




# The Development of Automatic Sprinkler System Concepts for Maritime Vehicle Carriers

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**Abstract.** Closed ro-ro spaces on maritime vehicle carriers are usually protected by a total-flooding carbon dioxide system. Such systems have many benefits, for example that there are no residues that can adversely affect the protected objects (in this case thousands of vehicles) and the agent is electrically non-conductive. However, there could be a considerable time delay from the start of a fire until the carbon dioxide system is discharged. Experience has shown that this delay time can cause significant fire damage and jeopardize the performance of the system. Within the EU funded LASH FIRE project, design and installation guidelines for supplementary automatic water-based fire sprinkler systems were developed. An important design feature is that the system automatically activates at an early stage of a fire. This would allow more time to fight the fire manually or to safely evacuate the space and discharge the CO<sub>2</sub> system when the fire is controlled to one or a few vehicles instead of at a time when it has escalated in size. The work was partly based on a comprehensive literature review that identified relevant standards and information applicable to the design of automatic fire sprinkler and deluge water spray systems. Large-scale fire tests verified that the suggested system designs were able to provide control of realistic vehicle fires, including fires in passenger cars and a freight truck.

**Keywords:** Sprinklers, Vehicle fires, Maritime vehicle carriers, Ro-ro spaces, Ships

## 1. Introduction

Maritime vehicle carriers are unique ships, specifically designed for the transportation of vehicles, with a box-like superstructure running the entire length and breadth of the hull. They typically have a stern ramp and a side ramp for loading of thousands of vehicles such as passenger cars, freight trucks, buses, railcars and tramways, boats, mining equipment and heavy machinery. Lifiable decks allow for high-vehicle clearance and the decks can be raised or lowered to adjust their heights for assorted cargo. An individual roll-on/roll-off (ro-ro) space could be on the order of 150 m to 200 m in length, 25 m to 30 m in width and have a clear

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height between about 1.8 m and 7.0 m. The latter is the height of the space that is usable for cargo. The dimension is measured from the flooring to the underside of any obstructions such as structural ceiling members, lights, ducts, piping or similar.

The ro-ro spaces are usually protected by a total-flooding carbon dioxide (CO<sub>2</sub>) system. The agent is a colourless, odourless, and chemically inert gas that is electrically non-conductive. It is considered effective and primarily extinguishes fire by lowering the oxygen level in a protected space. Minimal clean-up after discharge is required as there are no residues. CO<sub>2</sub> poses risk to personnel who may be exposed to it, and adequate safety precautions are required. There could be a considerable time delay until the CO<sub>2</sub> system is discharged in the event of a fire on board a vehicle carrier because time is needed to close the ventilation system, dampers, hatches and to confirm that no crew members are present in the protected ro-ro spaces. This time delay can result in extensive fire damage, as exemplified by the fires on board *Courage* in 2015 [1], *Honor* in 2017 [2] and *Höegh Xiamen* in 2020 [3]. All these fires likely started due to electrical arcing in a single passenger car. Despite the activation of the CO<sub>2</sub> system, the extensive fire damage led to scrapping of the entire ship in two of the cases.

Within the European Union funded project, Legislative Assessment for Safety Hazards of Fire and Innovations in Ro-ro ship Environment, or LASH FIRE ([www.lashfire.eu](http://www.lashfire.eu)), design and installation guidelines for supplementary, automatic water-based fire protection systems were developed. The work was partly based on a comprehensive literature review that identified fire statistics from fires in on-shore buildings with automatic sprinklers, information from applicable fire sprinkler tests, sprinkler installation standards, and other information applicable to the design of automatic fire sprinkler and deluge water spray systems. Based on the outcome of the literature review, design and installation guidelines for automatic sprinkler systems on maritime vehicle carriers were drafted. These guidelines were validated in large-scale tests using actual vehicles. Water mist fire protection systems were out of the scope of the project. No fire incident data with water mist fire protection systems for the type of hazard exist, so there is no sufficient statistics to determine the performance and reliability of the systems in actual fires.

It was recognized that sprinkler protection is challenging as the extremely tight packing of vehicles in the ro-ro spaces will promote rapid fire spread and shielded fires. Additionally, the spaces are large, subject to freezing, and deep ceiling deck beams make the optimal position of automatic sprinklers or open nozzles difficult. These aspects were covered in the design and installation guidelines.

## **2. Literature Review**

### **2.1. Fire Incident Data**

A total of 3096 fires in car parks were reported in the United Kingdom during the years 1994–2005 [4]. In 162 of these fires, an automatic fire sprinkler system was present. In 16 of the fires (9.9%), the sprinkler system activated and extinguished the fire and in 84 fires (51.9%), the sprinkler system activated and contained/con-

trolled the fire. In one fire (0.6%), the sprinkler system activated but the fire was not contained/controlled. For the remaining 61 fires (37.6%), the sprinkler system did not activate, probably as the fire was too small. In the 101 fires where the sprinkler system activated, it can be concluded that it extinguished or contained the fire in 100 cases. These statistics likely only include gasoline- or diesel-fuelled vehicles as battery electric vehicles were rare during the time period.

More recently, a couple of cases that include fires in battery electric vehicles were identified. An electric vehicle fire in a car park in The Netherlands was started deliberately on September 1, 2020. The sprinkler system controlled the fire, which did not spread to the battery pack. The car park and other vehicles were undamaged [5]. On November 21, 2021, there was a fire in the underground car park Marienplatzgarage in Ravensburg, Germany [6]. According to initial information, an electric vehicle parked on the first parking level and connected to a charging station was probably the cause of the fire. “The sprinkler systems and other fire protection devices worked extremely well”, according to the press spokesman for the Ravensburg fire brigade. Three other vehicles were damaged by the heat. In addition to the cars, two charging stations for electric cars, several lights and cables and the concrete ceiling were damaged. As early as 2014, there was a serious fire in the particular underground car park, which resulted in closure for six years and a restoration for several million euros. The garage was reopened in 2020, this time with an automatic sprinkler system.

## **2.2. Fire Sprinkler Test Data**

Some fire sprinkler test data that were considered useful for the work was found. In 2007 and 2008, BRE in United Kingdom conducted several multi-vehicle, full car fire tests in a parking garage mock-up having a floor area of 12 m by 6 m and a ceiling height of 2.9 m [4]. All of the cars were used and were selected on the basis of age, size and availability and were either less than five years old, or, if older, of a current model. Gas struts, air bags and other pressurised or pyrotechnic components were left in place, but their air conditioning gas was removed. For each of the cars, the fuel tank contained 20 l of fuel. Test 2 of the test programme was conducted with automatic sprinklers. The test set-up allowed collection of combustion gases and the measurement of the heat release rate. The sprinkler system was designed and installed as representative of a system in place in a typical multi-storey or underground car park, i.e., in accordance with the recommendations for Ordinary Hazard Group 2 occupancies (OH2) of BS EN 12845:2004 [7], that require a design density of 5 mm/min. The first sprinkler activated after 4 min, but the fire continued to grow, and eventually (after 55 min) reached a peak measured to 7 MW. All six installed sprinklers operated, the last two sprinklers after more than 45 min. The fire did not spread to the adjacent cars. The gas temperature at the ceiling peaked at almost 800°C. The report concludes that the effectiveness of sprinklers in limiting a fire to a single car was demonstrated, which supports findings reported verbally by the fire and rescue service.

In 2009, BRE conducted a single automatic sprinkler test using a two-car stacker configuration [8]. Automatic sprinklers were positioned both at the ceiling

above the stacker and above the car at the lower position. The fuel tanks of the cars were filled with 20 l of fuel. Four automatic sprinklers were installed at each 'corner' above the cars. The fire was ignited on the seat of the car at the lower position, with the driver's window open. After 13:06 [min:s], a sprinkler at the ceiling activated, followed by a second sprinkler at 14:41 [min:s]. At 22:47 [min:s] a third (and final) sprinkler at the low level activated. The water flow to the system was shut-off after one hour. It was concluded that automatic sprinklers at the ceiling contained the fire to the lower car, allowed some spread to the above vehicle, but prevented it from becoming fully involved.

