR 3 %	LEX	6,45 23:17	7,26 22,8	Type II 1,05 m	6:50 8:02 8:22
	Comments: Test similar to Test #1 but using F3-AR. The result shows a significantly better extinguishing performance, although the difference in performance compared to the AFFF-AR was less than in the WP1 tests. The water content at extinguishment was calculated to about 11 % and has probably not influenced the result significantly.					
8	AFFF-AR 3 %	CAF	11,9 18:20	7,26 22,8	Type II 1,05 m	No* No* No*
	Comments: Test similar to Test #1 but using CAF. * Unfortunately, the test ran out of premix solution at about 8:00 which corresponded to about 80 % control. The fire was therefore extinguished manually, first using foam application but, due to agitation of the fuel, the cover was used for complete extinction. Based on an extrapolation of the HRR measurements, it can be assumed that the fire had been completely extinguished in 10-11minutes if foam application had continued.					
9	AFFF-AR 6 %	CAF	16,7 52:10	3,63 11,4	Type II 1,05 m	0:50 1:50 2:00
	Comments: Similar to Test #5 but using CAF, i.e. using 6 % concentration but a low application rate. The test result showed a very fast control and extinguishing time. Note: This result turned out to be the best result during the WP2 test series.					
9B	AFFF-AR 6 %	CAF	See #9	3,63 11,4	Type III 1,05 m	3:00 3:50 4:00
	Comments: Due to the rapid extinction, an extension of Test #9 was performed with direct application. The foam layer was removed as quickly as possible and the same fuel was then used as the water content was judged to still be very low (estimated to about 1 %). The same premix as in Test #9 was used and it was decided to reduce the preburn time to 5 minutes*. The result indicated that a rapid control and extinguishment could be obtained using direct application. * The temperature measurements indicate that a 10 min preburn would have been more appropriate but would have resulted in less remaining fuel/higher water concentration.					

<table>
<tr><th>Test no</th><th>• Media
• Concentration</th><th>• Type of foam</th><th>• Expansion
• 25 % drainage (min)</th><th>• Application rate (l/m2 min)
• Flowrate (l/min)</th><th>• Application type
• Position above fuel</th><th>Time to
• 90 %
• 99 %
• 100 %
(min:s)</th></tr>
<tr><td rowspan="2">10</td><td>AFFF-AR
6 %</td><td>CAF</td><td>14,8
51:30</td><td>3,63
11,4</td><td>Type III
4 nozzles
2,55 m</td><td>2:30
3:44
3:56</td></tr>
<tr><td colspan="6">Comments: Similar to test #9B (direct application) but using “spiral jet nozzle application” (see Figure 11, photo 4) and a higher distance (2,55 m) between the nozzles and the fuel layer. The fire performance was even better in this test, possibly due to a more gentle application and an improved foam distribution.</td></tr>
<tr><td rowspan="2">11</td><td>F3-AR
3 %</td><td>CAF</td><td>15,8
34:13</td><td>3,63
11,4</td><td>Type II
1,05 m</td><td>12:10
13:23
13:30</td></tr>
<tr><td colspan="6">Comments: Similar to Test #9 but using F3-AR at 3 %. The result indicated a significantly lower extinguishing performance compared to the AFFF-AR used at 6 % but compared to Test #8 (AFFF-AR at 3 % and the double application rate, 7,26 l/m^2 min) the extinguishing performance was significantly better.</td></tr>
<tr><td rowspan="2">12</td><td>F3-AR
6 %</td><td>LEX</td><td>6,0
1:18:10</td><td>3,63
11,4</td><td>Type II
1,05 m</td><td>2:30
4:55
5:10</td></tr>
<tr><td colspan="6">Comments: Similar to Test #5 but using F3-AR at 6 % (instead of AFFF-AR at 6 %). The result indicated slightly better extinguishing performance compared to Test #5.</td></tr>
<tr><td rowspan="2">13</td><td>AFFF-AR
3 %</td><td>Cellular glass+
LEX</td><td>8,0
12:46</td><td>3,63
11,4</td><td>Cellular glass 50 mm
10 min waiting
LEX
Type III
1,05 m</td><td>3,5 MW reduced to 0,9 MW
2:40
4:30
4:35</td></tr>
<tr><td colspan="6">Comments: Test simulating a combination of applying cellular glass and direct application of low expansion foam. 50 mm (157 liters) of cellular glass was applied after 15 min preburn. Foam application was then started after a 10 minute waiting period. The cellular glass reduced the fire intensity to about 25 % of free burn conditions and the fire could then be extinguished relatively quickly using direct application.
(Due to lack of ethanol, the fuel depth was 415 mm. By mistake, the first 5 min of the test was not recorded by the video camera.)</td></tr>
</table>

5.2.2 Temperature and HRR measurements

Based on the tests in WP1, it was decided to use a preburn time of 15 min in all tests. As shown in Figure 14 the steel temperatures increased quickly during the first 5 minutes and were relatively stable after the 15 min preburn time. This is the same tendency as in the WP1 tests, but in this larger scale the maximum temperatures reached about 650 °C, about 100 °C higher than in WP1. The measurements also showed that the repeatability was very good (see Annex A for all results).

The temperatures could also be used to indicate the performance of the foam, in particular by TC 29 at the "front wall". The cooling effect of the steel at the impact position of foam was very clear, resulting in a very quick temperature drop. This was more significant than in WP1, which probably is a result of the higher total flow rate required to obtain the predetermined application rate.

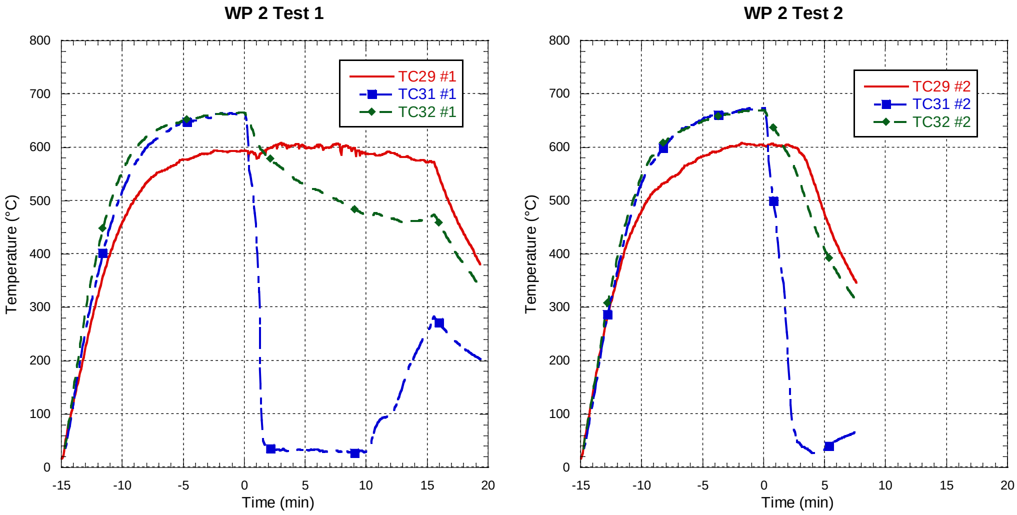


Figure 14 **Example of temperature data from Test #1 (no control within 15 min, nozzle moved sideways after 10:10 min) and Test #2 (extinguished at 4:10 min:s).**

As a complement to the temperature measurements, the HRR was also measured in the WP2 tests. As shown in Figure 15, the HRR had stabilized at about 3,6-3,8 MW (about 1,2 MW/m^2) after approximately10 min and was then reduced when foam application started. As shown in the diagrams, the HRR measurements provided a much better quantitative measurement of the fire control and extinguishment compared to the temperature measurements. The HRR was only slightly reduced at the start of foam application in Test #1 because no foam formation was achieved and during the remainder of the test the HRR dropped slowly, probably due to water dilution combined with some gel formation on some parts of the fuel surface. However, in Test #2, the HRR reduction was very fast from the start of foam application and indicates a 99 % control at about 4 min, which correlates very well with the visual observations.

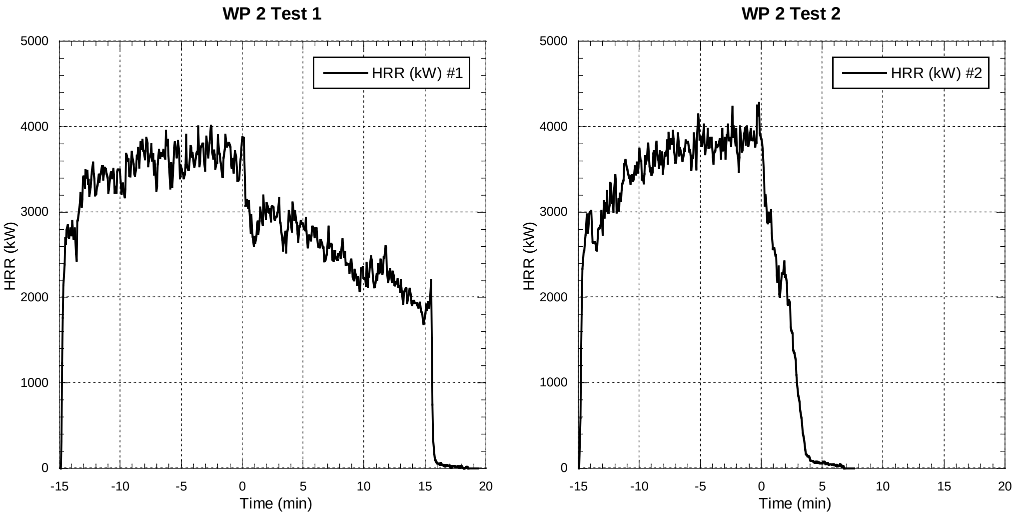


Figure 15 Example of HRR data from Test #1 (no control within 15 min) and Test #2 (extinguished at 4:10 min:s).

The fuel temperatures showed behaviour similar to WP1. However, based on the changed position of the thermocouples in the center of the tray, which were separated in WP2 by 15 mm (instead of 50 mm in WP1), more accurate measurement of the burning rate during the preburn time was possible. As shown in Figure 16, the temperature rise in TC21 to TC25 is very similar but separated in time as the fuel is consumed. Using the time when these thermocouples reach a fuel temperature of e.g. 50 °C shows that the time difference is about 3-3,5 min between each thermocouple. The total time difference between TC21 and TC25 is about 12,5 minutes in both tests in Figure 16 and as the distance between these TCs was 60 mm, this corresponds to an average burning rate of 4,8 mm/min.

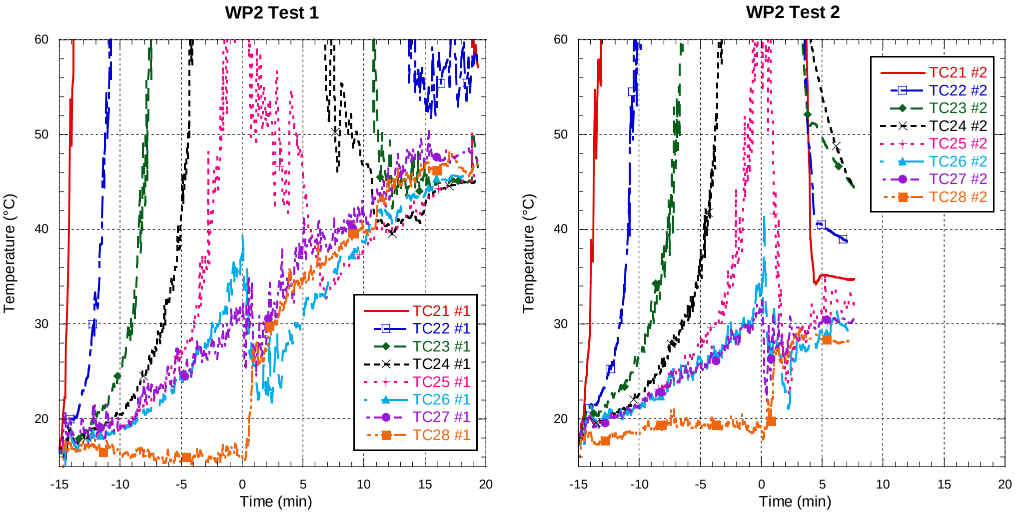


Figure 16 Example of fuel temperature data from Test #1 (no control within 15 min) and Test #2 (extinguished at 4:10 min:s).

6 Discussion

It is well known that extinguishment of fires involving water-miscible fuels, e.g. ethanol, can be challenging and there are a number of real tank fire incidents that have resulted in a complete burn-out. As mentioned in chapter 2.2, there are no well documented examples of tank fire incidents that were successfully extinguished according to our knowledge. The Nedalco fire might be an exception but the available information is very brief (see 2.2.1.2). In some incidents, the fire has been allowed to burn intentionally due to lack of extinguishing resources and focus has been on protection of surrounding tanks. However, there are also examples of unsuccessful attempts to extinguish the fire using traditional foam attack methods in which the eventual extinguishment was due to lack of fuel combined with water dilution (see 2.2.1.1 and 2.2.1.3).

Based on this history, the intention of the work in WP1 and WP2 in the ETANKFIRE project has been to investigate ways to obtain successful extinguishment under the more severe conditions that can be expected in a real scale tank fire situations. The test trays were therefore designed to allow for the use of larger quantities of fuel and a longer preburn time.

The following is a summary and discussion of the results obtained in the two work packages, WP1 using a test scale of 0,41 m^2 and WP2 using 3,14 m^2. In total 29 tests were conducted in WP1 and 14 tests in WP2, including the repeat tests in WP1 (#18, #18B) and WP2 (#9, #9B).

The main focus has been to use high quality alcohol resistant foams in the tests, although other types of extinguishing media have been involved in the tests, in particular in the smaller scale tests in WP1. Based on the WP1 experience, the most promising results were considered when planning and conducting further validating tests in the larger scale WP2. A tentative test plan was used as a start for the work in both WP1 and WP2 but was then continually updated as test results were obtained to optimize the information from the total number of tests available within the budget frame for each WP.

Focus has primarily been on evaluating extinguishing capability while aspects like burn back properties have not been considered or tested. Although this is an important factor in real fire situations, it was considered impossible to achieve comparable data because the test conditions varied, e.g. total foam application time.

6.1 Overall discussion WP 1

The initial two tests in WP1 were conducted according to SP Method 2580 to obtain an indication of the expected extinguishing performance according to EN 1568-4 for the two types of foam concentrate used in the project. The next tests were then focused on investigating the influence of various test conditions, such as depth of fuel and preburn time. Based on this, certain basic conditions were selected to investigate the influence of further parameters such as various types of expanded foam (LEX, MEX, CAF), application method (Type II, Type III, foam pourer) and impact/nozzle position in relation to the fuel surface.

All test results are summarised in Table 5 to visualize the various conditions/parameters evaluated in the tests but also to give an indication of which combinations were successful or unsuccessful. The numbers in the table refer to the test number (see Table 3 in 5.1.1 and diagrams/photos in Annex A and B) and the colours in the table translate to the following results:

- Green, a successful extinguishment within a relatively short time.
- Blue, reduced performance where the dilution effect had a significant influence.
- Orange, no or limited control and no extinguishment within 15 minutes of foam application (or until the test was terminated).

Table 5 Summary of all tests within WP1 with colours indicating the overall obtained result, Green-successful, Blue-significant reduced performance/dilution, Orange-no or limited control/no extinguishment. For detailed results, see Table 3 and Annex A and B.

	AFFF-AR 3 %	**AFFF-AR 6 %**	**F3-AR 3 %**	**Cellular glass+foam**	**AVD**	**N2**
LEX II Low position	1 (2580-tray) 3,4,5,6,7, 15		2 (2580) 16		17 (2580)	
LEX II	8,11, 21, 25 (Less fuel) 12 (2xAppl rate)	20	19	24		
LEX III				26 (2580) 27 (2580)		
MEX III	10		18,18B			
CAFS II	13					
CAFS III	28 (2580)					
Foam pourer	9 (LEX) 14 (CAF)					
Other media Type III				23 (Only cellular glass)		22

Note: “2580” in the table indicates the use of the fire tray according to SP Method 2580, i.e. using a fuel layer of 73 mm and 2 min preburn.

As a complement to Table 5, some comments from each test have been summarized below. For further information on each test, please also study the measurement results and photos provided in Annex A and B.

Both foam concentrates (AFFF-AR and F3-AR) performed very well in standard test conditions (SP Method 2580) and the results (extinction about 1:45 min, burn back about 30 min) indicate that the two foam concentrates would obtain a Class IA classification according to EN 1568-4 using ethanol (E97) as fuel. (Test #1 and #2).

The change from the 2580 tray to the WP1 tray, intended to simulate tank fire conditions in a better way, resulted in slightly more severe conditions, although the same fuel depth and preburn time were used. Using an increased fuel depth and a longer preburn time seemed to influence the severity of the tests to some extent (Test #3 - #7) and time to extinguishment was on the order of 2-5 minutes. Some of the variations in the time to extinguishment are partly related to variations in the impact position of the foam above the fuel, but probably also the conditions of the premix solution used in the tests (e.g. premix age and mixing procedure).

In order to study the importance of the impact force during foam application, the Type II application (backboard) was used but the impact position above the fuel was increased from 0,35 m (Test #5 - #7) to 1,05 m. This change gave completely different results. Instead of an extinguishment in 2-5 minutes, no control at all could be obtained. This result was verified by a number of subsequent tests with identical or very similar test conditions (Test #8, #11, #21) and further verified by repeat tests using the lower application position (Test #15, #16). In this case, the increased fuel depth and preburn time were probably very important to clearly identify the influence of impact position. Test #25, using 350 mm of ethanol (instead of 450 mm) showed a significantly improved performance due to the dilution effect; the water content was estimated at about 21 % at extinguishment. In Test #12 it was also shown that doubling the application rate could not fully compensate for the more severe application position until the dilution effect became significant (about 22 % at extinguishment) and thereby made extinguishment possible.

As the effect of the impact on the fuel surface was clearly a very important factor, a number of tests were made to investigate if a more gentle application could be obtained, either by simulating a fixed foam pourer system or by generating other types of finished foam (MEX, CAF). In Test #9, a foam pourer was mounted on the rim of the extended backboard (1,55 m above the fuel level), which under cold conditions enables the generated foam to flow gently along the tank wall down to the fuel surface. However, due to the longer preburn time (compared to standard testing procedures), the steel tank wall temperature was very high, preventing the foam, at least initially, sticking to the wall and thereby slide gently into the fuel. This also prevented an effective cooling of the wall and the overall consequence was that the foam was falling directly into the fuel, i.e. resulted in a Type III (direct) application. The conclusion of the test was that a foam pourer installation does not guarantee a gentle application in a real situation where the preburn time is long (in practice, probably much longer than the 15 minutes used in these tests).

A number of tests were made to study the influence of improved foam characteristics (higher expansion, more stable/slow draining foam) and to learn the extent that improved foam characteristics can reduce foam breakdown during application. This was verified by using e.g. 6 % concentration for the AFFF-AR (Test #20) and the use of CAF instead of aspirated foam (Test #13). The improvement by using CAF was also clearly shown in Test #14, using the foam pourer. The high steel temperature still prevented the foam from sticking to the wall, which resulted in a Type III (direct) application. However, the foam was robust enough to survive the impact on the fuel, and resulted in extinguishment in about 5 minutes.

The production of MEX using the AFFF-AR at nominal (3 %) concentration (Test #10) was not successful, the foam was still too weak to survive the direct application although the foam nozzle was positioned only 0,55 m above the fuel surface.

Some comparison tests with the fluorine free foam (F3-AR) indicated in general a fire performance significantly better than the AFFF-AR. The most significant difference was obtained when applied as LEX, Type II (Test #19) where an extinguishing time of 2:17 was obtained compared to no extinguishment at all. A similar difference occurred when F3-AR was used as MEX (Test #18, #18B) which resulted in extinguishment within about 2-3 min compared to no control and extinguishment in 15 min (Test #10).

Some other extinguishing media were tested as well in the WP1 tray. Applying liquid nitrogen (Test #22) reduced the intensity and heat radiation significantly, which was also confirmed by temperature measurements but a large portion of the gas was vented away due to thermal updraft. The nitrogen application was interrupted after 3:25 min as the extinguishment process seemed to have reached steady state. The test indicated that a fire with a long preburn time could not be expected to be extinguished with liquid nitrogen alone, using a reasonable amount of nitrogen.

The test using cellular glass as extinguishing media (Test #23) showed that the application can provide a significant reduction in the fire intensity, but likely not a very fast extinguishment. The test was terminated at 5:25 after start of application of the cellular glass because the extinguishment process seemed to have reached steady state. In the test, the average thickness of the cellular glass layer was about 180 mm. However, after the test it was noticed that there were large differences in the layer thickness. In the area with the thinner layer, fuel was visible at the surface of cellular glass layer and it was mainly this area that contributed to the fire. A continuous reduction of the fire intensity could have been expected if a more even layer thickness had been obtained and the fire control performance might have been further improved by cooling of the outside of the tank wall by a water spray. The main benefit is that the cellular glass can be applied directly to the fuel surface without any destruction and there is no continuous breakdown (drainage) making it necessary to renew the cellular glass layer.

Using a combination of a thin layer (20 mm in average) of cellular glass followed by a foam application (Type II) proved to be a very efficient combination as the cellular glass provided a barrier between the foam and fuel, resulting in an immediate foam layer formation and a very effective extinguishment (Test #24).

