Pool fire tests to establish fire performance criteria in large machinery spaces

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SP Fire Technology
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Abstract

A simple and robust test methodology that makes it possible to measure and quantify the effectiveness of water spray or water mist systems intended for 'large' shipboard machinery spaces, has been investigated previously and is summarised in SP Report 2005:33. The methodology is based on the measurement of gas temperatures with traditional wire thermocouples a short distance above a pool fire surface.

The objective of the tests presented here is to further explore and develop the methodology and to establish criteria for fire control, fire suppression and fire extinguishment, as defined in the 2003 edition of NFPA 750.

The results indicate that the methodology needs to be complemented with measurements of fire burn times, relative to the free-burn time of a pool fire.

Key words: Shipboard machinery spaces, fire, fire protection, water spray, water mist, Heat Release Rate.

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Table of contents

Preface

In 2001, the Swedish Government assigned VINNOVA, the Swedish Governmental Agency for Innovation Systems, the task of developing a special programme of development and research in the field of maritime safety. In cooperation with the separate Programme Board for Shipping and Safety, which was set up, VINNOVA awarded funding to 15 projects. One of the projects that received financing was focused on the use of water mist and water spray fire protection systems in machinery spaces onboard ships.

Two series of tests were conducted in the project between 2001 and 2003; the first series of tests was conducted inside a 500 m^3 test compartment [1] and the second series of tests was in a 250 m^3 test compartment [2]. The ceiling height was the same, 5,0 m, for both test compartments. The outcome of the project has been presented in detail previously [3, 4, 5]. In summary a new fire test approach was proposed, where the characteristics of the tested system are determined, in contrast to the simple measurements employed previously such as 'time to extinguishment'. In addition, this new approach allows scaling from the test compartment to smaller or larger compartments, given that the ceiling height and the water flux application rate of the system and the nozzle installation limitations are unchanged.

For small machinery spaces (traditionally <3000 m^3), it can be concluded that global oxygen depletion is the primary fire suppression and fire extinguishment mechanism. For large machinery spaces (sometimes referred to as Class 3 spaces), direct water spray impingement becomes an increasingly important mechanism. Due to this, another test approach is necessary to establish system efficiency.

Strengthened by the outcome of the previous project, The Swedish Mercantile Marine Foundation, VINNOVA, The Swedish Governmental Agency for Innovation Systems (project number 25744-1), and The Swedish Fire Research Board (project number 400-041) awarded funding to the present project focused on water spray and water mist protection of large shipboard machinery spaces. The internal SP project number was BRs 6099.

The ultimate goal of the project was to develop installation guidelines and fire test procedures for water spray and water mist fire protection systems for 'large' shipboard machinery spaces. This report constitutes the second part of the project, the first part is described in reference [6].

Sammanfattning

Projektets långsiktiga målsättning är att ta fram provningsmetoder och installationsanvisningar för vattenbaserade släcksystem i 'stora' fartygsmaskinrum. I nuläget används oftast koldioxidsystem men koldioxidsystemens vara eller icke vara diskuteras mycket och många redare söker miljö- och personsäkra alternativ. Ett vattenbaserat släcksystem har fördelen att det kan aktiveras i ett tidigt skede av brandförloppet och därmed minska brandskadorna.

I en första serie poolbrandförsök [6] utvärderades hur effektiviteten hos olika vattenspraysystem kan mätas. Under försöken mättes brandeffekten med hjälp av den så kallade Industrikalorimetern. Dessutom användes annan typ av mätutrustning, såsom mätning av gastemperaturen ovanför brandkällan, värmestrålningen och ett nyutvecklat mätinstrument, en s.k. ”Pipe Thermometer”. Utvärderingen visade att mätning av gastemperatur ovanför bränsleytan av en poolbrand bäst korrelerar mot den uppmätta brandeffekten.

I de försök som redovisas i denna rapport genomfördes kompletterande försök där brandeffekten och gastemperaturen över en bränsleyta mättes. Baserat på försökens resultat föreslås kriteria för kontroll av brand ('fire control'), dämpning av brand ('fire suppression') och släckning ('fire extinguishment') av en poolbrand.

Sökord: Fartyg, fartygsmaskinrum, brand, brandskydd, vattendimma, sprinkler

1 Introduction

1.1 Previous series of fire tests

During the first phase of the project [6], simple and robust test methodologies for measuring and quantifying the effectiveness of water spray or water mist systems in ‘large’ machinery spaces were investigated. Such spaces can be defined as enclosures where the global oxygen depletion is not the primary fire suppression and fire extinguishment mechanism.

A methodology based on Heat Release Rate calorimetry is usually the best alternative to measure the effectiveness of a water spray or mist system. Not all fire laboratories have access to such equipment, however, so alternative methods are needed. Such alternatives can include: measurement of temperatures, heat radiation, or combinations of these parameters. In order to explore which alternatives could be most feasible, a test program was undertaken to investigate a methodology that is based on a simple and robust technology without using Heat Release Rate calorimetry.

The efficiency of the water spray system was evaluated by comparing the data from free-burning tests to data from corresponding fire suppression tests. A hypothesis was investigated that the relative reduction, compared to corresponding free-burning test, in the average values of different instruments located in the vicinity of the fire correlates to the corresponding relative reduction in the average heat release rate and/or the convective heat release rate.

The study showed that the Pipe Thermometer was a better method than using heat flux meters or Plate Thermometers which were located at a distance from the fire source. However, the best correlation between the measured data and the measured heat release rate was found between the measured gas temperatures above the pool fire surface.

The tests show that the effect of water droplet interaction with the instruments is an important parameter to consider when designing the test set-up and the instrumentation. Under certain conditions this influences the outcome of the tests, even when using thermocouples. Protection of the instruments against direct impingement from water droplets is, therefore, very important.

It should be noted that the use of thermocouples has been applied previously by others. For example, an evaluation of the effectiveness of different sprinkler and water spray nozzles against liquid pool fires using gas temperature measurements above the fuel has been presented in reference [7]. These tests lacked the measurements using Heat Release Rate calorimetry, but used different fuels and different water spray nozzles.

1.2 The objective of these tests

The objective of the tests presented within this report was to further explore and develop the technique of measuring gas temperatures above the surface of a pool fire. Moreover, the intention was to establish criteria for **fire control**, **fire suppression** and **fire extinguishment**. The following definitions of this terminology are provided in the 2003 edition of NFPA 750 [8]:

- **Fire control:** Limiting the size of a fire by distribution of water so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling ceiling gas temperatures and reducing heat radiation to avoid structural damage.
- **Fire suppression:** The sharp reduction of the rate of heat release of a fire and the prevention of regrowth.
- **Fire extinguishment:** The complete suppression of a fire until there are no burning combustibles.

The wording “sharp reduction” related to fire suppression is noteworthy as it would suggest that the reduction of the heat release rate should be more or less immediate. It is also of note that the definition of fire extinguishment is related to fire suppression, i.e. the fire should be suppressed until it is completely extinguished. The measurement criteria that are suggested within this report are related the definitions presented above.

In sharp contrast to these definitions, the criteria given in IMO MSC/Circ. 668/728 [9, 10] and 1165 [11] require extinguishment of the test fires with the addition of a specific time requirement. In these documents containing machinery space fire test procedures, fires are allowed to burn for up to 15 minutes before they are extinguished.

2 Measurement equipment and instrumentation

2.1 The Industry Calorimeter

The tests were conducted under the Industry Calorimeter, a large hood connected to an evacuation system capable of collecting all the combustion gases produced by the fire. The hood is 6 m in diameter with its lower rim 7,2 m above the floor. Usually, a cylindrical fibreglass ”skirt”, hanging from the lower rim of the hood, is used to increase the gas collecting capacity of the hood. However, this skirt was not used for these tests. In the duct connecting the hood to the evacuation system, measurements of gas temperature, velocity and the generation of gaseous species such as CO_2 and CO and depletion of O_2, can be made.

Figure 1 The Industry Calorimeter was used to measure the convective Heat Release Rates from the fires.

Based on these measurements, both the convective and the total heat release rate can be calculated. The convective heat release rate is denoted HRRconv and can be defined as follows:

HRRconv: The convective part of the heat release rate measured during a test, calculated on the basis of the gas temperature and mass flow rate in the calorimeter system.

The total heat release rate is denoted HRRtot and can be defined as follows:

HRRtot: The total heat release rate measured during a test, calculated on the basis of oxygen depletion in the calorimeter system. HRRtot is comprised of both the convective and radiative heat release rate.

To shorten turn-around times for these tests and to simplify the test procedures, the **HRRconv** only was measured during these tests, not the **HRRtot**.

2.2 Gas temperature measurements

The gas temperatures above the surface of the pool fires were measured at nine (9) different measurement points with sheathed (Type K) thermocouples having a diameter of 1,5 mm and a welded measuring junction. One thermocouple was positioned directly above the centre point of the fire tray and four thermocouples, respectively, was positioned on 500 mm and 1000 mm radius. All the temperature measurement points and the associated channels are shown in Figure 2.

The vertical distance measured from the surface of the fuel and the tip of the thermocouples was 130 mm. Each thermocouple was protected from direct water spray impingement by a 20 mm by 20 mm shield made from nominally 1 mm thick stainless steel. The shield was positioned 20 mm above the tip of the thermocouple.

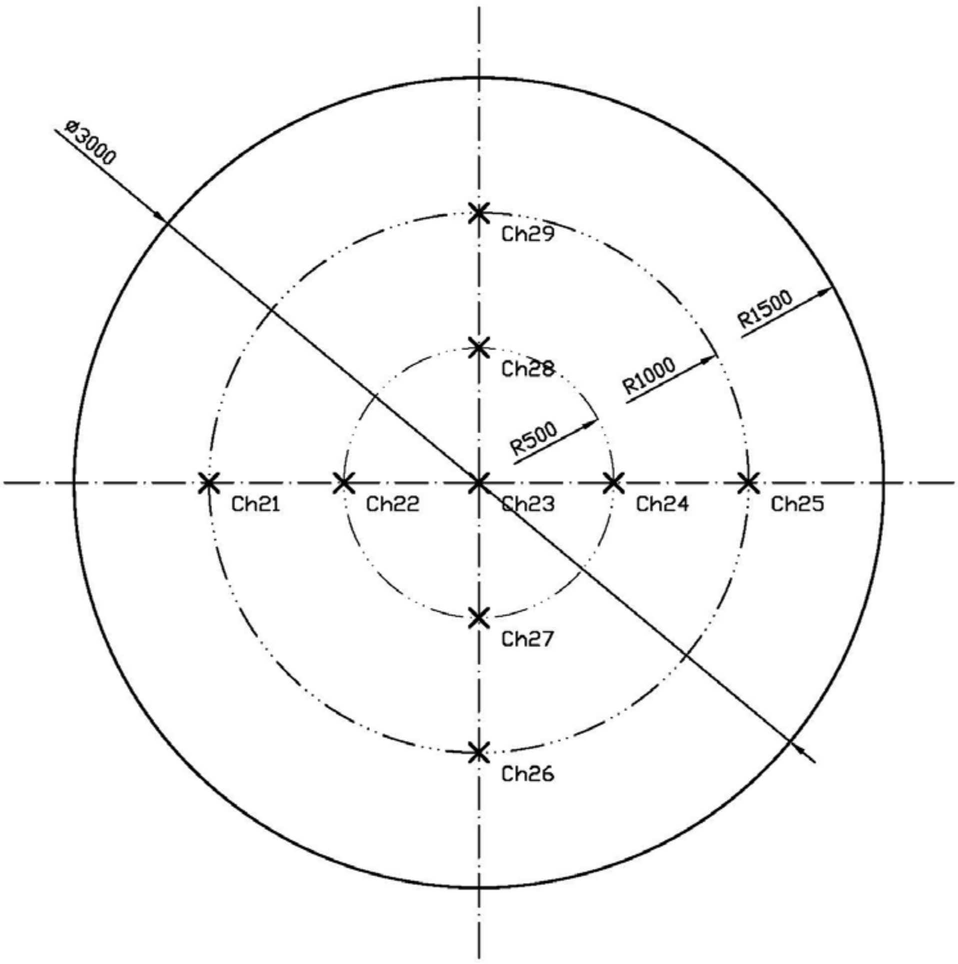


Figure 2 The temperature measurement points and the associated channels.

The thermocouples were held in position by two nominally 5 mm thick stainless steel wires, perpendicular to each other and stretched across the fire tray. In order to keep the thermocouples at a fixed vertical distance, parallel with the fuel surface, the steel wires were run over an edge and one end of the wires had a weight. This compensated for the length expansion when the wires were heated by the fire.

2.3 System water pressure and water flow rate measurements

The system water pressure was measured at the pump unit and at the pipe-work grid, using Transinstrument 2000A pressure transducers. The total water flow rate was measured using a Krohne 0 – 2000 L/min flow meter.

3 The system set-up

3.1 System pipe-work

A piping arrangement was fabricated consisting of a single feed, grid system, which was installed to minimise the difference between the flow rates of the nozzles. Two 32 mm cross connections, spaced 3,0 m apart, were made between the 50 mm mains to serve as the feed lines to the individual nozzles under the test. At 3,0 m spacing along the cross connections, 15 mm diameter pipe drops were installed down to the pendent nozzles. The system was fitted with a pressure transducer so that the operator could adjust the pump output and maintain the specific flowing pressure in response to any pressure changes. The system is shown in Figure 3.

3.2 Water spray nozzles and system pressures

3.2.1 Tests at 'high' vertical distance to the pool fire surface

The nozzles used in the tests were made by Tyco Fire Products and designated D3 Protectospray. The type D3 Protectospray nozzles are open (non-automatic) directional spray nozzles and they are designed for use in fixed water spray systems for fire protection applications. The nozzles are installed pendent and the external deflector type discharges a uniformly filled cone of medium velocity water droplets.

The nozzles are available in a wide variety of orifice sizes and spray angles. For these tests, nozzles with a spray angle of either 80° or 90° where chosen for the tests where the vertical distance from the nozzles to the pool fire surface was relatively high.

Discharge pressures of between 1,4 to 4,1 bars is recommended by the manufacturer. Higher discharge pressures will result in a decrease in coverage area since the spray patterns tend to draw inwards at higher pressures. However, the highest recommended discharge pressure was exceeded in some of the tests. The total flow rate for the four nozzles was either 126 L/min, 180 L/min or 270 L/min which corresponded to a nominal discharge density of 3,5 mm/min, 5,0 mm/min or 7,5 mm/min, respectively.

Table 2 summarises the different nozzles that were used in the tests at 'high' vertical distance to the pool fire surface, the nominal discharge density and the corresponding flowing pressures and flow rates.

Table 2 The nozzles that were used in the tests at 'high' elevation, the nominal discharge density and the corresponding flowing pressures and flow rates.

