



Methods and equipment for fire fighting with alternative fuel vehicles in ro-ro spaces

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Abstract

This report summarizes advantages and limitations of different systems and tactics used in fire fighting operations in ro-ro spaces. This comes from an increase need of effective and efficient fire fighting operations when alternative fuel vehicles (AFV) are involved. Tests have been conducted to evaluate systems' ability to reduce the risk of fire spread to adjacent objects and their practical usability in ro-ro spaces. The fire tests for example quantified the attenuation of radiation through the water spray (blockage effects) of different systems. The fire tests showed that several systems have the capacity to reduce the risk of fire spread, but this must be compared with how firefighters can use them in real fire fighting operations in ro-ro spaces. Furthermore, selected fire fighting tactics were practically evaluated for their possible use in ro-ro spaces. The results are applicable for new fire fighting tactics for safer and more efficient manual fire fighting operations.

Methods and equipment for fire fighting with alternative fuel vehicles in ro-ro spaces

Key words: Fire test, Alternative Fuel Vehicle, ro-ro spaces, fire fighting, electrical vehicles, gas vehicles

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Preface

The tests and the simulations performed constituted parts of the Swedish research project BREND (Brand i nya energibärare på däck/Fire in new energy carriers on deck). The project was led by RISE and funded by The Swedish Transport Administration (Trafikverket) and The Swedish Mercantile Marine Foundation (Stiftelsen Sveriges Sjömanshus).

RISE would like to thank the suppliers of tested systems: Dafo Brand AB, Presto Brandsäkerhet AB, Svenska Brandslangsfabriken AB, Cold Cut System AB, X-fire AB, GPBM Nordic AB and TST Sweden AB.

Tests were carried out in the fire hall at RISE Fire Research laboratory in Borås in December 2018 and at Guttasjön training field in May 2019. We would like to thank the personnel from Södra Älvsborgs Fire and Rescue Service, Stena Teknik and Destination Gotland, who took part in the tests. We would also like to thank the advisory group and the technicians at RISE and Guttasjön training field, who assisted in the performance of the tests.

Summary

RISE Research Institutes of Sweden have carried out fire tests to evaluate fire fighting methods in case of a fire involving alternative fuel vehicles (AFV) in a ro-ro space. This report presents how selected fire fighting methods were practically evaluated for their possible to use in ro-ro spaces. The results can be applied for safer and more efficient manual fire fighting operations, which is increasingly important when carrying AFVs.

The fire tests were performed in a large fire test hall at RISE Fire Research in Borås and the fire load was represented by a steel mock-up of a personal vehicle with a propane test rig, creating a fire of 4 MW. Steel walls, representing adjacent vehicles, were fitted with thermocouples to measure the temperature 0.6 m from the mock-up vehicle. Extinguishing media were applied between the mock-up and the steel wall on the left-hand of the vehicle and the temperature reduction was measured. The results present the reduction coefficient achieved by different systems, i.e. the heat blockage effect achieved by the systems. A high reduction coefficient indicates that the system has a high capacity to reduce heat exposure and prevent fire spread to an adjacent vehicle.

For handheld system, the highest reduction coefficient was achieved by the Industrial system and the FRS system (but only with a high water flow rate), providing both a reduction coefficient of 0.64. Reduction coefficient on the opposite side of the vehicle, from where the water was applied, also varied between the different systems. The highest reduction coefficient on this side was achieved by the high pressure 60 system, providing a reduction coefficient of 0.34. For water curtain system the Hose provided the highest capacity to reduce heat exposure on both side of the vehicle.

How different tactical options could optimize the performance of the handheld systems was evaluated primarily by visual observations. After the first part of the test was conducted (measuring blockage effects) the operator was able to oscillate the water spray, both up and down and over the vehicle. The operator also approached the vehicle from the front, at an angel of 45°, in order to observe the effects with respect to cooling or suppression. By varying the technique, it was possible to optimize the cooling effect on both sides of the vehicle, but the operator must be able to adjust cone angle and water spray pattern to maximize the effect. During this part of the tests it was possible to observe that some systems had a limitation in capacity with respect to cooling or suppression, especially if the pressure was low or if it had a low water flow rate. The water curtain systems were not able to affect the other side of the vehicle, which indicates the need of positioning the nozzle or hose on at least two sides of the burning vehicle to be able to efficiently prevent fire spread.

A field test (outdoor) was also conducted to evaluate the practical usability of the tested systems. A simulated ro-ro space was built up on a fire rescue training field where relevant crew tried different tactical options with the different system. It was found that a semi-rigid hose with a small inner diameter is much easier to handle in most cases but must be compared with desired capacity of pressure, water flow rate and throw length. A hose with a larger inner diameter will have greater stiffness which proved to be useful when trying to position water curtain nozzles. The tests showed that it is possible to position water curtain nozzles to prevent fire spread, but the hose most be further developed to be able to use in ro-ro spaces.

1 Introduction

This report is part of the final documentation of the research project BREND (2018-2019), investigating how Alternative Fuel Vehicles (AFV) can be handled in case of a fire in a ro-ro space. In the beginning of the project, a workshop was organized to discuss different challenges and possibilities with manual fire fighting of AFV fires in ro-ro spaces. A thorough literature study on fire hazards associated alternative fuel vehicles was the basis of this workshop, and numerous questions were raised during the workshop that needed to be considered in the tests. For example, how should the fire be reached and is there a safe escape route? From where can the fire be approached safely and how can the fire be suppressed without risking the safety of the firefighters? What are the consequences in relation to the choice of extinguishing agent? What are the possibilities and challenge with different fire fighting technics and tactics? These are all relevant questions that need answers, in particular in relation to alternative fuel vehicles.

The results from BREND are presented in two reports: (1) The main report documents the results of a literature study, workshop, simulations, summary of performed tests and a guidance paper on fire fighting tactics when AFVs are involved in fire in a ro-ro space. (2) A report presenting the results of the fire tests and field tests (present report).

From the literature review (Vylund et al 2019), it was concluded that when the fire is small and the fuel storage is not affected, the tactics should be the same for all types of vehicles. However, when the fire fighting team is ready to attack, the fire is likely large. If gas vehicles are present, they could therefore be affected by the fire. Manual fire fighting should then not be carried out near the fire. If an electrical vehicle is on fire and the fire provokes a thermal runaway in the battery, propagation inside the battery and resulting fire development will be very difficult to prevent, since it is extremely difficult to reach the cells of the battery with extinguish media. Even if the fire does not involve batteries or gas tanks, it is recommended to not be close proximity of a burning vehicle due to the risk of small explosions from e.g. air bags.

The carriage of AFVs makes it important to investigate the effectiveness of different suppression methods and equipment for defensive tactics, where fire is suppressed and fire spread is prevented efficiently and from a distance. Furthermore, in many ro-ro spaces it is difficult to reach the burning vehicle due to narrow distances between vehicles. Vylund et al (2019) also concluded that fire fighting teams on-board have limited time to practice and that it is important the system do not demand a lot of training to become efficient. It is also important that the equipment can be used in many situations, as it is not possible for the fire fighting team to carry a lot of different equipment with them. A quick response is important which requires that the equipment is easy to carry, set up and operate. Additionally, the water consumption is an aspect which is important to consider onboard.

1.10bjective

The objective was to find out advantages and limitation of new tactical methods and equipment for fire fighting operations in ro-ro spaces by evaluated them with respect to their capacity to prevent fire spread when AFVs are involved. The evaluation considering for example attenuation of radiation and usability in ro-ro spaces. The results were to be used to develop guidance for training and implementation of fire fighting methods and equipment on ro-ro ships.

With improved knowledge about advantages and limitations of various fire fighting methods and equipment, the prerequisites for accomplishing better and more efficient fire fighting operations will increase.

1.2 Delimitation

This report studies different systems that can be used in manual fire fighting operations. A more comprehensive discussion about fire fighting tactics, considering for example detection, use of sprinkler, decision support, etc. can be found in the main report (Vylund et al 2019).

A vehicle fire produces a large amount of dense toxic gases, at the same time as the ventilation possibilities in ro-ro spaces can be limited. The visibility for the firefighters is important in order to conduct their operations. It is seldom possible to force the air flow in a certain direction (except in specific locations between the inlet and the outlet) but there can be possibilities alter the ventilation to remove both smoke and toxic gases to a certain degree. There is however seldom a possibility to create a clear route for a fire fighting team. The effects of the ventilation on fire fighting are important but were not investigated in this study. The effects of different ventilation systems on smoke spread was although studied in the parallel study by Olofsson et al (2019).

