



Large-Scale Water Spray and Water Mist Fire Suppression System Tests for the Protection of Ro–Ro Cargo Decks on Ships

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Abstract. This paper summarises a series of large-scale fire suppression tests conducted to simulate a fire in the trailer of a heavy goods freight truck on a roll-on roll-off (ro–ro) cargo deck. The tests were conducted with a traditional deluge water spray system as well as a deluge high-pressure water mist system. Parameters such as the water discharge density, the system operating pressure, the nozzle K-factor and whether the fire was fully exposed to the water spray or shielded were varied. The total and convective heat release rate of the fire was measured in order to determine the fire suppression and fire control capabilities of the tested systems. Test results indicate that a water discharge density of at least 10 mm/min is necessary to provide fire suppression of a fire in a heavy goods freight truck, whilst 5 mm/min would provide fire control. Furthermore, the test results indicate that a high-pressure water mist system would require higher flow rates as compared to a traditional water spray system in order to provide fire control.

Keywords: Sprinkler systems, Water mist systems, Ro-ro cargo decks, Ships, Large-scale fire tests

1. Introduction

Vehicle spaces and ro–ro cargo decks on ships that cannot be closed and special category spaces¹ shall, according to the requirements of safety of life at sea (SOLAS) Chapter II-2, be fitted with a manually activated water spray system. For other types of ro–ro cargo spaces, where the risk of exposure of people to a potential fire or agent is lower—as passengers do not have access—carbon dioxide systems are normally used, although other types of inert gases, water spray or high-expansion foam systems are permitted. Detailed requirements for the design and installation of water spray systems for vehicle and ro–ro cargo decks are given in International Maritime Organization (IMO) Resolution A.123(V), published in 1967 [1]. Some detailed requirements that can be mentioned in particular are:

¹ “Special category spaces” are defined as enclosed spaces, situated above or below the bulkhead deck, intended for the carriage of motor vehicles with fuel in their tanks for their own propulsion and to which passengers have access.

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- The system shall be designed for a water discharge density of at least 3.5 mm/min for decks with a maximum height of 2.5 m and at least 5 mm/min for decks with higher height.
- The system is allowed to be divided into sections where each section should cover the entire width of the ship. Exemptions from this requirement may be allowed if the deck is separated longitudinally by 'A' class divisions.
- Each section must be at least 20 m long and the system's pumps must have a capacity sufficient for either the entire deck or at least two sections.
- At least one portable fire extinguisher must be available at each exit from the deck and at least three nozzles and a mobile foam cart shall be available on-board the ship.

The technical background of the requirements is unclear, but is likely a series of fire trials carried out in Denmark in 1961 [2].

In recent years, questions has been raised as to whether a water spray system in accordance with Resolution A.123(V) is able to control or suppress a fire on the ro-ro deck of a modern ship with modern cars, coaches and heavy goods vehicles [3]. With "fire control" is understood the limiting of the heat release rate of a fire. With "fire suppression" is understood a sharp reduction of the heat release rate and the prevention of regrowth.

A large-scale fire test with a layout that represented two heavy goods vehicles, side by side, on a ro-ro deck indicated that a water spray system would not provide fire suppression of such fires [4, 5]. Later, a feasibility study was carried out where the requirements and alternative sprinkler systems for ro-ro decks were discussed [6].

The influence of the ventilation conditions on fires on ro-ro decks has been investigated in model scale. These tests showed that a fire on a vehicle deck can be very large before it becomes ventilation controlled, due to the large volumes associated with ro-ro cargo decks. For decks that typically are 180 m in length, tests and calculations indicated that a fire can grow to almost 80 MW before the fire becomes ventilation controlled. The average gas temperature is high, of the order of 250°C to 300°C and consequently the temperature and heat radiation directly above the fire can be extremely high. There is an apparent risk for fire spread through the conduction of heat to decks above. As the maximum fire size is a function of the volume of the deck, sectioning of the deck can be an efficient way to limit the size of a fire [7].

The Maritime and Coastguard Agency has recently examined the issue of fire protection on ro-ro decks and, e.g., discuss the high fire load of ro-ro decks and the effectiveness of existing sprinkler systems. Their report draws two interesting conclusions: (1) the international shipping industry should coordinate their efforts and their knowledge in this area, (2) a program with large-scale fire tests should be carried out to increase the understanding regarding fires and fire scenarios on ro-ro decks including factors such as the type of combustible materials, ignition sources, vehicle size, vehicle breakdown on the deck, the position of sprinklers, water discharge densities ventilation flow rates, fire detection, additives to the water and drainage [8]. Based on this report, it was proposed that the ability to

use “water mist” systems or other types of fire-fighting systems be studied. The report and its conclusion were presented in a submission to the IMO FP51 in February 2007 [9].

In addition to the research described above, the EU project New European Ferry (NEF), whose outcome was presented in 2005, conducted an analysis of existing fire detection and water spray systems on ro-ro decks. Within the NEF project, better solutions were investigated with the help of CFD simulations. The analysis shows that a spill fire consisting of diesel combined with fire in a freight truck reaches a fire power of around 200 MW when the water spray system is not activated. A sprinkler designed under current requirements would only reduce the fire to between 40 MW and 60 MW, mainly because the vehicles prevent the water from reaching the seat of the fire. Higher water discharge densities do not seem to be more effective because of the shielding effect. An alternative system with low-mounted foam nozzles and water mist nozzles at the ceiling limited the spill fire such that that the total fire power was reduced to around 20 MW [10].

