



Literature study: The performance of carbon dioxide systems on ro-ro vehicle carriers

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Abstract

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The performance of carbon dioxide systems during vehicle fires on ro-ro vehicle carriers has not been documented. The first part of the report documents such fires. From 2013 to 2023, at least 22 severe fires started in the cargo space of ro-ro vehicle carriers. Eight fires started during loading operations (i.e., when the doors and ramps are open) and fourteen started while at sea. In eleven of the 22 fires, the found information verifies that a carbon dioxide system was used. In five of these verified incidents, the fire was suppressed or extinguished, in five of the incidents the fire was not suppressed nor extinguished, and in one case information about the performance is lacking. For the cases when fire was not extinguished, a long delay time combined with the fact that the space was not sufficiently sealed may explain the failure. Electrical failure, including short circuits, is a commonly noted fire cause in used cars onboard. One of the 22 fires probably originated in a new production electric vehicle; no other fires in electric vehicles were documented.

The second part of the report documents fire suppression tests. However, there are few fire suppression tests with lithium-ion batteries and carbon dioxide in the scientific literature. Findings include small-scale tests with handheld/portable fire extinguishers and not fixed, total-flooding systems. The identified studies indicates that full fire extinguishment of lithium-ion battery fires may not be possible with carbon dioxide. While carbon dioxide may not extinguish and cool down a battery cell effectively to prevent thermal runaway propagation, it may reduce the risk of fire spreading to nearby vehicles and other combustible materials. This has not been investigated and is part of the upcoming objectives in the COFFEE project.

Traditional search tools and engines were used to collect fire investigation reports, media articles, and research studies for this report.

Key words: Carbon dioxide, firefighting, fire incidents, maritime, marine, ro-ro, vehicle carriers, electric vehicle

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Preface

This literature study is part of the project Carbon diOxide Fire Fighting Experimental Evaluation, referred to as COFFEE. The overall aim is to ensure a safe transportation of lithium-ion battery driven vehicles in the cargo spaces of ro-ro vehicle carriers. Specifically, this project studies the traditional low-pressure carbon dioxide fire suppression system and its suitability for suppressing and/or delaying battery electric vehicle fires in cargo spaces of ro-ro vehicle carriers.

The project began with a comprehensive literature study to describe the fire suppression mechanisms, personnel safety issues and installation guidelines for carbon dioxide systems. Additionally, it collected existing data on fire incidents on ro-ro vehicle carriers, the performance of the fixed carbon dioxide system (if used) and lithium-ion battery fire suppression tests using carbon dioxide. This part is documented in this report.

The project is led and coordinated by RISE Research Institutes of Sweden. The project's reference group is comprised of experts from a range of organizations within the field. We are grateful for engaged participants and the discussions held. For contribution in the development of this report we thankfully acknowledge the following individuals:

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Summary

Vehicles are transported globally onboard ro-ro ships, tightly packed in a closed cargo space. The electrification of the transport sector and the rapid increase in electric vehicles transported on ro-ro vehicle carriers have highlighted the need to investigate the performance of carbon dioxide systems during vehicle fires on these carriers. This has not been documented before.

This report describes the fire suppression mechanisms, personnel safety issues and installation guidelines of carbon dioxide systems. Additionally, it summarizes existing data on fire incidents on ro-ro vehicle carriers, the performance of the fixed carbon dioxide system (if used) and lithium-ion battery fire suppression tests using carbon dioxide. Traditional search tools and search engines were used for collecting fire investigation reports, public media articles and research reports to document this.

During the 11-year period from 2013 to 2023, at least 22 severe fires started in the cargo space of ro-ro vehicle carriers. Eight fires started during loading operations and the rest while at sea. In eleven (50 %) of the 22 fires the information that was found verifies that the carbon dioxide system was used. In five of these verified incidents, the fire was suppressed or extinguished, in five of the incidents the fire was not suppressed nor extinguished, and in one case information about the performance is lacking. As it must be ensured that no person is left in the protected space, the time to discharge the system in case of fire is often long, typically in the order of 30 minutes. This may explain why the fire damage can be extensive even though the fires were extinguished. For the cases when fire was not suppressed nor extinguished, a long delay time combined with the fact that the space was not sufficiently sealed may explain the failure. For the majority of these unsuccessful cases, the fires started during loading operations, i.e., when external and internal doors and ramps are open. Electrical failure is a common fire causes (including short circuit) in used cars onboard. One fire probably started in a new production electric vehicle. Otherwise, no fires in electric vehicles were documented.

The second part of the report documents fire suppression tests with lithium-ion batteries. There are few fire suppression tests with lithium-ion batteries and carbon dioxide in the scientific literature. Findings include small-scale tests with handheld/portable fire extinguishers and not fixed, total-flooding systems. The hold time has not been significantly tested based on the results found in this study. The identified studies indicates that full fire extinguishment of lithium-ion battery fires may not be possible with carbon dioxide. The halogenated fire suppression agents used in the tests seems more efficient. However, these agents are not suitable for the protection of the cargo spaces onboard, due to very short discharge time requirements as well as current and expected environmental restrictions on their use.

While carbon dioxide may not extinguish and cool down a battery cell effectively to prevent thermal runaway propagation, it may reduce the risk of fire spreading to nearby vehicles and combustible materials. This has not been investigated and is part of the upcoming objectives in the COFFEE project.

1 Introduction

Today, the electrification of the transport sector has a strong momentum because of climate goals of net zero carbon footprint. This has led to a rapidly growing number of battery electric vehicles powered by lithium-ion batteries. These batteries contain flammable electrolyte and in case of mishandling, faults or manufacturing defects, there is a risk of so-called thermal runaway in the battery. This is a self-heating-process that releases flammable and toxic gases and can lead to fire and/or explosion [1].

Vehicles are being transported on ro-ro vehicle carriers between continents and near the coasts and these ships can carry several thousands of vehicles tightly packed in cargo spaces onboard. Vehicle carrier for deep-sea trade has a typical capacity of 6,500 – 8,000 Car Equivalent Units (CEUs). Short sea (coastal) trade vehicle carriers have a typical capacity of 800 – 3,000 CEUs. If a vehicle fire occurs it is an extremely challenging situation for the personnel to control and to put out the fire, regardless of whether it is a conventional or electric vehicle fire.

A pre-study by Lighthouse [2] draw attention to the risk and effects of transporting electric vehicles onboard, examines several incidents, discusses the regulatory initiatives and identifies different perceptions of risk and impacts among stakeholders. The study indicates a need for legal tools to deal with the risks and effects of electric vehicles fires and highlights the lack of effective equipment and specific training requirements for handling such fires on board ships [2].

The fixed fire-extinguishing systems onboard ro-ro vehicle carriers are typically either a low-pressure carbon dioxide system or a high-expansion foam system. With the rapidly growing quantity of battery electric vehicles being transported on ro-ro vehicle carriers, there is a lack of knowledge regarding the effectiveness of traditional low-pressure carbon dioxide systems, especially for fires in battery electric vehicles. Normally, ships have a supply of carbon dioxide sufficient for one single discharge, making the fire suppression capability of the system critical. The Carbon diOxide Fire Fighting Experimental Evaluation (COFFEE) project was therefore initiated to investigate the performance of carbon dioxide system for battery electric vehicle fires. The project started in January 2024.

1.1 Objectives

The objective of the COFFEE project is to study if a traditional low-pressure carbon dioxide system is adequate for suppressing and/or delaying battery electric vehicle fires in cargo spaces of ro-ro vehicle carriers.

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- 1 Wang, Qingsong, Mao, Binbin, Stoliarov, Stanislav I. and Sun, Jinhua, “A review of lithium ion battery failure mechanisms and fire prevention strategies,” *Prog. Energy Combust. Sci.*, vol. 73, pp. 95 -131, 2019
 - 2 Lundh, Monica, Malmberg, Lars-Göran and Martinson, Claes, “Regulatory aspects of Electric Vehicles and Fire in Maritime RoRo/RoPax Transports – A pre-study”, Lighthouse, February 2024

The literature study communicated in this report describes the fire suppression mechanisms, personnel safety issues and installation guidelines of carbon dioxide systems. Additionally, it summarizes existing data on fire incidents on ro-ro vehicle carriers, the performance of the fixed carbon dioxide system (if used) and lithium-ion battery fire suppression tests using carbon dioxide.

1.2 Methodology

Traditional search tools and search engines were used for collecting fire investigation reports, public media articles and research reports. Additionally, the reference group was provided with a draft report and asked to support with review, additional data and literature that were not identified through the search engines.

2 Carbon dioxide system: use and safety

This chapter introduces the properties of carbon dioxide and its safety concerns, as well as marine regulations for installation of carbon dioxide systems as fixed gas fire extinguishing system in ro-ro spaces (a type of cargo space) and machinery spaces.

2.1 Properties of carbon dioxide

Carbon dioxide (CO₂) fire extinguishing systems have been in use since the early 1900's, the first National Fire Protection Association (NFPA) standard on carbon dioxide fire systems was adopted in 1929. Until the late 1960's carbon dioxide was the only gaseous extinguishing agent in wide commercial use [3].

The chemical and physical properties of carbon dioxide have made it commonly used on board ships to protect machinery spaces and cargo spaces. Carbon dioxide is a gas at normal temperatures and atmospheric pressure. It is a colorless gas that at low concentrations is tasteless and odorless, however, at sufficiently high concentrations, it has a sharp, acidic odor [4].