VdS Schadenverhütung has published several fire test methods for water mist fire protection systems. One of these is a fire test method for parking garages [9]. The method simulates real conditions in a parking garage. The cars used in the tests are scrapped cars but must be intact with entire windscreens, etc. The car fuel tanks must be emptied of fuel. Three cars are parked side by side at a horizontal distance of 0.6 m, under a suspended ceiling. The fire is started with two trays of heptane that are placed under the middle car and ignited. The tested water mist system must be proven to have an efficiency comparable to that of traditional sprinklers. Therefore, reference fire tests are first performed with traditional sprinklers, which thus constitute the reference system. The system is designed for a water discharge density of 6.5 mm/min, which corresponds to 80 l/min per sprinkler. The test results from assignment tests are usually proprietary, but have been published with permission [10]. For these tests, the ceiling height was 3.0 m, and the cars were manufactured in the late 1990s. The reference tests with the traditional sprinklers showed good effectiveness. Since the fire is in principle completely hidden from direct water application by the body of the car, the primary effect is in preventing the spread of fire and to reduce the gas temperature at the ceiling. The average gas temperature at the ceiling was at most around 150°C during three independent fire sprinkler tests. The surface temperatures on the part of the body facing the centremost car on both target cars were measured with four thermocouples welded to the steel body; the average surface temperature of the adjacent cars peaked at around 100°C.

Concerns about the performance of deluge water spray systems (often referred to as 'drencher' systems) in ro-ro cargo spaces onboard ships have been raised regarding the increased number of battery electric vehicles being transported. A straightforward comparison of the fire suppression performance of a deluge water spray system for fires involving gasoline-fuelled and battery electric vehicles in test conditions as equivalent as possible was undertaken [11]. It was concluded that fires in the two types of vehicles are different but have similarities. A gasoline fuel spill fire develops very rapidly, peaks high but burns out fast, whilst a fire starting in the battery pack of a battery electric vehicle develops slower, is not as large but burns longer. The development of the fire in other combustibles, such as the tires, exterior and undercarriage plastic parts and inside the passenger compartment is similar. The overall conclusion from the tests was that a fire in an electric vehicle does not seem to be more challenging for the drencher system design given in MSC.1/Circ.1430 [12] than a fire in a gasoline-fuelled vehicle of comparable size.

### **2.3. Design Recommendations in Sprinkler Installation Standards**

The type of cargo transported on maritime vehicle carriers is broad and can be exemplified by a list of typical cargo by one of the ship operators: agriculture, automotive, boats and yachts, breakbulk, construction equipment, mining equipment, machinery, power equipment, railcars and tramways, trucks, buses, and trailers. It is obvious that the combustibles are to a large extent shielded from direct application of water from ceiling sprinklers or nozzles by the body of vehicles or cargo packaging. The amount of fuel in new vehicles transported on maritime vehicle carriers is limited, for passenger cars typically only around 5 l. The amount of fuel should be sufficient for driving the vehicles on and off the ship. It is, however, not uncommon that used vehicles are transported on maritime vehicle carriers where the amount of fuel could be larger. As the loading and unloading of the vehicles is made by dedicated staff, vehicles are positioned closer together on a maritime vehicle carrier than on ro-ro cargo and ro-ro passenger ships.

Design and installation guidelines for automatic sprinkler (wet-, dry-, or pre-action systems) and deluge water spray systems for open and closed ro-ro spaces and special category spaces is given in MSC.1/Circ. 1430 [12] as amended in [13, 14]. The recommendations cover aspects such as the system type, positioning of sprinklers, design densities and operating areas. As discussed, there are differences regarding the type of cargo that is transported in ro-ro and special category spaces on ro-ro cargo and ro-ro passenger ships as compared to closed ro-ro spaces on maritime vehicle carriers that should be recognized. Ro-ro cargo and ro-ro passenger ships are designed to transport freight trucks with cargo trailers or individual cargo trailers. These cargo trailers could contain high fire loads that require high water discharge densities. When the design and installation guidelines in MSC.1/Circ. 1430 were established, tests involving fires in simulated cargo trailers were conducted [15]. These tests confirmed that controlling a fire in a cargo trailer requires a high water discharge density.

Despite the differences in cargo, the design and installation guidelines in MSC.1/Circ. 1430 were used as the starting point for the work of establishing similar guidelines for closed ro-ro spaces onboard maritime vehicle carriers. Additionally, guidance was sought in standards developed by the National Fire Protection Association (NFPA), the European Committee for Standardization (CEN) and FM Global. These standards cover protection schemes for fire hazards similar to those found on maritime vehicle carriers.

Table 1 shows the minimum required water discharge density and minimum design area given in MSC.1/Circ. 1430/Rev.2.

Automatic sprinklers intended for spaces with a free height equal to or less than 2.5 m should have a nominal operating temperature range between 57°C and 79°C and standard-response characteristics. Standard-response refers to the reaction time of the sprinklers. Automatic sprinklers or nozzles intended for spaces with a free height in excess of 2.5 m should have a nominal operating temperature range between 121°C and 149°C and standard-response characteristics. Deluge systems should be designed for the simultaneous activation of the two adjacent deluge sections with the greatest hydraulic demand at the minimum water discharge density.

**Table 1**  
**The Minimum Required Water Discharge Densities and Minimum Design Areas Given in MSC.1/Circ. 1430/Rev.2**

Ceiling height (m)	Type of system	Minimum water discharge density (mm/min)	Minimum design area
≤2.5	Wet-pipe	6.5	280 m <sup>2</sup>
	Dry-pipe or pre-action	6.5	280 m <sup>2</sup>
	Deluge	5	2×20 m x B
> 2.5—≤6.5	Wet-pipe	15	280 m <sup>2</sup>
	Dry-pipe or pre-action	15	365 m <sup>2</sup>
	Deluge	10	2×20 m x B
> 6.5—≤10	Wet-pipe	20	280 m <sup>2</sup>
	Dry-pipe or pre-action	20	365 m <sup>2</sup>
	Deluge	15	2×20 m x B

*B* breadth of the protected space

The 2022 edition of NFPA 13 [16] provides the minimum requirements for the design and installation of automatic fire sprinkler systems and exposure protection sprinkler systems. Table 2 shows examples of occupancies that could be considered to have similarities with the fire hazard present in ro-ro spaces on maritime vehicle carriers, and the sprinkler protection criteria in terms of minimum water discharge densities and design areas. It is noted that the 2022 edition of NFPA 13 contains some applicable code changes as compared to the 2019 edition, “Automobile parking garages” is reclassified from Ordinary Hazard Group 1 to Ordinary Hazard Group 2, whilst the classification of “Automobile showrooms” remains Ordinary Hazard Group 1.

The design area is allowed to be reduced under certain conditions, without revising the water discharge density. The area of operation can be reduced by 25% when using high-temperature sprinklers for Extra Hazard Group 1 occupancies, which is relevant for hazards similar to ro-ro spaces. The area is, however, not allowed to be less than 185 m<sup>2</sup>. High-temperature sprinklers are defined as sprinklers having a nominal activation temperature of between 121°C and 149°C.

Fast-response sprinklers are not allowed for Extra Hazard occupancies or other occupancies where there are substantial amounts of flammable liquids or combustible dusts. The reason for this is the risk that sprinklers located outside the sprinkler operating area could activate during fast growing fires.