2 Tested system

Properties of fire fighting systems should be compared based on handling performance and requirements for efficiency and safety in connection with the fire fighting operations. Onboard crews have limited training in fire fighting according to international requirements. Fire fighting in ro-ro spaces involves restrictions in access to suppression agents and personnel. The focus was therefore to find fire fighting technics that are easy to use, require little personnel and education and which are also efficient and avoid risks for crew and persons onboard.

The systems used during the tests were firstly identified in a workshop together with ship personnel, authorities and Land based fire and rescue service, and secondly during interviews with system suppliers. The systems selected were divided in two groups:

- Handheld systems, and
- Water curtain systems.

The main difference between these systems types is that the firefighter needs to hold the first system, whereas water curtain systems only require presence of firefighters to assist the system.

A total of ten systems were studied and all of them are presented in the following sections.

It should be noted that another type of system was studied, namely AVD (see below), which however does not comply with the definitions of the above-mentioned system types. Systems complying with the two groups are based on the blockage of thermal radiation to avoid the spreading of fire. The system not complying with the definition is based on creating a non-flammable oxygen barrier between the fuel and the atmosphere, preventing further fire propagation.

2.1.1 Handheld systems

For the handheld system, a total of five systems were studied. The first one was one of the most common system used in the Swedish fire and rescue service, referred to as **fire and rescue service system (FRS)**, see Figure 1. The system can work with a water flow rate ranging between 40 to 500 l/min with a water pump pressure of 10 bar. The nozzle with a flow setting ring and a rotating toothed ring can create everything from a wide water mist spray to a straight narrow stream trajectory. Additionally, cone angle and water flow rate can be adjusted independently of each other. The nozzle was attached to a hose with an inner diameter of 38 mm.



Figure 1: FRS system used in test 3, test 12a and test 12b.

Thereafter, a nozzle with fixed toothed ring made for industrial applications was tested (see Figure 2), referred to as **industrial system**. The operator can adjust the water stream from a wide water mist spray to a jet stream. The maximal working pressure is 10 bar and the water flow rate range is 130 - 200 l/min. The hose used in the test was a semi-rigid hose (formtex industri extra) with an inner diameter of 25 mm.



Figure 2: Nozzle with fixed toothed ring and a semi-rigid hose (formtex industry extra) with an inner diameter of 25 mm.

Three different systems mainly used to cool hot gases from outside of a building were also tested. The systems create fine water mist with the potential to rapidly absorb heat from the hot flames and from the smoke. By evaporating water mist droplets, the partial pressure of oxygen inside the fire room is lowered and an inerting effect occurs. In order to take full advantage of this effect, it is important that the fire room is an enclosed space. Through the smaller water droplets and the smaller amount of water used with water mist, the water mist evaporates more efficiently than when extinguishing with conventional low pressure systems and larger droplets.

Fognail¹ (see Figure 3) has a water flow rate of about 70 l/min and is possible to use with two different nozzle patterns, attack and defence, respectively. In the test, the attack nozzle was used because the throw length of the water stream is longer than for the defence-nozzle. The system creates a water cone with a diameter of approximately 1 m and a throw length in the range of 7-10 m. Restrictions of the throw length and spread of water mist demands a certain proximity to the fire while the extinguishing attack continues. The fognail is usually applied by inserting the nail into the wall or openings of a building and then pulsating the water to obtain convection and steaming, but in this case it was used for direct application in manual fire fighting.



Figure 3: Fognail with attack nozzle.

The other systems were two different **high pressure systems with cutting function** (see example of one of the systems in Figure 4). One system had a pressure of 300 bar and a water flow rate of 60 l/min, and the other had a pressure of 350 bar and a significantly lower water flow rate of 22 l/min. The cutting function is achieved by a mixture of water and cutting agent (abbreviate) being ejected through a nozzle at high pressure. These high pressure systems create smaller droplets and the effects of the water mist can throw longer in the fire room than for example a fognail, which is used with lower pressure. The first 5-6 m of a water spray from a high pressure system (< 250 bar) with a water flow rate of 50-70 l/min is narrow, with the bulk of the water near the center of the spray. After 5-6 m the spray breaks up into a compact water mist with a cross-sectional area of about 3 m². The water droplets in the spray after the breakup are so small (volume diameter about 0.1 mm) that they are rapidly retard due to the friction with the quiescent air and, after a very short distance, undertake the same speed as the air. During the retardation, the kinetic energy of the droplets is transferred into the air,

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¹ Known in Sweden as "dimspik"

creating air flow corresponding to a fan with a capacity of $10-15 \text{ m}^3/\text{s}$. The fine droplets cause the radiation to be reduced by a factor of 5-10 when passing through a 3 m thick water mist at 6-10 m from the site of the firefighter operator (Holmstedt et al 2015).



Figure 4: High pressure system.

The final handheld system was a **foam-based** extinguishing system (see Figure 5), optimized for breaking surface tension of the water droplets and thereby creating increased cooling. The spray itself can be directed in such a way that it creates a heat shield to prevent fire spread against adjacent objects. The system consists of a special made semi-rigid hose with an inner diameter of 25 mm to simplify system handling. The tested system had a new nozzle, developed during the project, with optimized drip size to be able to generate a relatively fine jet creating a wall/heat shield that absorbs the heat radiation. During the test, a prototype of the nozzle was used because the nozzle was not fully optimized yet.



Figure 5: Foam-based system.

2.1.2 Summarize of handheld systems

In Table 1, a summary is given of the evaluated systems, their water flow rates and pressure during the tests, as well as their test numbers, which are used in the rest of the report.

| Name of system | Test number | Water flow rate (l/min) | Pressure at pump (bar) | Other information |
|-------------------|-------------|----------------------------|---------------------------|-------------------|
| FRS system | 3 | 160 | 9.3 (7 at nozzle) | 38 mm hose |
| FRS system | 12a | 139 | 6 (5.4 at nozzle) | 38 mm hose |
| FRS system | 12b | 350 | 10 | 38 mm hose |
| Industrial system | 4 | 190 | 10 (3.5 at nozzle) | 25 mm hose |
| Fognail | 5 | 70 | 7.5 | 38 mm hose |
| High pressure 22 | 6 | 22 | 350 | 12 mm hose |
| High pressure 60 | 7 | 60 | 300 | 12 mm hose |
| Foam-based | 11 | 60 | 6 | 25 mm hose |

Table 1: Presentation of the handheld systems and their test numbers.

2.1.3 Water curtain systems

A total of four water curtain systems were studied and the first one consisted of a hose fitted with exchangeable nozzles, illustrated in Figure 6. The hose was automatically stabilised when it was pressurized with water and created a wall of water jets that can reach up to 15 m in height. The hose can be used to prevent spread of fire between vehicles, with a minimum use of personal dealing with the equipment. At the end of the hose, there needs to be a counterpressure point which prevents the hose from turning. During the fire test, a hose with five open nozzles was used, while the rest of the nozzles were plugged. The nozzles used in the test had three outlets which created two waterjets on each side and one going straight up.



Figure 6: Photo of the hose that creates water curtain.

The other three tested system consist of different curtain nozzles. The nozzle is pressed to the ground by the water and therefore no personal needs to handle the equipment when in use. The smallest one had a water flow rate of **115** l/min and will produce a curtain of water which is approximately 12 m wide and 6 m high. Next up was a curtain nozzle with a water flow rate of **190** l/min, which also created a water curtain of approximately 12x6 m. The largest water curtain system had a capacity of up to **800** l/min rate and made a water curtain of approximately 25 m in width and 8 m in height.



Figure 7: Photo of a curtain nozzle with a maximum water flow rate of 190 l/min.

2.1.4 Summarize of water curtain system

The tested water curtain systems are listed in Table 2, with their water flow rates and pressures during the tests, as well as their test numbers, which are referred to in the rest of the report.

| Name of system | Test number | Water flow rate (l/min) | Pressure (bar) |
|----------------|-------------|----------------------------|----------------|
| Hose | 2 | 210 | 4.2 |
| Small nozzle | 8 | 115 | 5.1 |
| Medium nozzle | 9 | 190 | 6.5 |
| Large nozzle | 10a | 400 | 1.5 |
| Large nozzle | 10b | 800 | 6.0 |

Table 2: Presentation of the water curtain systems and their test numbers.