In order to develop a technical basis for replacing the design and installation guidelines of Resolution A.123(V), the IMPRO-project, “Improved water-based fire suppression and drainage systems for ro-ro vehicle decks” was initiated. The aim of this project was to evaluate modern water-based suppression technology in order to replace the design criteria in Resolution A.123(V), with the ultimate goal to increase the level of safety to a point where a fire can be at least suppressed, in order to allow for manual intervention under safe conditions.

The systems presented in this paper, and developed with ro-ro cargo decks on ships in mind, are applied to conditions with a high density of high risk vehicles coupled to a reduced ability for egress and manual intervention.

2. The Fire Test Set-Up

2.1. The Trailer Mock-Up

The mock-up was constructed to geometrically replicate a typical cargo trailer of a freight truck except that the overall length was shorter than in reality. A typical trailer could be in the order of 13.6 m in length. Tests were conducted both with

Table 1
The Dimensions of the Trailer Mock-Up

Proportions	Dimensions (m)
Length	5.50
Width	2.60
Overall height (without the roof)	3.50
Overall height (when the roof was used)	4.00 ^a
Height of cargo space (to the inside of the roof)	2.80
Height of cargo platform above ground	1.10

^a The maximum height of freight trucks in international traffic permitted under EU regulations. Higher freight trucks may be used in national traffic

and without a roof over the cargo space of the trailer model. Table 1 shows the dimensions of the trailer mock-up.

Six rows of commodity (see a detailed description below) were positioned on a platform such that longitudinal and transversal gaps of 100 mm were created between the stacks of commodity. For the tests with the roof on the trailer mock-up the amount of commodities was reduced to two rows, i.e., one-third of the amount of commodity used for the tests without the roof, refer to Figure 1.



Figure 1. The trailer mock-up without (top photo) and with a roof. Note that a smaller amount of commodity, two instead of six rows, was used for the tests with the roof. Steel screens instrumented with thermocouples were placed on both long side of the mock-up.

The reason for the reduced fire load when the fire was shielded for direct water application was the concern that the heat release rate of the fire would exceed the capabilities of the measurement equipment (as described in a separate section).

A steel screen was positioned parallel to the long sides of the trailer mock-up. The screens had a height (2.80 m) that corresponded to the height of the 'cargo space' of the mock-up. The tops of the screens were level with the top level of the roof over the trailer mock-up, i.e., 4.00 m above floor level. The length of 2.70 m was shorter than the overall length of the mock-up, but covered the two central stacks of commodity and extended halfway along the length (on either side) of the adjacent stacks. The surface temperatures of the steel screens were measured at 18 different measurement points. However, this data is not discussed within this paper as they correlated well with the trends of the other measurements.

2.2. The Commodity

The EUR Std Plastic commodity was used. This standard commodity consists of empty polystyrene (PP) cups without lids, placed upside down (i.e. open end down), in compartmented cartons, 120 cups per carton, refer to Figure 2.

The overall dimensions of one pallet load are 1,200 mm × 800 mm × 1000 mm (L × W × H) plus the height of the pallet (nominally 150 mm). The commodity contains 960 polystyrene cups per pallet load. The total weight (excluding the pallet) of one pallet load of the commodity is approximately 43.2 kg of which approximately 63% by weight is plastic, excluding the pallet. If the weight of the wooden pallet is included in this estimation, approximately 42% by weight is plastic.

For the tests, cartons were placed on a standard EUR wood pallet and the individual cartons were stapled against the wood pallet to increase stability. Two



Figure 2. One pallet load of the EUR Std plastic commodity (left) with a close-up photo of the arrangement of the plastic cups in the individual cartons (right).

pallets loads were positioned on top of each other which equalled an overall height of approximately 2.3 m. The vertical distance measured from the top of the commodity to the underside of the roof on the trailer mock-up (when used) was 0.5 m.

The EUR Std Plastic commodity is similar to the FM Global Std Group A Plastic commodity, i.e. it uses the same type materials, approximately the same overall size, the same density of plastic, etc. The FM Global Std Group A Plastic has been widely used in the fire protection community to create a representative “benchmark” warehouse fire hazard for evaluation of sprinkler fire protection performance in large-scale fire tests since the 1970s.

Although the EUR Std Plastic commodity does not represent the most severe commodity that can be found on a freight truck trailer in practice, it is considered representative of a high hazard commodity. The fact that it is established as a “benchmark” commodity in large-scale sprinkler fire tests makes it logical to use in these tests. Due to the high fire load, free-burn fire tests were not feasible. However, based on down-scaled (scale 1:4) fire tests conducted prior to the test programme an estimation of the severity of the fire load under free-burn conditions was possible. The test set-up was built in scale 1:4, which means that the size was scaled geometrically according to this ratio. Tests were conducted under a calorimeter in order to determine the heat release rate. The influence of the thermal inertia of the involved material, the turbulence intensity and radiation were neglected and the heat release rate, time, energy content and mass was scaled to large scale using established scaling laws [11]. Figure 3 shows the calculated total heat release rate for a test set-up consisting of six and two rows of commodity, respectively. For the latter case, a solid roof over the set-up was used.