For dry-pipe systems, the sprinkler operating area should be increased by 30% without revising the water discharge density. In storage occupancies, NFPA 13 requires that high-temperature rated sprinklers be used for dry-pipe systems in storage occupancies.

EN 128452015+A1:2019 [17] provides the minimum requirements for the design and installation of automatic sprinkler systems. Fire hazards similar to “Car parks” fall under Ordinary Hazard Group 2 (OH2). For such occupancies, a wet-pipe or pre-action system should be designed for a water discharge density of

**Table 2**  
**The Classification of Occupancies Used in NFPA 13 (2022) Together with Occupancy Examples That Are Relevant for the Cargo Transported on Maritime Vehicle Carriers, Characterization of the Hazard and the Sprinkler Protection Criteria**

Hazard class	Occupancy examples relevant for ro-ro spaces on maritime vehicle carriers	Fuel quantity and combustibility	Sprinkler (wet-pipe) protection criteria
Light Hazard occupancies	None	Spaces with low quantity and combustibility of contents	4.1 mm/min over 140 m <sup>2</sup> or 2.9 mm/min over 280 m <sup>2</sup>
Ordinary Hazard Group 1 (OH1)	Automobile showrooms	Moderate quantity and low combustibility, stockpiles <2,4 m high	6.1 mm/min over 140 m <sup>2</sup> or 4.9 mm/min over 280 m <sup>2</sup>
Ordinary Hazard Group 2 (OH2)	Automobile parking garages, exterior loading docks, repair garages	Moderate to high quantity and combustibility of contents, stockpiles <3,7 m	8.1 mm/min over 140 m <sup>2</sup> or 6.9 mm/min over 280 m <sup>2</sup>
Extra Hazard Group 1 (EH1)	Aircraft hangars, upholstering with plastic foams	Very high quantity and combustibility of contents, dust, lint or other similar materials present introducing the probability for rapidly developing fires	12.2 mm/min over 230 m <sup>2</sup> or 11.4 mm/min over 280 m <sup>2</sup>
Extra Hazard Group 2 (EH2)	Manufactured homes or modular building assemblies, car stackers and car lift systems with 2 cars stacked vertically	Very high quantity and combustibility of contents, substantial amounts of flammable or combustible liquids present, shielding of combustibles is extensive	16.3 mm/min over 230 m <sup>2</sup> or 15.5 mm/min over 280 m <sup>2</sup>

5 mm/min and an area of operation of 144 m<sup>2</sup>. A dry-pipe system should be designed for an area of operation of 180 m<sup>2</sup>. “Car workshops” fall under OH3 where a wet-pipe or pre-action system should be designed for a water discharge density of 5 mm/min and an area of operation of 216 m<sup>2</sup>. A dry-pipe system should be designed for an area of operation of 270 m<sup>2</sup>. “Depots for buses, unladen lorries and railway carriages” fall under High Hazard Production Group 2 (HHP2). For such occupancies, a wet-pipe or pre-action system should be designed for a water discharge density of 10 mm/min and an area of operation of 260 m<sup>2</sup>. A dry-pipe system should be designed for an area of operation of 325 m<sup>2</sup>.

The October 2021 interim revision of FM DS 3–26 [18] by FM Global provides recommendations for fire protection using automatic sprinkler systems in non-storage occupancies, i.e., an area or building consisting of equipment, processes, and/or materials that are not maintained in a storage arrangement. Three different hazard categories are used in the document, HC-1, HC-2, and HC-3. Several of the occupancies listed in Appendix C of the document are



relevant for the fire hazards found in ro-ro spaces on maritime vehicle carriers, refer to Table 3.

Thermal sensitivity is the measure of how fast the thermal element (glass bulb or fusible link) operates in a standardised test. Based on this time, the Response Time Index (RTI) can be calculated. The lower the RTI of a sprinkler, the faster it activates in a fire. But a low RTI is not necessarily the best option. For dry-pipe sprinkler systems, FM DS 3–26 recommends the use of upright or dry-pendent sprinklers with standard-response characteristics and a nominal 140°C temperature rating for HC-3 occupancies. The reason that standard-response sprinklers should be used is to prevent too many sprinklers from opening before water fills the pipework.

The automatic sprinkler system designs discussed above can be compared by multiplying the recommended minimum discharge density with the design area. Table 4 compares the sprinkler protection criteria in MSC.1/Circ. 1430/Rev.2 for ro-ro spaces having a free height up to and including 2.5 m with the criteria for OH2 occupancies per NFPA 13 (2022) and EN 12845:2015+A1:2019 as well as hazard category HC-3 occupancies per FM DS 3–26 (2021). The height of the space would only allow transportation of passenger cars.

The sprinkler protection design requirements are the most stringent in FM DS 3–26 in terms of the total water flow rate, but it is noted that the design is valid for occupancies having a ceiling height up to 9 m. The design recommendations in EN 12845:2015+A1:2019 result in the lowest total water flow rate. However, it can be observed that this design appears to be sufficient according to the sprinkler statistics from fires in car parks in United Kingdom as discussed earlier in the paper.

Table 5 shows a similar comparison for EH2 occupancies per NFPA 13 (2022), HHP2 occupancies per EN 12845:2015+A1:2019 and hazard category HC-3 occupancies per FM DS 3–26 (2021). The data are relevant for spaces with a height that allows transportation of larger vehicles. The design recommendations in MSC.1/Circ. 1430 result in the highest total water flow rates and those in EN 12845:2015+A1:2019 result in the lowest total water flow rates.

### **3. Large-Scale Validation Fire Sprinkler Tests**

#### *3.1. The Objective of the Large-Scale Validation Tests*

Based on the input from the literature study, design and installation guidelines for sprinkler systems aimed for maritime vehicle carriers were drafted and part of the design criteria was verified in large-scale validation tests. The draft guidelines contained specifications of the type of sprinklers or nozzles to be used, positioning of sprinklers or nozzles, water discharge design densities and the system design area.

A suspended ceiling was installed to provide a clear height of 2.0 m, 2.8 m, and 4.6 m, respectively. These ceiling heights are representative of those found on maritime vehicle carriers for the actual type of vehicles used in the tests.



**Table 3**  
**Examples of Occupancies Listed in FM DS 3-26 (October 2021) That Are Relevant for Closed Ro-Ro Spaces on Maritime Vehicle Carriers**

Hazard category	Examples of occupancies listed in FM DS 3-26 relevant for ro-ro spaces on maritime vehicle carriers
HC-1	None
HC-2	None
HC-3	Parking garage Car parks Manufacturing/assembly of wind turbines Manufacturing /assembly of aircraft Manufacturing /assembly of boats, highway trailers, trucks, boxcars, mobile homes, or similar Manufacturing /assembly of cars

**Table 4**  
**A Comparison of the Sprinkler Protection Designs in MSC.1/Circ. 1430/Rev.2 with Those in NFPA 13, EN 12845:2015 +A1:2019 and FM DS 3-26 for Spaces Where the Fire Hazard Is Similar to That Presented by Passenger Cars**

Standard	Wet-pipe system			Dry-pipe system			Sprinkler coverage area (m <sup>2</sup> )
	Density (mm/min)	Design area (m <sup>2</sup> )	Total water flow rate (l/min)	Density (mm/min)	Design area (m <sup>2</sup> )	Total water flow rate (l/min)	
MSC.1/Circ. 1430/Rev.2 (up 2,5 m)	6.5	280	1820	6.5	280	1820	10.24
NFPA 13, OH2	8.1	140	1134	8.1	182	1474	12.1
EN 12845:2015, OH2	5	144	720	5	180	900	12.0
FM DS 3-26, HC-3 (up to 9 m)	12	230	2760	12	330	3960	11.1

### 3.2. Suspended Ceiling with Ceiling Beams

The most common structural arrangement within the ro-ro spaces on vehicle carriers includes primary structural ceiling members in the transverse direction of the ship and longitudinal beams with one or two rows of pillars. The height ('depth') of the primary supporting structure (longitudinal and transversal beams) is in the range of 300 mm to 500 mm. Typical centre-to-centre spacing of transversal beams can vary from about 2.2 m to 4.2 m. The spacing of the longitudinal beams is usually in line with pillar spacing, and can vary from about 6.0 m to 15.0 m.