Nozzle	Nozzle K-factor [L/min/bar$^{1/2}$]	Nozzle spray angle [°]	Nozzle spacing [m × m]	Nominal discharge density [mm/min]	Nominal flowing pressure [bar]	Flow rate per nozzle [L/min]	Total flow rate [L/min]
D3 16-80	17,3	80º	3,0 × 3,0	3,5	3,3	31,5	126
D3 18-95	25,9	95º	3,0 × 3,0	3,5	1,5	31,5	126
D3 18-95	25,9	95º	3,0 × 3,0	5,0	3,0	45,0	180
D3 18-95	25,9	95º	3,0 × 3,0	7,5	6,8	67,5	270

The water was taken directly from the public water main and was increased (if necessary) to the desired pressure using a pump unit. For the tests where a foam additive was used, the pump unit was connected to a separate tank where water and the foam concentrate were pre-mixed to the recommended concentration.

The water discharge density of 5,0 mm/min corresponds to the requirements of Chapter 7 of the FSS Code [12]. Previously these requirements were found in SOLAS II-2, regulation 10.

Figure 3 *The system pipe-work when positioned at the 'high' elevation (left hand photo) and at the 'low' elevation above the pool fire tray.*

Figure 4 *The type of nozzles used in the tests, to the left a D3 Protectospray nozzle and to the right a Wormald MV nozzle.*

3.2.2 Tests at 'low' vertical distance to the pool fire surface

For the tests where the vertical distance from the nozzle and the pool fire surface was 0,55 m, nozzles with a 160° spray angle were used. These particular nozzles were made by Wormald Fire Systems (presently Tyco Fire & Integrated Solutions) and are similar in design to the D3 Protectospray nozzles described above. The nozzles are available in a similar range of orifice sizes and spray angles.

Discharge pressures of between 1,4 to 2,8 bars are recommended by the manufacturer. Higher discharge pressures will result in a decrease in coverage area since the spray patterns tend to draw inwards at higher pressures. However, the highest recommended discharge pressure was exceeded in both of the tests, in order to provide the desired discharge densities.

The total flow rate for the four nozzles was either 270 L/min or 360 L/min which corresponded to a nominal discharge density of 7,5 mm/min or 10,0 mm/min, respectively. Refer to Table 3 for the actual flowing pressures and flow rates.

Table 3 The nozzles that were used in the tests at 'low' elevation, the nominal discharge density and the corresponding flowing pressures and flow rates.

Nozzle	Nozzle K-factor [L/min/bar$^{1/2}$]	Nozzle spray angle [°]	Nozzle spacing [m × m]	Nominal discharge density [mm/min]	Nominal flowing pressure [bar]	Flow rate per nozzle [L/min]	Total flow rate [L/min]
MV25-160	38,2	160º	3,0 × 3,0	7,5	3,1	67,5	270
MV25-160	38,2	160º	3,0 × 3,0	10,0	5,6	90,0	360

4 Fire scenarios

4.1 Exposed diesel pool fires

The pool fires were arranged in a circular tray with a diameter of 3,0 m (7,07 m^2) having a rim height of 200 mm. In all, except one, tests the tray was filled with 10 mm of fuel, on a 140 mm bed of water. For the single exception, 20 mm of fuel was used on 130 mm of water, i.e. the same free-board was maintained.

The bottom of the tray was positioned 100 mm above the floor, as the bottom area required reinforcement and openings for the fork lift to allow the trays to be lifted. The tray was fitted with a device that prevented it from overflowing, which kept the rim height at a constant level of 50 mm. As water from the water spray nozzles entered the tray from above, water flowed out of the bottom level.

Table 4 provides information of the fire tray and the amount of fuel and water and Figure 5 shows the tray and the overflow device.

Table 4 The size of the pool fire tray.

Diameter [m]	Area [m^2]	Rim height [mm]	Amount of water [L]	Amount of fuel [L]	Free-board [mm]
3,0	7,07	200	990 (140 mm)	71 (10 mm)	50

Figure 5 The fire tray used in the tests with the wire thermocouples positioned above the pool fire surface. To the right, the overflow device at the side of the fire tray that kept the level of fuel constant is shown.

4.2 Obstructed diesel fire tray

This fire scenario simulates a fire in the bilges of a 'large' machinery space. The pool fire surface of the pool fire tray described above was therefore partly obstructed by four Ø=250 mm, L=3000 mm steel pipes. The nominal thickness of the steel was 0,5 mm. The steel pipes were positioned such that they obstructed four of the nine thermocouples and they obstructed approximately 27% of the horizontal area of the pool fire tray. Figure 6 shows the fire tray with the four steel pipes obstructing the surface.

Figure 6 The fire tray with the four steel pipes obstructing the surface.

4.3 The fuel used in the tests

Shell CityDiesel® was used as the fuel. The fuel had the following properties (test procedure within parenthesis):

Density at 15°C: 817 kg/m^3 (SS-EN-ISO 3675)
Viscosity at 40°C: 2,0 mm^2/s (CsT) (SS-ISO 3104)
Flash point: 74°C (SS-ISO 2719)
Water content: 34 mg/kg (ASTM D 1744)
Heat of combustion: 43,2 MJ/kg (ASTM D 2624)

The fuel temperature measured prior to the tests was between 15 to 20ºC.

4.4 Fire test procedures

The fires were ignited using a torch, and allowed to burn for one minute before the water flow was initiated. At this time, the whole of the pool fire surface was involved in the fire. For one test, the pre-burn time was increased to two minutes, having twice the amount of fuel. A small amount (1 L) of n-Heptane was used to obtain ignition in all tests and all water and fuel was changed between the tests.

Water was generally applied for ten minutes, after which the application was terminated. For the test where the fire was suppressed or controlled, the fire re-developed almost instantaneously and manual extinguishment was undertaken using a medium expansion foam nozzle. For the cases with limited fire control, the fuel was consumed during the ten-minute water discharge period or shortly thereafter, i.e. no manual extinguishment was necessary.

The fire test procedure was as follows:

-02:00 Start of the measurement
00:00 Ignition of the fire
01:00 Initiation of the water
11:00 Application of water terminated
11:30 Manual extinguishment using a foam nozzle (if necessary)
15:00 Termination of the test

4.5 Water discharge tests (in the previous series of tests)

In the previous series of tests [6], the actual water discharge densities corresponding to the nominal densities of 5,0 mm/min and 7,5 mm/min were used. The nozzles designated Protectospray D3 18-95 were used in the tests. The nozzle type has a K-factor of 25,9 (metric) and a spray angle of 95°.

The water density was measured between the four nozzles using 25 pcs of water collector trays under non-fire conditions. Each tray measured 500 mm by 500 mm and each discharge test was conducted for two minutes, after which the amount of water in each tray was determined by weighing the water.

It could be concluded that the water discharge density for the water spray system was relatively uniform between the four nozzles, with higher densities measured in the corner trays, i.e. the trays close to the nozzles. The average discharge density measured 4,72 mm/min and 6,63 mm/min, respectively, as compared to the nominal discharge density of 5,0 mm/min and 7,5 mm/min.

5 Test results and observations

This section provides a summary of the test conditions, test results and observations. All conclusions are based on the convective Heat Release Rate measurements and the visual observations.

5.1 Vertical distance to the fire source equal to 3,0 m

For the first series of fire tests the vertical distance measured from the nozzles to the surface of the pool fire was 3,0 m. The test conditions and test results are summarised in Table 5, followed by a discussion, test by test, of the test parameters and the test results.

Table 5 Summary of test conditions and fire test results.

	1	2	3	4	5	6
Date of test	Oct. 18, 2006	Oct. 18, 2006	Oct. 18, 2006	Oct. 18, 2006	Oct. 19, 2006	Oct. 19, 2006
Fire scenario	Exposed	Exposed	Exposed	Exposed	Exposed	Exposed
Nozzle identification	D3 18-95	D3 18-95	D3 18-95	D3 18-95	D3 18-95	D3 16-80
Water flow rate [L/min]	270	180	126	126	270	126
Nominal density [mm/min]	7,5	5,0	3,5	3,5	7,5	3,5
Vertical distance [m]	3,0	3,0	3,0	3,0	3,0	3,0
Test result	Fire suppression	Fire control	Limited fire control	Fire extinguish-ment	Fire suppression	Limited fire control
Notes:	-	-	-	1)	2)	3)

1) An AFFF type foam additive was added to the water.
2) Repeat of Test 1, however, the amount of fuel was increased to 142 L (20 mm) and the pre-burn time was increased to 120 seconds.
3) Repeat of Test 3, however, D3 16-80 nozzles were used.

Test 1

Test 1 was conducted with the D3 18-95 nozzles at a flow rate equal to 7,5 mm/min. The application of water suppressed the fire almost immediately and controlled it at a low level. After approximately 05:30 [min:sec], the fire re-developed slightly, although the fire size and the height of the flames was not high. When the water was shut-off the fire re-developed rapidly and was manually extinguished.

Test 2

For this test, the same type nozzles were used, however, the water flow was decreased in order to provide a discharge density of 5,0 mm/min. The fire was initially suppressed, but re-developed to a second peak, after which the fire size was gradually reduced. The water shut-off verified that fuel was left in the tray as the fire re-developed immediately.

Test 3

For Test 3, the flow rate was further decreased, to 3,5 mm/min. This water application rate provided a limited degree of fire control. Although the fire initially was suppressed it re-developed to a relatively high intensity. The amount of fuel was almost consumed when the application of water was turned off, and the fire did not re-developed, rather it self-extinguished 11:37 [min:sec] after ignition.

Test 4

Due to the poor results of Test 3, it was decided to investigate the effect of using a commercial foam additive to the water, keeping the water discharge density at 3,5 mm/min. The foam additive was of the AFFF type and an admixture of 1% was pre-mixed in a separate tank.

The use of the foam additive improved the efficiency of the system dramatically. The fire was suppressed immediately after activation and was completely extinguished after approximately 20 seconds.

In Figure 7, the convective Heat Release Rate histories of Tests 1 through 4, as compared to the free-burn test in Test 14 are presented. The graph shows the first ten-minute period of the tests. However, as discussed above, for some tests the shut-off of water resulted in a rapid re-growth of the fire that is not shown in graph.

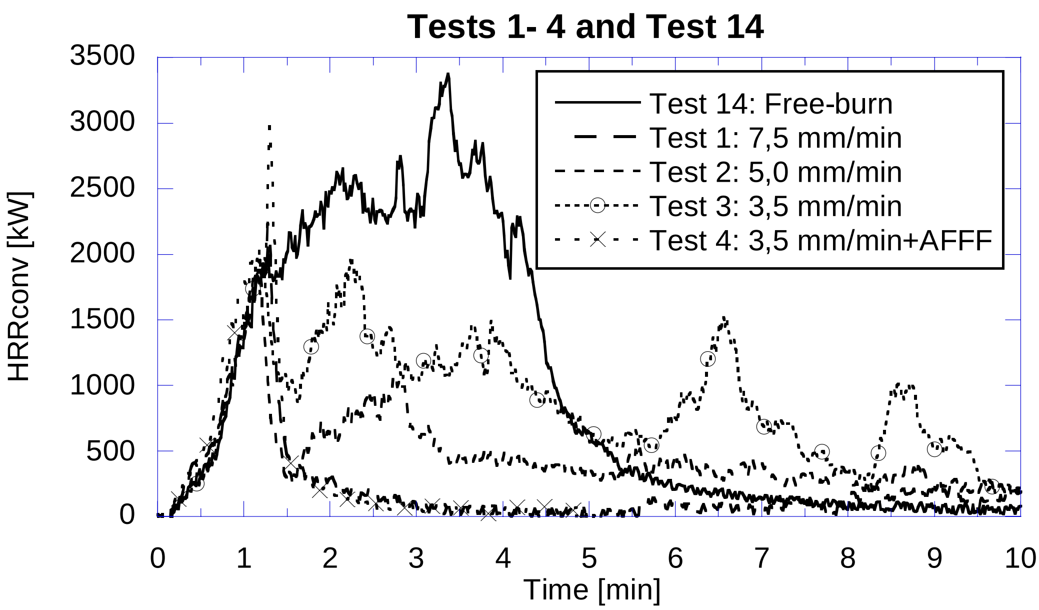


Figure 7 The convective Heat Release Rate histories of Tests 1 through 4, as compared to the free-burn test in Test 14.

Test 5

Test 5 was a repeat of Test 1, however, the amount of fuel was increased to 140 L (20 mm) and the pre-burn time was increased to two minutes. The intention was to allow the fire to grow larger prior to the activation of the system and to investigate how this influenced the performance of the nozzles tested at a discharge density of 7,5 mm/min.

The convective Heat Release rate was approximately 2,4 MW as compared to 2,0 MW at the time of activation. This had little effect on the performance of the system, the fire was immediately suppressed. The fire size was, however, slightly in excess of the level experienced in Test 1 after the initial suppression. This may be explained by the fact that the underlying layer of fuel and water probably attained a higher temperature during the longer pre-burn time of Test 5.

In Figure 8, the convective Heat Release Rate histories of Tests 1 and 5 are compared.

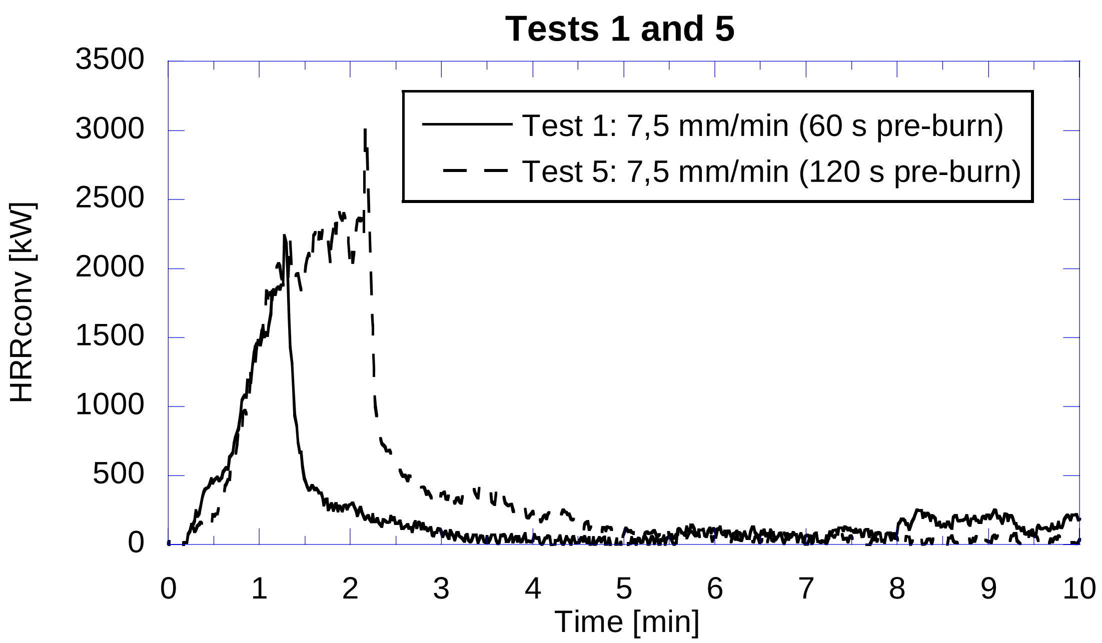


Figure 8 The convective Heat Release Rate histories of Tests 1 and 5.