Carbon dioxide has several benefits which makes it suitable for firefighting:

- It is easily available.
- It can be stored liquefied, either by being pressurized in pressure cylinders ('high-pressure systems') or by being cooled below the boiling point of -78,5 °C in a thermally insulated tank ('low-pressure systems').
- When the liquid carbon dioxide is released in a fire, it vaporizes rapidly, removing heat from the surrounding atmosphere and cooling down the environment.
- At normal temperature and pressures, carbon dioxide remains in the gaseous state and is about 1.5 times denser than air. This helps in displacing the air, as the gas act as a blanket that cuts off the supply of oxygen to a fire.
- It is non-corrosive.
- It is electrically non-conductive.
- It leaves no residue.
- It is non-flammable.

For shipboard applications these benefits are specially noted by the reference group:

- No electrical power is required. To discharge the system, a main valve and a section valve is manually opened.
- It is a simple and easy system to maintain and operate.
- The capacity can be increased, for example if a vessel is elongated. Many ship owners have recently doubled the capacity in order to improve their systems.
- It is a relatively inexpensive system and extinguishing media.

3 NFPA 12, "Standard on Carbon Dioxide Extinguishing Systems", 2022 edition, National Fire Protection Association

4 "Carbon Dioxide, Product Stewardship Summary", © Air Products and Chemicals, Inc., 2009

Carbon dioxide also has disadvantages:

- It is highly lethal at concentrations below those needed to extinguish fire.
- Fire re-ignition may occur if air is re-entering the protected compartment too soon after discharge, either due to leakage or if doors or hatches to the protected compartment are opened.

Carbon dioxide extinguishes fire by diluting the oxygen concentration in air to a level that will not sustain combustion. The normal concentration of oxygen in air is approximately 21 %. In order to obtain fire extinguishment, the oxygen concentration needs normally to be reduced to below 15 %. This corresponds to a concentration of carbon dioxide of about 35 %. The agent concentration must be maintained until the combustibles have been cooled to below self-ignition temperature, otherwise, fire re-ignition may occur. In practice, higher concentrations are used to compensate for leakage and to ensure extinguishing concentrations over a longer duration. Carbon dioxide is particularly suitable for extinguishment of flammable liquid and gas fires, referred to as Class B and Class C fires. For fires in for example wood, paper, and cotton (referred to as Class A fires), flames may be extinguished but smoldering fires may sustain. To completely extinguish such fires, very high concentrations of carbon dioxide or extended hold times are required.

2.2 Personnel safety

Wickham [5] claims that the health effect of exposure to high concentrations of carbon dioxide is typically misunderstood. It is often believed that the effect is hypoxia, i.e., the reduction of oxygen to a point where life cannot be supported. While that is the case for physiologically inert agents such as nitrogen and argon, carbon dioxide is a toxic gas that attacks the central nervous system. It shuts it down and cause death in less than a minute at concentrations half of what is used in fixed fire extinguishing systems, as most carbon dioxide total flooding systems are designed to provide concentrations above 34 %.

Permentier *et al.* [6] describes carbon dioxide intoxication as follows: “*Carbon dioxide does not only cause asphyxiation by hypoxia but also acts as a toxicant*”. Permentier *et al* refers to a study saying that it has been shown that carbon dioxide at high concentrations cause unconsciousness almost instantaneously and respiratory arrest within 1 minute. The reference also states that “*CO₂ levels of more than 30% act rapidly leading to loss of consciousness in seconds. This would explain why victims of accidental intoxications often do not act to resolve the situation (open a door, etc.)*”.

5 Wickham, Robert T. “Review of the Use of Carbon Dioxide Total Flooding Fire Extinguishing Systems,” US Environmental Protection Agency, August 2003

6 Permentier, Kris, Vercammen, Steven, Soetaert, Sylvia and Schellemans, Christian, “Carbon dioxide poisoning: a literature review of an often forgotten cause of intoxication in the emergency department”, *Int J Emerg Med.* 2017; 10: 14, Published online 2017 Apr 4. doi: 10.1186/s12245-017-0142-y

A study by the US Environmental Protection Agency [7] summarises the progressive adverse health effects with carbon dioxide exposure, refer to Table 1 .

Table 1 The acute health effects of high concentrations of carbon dioxide with increasing exposure levels of carbon dioxide [7].

Concentration of carbon dioxide (%)	Time	Effects
2	Several hours	Headache, dyspnea upon mild exertion
3	1 hour	Mild headache, sweating, and dyspnea at rest
4 – 5	Within a few minutes	Headache, dizziness, increased blood pressure, uncomfortable dyspnea
6	1 – 2 minutes ≤16 minutes Several hours	Hearing and visual disturbances Headache, dyspnea Tremors
7 – 10	Few minutes 1.5 minutes to 1 hour	Unconsciousness, near unconsciousness Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing
>10 - 15	1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness
17 – 30	Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death

There were *at least* 72 people who died from carbon dioxide fire extinguishing systems between 1975 and 1999, of which 64 deaths were be attributed to the circumstances shown in Table 2 [5].

Table 2 International causes of injuries and deaths associated with carbon dioxide discharges (1975 - 1999) [5].

Type discharge	Circumstances	Incidents	Deaths	Injured
Accidental	During maintenance on the CO ₂ system	9	8	10
	During maintenance near the CO ₂ system	8	19	19
	During testing	1	2	6
	During fire situation	2	10	7
	Faulty component or installation	2	4	13
	Operator error	2	1	4
	False alarm	2	1	15
Intentional	During testing or training	3	2	2
	During fire situation	5	15	8
	False alarm	1	2	1
	Total	35	64	85

There are personnel safety hazards associated with fixed carbon dioxide systems outside of the agent storage space and protected space. This is illustrated by an incident in a gloss paint manufacturing plant in Mönchengladbach in Germany, 2008 [8]. The discharge occurred at 06:00 in the morning in response to a fire. The gas was not contained in the

7 “Carbon Dioxide as a Fire Suppressant: Examining the Risks,” Report EPA430-R-00-002, United States Environmental Protection Agency, Washington, DC, February 2000

8 “Accidents with CO₂ extinguishing systems”, ARIA News flash, December 2008

building due to a failure of a door to close and spread outdoors. The plant's carbon dioxide tank was basically emptied, and 24 tons of liquefied carbon dioxide was released. The weather was calm and there was no wind outside, which allowed a gas cloud to form and spread out in the surrounding neighbourhood. A total of 107 individuals were intoxicated, of whom 16 had to be hospitalised, one of them needed intensive care. Because carbon dioxide is invisible, it was difficult for first responders to assess the extent of the danger. The emergency intervention mobilised significant personnel and equipment resources (about 350 to 400 rescue vehicles), and a number of difficulties were encountered. The first vehicles arriving on the scene stalled due to the lack of oxygen. A two-kilometre safety distance was established, and all rail and motorway traffic were stopped. As the cloud of carbon dioxide did not dissipate, two helicopters were eventually called in to fly over the area at low altitude, stirring the air, allowing concentrations to dilute. About fifty residents nearby were evacuated until the cloud had sufficiently dissipated. The residents were permitted to return to their homes by the end of the afternoon. It is noted that some other sources claims that 15 tons (instead of 24 tons) of carbon dioxide were released in the incident, for example reference [9]. The amount of gas, however, is low compared with what is needed in a cargo space on a vehicle carrier which can be 40-50 tons of carbon dioxide.

2.3 Installation requirements in the FSS Code

Chapter 5, “Fixed gas fire extinguishing” of the International Code for Fire Safety Systems, the FSS Code [10], contains the requirements for fixed gaseous fire extinguishing systems on ships. Some of the general requirements, with focus on cargo spaces, are discussed below.

When more than one space require protection, the available quantity of carbon dioxide need not to be more than that required for any one protected space. Hence, when multiple spaces require protection, the available quantity of carbon dioxide should be dimensioned to cover the largest protected space. The system should have control valves to direct the agent into the appropriate space. Adjacent spaces with independent ventilation systems not separated by at least A-0 class divisions should be considered as the same space. (FSS Code Chapter 5, Paragraph 2.1.1.1).

The distribution piping shall be arranged, and discharge nozzles be positioned such that a uniform distribution of the agent is obtained. System flow calculations shall be performed using a calculation technique acceptable to the Administration. (FSS Code Chapter 5, Paragraph 2.1.2.1)

Unless permitted by the Administration, pressure containers required for the storage of agent shall be located outside the protected spaces. (FSS Code Chapter 5, Paragraph 2.1.2.2)

9 “CO₂, energy transition and champagne!“, <https://www.gexcon.com/blog/co2-energy-transition-and-champagne/>, dated December 22, 2021

10 “International Code for Fire Safety Systems, Chapter 5 - Fixed gas fire extinguishing, For ships constructed from 2010-07-01”, International Maritime Organization

All distribution piping, fittings and nozzles in the protected spaces shall be constructed of materials having a melting temperature which exceeds 925 °C. The piping and associated equipment shall be adequately supported. (FSS Code Chapter 5, Paragraph 2.1.2.5)

There shall be automatic audible and visual warnings of the discharge of agent into any ro-ro spaces. The audible alarms shall be located to be audible throughout the protected space. The pre-discharge alarm shall be automatically activated (e.g., by opening of the release cabinet door). The alarm shall operate for the length of time needed to evacuate the space, but in no case less than 20 seconds before the agent is released. (FSS Code Chapter 5, Paragraph 2.1.3.2)

The means of control shall be readily accessible, simple to operate and be grouped together in as few locations as possible at positions not likely to be cut off by a fire in a protected space. At each location there shall be clear instructions relating to the operation of the system having regard to the safety of personnel. Automatic discharge of agent shall not be permitted, except as permitted by the Administration. (FSS Code Chapter 5, Paragraphs 2.1.3.3 and 2.1.3.4)

The quantity of carbon dioxide to be used in different spaces on board ships is given in paragraph 2.2.1 of the FSS Code Chapter 5, cited below. The design for vehicle spaces and ro-ro spaces is given in paragraph 2.2.1.2 and is marked in **bold**.