**Table 5**  
**A Comparison of the Sprinkler Protection Designs in MSC.1/Circ. 1430 with Those for EH1 per NFPA 13, HHP2 Occupancies Per EN 12845:2015+A1:2019 and HC-3 per FM DS 3-26 for Spaces Where the Fire Hazard Is Relevant for Larger Vehicles**

Standard	Wet-pipe system			Dry-pipe system			Sprinkler coverage area (m <sup>2</sup> )
	Density (mm/min)	Design area (m <sup>2</sup> )	Total water flow rate (l/min)	Density (mm/min)	Design area (m <sup>2</sup> )	Total water flow rate (l/min)	
MSC.1/Circ. 1430/Rev.2 (6.5 m to 10 m)	20	280	5600	20	365	7300	10.24
NFPA 13, EH2	16.3	230	3749	16.3	299	4874	9.3
EN 12845:2015, HHP2	10	260	2600	10	325	3250	9.0
FM DS 3-26, HC-3 (up to 9 m)	12	230	2760	12	330	3960	11.1

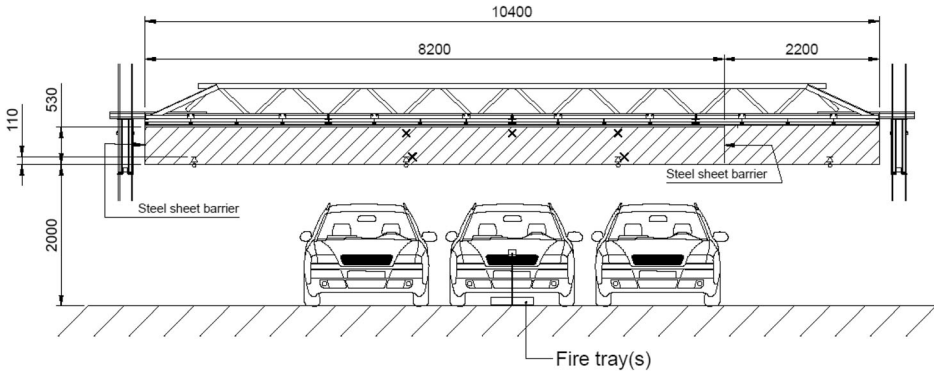
Large-scale validation fire sprinkler tests were conducted using a dry-pipe sprinkler and a deluge water spray system design. A total of six tests were performed, using either a passenger car, a van, or a freight truck as the primary fire source.

The tests were conducted under a flat, smooth, suspended ceiling measuring 10.2 m (L) by 10.4 m (W), i.e., 106 m<sup>2</sup>. The ceiling height was adjusted during the tests to provide a realistic clearance, as measured from the floor to the underside of the ceiling beams, for ro-ro spaces on maritime vehicle carriers. The ceiling had 530 mm deep transversal (related to the orientation of the vehicles) beams on a centre-to-centre distance of 3.0 m. Vertical steel sheet barriers were installed to create two 8.2 m long ‘ceiling pockets’, each containing three sprinklers or nozzles on a branch line. The beams and the vertical barriers were made from nominally 1 mm thick steel sheets. Figure 1 shows a side view sketch of the suspended ceiling and beam arrangement.

Figure 2 shows a plan view sketch of the suspended ceiling and beam arrangement.

### 3.3. The Vehicles Used in the Tests and Their Arrangement

The vehicles used in Tests 1 through 5 were used vehicles, purchased from a local auto wrecker. All cars were of standard size from the early 2000s and reasonably representative of present day’s modern cars with regard to construction, fire load and design. The cars were drained of all fluids, such as petrol or diesel, engine oil, gear box oil, power steering fluid, transmission oil, coolant, brake fluid and windshield washer fluid by the auto wrecker. Additionally, the catalytic converter, bat-



**Figure 1. A side view sketch of the suspended ceiling and beam arrangement. All measures in mm.**

tery and the air bags were removed or punctured. For safety reasons, all tires, shock absorbers and gas dampers were de-pressurized or punctured. The cars were thereafter placed on small wood blocks to achieve the correct height over the floor. Figure 3 shows the primary test set-up.

The horizontal distance measured between the side of the middle car and the target car at each side was approximately 300 mm. The distance was measured wheel-to-wheel.

The target cars were re-used if no damages occurred in a test. If minor damage occurred, the positions of the target cars were switched, such that an undamaged side faced the middle car.

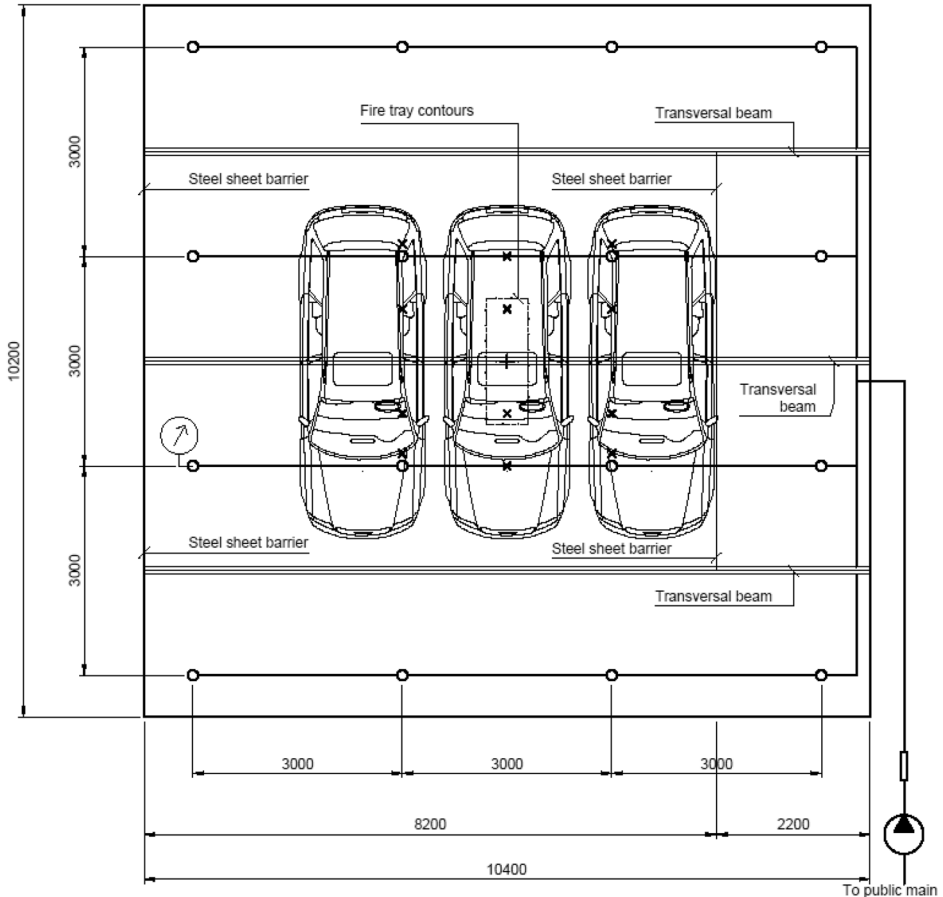
The van used in Test 5 was prepared in a similar manner to the passenger cars, as described above. One passenger car was positioned at each side of the van at a horizontal distance of approximately 300 mm. Figure 4 shows the test set-up.