In addition to the tests in the WP1 tray, some further tests were also made in the 2580 tray. This limited the fuel layer to 73 mm and the preburn time to 2:00 min but provided the opportunity to get some indicative test results related to forceful application of low expansion foam.

Common knowledge is that Type III (direct) application is not possible for aspirated LEX because the foam splashes directly into the fuel, resulting in immediate destruction. However, based on the results of Test #24, two tests with Type III application were performed with an initial application of cellular glass to provide a barrier between the fuel and foam. A 10 mm layer (Test #26) did not provide a sufficient barrier to achieve fire control. A layer of 30 mm (Test #27) resulted in an extinguishment in less than 1:30. This showed that that the combination of cellular glass and foam might have potential to improve extinguishing performance dramatically and even make it possible to use direct application of the foam.

Based on the positive experience from using CAF (Test #13, #14), one test with direct application was also conducted with CAF (Test #28). The test showed that fire extinguishment was also possible using Type III-application when applied as CAF with a relatively high expansion ratio. This result once again demonstrated the importance of improved foam characteristics.

A test with AVD (Test #17) as an alternative to an ordinary alcohol resistant foam showed that the product might have a significant potential as a fire extinguishing medium under severe conditions. The performance may have been further improved if applied as CAF. The main difference compared to foam is that it is not used as a concentrate that is mixed with water but as a ready solution. The resistance against the fuel and the extreme burn back resistance indicates that a reduced application rate would be possible and the total amount of AVD solution would be significantly less than the required firefighting foam solution and would act similar to cellular glass. The test was made with Type II application but it is very likely that a Type III application would have given a similar result.

6.2 Overall discussion WP2

All tests in WP2 were conducted in the tank model tray, with similar construction as the WP1 tray but having a fire area of 3,14 m^2. The fuel depth was 450 mm and the preburn time was 15 min in all tests[1]. The main focus was to verify the most promising results from WP1 using firefighting foam but one test was also made with a combination of cellular glass and foam.

The larger test tray, combined with a number of foam nozzles having different flow rates, allowed further evaluation of the application rate within the range of 3,63-7,26 l/m^2 min. The higher application rate (7,26 l/m^2 min) correlates reasonably well with the application rate used in the EN 1568-4 standard (see chapter 3.2.2). This means that the tests with the lowest application rate (3,63 l/m^2 min) correspond to about 50 % of the application rate used in EN1568-4 testing.

All test results are summarised in Table 6 to visualize the various test conditions and parameters and also to give an indication of which combinations were successful or unsuccessful by colour markings. The numbers in the table refer to the test number (see Table 4 in 5.2.1 and diagrams/photos in Annex A and B). The colours in the table translate to the following results:

- Green, a successful extinguishment within a relatively short time
- Blue, reduced performance resulting in a prolonged time to control and extinguishment
- Orange, no or limited control and no extinguishment within 15 minutes of foam application (or the test was terminated)

Table 6 **Summary of all tests within WP2 with colours indicating the overall obtained result, Green-successful, Blue-significant reduced performance/dilution, Orange-no or limited control/no extinguishment. For detailed results, see Table 4 and Annex A and B.**

	AFFF-AR 3 %	**AFFF-AR 6 %**	**F3-AR 3 %**	**F3-AR 6 %**
LEX II				
7,26	🟧 1	🟩 2	🟦 7	
4,77		🟩 3, 6 1)		
3,63		🟩 5		🟩 12
LEX III				
3,63	🟩 13 (Cellular glass+AFFF-AR 3 %)			
MEX III				
4,77		🟩 4		
CAFS II				
7,26	🟧 8			
3,63		🟩 9	🟦 11 3)	
CAFS III				
3,63		🟩 9B, 10 2)		

1) Backboard application 2,05 m above fuel surface
2) Spiral jet nozzles positioned 2,55 m above fuel
3) No significant dilution effect, water content estimated to about 10 % at extinction.

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[1] With exception for Test #13, using 415 mm due to lack of fuel, and Test #9B (immediate repeat of Test #9) using a preburn time of 5:00 and the same fuel without any re-filling.

A more detailed presentation of the time to extinguishment as a function of application rate is presented in Figure 19. As a complement to Table 6 comments from each test have been summarized below. For further information on each test, please also study the measurement results and photos provided in Annex A and B.

The intention of the first test in WP2 (Test #1) was to investigate the correlation with the test conditions in WP1. The most critical test seemed to be the use of the AFFF-AR at nominal (3 %) concentration and a Type II application 1,05 m above the fuel surface. In this WP2 test the foam application could not provide control of the fire within 15 minutes and the test had to be manually terminated. This result corresponds directly to the similar WP1 tests (Test #8, #11, #21).

Based on the experience from WP1, improved foam characteristics seemed to be important. Using the AFFF-AR 3x3 at double concentration (6 %) provided the fastest extinguishment of all tests in WP1. The same conditions were therefore used for Test #2, which generated a very good foam characteristics (with respect to expansion and drainage) and resulted in complete extinguishment in 4:10 min, once again showing the importance of the expanded foam characteristics.

Using the improved foam characteristics (6 % concentration), Test #3 and #5 showed that the application rate could be reduced to 50 % of the “basic” application rate (3,63 l/m^2 min compared to 7,26 l/m^2 min) without any significant drop in fire extinguishing performance. This was also verified in Test #9, #9B, #10, and for the F3-AR foam in Test # 7, #11, #12 as discussed further below.

In Test #6, it was also shown that even when using an increased impact force (foam application position 2,05 m above the fuel surface), it was still possible to extinguish the fire with good result, although the intermediate application rate (4,77 l/m^2 min) was used.

Test #4 showed that a good extinguishing performance could be obtained at the intermediate application rate (4,77 l/m^2 min) by using a MEX foam with improved foam characteristics. The test indicates a correlation with WP1 Test #10, which failed extinguishment (3 % concentration) and WP1 Test#18 and #18B using the F3-AR foam concentrate, which showed a very good fire performance due to the improved foam characteristics.

In Test #7, the F3-AR foam concentrate was used at a nominal concentration (3 %) for producing a low expansion foam. The result indicated a certain correlation with WP1 (Test #19) which showed a much better performance compared to the AFFF-AR at 3 % although the extinguishing performance in Test #7 was not as good as in the WP1 test. This could probably be a result of the increased test scale and the use of a different foam nozzle, providing a somewhat lower expansion ratio and faster drainage (about 6,5/23 min versus 7,8/32 min in WP1 Test #2).

Test #8, using the AFFF-AR at 3 % as CAF, indicated a lower extinguishing performance compared to WP1 (Test #13). The reason was possibly due to scale effects and somewhat lower expansion. However, a full comparison is not possible as the fire was only controlled to 80 % before the premix solution ran out. Based on an extrapolation of the HRR measurement, extinguishment could have been expected after 10-11 min.

In Test #9, the CAF characteristics was improved further by increasing the concentration to 6 % (AFFF-AR), resulting in an expansion ratio of 16,7 and a 25 % drainage time of about 52 minutes. Although using the lowest application rate (3,63 l/m^2 min), this test gave the best fire performance of all tests performed during WP2 with a complete extinction of 2:00 min:s. The additional Test #9B indicated that it was also possible to obtain good fire performance even when using direct application (Type III). It should be noted that the fuel was re-used from Test #9 and the selected preburn time was only 5 min, while an analysis of the temperature measurements indicated that 10 min preburn would have been more appropriate.

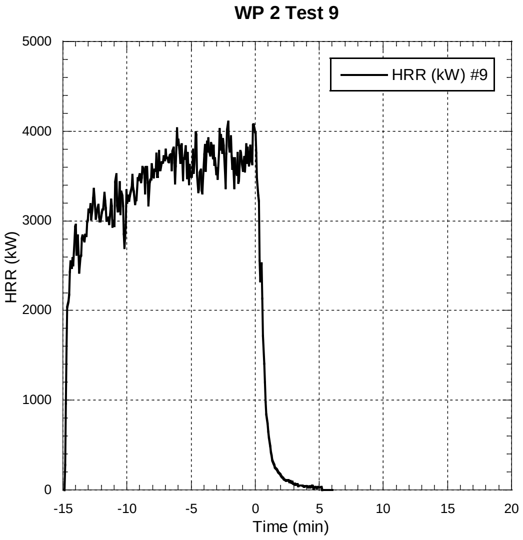

Figure 17 **HRR-measurement from Test #9, using CAF (AFFF-AR 6 %, 3,63 l/m^2) which provided the best results of all tests in WP2 using Type II application.**

Test #10, using the same characteristics of CAF (AFFF-AR 6 %) and application rate as in Test #9, showed that direct application (Type III) through spiral jet nozzles from an even higher position (2,55 m) above the fuel level was also capable of providing good fire extinguishing performance. A combination of the high expansion ratio and long drainage time resulting in a more gentle application and an improved foam distribution over the fuel surface are probably key factors. However, in a large scale fire situation, foam losses due to thermal updraft could be a problem if the distance to the fuel was increased.

In Test #11, the F3-AR foam was used as CAF at nominal concentration (3 %). The result indicated a lower fire extinguishing performance compared to the AFFF-AR using 6 % (Test #9). However, comparing the results with Test #8, where the AFFF-AR was used at 3 % and twice the application rate, the F3-AR foam still indicates an overall better performance.

In Test #12, the F3-AR foam was used as LEX at double concentration (6 %) and was thereby comparable with Test #5 (AFFF-AR at 6 %). The results for the F3-AR foam indicate a lower expansion ratio but a longer drainage time, resulting in a slightly better control and extinguishing performance.

Test #13 was intended to verify the possibility of using a combination of cellular glass and foam application, which was shown to be a successful combination in WP1 (Test #27). Following the application of cellular glass, conventional LEX foam at recommended concentration (3 %) was applied using direct (Type III) application at a low application rate (3,63 l/m^2 min). The results showed that the 50 mm layer of cellular glass that was applied first, reduced the fire heat release rate to 25 % (0,9 MW) compared to free-burning conditions (3,5 MW) within minutes, see Figure 18. When the foam application started 10 minutes later, a foam layer was established immediately and although the foam layer was spreading somewhat slower on the cellular glass compared to a free fuel surface, there was very limited foam destruction and the fire was therefore easily extinguished in less than 5 minutes.

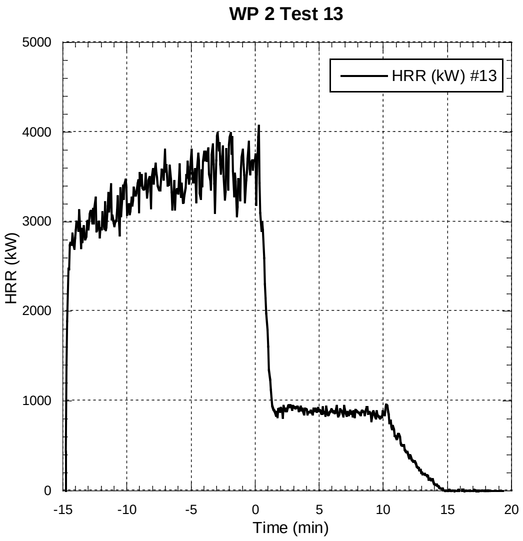

Figure 18 **HRR-measurement from Test #13 using a combination of cellular glass and direct application (Type III) of low expansion foam at nominal (3 %) concentration and the lowest (3,63 l/m^2 min) application rate.**

The temperature measurements showed about 100 °C higher steel tank wall temperatures at the end of the preburn time compared to WP1 but the fuel temperatures behaved about the same with a significant temperature increase to about 45-50 °C during foam application in cases where no or limited fire control was obtained (Test #1, #8).

The burning rate was about 4,8 mm/min in the WP2 tests, compared to about 4 mm/min in the WP1 tests and 3 mm/min measured in the small scale (2 m^2) free burning test conducted in WP5 [1]. The increased burning rate also influenced the dilution effect slightly but as a lower application rate could be used in many of the WP2 tests, the dilution effect was in most tests very limited. During Test #1, where no fire control was obtained, the water content was calculated to be about 25 % when the foam application was terminated but in all other tests with somewhat longer extinguishing/foam application time (Test #7, #8 and #11), the calculated water content was significant lower, 11,2 %, 10,8 % and 9,6 %, respectively, and is not expected to have a major influence on the extinguishing performance. In the calculations, the burning rate is based on the HRR measurements, and has been assumed to be an average of 2,4 mm/min during the foam application (3,6 mm/min in Test #1). This corresponds to 50 % (75 % in Test #1) of the burning rate before start of extinguishment. The foam destruction was assumed to be 75 % of the applied foam solution (100 % in Test #1). No verifying analyses of water content has been performed.

6.2.1 Summary of extinguishing performance versus application rate

In the WP2 tests, there was a possibility to vary the application rate and Figure 19 summarizes all the tests showing the time to extinguishment as a function of application rate. It is clear that the finished foam characteristics are far more important than the application rate, where a stable foam has the possibility to survive the landing on the fuel surface, even at more severe foam application conditions. Using improved foam characteristics made it possible to reduce the application rate to 50 % and still obtain about the same performance.

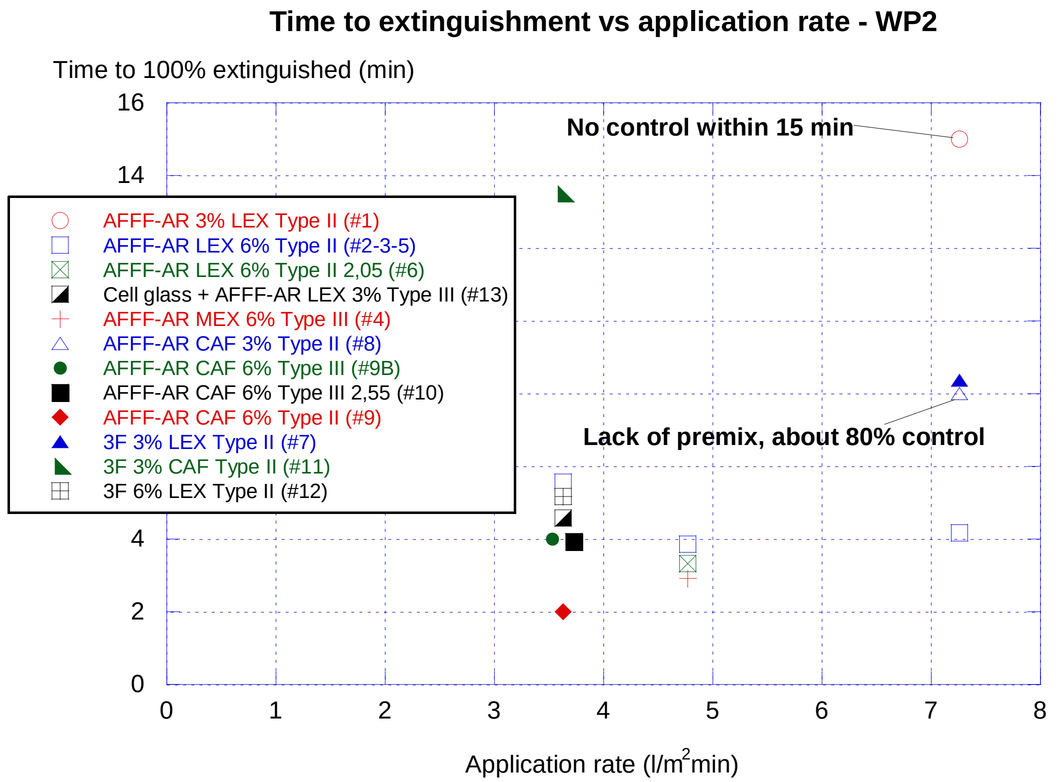

Figure 19 Time to 100 % extinguishment as a function of application rate in the WP2 tests. The results indicate that the finished foam characteristics are far more important than a higher application rate to obtain a successful extinguishment. Note: Test #1 (AFFF-AR 3 % LEX Type II) and Test #8 (AFFF-AR 3 % CAF Type II) are marked in the diagram although they did not extinguish the fire.

7 Summary and conclusions

Extinguishment of a tank fire containing ethanol (or other water-miscible fuel) is a very challenging situation and only alcohol resistant foam concentrates of “top quality” should be considered. The ETANKFIRE project results show that the standardized tests do not reflect a real scale tank fire situation. Large volumes of fuel, long preburn times and the higher impact force of the foam, e.g. during combination of an indirect (Type II) foam application due to a higher fall height from the impact position to the fuel surface, or a direct (Type III) application, are all factors that make real life conditions more severe. The tests have also indicated that using a fixed foam pourer system will not guarantee a gentle application due to hot steel walls after a longer preburn time.

The conclusions and recommendations given below should therefore be considered to increase the likelihood for a successful tank fire extinguishing operation.

- Extinguishment of an ethanol tank fire requires specific characteristics of the finished foam in terms of both expansion and drainage. Foam application using a non-aspirated foam monitor is unlikely to succeed in extinguishing a tank fire. It is recommended to use an air aspirating foam generation nozzle that provides an expansion ratio of 8-10 and 25 % drainage on the order of 30 minutes or more. In the tests, successful extinguishments were mainly achieved when using twice the recommended foam concentration, e.g. using 6 % instead of the recommended 3 %. Using the recommended foam concentration resulted in a complete failure to extinguish the fire in several tests.

- To obtain these enhanced foam characteristics, a significantly increased concentration of the foam concentrate compared to the recommended concentration by the manufacturer is likely necessary, or alternatively, a specially formulated concentrate for this application would be required. It should be noted that the foam concentrates used were designed to be proportioned at 3 % (97 parts water + 3 parts foam concentrate). The foam concentrates used are commercially available 3x3 concentrates having high performance ratings under UL 162 and EN 1568 Part 4. The results from the WP2 tests indicate that the most common test standards for foam concentrates (EN1568, UL 162) do not reflect a tank fire situation and thereby do not provide an incentive for the manufacturers to formulate and test their foam concentrates to handle more severe fire conditions such as a simulated tank fire scenario. The test methodology used in WP2 showed that the necessary expansion ratio and more specifically the bubble stability (drainage time) could not be achieved with a 3 % foam solution.

- A general rule when fighting fires in water-miscible products is to always apply the foam as gently as possible. However, improving the characteristics of the finished foam will further enhance the possibility for a gentle landing of the foam and the ability to reduce foam destruction as much as possible. Improved foam characteristics and a gentle foam application are far more important than the application rate. By improving the characteristics of the finished foam, the tests showed that it was still possible to obtain very good extinguishing performance although the application rate was reduced to 50 % of the nominal application rate used in standard testing. This means that even if using twice the recommended concentration, the total amount of foam concentrate used could be equal or less due to the improved overall performance.

- Using CAF instead of aspirated low expansion foam (LEX) provides a possibility to enhance the foam characteristics (expansion and drainage) even further and provides better control of the generated foam properties. In some tests, it was possible to obtain successful performance even when using direct (Type III) application.

- In most foam system standards [2, 3], the use of fixed systems such as fixed foam pourer[2] application is considered more effective and requires, in relative terms, a significantly lower application rate and a shorter operating time compared to monitor application. However, some tests conducted with a simulated foam pourer system and LEX foam in WP1 did not show successful extinguishing performance due to the effect of the high temperature of the tank wall. During cold conditions, the foam flowed gently along the wall down to the fuel surface (according to the definition) but after the 15 min preburn, the steel tank wall temperature was approximately 550 °C causing an immediate evaporation of the foam closest to the tank wall surface and forming a steam layer that pushed the foam stream away from the wall. The consequence was a free fall of foam to the fuel surface, resulting in a severe direct (Type III) application. When using aspirated LEX foam, the foam was completely destroyed and no control of the fire could be obtained. In a test applying CAF through the foam pourer, the same phenomena occurred resulting in a free fall of the foam to the fuel surface but the improved foam characteristics enabled to foam to survive the landing and form a foam layer that was able to control and extinguish the fire. In both tests, there was initially also a loss of foam due to the thermal updraft from the fire.

- For water-miscible fuels (e.g. ethanol, methanol), the use of monitors is not recommended in foam system standards [2, 3], as a gentle application is considered difficult or even impossible to achieve using monitors. Industry advice to apply the foam stream towards the back wall of a tank to reduce the impact force of the foam will in practice be very difficult. The test results also clearly show the importance of gentle application and the need for improved foam characteristics which will be very difficult to obtain using the type of large scale foam monitors (often non-aspirating) frequently used by the industry for tank fire protection.

- A possible option to improve extinguishing performance, and in particular to ensure a more gentle application of the foam onto the fuel, is to combine the use of cellular glass and foam application. As the cellular glass is not destroyed by the fire, it can be applied in advance of the foam application. By using this technique, it was possible to obtain a very good extinguishing performance when using the nominal foam concentration of 3 %, a lower application rate (50 % of nominal) and direct (Type III) application. The application of a cellular glass layer at the initial stage of the fire also has the advantage that it reduces the fire intensity significantly and thereby reduces the risk for fire escalation and need for cooling. When applying the foam to obtain a final extinguishment, the layer of cellular glass reduces the mixing of the foam and fuel, allowing an effective foam layer to be established. In the ETANKFIRE WP2 Test #13, a cellular glass layer of 50 mm was used, but in real scale applications using larger scale foam equipment, a thicker layer (75-100 mm) would be recommended to withstand the more severe foam application due to higher flow rates. A thicker layer of cellular

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[2] **Fixed foam pourer (foam discharge outlet):** Component which discharges foam gently and indirectly onto the fuel surface (definition according to EN 13565-2)

glass would also reduce the fire intensity even further until the final extinguishment operation starts.