2.1.5 Other systems

AVD² (Aqueous Vermiculite Dispersion) is an aqueous dispersion of chemically exfoliated vermiculite, applied under the form of a mist. When applied on a burning/flaming surface, it creates a film that instantly dries and then produces a non-flammable oxygen barrier between the fuel and the atmosphere. It was developed mainly

² <u>https://www.avdfire.com/</u>

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for battery fires, preventing further thermal runaway, and by extension, propagation of fire.

As the system does not only reduce the attenuation of radiation as the other systems do only visible observations of the performance of AVD are given in this report.

3 Laboratory fire tests

The fire load was represented by a single vehicle fire. It is not possible to perform a manual fire fighting operation when a cargo or serval cars are burning at the same time due to the high heat release rate, gas temperatures and large quantities of dense smoke that is both toxic and makes it impossible to observe the fire development. The test setup was hence represented by a scenario as shown in Figure 8.



Figure 8: Representative scenario for test-setup.

3.1Fire test set-up

The fire test source needs to represent a scenario where vehicles are located very closed to each other on a ro-ro passenger ship. The fire scenario must be realistic but manageable and the procedures must be as reproducible as possible.

3.1.1 Fire source

The test set-up consisted of a metal chassis to simulate the geometrical dimensions of a "large" sized passenger vehicle (Arvidsson and Vaari 2006), i.e. a SUV as shown in Figure 9. As the objective of the test series was to evaluate spread of fire and not to evaluate the possibility to extinguish the fire, the fire source was established using a propane fire rig with a capacity of 4 MW. This heat release rate corresponds to a single car fire (Vylund et al, 2019). By using such a test rig, the fire scenario became repeatable and limited the amount of toxic gases and smoke. The gas burner was placed under the targeted vehicle.



Figure 9: Fire test set-up, simulating the geometrical dimension of a "large" sized car (Arvidsson and Vaari 2006).

3.1.2 Instrumentation and measurement equipment

Fire spread to adjacent vehicles was evaluated with and without application of different extinguishing media. Vertical steel walls were positioned parallel with the long sides, respectively, of the car mock-up with a horizontal distance of 0.6 m (see Figure 10). This distance is representative for the typical distance between vehicles in a ro-ro space. The walls extended 4.0 m above floor level, to measure the possibility of fire spread to an adjacent trailer. A horizontal part of the walls, having a width of 0.6 m, simulated the top part of an adjacent vehicle. The operator was standing 8 m from the vehicle, except in test 5 and test 11, where the operator was standing 3 m from the vehicle. This was necessary as the operator was not able to reach with the jet all the way to the mock-up. A construction was built so that the nozzle could be positioned at the same height and same distance from the vehicle every time (operator independent). The operator placed the nozzle in the structure and aimed the water spray between the vehicle and the closest steel wall with a duration of 4 minutes.



Figure 10: Position of the steel walls in the fire tests and position of the fire fighting operator.

The surface temperatures of the steel walls were measured at 24 different measurement points. The nominal thickness of the steel sheets used for the walls was 1.5 mm. Three of the measurement points were positioned on the horizontal top surface of the steel plate and the remaining 21 measurement points on the vertical surface facing the trailer mock-up.

The measurements were made with (Type K) thermocouples having a diameter of 0.5 mm, spot-welded directly to the back side of the steel plate. Figure 11 presents the position of the thermocouples relative to the position of the car. A table of the temperature measurement points and the associated channels is presented in the Appendix.



Figure 11: Position of thermocouples in the fire test mock-up.

3.2 Fire test results

The fire test results are below presented for the two categories of systems, namely:

- Handheld systems, and
- Water curtain systems

3.2.1 Results for handheld systems

The results presented are the normalized steel temperatures (ratio of current measured temperature divided by the maximum measured temperature) given by the thermocouples presented in Table. The other thermocouples were excluded since the temperature increases were not enough to determine any distinction between before and after starting the suppression system.

| Measurement channels | | | |
|----------------------|---|--|--|
| Right hand side wall | Left hand side wall – Side where systems are tested | | |
| C7 | C47 | | |
| C8 | C48 | | |
| С9 | C49 | | |
| C10 | C50 | | |
| C11 | C51 | | |
| C12 | C52 | | |
| C13 | C53 | | |
| C14 | C54 | | |
| C15 | C55 | | |
| C16 | C56 | | |
| C17 | C57 | | |
| C18 | C58 | | |

Table 3: Thermocouples used for the analysis of fire tests results.

For a better readability of the results, a normalization was done of the steel temperatures, by dividing all temperature by their maximum values during the test period. This yield normalized temperature values between 0 and 1. To illustrate this, the results from Test 3 - FRS system are presented in Figure 12. It should be noted here that the thermocouple C58 is not represented in the graph because it was impacted directly by the water and shows the cooling effect of direct water impact.



Figure 12: Normalized temperature of the steel wall where the water system was applied in test 3 – FRS system. The time on the x-axis is from activation of the system and in relation to the time of ignition at time zero.

Based on Figure 12, the average normalized temperature after 4 minutes use of the suppression system is 0.51. This temperature reduction can be represented by a coefficient of reduction which is 1-0.51=0.49. Average taken after 4 minutes use of system was chosen due to the stabilization of the measurements. After 4 minutes only small changes were observed in the curves.

The reduction coefficient represents the reduction of temperature, or in other words, the blockage effect³ of the systems. A high coefficient indicates that the system has a high capacity to prevent fire spread to an adjacent vehicle. In the main part of this report, only a table (see for example Table 4) summarizing the reduction coefficient of each system. All graphs from the test series can be found in the Appendix.

In test 7 (High pressure 60), some of the thermocouples were hit by water and therefore only showed the direct cooling effect of water on the steel screens. These thermocouples were not included in the average values.

Test 12 tested the FRS-system again but with different water flow and pump pressure. The average temperature reduction was measured after the temperature had stabilized. Just as in test 7, some thermocouples were hit by water in test 12b, and these thermocouples were not included in the average values.

It should be noted that the result for test 11 (foam-based system) is not presented in Table 4 and Table 5. The reason is that this system does not produce a pure water spray (water plus foam) as the other systems do. Therefore, the temperature reduction is highly diverged, and the determination of the reduction coefficient was not possible.

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³ The blockage effect is the reduction of the heat radiation (attenuation) by the water.

| Tests | Reduction coefficient | | |
|------------------------------|-----------------------|--|--|
| 3 – FRS system (160 l/min) | 0.49 | | |
| 4 – Industrial system | 0.64 | | |
| 5 - Fognail | 0.27 | | |
| 6 – High pressure 22 | 0.34 | | |
| 7 – High pressure 60 | 0.54 | | |
| 12a – FRS system (139 l/min) | 0.51 | | |
| 12b – FRS system (350 l/min) | 0.64 | | |

Table 4: Reduction coefficient representing the blockage effect of studied handheld systems. A high number indicates better blockage effects.

As explained above, a steel wall was also installed on the other side of the vehicle. The surface temperatures at the opposite side of the nozzle position represents the capacity of the suppression system to reduce the spread of the fire on the other side of a vehicle. This is valid even if the suppression system was only applied on one side of the vehicle.

The results are obtained in the same way as explained before (graphs are shown in the Appendix) and summarized in the Table 5.

Table 5: Result of the handheld systems according to their capacity of reducing the spreading of fire on the other side of the vehicle (no water side). A high number indicates better blockage effects.

| Tests | Reduction coefficient | | | |
|------------------------------|-----------------------|--|--|--|
| 3 – FRS system (160 l/min) | 0.23 | | | |
| 4 - Industrial system | 0.27 | | | |
| 5 - Fognail | 0.12 | | | |
| 6 – High pressure 22 | 0.12 | | | |
| 7 – High pressure 60 | 0.34 | | | |
| 12a – FRS system (139 l/min) | 0.14 | | | |
| 12b – FRS system (350 l/min) | 0.24 | | | |

It should be noted here that Fognail and high pressure 22 system obtained the same reduction coefficient, but the curves are more scattered for test 6.