The freight truck used in Test 6 had no engine and gear box and therefore three wood pallets were positioned inside the engine compartment to represent the fire load of combustibles on and around an engine, such as rubber and plastic components. To be able to remove the freight truck from the fire test hall after the test, it was essential that the rear tires were not damaged. Therefore, these tires were protected by fire insulation boards.

Nominally 1.5 mm thick vertical steel sheet screens were positioned parallel with the sides of the truck at a horizontal distance of 300 mm, in order to represent adjacent, large type vehicles. The screens had a height of 4.0 m, which was slightly greater than the height of the freight truck. The length of each screen was 1.8 m. The vertical centreline of each screen was aligned with the front wheel axle of the freight truck. Figure 5 shows the test set-up.

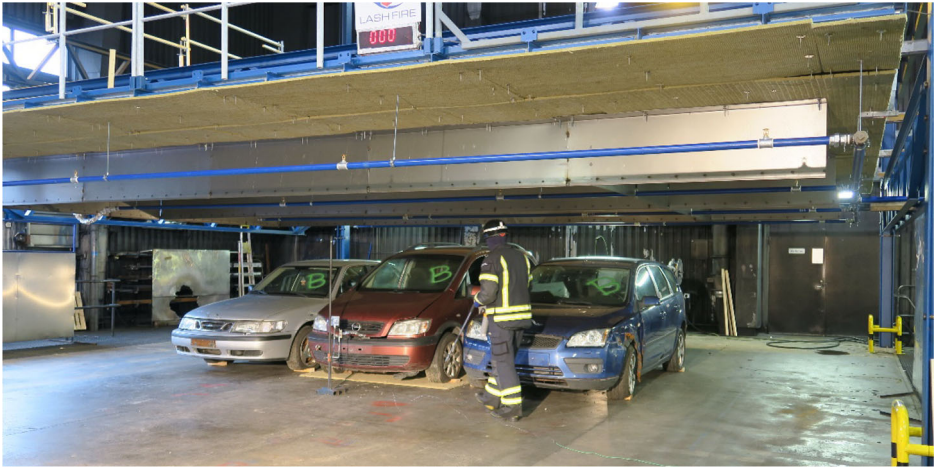
### **3.4. Fire Test Program**

As mentioned, six large-scale validation fire sprinkler tests were conducted using a dry-pipe sprinkler and a deluge water spray system design. Table 6 shows the fire test program.



**Figure 2. A plan view sketch of the suspended ceiling and beam arrangement. All measures in mm.**

Two ignition scenarios were used. For Tests 1 and 3, fire was initiated inside the centremost car with the driver's side window rolled down. A small fire ignition source was positioned in the driver's seat, up against the backrest of the seat. For Tests 2, 4, 5 and 6, fire ignition was achieved using two trays centred underneath the centremost vehicle. Each tray measured 900 mm×600 mm×75 mm (0.54 m<sup>2</sup>) and was filled with 15 l (28 mm) of heptane on a 15 l (28 mm) layer of water. The total amount of heptane fuel was thereby 30 l. For Test 2, the fire trays were positioned long side to long side under the middle car. For Test 4 and Test 5, the fire trays were positioned short side to short side under the middle car. For Test 6, with the freight truck, the fire trays were oriented long side to long side under the freight truck but separated by concrete blocks that supported the front wheel axle of the truck.



**Figure 3. Tests 1-4: The test set-up as seen prior to Test 1. The clear height, as measured from the floor to the underside of the ceiling beams, was 2.0 m. Passenger cars were used in Tests 1 to 4.**



**Figure 4. Test 5: The test set-up as seen prior to Test 5. The clear height, as measured from the floor to the underside of the ceiling beams, was 2.8 m.**

### *3.5. The System Pipework, the Sprinklers, and the Nozzles*

Sixteen sprinklers or water spray nozzles were installed at a 3.0 m by 3.0 m spacing, with the centre point of the suspended ceiling between the four centremost sprinklers or water spray nozzles. The pipework consisted of DN40 (1 ½”) branch lines connected to a DN50 (2”) distribution pipe that was connected via a water flow meter to the water pump of the fire test hall. The water pump was equipped with a frequency control such that the flow rate and pressure



**Figure 5. Test 6: The test set-up as seen prior to Test 6. The clear height, as measured from the floor to the underside of the ceiling beams, was 4.6 m.**

**Table 6  
The Large-Scale Validation Test Program**

Test	Type of vehicle	Clear height (m)	Fire ignition scenario	Type of system
1	Passenger car	2.0	Inside the passenger compartment	Dry-pipe
2	Passenger car	2.0	Pool fire trays underneath vehicle	Dry-pipe
3	Passenger car	2.0	Inside the passenger compartment	Deluge
4	Passenger car	2.0	Pool fire trays underneath vehicle	Deluge
5	Van	2.8	Pool fire trays underneath vehicle	Dry-pipe
6	Freight truck	4.6	Pool fire trays underneath vehicle	Dry-pipe

could be adjusted during a test. The middle passenger car and the van were positioned with the centre point between the four tires centred between the centremost four sprinklers or water spray nozzles. The freight truck was positioned with the front wheel axle aligned between the two centre branch lines.

Four of the tests involved a dry-pipe system using upright, standard coverage automatic sprinklers having glass bulbs. The sprinklers had different operating temperatures, thermal response (Response Time Index) characteristics and K-factors dependent on the clear height. When installed, the plane of the sprinkler frame arms was parallel to the branch lines of the pipe work. The vertical distance from the deflector of the sprinklers and the underside of the ceiling was 420 mm. The deflector of the sprinklers was thereby vertically 110 mm above the underside of the ceiling beams. The system piping was pressurized with compressed air to about a 1 bar over-pressure with the main control valve to the system closed.



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When a pressure drop in the system pipework was recorded, a delay time of approximately 45 s was applied before the main valve was opened to allow water to enter the pipework. The water travel time was short, on the order of a few seconds. Discharge at the intended (full) water flow rate was achieved about 10 s to 20 s thereafter. The system water pressure was held constant at the minimum design pressure, irrespective of the number of activated sprinklers. This is a conservative approach commonly used in fire sprinkler testing. In an actual case, system pressure would be higher when the first sprinklers activate and would gradually reduce once additional sprinklers operate.

Two of the tests involved a deluge system using 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. Following the dry-pipe system tests, the system branch lines were rotated 180° and the height was adjusted such that the deflector of the nozzles was vertically 110 mm above the underside of the ceiling beams, similar to the automatic sprinklers. The nozzles were installed with their frame arms parallel with the branch lines. The system valve was opened 60 s after recording a gas temperature of 78°C by at least two sheathed ( $\text{Ø} = 0.5 \text{ mm}$ ) thermocouples installed 6.0 m apart in each of the ‘ceiling pockets’. These thermocouples simulated spot-type heat detectors. Table 7 summarizes the system parameters in the tests.

Water was applied for 30 min in all tests except for Test 3, where the application time had to be reduced to 28:30 [min:s] to prevent overfilling of a water run-off collection basin in the fire test hall.

### **3.6. Instrumentation and Measurements**

Sheathed ( $\text{Ø} = 1 \text{ mm}$ ) thermocouples were used to measure ceiling gas temperatures directly above and to the side of the middle of the vehicles, to determine the thermal exposure of the fire on the ceiling. In total, twelve thermocouples were used, positioned in three rows with four thermocouples above the middle vehicle. The centermost row was directly above the longitudinal centerline of the vehicle. The thermocouples were spaced 1.5 m by 1.5 m and were installed 75 mm below the ceiling.