- The bulk of the tests were conducted using AFFF-AR 3x3, but some tests were also conducted with F3-AR 3x3. The test results according to SP Method 2580 showed an almost identical extinguishing performance while the burnback time for the 3F-AR foam was about 30 % longer. Based on the results, both concentrates indicated a 1A classification according to EN 1568-4 with good margin. Also the fire tests in WP1 and WP2 showed in general that the fire extinguishing performance of the F3-AR foam was equal or in several tests significantly better than the AFFF-AR.

- In addition to the recommendations given above, a general recommendation for tank firefighting of ethanol and other water-miscible fuels, would be to only use alcohol resistant foam concentrates which have obtained the highest performance classification, e.g. Class 1A according to EN 1568-4. However, as shown by the tests in this project and previously discussed in this chapter (second bullet point), a high performance classification according to existing test standards is not a guarantee for a successful result in a tank fire situation and the performance under these more severe conditions might still vary significantly between individual foam concentrates. It might also be necessary to use a higher foam concentration than the nominal value declared by the foam manufacturer. It is also important to consider that various fuels might have significantly different properties compared to those fuels used during approval testing, which could further influence the extinguishing performance. It is therefore strongly recommended to verify the performance of any foam/fuel combination using a test setup and procedures similar to those used in the ETANKFIRE project.

- It should also be emphasized that even though the ETANKFIRE tests were conducted with considerably more fuel, a longer preburn time and a more severe foam application compared to standard tests conditions, the test scales used in the WP1 and WP2 tests were very limited compared to a real tank fire situation. As the increased scale in a real tank fire situation would likely increase the severity of the firefighting operation even further; it is also recommended to verify the most promising results in larger scale. The ETANKFIRE tests, both in WP1 and WP2, showed that the application impact force is critical, i.e. the position and height of the foam relative to the fuel surface, although improved foam characteristics could to a certain extent compensate for such conditions. The conditions that were used during the tests are very hard to translate to real, large scale conditions and would be one of the main factors to verify in future work as suggested for Phase 2 of the ETANKFIRE project (see Figure 1). Such validation of the results could provide unique possibilities to improve foam system standards, e.g. NFPA11 and EN 13565-2 for extinguishment of water-miscible fuels as well as test standards for foam concentrates (e.g. UL 162, EN 1568-4).

- The Phase 2 fire tests will preferably be conducted in a facility having a diameter in the range of 10-15 m with a significant fuel depth and extended preburn time. In order to mimic a real tank fire situation, at least part of the test facility perimeter should have an extended tank wall construction. A minimum of four tests would be sufficient to confirm the findings of Phase 1.

- To realize Phase 2 of the ETANKFIRE project, additional partners are required to obtain necessary funding.

8 References

1. Sjöström, J., Appel, G., Amon, F., and Persson, H., "ETANKFIRE-Experimental results of large ethanol fuel pool fires", SP Technical Research Institute of Sweden, SP Report 2015:12, Borås, Sweden, 2015.
2. "NFPA 11 Standard for Low-, Medium-, and High-Expansion Foam", National Fire Protection Association, 2016.
3. "EN 13565-2:2009 Fixed firefighting systems - Foam systems - Part 2: Design, construction and maintenance", CEN European Committee for Standardization, 2009.
4. "UL 162 Standard for Foam Equipment and Liquid Concentrates", UL, 1994.
5. "EN 1568-1:2008 Fire extinguishing media-Foam concentrates-Part 1: Specification for medium expansion foam concentrates for surface application to water-immiscible liquids", CEN.
6. "EN 1568-2:2009 Fire extinguishing media-Foam concentrates-Part 2: Specification for high expansion foam concentrates for surface application to water-immiscible liquids", CEN.
7. "EN 1568-3:2008 Fire extinguishing media-Foam concentrates-Part 3: Specification for low expansion foam concentrates for surface application to water-immiscible liquids", CEN.
8. "EN 1568-4:2008 Fire extinguishing media-Foam concentrates-Part 4: Specification for low expansion foam concentrates for surface application to water-miscible liquids", CEN.
9. "LASTFIRE Fire test specification", LASTFIRE.
10. "Foam test for storage tank fires, water miscible fuels, Test protocol, November 2011", LASTFIRE.
11. "FAIRFIRE - Fire fighting foams: Small scale fire test procedure", SP Technical Research Institute of Sweden, 1996.
12. "SP-Method 2580, Foam concentrates-Quality control, Edition 2, January 2002", SP Technical Research Institute of Sweden.
13. Persson, H., and Lönnermark, A., "Tank Fires - Review of fire incidents 1951-2003", SP Swedish National Testing and Research Institutes, SP REPORT 2004:14, Borås, Sweden, 2004.
14. Persson, B., Lönnermark, A., Persson, H., Mulligan, D., Lancia, A., and Demichela, M., "FOAMSPEX - Large Scale Foam Application - Modelling of Foam Spread and Extinguishment", SP Swedish National Testing and Research Institute, SP Report 2001:13, Borås, Sweden, 2001.
15. Bootsma, H., "Personal communication with Chief Superintendent Hans Bootsma", New South Wales Fire Brigades, Australia, 2007.
16. Hawrelak, R. A., "Ethanol Tank Fire, Manildra Inc., Port Kembla, NSW, Australia, 3 Mar 04".
17. Braga, G. C. B., "Tank fire in Ourinhos, San Paulo, Brazil", 2013.
18. Ramsden, N., "Ethanol tank fires in Brazil", 2013.
19. "Incêndio em tanque de álcool em usina de Ourinhos já dura 30 horas, http://g1.globo.com/sp/bauru-marilia/noticia/2013/01/incendio-em-tanque-de-alcool-em-usina-em-ourinhos-continua-apos-24h.html ", Bauru e Marília, .
20. "Explosão destrói tanque de etanol com capacidade de 3 milhões de litros, http://g1.globo.com/sp/bauru-marilia/noticia/2013/12/explosao-destroi-tanque-de-etanol-com-capacidade-de-3-milhoes-de-litros.html", Bauru e Marília.
21. Mahnken, G., "Media reports of fires in ethanol storage tanks in Brazil 1989-2007", FM Global.
22. "Aqueous Vermiculite Dispersion", Dupré Minerals, http://www.dupreminerals.com/en/products/vermiculite-dispersion.
23. "What is AVD", Dupré Minerals, http://www.avdfire.com.

24. Persson, H., and Rahm, M., "Användning av expanderat glas som brandskydd inom petrokemisk industri", SP Technical Research Institute of Sweden, SP Report 2010:40, Borås, Sweden, 2010.
25. Persson, H., and McNamee, M., "Foam glass provides effective fire protection in bunded areas", *FS-World*, Fall 2011, 2011.
26. " Nordtest Method NT Fire 023 Edition 2, Fire extinguishing foam concentrates", Nordtest.
27. Dahlberg, M., "The SP Industry Calorimeter: For rate of heat release measurements up to 10 MW", SP Swedish National Testing and Research Institute, SP REPORT 1992:43, Borås, Sweden, 1993.

Annex A Measuring data

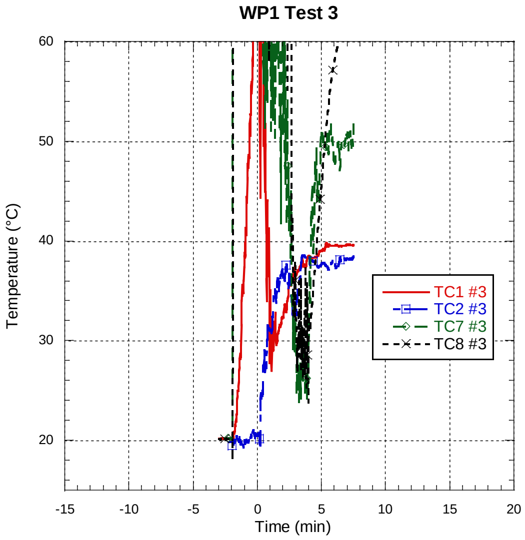
Annex A presents measuring data from the WP1 and WP2 tests. In WP1, the measurements only involved the tests in the “WP1-tray” (i.e. not Test # 1, #2, #17, #26, #27, #28). For each test, there are two graphs showing the fuel temperature and the steel temperature, respectively.

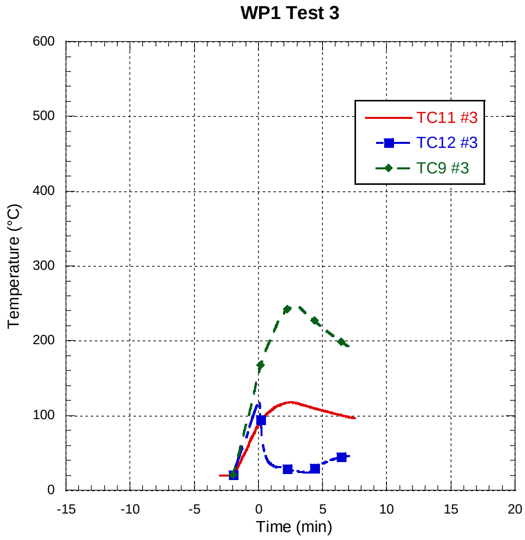
For the WP2-tests, there are four graphs from each test, showing the fuel temperature, the steel temperature, the plate thermometer temperature and the HRR-data, respectively.

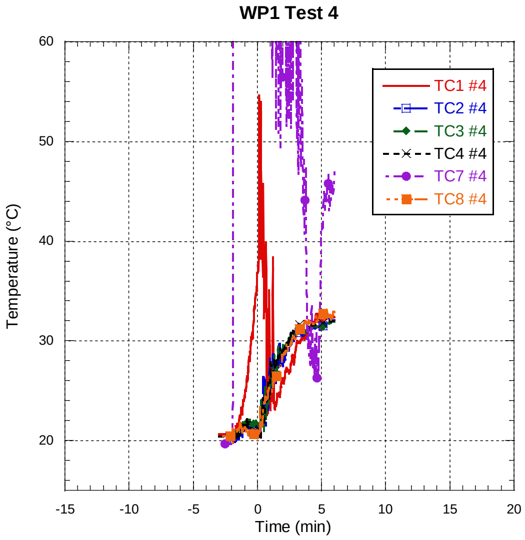
The graphs are identified by the WP-number and test-number in the heading of each graph and they are presented in test order.

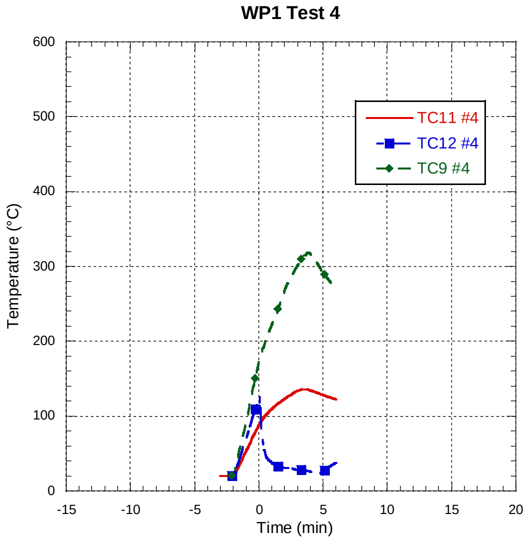
To obtain full information of the test conditions and test results, see Table 3 and Table 4 in the main report. Further details on the measurements, e.g. the positions of the thermocouples, are described in chapter 3.1.1 and 3.2.1 in the report.

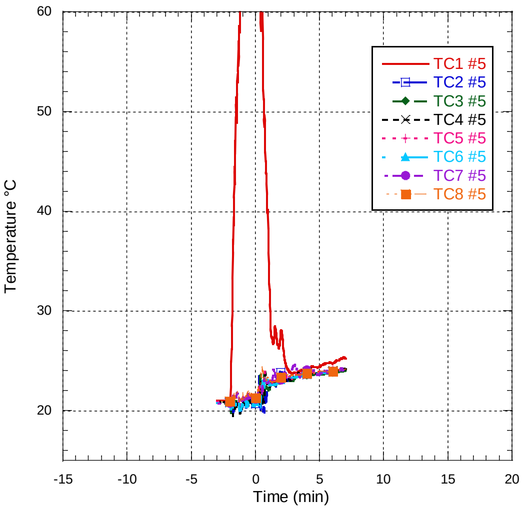
1.1 Measuring data from the WP1-tests







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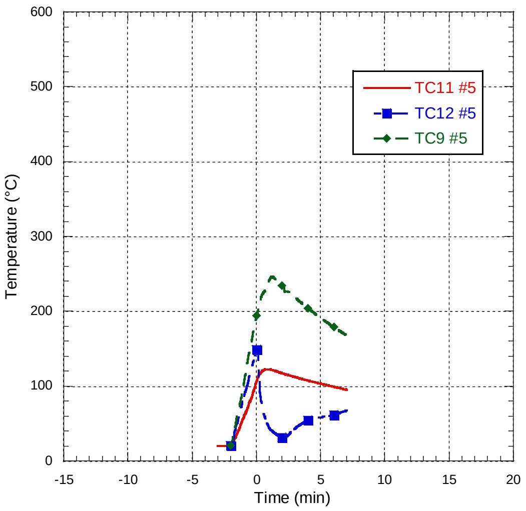
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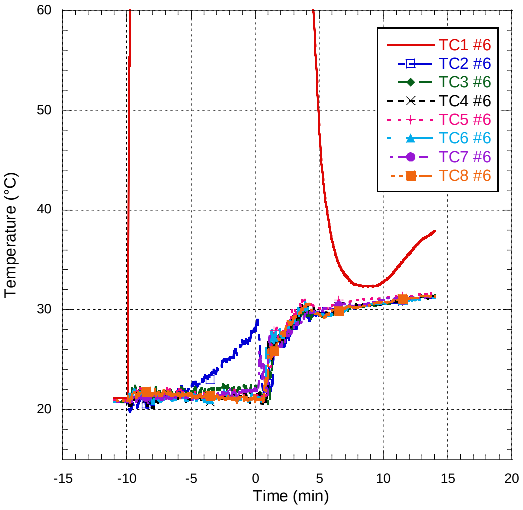
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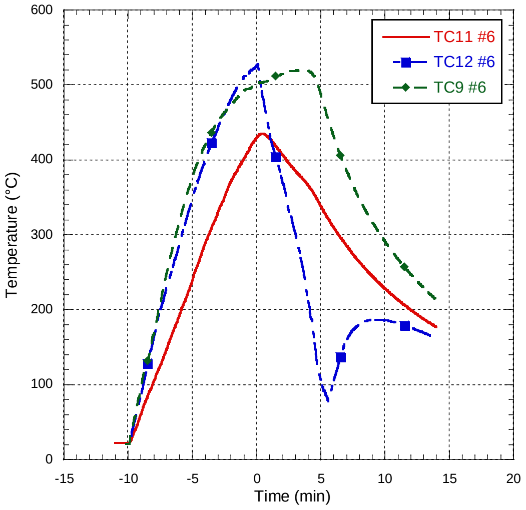
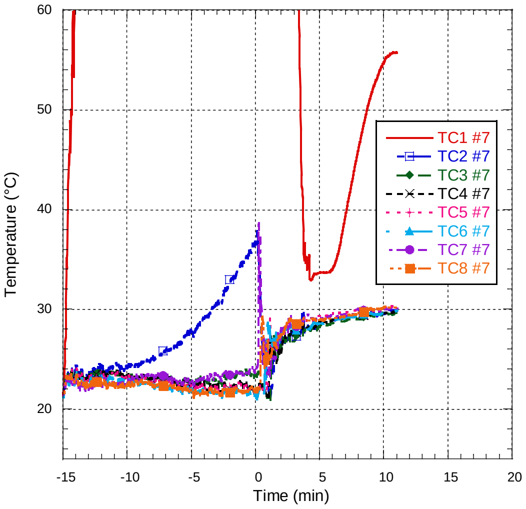
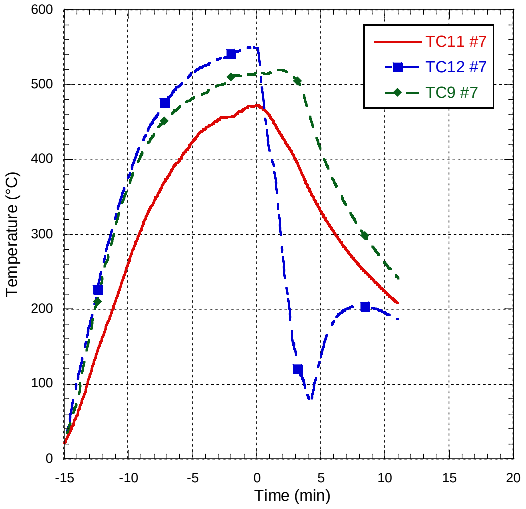
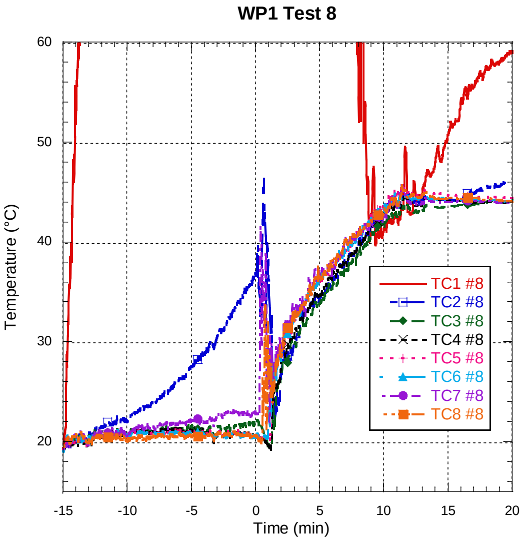
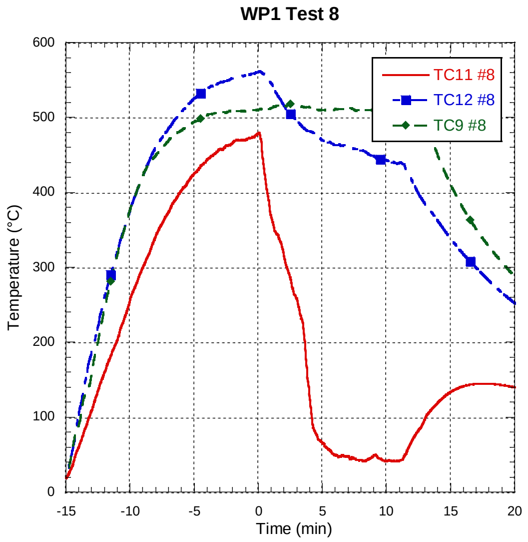
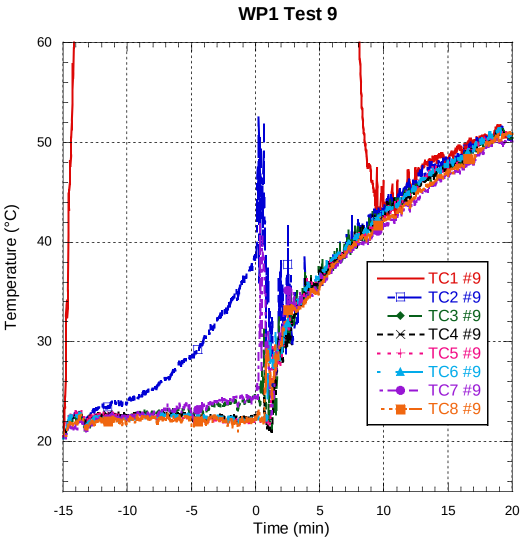

WP1 Test 6

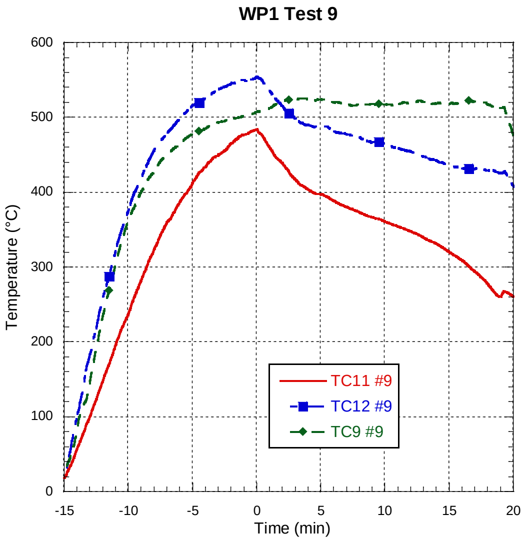

WP1 Test 7

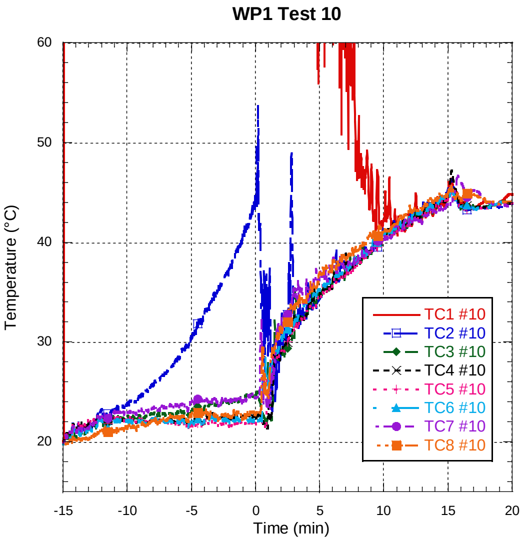

WP1 Test 7

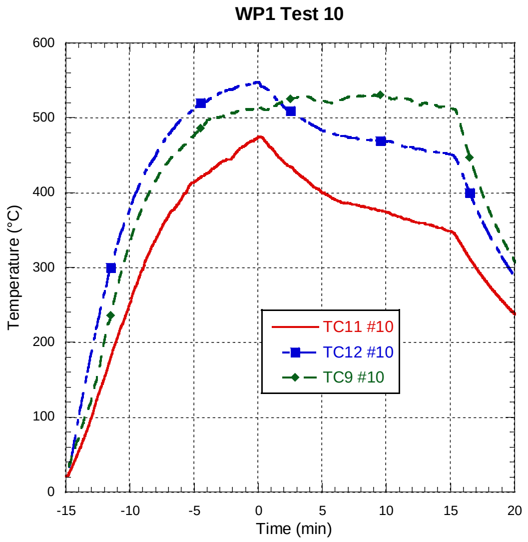

WP1 Test 8
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #8
TC2 #8
TC3 #8
TC4 #8
TC5 #8
TC6 #8
TC7 #8
TC8 #8