“2.2.1 Quantity of fire-extinguishing medium

2.2.1.1 For cargo spaces, the quantity of carbon dioxide available shall, unless otherwise provided, be sufficient to give a minimum volume of free gas equal to 30% of the gross volume of the largest cargo space to be protected in the ship.

2.2.1.2 For vehicle spaces and ro-ro spaces which are not special category spaces, the quantity of carbon dioxide available shall be at least sufficient to give a minimum volume of free gas equal to 45% of the gross volume of the largest cargo space which is capable of being sealed, and the arrangements shall be such as to ensure that at least two thirds of the gas required for the relevant space shall be introduced within 10 min. Carbon dioxide systems shall not be used for the protection of special category spaces.

2.2.1.3 For machinery spaces, the quantity of carbon dioxide carried shall be sufficient to give a minimum volume of free gas equal to the larger of the following volumes, either:

- .1 40% of the gross volume of the largest machinery space so protected, the volume to exclude that part of the casing above the level at which the horizontal area of the casing is 40% or less of the horizontal area of the space concerned taken midway between the tank top and the lowest part of the casing; or*
- .2 35% of the gross volume of the largest machinery space protected, including the casing.*

2.2.1.4 The percentages specified in paragraph 2.2.1.2 above may be reduced to 35% and 30%, respectively, for cargo ships of less than 2,000 gross tonnage where two or

more machinery spaces, which are not entirely separate, are considered as forming one space.

2.2.1.5 For the purpose of this paragraph the volume of free carbon dioxide shall be calculated at 0.56 m³/kg.

2.2.1.6 For machinery spaces, the fixed piping system shall be such that 85% of the gas can be discharged into the space within 2 min.

2.2.1.7 For container and general cargo spaces (primarily intended to carry a variety of cargoes separately secured or packed) the fixed piping system shall be such that at least two thirds of the gas can be discharged into the space within 10 min. For solid bulk cargo spaces the fixed piping system shall be such that at least two thirds of the gas can be discharged into the space within 20 min. The system controls shall be arranged to allow one third, two thirds or the entire quantity of gas to be discharged based on the loading condition of the hold.”

Note to 2.2.1.4: Ro-ro vehicle carrier for deep-sea trade has a typical gross tonnage of 55,000 to almost 90,000. Short sea (coastal) trade vehicle carriers have a gross tonnage of 15,000 to 40,000.

3 Fire incidents on ro-ro vehicle carriers

Fire incidents on ro-ro vehicle carriers are significant safety concerns due to the nature of the cargo and the design of these vessels. Vehicles are often stowed tightly to maximize cargo load, which can make it difficult to access and extinguish fires.

For the COFFEE project, it is important to explore the time until the fixed carbon dioxide extinguishing system is activated and the performance of the system, this is done based on previous incidents. It is also interesting to understand the origin of vehicle fires to further understand the issues onboard.

3.1 Identified fire incidents

Fire incidents on ro-ro vehicle carriers were identified from various sources and the outcome of the fires are summarised in the following sections. The ships had either fixed carbon dioxide or high-expansion foam total-flooding systems or was unknown. The cause of fire, the delay time until discharge and the performance of both types of systems were of interest to study.

The fire incidents that were identified are listed in chronological order in Table 3. The list does only include fires that started in the cargo space and not engine room fires or other fires on board ro-ro vehicle carriers.

Table 3 The fire incidents on ro-ro vehicle carriers that were identified. It should be noted that for some of these cases the ship was considered a Constructive Total Loss (CLT) even though the fixed carbon dioxide system was discharged, and the fire was extinguished.

Name of ship	Year of incident	Date of incident	Location	Firefighting system	Main information source
Golden Fan	2013	June 22	At port (Yokohama, Japan)	CO ₂ - discharged	Fire investigation report
Grande Colonia	2013	October 25	At port (Antwerp, Belgium)	Unknown	Public media
Asian Empire	2014	April 19	Pacific Ocean (Japan)	Unknown	Public media
Courage	2015	June 2	Coastal (North Sea)	CO ₂ - discharged	Fire investigation report
Silver Sky	2016	October 19	At port (Antwerp, Belgium)	CO ₂ - discharged	Fire investigation report
Honor	2017	February 24	Coastal (English Channel)	CO ₂ - discharged	Fire investigation report
Mignon	2018	April 4	Ocean (South China Sea)	CO ₂ - discharged	Fire investigation report
Auto Banner	2018	May 21	At port (Incheon, South Korea)	CO ₂ - discharged	Fire investigation report
Sincerity Ace	2018	December 30	Ocean (Pacific Ocean)	Unknown (but likely high-expansion foam)	Public media
Grande America	2019	March 10	Coastal (France)	CO ₂ - discharged	Public media
Grande Europa	2019	May 15	Mediterranean Sea (Palma de Mallorca)	Unknown	Public media
Platinum Ray	2019	May 22	At port (Ulsan, South Korea)	CO ₂ - discharged	Public media
Diamond Highway	2019	June 15	Ocean (South China Sea)	Unknown	Public media
Høegh Xiamen	2020	June 4	At port (Jacksonville, USA)	CO ₂ - discharged	Fire investigation report
Hansung	2020	September 27	At port (Fukuoka, Japan)	Unknown	Public media
Golden Ray	2021	September 8	Coastal (Brunswick, USA)	Unknown	Public media
Felicity Ace	2022	February 16	Ocean (the Atlantic)	High-expansion foam	Fire investigation report
Angara	2022	June 25	Ocean (Japan)	Unknown	Public media

Name of ship	Year of incident	Date of incident	Location	Firefighting system	Main information source
Ah Shin	2023	February 3	Ocean (Vietnam)	CO ₂ - discharged	Public media
Grande California	2023	February 19	Coastal (Spain)	Unknown (but likely carbon dioxide)	Public media
Grande Costa D'Avorio	2023	July 5	At port (Newark, USA)	CO ₂ - discharged	Public media
Fremantle Highway	2023	July 25	North Sea (Netherlands)	High-expansion foam	Public media

The ships listed in Table 3 were built from 1985 (Golden Fan) to 2021 (Grande California).

For some of the incidents, fire investigation reports were available. These reports provide detailed information about the ship and the timeline of the fire event, making it possible to draw relevant conclusions about the course of the fire. For many of the fire incidents in the list, however, fire investigation reports have either not yet been issued or are not publicly available. By combining information from different public media sources, a general understanding of the fire incident can be made but the information is often too limited to draw any far-reaching conclusions.

In addition to the fires listed in Table 3, there have been a number of vehicle fires on board ro-ro passenger (ro-pax) ships [see for example 11 and 12], for example the fires on board Hyundai Seolbong (2011), Kriti II (2012), URD (2014), Norman Atlantic (2014), New Golden Bridge (2019) and Silver Cloud (2020). Note: For personnel safety reasons, the ro-ro spaces on a ro-pax ship, which passengers have access to (called special category spaces) are protected with water spray ('drencher') systems instead of carbon dioxide or high expansion foam systems.

The following sections summarizes the information that was found for each identified fire incident, with focus on the aspects that were relevant for the scope of the project.

3.2 Golden Fan (2013)

The ship is a ro-ro vehicle carrier built in 1985 that can load up to 2,768 vehicles. On June 22, 2013, at 07:06 the ship berthed the Port of Yokohama, Japan. At 15:00, loading operations of 771 vehicles were completed. The total number of vehicles onboard at that time was of 1,536 units. All ventilation and cargo hold fan vents were closed according to the fire investigation report [13].

11 Kim, Kyunghwan and Jeon, Hyeonmin, "The causes and responses to cargo hold fire accidents in RoRo ships using AcciMap", <https://doi.org/10.1080/25725084.2023.2274227>, Journal of International Maritime Safety, Environmental Affairs, and Shipping, Volume 7, 2023, Issue 4

12 "Ro-ro space fire database and statistical analysis report", LASH FIRE, 2020-03-29

13 "REPORT OF INVESTIGATION ON CARGO HOLD FIRE AT YOKOHAMA M.V. "GOLDEN FAN", IMO number 8511263 Register Number 15266-85-E At Yokohama, Japan on the 22nd June 2013", Panama Maritime Authority, Directorate General of Merchant Marine Accident Investigation Department

According to the fire investigation report, smoke was observed at 15:15 on vehicle deck 5 by a tally man (keeping records during loading). The area was investigated, and it was concluded that the smoke originated from vehicle deck 4, hold 2, which was reported to the bridge. At 15:16, fire alarm was raised from the bridge. At 15:26, fire hoses were rigged on decks 3 and 4, and the watertight door was slightly opened on car deck 4, hold 2. Heavy smoke and flames were observed, and the watertight door was immediately closed. All crew mustered with nobody reported missing and at 15:27 shoreside fire brigade assistance was requested.