In Test 1 to Test 5, surface temperatures on each of the target cars, on the sides facing the middle car, were measured with four wire ( $\text{Ø} = 0.5 \text{ mm}$ ) thermocouples spot-welded to the steel body. A small area of the paint of the body was sanded before the thermocouple was welded to the steel. A thermocouple was installed on the front and back fender directly above the center point of the wheel. A thermocouple was installed on the front door and on the back door. The horizontal distance between the thermocouples on the front fender and front door was 750 mm. The horizontal distance between the thermocouples on the back fender and the back door was 750 mm. All thermocouples were installed at a vertical distance of 750 mm above the floor.

For Test 6, the surface temperatures of each of the steel screens positioned to the side of the freight truck were measured at four different points, along the vertical centreline of each screen. The topmost position was 500 mm below the top,



**Table 7**  
**The System Parameters in the Large-Scale Validation Tests**

Test	Type of system	K-factor ( $(l/min)/\sqrt{\text{bar}}$ )	Temperature rating ( $^{\circ}\text{C}$ )	Response Time Index ating (with glass bulb diameter)	Desired discharge density (mm/min)
1	Dry-pipe	80,6	68	Fast-response (3 mm)	10
2	Dry-pipe	80,6	68	Fast-response (3 mm)	10
3	Deluge	59	N/A	N/A	7.5
4	Deluge	59	N/A	N/A	7.5
5	Dry-pipe	115	141	Standard-response (5 mm)	15
6	Dry-pipe	115	141	Standard-response (5 mm)	20

*N/A* Not Applicable

the bottommost was 500 mm above the floor and the two in between were symmetrically between these two positions, i.e., separated by 1000 mm. The vertical centreline of each screen was aligned with the front wheel axle of the freight truck.

### 3.7. Test Results and Discussion

As already described, the tests were conducted using actual vehicles: passenger cars (four tests), a van (one test) and a freight truck (one test). The ceiling was installed to provide a clear height of 2.0 m, 2.8 m, and 4.6 m, respectively. These ceiling heights are representative of those found on maritime vehicle carriers for the actual type of vehicles used in the tests.

The average ceiling gas temperature was one of the parameters used to evaluate the performance of the tested systems. The ceiling gas temperatures were measured above the vehicles by twelve thermocouples. There was a significant variation in temperature between the individual measurement points during a test. However, the advantage of using an average value for the test-to-test comparison is that a single measurement point, whether it be high or low, has a reduced influence on the overall assessment. The average gas temperature captures the trends of the fire and the performance of the systems. Still, the test-to-test comparisons should be regarded as indicative, as it is virtually impossible to replicate the fire test scenarios because different makes of cars were used and due to random effects associated with any fire testing.

Tests 1 and 2 were conducted with a dry-pipe system discharging 10 mm/min (refer to Table 7). The fire was either started inside the middle car (Test 1) or by using two heptane pool fire trays underneath the middle car (Test 2). The average ceiling gas temperature was significantly higher in Test 2. The reason is primarily that the water discharging from the sprinklers had limited, if any effect on the shielded pool fire underneath the car and the flames from the pool fire trays reached the ceiling. As soon as the heptane fuel was consumed, the gas tempera-

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tures dropped rapidly. A total of three sprinklers activated in Test 1 and six sprinklers in Test 2.

Figure 6 illustrates the fire size shortly before water was discharged through the six automatic sprinklers that had activated in Test 2 and two minutes thereafter. It can be observed that the 'ceiling pockets' formed by the transversal beams and the steel sheet barriers installed perpendicular to these beams collected the hot gases from the fire. This arrangement enabled the activation of the automatic sprinklers closest to the fire, despite their distant installation from the ceiling surface.

Figure 7 shows the fire damage to the car in the middle and to the one to the left that was partly involved in the fire.

Tests 3 and 4 were conducted with a deluge water spray system discharging 7.5 mm/min, with fire ignition inside (Test 3) or in pool fire trays below (Test 4) the middle car. The average ceiling gas temperature was significantly higher in Test 4, which strengthens the observation that a pool fire tray ignition scenario underneath a car is more severe than fire ignition inside a car. Figure 8 illustrates the performance of the deluge water spray system in Test 4.

Figure 9 shows the fire damage to the middle car in Test 4.

Figure 10 shows the average ceiling gas temperatures for all four tests.

Fire spread to adjacent cars was only observed in one of the four tests (Test 2) with passenger cars. It cannot be determined at which time this spread occurred, but it is observed that fire spread occurred at the rear part of the car when the rear tire of the left side car caught fire and the rear window broke. Despite the fire spread, the overall fire size did not increase.

The average surface temperatures on the adjacent cars were significantly higher when the fire was started with the pool fire trays underneath the middle car. This is expected as the flames from under the car exposed the adjacent cars much more than the flames from the open side window associated with the fire being started inside the car. Figures 11 and 12 show the average surface temperatures on the adjacent cars for the passenger car tests.

For all four tests described above, it was observed that a substantial portion of the combustible material inside the middle car remained unburnt after the fire. This is an indication that water entered the car through the side window that had been left intentionally open (Test 1 and Test 3) and through the windows that broke during the course of the test. It is recognised that a fire inside a car needs to be supplied with air to grow large. This requires that one or several windows break, but their opening also allows water to reach the interior, thereby preventing the fire from growing to its full potential size.

In Test 5, using the van, the discharge of water from the automatic sprinklers failed due to an electrical malfunction of the solenoid valve for the water supply. This fire is thereby an illustration of the severity of a vehicle fire without a sprinkler system. The average ceiling gas temperature exceeded 700°C in a few minutes and several of the individual measurement points exceeded 1000°C. Fire spread to both adjacent cars occurred and the average surface temperatures on the sides of the adjacent cars peaked at between 728°C and 876°C. Without manual firefighting, the fire would have run out of control and all three vehicles would have



**Figure 6. Test 2: The fire size at 02:49 [mins:], moments before water was discharged through the six automatic sprinklers that had activated (top) and two minutes thereafter (bottom) at 04:49 [mins:].**

burned almost completely. Figure 13 illustrates the severity of the fire in Test 5, during the manual termination using fire hoses.

Figure 14 shows the measurement data.

Test 6 included a freight truck and adjacent vehicles were simulated by two vertical steel sheet screens. A dry-pipe system was tested, and the water flow rate was pre-set with six flowing sprinklers to provide a discharge density of 20 mm/min. However, a total of seven sprinklers activated corresponding to a 17.5 mm/min discharge density.

Figure 15 shows the fire size a few seconds prior to discharge of water from the automatic sprinklers at the ceiling and Fig. 16 shows the external damage after the test.

The fire was controlled by the sprinkler system and the gas temperatures at the ceiling and the surface temperatures of the steel sheet screens were promptly reduced. During the course of the fire, the windscreen, and the side windows broke, which on one hand increased the severity of the fire but on the other hand allowed water to partly reach the fire. Fire re-growth occurred once the water flow



**Figure 7. Test 2: The fire damage to the car in the middle (top) and to the car to the left (bottom) that was partly involved in the fire.**

to the system was turned off after the 30 min discharge time, illustrating the benefit of the sprinkler system, refer to Fig. 17.

### ***3.8. Lessons Learned from the Large-Scale Validation Tests***

One of the challenges of using automatic sprinklers in ro-ro spaces on maritime vehicle carriers is the presence of deep transversal beams. These beams tend to channel the hot gases from the fire in two directions, which prevents them from spreading out under the ceiling uniformly to the nearest four sprinklers. To limit the number of automatic sprinklers that would operate in a fire, steel sheet barriers were used to form two ceiling pockets that included three sprinklers on a branch line. The deflectors of the sprinklers were 420 mm below the ceiling, which typically would significantly delay the operation of sprinklers without the presence of any barriers that stop the flow of hot gases under the ceiling. The steel sheet barriers proved very efficient. The hot combustion gases filled the ceiling pockets



**Figure 8. Test 4: The fire size at 04:00 [mins] (top) moments before and at 04:30 [mins] (bottom), shortly after the discharge of water of the deluge water spray system.**

and the sprinklers closest to the fire operated once the operating temperature of the sprinklers was exceeded.