3.2.2 Results for water curtain systems

For water curtain systems, it is more difficult to draw conclusion about the blockage effect. Actually, the curves for the temperatures of the steel walls show a steep decrease that cannot be correlated with the blockage effect of the water spray. The steep decrease is more related to water impinging the wall, as can be observed in Figure 13.



Figure 13: Normalized temperature of the steel screen where the water system was applied in test 9. C56 to C58 is not represented in the graph because of direct water impact.

In order to investigate this issue, a second type of experiment was performed using a thermal camera (Infra Red camera) for FRS system, Industrial system, high pressure 60 system and water curtain systems.

The camera records the radiance⁴ emitted by the flame and when a system is positioned between the camera and the fire, a new radiance is recorded (see Figure 14). The ratio between the radiance with and without activated systems gives an indicator of the systems' capacity to reduce heat exposure and prevent fire spread to an adjacent vehicle.



Figure 14: Scenarios of the thermal camera tests.

⁴ The radiance is the flux of radiation emitted by unit area of a source.

In order to evaluate the consistency between the two different fire tests, the thermal camera tests were performed not only for the water curtain system but also for the handheld systems.

The results for the latter test series are presented in Table 6. A high blockage ratio means that the blockage effect of the system is better. It should be noted that the hose in test 4 had an inner diameter of 32 mm instead of 25 mm as in the ordinary fire tests.

| Tests | Radiance without system | Radiance with system | Blockage ratio |
|-----------------------|-------------------------|----------------------|----------------|
| 3 – FRS system | 0.126 | 0.065 | 2.1 |
| 4 – Industrial system | 0.125 | 0.011 | 12.5 |
| 7 – High pressure 60 | 0.141 | 0.046 | 3.04 |

 Table 6: Results from the thermal camera fire tests for the handheld systems.

Results from Table 6 and Table 4 are similar. This conclusion shows that the thermal camera tests can be applied for the water curtain systems as well.

In Table 7, the results of the water curtain systems, based on the thermal camera tests, are presented. It should be noted that no result is presented for system 8, due to technical measurement

Table 7: Results from the thermal camera fire tests for the water curtain systems.

| Tests | Radiance without system | Radiance with system | Blockage ratio |
|---------------------------------|-------------------------|----------------------|----------------|
| 2 - Hose | 0.116 | 0.020 | 5.8 |
| 9 – Medium nozzle | 0.112 | 0.031 | 3.04 |
| 10b – Large nozzle 800 l/min | 0.126 | 0.025 | 5.05 |

As done for the handheld systems, results for the water curtain systems concerning their capacity to reduce heat exposure on the other side of a vehicle when the system is concentrated on the original side is shown in Table 8.

Table 8: Result of the water curtain according to their capacity of reducing the spreading of fire on the other side of the vehicle (no water side).

| Tests | Reduction coefficient |
|------------------------------|-----------------------|
| 2 - Hose | 0.38 |
| 8 – Small nozzle | 0.05 |
| 9 – Medium nozzle | 0.05 |
| 10a – Large nozzle 400 l/min | 0.15 |
| 10b – Large nozzle 800 l/min | 0.47 |

It should be noted here that the value of the reduction coefficient for test 8 – small nozzle cannot be compared with other coefficient due to the high scatter of the measurements (see the curve in the appendix).

3.2.3 Summary fire test result

The fire test results from all of the fire tests are summarised in Table 9, except test 11 (foam based system) as the determination of the reduction coefficient was not possible.

Table 9: Reduction coefficient representing the blockage effect of studied handheld systems. A high number indicates better blockage effects.

| Name of the system | Test number | Water flow rate (l/min) | Pressure at pump (bar) | Reduction coefficient | Reduction coefficient |
|----------------------|----------------|----------------------------|---------------------------|--------------------------|-----------------------|
| | 3 | 160 | 9.3 (7 at nozzle) | 0.49 | 0.23 |
| FRS system | 12a | 139 | 6 (5.4 at nozzle) | 0.51 | 0.11 |
| | 12b | 350 | 10 (7 at nozzle) | 0.64 | 0.24 |
| Industrial system | 4 | 190 | 10 (3.5 at nozzle) | 0.64 | 0.27 |
| Fognail | 5 | 70 | 7.5 | 0.27 | 0.12 |
| High pressure 22 | 6 | 22 | 350 | 0.34 | 0.12 |
| High pressure 60 | 7 | 60 | 300 | 0.54 | 0.34 |
| Hose | 2 | 210 | 4.2 | Blockage ratio 5.8* | 0.38 |
| Small nozzle | 8 | 115 | 5.1 | - | 0.05 |
| Medium nozzle | 9 | 190 | 6.5 | Blockage ratio 3.0* | 0.05 |
| Large nozzle | 10a | 400 | 1.5 | - | 0.15 |
| Large nozzle | 10b | 800 | 6.0 | Blockage ratio 5.1* | 0.47 |

*A thermal camera test was performed where a higher blockage ratio means that the blockage effect of the system is better.

3.3 Visual observations during the fire tests

During the fire tests, photos were taken in order to describe some of the major findings from the tests.

3.3.1 Handheld systems

First the operator was standing at a fixed distance (7.8 m) from the vehicle, directing the water spray between the vehicle and the steel wall. The aim of this part of the test was to compare the blockage effect between the different systems, as presented in chapter 3.2. After the first part of the test, the operator was able to work with the suppression system in order to observe the effects with respect to cooling and suppression. This last step was planned to serve as an indication of the possibility to optimize the effect of the system by varying e.g. the cone, flow or pressure. The operator followed the following scheme:

- 1. **Fan**: Start of fan to see if the water stream is affected. The airspeed from at the fan outlet was about 5 m/s.
- 2. Oscillate: Oscillate up and down to compare if the blockage effect is improved.

- 3. **Over vehicle**: Oscillate over the vehicle to see if it is possible to lower the temperature on both sides of the vehicle.
- 4. **45° angle**: Approach the vehicle from the front at an angle of 45° and then compare if the water spray can reach over the vehicle and cool the steel wall. The operator was standing at a distance of 6.5 m from the nearest corner of the vehicle.
- 5. **Attack:** The operator gets closer to the vehicle and tries to cover the vehicle with the water spray. This was done in order to compare if it is possible to decrease the temperature both on the left and right of the steel wall.

3.3.1.1 Test 3 and 4 - FRS and industrial systems

The systems had the possibility to vary the cone angle of the water spray. This means that both systems could easily adjust the water cone from a jet stream with long trajectory to a wide cone with blockage effect of radiation. Figure 15 shows the cone angle during the first part of tests. For the FRS system, a clear effect of the water mist was observed behind the vehicle, which enabled the distance between the operator and fire-exposed vehicles to be extended by another 5-10 m, while maintaining effective suppression. For the industrial system, this distance was shorter. When a fan was started it was possible to observe how the water droplets were transported to the other side of the vehicle, but without effecting the temperature at the steel wall. Oscillation of the hose up and down created a stirring effect and turbulence of the air adjacent to the spray. When oscillating over the vehicle, both systems had the possibility to reach the other side of the vehicle and decrease the temperature on that side.

When the operator approached from a 45° angle, the water spray could easily reach over the vehicle and cool the steel wall on the other side, illustrated in Figure 16. It can be observed that the FRS system was able to reach to the other side better and with a wider water spray. The water flow rate for the FRS system was almost 300 l/min and around 200 l/min for the industrial system.

The appearance of the water spray is mainly controlled by the angle of the water cone, the pressure and the water flow rate. Nozzles with a flow setting ring and a rotating toothed ring (FRS system) have more possibilities to adjust the water spray to a desired setting than nozzles with fixed toothed rings (Industrial system). Nozzles with fixed toothed rings often deliver a water spray with high density, especially when the cone angle is wide, as illustrated by the differences in the spray cones between FRS system and Industrial system in Figure 17. But even if the density of the water spray is higher for Industrial system than FRS system, the higher water flow rate for the FRS system provides better cover of the vehicle.



Figure 15: Test 3 – FRS system (upper) and test 4 – Industrial system (lower) when the operator was aiming the spray between the vehicle and the steel screen. Industrial system had a denser and wider cone of water mist than the FRS system.