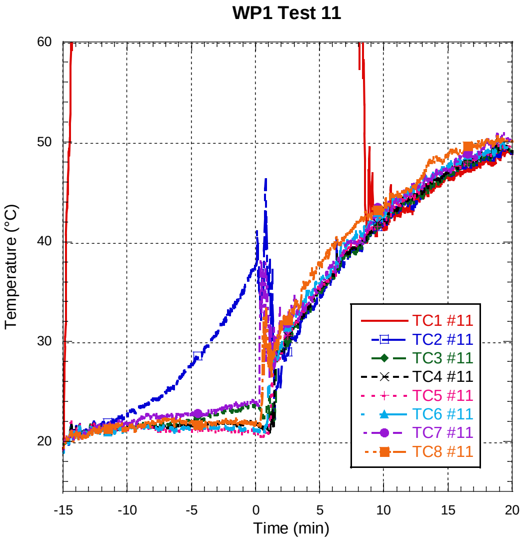

WP1 Test 8
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #8
TC12 #8
TC9 #8

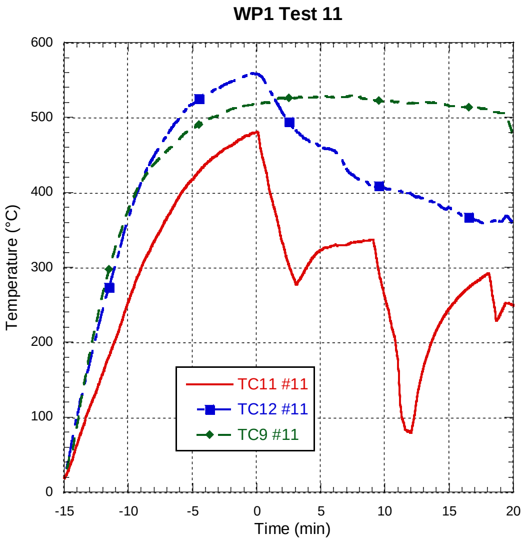

WP1 Test 9
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #9
TC2 #9
TC3 #9
TC4 #9
TC5 #9
TC6 #9
TC7 #9
TC8 #9

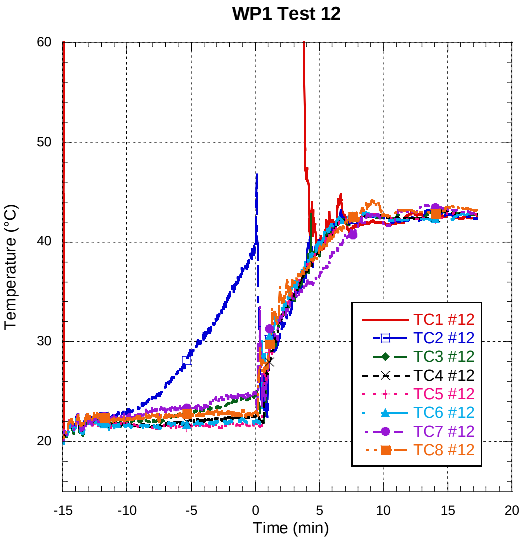

WP1 Test 9
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #9
TC12 #9
TC9 #9

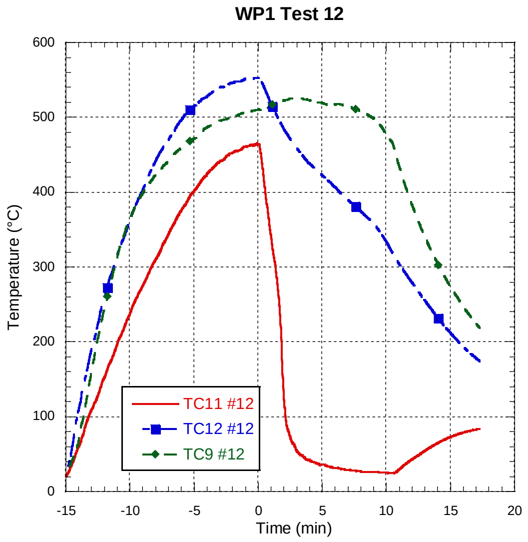

WP1 Test 10
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #10
TC2 #10
TC3 #10
TC4 #10
TC5 #10
TC6 #10
TC7 #10
TC8 #10

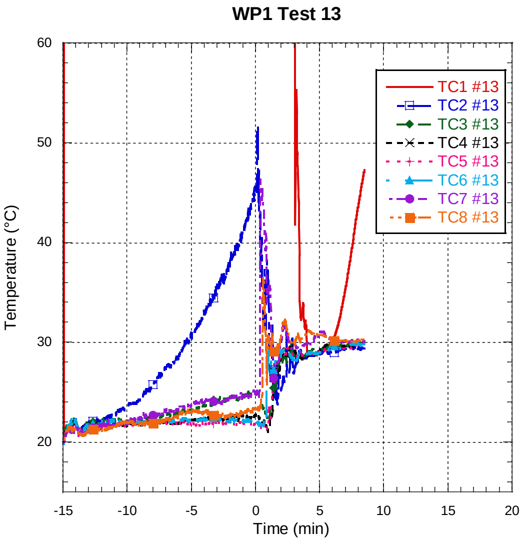

WP1 Test 10
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #10
TC12 #10
TC9 #10

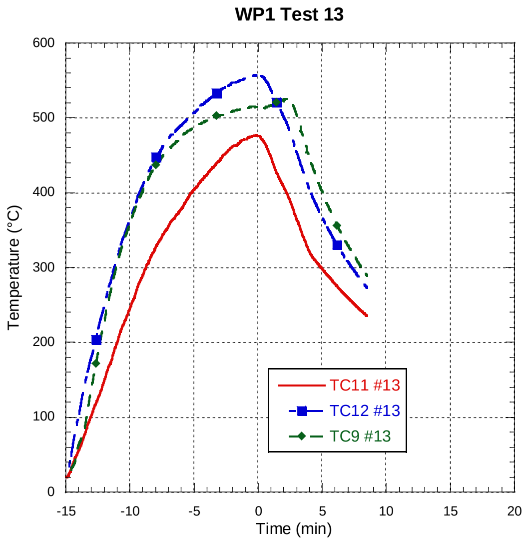

WP1 Test 11
Temperature (°C)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
Time (min)
TC1 #11
TC2 #11
TC3 #11
TC4 #11
TC5 #11
TC6 #11
TC7 #11
TC8 #11

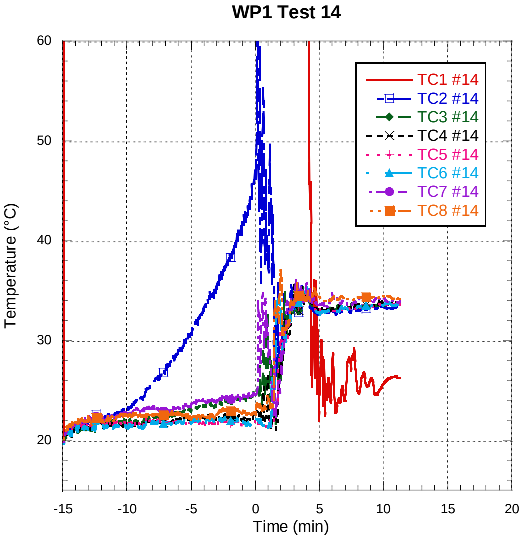

WP1 Test 11
Temperature (°C)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
Time (min)
TC11 #11
TC12 #11
TC9 #11

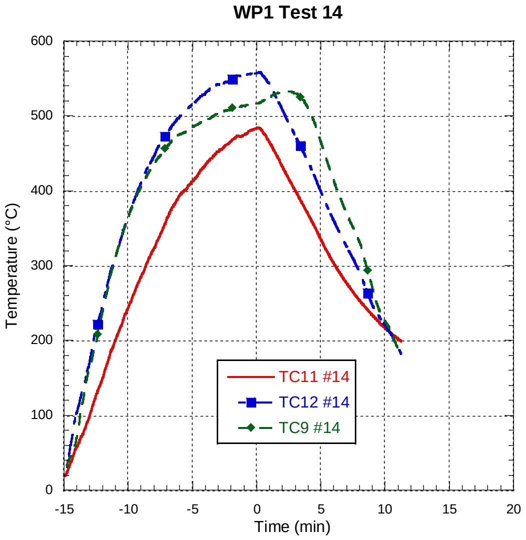

WP1 Test 12
Temperature (°C)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
Time (min)
TC1 #12
TC2 #12
TC3 #12
TC4 #12
TC5 #12
TC6 #12
TC7 #12
TC8 #12

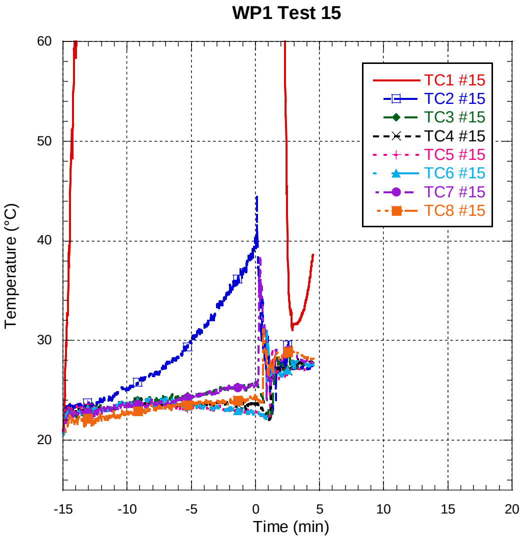

WP1 Test 12
Temperature (°C)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
Time (min)
TC11 #12
TC12 #12
TC9 #12

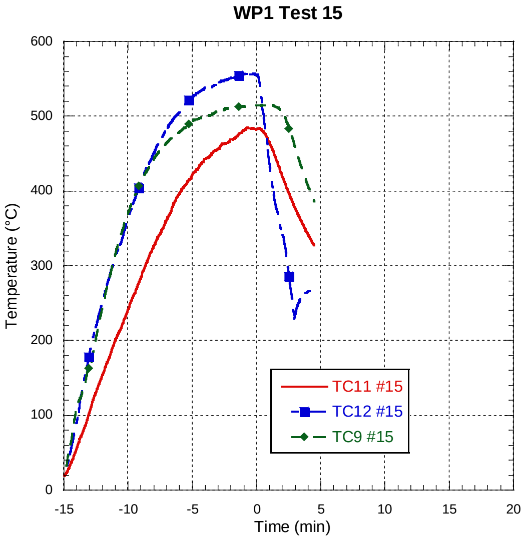

WP1 Test 13
Temperature (°C)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
Time (min)
TC1 #13
TC2 #13
TC3 #13
TC4 #13
TC5 #13
TC6 #13
TC7 #13
TC8 #13

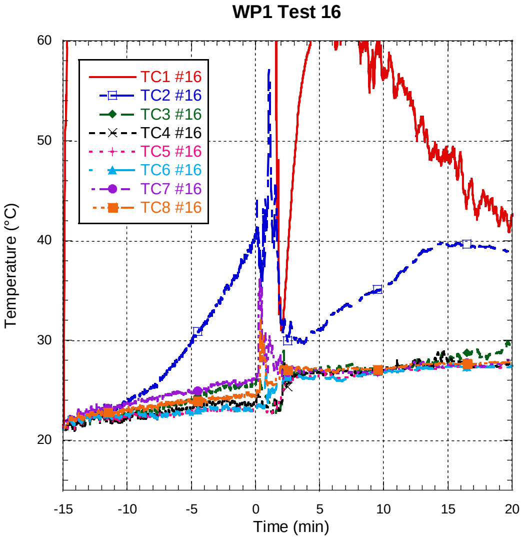

WP1 Test 13
Temperature (°C)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
Time (min)
TC11 #13
TC12 #13
TC9 #13

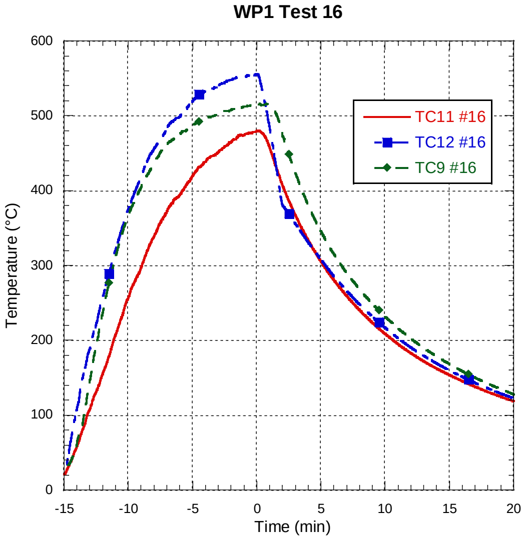

WP1 Test 14

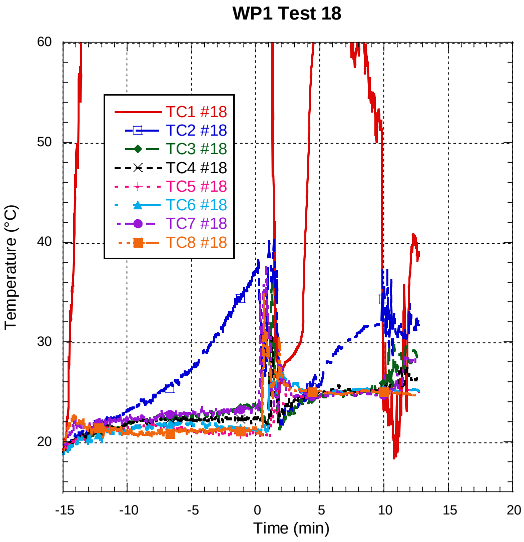

WP1 Test 14

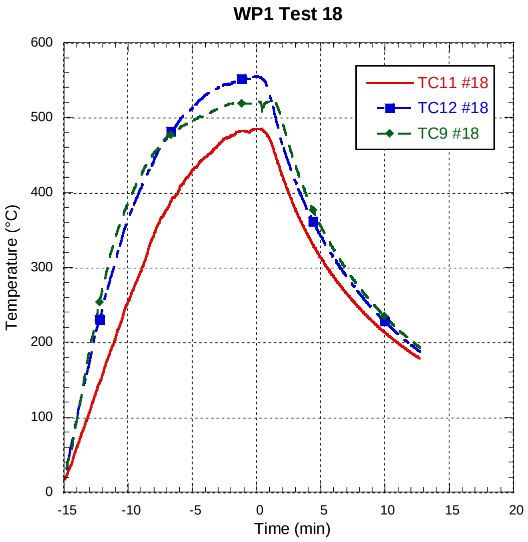

WP1 Test 15

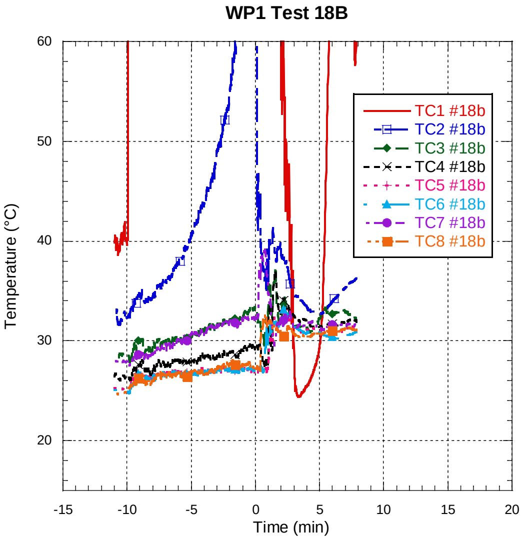

WP1 Test 15

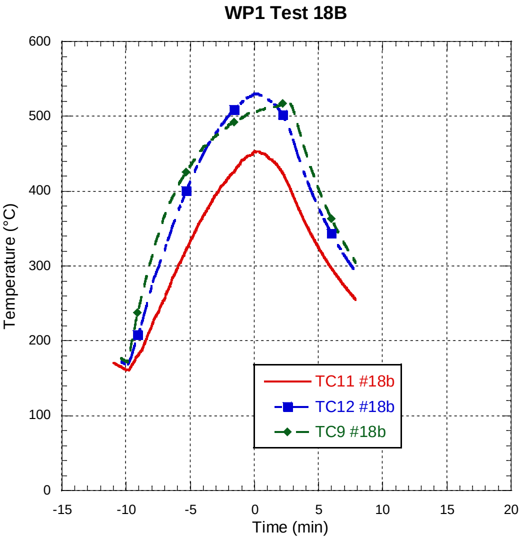

WP1 Test 16

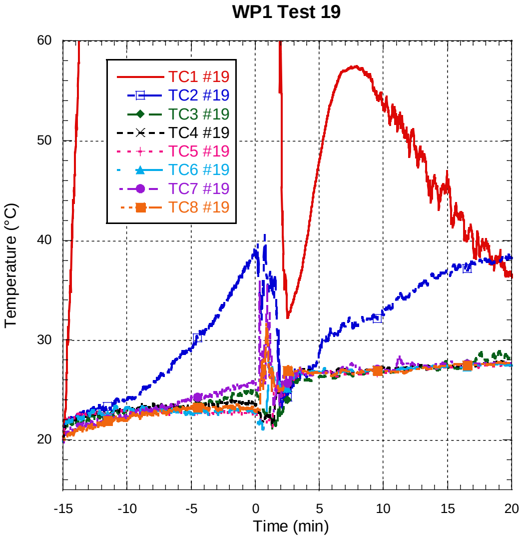

WP1 Test 16

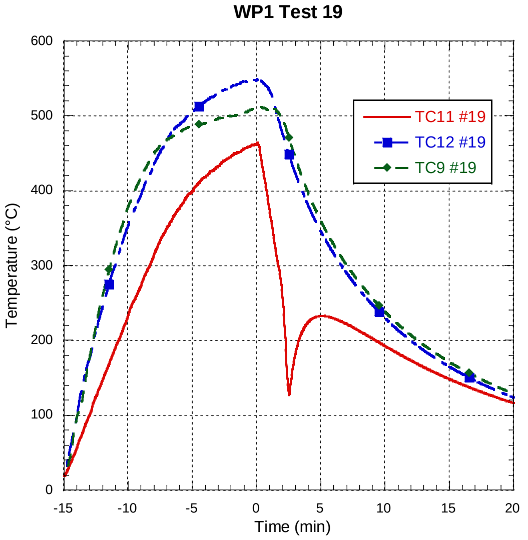

WP1 Test 18
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #18
TC2 #18
TC3 #18
TC4 #18
TC5 #18
TC6 #18
TC7 #18
TC8 #18

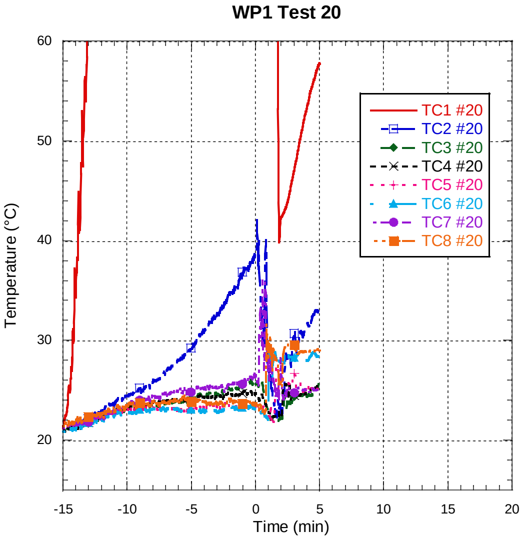

WP1 Test 18
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #18
TC12 #18
TC9 #18

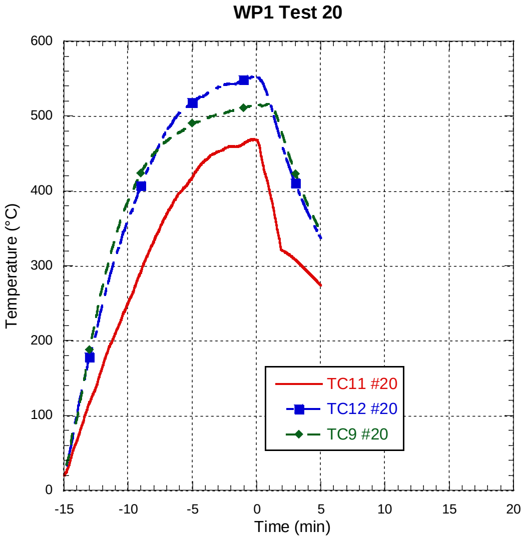

WP1 Test 18B
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #18b
TC2 #18b
TC3 #18b
TC4 #18b
TC5 #18b
TC6 #18b
TC7 #18b
TC8 #18b