Relatively high ceiling gas temperatures were recorded in Test 2 (passenger cars) and Test 6 (freight truck). One of the reasons is that the pool fire underneath the vehicle was shielded from direct application of water. Another reason may be the relatively long vertical distance (420 mm) between the underside of the ceiling and the sprinkler deflectors. This vertical distance occurs from the desire to provide an unobstructed (by the ceiling beams) discharge of water. The large distance from the ceiling will limit the cooling capability by the water spray of the hot combustion layer that forms above the sprinklers. To reduce ceiling gas temperatures and provide direct cooling of the steel ceiling in an actual ship, it is therefore suggested that conventional upright or pendent sprinklers should be used if the vertical distance from the underside of the ceiling to the deflector exceeds 300 mm. These types of sprinklers are designed to discharge 40% to 60% of the water upwards to provide direct cooling of the ceiling construction and the remaining water is directed downwards. If installed in excess of 300 mm vertically from the underside of the ceiling, the circular ceiling area above and around the sprinkler that is directly wetted by the water spray is relatively large.



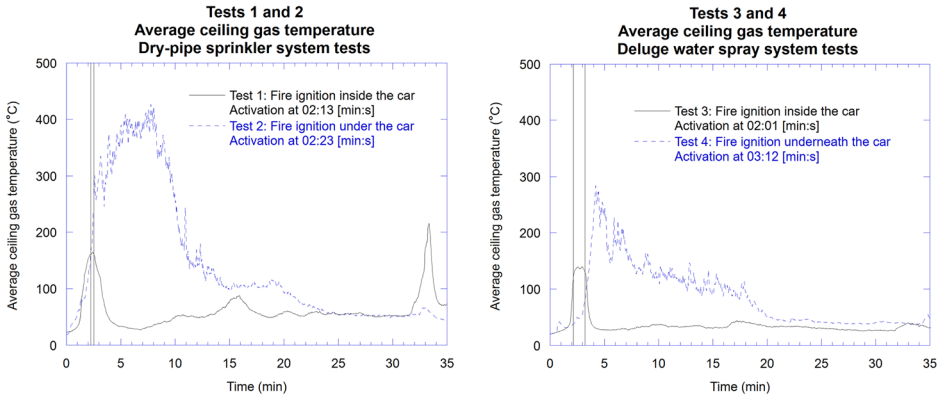


**Figure 9. Test 4: The fire damage to exterior (top) and parts of the interior (bottom) of the middle car.**

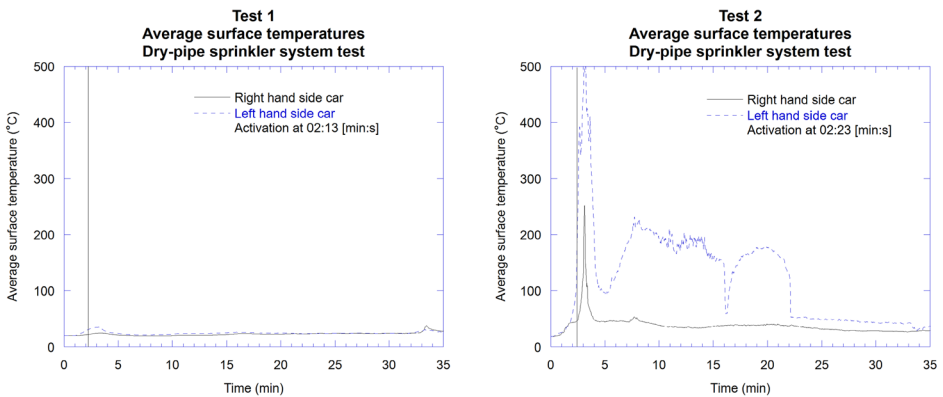
Tests 2 and 6 were the tests where the largest number of automatic sprinklers activated, six and seven sprinklers, respectively. The suggested dry-pipe system design (discussed below) includes more than twice the number of sprinklers in order to account for issues not covered by the fire tests.

#### **4. The Design and Installation Guidelines**

Based on the literature review it was concluded that the existing field experience from fires in parking garages with automatic sprinklers indicates that a fire is extinguished or controlled in the vast majority of cases. The fire sprinkler tests that were identified support this observation. It was however, noted that the fire sprinkler statistics and the fire tests reflect vehicles that are at least 20 years old. A



**Figure 10. The average ceiling gas temperatures in the dry-pipe sprinkler tests (Tests 1 and 2) and the deluge water spray system tests (Tests 3 and 4).**

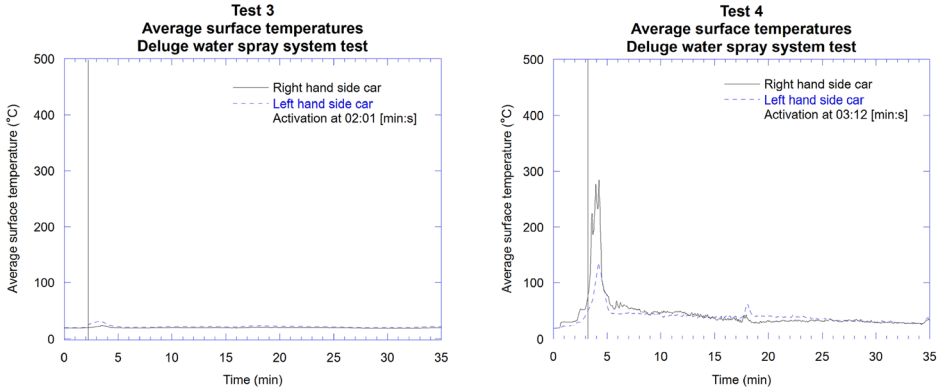


**Figure 11. The average surface temperatures on the right and left side target cars in Test 1 and Test 2. In Test 1, the fire was initiated inside the middle car, in Test 2, it was initiated with pool fire trays under the middle car.**

few (successful) actual fires involving modern battery electric vehicles were identified. Those and a recent series of fire tests indicate that fires in battery electric vehicles do not seem to be more challenging for the drencher system design used on ro-ro cargo ships than fires in gasoline-fuelled vehicles.

The review of the design and installation guidelines for automatic sprinklers shows that the sprinkler system design for fire hazards determined to be similar to those found in the ro-ro spaces of maritime vehicle carriers is quite diverse. A recent (2022) reclassification of “Automobile parking garages” in NFPA 13 was noted, probably to reflect that modern passenger cars are larger and contain sig-





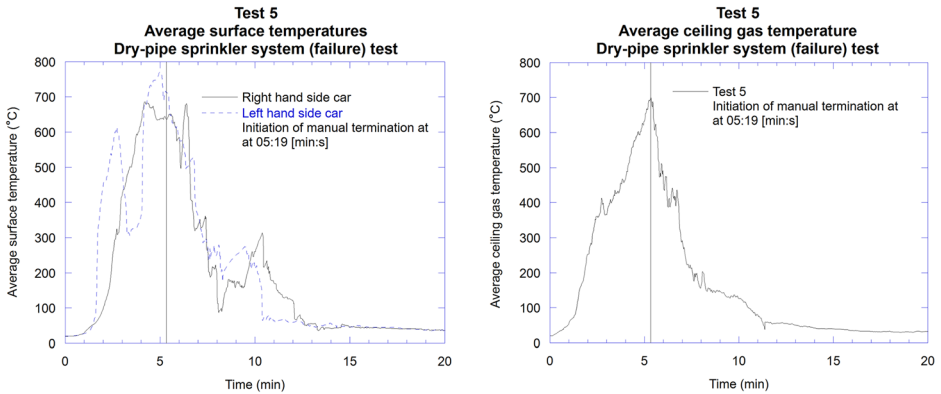
**Figure 12. The average surface temperatures on the right and left side target cars in Test 3 and Test 4. In Test 3, the fire was initiated inside the middle car, in Test 4, it was initiated with pool fire trays under the middle car.**



**Figure 13. Test 5: Manual fire-fighting at 05:49 [min:s] using hose streams.**

nificantly more plastic than older cars. Larger cars would also result in a shorter distance between cars in parking garages, which promotes fire spread.