At 15:42, the fixed carbon dioxide system was discharged to compartment 1, on decks 4, 3, 2 and 1, i.e., 27 minutes after the first observation of smoke. At 15:59, shoreside fire fighters arrived at the pier, including eleven fire engines and two choppers and at 16:00 the Yokohama coast guard and coast guard's firefighting vessel arrived on seaside.

At 16:13, four shoreside firefighters entered the vessel from the stern ramp to investigate the location of fire. At 16:41, they advised the master to undertake a second discharge of carbon dioxide, which was made at 16:45, one and a half hour after the first observation of smoke.

At 17:25, five shoreside firefighters entered the cargo hold from the stern ramp and two other firefighters were standby at the ramp to monitor temperature of the watertight door to deck 4, hold 2. The temperature average was 34°C. At 18:00, shoreside firefighters advised a third discharge of carbon dioxide, which was undertaken at 18:04. At 20:04 and later at 23:31, shoreside firefighters entered from the stern ramp to deck 4, hold 3 to examine the oxygen and carbon dioxide concentrations.

At 04:40 on June 23, the cargo hold fan was started for hold 2 of all vehicle decks and at 05:00 two shoreside firefighters reported that there was still a high concentration of carbon dioxide on deck 4, hold 2, advising to continue with ventilation. At 07:20, fire fighters opened the watertight door for deck 2, hold 2. They found no cars burnt, only soot deposited over cars and on the inner ship side. At 07:52, the fire fighters opened the watertight door to deck 1, hold 2 and did neither found any burnt cars, only soot over cars and partly on the ship inner side.

At 08:40, the watertight door to deck 4, hold 2 was opened and two burnt cars and four adjacent damaged cars were found. At 12:06, operations from deck 5, hold 4 and 3 started in order remove damaged cargo and at 17:00 unloading operations were completed. In the afternoon of June 24, the ship was able to sail away from the Port of Yokohama, Japan.

No structural damages were reported other than some areas of coatings affected by the fire and the heat. A total of eight vehicles were damaged, two were burned and six others affected by the flames and the heat. It was concluded that the reaction of the stevedores and the crew was good and quick, hence avoiding rapid fire spread and more damages. The fire was reported to have been started in the electrical system in one of the vehicles. The fire investigation report recommends owners/managers that pre-loading surveys of used vehicles should be more thorough, that incident reports should be distributed to raise awareness of the potential hazard with used vehicles and that final visual checks of stowed vehicles prior closing watertight doors should be considered.

Comments: This case is an example where the carbon dioxide was discharged and successfully extinguished the fire with little fire damage. The fact that the system was

discharged 27 minutes after the first observation of smoke and the limited fire damage could be an indication that the initial fire growth rate was relatively slow. The fixed carbon dioxide system was discharged three times; however, the fire investigation report has no information on whether the system was re-filled with additional gas during the operation. The spaces could have been small enough so that the storage was enough for these three shots (without re-filling).

3.3 Grande Colonia (2013)

This fire occurred on October 25, 2013, when the ro-ro vehicle carrier was loading vehicles at the port of Antwerp in Belgium. The fire was under control after 2 hours with the assistance of the shoreside fire department. No injuries were reported. The ship was built in 2007 [14].

Comments: No more detailed information about this fire was found.

3.4 Asian Empire (2014)

A fire started on board the ro-ro vehicle carrier Asian Empire, built in 1998 [15], while sailing in the Pacific Ocean, about 400 nautical miles (about 740 kilometres) southeast of Japan, while on route to Panama with a cargo of vehicles. The fire started in the cargo space and quickly got out of control. Japan's Fourth Regional Coast Guard Headquarters received an emergency call at around 05:30 local time and sent patrol boats to search for the ship. A patrol boat arrived at the site of the drifting ship at 21.00 local time. No flames, smoke or signs of pollution were observed, and the hull temperature was down to 24 - 25°C on the readings from a remote heat measuring instrument. The crew of 24 were evacuated from the ship via lifeboats and rescued by the Asian Adonis, which was trading in the vicinity and altered its course to assist. There were no reported injuries [16, 17, 18].

Comments: It is unclear if a fixed carbon dioxide system was installed and used based on the information in the references. Unconfirmed reports claim that the carbon dioxide system was discharged but that the fire re-developed. This information also states that sea water was distributed through the fixed carbon dioxide system piping before the ship was abandoned.

14 <https://www.vesselfinder.com/vessels/details/9318527> (accessed on June 18, 2024)

15 <https://www.vesselfinder.com/vessels/details/9176606> (accessed on August 29, 2024)

16 Hancock, Paul, "ASIAN EMPIRE", <https://shipwrecklog.com>, published on April 19, 2014

17 "South Korean car carrier catches fire in Pacific Ocean", <https://www.vesseltracker.com>, published on April 20, 2014

18 "JCG patrol boat locates drifting vessel Asian Empire", <https://www.vesseltracker.com>, published on April 23, 2014

3.5 Courage (2015)

According to the fire investigation report, a fire started on June 2, 2015, in the cargo hold of the ro-ro vehicle carrier *Courage* when on route from Bremerhaven, Germany, to Southampton, United Kingdom [19]. The ship was built in 1991.

The ship had twelve ro-ro cargo decks, where decks 3, 5 and 8 were hard decks that were gastight, all other decks were moveable. The ship was transporting new production vehicles, military vehicles as well as personally owned vehicles and household goods shipments for military and government personnel. The cargo decks were protected by a low-pressure carbon dioxide system that was divided into four zones. Each deck had two loops of smoke detectors in series, one forward and one aft.

At about 22:15, a smoke alarm was activated at the aft part of deck 10. When investigated, heavy smoke from below was observed by a crew member when approaching the deck via one of the staircases. He radioed the bridge, informed about the smoke, and told the bridge to sound the alarm.

The crew mustered and a fire team advanced towards the deck through one of the staircases. As they approached, the smoke changed from grey to dark and started to come out more forcefully. Bubbling of paint on the weather deck was reported. Due to the intensity of the smoke, the fire team closed the watertight door from the weather deck to the ladderway and withdrew to set up boundary cooling while the master ordered operation of the carbon dioxide system. The system was discharged at 22:50, i.e., 35 minutes after the first smoke alarm. It was thereafter observed that the smoke intensified for a short period of time before stopping completely. The crew continued boundary cooling and monitored the temperature in the space through the next morning.

At 22:53, the UK Coast Guard was contacted, and the ship was instructed to continue to Southampton where it anchored offshore at about 11:00 on June 3. The crew spent the next several days working with the Coast Guard and port officials to develop a plan to carry out ventilation of the affected cargo spaces.

The post-fire investigation described in the fire investigation report identified the likely origin of the fire to be a ramp on the starboard side, aft, from deck 8 to deck 10. Vehicles on this ramp were destroyed by fire, and there was a substantial damage to the ramps from deck 10 to deck 11 and from deck 11 to deck 12 that were immediately above this area.

The likely cause of the fire was electrical arcing in the automatic braking system module of a passenger car manufactured in 2002. It was found that this particular make and model was the subject of recalls in 2007 and 2010 due to non-crash-related fires or thermal events in the vehicles' engine compartment. The owner of the vehicle had been overseas for a number of years and was not aware of the recalls. The fire was extinguished by the operation of the fixed carbon dioxide system. No persons were injured but based on the extent of fire damage, the owner of the ship decided to scrap it.

Comments: The extensive fire damage illustrates how fast a fire that starts small (electrical arcing) could spread to an extent that results in severe damage. The activation

19 "Fire aboard Vehicle Carrier *Courage*", accident no: DCA15RM024, National Transportation Safety Board Marine Accident Brief, Issued: June 29, 2017

of the fixed carbon dioxide system extinguished the fire, but despite this, fire damage was so extensive that the ship was scrapped.

3.6 Silver Sky (2016)

A fire started on board the 1989-built ro-ro cargo vessel Silver Sky on October 19, 2016, while the ship was moored at the Port of Antwerp in Belgium. The ship was loading second-hand vehicles bound for West Africa [20]. Multiple shoreside fire brigades were alerted, and firefighting tugs sprayed water to cool the hull. The 24 crew members were evacuated from the ship and there were no reports of injuries because of the fire [21]. On the morning of October 21, the fire continued to rage, the temperature prevented shoreside firefighters from boarding the ship. The fire was finally declared under control in the afternoon of October 22. “This fire is the most complicated that the firefighters have dealt with in 2 years,” said a spokesperson for the port. After pumping off polluted extinguishing water, the Silver Sky had no other option than to be scrapped [22].