Figure 16: Test 3 – FRS system (upper) with a water flow rate of 290 l/min and test 4 – industrial system (lower) with a water flow rate of 190 l/min when approaching the vehicle from the front at an angle of 45° .



Figure 17: Test 3 – FRS system (upper) with a water flow rate of 270 l/min and test 4 – Industrial system (lower) with a water flow rate of 200 l/min when approaching the vehicle from the front at an angle of 45° .

3.3.1.2 Test 5 - Fognail

Use of a fognail requires that the operator moves towards the burning vehicle to attain effect on the fire, since there are limitations in the range and spread of the water fog. The fan affected the fine water mist from the fognail and transported it over to the other side. As can be observed in Figure 18, the fine water mist does not reach over the vehicle and is not able to cool the steel walls on the other side. Figure 18 also shows that the nozzle pressure causes the cone angle to become uneven. The water mist is not homogeneous and the throw length is limited. Higher pressure in the pump resulted in longer throw length and higher density of the water mist spray.



Figure 18: Test 5 - Fognail. A fine no homogeneous water mist spray is created, but the reach of the water spray is limited.

3.3.1.3 Test 6 - High pressure 22

The system creates a fine water mist with a high momentum near the nozzle. Behind the vehicle, almost no water reached to the floor and most of the water appeared to vaporize due to the fire. The fan affected the spray and transported the fine water-droplets to the other side of the vehicle. Oscillation over the vehicle did not affect the steel wall on the other side. From a 45° angle, the spray is reached over the vehicle, but the distance between the vehicle and the operator could probably not be extended.



Figure 19: Test 6 - High pressure 22. A fine water mist with a high momentum was created.

3.3.1.4 Test 7 - High pressure 60

For the high pressure 60 system, the throw length of the water spray reached to the end of the fire hall, as illustrated in Figure 20. It was possible to decrease the temperature on both sides of the vehicle when oscillating over the vehicle or approaching the vehicle from a 45° angle. The fan did not affect the water spray at all. To be able to cover the whole vehicle with water mist, the operator should not be close to the vehicle, as the spray does not break up until after 5-6 m. The distance to the breakup can be shortened if the operator oscillates the nozzle.



Figure 20: Test 7 - High pressure 60. A fine water mist with a high momentum is created.

Test 11 – Foam-based

The advantage of a foam-based system is to reduce the surface tension of the water droplets and consequently increase the cooling effects. The cooling effect is depending on the cooled material, and in this case the foam-based system did not improve the cooling effect compared with water since the material of the wall was steel. The spray pattern was too narrow to create a heat shield to the adjacent objects, as illustrated in Figure 21. The system was easy to handle but the low pressure gave a short throw length and the operator had to get closer to the vehicle.



Figure 21: Test 11 – Foam-based system illustrated that the spray pattern was too narrow to create a heat shield to the adjacent object.

3.3.2 Water curtain systems

The different water curtain systems were positioned between the vehicle and the steel wall before ignition of the gas burner. The water system started when the temperature on the steel wall was stabilized.

3.3.2.1 Test 2 - Hose

The hose was placed between the vehicle and the steel wall on the left. At the start of the test the water flow rate was 210 l/min and the water pressure were 4.2 bar. After five minutes, the water flow rate increased to 310 l/min. The combination of three directional water jets from each nozzle resulted in a dense water mist screen, illustrated in Figure 22. The stirring effect in the curtain was facilitated by the directions of the nozzles being different and overlapping each other. The cooling effect by direct water on the steel walls lowered the temperature directly, described in section 3.1.1 of the Appendix and illustrated in Figure 23. This could also be seen visually, where water mist spread throughout the whole fire test hall, especially after increasing the water flow rate to 310 l/min.



Figure 22: Test 2 - Hose with waterflow 210 l/min (upper) respective 310 l/min (lower).



Figure 23: IR photos taken during test 2 before water application (left) and after water application of 210 l/min (middle) and 310 l/min (right).

3.3.2.2 Test 8 - Small nozzle

The curtain nozzle was placed at the front wheel on left side of the vehicle. The flow rate was 115 l/min and the water pressure was 5.1 bar. The water did not reach up to the ceiling, nor did it cover the whole vehicle, as seen Figure 24. The limitations of the spray to cover and cool (see section 3.1.2 of the Appendix and Figure 25) could be derived from limitations in the water flow rate (115 l/min) and water pressure of 5.1 bar.



Figure 24: Test 8 - Small nozzle, the water did not reach up to the ceiling nor did it cover the whole vehicle.



Figure 25: IR photos taken during test 8, before water application (left) and after water application (right)

3.3.2.3 Test 9 - Medium nozzle

The medium nozzle was placed at the front wheel on left side of the vehicle. The flow rate was 190 litres/minute and the water pressure was 6.5 bar. The amount of water and pressure through the nozzle seemed enough to be able to cover more than one vehicle (see Figure 26 and Figure 27) and cooling effects on the steel wall was higher than for the small nozzle in test 8.



Figure 26: Test 9 - Medium nozzle covered the whole vehicle.



Figure 27: IR photo taken during test 9, before water application (left) and after water application (right).

3.3.2.4 Test 10 - Large nozzle

The large nozzle was placed close to the left back-wheel of the vehicle. Initially the system was activated with a water flow rate of 400 l/min and a water pressure of 1.5 bar. After that, the water flow rate was increased to 800 l/min and the water pressure was increased to 6 bar to also evaluate the system maximum water flow rate.

The water flow rate of 400 l/min and water pressure 1.5 bar provided a water curtain with large droplets that effectively cooled the nearest steel wall (see section 3.1.4 of the Appendix), but only locally. When the flow rate increased to 800 l/min and the water pressure to 6 bar, a more finely divided water mist was created which spread throughout the fire hall (see Figure 28) and lowered the temperature also on the steel wall on the other side of the vehicle, as described in 3.2.4 of the Appendix. The difference between 400 and 800 l/min water flow rate is clearly noticeable, see Figure 29.



Figure 28: Test 10 - Large nozzle, 400 l/min (upper) respective 800 l/min (lower).



Figure 29: IR photos taken during test 10, before water application (left) and after water application with 400 l/min (middle) and 800 l/min (right).

3.3.3 Other system - AVD

The last system to be tested (AVD) was applied on a wheel placed 0.6 m from the left front wheel of the mock-up before fire start. The media was also applied on the steel wall and on the mock-up vehicle. A total of 4.8 litre of AVD was used. The temperature of the steel wall was measured and the stabilisation of the temperature was reached after approximately 8 minutes after the gas burner was ignited. The duration of the test was 23 minutes. AVD did not have an effect on the temperature of the steel walls, but the wheel placed next to fire did not burst into flames during the fire test, as seen in Figure 30. The AVD system seems promising as a fire extinguishing agent by limiting or avoiding the flame propagation or reignition.



Figure 30: The wheel placed on the left-hand of the vehicle did not burst into flames when exposed to a 4 MW vehicle fire for 23 minutes.

4 Field tests

The fire laboratory tests quantified the blockage effects for different systems and also indicated possible tactical options, e.g. throw lengths, water distribution and possibility to optimize the effect by varying the cone, flow or pressure. However, the fire tests did not take in consideration how the system can be applied during a real fire fighting operation in ro-ro spaces. Therefore, the different suppression systems were evaluated in open field together with relevant crew.

The first tests aimed at investigating if it was possible to reach the set of the fire with water. Depending on the chosen method, it may be difficult to reach the set of the fire because the equipment is to heavy or cumbersome. The field test therefore evaluated the heaviness and stiffness of different hoses. Throw length was also investigated, to evaluate if it is possible to reach the fire from a longer distance longer than considered in the fire test.

When in use, the water curtain systems did not need an operator, but they still needed to be positioned close to the burning vehicle to lower the risk of fire spread. The field tests evaluated different tactical options to position the different nozzles.

4.1Test set-up

To simulate the environment on-board a ro-ro ship, 17 vehicles and two containers were placed close together with a distance between vehicles of 30-60 cm as shown in Figure 31. The two containers simulated a heavy goods vehicle trailer. The ground surface was gravel. Fire fighting crew from current ships evaluated the easiness of reaching the simulated fire with different hoses, systems and tactics.



Figure 31: Test set-up using cars and containers, to simulate a loaded ro-ro space.