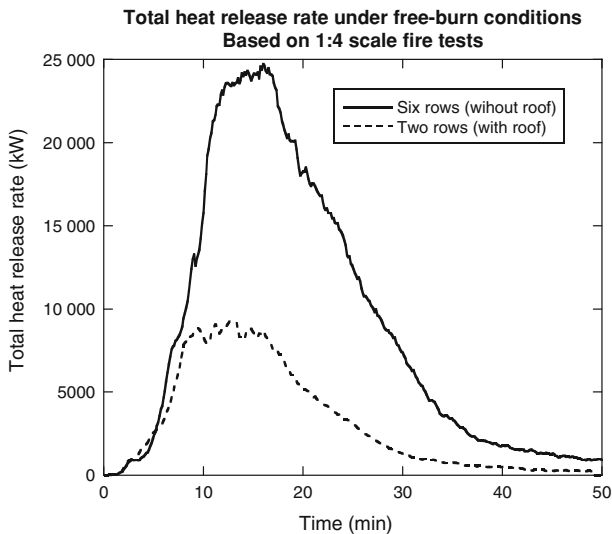


Figure 3. The potential severity of the test set-up based on down-scaled fire tests.

The tests indicate that six rows of commodity corresponds to a potential peak total heat release rate of almost 25 MW and two rows corresponds to a potential peak total heat release rate around 9 MW.

3. The Fire Suppression Systems

Two different fire suppression systems were used: a traditional deluge water spray system and a deluge high-pressure water mist system.

The piping arrangement for the water spray system was fabricated in a tree configuration. The system consisted of four 25 mm branch lines with nozzle connections for eight nozzles at a 3.2 m × 3.0 m nozzle spacing, i.e. a coverage area of 9.6 m² per nozzle. The pipe-work and the position of the nozzles relative to the trailer mock-up is shown in Figure 4.

The piping arrangement for the high-pressure water mist system was constructed in a similar fashion, except that 12 mm branch lines were used. The

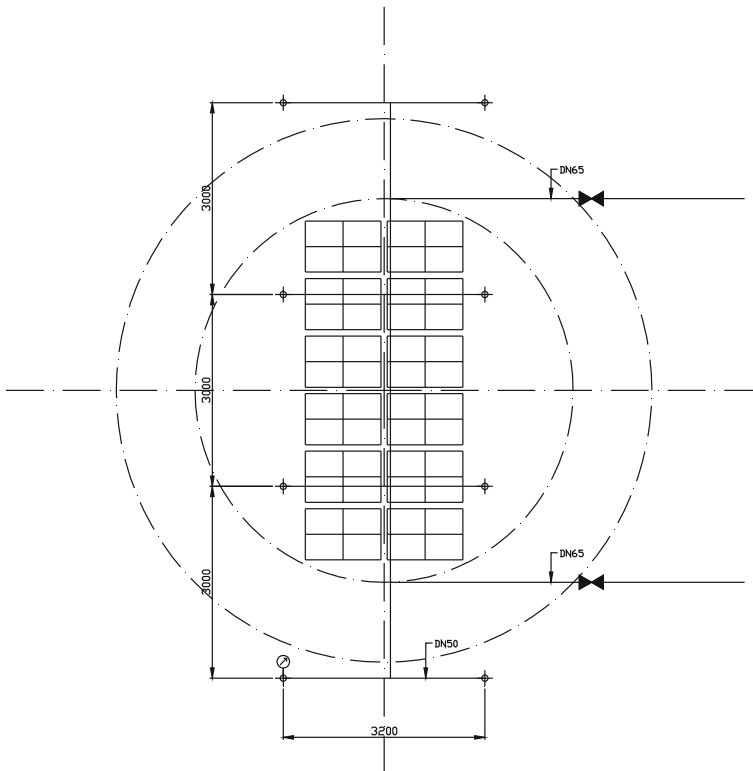


Figure 4. Top view of the position of the water spray and water mist nozzles relative to the trailer mock-up, with indications of the position of the Industrial Calorimeter used to measure the heat release rate.

pipng for the high-pressure water mist system was attached directly below the piping for the water spray system, which was elevated to keep the vertical distance from the tips of the water mist nozzles to the top of the test set-up analogous. The water spray system was therefore fully functional and used as a safety precaution during the water mist tests.

The vertical distance measured from the nozzles to the roof (when used) of the trailer mock-up was 0.5 m and the vertical distance to the top of the stacks of commodity was approximately 1.0 m.

The medium velocity nozzles used for the water spray system were open (non-automatic), pendent, directional discharge water spray nozzles. The nozzles had an external deflector that discharged a uniformly filled cone of medium velocity water droplets. The overall spray angle was approximately 180°. The K-factor of the nozzles was 43 (metric), 59 (metric), 81 (metric) and 104 (metric), respectively. The nozzle pressures ranged from 1.2 bar to 4.9 bar during the tests. The nozzles were provided by TYCO Fire Suppression & Building Products in Sweden.

The high-pressure water mist nozzles were open (non-automatic) multi-orifice nozzles without any external deflector. When spraying, the nozzle discharge formed a solid cone-shaped spray pattern of high velocity jets that broke up into small water droplets at a relatively short distance from the nozzle orifices. The overall spray angle was approximately 160°. The K-factor of the nozzles was 3.6 (metric), 4.4 (metric) and 6.1 (metric), respectively. The tests were conducted at either 100 bar or 84 bar. The nozzles and the associated equipment were provided by Ultra Fog AB in Sweden. The water spray medium velocity nozzles and high-pressure water mist nozzles are depicted in Figures 5 and 6, respectively.

In order to provide fire suppression, full coverage of the water spray over the burning surfaces is important. For the fire test set-up used in these tests, the coverage between the four central nozzles is important to distribute water towards the central flue spaces of the commodity stacks. Distribution of water on the outside of the stacks of the commodity is also important. Prior to these large-scale tests, water distribution tests were conducted to select the best possible nozzles with a focus on such features [12]. Indeed, the nozzles used in the tests may represent the best the market could offer for this specific hazard.