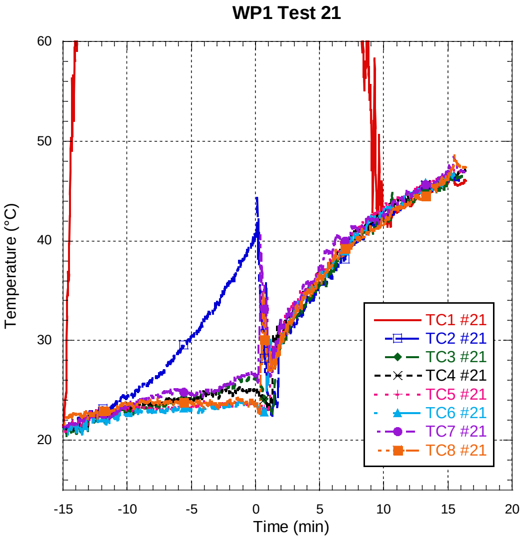

WP1 Test 18B
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #18b
TC12 #18b
TC9 #18b

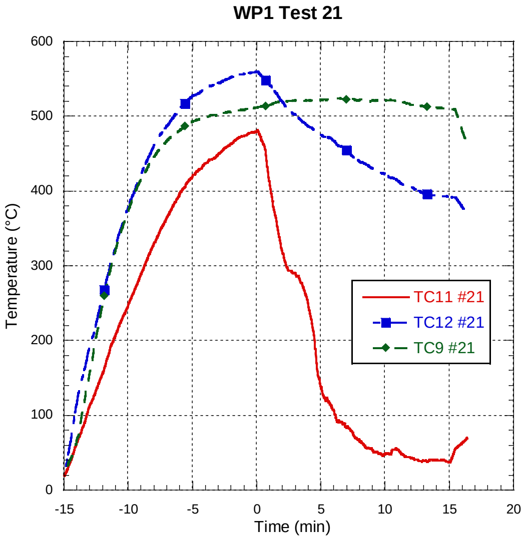

WP1 Test 19
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #19
TC2 #19
TC3 #19
TC4 #19
TC5 #19
TC6 #19
TC7 #19
TC8 #19

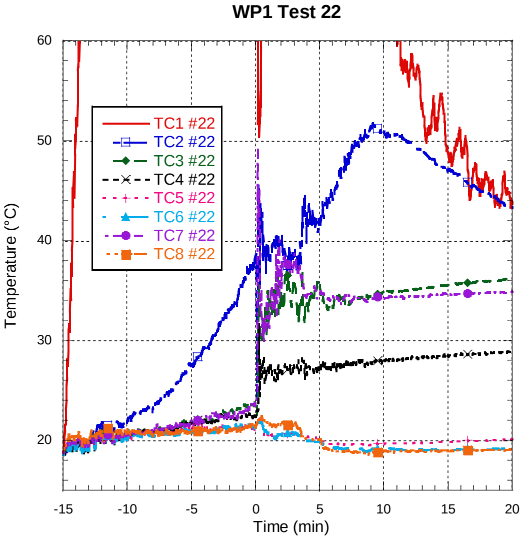

WP1 Test 19
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #19
TC12 #19
TC9 #19

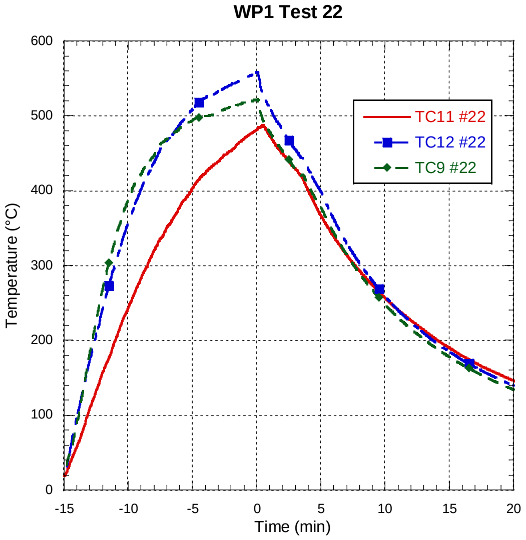

WP1 Test 20
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #20
TC2 #20
TC3 #20
TC4 #20
TC5 #20
TC6 #20
TC7 #20
TC8 #20

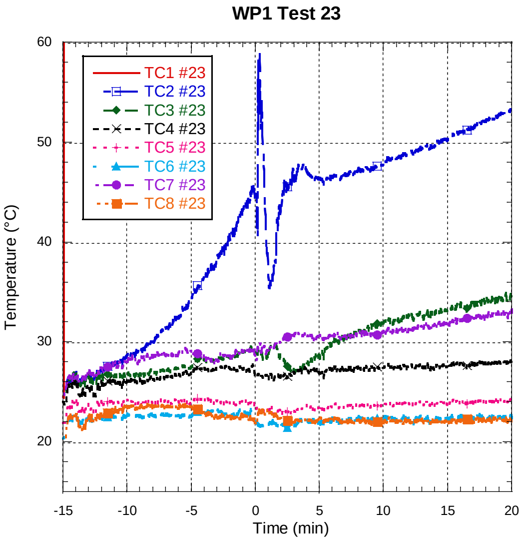

WP1 Test 20
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #20
TC12 #20
TC9 #20

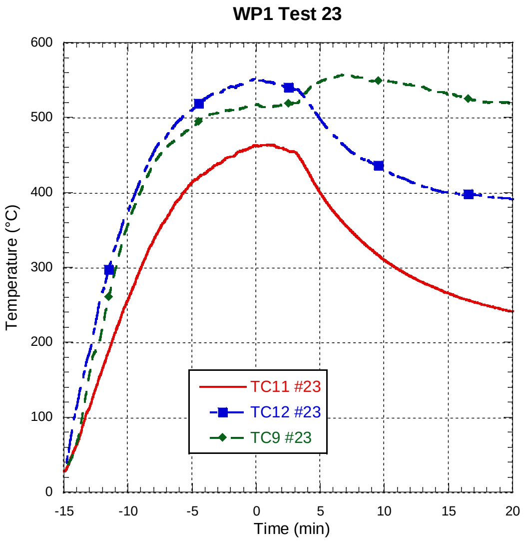

WP1 Test 21
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #21
TC2 #21
TC3 #21
TC4 #21
TC5 #21
TC6 #21
TC7 #21
TC8 #21

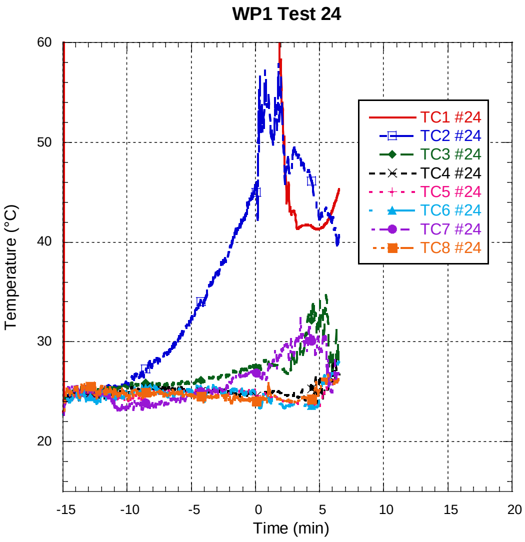

WP1 Test 21
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #21
TC12 #21
TC9 #21

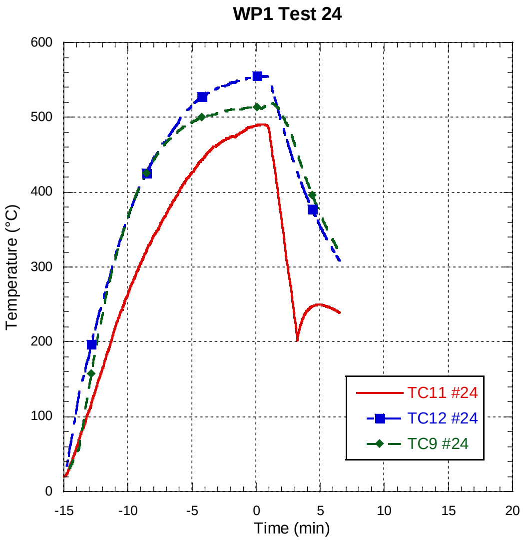

WP1 Test 22
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #22
TC2 #22
TC3 #22
TC4 #22
TC5 #22
TC6 #22
TC7 #22
TC8 #22

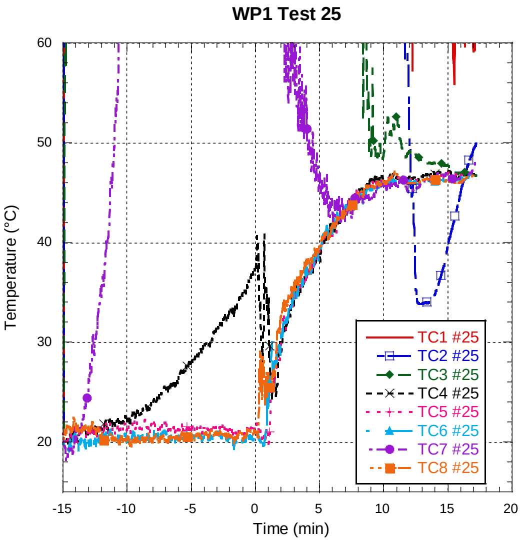

WP1 Test 22
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #22
TC12 #22
TC9 #22

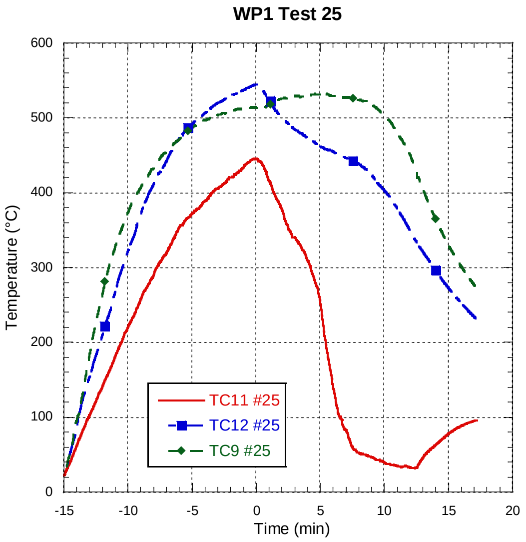

WP1 Test 23
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #23
TC2 #23
TC3 #23
TC4 #23
TC5 #23
TC6 #23
TC7 #23
TC8 #23


WP1 Test 23
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #23
TC12 #23
TC9 #23

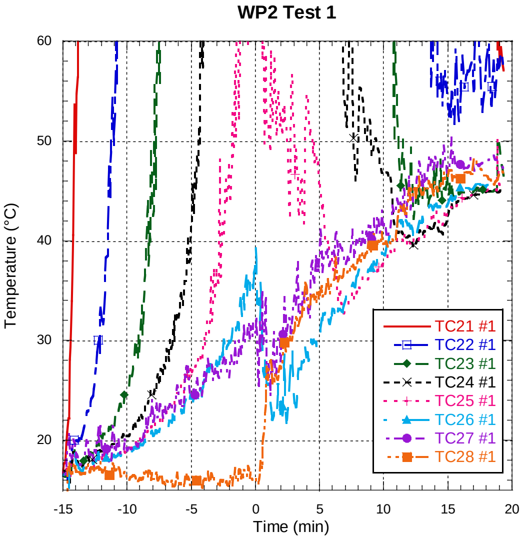

WP1 Test 24
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #24
TC2 #24
TC3 #24
TC4 #24
TC5 #24
TC6 #24
TC7 #24
TC8 #24

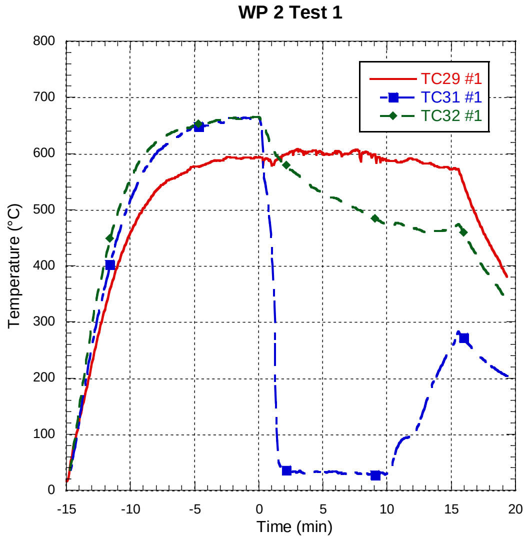

WP1 Test 24
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #24
TC12 #24
TC9 #24

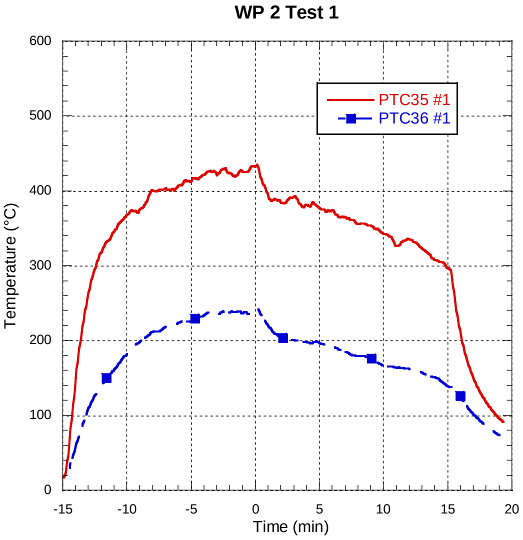

WP1 Test 25
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC1 #25
TC2 #25
TC3 #25
TC4 #25
TC5 #25
TC6 #25
TC7 #25
TC8 #25

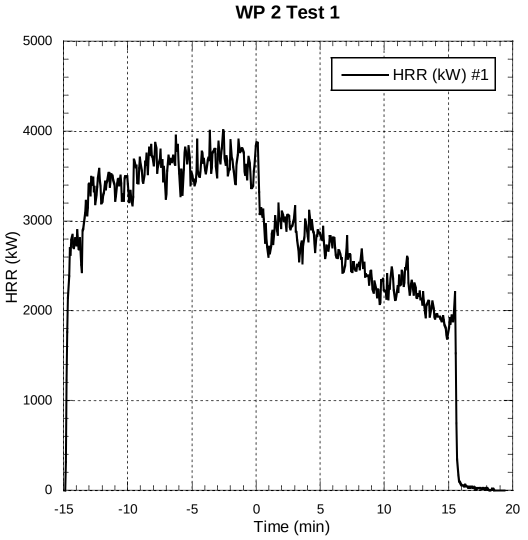

WP1 Test 25
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC11 #25
TC12 #25
TC9 #25

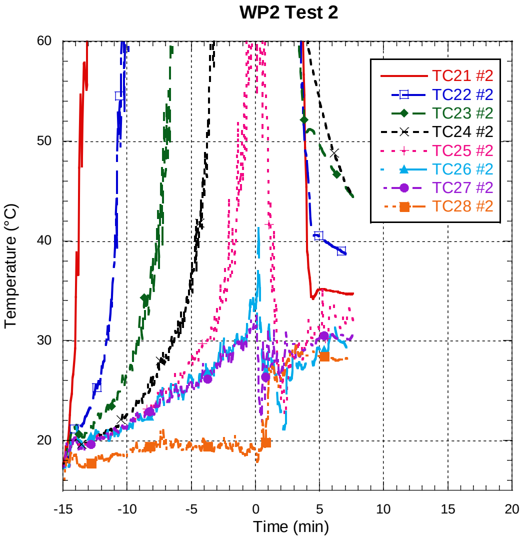
1.2 Measuring data from the WP2 tests

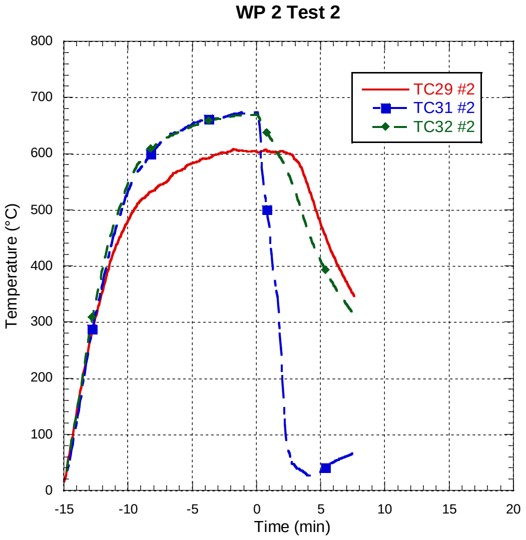


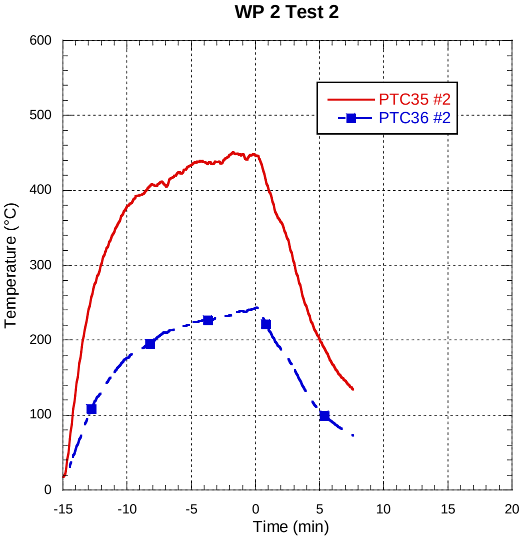


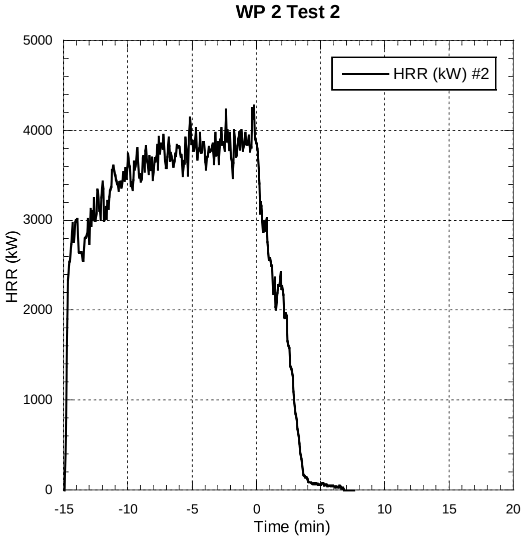


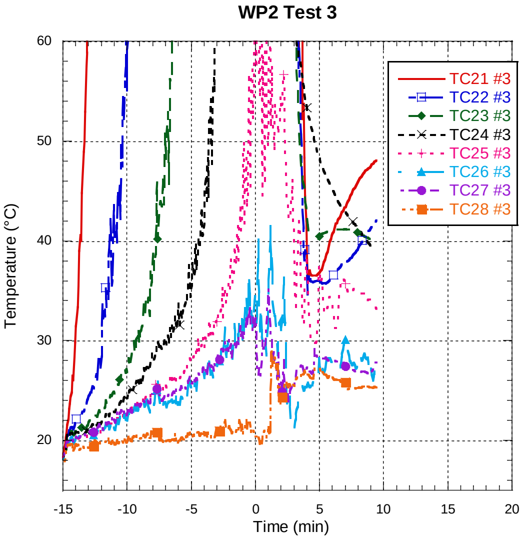


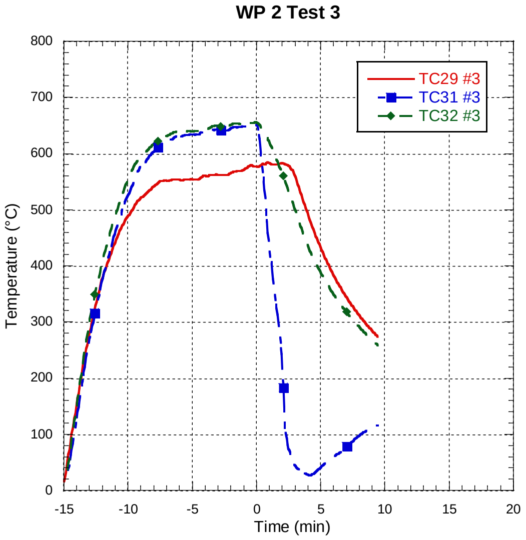

WP2 Test 2
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC21 #2
TC22 #2
TC23 #2
TC24 #2
TC25 #2
TC26 #2
TC27 #2
TC28 #2

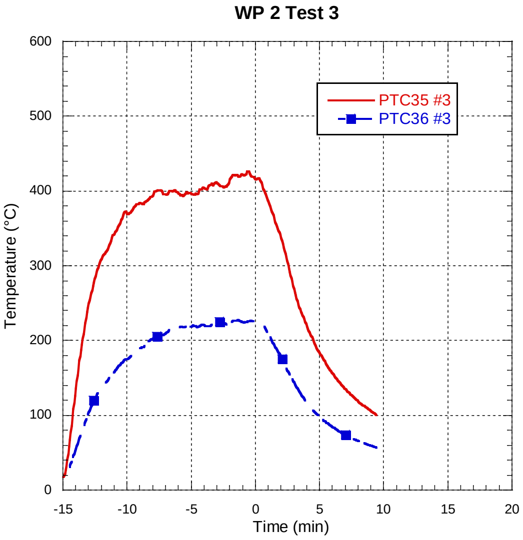

WP 2 Test 2
Temperature (°C)
Time (min)
800
700
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC29 #2
TC31 #2
TC32 #2