A fire investigation report [23] provides more information about the incident. Approximately 1,218 cars and trucks were on board, and the schedule was to continue loading cars the next day when the fire was observed by a crew member on deck 7 at approximately 23:45. The crew immediately informed the third officer, that proceeded to the deck where he saw flames and pushed the fire alarm button. No fire was at that moment noted on deck 5. The coordination centre of Antwerp was officially informed about the incident at 23:55 and at 23:58, 13 minutes after the observation of the fire, the fire alarm from the fire detectors automatically sounded. All ramps between the vehicle decks were open although cargo operation had finished for the day almost two and a half hours before the fire started. The ventilation system was closed by the crew as well as all the starboard side dampers/vents but not all port side vents because they were not possible to be reached. The shoreside fire brigades arrived at the pier five minutes after the official information to the Coordination Center and started planning the firefighting operation. It was decided to try suppressing the fire from berth by means of water, but this method was unsuccessful. It was therefore decided to board the ship by an aerial lift in order to close the stern ramp. After closing the stern ramp, two persons from the fire brigade and the third mate boarded the vessel and went to the carbon dioxide release station to discharge carbon dioxide to the fire affected spaces. Approximately 30 minutes

20 “Car carrier on fire in Port of Antwerp”, <https://www.freightnews.co.za>, published on October 21, 2016

21 Hancock, Paul, “ASIAN EMPIRE”, <https://shipwrecklog.com>, published on October 23, 2016

22 Bois Des, Robin, “Shipbreaking, Bulletin of information and analysis on ship demolition, # 48, from April 1 to June 30, 2017”, July 31, 2017

23 “INVESTIGATION REPORT CONCERNING FIRE AND EXPLOSION INCIDENT THAT OCCURRED ON DECK NO.7 ON M/V “SILVER SKY””, Report: M/V “SILVER SKY” R-012-2017-DIAM, No.8519722, DATE: OCTOBER 19 th, 2016”, Panama Maritime Authority, Merchant Marine General Directorate, Department of Maritime Casualty Investigations

later, a second release of the remaining carbon dioxide was made but problems occurred due to leakage of the main valve. However, deck 7 was not directly covered by discharge nozzles as deck 8 is a liftable deck and no nozzles had been installed. During the release of carbon dioxide, units from the shoreside fire brigades were also cooling the vessel by water both from pier and sea using two tugboats. Additionally, 240 tons of carbon dioxide were supplied to the ship by trucks.

The fire was finally fully suppressed on the afternoon of October 22, 2016, almost three days after its beginning. The crew did not participate to the firefighting after abandoning the vessel. The exact extent of vessel's damages could not be recognized during the casualty investigation, but the following damages were reported: vehicle decks 7, 8, 9 and 10 were affected by fire, part of deck 8 collapsed, approximately 525 units were damaged/lost (some destroyed from the fire while others from smoke/heat), the upper electrical installation including the switchboard was destroyed from the fire, part of the crew accommodation and bridge were affected from the smoke and deck 10 was deformed and hogging/sagging was observed on several areas of its fore part.

The exact source of fire was not yet established during the issuing of the fire investigation report. Four vehicles were considered as the assumed fire origin. Three of them were trucks while the fourth was a camper van (which was thought to be the most possible source).

Comments: Although no exact time-information is reported in the fire investigation report it can be assumed it took at least 20 minutes from the fire was first observed. The ship's suppression system did not extinguish the fire. However, carbon dioxide from an onshore supply, along with water-cooling the ship from the outside, was eventually used to stop the fire. Fire damage was extensive.

3.7 Honor (2017)

On February 24, 2017, a fire started on the upper vehicle deck on the ro-ro vehicle carrier Honor (built in 1996) when on route from Southampton, England, to Baltimore, USA according to the fire investigation report [24]. The fire was extinguished by the operation of the fixed carbon dioxide system. One crew member was injured (no detailed information about the reason for the injury is available) during the fire-fighting efforts and the fire damage was extensive to the cargo hold and the cargo of about 5,000 vehicles.

The ship had thirteen ro-ro cargo decks connected through ramps. The ship was transporting new production vehicles, military vehicles as well as personally owned vehicles and household goods shipments for military and government personnel. The upper deck, which was aft of the ship's crew accommodation spaces was known as the "garage deck" and used for car stowage. The cargo decks were protected by a low-pressure, single-tank, carbon dioxide system that was divided into five zones, four zones for the cargo hold and one zone for the engine compartment.

At 03:02 on February 24, 2017, a pre-warning alarm on the fire detection panel sounded on the bridge. The alarm indicated a problem on the garage deck, so a crew member was

24 "Fire on board Vehicle Carrier Honor", accident no: DCA17RM007, National Transportation Safety Board Marine Accident Brief, Issued: March 6, 2017

sent aft to investigate this. While on his way to the garage the pre-warning alarm became a full alarm. He opened the door and inspected the space observing that there was smoke in the garage and a few seconds later he also reported to the bridge that there was a fire. There was too much smoke to access the space from the mid-section of the garage and attempts were made to approach the fire from the aft entrance of the space. At 03:11, the general alarm was sounded. Two attempts were made to enter the space using firefighting gear, but the space was inaccessible due to thick black smoke. At 03:25, visible flames were reported outside the garage, both on the deck above and at the aft end of the space. By 03:28, it was confirmed that all ventilation to the area had been closed.

The crew started boundary cooling and another muster was taken to confirm that no one was inside the affected space. At 03:39, i.e., 37 minutes after the first fire alarm, the master instructed the chief engineer to discharge the carbon dioxide. Following the discharge, the surrounding area was inspected for visible smoke, hot spots, or other signs of fire, while the crew continued to actively monitor and cool the adjacent bulkheads and decks. When external signs indicated that the fire was out, the chief mate and chief engineer put on self-contained breathing apparatuses and protective equipment and inspected the affected area. They used thermal imaging devices to ensure that the fire was out. The ship had no remaining carbon dioxide after the discharge and the master contacted the UK Maritime Coastguard Agency to return to Southampton and that no additional underway assistance was needed.

At about 12:00 on February 24, 2017, local Coast Guard and fire officials boarded the ship via helicopter for inspection prior to the ship being permitted to enter the port. Upon arrival to Southampton the ship was vented while anchored before returning to berth for the investigation.

It was concluded that the crew's appropriate and effective use of the carbon dioxide system, along with boundary cooling, likely prevented the spread of the fire and reduced the damage. The likely cause of the fire was a fault in the starter motor solenoid (i.e., the 12 V battery was not disconnected) in one of the personally owned (used) vehicles in shipment. Preliminary testing of this scenario confirmed that a fault within the solenoid could cause ignition of the insulation and covering on the adjacent wiring.

Comments: This fire is another example of an electrical cause of fire and extensive fire damage on a ro-ro vehicle carrier, despite the activation of the fixed carbon dioxide system. The fire broke out in the uppermost fire zone, which may have helped prevent it from becoming uncontrollable. The system was operated about 37 minutes after the first fire alarm.

3.8 Mignon (2018)

On April 4, 2018, the fire alarm started on the ro-ro vehicle carrier Mignon (built in 1999) according to the fire investigation report [25, 26]. The ship has a capacity for 7,200 passenger cars on thirteen ro-ro cargo decks with decks 5, 7 and 9 having hoistable decks. The cargo hold is divided into four fire zones denoted A to D and the fire started in zone D consisting of decks 1 to 5. Between these decks there are openings for ramps and cargo lashing holes.

Smoke and fire were detected on the lowest deck, deck 1, at 17:26 when in the South China Sea off the Philippines. The ship had departed from ports in Japan and South Korea, where various vehicles had been loaded, and was now on route to Europe. Vehicles were stowed on all decks and the ship was almost fully loaded. There were both new and used cars, as well as construction machinery, on board. The passenger cars on decks 1 and 2 were used.

The first fire alarm, which came from a detector in the aft part of the hold on deck 1, was shortly followed by fire alarms from several other detectors and later from additional detectors on the decks above. Two crew members verified that there was a fire and the decision to discharge the carbon dioxide system was taken. The time was then 17:37 but the written instructions for the discharge of the system was unclear and additional five minutes passed before it was manually activated. The time was then 17:52, i.e., 26 minutes after the fire alarm was triggered.

During the 15-minute discharge, smoke was observed from one of the ventilators on the upper deck. The dampers in the ventilators were supposed to automatically close when the fire alarm or system was activated, but one damper remained open. The damper could be quickly closed manually.

The carbon dioxide system was automatically shut down after 15 minutes, and after another two hours, a couple of crew members checked whether the extinguishing attempt had been successful. As the hold had not yet been ventilated, they wore breathing apparatus. No fire could be found, but fire-damaged cars on deck 1 and structural damage on deck 2 were observed. It was also found that the fire had caused damage to electrical wiring and hydraulics. After the inspection, the cargo space was kept closed until the next day when a new inspection was carried out. Based on this inspection it was decided that the cargo area should be ventilated so that the hydraulic pipes and electrical cables could be temporarily repaired. These repairs were necessary because the ballast tanks were inoperable, and the ship had begun to list slightly as fuel was consumed from the tanks.

The fire investigation showed that the fire was most likely caused by a short circuit in the starter motor of a used passenger car. Thereafter, the fire spread to combustible material in the car's engine compartment and passenger compartment and to other cars and parts of the ship's structure. Contributing reasons for the fire being able to spread was that the

25 "Slutrappport RS 2019:02, MIGNON – Brand i lastrummet den 4 april 2018", Diariendr S-59/18, ISSN 1400-5735, Statens haverikommission, 2019-03-28

26 "Fire on the pure car and truck carrier MIGNON on 4th of April 2018", The Swedish Accident Investigation Authority, Last updated: December 1, 2023

cars were loaded close to each other and that the side windows on the driver's sides of the cars were open.

Comments: Fixed carbon dioxide system was discharged 26 minutes after the fire alarm was triggered and successfully extinguished the fire.