Test 6

This intention of this test was primarily to compare the performance of the D3 18-95 nozzles at 3,5 mm/min (refer to Test 3) with D3 16-80 nozzles at the same discharge nozzle. This nozzle type has a smaller orifice size (lower K-factor) and a slightly more narrow discharge pattern. The smaller orifice size and the associated higher system pressure are expected to provide smaller droplet sizes.

The performance of the two nozzles was quite similar, as can be observed in Figure 9. The phases where the fire is suppressed and grew back in intensity are similar; although the overall impression is that less fire control was achieved with the D3 16-80 nozzles.

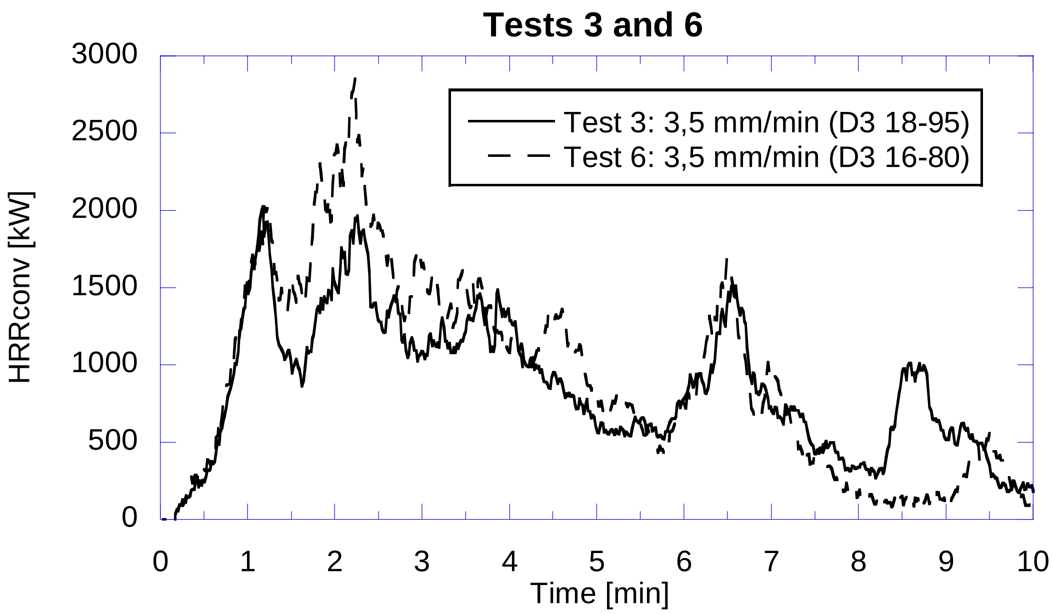


Figure 9 The convective Heat Release Rate histories of Tests 3 and 6. The tests were conducted at the same discharge density using different type nozzles.

5.2 Vertical distance to the fire source equal to 6,5 m

For these tests, the grid of nozzles was raised, such that the vertical distance measured from the nozzles and the surface of the pool fire was 6,5 m.

Three tests were conducted, with the intention to provide data directly comparable to Tests 1 through 3. The test conditions and test results are summarised in Table 6, followed by a discussion, test by test, of the test parameters and the test results.

Table 6 Summary of test conditions and fire test results.

	7	8	9
Date of test	Oct. 19, 2006	Oct. 19, 2006	Oct. 19, 2006
Fire scenario	Exposed	Exposed	Exposed
Nozzle identification	D3 18-95	D3 18-95	D3 18-95
Water flow rate [L/min]	270	180	126
Nominal density [mm/min]	7,5	5,0	3,5
Vertical distance [m]	6,5	6,5	6,5
Test result	Fire extinguishment	Fire control	Limited fire control
Notes:	-	-	-

Test 7

For test 7, D3 18-95 nozzles were used at discharge density of 7,5 mm/min, i.e. a direct comparison can be made to Test 1. The fire was sharply suppressed and was completely extinguished 02:10 [min] after the activation of the system, indicating that the performance of the system was improved at higher elevation from the fire.

There could be several reasons for this change in performance, for example that the water discharge was more uniform, that the interaction of the water droplets with the fuel surface was less firm or that the interaction between the water droplets and the flames was improved. Figure 10 provides a comparison of Tests 1 and 7.

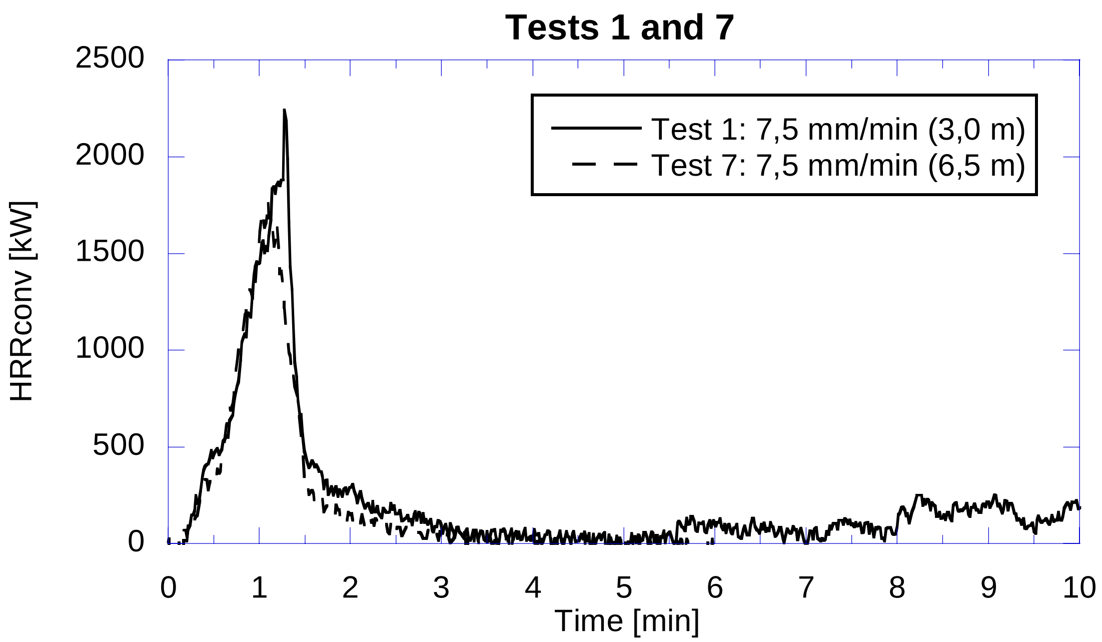


Figure 10 The convective Heat Release Rate histories of Tests 1 and 7. The tests were conducted at the same discharge density, with different distances (3,0 m or 6,5 m) measured from the nozzles to the surface of the pool fire.

Test 8

For Test 8, D3 18-95 nozzles were used at discharge density of 5,0 mm/min, i.e. a direct comparison can be made to Test 2. In parallel to the test-to-test comparison at 7,5 mm/min, the results indicate that the performance was slightly improved with the system at a higher elevation, see Figure 11.

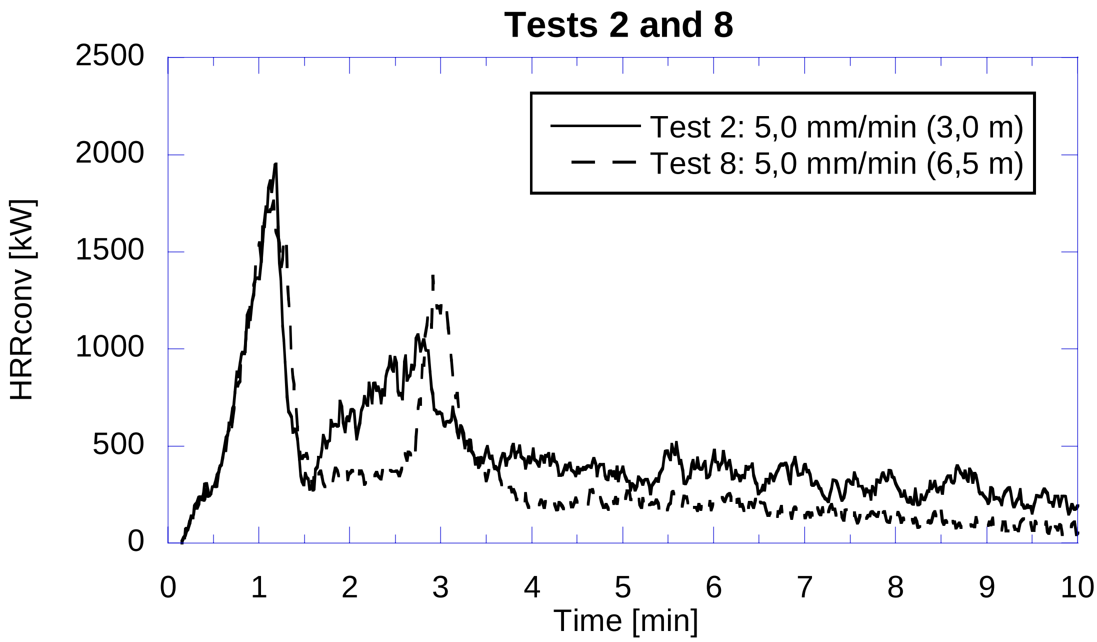


Figure 11 The convective Heat Release Rate histories of Tests 2 and 8. The tests were conducted at the same discharge density, with different distances (3,0 m or 6,5 m) measured from the nozzles to the surface of the pool fire.

Test 9

For Test 9, D3 18-95 nozzles were used at discharge density of 3,5 mm/min, i.e. a direct comparison can be made to Test 3. In contrast to the test-to-test comparison at 7,5 mm/min and at 5,0 mm/min, respectively, the results indicate that the performance was reduced. There may be several explanations to this, however, the most likely is that less water was able to penetrate the fire plume and flame and cool the fuel surface.

The fuel was consumed at 10:04 [min:sec] after ignition, further indicating the reduced performance at the higher elevation. Figure 12 shows a comparison between Test 3 and 9.

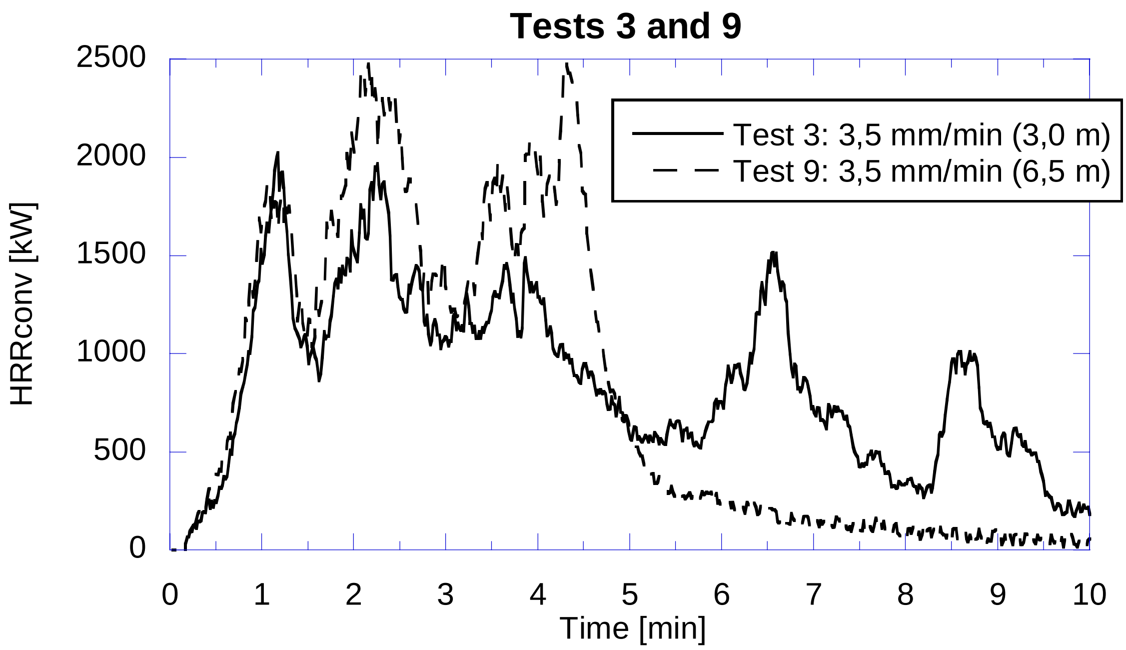


Figure 12 The convective Heat Release Rate histories of Tests 3 and 9. The tests were conducted at the same discharge density, with different distances (3,0 m or 6,5 m) measured from the nozzles to the surface of the pool fire.

5.3 Vertical distance to the fire source equal to 0,55 m

The intention of these tests was to simulate a pool fire below bilge plates of a shipboard machinery space. Therefore the vertical distance between the nozzles and the pool fire surface was relatively short. For two of the tests, the pool fire was obstructed by four Ø=250 mm steel pipes, in order to further simulate actual conditions in these typically cluttered spaces. Because of the limited vertical distance from the nozzle and the pool fire surface, nozzles with a 160° spray angle were used.

The test conditions and test results are summarised in Table 7, followed by a discussion, test by test, of the test parameters and the test results.

Table 7 Summary of test conditions and fire test results.

	10	11	12	13
Date of test	Oct. 20, 2006	Oct. 20, 2006	Oct. 20, 2006	Oct. 20, 2006
Fire scenario	Exposed	Exposed	Obstructed	Obstructed
Nozzle identification	MV25-160	MV25-160	MV25-160	MV25-160
Water flow rate [L/min]	270	360	360	360
Nominal density [mm/min]	7,5	10,0	10,0	10,0
Vertical distance [m]	0,55	0,55	0,55	0,55
Test result	Limited fire control	Fire control	Limited fire control’	Fire extinguishment
Notes:	-	-	-	1)

1) An AFFF type foam additive was added to the water.

Test 10

Test 10 was conducted at a nominal discharge density of 7,5 mm/min, with the pool fire fully exposed. Visually, the pool fire surface was completely covered by the water spray, although the overlap at the centre of the pool was limited. The results from the test can be directly compared to Test 1, even though different nozzle types were used, refer to Figure 13.

The comparison indicates that performance was reduced at the lower elevation. Whether this was due to a reduction in the water spray uniformity over the fuel surface, limited flame cooling or because of an increased agitation of the fuel surface by the water droplets is difficult to determine. Most probably the effect is due to a combination of factors. The fire re-developed after the application of water was turned off; however, the amount of fuel remaining at this point was so small that the fire burnt out without the need for manual extinguishment.