4. Instrumentation and Measurements

The tests were conducted under the industrial calorimeter, a large hood connected to an evacuation system capable of collecting all the combustion gases produced by the fire. In the duct connecting the hood to the evacuation system, measurements of gas temperature, velocity and the generation of gaseous species such as CO₂ and CO and depletion of O₂, can be made. Based on these measurements, both the convective and the total heat release rate can be calculated. These, and the other parameters described below, were used for the evaluation of the test results.

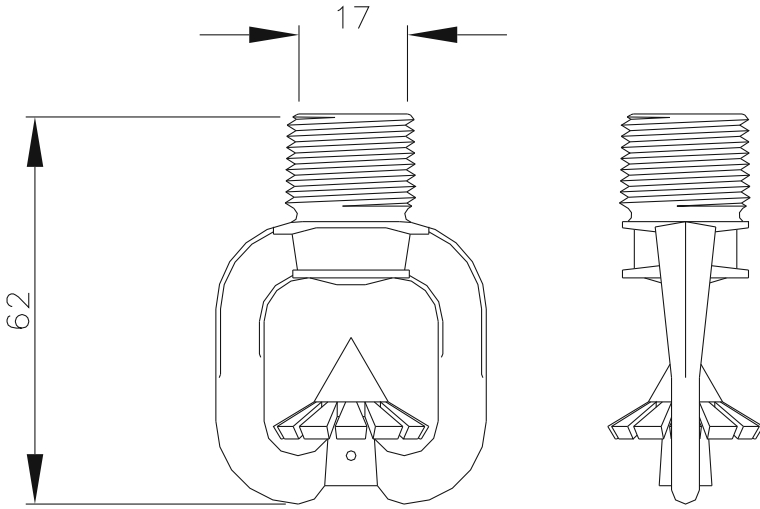


Figure 5. A principle drawing of the open (non-automatic) medium velocity nozzles used with the water spray system. The actual nozzles used in the test have a horizontal deflector.

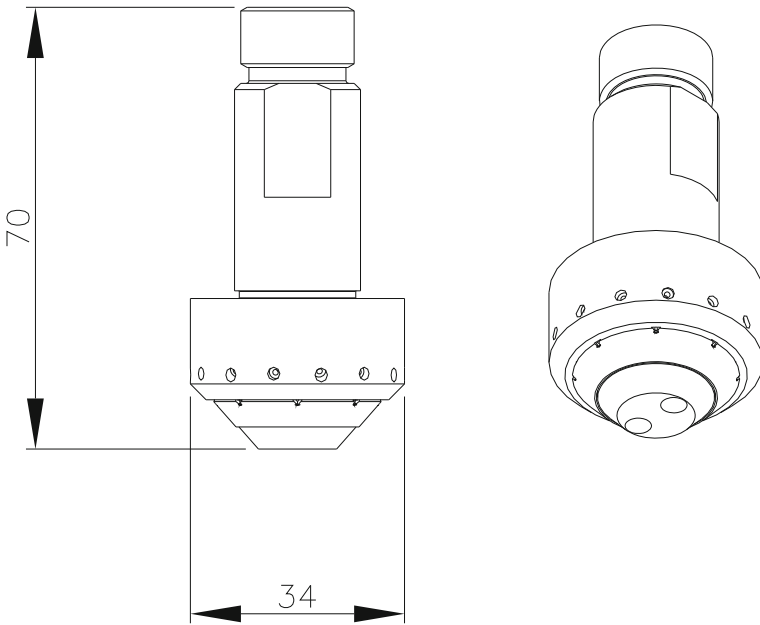


Figure 6. A principle drawing of the open (non-automatic) high-pressure water mist nozzles used in the tests.

4.1. *HRR_{conv}*

The convective heat release rate measured during a test is calculated on the basis of the gas temperature and mass flow rate in the calorimeter system. The convective fraction of the total heat release varies with the fuel and other factors, but usually approximately two-thirds of the energy generated by a fire is released through convection. Additionally, convection has a strong impact on the velocities and temperatures within the fire plume. The velocity and temperature in the fire plume determines the rate of heat transfer, i.e., the convective heat release rate is also essentially responsible for the activation of sprinklers and the heating of the overhead ceiling or deck. The maximum convective heat release rate is, therefore, one of the most important quantities for characterising fire severity. For these tests, the maximum “one minute average” was calculated. This metric is preferred over the instantaneous maximum as spikes due to, e.g., environmental changes, electrical noise, etc., have minimal influence on the averaged value.

4.2. *HRR_{tot}*

The total heat release rate measured during a test is calculated on the basis of the oxygen depletion of the fire, as measured in the calorimeter system. HRR_{tot} is comprised of both the convective and radiative heat release rate, as well as the heat being conducted away and absorbed within the test set-up. During the fully developed stage of a fire, however, heat conduction and absorption is relatively small compared to the convective and radiative components. Radiation is the primary mechanism by which fire spreads across aisles and other open spaces to adjoining combustibles. It is also, in part, responsible for lateral fire spread throughout a large fuel array, as well as an overall fundamental measure of fire severity. This parameter was also calculated as the maximum “one minute average”.

4.3. *The total convective energy*

The energy convected upwards is largely responsible for heating of the exposed steel at the ceiling (or a steel deck) and the activation of automatic sprinklers. The total convective energy, calculated from fire ignition until the termination of a test helps to characterise fire severity; as in the case of heat transfer, duration is as important as magnitude. Some fires are very intense but short-lived and their thermal impact may be less severe than a fire of lower intensity with a longer duration. The total convective energy is an important measure of a fire’s maximum potential for causing thermal damage.