4.2 Ergonomics of handheld systems

The firefighters tested to drag different hoses around corners and tires and compared the heaviness of dragging and operating the waterflow for a long period of time. They tested

both lay-flat hoses and semi-rigid hoses with different inner diameters as well as a high pressure 60 system.

As expected, hoses with increased diameter weight more and create a greater stiffness when the hose is pulled around corners and tires. If the lay-flat hose was not filled with water, the risk was high that it got stuck under a tire. This risk was much higher than if the hose was pressurized. It was also necessary to pressurize the hose carefully so that folds did not prevent the water to flow.

The semi-rigid hose was experienced as smoother and with a lower risk of getting stuck under the tires. A semi-rigid hose fitted in a hose reel or cabinet is easy to pull out and has a low weight and is less likely to get stuck under tires or other obstacles. This can reduce the time to reach the fire compared to when using a flat hose (no water). A flat hose is often folded so that it requires a larger free surface when firefighters roll out the hose. A flat hose can also be collected in a cassette from which the hose is pulled out when the firefighters are moving.

The largest hose (42 mm) is heavier to operate with water for a long time compared to smaller semi-rigid hoses. Furthermore, even if the hose of a high pressure system is easy to maneuver, it may be heavier in long periods due to the higher reaction forces from the hose.

4.3 Water flow rate and throw length

Tests were performed to evaluate the ability of different systems to increase the safety distance, i.e. at what distance can the operator safely stand but still be able to reach the fire. In all tests (except with the high pressure system), the same nozzle was used. The operator applied water along the corridor between the vehicles, and the width of the water cone was adjusted so it covered the space between the vehicles (around 60 cm). If the operator adjusted the water cone narrower, the throw length of the water became longer, but the ability of the water mist to cool the hot gases was reduced.

By increasing the inner diameter e.g. from 25 to 32 mm, the throw length can be extended while maintaining the shape of the spray. This is because a larger inner diameter of the hose means that the possibility of increasing the nozzle pressure with less pressure and flow losses from the pump. The increase of the water flow rate shows a negligible influence of the throw length, as shown in Table 10.

If the operator is oscillating the nozzle, the throw length is decreased but the water mist is more widely spread in the near area.

| Hose inner diam. | Water flow rate | Maximum throw length |
|-------------------|-----------------|----------------------|
| 25 mm, semi-rigid | 150 l/min | ~20 m |
| 32 mm, semi-rigid | 150 l/min | ~25 m |
| | 230 l/min | ~26 m |
| 38 mm, lay-flat | 360 l/min | ~30 m |
| High pressure | 60 l/min | > 50 m |

Table 10: Maximal throw length for different hoses, measured approximately.

4.4 Water curtain systems

Tests have been conducted for different ways of positioning water curtain systems. First, positioning of the water curtain hose is described followed by description of different ways of position the water curtain nozzles.

4.4.1Hose

The test with the hose creating a water curtain started out by just rolling out the hose in the corridor between the vehicles. On land, the hose is often stabilized by blocks, thus the water curtain will be directed upwards. In an on-board application, it would be preferred to not use blocks as it would be an extra equipment to carry, but the conclusion from the test is that blocks are preferred to optimize the direction of the water curtain. It is also important that the hose is in in the middle of the corridor and not curved, as illustrated in Figure 32 where the direction of the water spray is scattered due to the curved hose. It was also concluded that it is difficult to change the position of the hose after pressurizing the hose and starting water application.



Figure 32: Hose creating water curtain, applied in a corridor between vehicles. The hose is curved and blocks to stabilize the hose are missing, hence the water curtain is not optimal.

The second test with the hose included trying different ways of positioning the hose without firefighters being too close to the burning vehicle. The test was done with a firefighter dragging the hose along the corridor second next to the burning vehicle. Another firefighter stayed behind until the first firefighter had passed the burning vehicle. Then the tactic was to throw the hose over the roof of the adjacent vehicle and place it in right position next to the burning vehicle. However, even if the hose was not filled with water, it was too heavy to throw over the roof of the vehicles. Therefore, a wire was attached to the end of the hose and the first firefighter instead pulled the wire with him. The wire could easily be thrown over the roof of the adjacent vehicle and after that the hose was dragged into position from a safe place, as illustrated in Figure 33.



Figure 33: Test procedure with a hose creating a water curtain. (1) The first firefighter takes the wire attached to the hose and passes the burning vehicle in the corridor second next to the fire. (2) The firefighters throw the wire over the roof of the vehicles, so the wire is positioned in the corridor next to the burning vehicle. (3) The first firefighter drags the hose into position.

This test showed that it is possible to position the hose without being adjacent to the burning vehicle. However, in a real fire situation there will be a huge amount of smoke and heat inside the ro-ro space. Therefore, there is a need for an extra handheld hose to protect the firefighters. It would also be beneficial if the inner diameter of the hose was smaller, both due to the weight and the substantial water flow rate. An easier way of positioning the hose is required in order to be used during a fire fighting operation. The hose could also be used as a precaution after a fire. It could also be built in a square loop to cover a passenger car with water mist. After a fire has been extinguished, the firefighters could place the hose around the vehicle and if it re-ignites it is possible to directly apply a water shield around the vehicle from a safe place. Another application could be to place the hose under the deck of the burning vehicle in order to cool the deck from below and prevent "hotspots" and potential fire propagation to other decks.

4.4.2 Curtain nozzle

A curtain nozzle will automatically be placed in an upward position after start of water application even if the nozzle was upside-down from the beginning. During the fire test, the smaller plastic curtain nozzle (left photo in Figure 34) was damaged when it rotated to an upward position after the water flow was started. The nozzle will create a water curtain perpendicular to the hose, as seen in Figure 34.



Figure 34: Curtain nozzles with water flow rates of 190 l/min (left) and 800 l/min (right). Photo: Dafo Brand.

Figure 35 illustrates the first attempt to position the nozzle in order to protect against further fire spread from the burning vehicle or vehicles. The firefighter team advanced towards the fire with a standard hose and nozzle as protection. The first firefighter used water mist to protect against radiation and suppressed the fire meanwhile the second firefighter threw the curtain nozzle close to the vehicle. When the curtain nozzle was in position, both firefighters retreated to a safe position and pressurized the water curtain. Two drawbacks of this attempt could be observed; firefighters still need to be close to the burning vehicle and it was difficult to position the nozzle in an optimal way, particularly because the hose is perpendicular to the water curtain.

If the nozzle would create a water curtain in the same direction as the hose, it would have been easier to position the nozzle in an optimal way. Such a hose can for example be seen in Figure 36, from Öckerö training ground.



Figure 35: The first firefighter creates a protecting watermist meanwhile the second firefighter positions the curtain nozzle next to the simulated burning vehicle with the aim to protect the black vehicle from fire exposure.



Figure 36: Curtain nozzle used at Öckerö training ground.

A second attempt was made trying to position the nozzle while the firefighters walked along the short side of the deck and hiding as protection behind the vehicle next to the burning vehicle. Three different ways of position the nozzle was tested; (1) throw the nozzle over the vehicle, (2) push the nozzle under the vehicle, and (3) throw the nozzle between the back and the front of the vehicle. Figure 37 shows how the firefighter tried to throw the nozzle over the vehicle and to push the nozzle under the vehicle, respectively.



Figure 37: The firefighter tries to position the curtain nozzle by either throwing the nozzle over the vehicle (left) or by pushing it under the vehicle (right).

It was easier to position the nozzle when approaching the burning vehicle from the side and either push it under the vehicle or between two vehicles. By doing so, the firefighter is also able to use the adjacent vehicle as a protecting shield. Throwing the hose and nozzle over a vehicle is not to recommend as it was difficult to position the nozzle well when the hose was laying over the vehicle. During the test, different hoses were used and the easiest hose to control when pushing the nozzle under the vehicle was a pressurize hose with an inner diameter of 42 mm. The firefighter estimated that it was possible to push the nozzle under more than one vehicle, which could be useful to gain a larger safety distance. The hose with an inner diameter of 32 mm was semi-rigid, but it was still more difficult to control the hose and push it under the vehicle to the right position than the lay-flat hose with an inner diameter of 42 mm. Both the smaller and the larger curtain nozzle was possible to push under the vehicle, but the smaller plastic nozzle was easier to handle. The design of the nozzle can be developed further to make it slide easier on the surface and minimize the risk of getting caught in uneven ground surfaces.