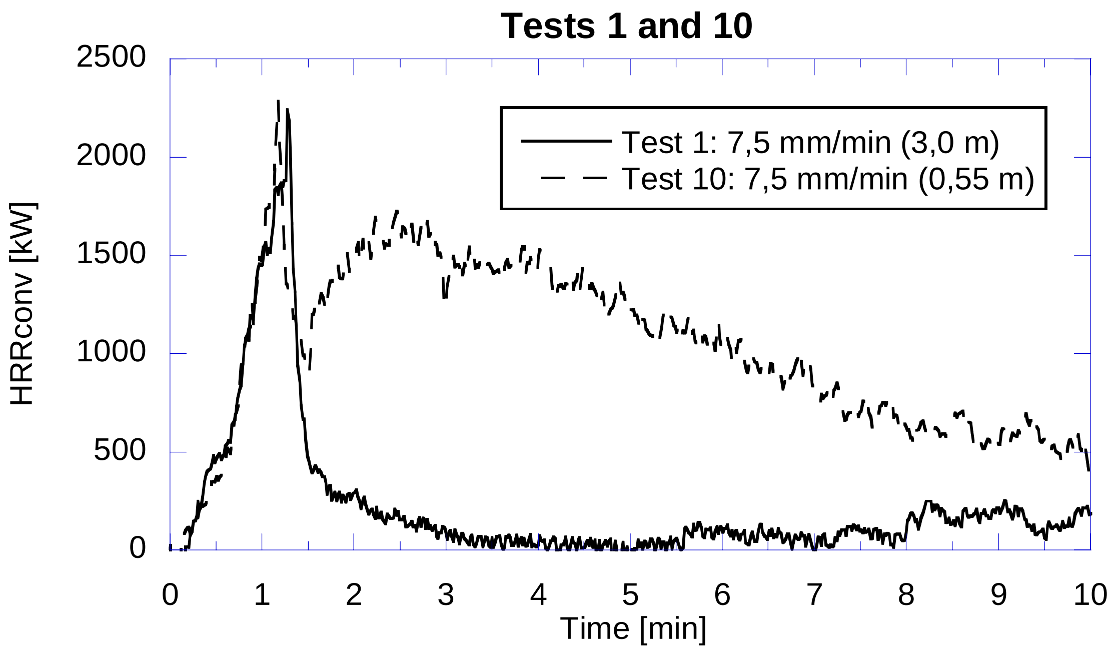


Figure 13 The convective Heat Release Rate histories of Tests 1 and 10. The tests were conducted at the same discharge density, with different vertical distances (3,0 m and 0,55 m, respectively) measured from the nozzles to the surface of the pool fire. Note that the low height required a nozzle with a larger spray angle.

Test 11

For Test 11, the discharge density was increased to 10,0 mm/min, keeping all other parameters constant, i.e. a direct comparison with Test 10 is possible, see Figure 14.

The results show that the performance was improved, the fire was still not suppressed at the higher flow rate, but controlled to a moderate level. Most of the fuel had been consumed when the water was turned off, the fire re-developed but the fuel burnt out quickly.

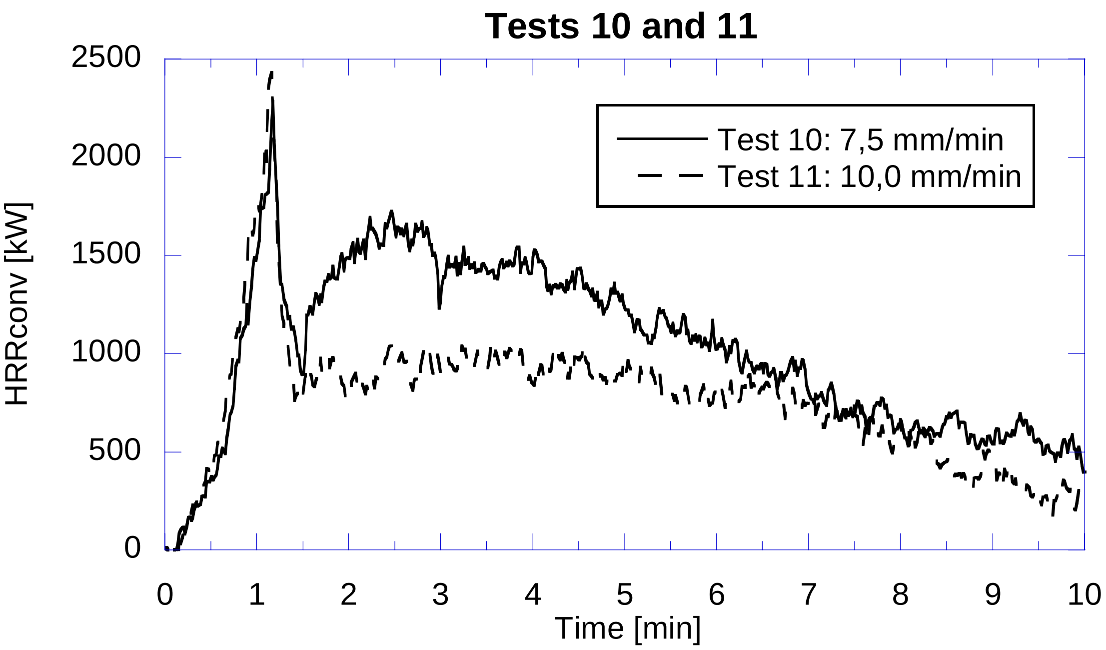


Figure 14 The convective Heat Release Rate histories of Tests 10 and 11. The tests were conducted with the same vertical distance from the nozzles to the surface of the pool fire, but with different discharge densities.

Test 12

For this test, the pool fire surface was obstructed by four Ø=250 mm steel pipes. The discharge density was kept at 10,0 mm/min, as it was expected that the obstructions would reduce the performance. A direct comparison can be made with Test 11, refer to Figure 15.

Visually, the obstruction steel plates prevented a large portion of the water from entering the fire tray, which correlates well with the fire test result. All the fuel was consumed after 07:20 [min:sec], i.e. several minutes before the water was turned off.

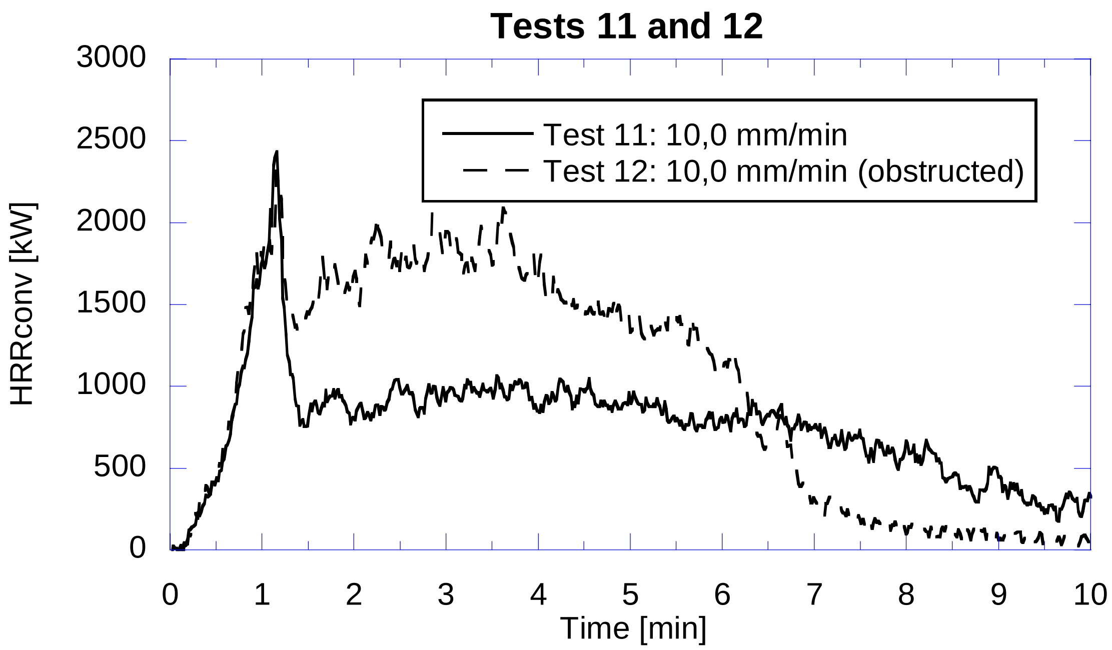


Figure 15 The convective Heat Release Rate histories of Tests 11 and 12. The tests were conducted with the same discharge density, but the pool fire surface was obstructed in Test 12.

Test 13

Based on the poor results of Test 12, it was decided to investigate the effect of using a commercial foam additive to the water, keeping the water discharge density at 10,0 mm/min. The foam additive was of the AFFF type and an admixture of 1% was pre-mixed in a separate tank.

The foam additive improved the efficiency of the system significantly; the fire was suppressed approximately one minute after activation and was completely extinguished 02:20 [min:sec] after activation. Figure 16 shows a comparison between Tests 12 and 13.

The performance of the system was not as impressive as in Test 4, i.e. the other test that was conducted with the foam additive. However, in the case of test 4 the fire was fully exposed and the vertical distance to the fire was higher, although the discharge density was lower.

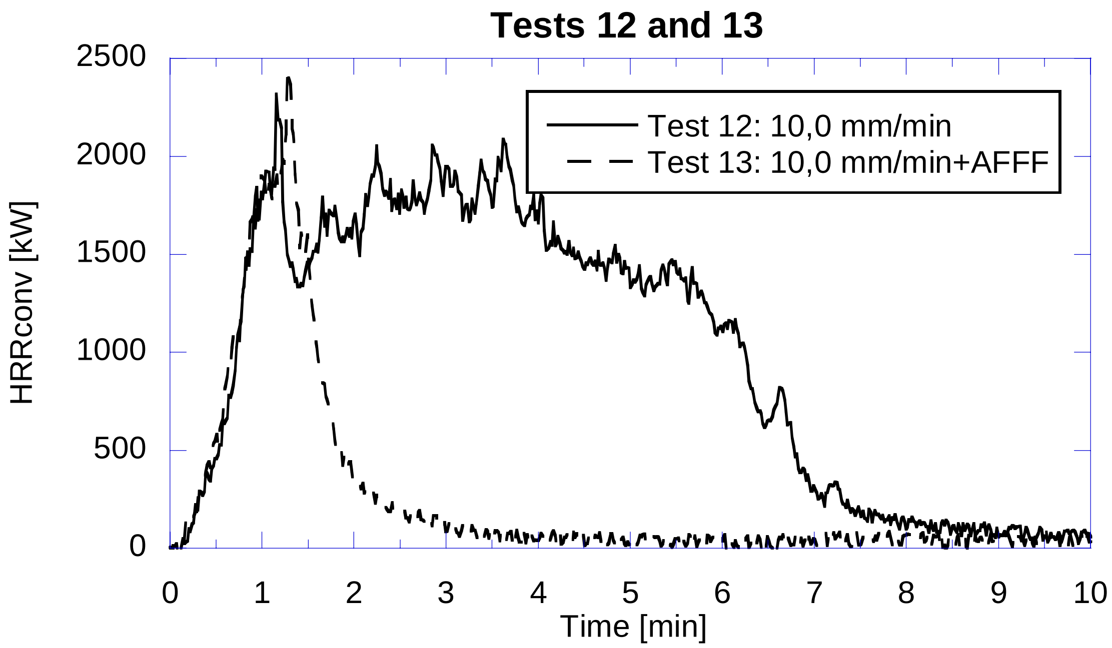


Figure 16 *The convective Heat Release Rate histories of Tests 12 and 13. The tests were conducted with the same discharge density, but an AFFF foam additive was used in Test 13.*

5.4 Free-burn fire test

A free-burn fire test was conducted in order to provide reference data to the other tests, refer to Figure 17. The amount of fuel (10 mm) was sufficient for a burn time of approximately four minutes. After this, the fire intensity was gradually reduced. At 05:30 [min:sec] after ignition only small flames around the edges of the fire tray were visible and the final flame was out at 06:40 [min:sec].

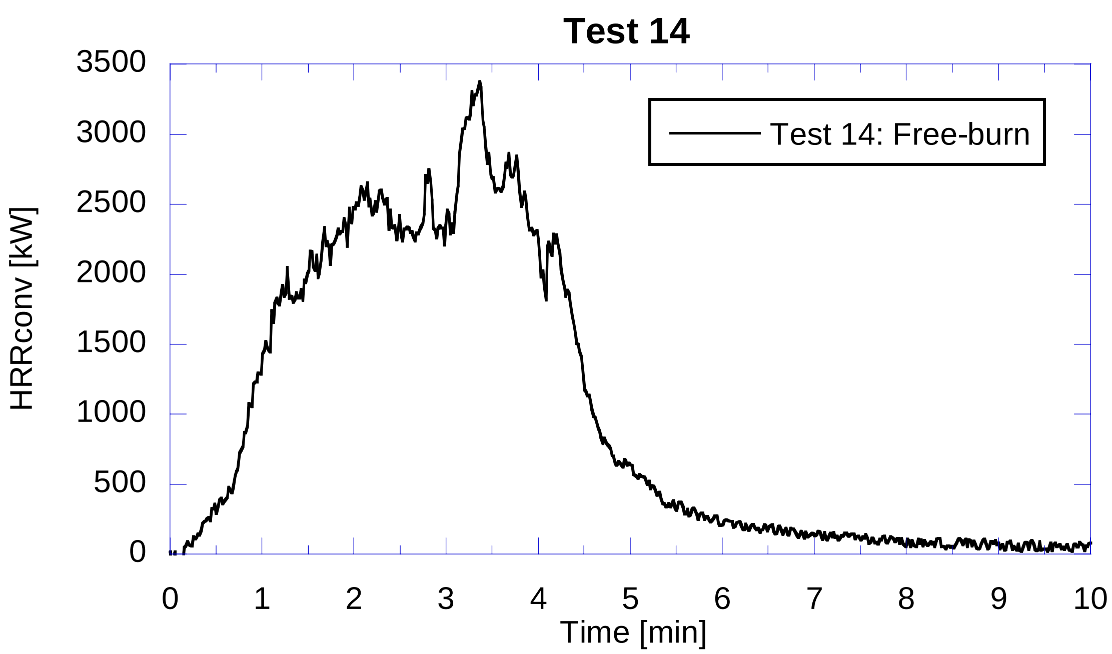
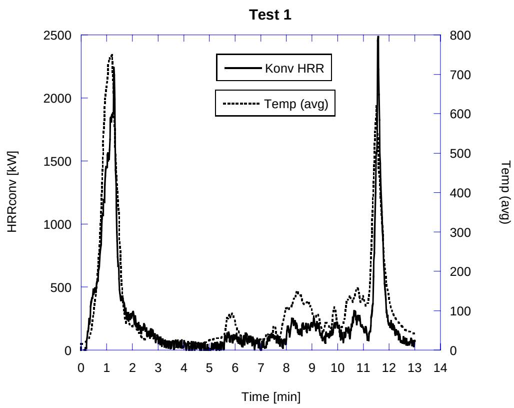


Figure 17 *The convective Heat Release Rate history of the free-burn fire test of Tests 14.*

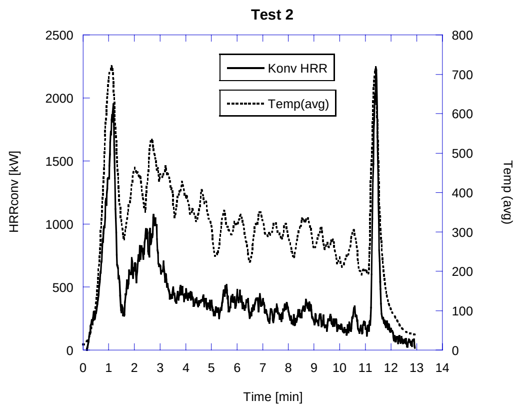
6 Analysis of the measurement data

6.1 Comparing the measurement graphs

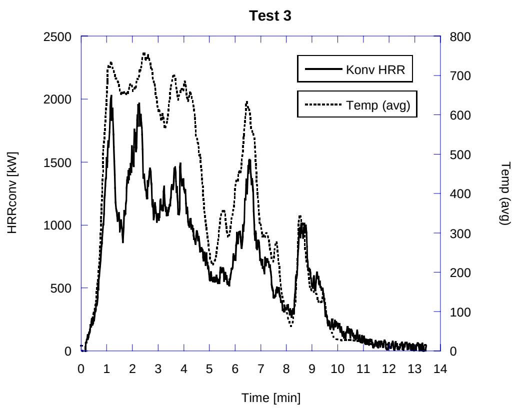
Given below are some illustrative measurements where the convective Heat Release Rate and the average gas temperature above the fuel surface have been plotted. The graphs have been chosen to illustrate ‘fire suppression’ (Test 1), ‘fire control’ (Test 2) and ‘limited fire control’ (Tests 3 and 10, respectively). The time scale has been chosen to also include the part of the test where the water flow was shut-off, when the fire was allowed to re-develop and then manually extinguished.