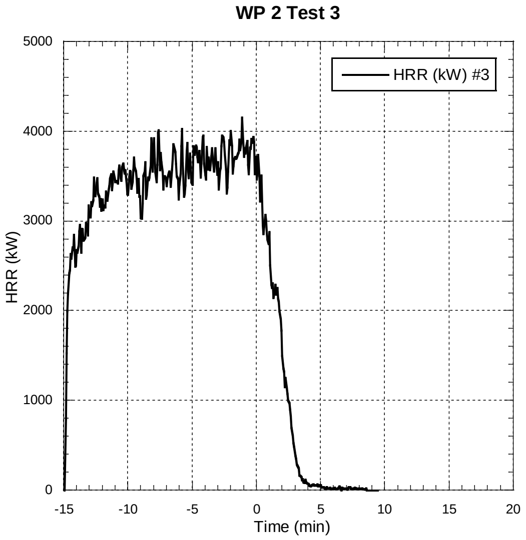

WP 2 Test 2
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
PTC35 #2
PTC36 #2

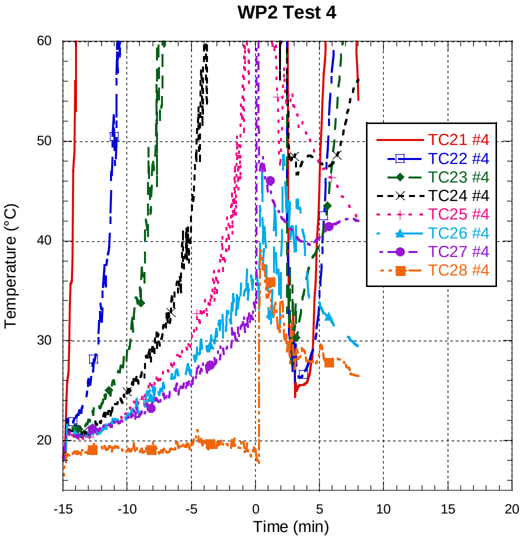

WP 2 Test 2
HRR (kW)
Time (min)
5000
4000
3000
2000
1000
0
-15
-10
-5
0
5
10
15
20
HRR (kW) #2

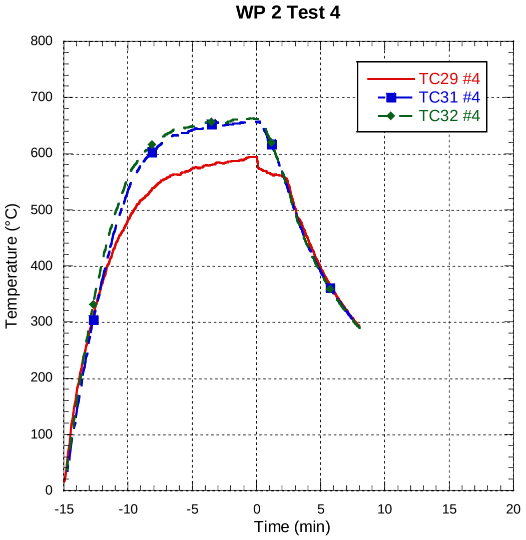

WP2 Test 3
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC21 #3
TC22 #3
TC23 #3
TC24 #3
TC25 #3
TC26 #3
TC27 #3
TC28 #3

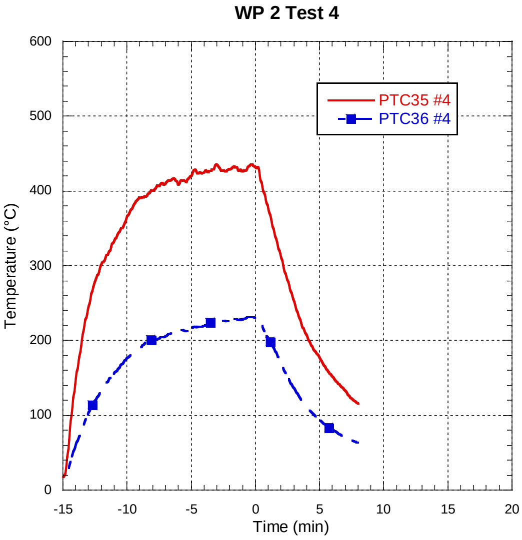

WP 2 Test 3
Temperature (°C)
Time (min)
800
700
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC29 #3
TC31 #3
TC32 #3

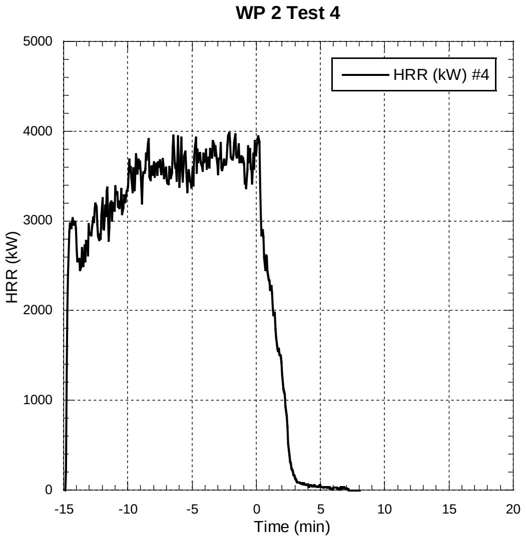

WP 2 Test 3
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
PTC35 #3
PTC36 #3

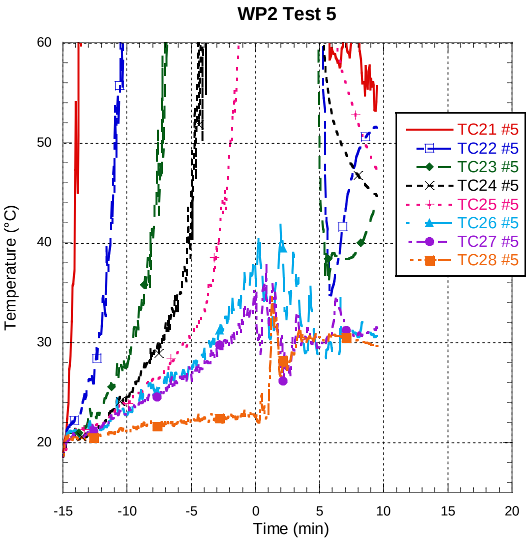

WP 2 Test 3
HRR (kW)
Time (min)
5000
4000
3000
2000
1000
0
-15
-10
-5
0
5
10
15
20
HRR (kW) #3

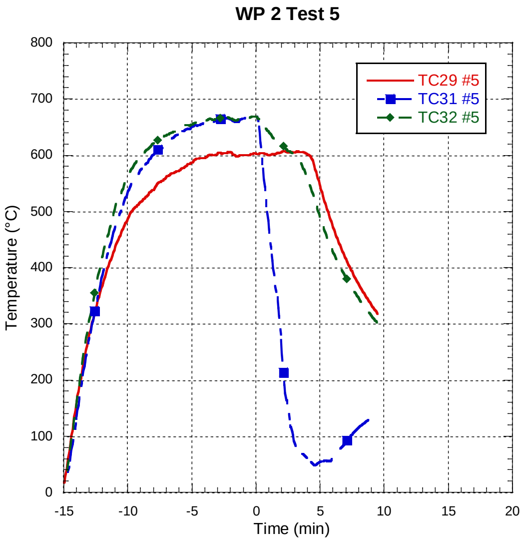

WP2 Test 4

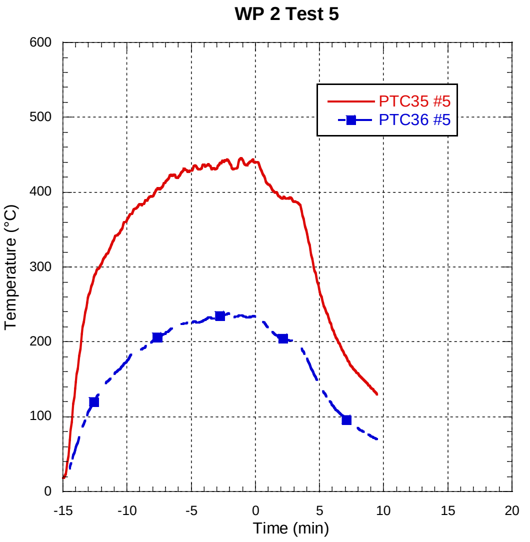

WP 2 Test 4

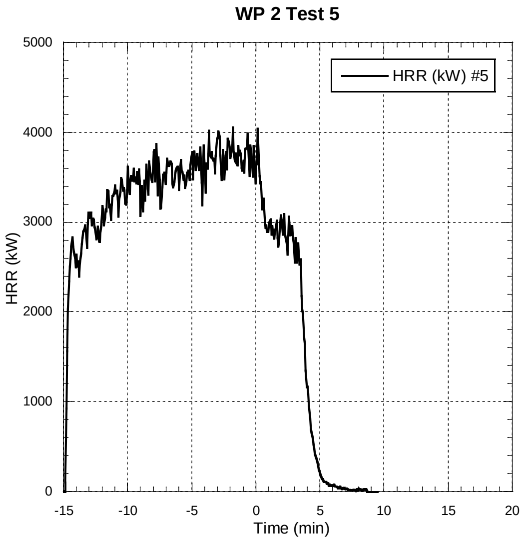

WP 2 Test 4

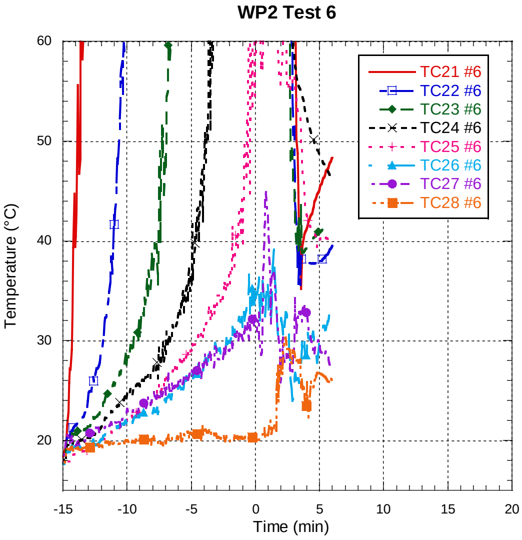

WP 2 Test 4

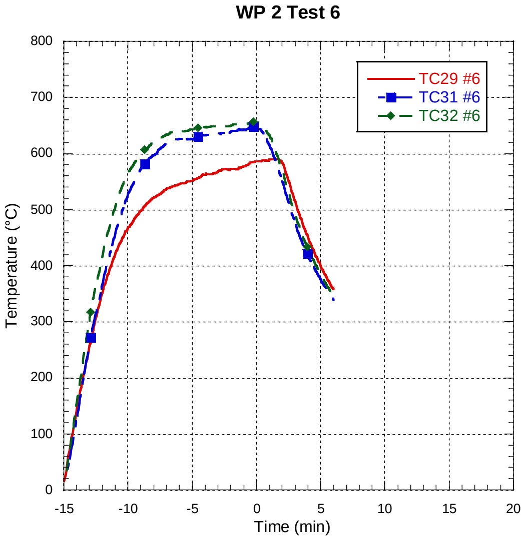

WP2 Test 5
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC21 #5
TC22 #5
TC23 #5
TC24 #5
TC25 #5
TC26 #5
TC27 #5
TC28 #5

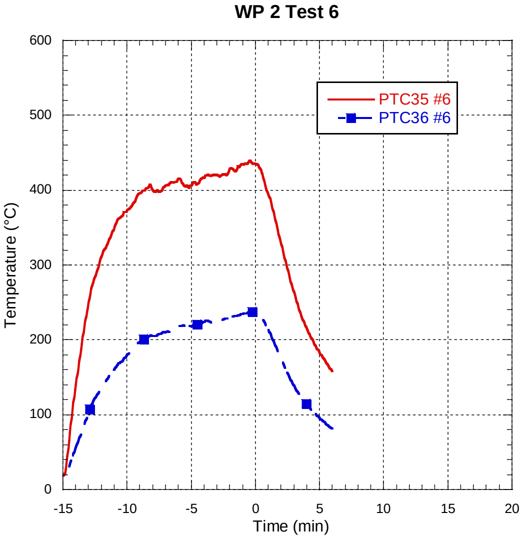

WP 2 Test 5
Temperature (°C)
Time (min)
800
700
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC29 #5
TC31 #5
TC32 #5

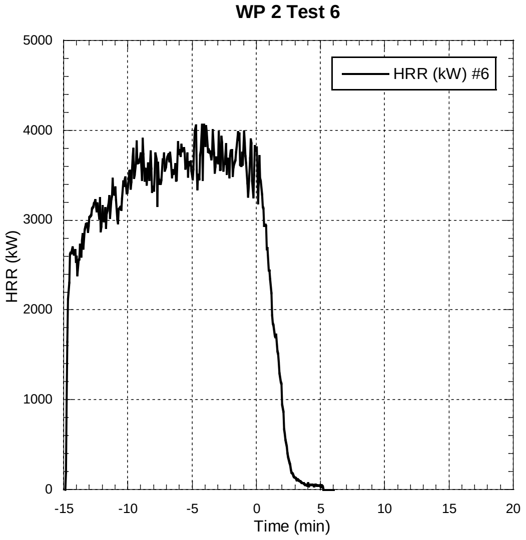

WP 2 Test 5
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
PTC35 #5
PTC36 #5

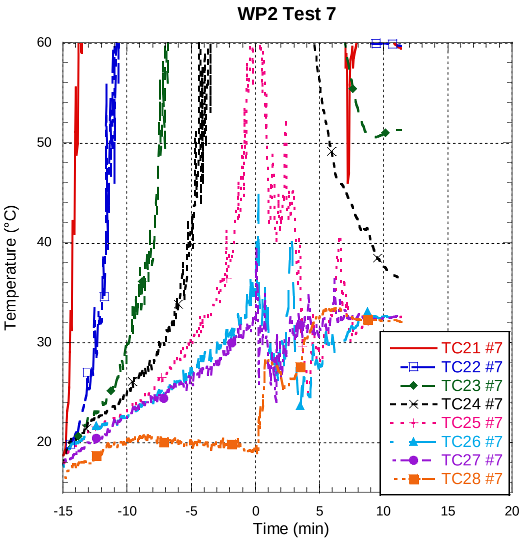

WP 2 Test 5
HRR (kW)
Time (min)
5000
4000
3000
2000
1000
0
-15
-10
-5
0
5
10
15
20
HRR (kW) #5

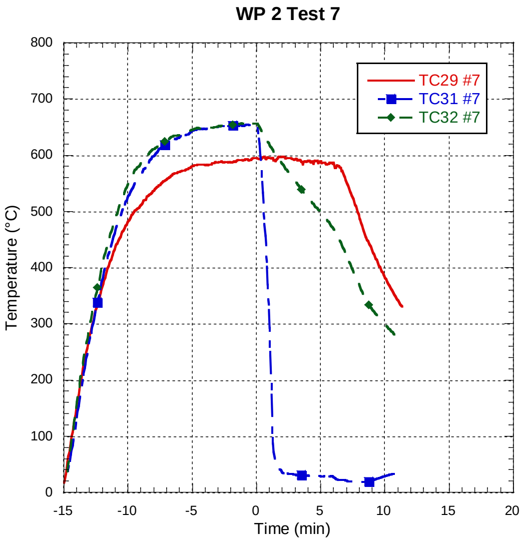

WP2 Test 6

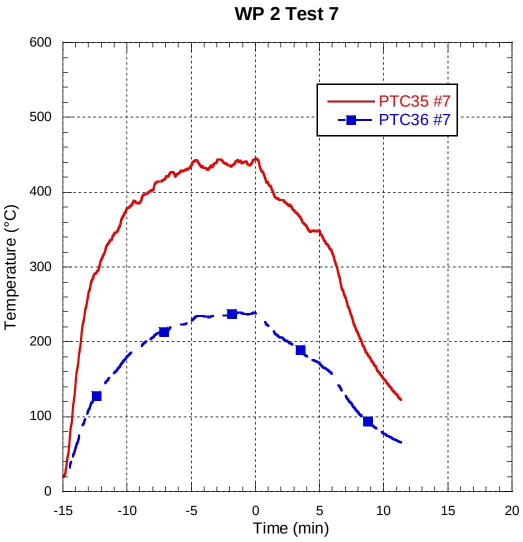

WP 2 Test 6

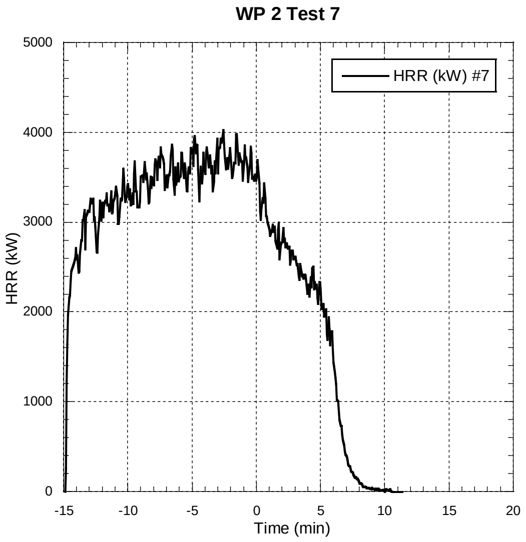

WP 2 Test 6

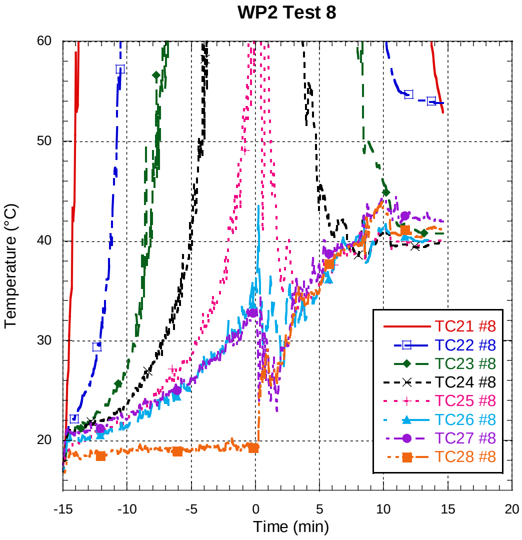

WP 2 Test 6

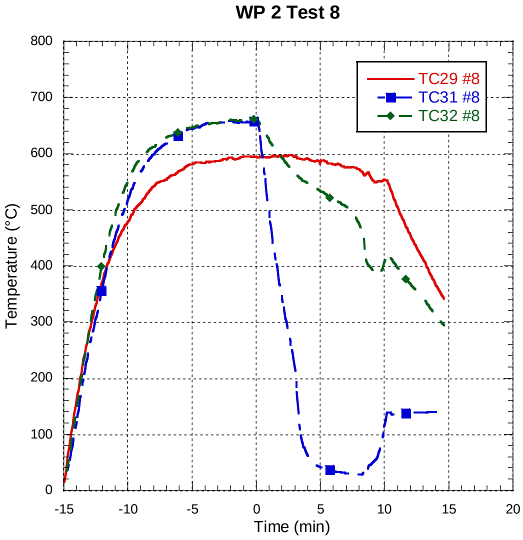

WP2 Test 7
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC21 #7
TC22 #7
TC23 #7
TC24 #7
TC25 #7
TC26 #7
TC27 #7
TC28 #7

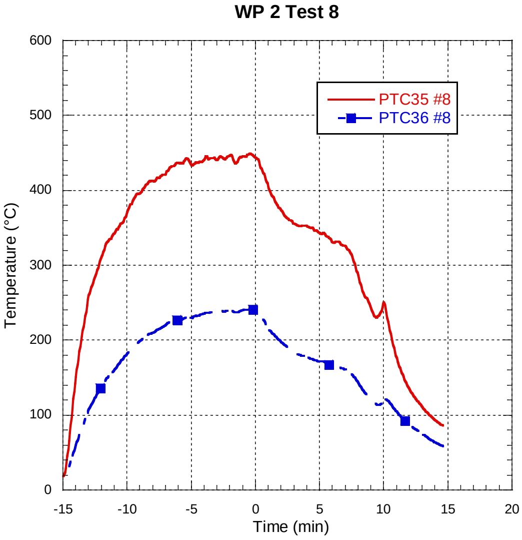

WP 2 Test 7
Temperature (°C)
Time (min)
800
700
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC29 #7
TC31 #7
TC32 #7

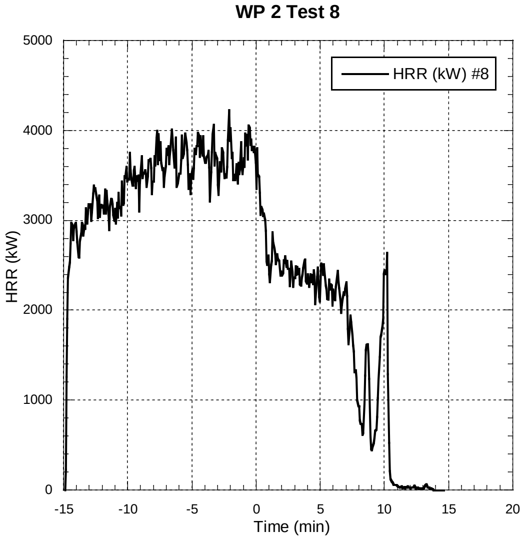

WP 2 Test 7
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
PTC35 #7
PTC36 #7