4.4. *The total energy*

The total energy, in this case determined from fire ignition until the termination of a test, is a measure of the amount of combustibles being consumed.

5. Fire Test Procedures

The commodity was ignited at the flue, near the bottom of the central stacks using four standardised ignition sources positioned directly against the corrugated cartons. The ignition source consisted of a cube, 60 mm × 60 mm × 75 mm, made from pieces of insulating fibre board. Each cube was soaked with 120 mL of heptane and wrapped in a polyethylene plastic foil bag prior to the test. The tested system was manually activated at a convective heat release rate of 3 MW, which equalled a total heat release rate of approximately 5 MW. Figure 7 shows

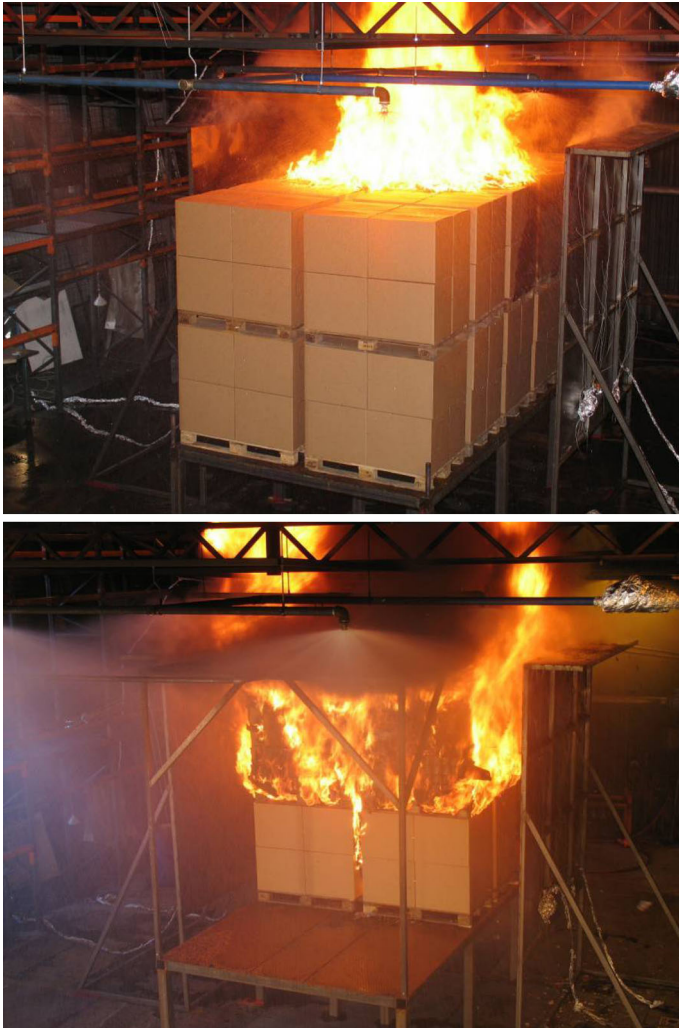


Figure 7. The fire size of approximately 5 MW at the manual activation of the system for the tests without (*top photo*) and with the roof on the trailer mock-up.

the fire size at the manual activation of the system. For one of the tests, the system was manually activated at a convective heat release rate of 6 MW, which equalled a total heat release rate of approximately 10 MW. The intent of the test was to explore the fire suppression capabilities against a fire twice as large as in the other tests.

The heat release rates at activation are considered realistic for actual fires, where the deluge system typically is manually activated. It was also considered important that the fire was well-established in the commodity prior activation.

6. Fire tests

The following 14 fire tests were conducted with and without the roof on the trailer mock-up, refer to Tables 2 and 3, respectively.

For the tests with the roof on the trailer mock-up, the amount of commodity was reduced to two rows, i.e., one-third of the amount of commodity used for the tests without the roof.

7. Fire Test Results

Figures 8, 9 and 10 shows the measured total heat release rates as a function of the system discharge densities, the convective heat release rate histories are not given in this paper but can be found in reference [6].

8. Discussion

8.1. Fire Tests Without the Roof on the Trailer Mock-Up

Figures 11 and 12 show histograms of the maximum 1 min average total and convective heat release rates and the total and convective energy, over the full test duration time, respectively, for all tests without the roof on the trailer mock-up.

The tests where the fires were fully exposed to the water spray, i.e. the tests without the roof, show that there is a clear relationship between the level of fire suppression performance and the water application rate. A discharge density of 15 mm/min provided immediate fire suppression, 10 mm/min fire suppression, and 5 mm/min, fire control.

When discharging 10 mm/min at the higher system operating pressure, i.e. 4.9 bar instead of 1.2 bar, improved performance based on a comparison of both the total and convective energy, was achieved with the water spray system. This is an indication that smaller droplets improve system performance with regards to fire damages and the potential for causing thermal damage. The maximum 1 min average total and convective heat release rates were, however, similar to the test when 10 mm/min was discharged at the lower system operating pressure. This shows that the fire suppression capabilities were similar, irrespective of the system operating pressure.