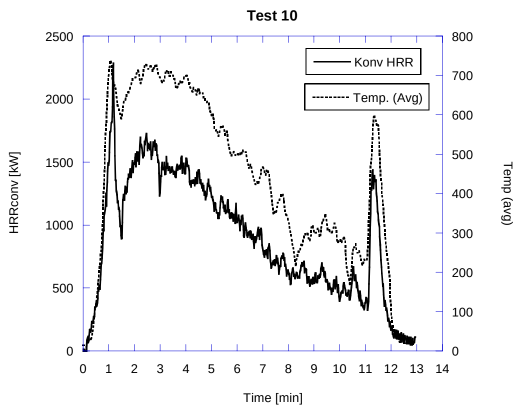
(a) fire suppression



(b) fire control



(c) limited fire control



(d) limited fire control

Figure 18 Illustration of the correlation between the convective Heat Release Rate and the average gas temperature above the fuel surface.

For all these tests, it is noteworthy that the temperature measurements capture most changes in the convective Heat Release Rate of the fire, which would be expected as the convective Heat Release Rate is based on the gas temperature and the mass flow rate in the calorimeter system. However, as discussed in more detail below, the best correlation is achieved for the cases where the fire was suppressed.

Measurements for all tests are provided in Appendix A and selected photos in Appendix B.

6.2 Detailed analysis of the measurement data

The evaluation is based on a comparison between the average convective Heat Release Rate (HRRconv) and the average gas temperature, measured from the time the system was activated and during a five or ten minutes time interval, respectively, i.e. from 01:00 – 06:00 [min:sec] or from 01:00 – 11:00 [min:sec].

6.2.1 Average gas temperature (01:00 – 06:00 [min:sec])

This period of time captures any fire suppression or fire extinguishment, as per the definitions discussed in section 1.2 of the report. For the free-burn test in Test 14, the average HRRconv and gas temperatures were calculated from 01:00 – 04:20 [min:sec]. After this period of time, the fuel started to become consumed and the fire size was gradually decreased. With more fuel, the fire size and the gas temperatures above fuel surface would have been more or less constant for a longer period of time.

The ratio of between the average HRRconv and gas temperature for the actual test and the free-burn test was calculated, refer to Table 8.

Table 8 The average HRRconv and gas temperatures over a five-minute period.

Test	Average HRRconv (01:00 – 06:00) [kW]	HRRconv ratio (01:00 – 06:00)	Average gas temperature (01:00 – 06:00) [°C]	Average gas temperature ratio (01:00 – 06:00) [°C]	Accuracy [%]
1	238	0,10	96	0,13	30
2	579	0,25	396	0,54	120
3	1105	0,47	567	0,77	65
4	309	0,13	115	0,16	20
5	718	0,30	246	0,33	10
6	1359	0,58	599	0,82	42
7	161	0,07	77	0,11	54
8	456	0,19	308	0,42	117
9	1394	0,59	564	0,77	30
10	1377	0,58	651	0,89	52
11	960	0,41	367	0,50	23
12	1620	0,69	553	0,75	10
13	332	0,14	145	0,20	40
14	2354[1)]	1,00	732[1)]	1,00	--

1) The average HRRconv and gas temperature was calculated from 01:00 – 04:20 [min:sec] for Test 14.

The calculated values are compared in Figure 19.

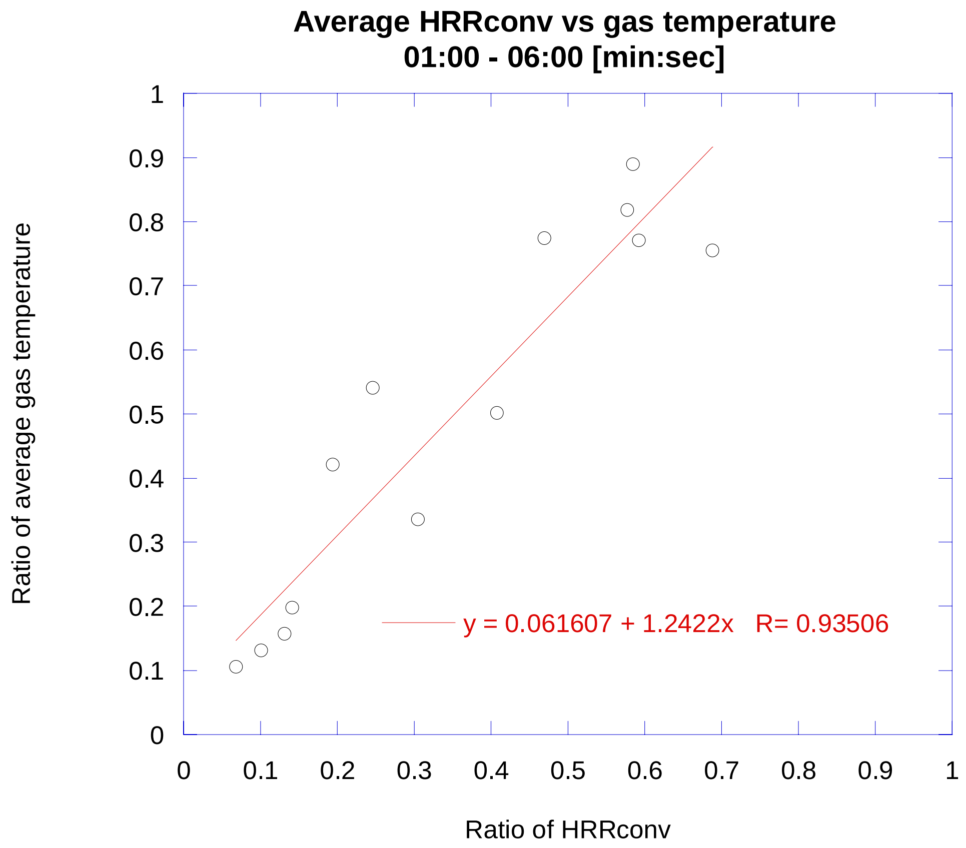


Figure 19 Relative reduction of the average gas temperature as a function of the convective Heat Release Rate.

6.2.2 Average gas temperature (01:00 – 11:00 [min:sec])

The exact same approach was used, however, with a time period from 01:00 – 11:00 [min:sec], refer to Table 9 for the results.

Tests 4 and 7, respectively, were excluded from the evaluation, simply because the fires were completely extinguished in such a short time, i.e. the evaluation from 01:00 – 06:00 [min:sec] is more relevant.

Table 9 The average HRRconv and gas temperatures over a ten-minute period.

Test	Average HRRconv (01:00 – 11:00) [kW]	HRRconv ratio (01:00 – 11:00)	Average gas temperature (01:00 – 11:00) [°C]	Average gas temperature ratio (01:00 – 11:00) [°C]	Accuracy [%]
1	186	0,08	87	0,11	38
2	427	0,18	179	0,24	33
3	825	0,35	388	0,53	51
4	N/A	--	--	--	--
5	383	0,16	143	0,20	25
6	881	0,37	377	0,52	40
7	N/A	--	--	--	--
8	288	0,12	183	0,25	108
9	747	0,32	293	0,40	25
10	1019	0,43	495	0,67	56
11	731	0,31	305	0,42	35
12	927	0,39	326	0,44	13
13	187	0,08	82	0,11	38
14	2354 1)	1,00	732 1)	1,00	--

1) The average HRRconv and gas temperature was calculated from 01:00 – 04:20 [min:sec] for Test 14.

The calculated values are compared in Figure 20.

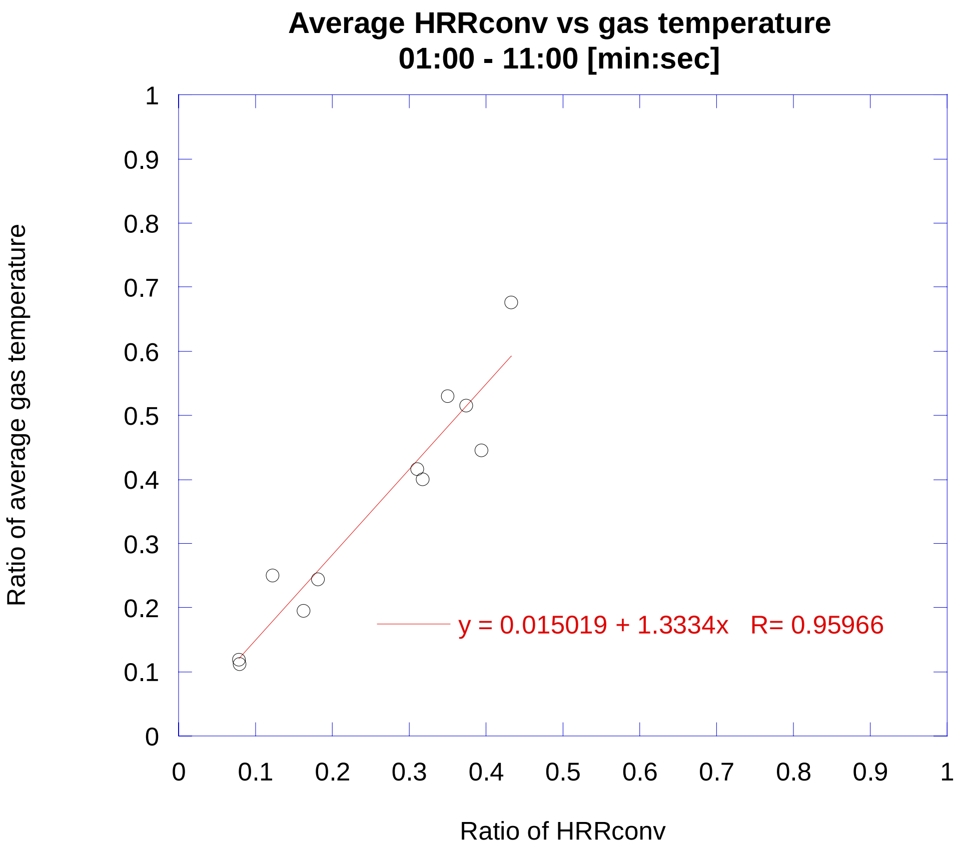


Figure 20 Relative reduction of the average gas temperature as a function of the convective Heat Release Rate.

7 Discussion of the tests and the test results

7.1 Objective

The test programme was intended to investigate both the performance of the water spray nozzles that were tested and issues related to the test methodology. Specific points of interest concerning these two aspects of the study are summarised below.

7.1.1 Issues related to the performance of the tested water spray nozzles

A number of parameters effect the performance of the nozzles. These were investigated as follows:

- **The influence of the vertical distance** measured from the pool fire surface and the water spray nozzles. Tests were conducted at three different vertical distances measured from the pool fire surface and the nozzles to explore this parameter.

- **The influence of the water discharge density**, although it should be kept in mind that the discharge pressure also was changes during this comparison, as the same type nozzle was used.

- **The influence of water droplet sizes**, i.e. tests was conducted at the same water discharge density with nozzles having different K-factors. A smaller K-factor will generally result in the smaller water droplets.

- **The influence of the degree of obstruction of the pool fire.** The pool fire was either fully exposed or partially obstructed by four Ø=200 mm steel pipes. The latter simulated bilge fires, spaces that are typically much cluttered.

- **The effect of the use of a foam additive.** Repeat tests were conducted with and without a foam additive to investigate this parameter.

7.1.2 Issues related to the test methodology

Further evaluation of the correlation between gas temperature measurements above the pool fire surface and Heat Release Rate measurements, as proposed in reference [6] was conducted. The convective Heat Release Rate was found to correlate well to temperature measurements above the pool fire.

7.2 Observations

7.2.1 The performance of the tested water spray nozzles

The following observations were made:

- A water discharge density of 7,5 mm/min provided fire suppression when the vertical distance from the fire to the nozzles was 3,0 m. This density (same nozzle type) extinguished the fire when the vertical distance was increased to 6,5 m.

- A water discharge density of 5,0 mm/min provided fire control when the vertical distance from the fire to the nozzles was 3,0 m. The performance was slightly improved at a vertical distance of 6,5 m.

- A water discharge density of 3,5 mm/min provided a limited degree of fire control when the vertical distance from the fire to the nozzles was 3,0 m. The performance was, in contrast to the results discussed above, further reduced at a vertical distance of 6,5 m.

- The influence of water droplet size was investigated in two tests, i.e. the tests were conducted at the same water discharge density with nozzles having different K-factors. The results indicate the performance was slightly reduced with smaller droplets.

- For the tests where the vertical distance from the fire to the nozzles was 0,55 m, nozzles with a larger spray angle were used. A water discharge density of 10,0 mm/min was necessary to provide fire control, a density of 7,5 mm/min only provided a limited degree of fire control. No tests were conducted at higher water densities.

- The influence of the degree of obstruction of the pool fire. The pool fire was either fully exposed or partially obstructed by four Ø=200 mm steel pipes. The latter simulated bilge fires, spaces that are typically severely cluttered. The obstruction had a significant negative influence on the performance of the system.

- The use of a foam additive increased the performance of the system significantly. The fire was suppressed and fully extinguished at water discharge densities that only provided limited fire control without the foam additive.

Finally, one of the results from the previous series presented in reference [6] is worth mentioning, namely the trend towards improved performance with increased size of the fire tray. This can be explained by the fact that the influence of the rim of the fire tray became smaller with larger tray diameter. In other words, given that the system had the capacity to suppress the smaller of the fire trays, the larger fire trays were, relatively, easier for the system to suppress.

7.2.2 The test methodology

The following observations were made:

- The steel wires used for the attachment of the thermocouples had, although they were thin, some degree of shadow effect and acted as a source of re-ignition. It was visually observed that flames were more likely to be suppressed or extinguished at the areas between the wires than directly under the wires.

- The gas temperature measurements consistently underestimated the performance of the tested systems, i.e. the level of fire suppression was generally better than indicated by the gas temperature measurements.

- The best correlation between the gas temperature measurements and the convective Heat Release Rate measurements, at least in absolute numbers, were experienced for the tests where the fire was suppressed. Less correlation was experienced for fires that were controlled.