5 Discussion

The performed tests have evaluated the blockage effect of different systems (chapter 3.2), how different tactical options can optimize this effect (chapter 3.3) and how different systems can be used safely during a fire fighting operation in ro-ro spaces (chapter 4). From these tests, advantages and limitations of different systems existing on today's market have been assessed.

The advantages and limitations of different systems are discussed below in case of a manual fire fighting operation in a ro-ro space. There is always a lot of different aspects that need to be considered in a real-life situation, why the discussion below should be used as a guidance when evaluating what type of system should be used.

Handheld systems and water curtain systems are two tactical possibilities and one cannot exclude the other. Handheld systems are needed for firefighters to be able to position the water curtain, but when operating the curtain nozzle, no personnel is needed. The curtain nozzle therefore enables personnel to perform other tasks while the curtain nozzle is active and reduces the risk of fire spread.

5.1 Handheld systems

The advantages and limitations of different handheld system are discussed below.

5.1.1 FRS system

The advantage of this system is the ability to adjust it according to the fire situation. Both the water flow rate and the angle of the cone can independently be changed to obtain a water spray as optimal as possible to extinguish the fire, e.g. depending on whether the operator is close to the fire or further away. The system can be used both for surface cooling and for extinguishing the fire and for blocking heat radiation to protect firefighters. Except for the high pressure 60 system, the FRS system showed the longest throw lengths with retained cone angle. The throw length depends on the nozzle pressure and the water flow rate. The use of a hose with a larger inner diameter will decrease pressure losses from the pump, compared with use of a hose with a smaller inner diameter (e.g. industrial system).

The blockage effect is better with a higher water flow rate of water, but even at a low water flow rate it is still possible to prevent fire spread. On the opposite side of the vehicle, where no water was sprayed, the blockage effect was better when the pump pressure was 10 bar (independently of water flow rate), but worse when the pump pressure was 6 bar. This indicates that the system should work with a certain pressure to optimize its performance.

The system will probably not be greatly affected by moderate winds that can exist in open ro-ro spaces.

A limitation of FRS system is that the hose is heavier than the other systems used in the tests and laying out the hose can be more difficult. The system also demands a large total water consumption if the system is not used with care. The possibilities to adjust the nozzle to the situation will be most beneficial if the firefighters are well trained. Hence,

to produce the best possible effect of the fire fighting systems, both training in the systems and an understanding of fire dynamic is required.

5.1.2 Industrial system

This system has the ability to be adjusted according to the fire situation, but the range of the water flow rate is smaller than for FRS system. Furthermore, it is not possible to adjust cone angle and water flow rate independently of each other. The throw length of the system was judged enough to reach and cool an adjacent vehicle based on the laboratory fire tests (from 8 m distance), but the water spray could probably not be extended much further and still be effective. If a hose with a larger inner diameter would be used, the throw length could probably be extended.

The system had a superior blockage effect on the side where the water spray was directed and also had one of the highest reduction coefficients on the opposite side of the vehicle when the pump pressure was 10 bar. The hose used (semi-rigid hose with an inner diameter of 25 mm) was easy to handle and if fitted in a hose reel cabinet, the time for the firefighters to be ready to put water on the fire may be reduced compared with the FRS system.

The system will probably not be greatly affected by moderate winds that can exist in open ro-ro spaces.

It is easier to handle the nozzle compared with the FRS system, as it is adjusted to a certain pressure and water flow rate and the operator only needs to adjust the cone angle.

5.1.3 Fognail

Fognails produce a fine water mist that can effectively be evaporated. Limitations of the system were the short throw length and the low water flow rate. The system will also probably be affected by moderate winds that can exist in open ro-ro spaces. Higher pressure would been beneficial for creating longer throw lengths and higher density of the water.

5.1.4 High pressure systems

A high pressure system can compensate for a lower water flow rate and be as efficient to achieve a blockage effect as a system with a higher water flow rate and lower pressure. However, a water flow rate of 22 l/min was not enough to provide an efficient blockage effect. When the water flow rate was only 22 l/min, all the droplets seemed to be vaporised in the fire and the blockage effect was less than for the other systems (except fognail). The 22 l/min system also had a limited effect when trying to cool the wall on the other side of the vehicle.

The high pressure system with a 60 l/min water flow rate showed a high blockage effect, even if the water flow rate was considerably less than with the FRS and industrial system. For example, the blockage effect with the 60 l/min high pressure system was 11 % better than with the industrial system, even if the water flow rate was less than half. However, a high pressure system cannot totally compensate a larger water flow rate, as can be seen when comparing the 22 l/min high pressure system with the FRS and industrial system.

The 60 l/min high pressure system had the highest reduction coefficient on the other side of the vehicle (where the water mist was not directed) for handheld system. The visible observations from the tests indicate that the high pressure systems create a stirring effect and turbulence with incoming air in the water mist, which filled the fire test hall with water mist. This might explain why the system had a better blockage effect on the other side of the vehicle than systems with larger droplets and lower pressure.

Thanks to the high pressure, the throw length was long even if the water flow rate was small. The system with 60 l/min will probably not be affected by moderate winds that can exist in open ro-ro spaces in the first 5-6 m, where the momentum of the water spray is high. After that, the water droplets from the spray will slow down and more easily be affected by wind. Therefore, it is important to consider the wind direction when using high pressure systems from a long distance.

None of the high pressure systems were flexible, and it was not possible to adjust the water spray, like with the low pressure system. The low flow system (22 l/min) had, like fognails, two different nozzles to choose between. For the 60 l/min system, the operator could not stand too close to the vehicle because the water spray was too narrow the first 5-6 m. For the 22 l/min system, the water spray broke up closer to the operator.

Furthermore, high pressures systems, especially in combination with large flows, create reaction forces that made the systems difficult to handle and the operator got tired faster.

5.1.5 Foam-based system

The foam-based system could be used to cool the adjacent vehicles. The jet produced during the tests was narrow with large droplets and did not create a heat shield that could absorbs the heat radiation like the other systems. The advantage of the system could be to extinguish near the vehicle due to the reduced surface tension of the water droplets, but this was not considered in the fire tests.

5.2 Water curtain systems

The blockage effect of the different water curtain systems was similar, but the reach of the water spray and how the systems can be applied in a ro-ro space were different. The hose and larger nozzle (800 l/min) will likely cover a trailer whereas the smaller water curtain can cover one or two vehicles. At the same time, the smaller water curtain is easier to handle and is therefore easier to position close to the fire. The larger nozzle will also release a large amount of water, which can be a problem on deck. Further aspects between the different water curtain systems are elaborated below.

5.2.1Hose

The advantage of the hose was the capability to effectively cool the walls and spread water mist long distances. During the fire test, only five nozzles on the hose were used and if more nozzles are needed, a higher water flow rate and pressure would be required to be able to obtain a dense water curtain. A limitation of the hose is how it is practically to be used during a firefighter operation in a ro-ro space. Suggested applications can be to position it around an electrical vehicle after the fire is extinguished. If the vehicle reignites, it would be possible to directly apply a water curtain and prevent spread of fire. The hose can also be used to cool the deck above the fire to prevent "hotspots" and potential fire propagation to other decks.

5.2.2 Curtain nozzles

The advantage of the curtain nozzles is that they can be positioned easier than the hose, especially the small and medium nozzles. These are also easier for a firefighter to carry and handle than a larger one. Positioning of the nozzle will require closeness to the burning vehicle, but with the right tactics the firefighter can position the nozzle using another vehicle as a protecting shield.

The small curtain nozzle did not attain a sufficient water flow rate to cool down the walls nor to cover the whole vehicle. The medium nozzle produced a water flow rate of 190 l/min could cover at least one vehicle with a dense water curtain that was able to cool surfaces and reduce radiation.

Only the hose and the large nozzle with a water flow rate of 800 l/min had the ability to spread some of the water mist to the other side of the vehicle. The big droplets that were created when the water flow rate was only 400 l/min and the pressure only 1,5 bar did not affect the other side of the vehicle, where the water curtain was not placed.

The plastic cover of the small and medium nozzles was fragile, and the design of the nozzles could be developed further to increase robustness.