Table 2
Fire Tests Conducted Without the Roof on the Trailer Mock-Up

Type of system	Nozzle K-factor ((L/min)/bar ^{1/2})	System operating pressure (bar)	Water flow rate per nozzle (L/min)	Total water flow rate (L/min)	Nominal discharge density (mm/min)
Water spray	103.7	1.9	144	1,152	15
Water spray	80.6	1.4	96	768	10
Water spray	43.2	4.9	96	768	10
Water spray	43.2	1.2	48	384	5
Water mist	3.6	100	36	288	3.75
Water mist	4.4	100	45	360	4.6
Water mist	6.1	84	56	447	5.8
Water spray ^a	43.2	4.9	96	768	10

^a Manually activated at a convective heat release rate of 6 MW instead of 3 MW

Table 3
Fire Tests Conducted with the Roof on the Trailer Mock-Up

Type of system	Nozzle K-factor ((L/min)/bar ^{1/2})	System operating pressure (bar)	Water flow rate per nozzle (L/min)	Total water flow rate (L/min)	Nominal discharge density (mm/min)
Water spray	103.7	1.9	144	1,152	15
Water spray	80.6	1.4	96	768	10
Water spray	43.2	4.9	96	768	10
Water spray	43.2	1.2	48	384	5
Water spray ^a	103.7	1.9	144	1,152	15
Water mist	6.1	84	56	447	5.8

^a Repeat test due to a leakage of the roof

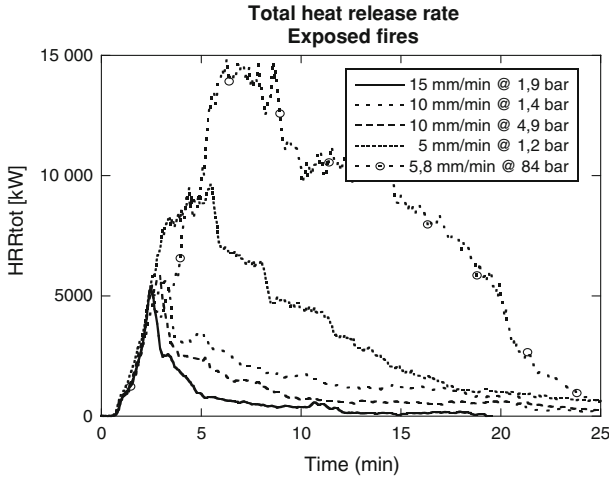


Figure 8. Total heat release rate histories for the fire tests without the roof on the trailer mock-up.

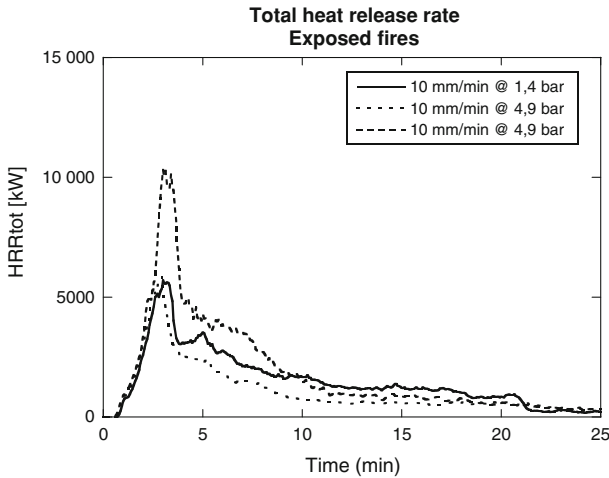


Figure 9. A comparison of the total heat release rate histories for the fire tests discharging 10 mm/min, including the test where the system was activated at 10 MW instead of 5 MW. All tests without the roof on the trailer mock-up.

For the final test, the activation of the system (also 10 mm/min at 4.9 bar) was intentionally delayed until the fire size was twice as large as in the other tests. Despite this, the fire was almost immediately suppressed.

The first two tests with the high-pressure mist system were conducted at discharge densities of 3.75 mm/min and 4.6 mm/min, respectively. Both tests had

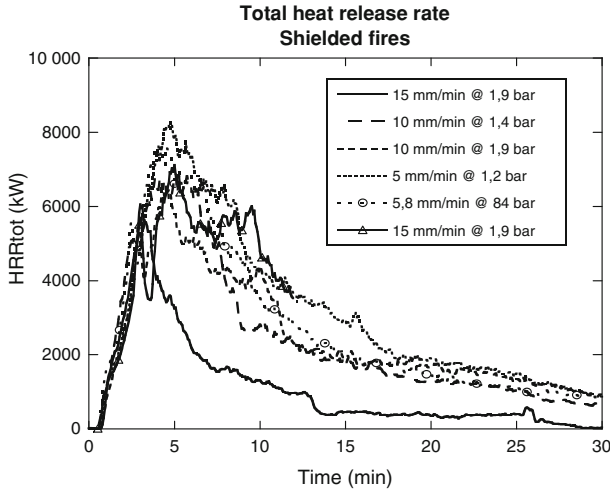


Figure 10. Total heat release rate histories for the fire tests with the roof on the trailer mock-up. Note: Leakage of the roof over the trailer occurred in the first test at 15 mm/min, hence the improved performance.