- Better correlation between the gas temperature measurements and the convective Heat Release Rate measurements was found when the evaluation was based on a ten-minute period rather than a five-minute period (provided those fires that were rapidly extinguished were removed from the correlation).

7.3 Improvements of the methodology and acceptance criteria

As discussed above, the best correlation between the gas temperature measurements and the convective Heat Release Rate measurements were achieved when the fire was suppressed. It could also be concluded that better correlation was experienced for a longer evaluation time period, i.e. when the natural decay period (due to the consumption of the fuel) of the fire was included.

The observations can probably be explained by the fact that gas temperatures were measured with only one level of thermocouples and this level was relatively close to the fuel surface. When the flames were suppressed or completely extinguished, lower temperatures were recorded – which correlated well with the reduced convective Heat Release Rate. When flames were above the level of thermocouples, the recorded temperatures were high, irrespective of the fact that the fire to some degree was controlled. It is clear that in order to improve the methodology, additional levels of thermocouples should be installed at higher levels above the fuel surface.

Based on the data provided in this report, the following criteria are suggested; refer to Table 10, for any forthcoming fire test procedures. The criteria are related to the definitions of fire control, fire suppression and fire extinguishment defined in the 2003 edition of NFPA 750, as discussed under section 1.2 of this report.

Table 10 Suggested criteria based on the tests.

Performance criteria	Measurement criteria*	Evaluation time period
Fire control	≤0,50	Ten minutes
Fire suppression	≤0,20	Five minutes
Fire extinguishment	≤0,20 + no visual flames	Five minutes

*) Based on the calculated ratio between the average gas temperature during a reference free-burn test and the actual fire test.

7.4 A complementary approach – the measurement of the burn time

An alternative or complementary approach to gas temperature measurements could be based on the burn time of the fire, given a certain fuel layer thickness. For the tests discussed within this report, a 10 mm layer of fuel was used in all, except for one test. This amount of fuel resulted in a free-burn time of 06:40 [min:sec], measured until all fuel was consumed. For the tests where only a limited degree of fire control was achieved, the amount of fuel lasted throughout, or almost throughout the test, i.e. for around ten minutes after the activation of the system. For several tests with limited degree of fire control, the fires re-developed but the fuel burnt out shortly thereafter and manual extinguishment was not necessary. For the fire tests where the fire were suppressed or control, the fires were manually extinguished after it was verified that they re-developed, i.e. that there was a larger amount of fuel left in the fire tray.

In analogy with the criteria discussed above, a relevant criteria for fire control could probably be that the burn time for the tested system is twice the burn time for the reference free-burn test.

For fire suppression, a relevant criteria, in analogy with the convective Heat Release Rate measurements in this test programme, is probably that the burn time is five times longer than a free-burn test. Fire extinguishment could be defined as a visual or measured suppression of the fire, with no visible flames observed no later than five minutes after the initiation of the application of water.

A simple test approach could be illustrated with the following three examples, which is based on the assumption that the free-burn time is five minutes; however, the evaluation could of course be based on a shorter free-burn time.

Example 1: Determination of 'fire control' capabilities

00:00	Ignition of the fire
01:00	Initiation of the water
11:00	The application of water is terminated and it is verified that the fire re-develops
12:00	Termination of the test

Example 2: Determination of 'fire suppression' capabilities

00:00	Ignition of the fire
01:00	Initiation of the water
26:00	The application of water is terminated and it is verified that the fire re-develops
27:00	Termination of the test

Example 3: Determination of 'fire extinguishment' capabilities

00:00	Ignition of the fire
01:00	Initiation of the water
06:00	The application of water is terminated and it is verified that the fire does not re-develop
07:00	Termination of the test

Note: For systems that use a foam additive, the five-minute discharge should be followed by a five-minute discharge of water, before the application is stopped. This is an approach used in for example UL 162 [13] and requires that the layer of foam has a certain resistance to a water spray. After the application of water, re-ignition and burn-back tests are conducted. The reason for this approach is that a foam-water sprinkler system usually is designed for a limited discharge duration time with foam, followed by a longer discharge of water. The water discharge may deteriorate the foam blanket and a fire can re-develop unless the foam properties are sufficient.

It may be necessary to use gas temperature measurements above the fuel surface in order to verify and define the following parameters:

- **The free-burn time.** The free-burn time need to be adequately defined to avoid including the decay period when only small flames burn over the fuel surface or around the perimeter of the fire tray. If the free-burn time is defined from ignition and until the average gas temperature is below, for example, 500°C, a much more accurate definition is provided[1].

- **Fire re-development.** After the application of water is terminated it is necessary to ensure that there is fuel left in the fire tray. This can be verified in analogy with the methodology described above, i.e. that the fire burns back and the average gas temperature exceeds 500°C for a certain period of time before the fuel is completely consumed.

[1] With this definition, the free-burn time of Test 14 would be 04:40 [min:sec], as compared to 06:40 [min:sec] until all fuel was completely consumed.

8 Conclusions

A simple and robust test methodology that make it possible to measure and quantify the effectiveness of water spray or water mist systems intended for ‘large’ shipboard machinery spaces, has previously been investigated. The methodology is based on the measurement of gas temperatures with traditional wire thermocouples, a short distance above a pool fire surface.

The objective of the tests presented here was to further explore the methodology developed in a previous project, and to establish criteria for fire control, fire suppression and fire extinguishment, as defined in the 2003 edition of NFPA 750.

Although this was achieved, the results indicate that the methodology needs to be complemented with measurements of burn times, relative to the free-burn time of a pool fire. Such a methodology is discussed within the report.

Further to the evaluation of the methodology and the establishment of performance criteria, the performance of the tested water spray nozzles was documented.

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9 "Alternative arrangements for halon fire-extinguishing systems in machinery spaces and pump-rooms", MSC/Circ. 668, 30 December, 1994 - Appendix B, "Interim test method for fire testing equivalent water-based fire-extinguishing systems for machinery spaces of Category A and cargo pump-rooms", International Maritime Organization, London, UK

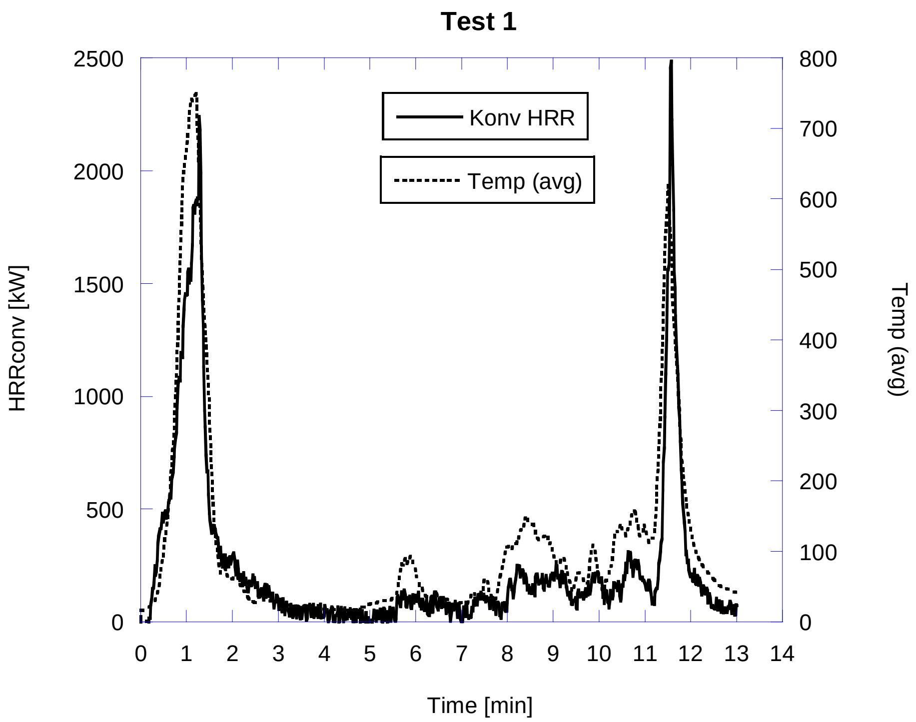
10 "Revised test method for equivalent water-based fire-extinguishing systems for machinery spaces of Category A and cargo pump-rooms" contained in MSC/Circ.668, 4 June, 1996, International Maritime Organization, London, UK

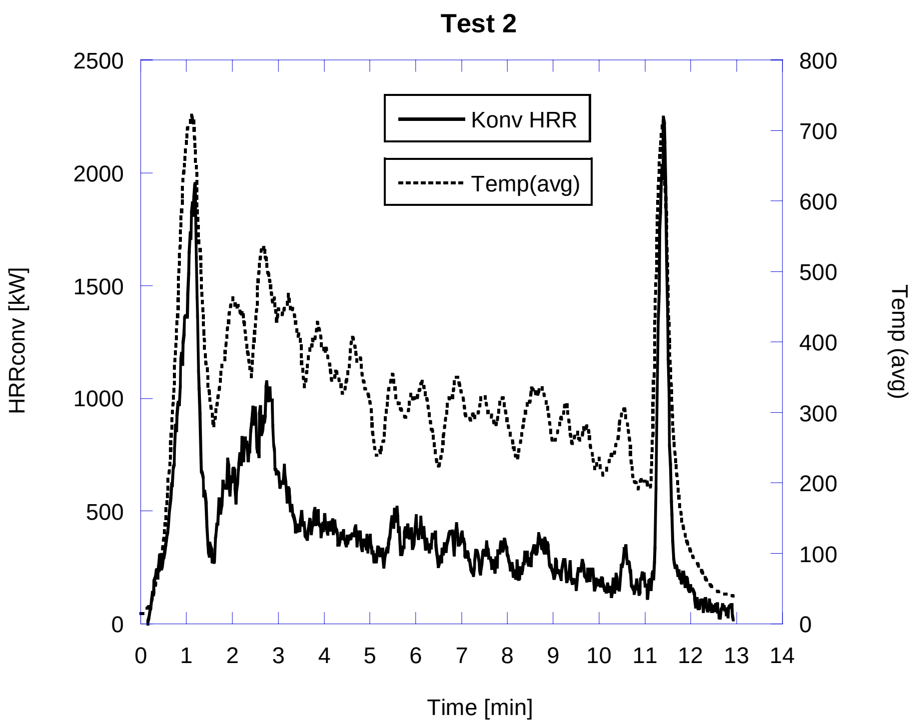
11 "Revised guidelines for the approval of equivalent water-based fire-extinguishing systems for machinery spaces and cargo pump-rooms", contained in MSC/Circ. 1165, 10 June, 2005, International Maritime Organization, London, UK

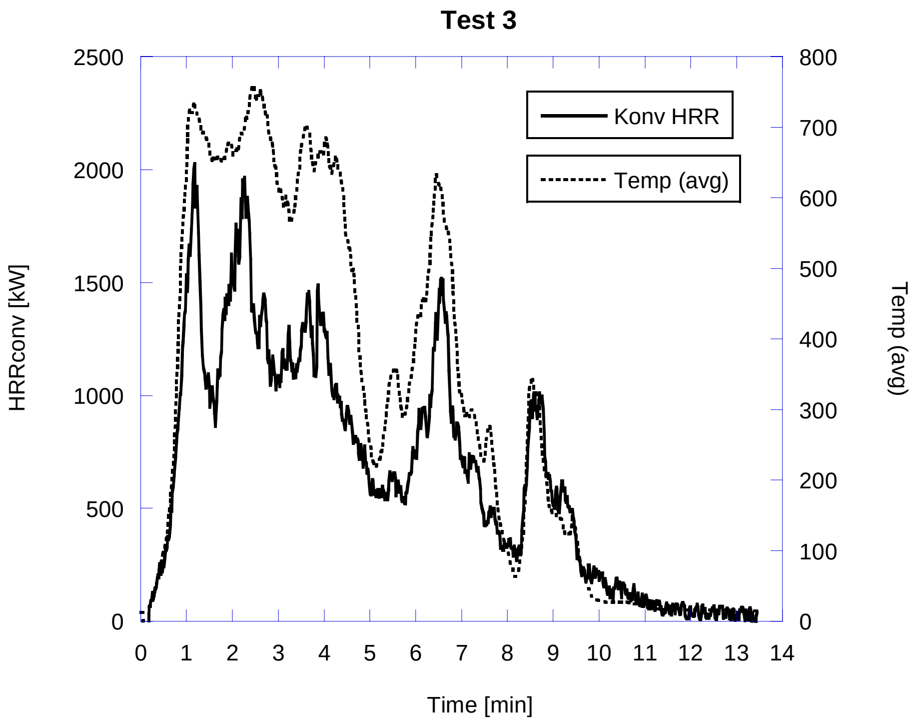
12 International Code for Fire Safety Systems (FSS Code), Resolution MSC.98(73), International Maritime Organization, London, UK, 2001

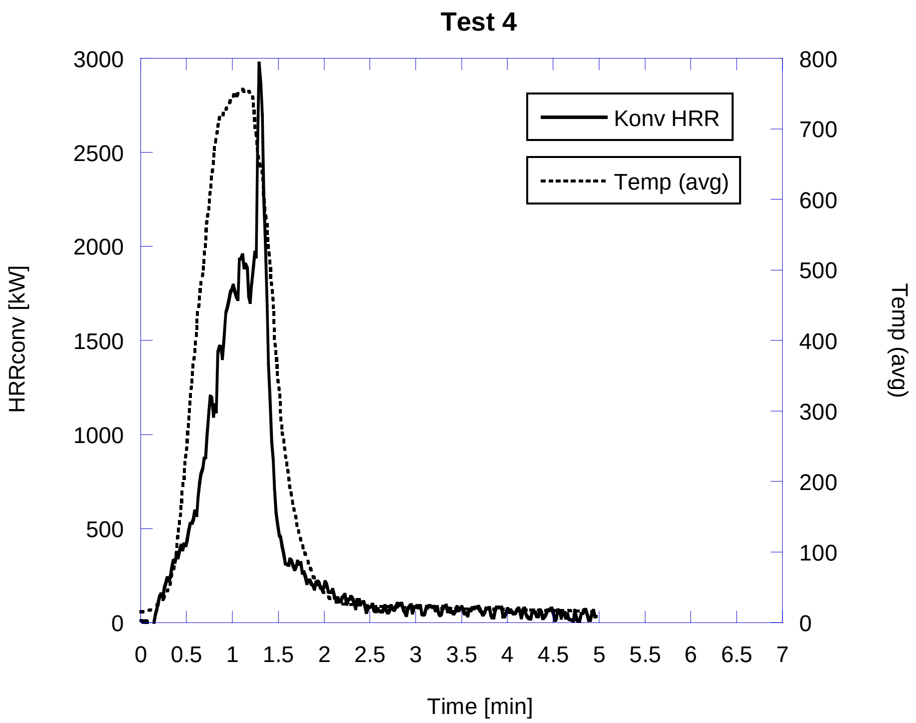
13 UL 162, Standard for Foam Equipment and Liquid Concentrates, Underwriters Laboratories, Inc, ISBN 1-55989-561-6, Seventh Edition, March 30, 1994