3.9 Auto Banner (2018)

The ro-ro vehicle carrier Auto Banner was built in 1988 and has a maximum capacity of 6,022 CEUs. The fire onboard started in the cargo area on May 21, 2018, when at the Port of Incheon in South Korea. The ship was loaded with about 2,000 used vehicles bound for Libya [27].

Decks 1 (lowest deck) to 13 (highest deck) are ro-ro vehicle spaces. The fixed carbon dioxide system had two low-pressure tanks filled with 22 tons and 16,2 tons, respectively, according to the fire investigation report [28]. The tanks can be selected using control valves in the cylinder room. When using both tanks, the discharge time is less than 10 minutes. Before entering the Port of Incheon, the ship had discharged its entire cargo in Portland in the USA on May 2, 2018, and departed, in ballast, for South Korea, on May 3. The plan was to load a total of 4,315 second-hand cars at the Port of Incheon, depart on May 22, load additional cars onto decks 7 and 8 at the Port of Ulsan on May 24, and then proceed to the Port of Misrata, Libya, to unload the cargo.

The car involved in the accident entered the ship through the stern ramp at around 08:57 on May 21, 2018, and was secured at deck 11 at around 08:59. At that time, there were five stevedores, with the ship's boatswain on deck 11. Two of them carried out lashing, the other two carried out parking, and one flagman directed cars onto the deck. At around 09:38 smoke was observed coming out from the hood of a white car. The boatswain reported the observation to the captain and a watch-keeping officer via a transceiver. Thereafter, he obtained a portable fire extinguisher and discharged it at the radiator of the car. A stevedore also came to the scene with a fire extinguisher and discharged it at the radiator as well.

In order to block air ventilation to the fire, the captain turned off the ventilation fan serving fire zone number 4 (decks 9, 10, and 11). The first team of firefighters from the local fire service arrived at around 09:44. They instructed the crew members, who were preparing for firefighting operations, to move to a safe location. The shoreside firefighters entered deck 11 at 09:53 and tried to access the fire, but thick smoke spreading throughout the area forced them to retreat outside. Upon receiving the request to evacuate the crew to a safer place, the captain moved the crew to the stern part of the upper deck, directing them to close the dampers while moving at 09:55. At the stern of the upper deck, he counted crew members and confirmed that there were no crew left behind at the fire site. As the first attempts of firefighting operations by the shoreside

27 "Car Carrier Catches Fire at Port of Incheon, South Korea - Incident Video", <https://gcaptain.com/>, published on May 21, 2018

28 "Marine Safety Investigation Report on the AUTO BANNER, Fire Accident at Incheon Port while Berthed", Korea Maritime Safety Tribunal Marine Safety Investigation Team, Date of Accident: May 21st, 2018, Date of Publication: March 16th, 2020

firefighters failed, the captain suggested that the carbon dioxide system should be used, which was agreed.

The carbon dioxide systems were discharged into two areas, the cargo hold and the engine room, in fire zone number 4 at around 10:05. Following the discharge, white smoke was emitted from the dampers on the upper deck. When observing that the colour of the smoke changed into black, the captain however assumed that the discharge had failed to control the fire. The gastight doors of decks 9 and 11 were open, unsealing the site of the fire, which could have been a reason for the assumed failure. Therefore, the captain ordered closure of the stern ramp to seal the hull but due to loss of electrical power, the stern ramp could not be closed.

Although the area in which the fire was burning had not yet been sealed, the captain decided to use the remaining carbon dioxide in an attempt to slow down fire spread. The system was discharged into the cargo hold again at around 10:11. The fire size seemed to temporarily be reduced, however, it soon re-developed. As the second attempt resulted in failure, the firefighters noticed that the upper deck above deck 11 was melting. Based on the observation, it was decided that the crew and other personnel should evacuate the ship.

At around 11:43, the Incheon fire department evacuated all 28 crew members and other personnel aboard, using aerial ladder trucks and hydraulic platform fire engines. Thereafter, holes were cut in the hull and water fire trucks started discharging water through the holes at around 12:51. On the next day, May 24, 2018, the fire onboard the ship was completely suppressed at around 05:05 (after a total of 67 hours and 26 minutes). Extinguishment of the remaining fire was completed at around 18:00 on the same day.

The fire spread from deck 11 to vehicle decks 12 and 13, the upper deck, the bridge, the accommodation areas, and the ship's office. It also spread to deck 10, located in the lower part of the ship. All navigational and electrical equipment, onboard facilities, and 1,588 cars were burnt. It was not possible to identify the exact point of fire origin or cause based on the remaining debris, as the engine bay of the car was severely burned.

The fixed carbon dioxide system was used twice. In the first attempt, the intent was to discharge gas in fire zone no. 4 and vehicle decks 9, 10, and 11. However, as another valve connected to the engine room was open at the time, the gas was also discharged in the engine room. Likely, because the space of the fire was not properly sealed, there was no effective smothering of the fire. The gas was also not deployed in the area effectively. The gas that was discharged in the engine room caused the electrical generators to cease operation, which resulted in a blackout.

During the second use of the system, the gas was discharged only into fire zone no. 4. However, the space was not sealed as it had been during the first discharge and the flames were only initially suppressed because. Consequently, the fire soon re-developed and continued to burn. After having been towed to Bangladesh, the ship was scrapped.

Comments: The carbon dioxide system was used twice, both times in fire zone 4. However, the fire spread to another fire zone. A possible reason for the failure could be that the amount of gas was insufficient, that the compartments were not sealed, and it could also be that the fire already spread to the next fire zone prior discharge.

3.10 Sincerity Ace (2018)

The ro-ro vehicle carrier Sincerity Ace was built in 2009 and has a maximum capacity of 5,200 vehicles (other sources claim 6,400 vehicles). The fire started late on December 30, 2018, while in the middle of the Pacific Ocean about 1,800 nautical miles (about 3,200 kilometres) northwest of Hawaii. The ship was on route from Yokohama, Japan, to Honolulu, Hawaii, transporting 3,500 vehicles and had 21 crew members. The fire appeared to have started on a lower-level deck [29, 30].

By 01:00 on December 31, 2018, the fire was out of control, forcing the master to order the crew to leave the ship. Due to its distance to land, nearby commercial ships were the first to arrive on scene, helping to rescue 16 crew members but also identified four people who were floating unresponsive in the rough seas. One crew member was never found. The fire continued to burn in the unmanned ship for at least five days and the ship was eventually towed back to Japan [29, 34]. The tow began on January 9, 2019 [31].

Comments: The information found is only media reports. Since this is a sister ship to Felicity Ace according to the reference group, it is likely that it was equipped with the same type of system, a high-expansion foam system. It is unclear if any of the vehicles onboard were battery electric vehicles.

3.11 Grande America (2019)

The combined ro-ro and containership (con-ro) Grande America was built in 1997. When on route from Hamburg, Germany to Casablanca, Morocco, a fire broke out on March 10, 2019, at about 16:10. The fire started in the forward area of deck 2 according to the fire investigation report [32]. The cargo consisted of 2,184 new and used vehicles and 365 cargo containers on the upper decks.

The fire was initially fought by a firefighting team with two dry-chemical fire extinguishers and with fire hoses. The teams informed that sparks could be seen coming out from one of the trucks in the bow of deck 2. After the initial attempts to fight the fire, the ventilation system in the space was shut-off and the carbon dioxide system was discharged. At around 17:00 the same firefighting team was sent to verify the conditions in the space and communicated the presence of smoke apparently without flames. Once the team returned to the command bridge, it was decided to discharge additional carbon dioxide.

29 “Five presumed dead, 16 rescued after fire on Pacific vehicle carrier”, Professional Mariner, published on February 27, 2019

30 Kozak, Graham, “A Stricken Cargo Ship Packed with Nissans Is On Fire In The Pacific”, www.autoweek.com, published on January 4, 2019

31 Williams, Marcus, “Fire-damaged Sincerity Ace towed back to Japan”, Automotive Logistics, published on February 13, 2019

32 “M/V GRANDE AMERICA, Fire on board and subsequent sinking off Cape Finisterre 10th March 2020”, Final Report, Ministry of Infrastructures and Transport

As soon as the fire was extinguished, the ship took course to the port of La Coruna in Spain for appropriate investigations and to recharge the carbon dioxide system. However, at around 17:30 white smoke was observed between the cargo containers positioned on the weather deck and flames were observed between two containers located on the second tier, one of which contained dangerous goods. The firefighting teams immediately started fighting the new fire using two fire hoses to attack the fire and two fire hoses to cool the deck. The new emergency situation was immediately communicated with onshore resources and at around 23:00, realizing the impossibility of extinguishing the fire with only the on-board equipment, the ship asked for support. Shortly thereafter the Royal Navy HMS Argyll frigate, on its way back to the English coasts, contacted Grande America and communicated that it was directed to their position to aid. The crew continued to fight the fire with all means available. But because of the worsening weather and sea conditions, and as the fire had flared up in several cargo containers, it was decided to abandon the ship.

All 26 crew members and the only passenger were rescued by HMS Argyll while the Grande America, that was completely on fire, drifted away. Neither the crew member nor the passenger reported any physical injuries. French authorities noted the sinking of the ship at 15:26 on March 12.

No fire investigation was possible due to deep lack of evidence, the fact that Voyage Data Recorder (VDR) was missing, not clear declarations released by the crew and the fact that the ship sunk. However, some hypothesis was made. According to the crew there were two fires within a short period of time (around one and half hour) in two different decks. By analysing the ventilation system of the ship, it did not appear to be a clear relationship between the two fires. The two hypotheses concluded in the fire investigation report is that the two fires started by coincidence, although this is very unlikely, or that the fires were the result of arson.