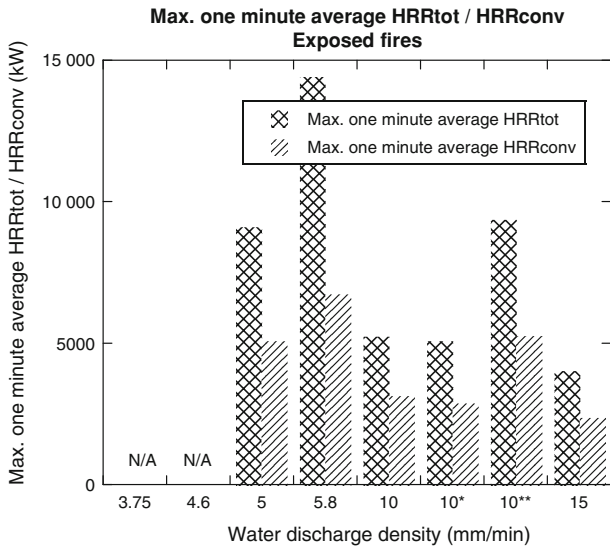


Figure 11. The maximum 1 min average total and convective heat release rate for the fire tests without the roof on the trailer mock-up. The (*) indicates the test discharging 10 mm/min at 4.9 bar instead of at 1.9 bar and () the test where the system was activated at 10 MW instead of 5 MW.**

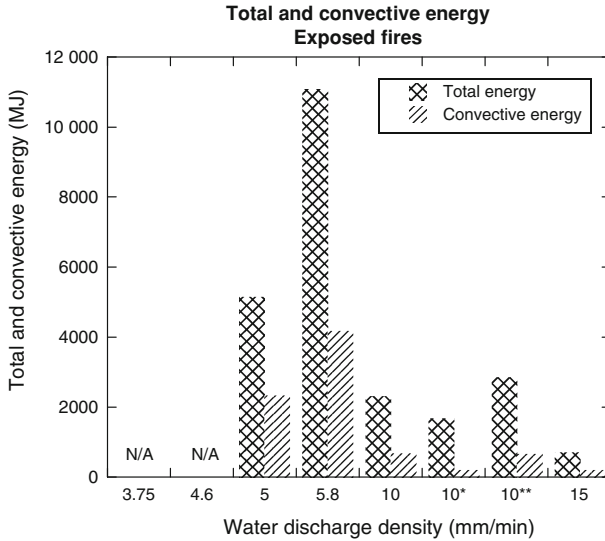


Figure 12. The maximum total and convective energy for the fire tests without the roof on the trailer mock-up. The (*) indicates the test discharging 10 mm/min at 4.9 bar instead of at 1.9 bar and () the test where the system was activated at 10 MW instead of 5 MW.**

to be terminated as the fires grew out of control of the system capabilities. To stop the fire growth, the water spray system, whose piping and nozzles remained installed over the pipe-work of the mist system as a safety precaution, had to be manually activated. In both cases, the activation of the water spray system suppressed the fire immediately, however, the heat release rate histories are not shown here and the remaining fire was manually extinguished very easily. As the water flow meter of the water spray system was connected to the measurement system, it was possible to determine the water discharge densities that were applied when additional water was used. For the test at 3.75 mm/min, the application of water spray was started when the fire exceeded a total heat release rate of 18 MW and the water discharge density equalled almost 14 mm/min. For the test at 4.6 mm/min, the application of water spray was started when the fire exceeded a total heat release rate of 15 MW and the water discharge density was 14 mm/min.

The third fire test with the high-pressure water mist system was conducted with a water discharge density of 5.8 mm/min, which provided fire control. Nonetheless, the maximum 1 min average total and convective heat release rates were approximately twice as high for this test as compared to the test with the water spray system at 5 mm/min.

The total and convective energy was also approximately twice as high for the test with the water mist system compared to the water spray system test at 5 mm/min which would indicate a high potential for causing thermal damage. Visually it could also be determined that considerably more combustible material was consumed during the water mist test.

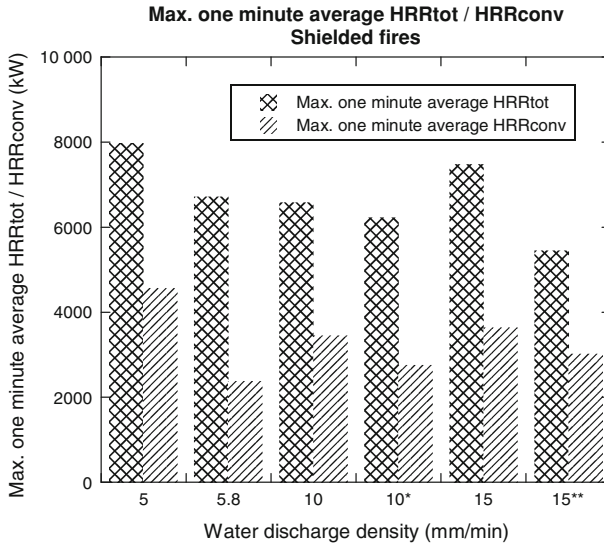


Figure 13. The maximum 1 min average total and convective heat release rate for the fire tests with the roof on the trailer mock-up. The (*) indicates the test discharging 10 mm/min at 4.9 bar instead of at 1.9 bar and () the test at 15 mm/min where the leakage of the steel roof over the trailer occurred.**

The explanation for the performance of the water mist as compared to the water spray system is probably as follows: for a water spray or water mist system to successfully suppress a fire in ordinary combustibles, the droplets must be capable of penetrating the fire plume to reach the burning fuel surface. In other words, the total downward momentum of the water spray needs to overcome the upward momentum of the fire plume. Penetration of droplets may also be reduced by the evaporative loss of the smallest droplets as they pass through the fire plume. Although this will tend to cool the flame gases, it will contribute little to the control of a fast-growing fire [13].

8.2. Fire Tests with the Roof on the Trailer Mock-Up

Figure 13 shows a histogram of the maximum 1 min average total and convective heat release rates, respectively. Figure 14 show a histogram of the total and convective energy, respectively, from fire ignition to 14:00 [min:s]. Due to a short-circuit in the electrical power supply to the high-pressure pump unit, the application of water was stopped at 14:00 [min:s] during the water mist test. A straightforward comparison of the total and convective energy over the full test duration time is, therefore, not possible.