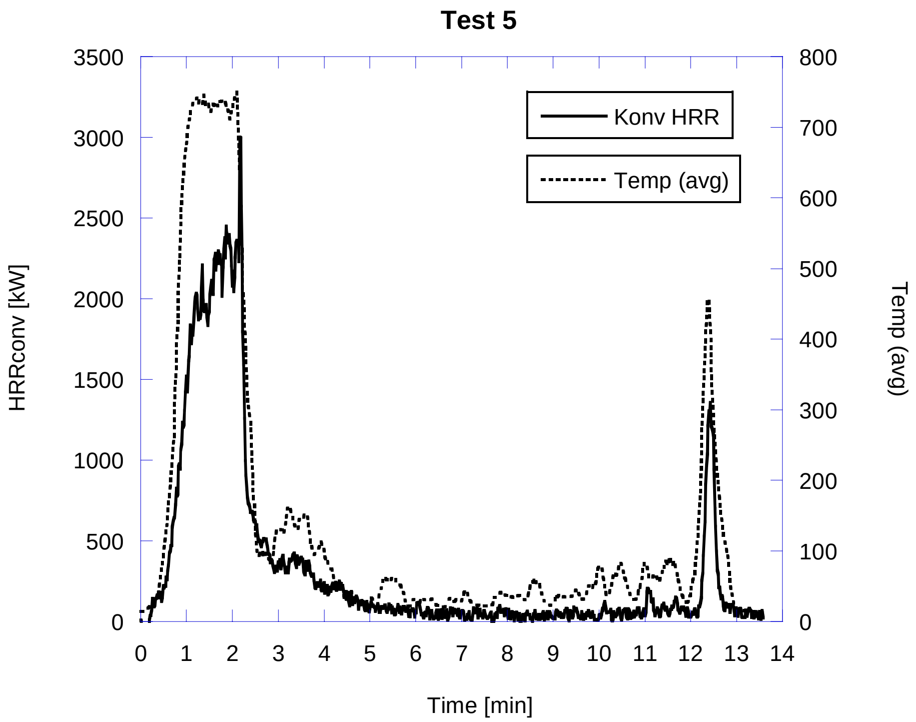
Appendix A: Measurement graphs

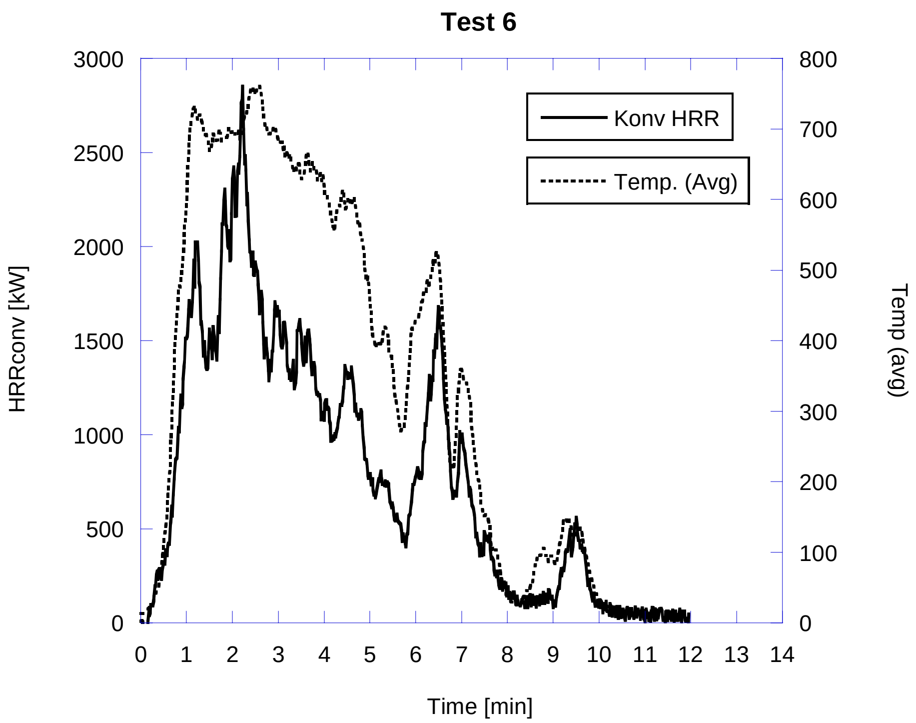


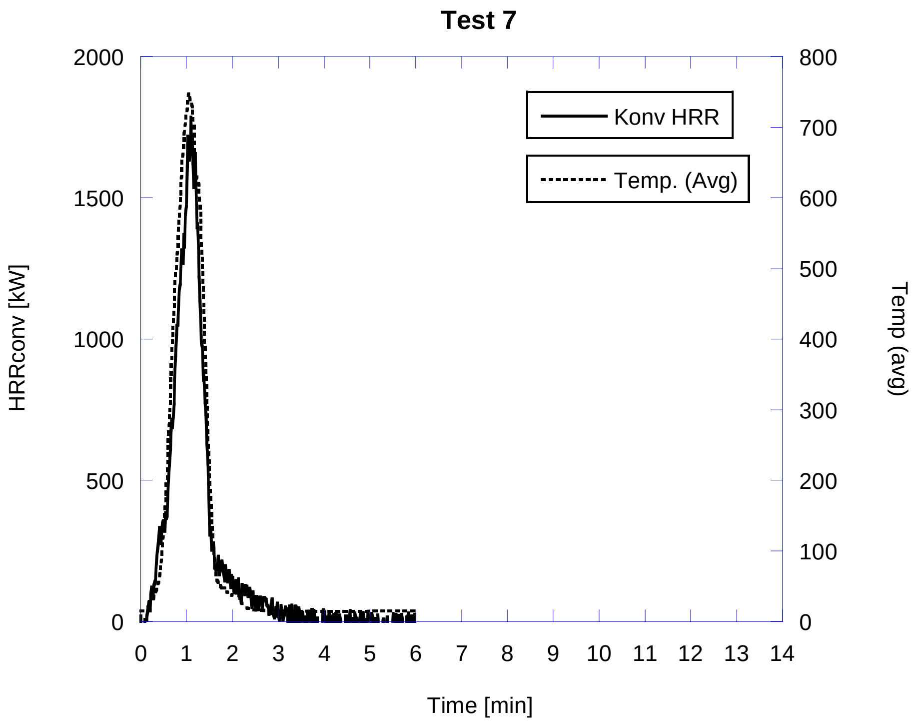


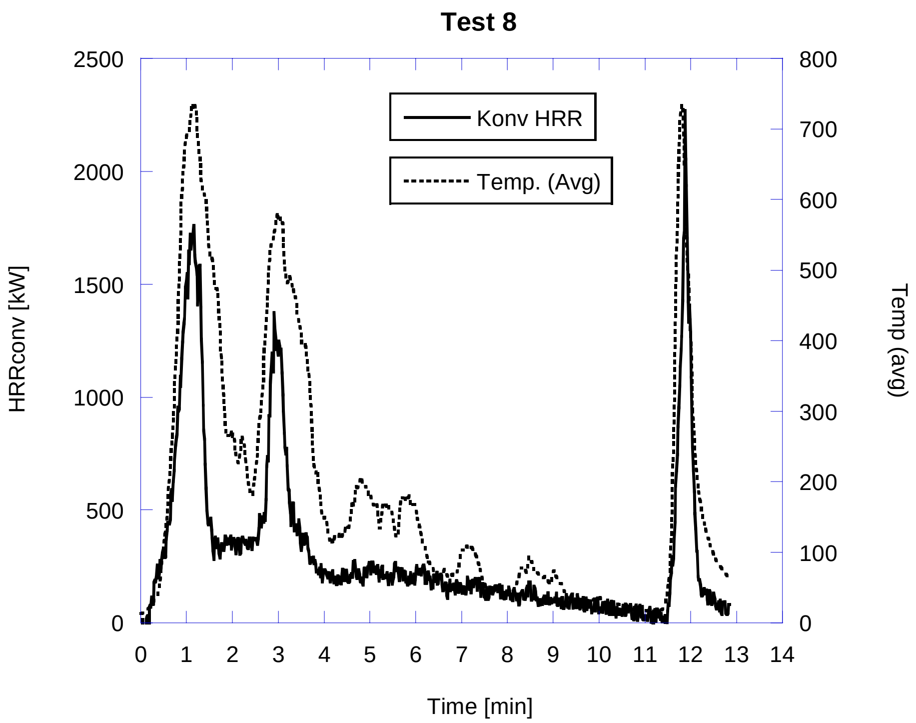

Test 3
Konv HRR
Temp (avg)
HRRconv [kW]
Temp (avg)
Time [min]
2500
2000
1500
1000
500
0
800
700
600
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

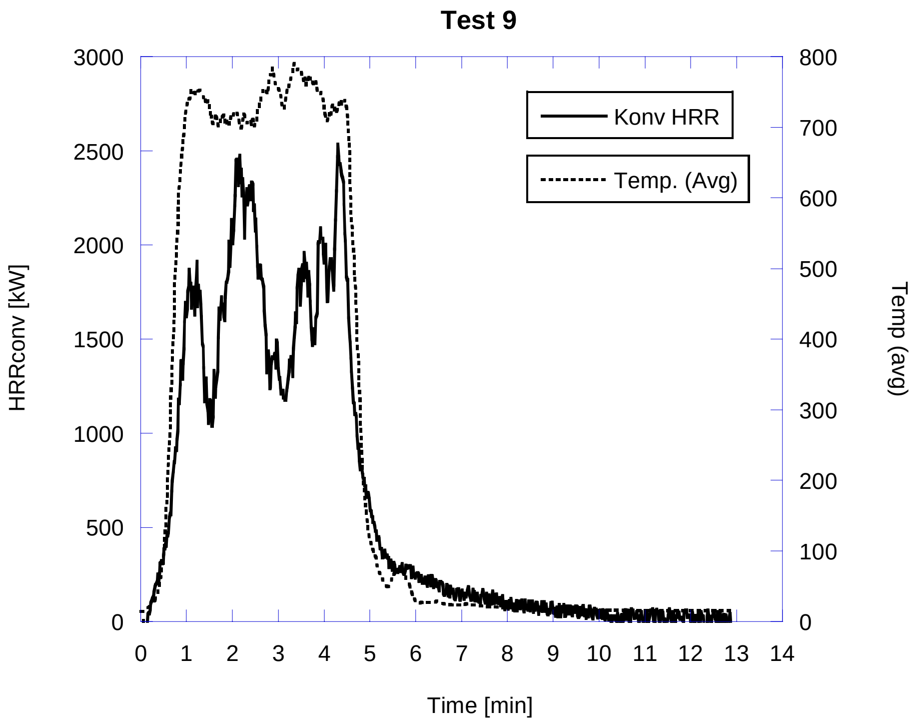

Test 4
Konv HRR
Temp (avg)
HRRconv [kW]
Temp (avg)
Time [min]
3000
2500
2000
1500
1000
500
0
800
700
600
500
400
300
200
100
0
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7

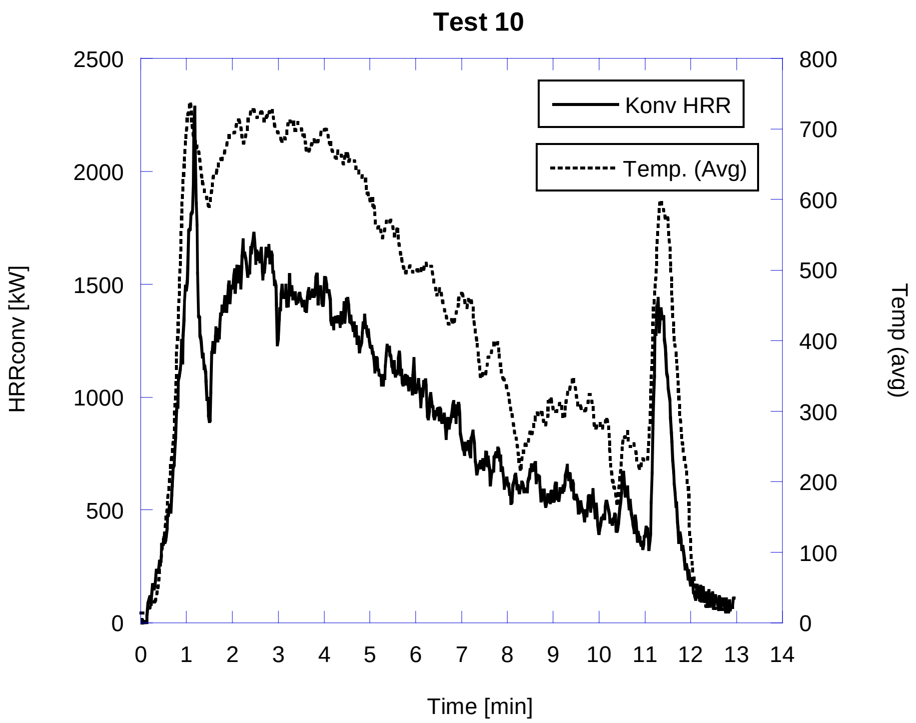

Test 5
Konv HRR
Temp (avg)
HRRconv [kW]
Temp (avg)
Time [min]
3500
3000
2500
2000
1500
1000
500
0
800
700
600
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

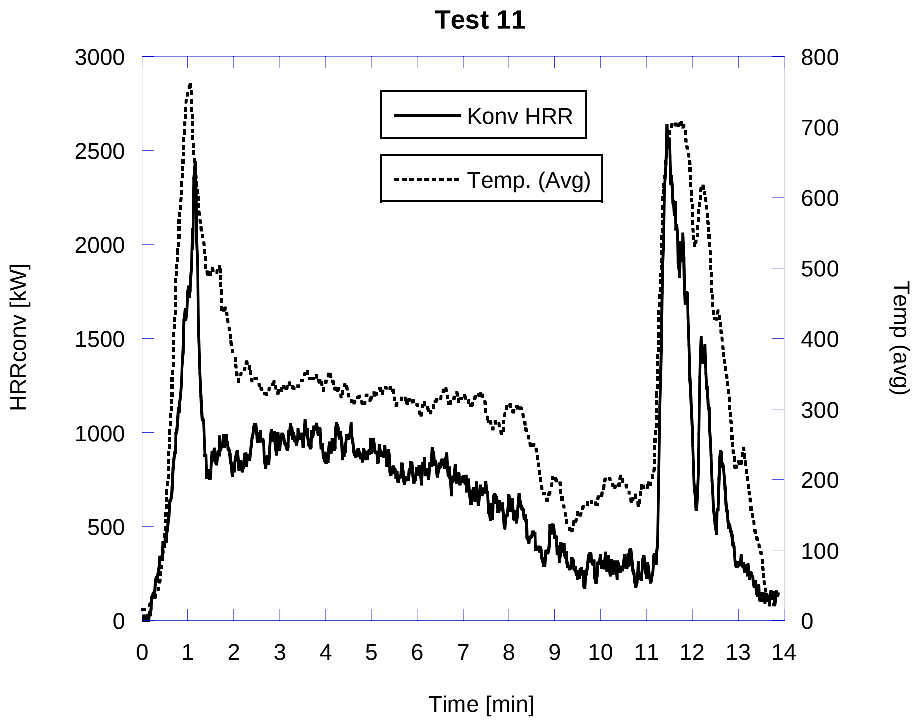

Test 6
Konv HRR
Temp. (Avg)
HRRconv [kW]
Temp (avg)
Time [min]
3000
2500
2000
1500
1000
500
0
800
700
600
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