Comments: The “first” fire seemed to be extinguished after carbon dioxide release, but a “second” fire started in another deck. A suggestion from the fire investigation report is that carbon dioxide was faulty released into the engine room and caused a black out. From the investigation report it is stated that the release of carbon dioxide and subsequent phases lack evidence and could not be analysed, hence the performance of the carbon dioxide system is unknown.

3.12 Grande Europa (2019)

A few weeks after the sinking of con-ro Grande America off the French coast due to a fire, another ship (built in 1998) of the same ship owner caught fire in the Mediterranean. The ro-ro vehicle carrier Grande Europa, while on route from Salerno in Italy to Valencia in Spain, had a fire onboard when transiting off the island of Palma de Mallorca, Spain [33].

The fire started on May 15, 2019. The cargo consisted of 1,687 vehicles, including cars, vans, trucks, and excavators. The majority of the vehicles were new and there were also 49 containers onboard, containing mainly food products. The initial fire started on

33 Capuzzo, Nicola, “Grimaldi car carrier Grande Europa catches fire in the Mediterranean”, www.splash247.com, published May 15, 2019

vehicle deck 3 at about 12:45 but was extinguished by the crew in about 45 minutes. However, a few hours later, on about 16:00, a second fire started on deck 8 which spread to deck 9. The crew again intervened with firefighting equipment. Fifteen crew members were evacuated at about 09:30 on May 16, 2023, by a Spanish Coast Guard helicopter, all of them in good condition. The fire was put out about 14:00 the same day with the use of a Spanish firefighting tug. The preliminary investigation by the ship owner suggested that the two fires started in two different new vehicles transported on board and then spread to the other vehicles nearby [34, 35].

In June 2029, three officers of the Grimaldi Group who were onboard the Grande Europa when it caught fire off Mallorca was arrested in Spain for assumed arson. The crew members are facing accusations of starting the two fires on the ship [36].

Comments: It is unclear if a carbon dioxide system was installed and used and if the vehicles were battery electric vehicles.

3.13 Platinum Ray (2019)

The ship was built in 2000 and is a ro-ro vehicle carrier. A fire broke out on one of the vehicle decks at 10:15 in the morning of May 22, 2019, while the ship was loading new cars at Hyundai Motor Company in Ulsan in South Korea [37]. The ship was bound to carry 2,163 vehicles to the USA on decks 1 to 5. Within four minutes of the alert, the fire department mobilized 26 units including pump vehicles and 103 firefighters. The ro-ro vehicle decks were filled with smoke that limited the visibility. When firefighters reached the third deck, a hot spot was detected and the first and second decks below were even hotter. It was judged that firefighters would have difficulties to enter, and it was decided to use the carbon dioxide system of the ship. At 12:50 the system was activated on the decks 1 and 2 and it was judged that the fire was suppressed. Thereafter, the fire brigade entered the affected decks and extinguished the remaining fires with fire hoses. At 15:20, five hours after its start, the fire was fully extinguished. A total of 30 cars on the first deck (where it was believed that the fire started) and 31 cars on the second deck were destroyed, but 2,102 cars were saved from destruction. Due to the carbon dioxide system discharge, it was possible to shorten the suppression time and prevent further damage. Three people were treated for smoke inhalation, and one of the firefighters was injured and moved to the hospital. The whole cargo was to be unloaded again and checked for damage.

Comments: This fire illustrates the rapid fire spread within a cargo space and to other spaces. The carbon dioxide system was discharged after approximately 2,5 hours after

34 Schuler, Mike, “A Brief Look Back at Recent Car Carrier Fires”, www.gcaptain.com, published on July 27, 2023

35 Two fires break out on Grande Europa”, www.freightwaves.com, published on May 16, 2023

36 “Three Grande Europa Crew Arrested for Alleged Arson”, <https://safety4sea.com>, published on June 18, 2019

37 “PLATINUM RAY, Cargo Ship”, www.vesseltracker.com, published on May 28, 2019

the fire started and it seems that it had a good effect with the assistance from the crew undertaking manual firefighting.

3.14 Diamond Highway (2019)

A fire broke out on the ro-ro vehicle carrier (built in 2004) on June 15, 2019. The ship was travelling between Singapore and the Philippines when it caught fire northwest of the Philippines. All 25 crew members were forced to abandon from the ship and were later picked up by a bulk carrier on route to Thailand without any injuries [38].

The Malayan Towage and Salvage Corporation (MTSC) partnered with Nippon Salvage, to respond to the fire. MTSC sent out two ships to carry out emergency response services, including firefighting and emergency towage. Operations were carried out in close consultation with the relevant local authorities and Diamond Highway was safely delivered to Batangas Bay and then Subic Bay, the Philippines, to undergo temporary repairs and to unload its cargo [39].

The ship was declared a total loss and was anchored in the vicinity of the town of Consolacion in the Philippines until December 2021, when Typhoon Odette caused it to drift and run aground at Punta Engaño. On April 28, 2023, the cutting of metal by the shipbreaking workers caused a fire that lasted for 10 hours [40]. All personnel working on the recycling operations were safely evacuated according to the local coast guard [41].

Comments: It is unclear if a carbon dioxide system was installed and used. There are neither credible nor other reports about the installed system or detailed actions taken.

3.15 Höegh Xiamen (2020)

The ro-ro vehicle carrier Höegh Xiamen was built in 2010, designed for unrestricted oceangoing worldwide service with a capacity of 4,900 vehicles. The ship caught fire at about 15:44 on June 4, 2020, while in Jacksonville, Florida, USA during loading operations, according to the fire investigation report [42]. The fire was discovered by crew members on deck 8, which had been loaded with used vehicles. It was also observed that flaming material was dripping to deck 7 through holes used for lashing on deck 8, i.e., the fire was spreading from the deck with the initial fire to the deck below. The fire

38 Williams, Marcus, “Fire on K-Line car carrier forces crew to abandon ship”, www.automotivelogistics.media, published on June 19, 2019

39 “MTSC Contracted by Nippon Salvage For Fire Fighting And Emergency Services To Fire Casualty In The Philippines”, www.salvtug.com/news/, published on June 17, 2019

40 Stinus-Cabugon, Mari, “Marina and the dismantling of the MV Diamond Highway”, *The Manila Times*, published on March 18, 2024

41 Dixon, Gary, “Cursed car carrier Diamond Highway burns again in the Philippines”, www.tradewindsnews.com, published on May 1, 2003, and updated on May 3, 2023

42 “Fire aboard Roll-on/Roll-off Vehicle Carrier Höegh Xiamen, Pier 20, Blount Island Jacksonville, Florida June 4, 2020”, National Transportation Safety Board, MAR 21/04, Adopted December 1, 2021

investigation report state that fire and alarm system was deactivated and reactivated about one minute after smoke was observed by the crew. Smoke detectors thereafter alarmed on cargo decks 8, 7, 10, and 11 (in that order), indicating the fire was spreading.

The crew members tried to fight the fire but had to retreat due to heavy smoke. Shoreside fire department teams from the Jacksonville Fire and Rescue Department arrived at the scene at 16:03. The captain, after consulting with the fire department, decided to discharge the carbon dioxide system into decks 7 and 8. These two decks covered one (Zone 3) of the five fire zones. Due to some reason, the carbon dioxide system could not be released from the CO₂ room, so it had to be released from the fire control room (both located on deck 12). Thereafter the crew evacuated from the ship. The firefighters monitored the fire using a thermal imaging camera and judged that the fire was continuing to spread despite the discharge of carbon dioxide. Therefore, they decided to enter decks 7 and 8 from the port aft stairwell. Upon entry on deck 8, firefighters encountered two smouldering vehicles and only a small amount of fire on the port bulkhead. When evacuating smoke through hatches on deck 12 (weather deck) firefighters opened a door to deck 9 (another fire zone) and found black, thick smoke.

Nine firefighters were subsequently injured, five of them seriously, in an explosion. The “explosion” occurred about the same time that the firefighters opened an exhaust in the aft ventilation trunks located near the port aft stairwell. Deck 9 likely contained a rich atmosphere of heated flammable vapours (thick, black smoke had been observed), which rapidly combusted when fresh air was introduced via the opening of the ventilation trunks for decks 9 and 10/11. The firefighters who were in the stairwell and on deck 5 near the stairwell during the over-pressurization event described a violent rush of extremely hot air. Consequently, a defensive strategy was adopted, cooling external exposed surfaces of the ship with fire monitors and fire hoses.

The fire investigation showed that fire detection system was not reactivated after loading procedures and the detection may have been delayed as there were no procedures on when to reactivate it after loading. The shoreside fire department’s response was also delayed because the master of the ship did not have contact information immediately available.

The fire burned for over a week and resulted in a total loss of the vessel and its cargo of 2,420 used vehicles. The total damages are estimated at \$40 million. After salvage operations were completed, the vessel was towed to Turkey to be recycled. The fire investigation report concludes that many of the vehicles had 12 V batteries that were not disconnected and secured in accordance with established procedures. It is likely that the fire was caused by an electrical arc or component fault in one of the used vehicles.