All discharge densities had limited fire suppression performance, as indicated by the high maximum 1 min average heat release rates.

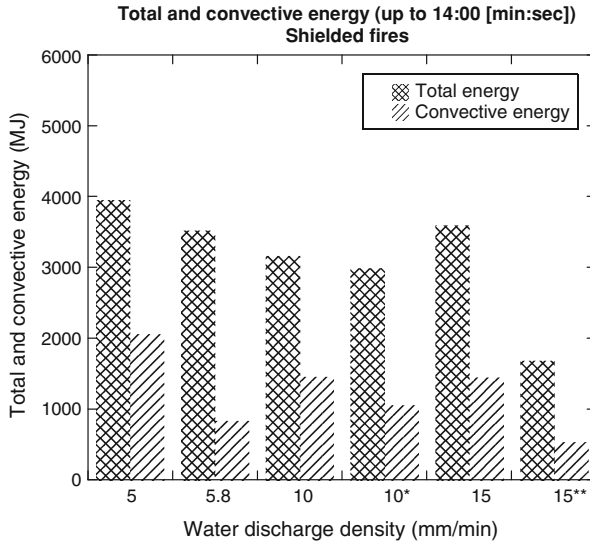


Figure 14. The total and convective energy as a function of the water discharge densities, calculated from fire ignition to 14:00 (min:s), for the fire tests with the roof on the trailer mock-up. The (*) indicates the test discharging 10 mm/min at 4.9 bar instead of at 1.9 bar and (**) the test at 15 mm/min where the leakage of the steel roof over the trailer occurred.

Almost all combustible material was consumed in the tests. The best reduction of the total energy was achieved in the tests with a water discharge density of 10 mm/min at 4.9 bar pressure. The least reduction of the total energy was recorded with a discharge density of 5 mm/min, where virtually all combustible material was consumed.

The most efficient reduction of the convective heat release rate and the associated convective energy for the water spray system tests was demonstrated when discharging 10 mm/min at 4.9 bar. The water discharge density of 5 mm/min reduced the convective heat release rate the least of the tested water spray systems, which probably is due to the low discharge density.

It is noteworthy that water spray system test at 15 mm/min performed worse than both water spray system tests at 10 mm/min. The reason may be the larger K-factor nozzles, associated with larger droplets, used to discharge 15 mm/min.

A small leakage of the steel roof was discovered after the first test at 15 mm/min and the test was therefore repeated. The leakage appeared along the junction between steel plates used for the roof. The steel plates moved apart during the test and the two longitudinal, parallel gaps that were formed were of the order of a few millimetres in width. Although the test data cannot be used for a direct comparison with the other tests, the reduction of the fire size that was experienced is interesting to note. If the roof on a real vehicle burns through, water

from the water spray system will have access to the fire and the performance will be significantly improved even if the leakage area is small.

Only one test was conducted with the high-pressure water mist system which makes a comparison of the efficiency at different discharge densities with this system impossible. When comparing the results with the water spray system tests it can be concluded that the water mist system reduced the total energy to a level that was slightly lower than the water spray system discharging at 5 mm/min. However, the reduction was not as efficient as the water spray system when discharging at 10 mm/min.

For the water mist system, the total convective energy was reduced to a level that was significantly less than all water spray system tests which underlines the improved cooling efficiency of the smaller water droplets.

This can be attributed to the improved cooling of hot combustion gases of the smaller droplets and will translate to a reduced potential for thermal damage to a steel deck above the fire. However, no improved reduction of the total heat release rate and the associated total energy was documented, i.e., the ability to reduce the actual heat release rate was not enhanced. Visually, it could be determined that almost all combustible material had been consumed during the water mist system test.

9. Conclusions

The tests where the fires were fully exposed to the water spray show that there is a clear relationship between the level of suppression performance and the water application rate. A discharge density of 15 mm/min provided immediate fire suppression, 10 mm/min fire suppression, and 5 mm/min fire control. However, improvements in performance were documented with a higher system operating pressure and associated smaller water droplets, i.e. when 10 mm/min was applied at 4.9 bar instead of 1.2 bar. An increased system operating pressure could also increase the velocities and the mobility of the droplets, but this is counteracted to a certain degree due to a reduction of the ability of the droplets to penetrate the fire plume due to their lesser size. Care should therefore be given to the maximum installation height of such a system on an actual ro-ro cargo deck.

The high-pressure water mist system provided fire control at a discharge density of 5.8 mm/min, but not to the level that was achieved with the water spray system at 5 mm/min. Water mist tests at 3.75 mm/min and 4.6 mm/min, respectively, provided no fire control and had to be terminated.

For the tests where the fire was shielded from direct water application, i.e. when a roof was used over the cargo space of the trailer model, the tested systems had a limited effect on the total heat release rate and the associated total energy, indicated by the fact that almost all combustible material was consumed. The most efficient reduction of the convective heat release rate and the associated convective energy during the water spray system tests was demonstrated with an application rate of 10 mm/min at an operating pressure of 4.9 bar. The water spray system tests also indicate that if the roof on a real vehicle burns through, water will have

access to the fire and the suppression performance will be significantly improved, even if the leakage area is small.

The high-pressure water mist system provided an improved reduction of the convective heat release rate and the associated convective energy as compared to the water spray system of the shielded fire. This can be attributed to the improved cooling of hot combustion gases of the smaller droplets. However, no improved reduction of the total heat release rate and the associated total energy was documented, i.e., the ability to reduce the actual heat release rate was not enhanced.

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