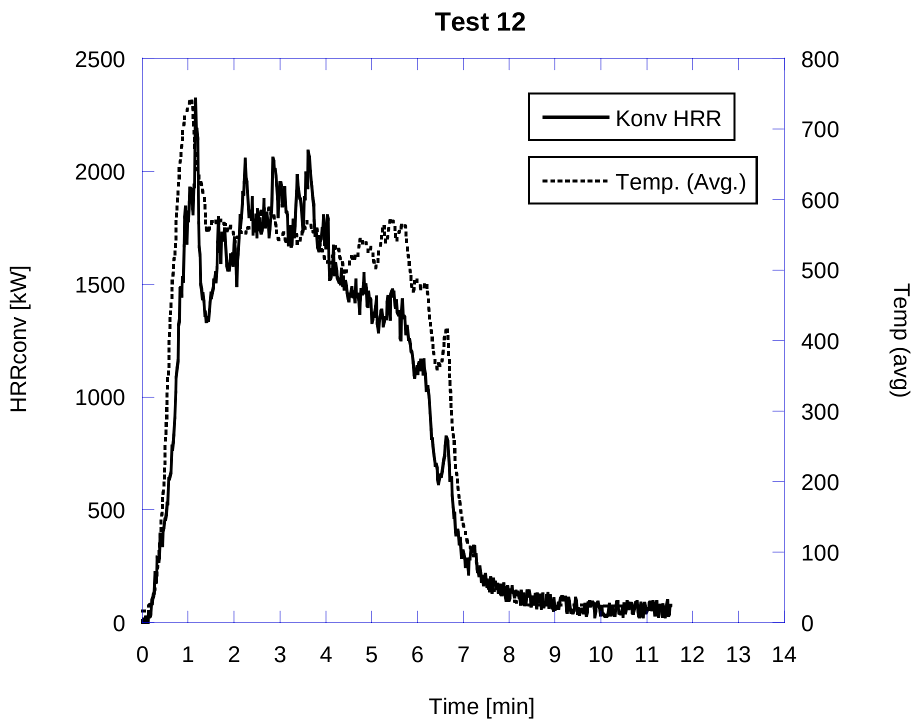

Test 7
Konv HRR
Temp. (Avg)
HRRconv [kW]
Temp (avg)
Time [min]
2000
1500
1000
500
0
800
700
600
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

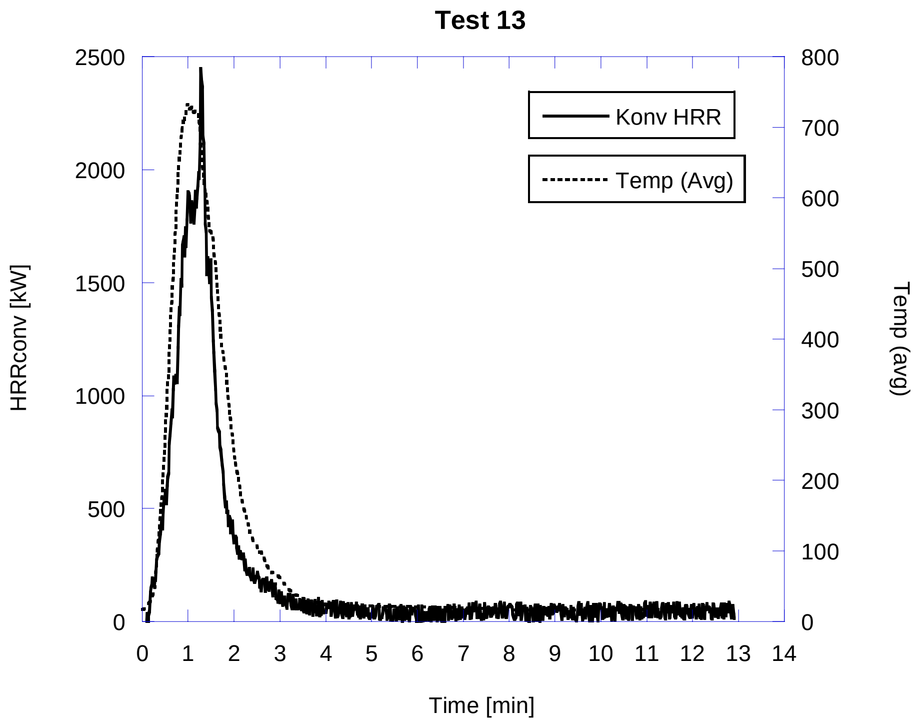

Test 8
Konv HRR
Temp. (Avg)
HRRconv [kW]
Temp (avg)
Time [min]
2500
2000
1500
1000
500
0
800
700
600
500
400
300
200
100
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

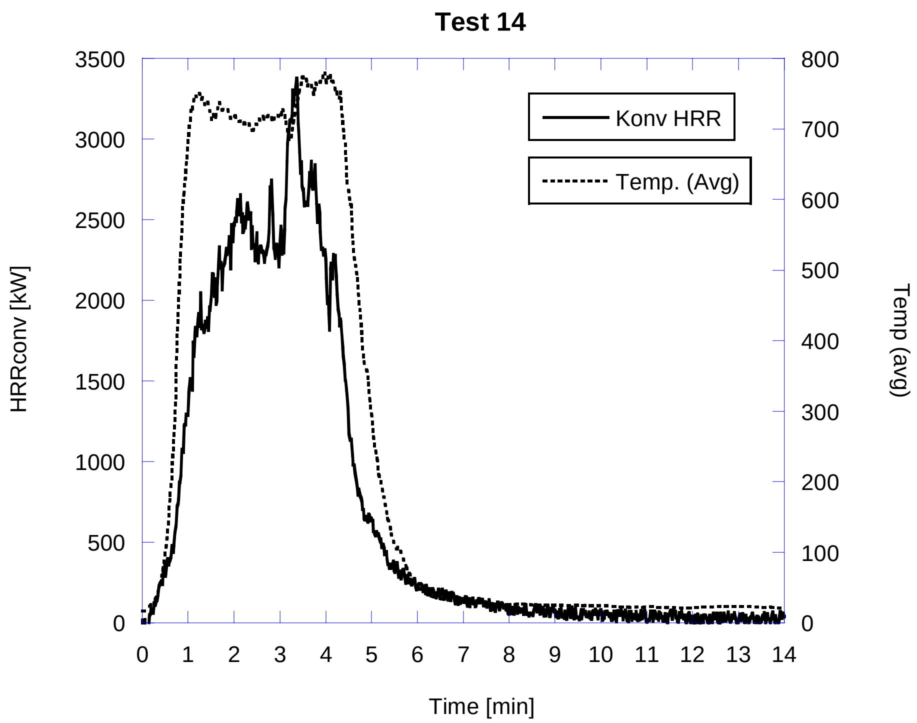

Test 9
HRRconv [kW]
Temp (avg)
Time [min]
Konv HRR
Temp. (Avg)
0
500
1000
1500
2000
2500
3000
0
100
200
300
400
500
600
700
800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14


Test 10
HRRconv [kW]
Temp (avg)
Time [min]
Konv HRR
Temp. (Avg)
0
500
1000
1500
2000
2500
0
100
200
300
400
500
600
700
800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14


Test 11
Konv HRR
Temp. (Avg)
HRRconv [kW]
Temp (avg)
Time [min]
0
500
1000
1500
2000
2500
3000
0
100
200
300
400
500
600
700
800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14


Test 12
Konv HRR
Temp. (Avg.)
HRRconv [kW]
Temp (avg)
Time [min]
0
500
1000
1500
2000
2500
0
100
200
300
400
500
600
700
800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14


Test 13
HRRconv [kW]
Temp (avg)
Time [min]
Konv HRR
Temp (Avg)
0
500
1000
1500
2000
2500
0
100
200
300
400
500
600
700
800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14


Test 14
HRRconv [kW]
Temp (avg)
Time [min]
Konv HRR
Temp. (Avg)
0
500
1000
1500
2000
2500
3000
3500
0
100
200
300
400
500
600
700
800
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

Appendix B: Selected photos from the tests

Photo 1 *The 3,0 m diameter (7,07 m^2) fire tray, with the steel wires with attached thermocouples above the fuel surface.*

Photo 2 *The overflow device that kept the rim height constant.*

Photo 3 *The system pipe-work, which was attached to a framework construction that partly were fire insulated.*

Photo 4 *The Industry Calorimeter that was used to measure the convective Heat Release Rate.*

Photo 5 Test 1: The fire was suppressed almost immediately.

Photo 6 Test 1: During several minutes, the fire was virtually extinguished but continued to burn around the perimeter of the fire tray.

Photo 7 *Test 1: The fire size increased after approximately eight minutes, but was still kept down by the system.*

Photo 8 *Test 2: This fire controlled by the system, at a discharge density of 5,0 mm/min.*

Photo 9 The typical 'limited fire control' scenario that was achieved by a discharge density of 3,5 mm/min in Test 3.

Photo 10 The use of foam in Test 4. A layer of foam has started to build across the fuel surface.

Photo 11 The final extinguishment in Test 4 occurred after only 20 seconds.

Photo 12 For Tests 7 – 9, the grid of nozzles was installed 6,5 m above the fire. In Test 7 (pictured), the water discharge density of 7,5 mm/min provided fire suppression and eventually fire extinguishment (see Photo 13).

Photo 13 Test 7: Fire extinguishment at 02:10 [min:sec].

Photo 14 Test 10: The water discharge density of 7,5 mm/min provided 'limited fire control'.

Photo 15 *Test 11: When the water discharge density was increased to 10,0 mm/min, 'fire control' was achieved.*

Photo 16 *A close-up picture of the spray pattern of the nozzle type used for the tests where the distance to the fire was 0,55 m.*

Photo 17 *The four Ø=250 mm steel pipes that was used to obstruct the pool fire surface in Tests 12 and 13, respectively.*

Photo 18 *Test 12: Only a limited degree of fire control was achieved, as a large portion of the water spray from the nozzles were obscured by the steel pipes.*

Photo 19 Test 13: An AFFF foam additive was used and the fire size was gradually reduced as the foam spread across the pool fire surface.

Photo 20 Test 13: The foam that did not enter the fire tray spread across the floor of the fire test hall.

Photo 21 *Test 13: Moments before full fire extinguishment. The surface is almost completely covered by a layer of foam.*

Photo 22 *Test 14: The free-burn fire test, after approximately 03:30 [min:sec] after ignition, where the fire is at its peak.*

Photo 23 Test 14: The fire size is reduced, although flames are covering the whole of the surface.

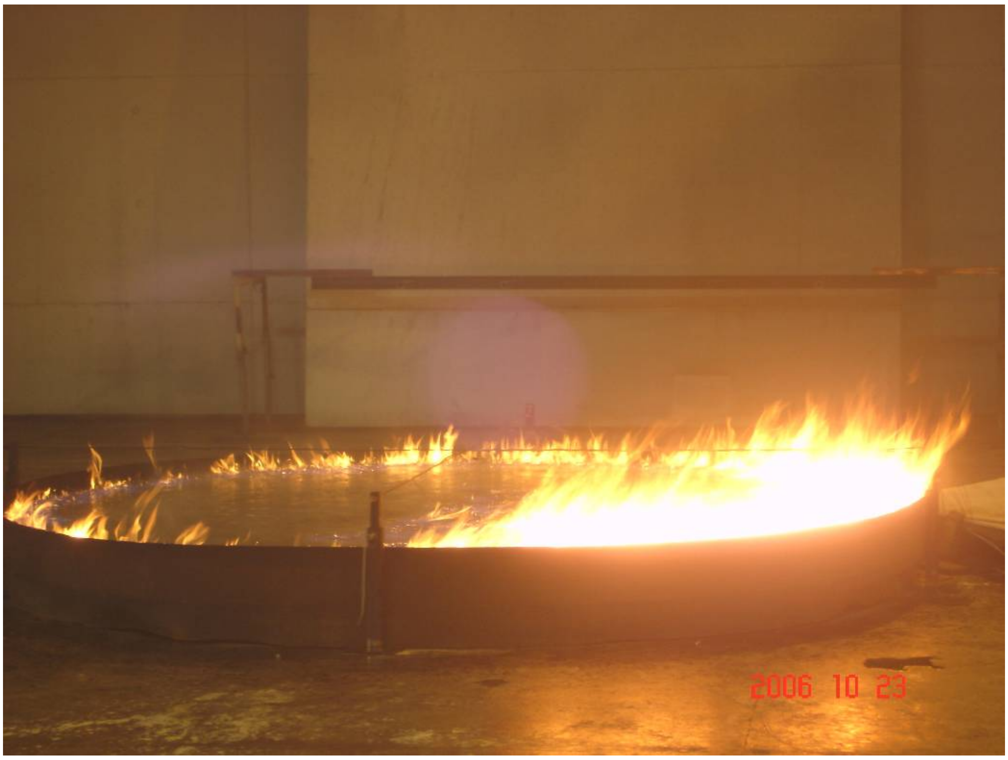


Photo 24 Test 14: Small flames, primarily around the perimeter of the fire tray.

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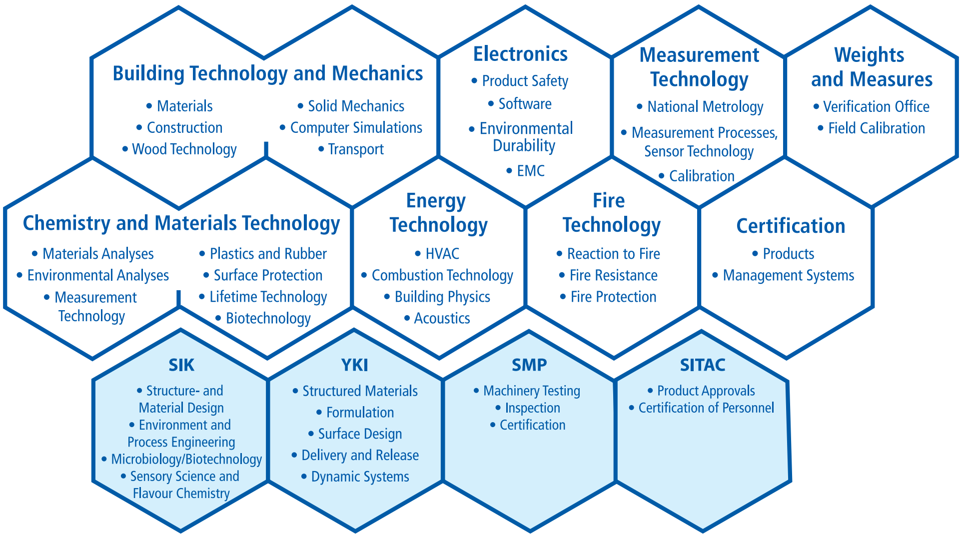

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