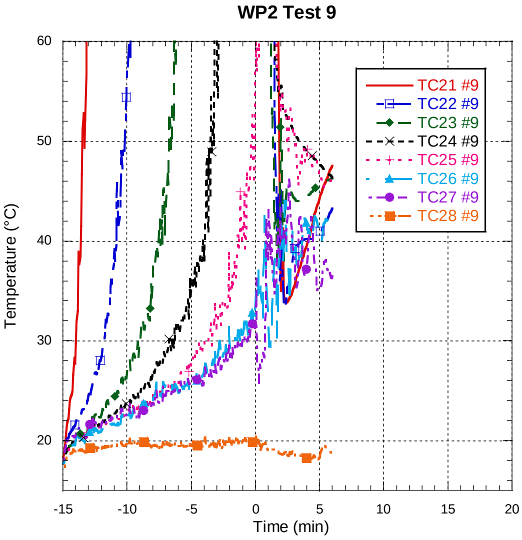

WP 2 Test 7
HRR (kW)
Time (min)
5000
4000
3000
2000
1000
0
-15
-10
-5
0
5
10
15
20
HRR (kW) #7

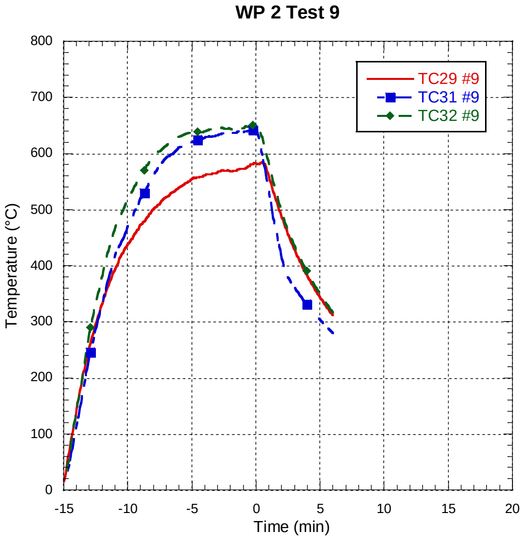

WP2 Test 8

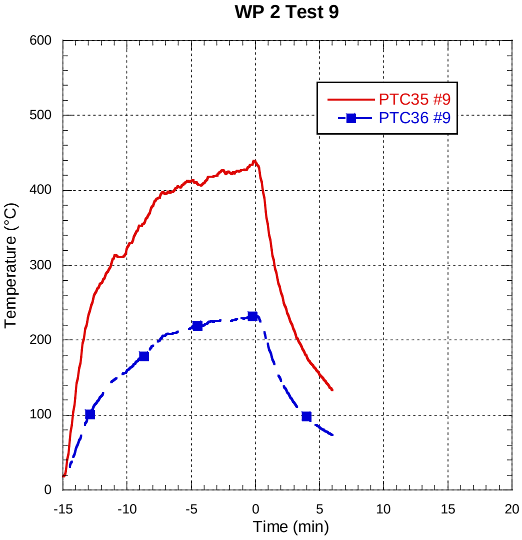

WP 2 Test 8

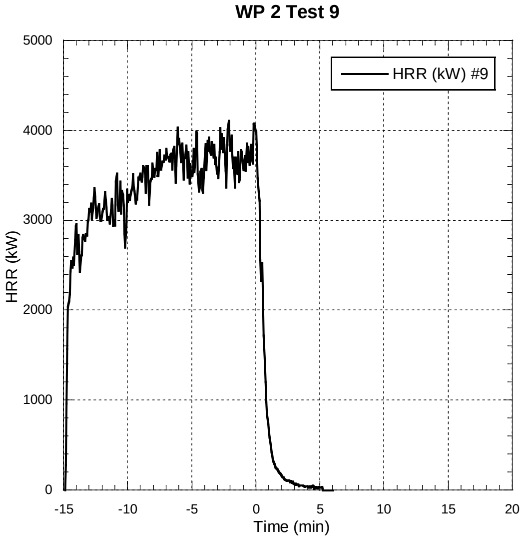

WP 2 Test 8

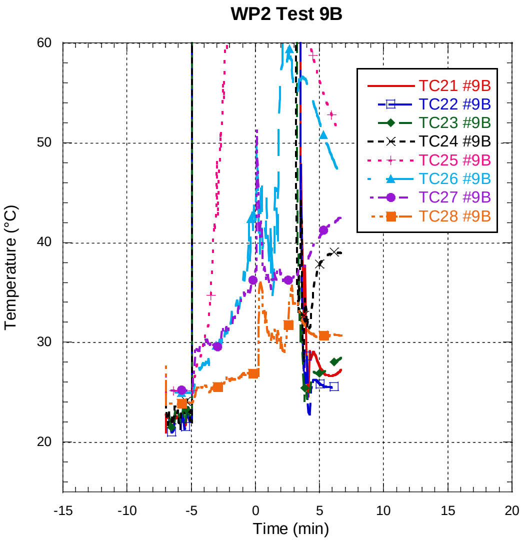

WP 2 Test 8

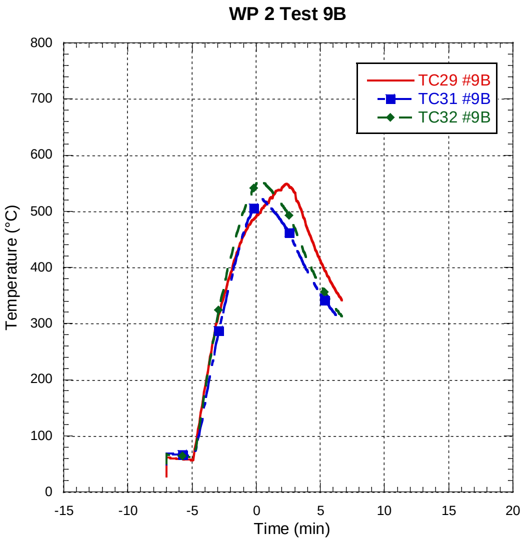

WP2 Test 9

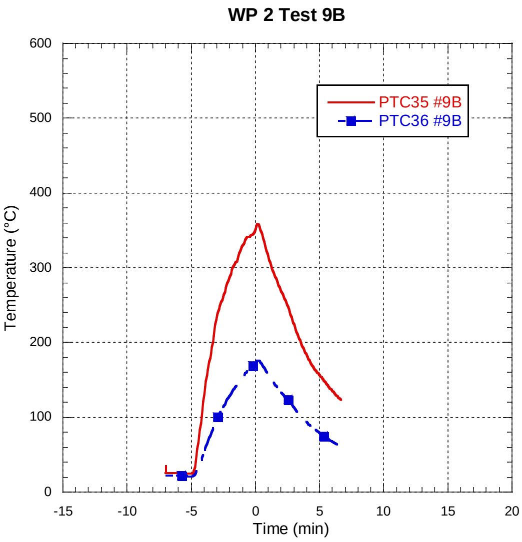

WP 2 Test 9

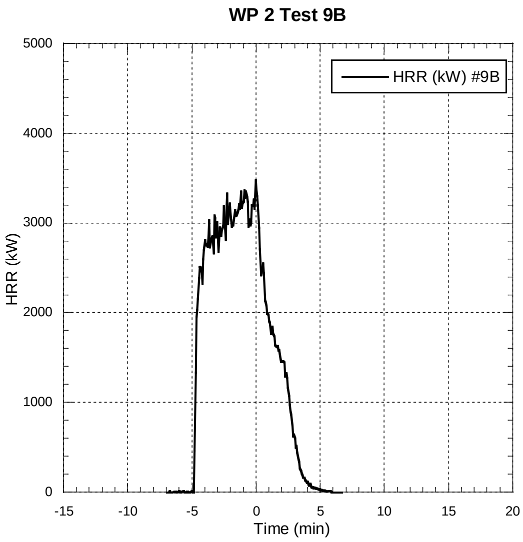

WP 2 Test 9

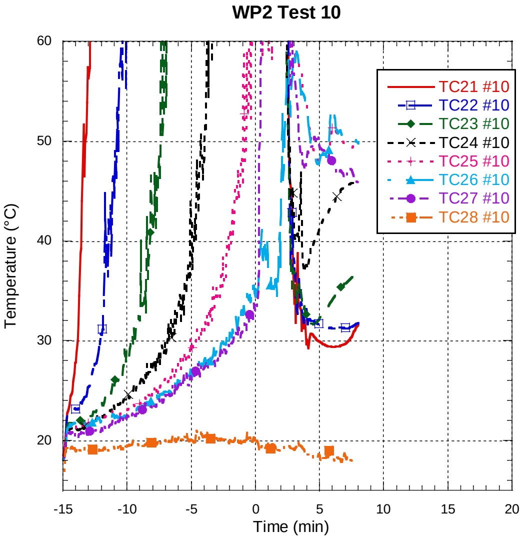

WP 2 Test 9

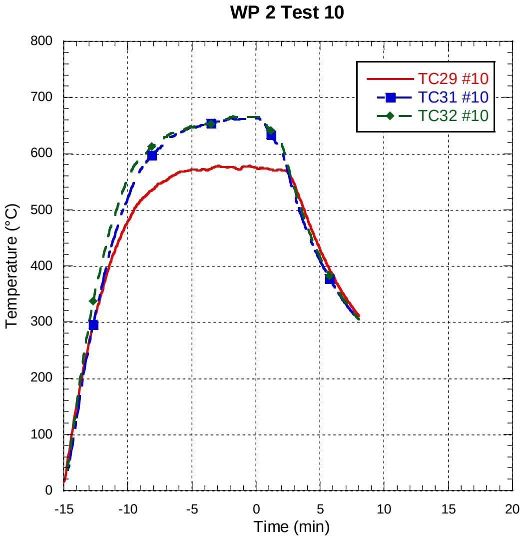

WP2 Test 9B
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC21 #9B
TC22 #9B
TC23 #9B
TC24 #9B
TC25 #9B
TC26 #9B
TC27 #9B
TC28 #9B

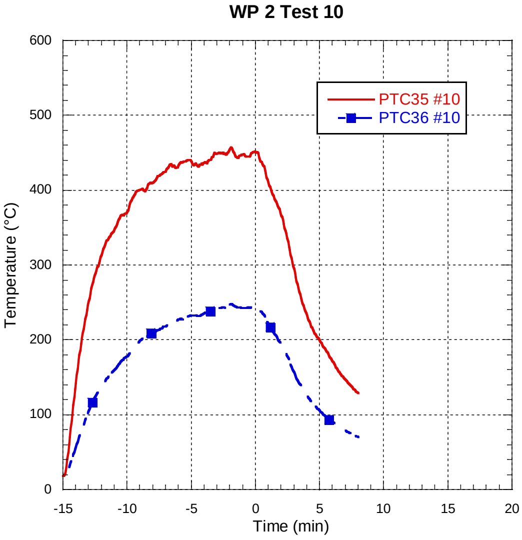

WP 2 Test 9B
Temperature (°C)
Time (min)
800
700
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC29 #9B
TC31 #9B
TC32 #9B

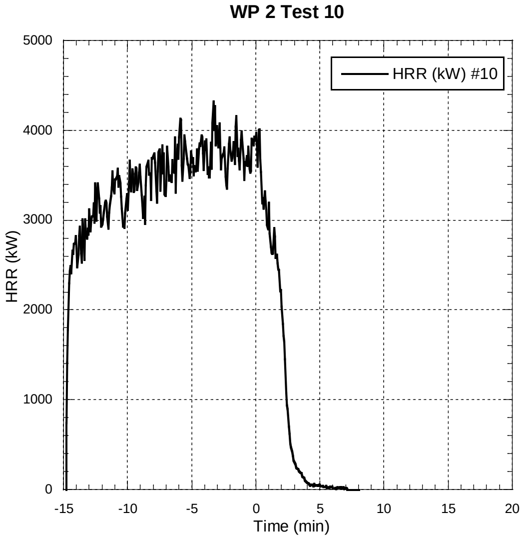

WP 2 Test 9B
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
PTC35 #9B
PTC36 #9B

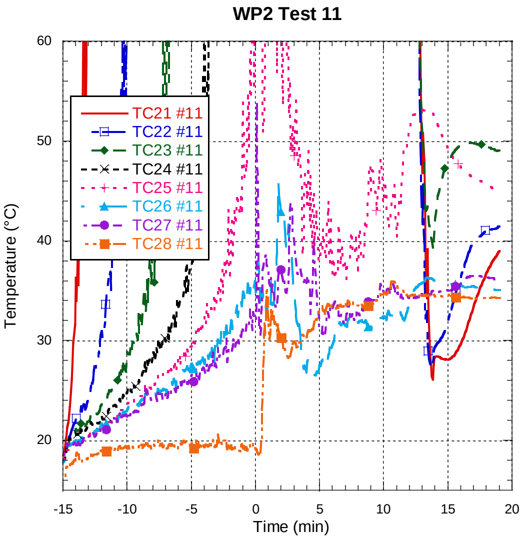

WP 2 Test 9B
HRR (kW)
Time (min)
5000
4000
3000
2000
1000
0
-15
-10
-5
0
5
10
15
20
HRR (kW) #9B

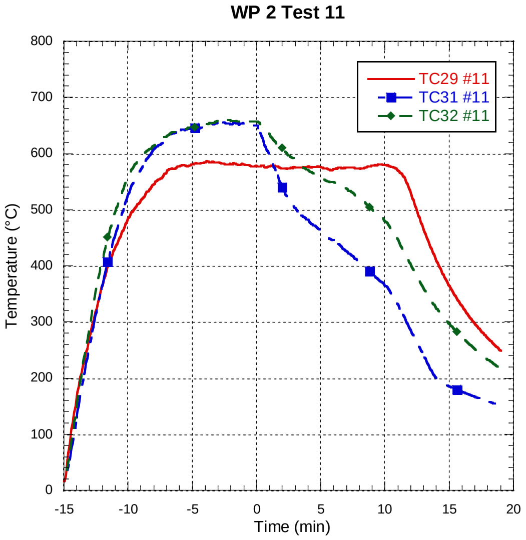

WP2 Test 10
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC21 #10
TC22 #10
TC23 #10
TC24 #10
TC25 #10
TC26 #10
TC27 #10
TC28 #10

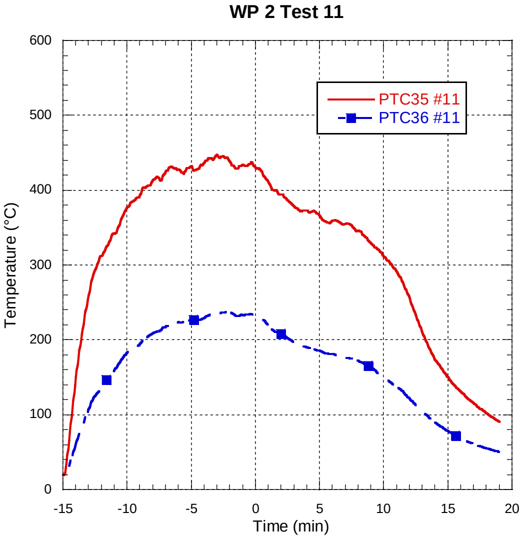

WP 2 Test 10
Temperature (°C)
Time (min)
800
700
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC29 #10
TC31 #10
TC32 #10

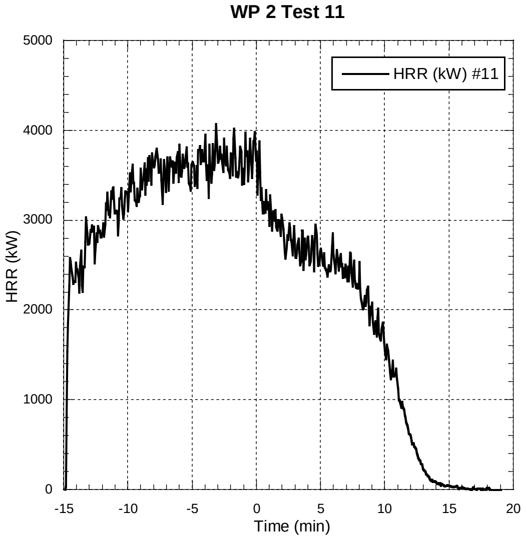

WP 2 Test 10
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
PTC35 #10
PTC36 #10

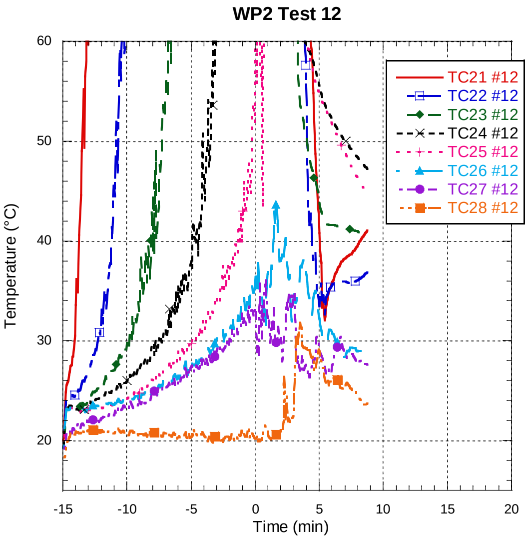

WP 2 Test 10
HRR (kW)
Time (min)
5000
4000
3000
2000
1000
0
-15
-10
-5
0
5
10
15
20
HRR (kW) #10

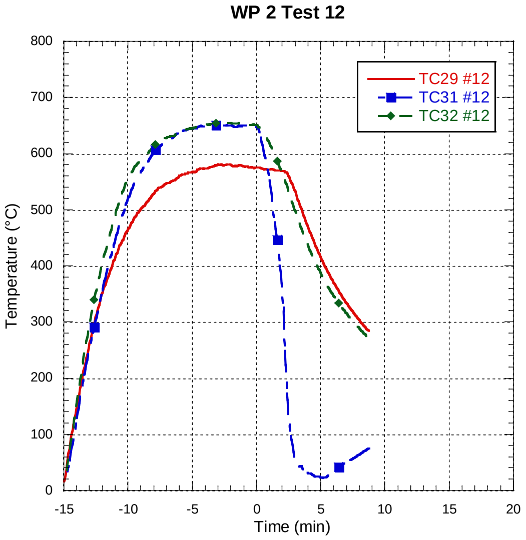

WP2 Test 11
Temperature (°C)
Time (min)
TC21 #11
TC22 #11
TC23 #11
TC24 #11
TC25 #11
TC26 #11
TC27 #11
TC28 #11
60
50
40
30
20
-15
-10
-5
0
5
10
15
20

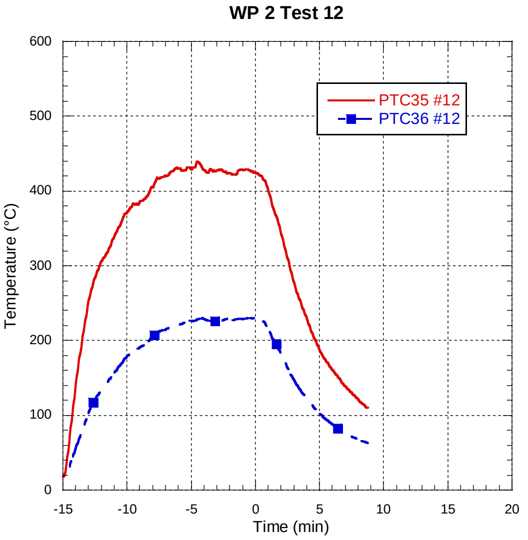

WP 2 Test 11
Temperature (°C)
Time (min)
TC29 #11
TC31 #11
TC32 #11
800
700
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20

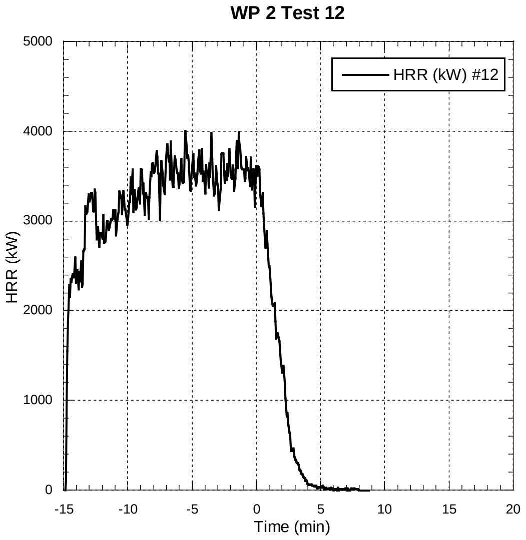

WP 2 Test 11
Temperature (°C)
Time (min)
PTC35 #11
PTC36 #11
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20

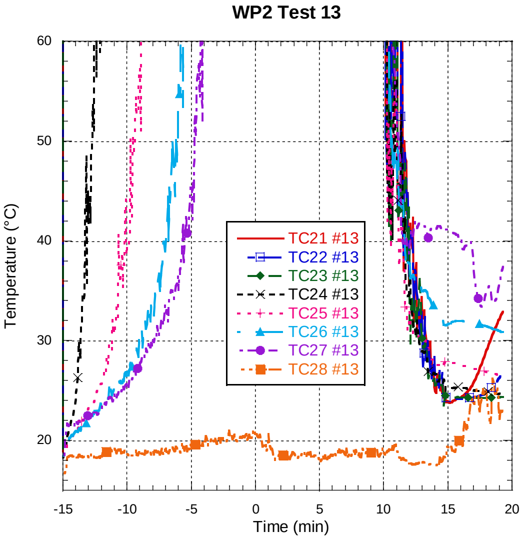

WP 2 Test 11
HRR (kW)
Time (min)
HRR (kW) #11
5000
4000
3000
2000
1000
0
-15
-10
-5
0
5
10
15
20