Based on the input from the literature study, design and installation guidelines for maritime vehicle carriers were drafted and part of the design criteria was verified in the large-scale validation tests discussed above. As the horizontal distances between vehicles transported on maritime vehicle carriers is significantly shorter than the horizontal distances found in on-shore parking garages, the water discharge densities were selected to be similar or higher than recommended in the sprinkler standards. This was to ensure a high initial water discharge to prevent or



**Figure 14. The average ceiling gas temperature and the average surface temperatures on the sides of the adjacent cars in Test 5, where water discharge failed due to an electrical malfunction of the system control valve.**



**Figure 15. Test 6: The fire size at 02:00 [min:s], a few seconds prior to discharge of water from the sprinklers that had activated. Full discharge from the opened sprinklers was recorded at about 02:29 [min:s].**

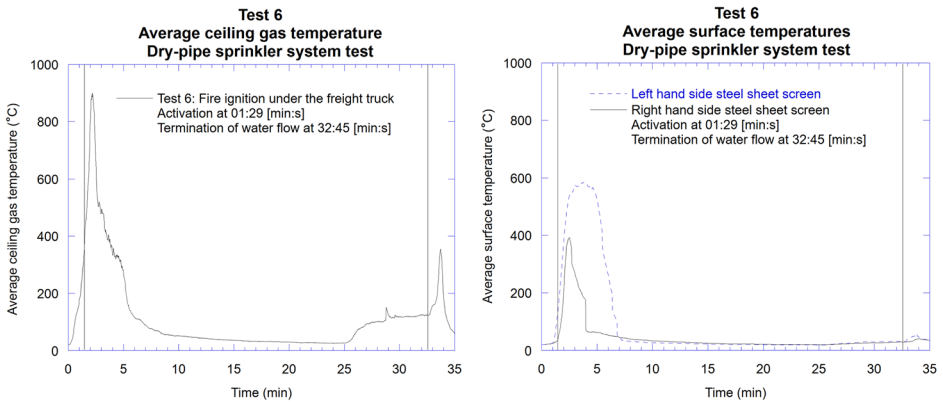
limit fire spread between vehicles. The chosen design areas are, however, typically smaller, resulting in total water flow rates comparable to the highest requirements in the sprinkler standards.

Table 8 shows the proposed design system criteria.

For discharge densities exceeding 10 mm/min, either nominally K115, K160 or larger K-factor automatic sprinklers should be used. Automatic sprinklers should



**Figure 16. Test 6: External fire damage to the freight truck.**



**Figure 17. The average ceiling gas and the average surface temperatures on the steel sheet screens in the freight truck test in Test 6.**

be installed at a maximum coverage area of 12 m<sup>2</sup>, which provides a system design that includes at least 12 sprinklers in a wet-pipe system and at least 15 sprinklers in a dry-pipe system.

Standard coverage pendent or upright spray sprinklers should be used if the vertical distance from the sprinkler deflector to the underside of the ceiling does not exceed 300 mm. If this distance is exceeded, standard coverage conventional pendent or upright K80 or K115 sprinklers, or, alternatively, standard coverage K160 pendent or upright spray sprinklers should be used. This recommendation

**Table 8**  
**The Recommended Design for Wet-, Dry-, Pre-action and Deluge**  
**Systems in Ro-Ro Spaces of Maritime Vehicle Carriers**

Type of system	Clear height	Nominal temperature rating (°C)	RTI rating	Minimum discharge density (mm/min)	Design area (m <sup>2</sup> )
Wet-pipe	≤2.4 m	70	Fast- or standard-response	10	144
Dry- or pre-action		70	Fast- or standard-response		180
Deluge		–	–	7,5	2 or 4 deluge sections
Wet-pipe	> 2.4 m–≤ 4.0 m	70	Standard-response	15	144
Dry- or pre-action		140	Standard-response		180
Deluge		–	–	10	2 or 4 deluge sections
Wet-pipe	> 4.0 m–≤ 7.0 m	70	Standard-response	20	144
Dry- or pre-action		140	Standard-response		180
Deluge		–	–	15	2 or 4 deluge sections

was a result of the fire test results, where relatively high ceiling gas temperatures were recorded because of the large sprinkler deflector-to-ceiling distance.

The obstructed ceiling constructions, with deep transversal beams typically found on maritime vehicle carriers required detailed installation guidelines to be developed regarding the positioning of automatic sprinklers. Regarding this issue, recommendations by NFPA 13 and FM Global were consulted, and recent research [19] carried out by FM Global proved to be valuable. By trapping the heat in the channels formed by beams the automatic sprinklers closest to the fire will activate. Steel sheet barriers are to be installed perpendicular to, and the full depth of, the transversal ceiling structural members such that the volume created by the channels is limited.

Open deluge water spray nozzles should be positioned in order to distribute water over and between all vehicles or cargo in the area being protected. The maximum horizontal spacing between nozzles should not exceed 3.0 m. A deluge system is supposed to be activated by a separate fire detection system having either spot-type heat detectors or line-type heat detectors installed under the ceiling. The LASH FIRE project results indicate that a deluge system is considerably more complex and expensive to configure in ro-ro spaces on maritime vehicle carriers than a wet- or dry-pipe system [20]. Another drawback with deluge systems

is that the total water flow rate is significantly higher than that of wet- or dry-pipe systems due to the minimum sizes of the deluge zones. The use of deluge water spray systems in practice is therefore judged unlikely.

It should be noted that the water-based system is intended to be supplementary to the fixed-installed CO<sub>2</sub> system in ro-ro spaces and is not a stand-alone system. Full fire extinguishment relies on proper discharge of the CO<sub>2</sub> system. The water supply of the system should be sufficient for continuous discharge for at least 30 min, otherwise the system should be fitted with a permanent sea inlet to be capable of operation using sea water. Another difference is that redundant pumps are not required.

The full design and installation guidelines can be found in [20].

## **5. Conclusions**

Closed ro-ro spaces on maritime vehicle carriers are usually protected by a total-flooding CO<sub>2</sub> system. There could be a considerable time delay from the start of a fire until the CO<sub>2</sub> system is discharged, and experience from actual fires has shown that this delay time can cause significant fire damage and jeopardize the performance of the system.

Design and installation guidelines for automatic water-based fire sprinkler systems were developed. It should be recognized that existing IMO guidelines in MSC.1/Circ.1430, as amended, are intended for ro-ro spaces and special category spaces having different conditions than ro-ro spaces on vehicle carriers. The design and installation guidelines were based on the existing IMO guidelines but provide more detailed advice for example regarding positioning of automatic sprinklers with respect to ceiling beams. The system is also regarded as a supplementary system; therefore, the water supply requirements are less stringent.

The system is supposed to automatically activate at an early stage of the fire and limit the size of a vehicle fire. This would allow more time to fight the fire manually or to safely evacuate the space and discharge the CO<sub>2</sub> system when the fire is controlled to one or a few vehicles instead of at a time when it has escalated in size.

The development of the design and installation guidelines was based on information in appropriate sprinkler installation standards and the concept was validated in large-scale fire sprinkler tests. The strength of the concepts is that they rely on both long-term field experience, conventional and proven system components, and installation practices as well as the performance validation tests.

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## **Declarations**

**Conflict of interest** All authors declare that they have no conflicts of interest.

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