6 Conclusion

The tests demonstrated the advantages and limitations of different systems for manual fire fighting existing on the market. To conduct a fire fighting operation in a ro-ro space, the used fire fighting system must be easy to handle, not require a lot of pre-training, be effective and possible to use in many different fire situations.

Easy to handle and understand

The practical evaluation showed that a smaller hose is easier to handle but at the same time the pressure loss in the system when transporting the water will increase, which can decrease the capacity to reduce heat exposure. Easiness is important in order to save time and to make a fast response but at the same time consideration to the water spray capacity is necessary. Furthermore, the reaction force from high pressure systems or high water flow systems can require more personnel and implies a faster tiredness of the operator. It is heavier and more difficult to handle large water flows rates but with the right tactics there is no need for very large water flow rates.

A well-known fact is that a high water flow rate can compensate for poor fire fighting techniques. However, the FRS system has the greatest possibility to adjust the system to desired settings, but at the same time it requires more knowledge and training in fire fighting techniques compared to the industrial system. A high pressure system will also require more advanced training.

Water curtain systems can be used as a tactical option to reduce the risk of fire spread from a vehicle fire. The hose and the larger nozzle were cumbersome to carry and handle, but the smaller water curtain nozzle was easy to carry and handle.

Capacity to reduce fire propagation from a distance

All handheld systems, except fognail, high pressure 22 and the foam-based system reduced the heat exposure in half or more. All systems were able to cool the steel wall (simulating an adjacent vehicle) by direct application, but with fognail and high pressure 22 it was more difficult to reach both walls than with the other systems. With the foam-based system, the firefighter needed to be close to the vehicle to be able to reach the fire. The short throw length and small water flow rate made it difficult to reach the fire from a safe distance. For the water curtain systems, all systems except the small water curtain system showed a good blockage effect.

A safe distance for firefighters can be based on a long throw length, which depends on the pressure, flow rate and type of nozzle and hose. The tests showed that a fan can be used to extend the reach of a water mist or to transport the water mist in a certain direction. The fan contributes to turbulence, which increases the ability for surface cooling and dispersing accumulated fire gases. Turbulence can also be created by oscillating the water spray. It is also important to work with the wind direction to optimize the effect of the water.

It was possible to observe an effect on the other side of the vehicle than where the water was directed for some of the systems. However, to be able to prevent fire spread in all directions it was necessary to oscillate the handheld systems over the vehicle and for the water curtain systems it was necessary to position them on at least two sides of the vehicle. The large droplets that were created with low pressure systems did not affect the other side of the vehicle.

Adjust to the situation

The FRS system and Industrial system could both be adjusted during a fire fighting operation to fit the situation. The FRS system had more possibilities than the Industrial system, but it requires more training. The other systems tested were more difficult to adjust.

Water consumption

There is always a risk when choosing tactics and methods that consume large quantities of extinguishing water. Long duration fire fighting with high water flow rates may pose a risk of instability on a ship and the fire tests showed that a large volume of water is not always better to prevent propagation to adjacent vehicles. This must be considered when planning and designing for fire fighting systems onboard ro-ro ships.

7 References

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Appendix - Results of the fire tests 1 Temperature measuring points

Measurement channels Position Left hand side screen Right hand side screen C1 C41 Horizontal top surface C2 C42 Horizontal top surface (midline) СЗ C43 Horizontal top surface C4 C44 Vertical surface, 150 mm below top C5 C45 Vertical surface, 150 mm below top (midline) C46 C6 Vertical surface, 150 mm below top C7 C47 Vertical surface, 775 mm below top C8 C48 Vertical surface, 775 mm below top (midline) C9 C49 Vertical surface, 775 mm below top C10 C50 Vertical surface, 1400 mm below top C51 Vertical surface, 1400 mm below top (midline) C11 C12 C52 Vertical surface, 1400 mm below top C13 C53 Vertical surface, 2025 mm below top C14 C54 Vertical surface, 2025 mm below top (midline) C15 C55 Vertical surface, 2025 mm below top C16 C56 Vertical surface, 2650 mm below top C17 C57 Vertical surface, 2650 mm below top (midline) C18 C58 Vertical surface, 2650 mm below top C19 C59 Vertical surface, 3275 mm below top C20 C60 Vertical surface, 3275 mm below top (midline) C21 C61 Vertical surface, 3275 mm below top C22 C62 Vertical surface, 3900 mm below top C23 C63 Vertical surface, 3900 mm below top (midline) C24 C64 Vertical surface, 3900 mm below top

Table: The temperature measuring points and the associated channels.

2 Handheld systems

All figures in below shows normalized temperature of the steel wall. The time on x-axis is from activation of the system and in relation to the time of ignition at time zero. The capacity to reduce heat exposure and prevent fire spread to an adjacent vehicle is represented by a coefficient of temperature reduction which is the average normalized temperature reduction after 4 minutes. The average is mainly based on thermocouple C47 to C58 but for some tests the average is based on fewer thermocouples, see below respectively figure.

2.1Temperature of the steel panel by applied water



2.1.1 Test 3 - FRS system

Figure A 1: The average normalized temperature reduction after 4 minutes was based on thermocouple C47 to C57. C58 was excluded because impacted by water.



2.1.2 Test 4 - Industrial system

Figure A 2: The average normalized temperature reduction after 4 minutes was based on thermocouple C47 to C57. C58 was excluded because impacted by water.



2.1.3 Test 5 - Fognail

Figure A 3: The average normalized temperature reduction after 4 minutes was based on thermocouple C47 to C57. C53 and C56 were excluded because impacted by water.



Figure A 4: The average normalized temperature reduction after 4 minutes was based on thermocouple C47 to C58.





Figure A 5: The average normalized temperature reduction after 4 minutes was based on thermocouple C47 to C49. Rest of the thermocouples was excluded due to this only showed the cooling effects.



2.1.6Test 11 - Foam-based system

Figure A 6: The temperature reduction was to scatter to make an average.



2.1.7 Test 12 - FRS system

Figure A 7: The average normalized temperature reduction after 4 minutes was based on thermocouple C48 to C58. C47 seems not to follow the tendency of other thermocouples

2.2 Temperature of the steel panel opposite of applied water



2.2.1 Test 3 - FRS system

Figure A 8: The average normalized temperature reduction after 4 minutes was based on thermocouple C7 to C18.



2.2.2Test 4 - Industrial system





2.2.3 Test 5 - Fognail

Figure A 10: The average normalized temperature reduction after 4 minutes was based on thermocouple C7 to C18.



Figure A 11: The average normalized temperature reduction after 4 minutes was based on thermocouple C7 to C17.





Figure A 12: The average normalized temperature reduction after 4 minutes was based on thermocouple C7 to C18.

2.2.4 Test 6 - High pressure 22



2.2.6 Test 11 - Foam-based system

Figure A 13: The temperature reduction was to scatter to make an average (first 4 minutes). The water was hitting the wall between 17 and 21, thereafter the temperature quickly increased again.



2.2.7 Test 12 - FRS system

Figure A 14: The average normalized temperature reduction after 4 minutes was based on thermocouple C7 to C17.

3 Water curtain systems

3.1Temperature of the steel panel by applied water

3.1.1 Test 2 - Hose



Figure A 15: The thermocouples only show cooling effect.



3.1.2 Test 8 - Small nozzle

Figure A 16: Thermocouples was to scatter to be able to calculate an average.

3.1.3 Test 9 - Medium nozzle



Figure A 17: The thermocouples only show cooling effect.



3.1.4 Test 10 – Large nozzle

Figure A 18: The thermocouples only show cooling effect.

3.2 Temperature of the steel panel opposite of applied water

3.2.1 Test 2 - Hose



Figure A 19: The average normalized temperature reduction after 4 minutes was based on thermocouple C7, C10 and C16. Rest of the thermocouples was excluded due to only showing cooling effect.



Figure A 20: The average normalized temperature reduction after 4 minutes was based on thermocouple C7 to C18.



3.2.3 Test 9 - Medium nozzle

3.2.2 Test 8 - Small nozzle

Figure A 21: The average normalized temperature reduction after 4 minutes was based on thermocouple C7 to C18.



3.2.4 Test 10 - Large nozzle

Figure A 22: The average normalized temperature reduction after 4 minutes was based on thermocouple C7 to C18.

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