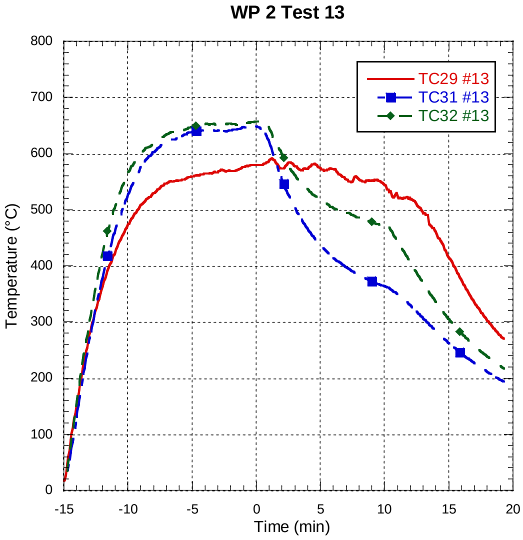

WP2 Test 12
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC21 #12
TC22 #12
TC23 #12
TC24 #12
TC25 #12
TC26 #12
TC27 #12
TC28 #12

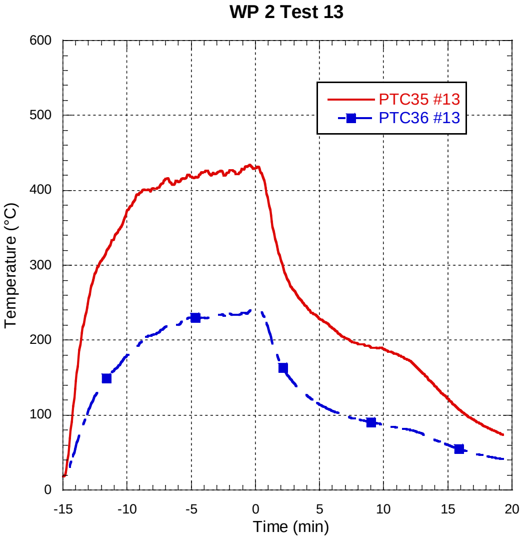

WP 2 Test 12
Temperature (°C)
Time (min)
800
700
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC29 #12
TC31 #12
TC32 #12

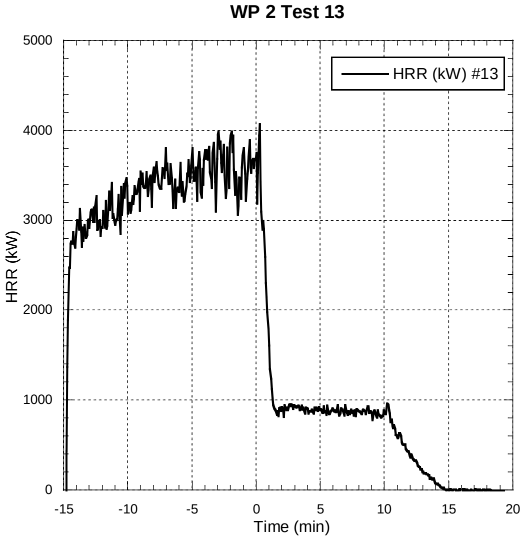

WP 2 Test 12
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
PTC35 #12
PTC36 #12


WP 2 Test 12
HRR (kW)
Time (min)
5000
4000
3000
2000
1000
0
-15
-10
-5
0
5
10
15
20
HRR (kW) #12


WP2 Test 13
Temperature (°C)
Time (min)
60
50
40
30
20
-15
-10
-5
0
5
10
15
20
TC21 #13
TC22 #13
TC23 #13
TC24 #13
TC25 #13
TC26 #13
TC27 #13
TC28 #13


WP 2 Test 13
Temperature (°C)
Time (min)
800
700
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
TC29 #13
TC31 #13
TC32 #13


WP 2 Test 13
Temperature (°C)
Time (min)
600
500
400
300
200
100
0
-15
-10
-5
0
5
10
15
20
PTC35 #13
PTC36 #13


WP 2 Test 13
HRR (kW)
Time (min)
5000
4000
3000
2000
1000
0
-15
-10
-5
0
5
10
15
20
HRR (kW) #13

Annex B Photos

Annex B presents one or several photos from most of the WP1 and WP2 tests. The text below the figure identifies the test number and the figure given in parenthesis identifies the number of the specific picture.

To obtain full information of the test conditions and test results, please see Table 3 (WP1-results) and Table 4 (WP2-results) in the main report.

Measuring results are presented in Annex A.

1.1 Photos from WP1 tests

Figure 1 Test#1 (029) Test according to SP method 2580 using ethanol as fuel.

Figure 2 Test#1 (032) Picture after extinguishment showing the foam impact point at the backboard.

Figure 3 Test #3 (073) First test in the WP1 fire tray, 73 mm fuel, foam impact position 0,725 m above fuel surface.

Figure 4 Test #4 (087) 225 mm fuel, foam impact position 0,575 m above fuel surface.

Figure 5 Test#5 (005) 450 mm fuel, preburn 2 minutes, foam impact position 0,35 m above fuel surface.

Figure 6 **Test#6 (013) 450 mm fuel, preburn 10 minutes, foam impact position 0,35 m above fuel surface.**

Figure 7 **Test#7 (022) 450 mm fuel, preburn 15 minutes, foam impact position 0,35 m above fuel surface.**

Figure 8 Test#8 (009) Foam impact position higher, 1,05m above fuel surface.

Figure 9 Test#9 (031) Foam chamber application, 1,55m above fuel surface. Free fall of foam due to the hot steel wall.

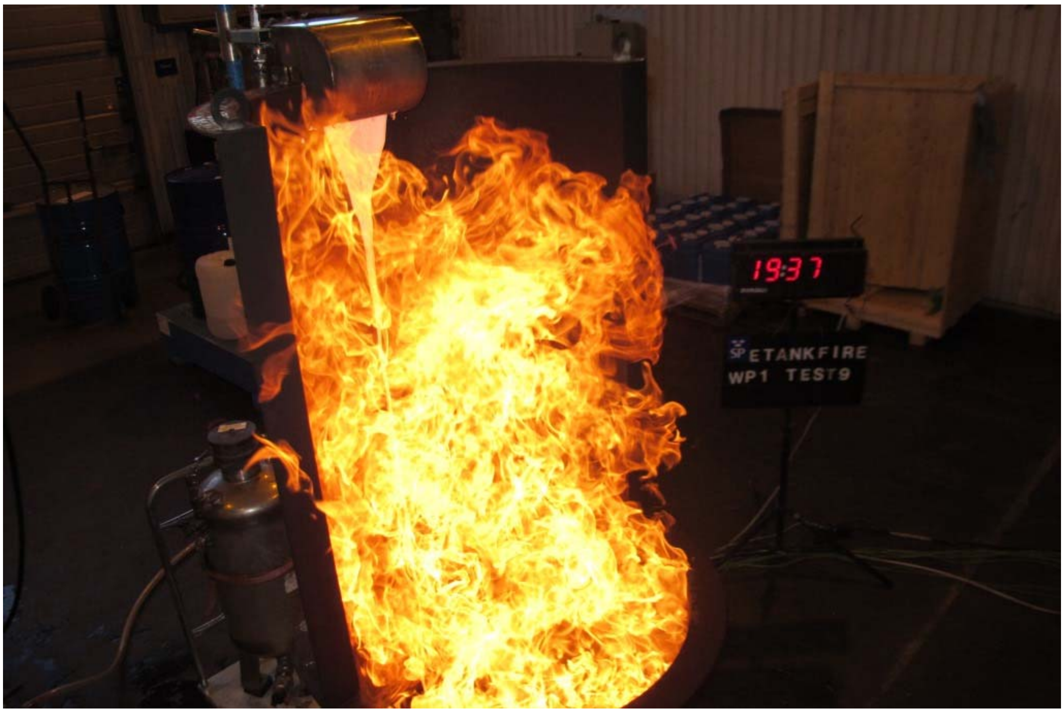


Figure 10 Test#9 (038) Foam chamber application, 1,55m above fuel surface. Still free fall of foam due to the hot steel wall (4:37 min:s after start of application).

Figure 11 Test#10 (065) Medium expansion foam, Type III application 0,55m above fuel surface.

Figure 12 **Test #11 (005) Foam impact position 1,05m above fuel surface but changed every 3 minutes (picture show foam impact on the right hand side).**

Figure 13 **Test #12 (025) Double application rate (2x UNI86R nozzles), foam impact position, 1,05m above fuel surface.**

Figure 14 **Test #13 (052) CAF, foam impact position, 1,05m above fuel surface. The foam stream was not fully coherent and part of the foam did not reach the fire tray.**

Figure 15 Test#14 (008) CAF application via the foam chamber on a cold steel surface.

Figure 16 Test#14 (012) CAF application via the foam chamber after 15 min. Free fall of foam due to the hot steel wall (0:55 min:s after start of application).

Figure 17 Test#14 (015) CAF application via the foam chamber. Still free fall of foam (3:14 min:s after start of application).

Figure 18 Test#15 (033) Repeat of Test #7, foam impact position 0,35 m above fuel surface.

Figure 19 Test#16 (040) Similar to Test #15 with foam impact position 0,35 m above fuel surface but using F3 foam.

Figure 20 Test#17 (006) Test in the 2580 tray using AVD and a UNI86R nozzle.

Figure 21 Test#17 (011) Check of the burnback resistance of the AVD foam layer.

Figure 22 Test#18 (025) Planned to be similar to test 10 but using F3 foam. Bad coherence of the foam stream resulted in a mixture of Type II and Type III application.

Figure 23 Test#18B (031) Repeat of Test # 18 with improved coherence of the foam stream resulting in a Type III application. (Fuel from Test #18 re-used and preburn time 10 minutes.)

Figure 24 Test#19 (004) Similar to Test #8 but using F3 foam, foam impact position 1,05m above fuel surface.

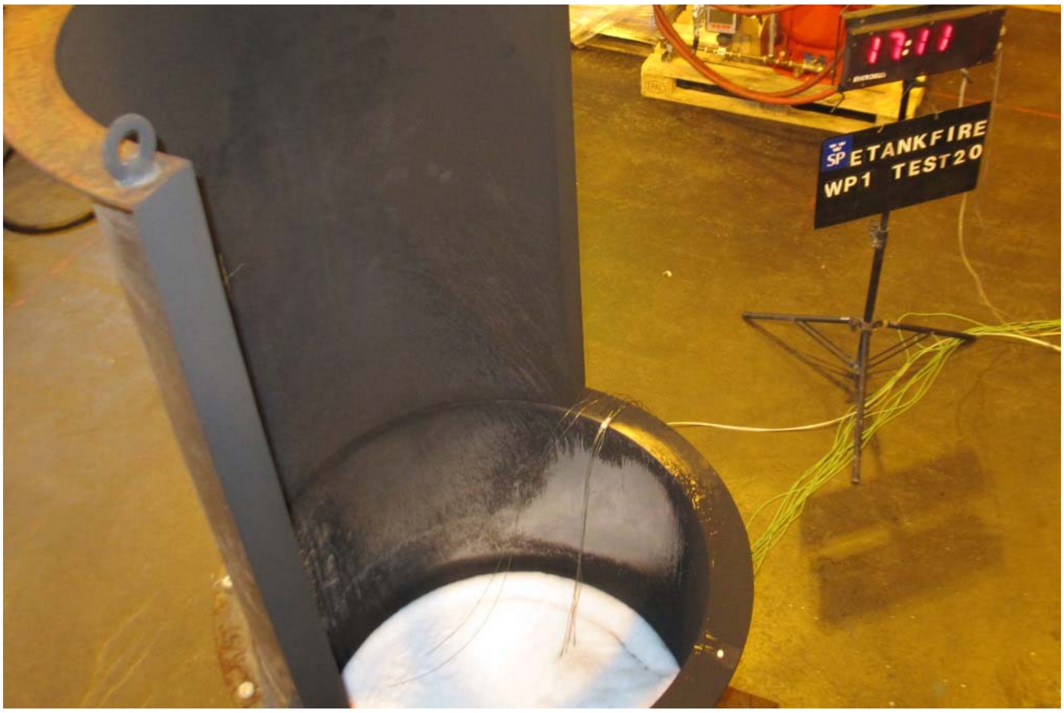


Figure 25 Test#20 (009) Similar to Test #8 but using AFFF-AR at 6%.

Figure 26 Test#21 (021) Repeat of Test #8 to confirm previous result.

Figure 27 **Test#22 (003) Sampling of liquid nitrogen to determine the flowrate before the fire test.**

Figure 28 **Test#22 (031) Liquid nitrogen applied directly onto the burning fuel surface.**

Figure 29 Test#22 (032) Liquid nitrogen controlling the fire but blue, almost invisible flames, are still present.

Figure 30 Test#23 (044) Application of cellular glass corresponding to an average thickness of 183 mm.

Figure 31 Test #23 (054) The fire intensity is reduced by the layer of cellular glass.

Figure 32 Test#23 (055) Side view of the fire at similar time as in previous picture (054).

Figure 33 Test#23 (061) The layer of cellular glass after the fire has been manually extinguished. It was observed that there was a considerable difference in the depth of the cellular glass layer and the black surface indicate the area with the least depth.

Figure 34 Test#24 (070) Application of cellular glass (average thickness 20 mm) followed by foam application at 1,05 m above the fuel/cellular glass surface.

Figure 35 Test#25 (104) Similar to Test #8 and #21 but using 350 mm of fuel.

Figure 36 Test#26 (011) Test in the 2580-tray applying cellular glass (average 10 mm) followed by Type III foam application. The cellular glass layer was too thin and was pushed away by the foam stream at the point of impact.

Figure 37 Test#27 (025) Test in the 2580-tray applying cellular glass (average 30 mm) followed by Type III foam application. Due to the thicker layer of cellular glass, no open fuel surface was created.

Figure 38 Test#28 (032) Test in the 2580-tray using CAF and Type III foam application. Although a significant portion of the foam landed outside the fire tray due to bad coherence of the foam stream, an effective foam layer was established on the fuel.

Figure 39 Test#28 (034) Test in the 2580-tray using CAF and Type III foam application showing the fire almost extinguished.

1.2 Photos from WP2 tests

Figure 40 **WP2-Test#1 (032) Test with AFFF-AR, 3%, under similar conditions as WP1-Test #8, foam impact position 1,05m above fuel surface. Picture shows the fire after about 15 minutes of foam application and as in the WP1 test, no control of the fire was obtained.**

Figure 41 **WP2-Test#2 (014) Identical to WP2-Test#1 but using AFFF-AR at 6% concentration (instead of 3%).**

Figure 42 WP2-Test#2 (016) Using AFFF-AR at 6% concentration improved the fire extinguishing performance considerably.

Figure 43 WP2-Test#3 (035) Similar to WP2-Test #2 but using lower application rate (4,77 l/m^2 min)

Figure 44 WP2-Test #4 (023) Type III application of medium expansion foam (MEX), nozzle position 1,05 m above the fuel surface. (4,77 l/m^2 min)

Figure 45 WP2-Test #5 (048) Similar to WP2-Test #2 and #3 but using even lower application rate (3,63 l/m^2 min)

Figure 46 WP2-Test #6 (014) Similar to WP2-Test #3 (4,77 l/m^2 min) but with foam impact position 2,05 m above the fuel surface.

Figure 47 WP2-Test #7 (022) Similar to WP2-Test #1 but using F3-foam (3% concentration).

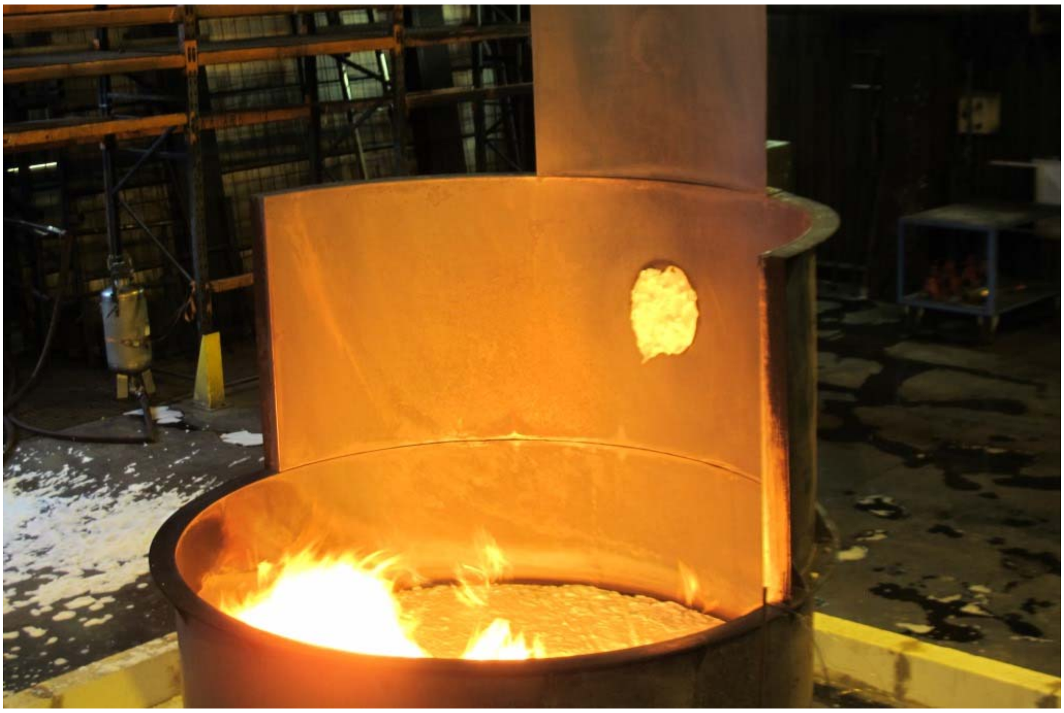


Figure 48 WP2-Test #8 (005) Similar to WP2-Test #1 (AFFF-AR 3%) but applied as CAF. Photo taken shortly after 8 min of foam application when we ran out of premix. The fire was extinguished manually.

Figure 49 WP2-Test #9 (016) Similar to WP2-Test#5 (AFFF-AR 6%, 3,63 l/m^2 min) but applied as CAF.

Figure 50 WP2-Test #9B (029) Retest using the same fuel as in Test #9, but using Type III application. (Preburn time reduced to 5 min).

Figure 51 WP2-Test #10 (034) Type III application of CAF (AFFF-AR 6%, 3,63 l/m^2 min) using a “spiral jet nozzle” arrangement located 2,55 m above the fuel surface .

Figure 52 WP2-Test #11 (074) Similar to WP2-Test #9 (3,63 l/m^2 min) but using F3 foam at 3%.

Figure 53 WP2-Test #12 (012) Similar to WP2-Test#5 (3,63 l/m^2 min) but using the F3 foam at 6%.

Figure 54 WP2-Test #13 (033) Test combined with application of cellular glass (average depth 50 mm), 10 min waiting followed by Type III foam application (AFFF-AR 3%, 3,63 l/m^2 min).

Figure 55 WP2-Test #13 (038) Within about 2 minutes, the fire intensity is reduced to about 25 % of its original intensity due to the applied layer of cellular glass.

Figure 56 WP2-Test #13 (041) Type III foam application starts 10 min after application of cellular glass. A foam layer is immediately established on the cellular glass.

Figure 57 Test #13 (043) The layer of cellular glass is nearly covered by the foam and the remaining fire is almost extinguished.

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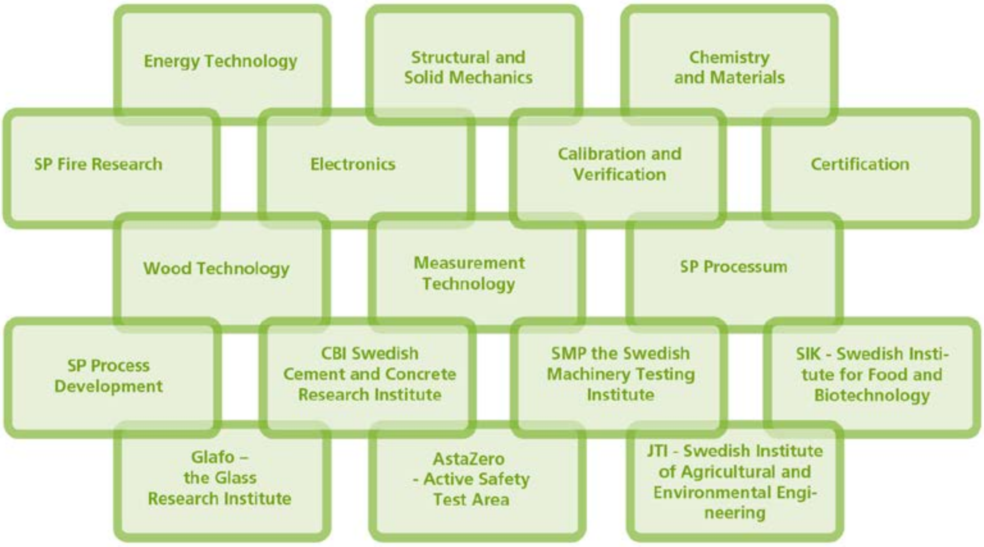

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