Comments: This fire is an example of an electrical cause of fire and extensive fire damage on a ro-ro vehicle carrier. The fire spread from one fire zone, no. 3 comprising deck 7 and deck 8, to fire zone no. 4 comprising deck 9. This is thereby an illustration of fire spread between fire zones, that time to discharge is crucial and that manual fire-fighting operations are hazardous.

3.16 Hansung (2020)

A fire broke out on one of the decks of the ro-ro vehicle carrier Hansung on the afternoon of September 27, 2020. The ship was built in 1985, and it was berthed at Hakata,

Fukuoka, northwest Kyushu Island, Japan when the fire started. It is unclear what caused the fire, which destroyed more than a dozen cars. It is reported that at least one Russian crew member sustained burns and required hospitalization [43]. The ship was loading second-hand cars. The fire was extinguished within three hours with assistance from shoreside firefighters. At least 12 used cars on a vehicle deck sustained fire damage. One Russian crew suffered hands burns and was hospitalized [44].

Comments: Little information was found related to the fire. It is unclear if a carbon dioxide system was installed and used.

3.17 Golden Ray (2021)

The Golden Ray (built in 2017) capsized off the coast of Georgia, USA with 4,200 vehicles on board. The ship left the Port of Brunswick on September 8, 2019, after unloading and loading vehicles and was on its way to Baltimore, USA. As the vessel made a turn to the right, it heeled quickly to its left side, eventually settling at an angle of 90 degrees. The capsizing of the ship was caused by incorrect calculations about the vessel's stability, according to an accident report by the National Transportation Safety Board [45]. The report also concludes that two watertight doors had been left open, which caused the ship to flood after it capsized. The flooding trapped four crew members who were later rescued.

The ship was subject of a complex salvage effort for more than 18 months, when it caught fire on May 14, 2021. Only about 1000 of the ruined cars, trucks, and SUVs on board had been removed from the wreck. On May 15, 2021, it was reported that the fire inside the ship was out [46].

The final piece of an overturned ship off the coast of Georgia was removed in October 2021. It took almost a full year before the eighth and last segment was taken away on a flatboat [47].

Comments: The fire started during the dismantling of the wrecked ship and the fire is therefore different than the other fires discussed in the report.

43 Rhine, Eric, "Fire on Russian Cargo Ship HANSUNG", <https://www.spaglaw.com/blog/>, published on September 27, 2020

44 "Russian ro-ro ship fire at Hakata, Japan", <https://www.seaandcoast.in>, published on September 28, 2020

45 "Capsizing of Roll-on/Roll-off Vehicle carrier Golden Ray St. Simons Sound, Brunswick River, near Brunswick, Georgia September 8, 2019", Marine Accident Report, NTSB/MAR-21/03, PB2021-100930, National Transportation Safety Board, adopted August 26, 2021

46 Lawrence, Andrew, "Golden Ray, the Capsized Ship, Caught Fire off Georgia Coast", published (updated) on May 15, 2021

47 "Final section of the Golden Ray removed from the St. Simons Sound", <https://www.wtoc.com>, published on October 26, 2021

3.18 Felicity Ace (2022)

The ro-ro vehicle carrier *Felicity Ace* was built in 2005. The ship caught fire on February 16, 2022, approximately 90 nautical miles (about 162 kilometres) southwest of the Azores as the ship was on route from Emden, Germany to the east coast of USA. All 22 crew members abandoned the ship safely. The ship was reportedly transporting nearly 4,000 vehicles, including some electric vehicles and luxury brands. The fire continued to burn until the ship sank about two weeks later, on March 1, 2022, according to the fire investigation report [48].

The fire investigation report provides more details about the incident and the possible cause of the fire. The ship was transporting a total of 3,965 vehicles of which 574 were electrical vehicles. The ship has a capacity to carry a maximum of 5,232 standard cars distributed on eleven vehicle decks. At 08:30 on February 16, 2022, a smoke detector was automatically activated indicating smoke on deck 1 (the uppermost vehicle deck), in the aft part of hold 4. A crew member went to the area and observed heavy black smoke and was capable to see flames from three to four vehicles. The crew member immediately informed the officer of the watch while picking up fire extinguishers. With the help of a colleague, he tried to approach the fire, but there was too much smoke and they could hear small explosions. None of the portable fire extinguishers were discharged. The fire teams were ready in a very short time, but due to the conditions on the deck, with poor visibility, they chose not to enter the space. Instead, the decision was made to activate the fixed fire-fighting system.

The ship had a fixed high-expansion foam system according to the fire investigation report, with air ducts to each of the decks having a foam generator with an electrical fan that forces the generated foam into the space. During operation of the system, it was observed from the indication lights of the control panel that the foam fans which were supposed to start automatically did not appear to operate. While attempts were made to start the foam fans, the fire team was reporting that the fire was out of control. As the discharge of foam failed, allowing the fire to spread, the crew abandoned the ship but within one hour the crew was rescued by another ship. A salvage company approached to provide boundary cooling on hull and side structures, but the fire seemed to spread to all vehicle decks. The salvage company finally was able to tow the ship, but it sank 12 days after the start of the fire. The cause of sinking is unknown.

According to the fire investigation report, the fire started in one of the battery electric vehicles, giving to the evidence of the crew. The reasons why the vehicle ignited is unknown but likely to be due to a defective battery cell due to high temperature, damage during assembling of the vehicle or a crack on insulation between the anode and the cathode causing a short circuit. It is unknown why the foam fan failed to start, but since the electrical motor was fitted at the deck level near the fire it likely failed due to damage to electrical cables from flames or heat.

48 “REPORT ON THE INVESTIGATION OF FIRE ON M.V. “FELICITY ACE” IMO number 9293911”, Report No: R-013-2022 -DIAM, Panama Maritime Authority, General Directorate of Merchant Marine, Maritime Affairs Investigation Department

Comments: It seems that the fire started in one of the battery electric vehicles being transported. The ship had a fixed high-expansion foam system that failed to operate due to technical issues with the foam fans. No information about the time delay from the start of the fire until the activating attempt of the foam system is given in the fire investigation report.

3.19 Angara (2022)

The Russian 1995-built ro-ro vehicle carrier Angara was transporting 570 cars from Japan to Vladivostok, Russia when a fire started on June 25, 2022 [49]. At about 07:00 on June 25, the ship departed an anchorage off Toyama, Japan for Vladivostok, Russia with a cargo of 570 used cars. At about 14:30 a fire broke out according to the Japan Coast Guard. Automatic Identification System (AIS) data confirms that the ship dropped speed to 1.5 knots at that time and changed heading, indicating that the ship was adrift. At about 04:00 on the morning of the June 26, the AIS signal disappeared. The Japan Coast Guard vessel Hamayuki responded to the emergency and helped rescue the 25 crew members and they were safely returned to shore, but the ship burned through her cargo decks and her accommodations section. The cause of the fire has not yet been established [50].

Comments: Little official information was found about this fire. It is unclear if a carbon dioxide system was installed and used.

3.20 Ah Shin (2023)

The ship is a ro-ro vehicle carrier built in 1999. The fire ship was carrying more than 4,500 cars and was on route from South Korea to Singapore. The fire is believed to have started on February 3, 2023. There were 21 crew members on board and all of them were reported safe [51].

One reference state that: “The ship has used up 50 tonnes of CO₂ in its firefighting system, but the fire is not yet under control. The vessel is adrift at a slow speed, some 25 nautical miles southeast of Vũng Tàu. The vessel’s owner has asked Việt Nam to provide more CO₂ to control the fire.” [52].

Another source says that the fire was initially reported to have affected vehicles transported on decks 8, 9 and 10 but that the crew may have brought the fire under

49 Panasovskyi, Maksim, “Russian vessel "Angara" with 570 cars on board burned in the Sea of Japan - the Japanese refused to fight it”, <https://gagadget.com>, published on June 26, 2022

50 “Russian-operated ro/ro catches fire off Japan”, <https://maritime-executive.com/>, published on June 27, 2022

51 Schuler, Mike, “Car Carrier Suffers Fire Off Vietnam”, www.gcaptain.com, published on February 6, 2023

52 “Maritime authorities ready to support cargo ship after fire”, <https://vietnamnews.vn>, published on February 6, 2023

control using the fixed carbon dioxide system [53]. Assistance was requested from the local Authorities but weather conditions in the region may have delayed other vessels attending. In a news update of the same source a few days later it was stated that the fire had been extinguished and a team of experts approved by the local Authorities was able to attend on board to inspect the extent of damage.

Comments: There are neither credible nor other reports about the installed system or detailed actions of the crew. It seems that the carbon dioxide system was used, but its effectiveness is unclear.

3.21 Grande California (2023)

The ship was built in 2021 and is a ro-ro vehicle carrier. When sailing from Antwerp in Belgium for Gioia Tauro in Italy, a fire broke out on one of the ro-ro vehicle decks as the ship was sailing west of La Corunna, Spain, in the early hours of February 19, 2023. The ship was transporting about 4,500 vehicles, including 48 battery electric vehicles. The fire was reported extinguished [54]. The crew were using the firefighting equipment on board to extinguish the fire. Salvamento Marítimo (Sasemar), the Spanish maritime rescue society positioned its tug María Pita near the ship as a preventive measure. The ship anchored at the Cíes Islands where it was expected to remain for about 24 hours to verify the complete extinguishing of the fire [55].

Comments: From the two references it is not known if a carbon dioxide system was installed and used. The reference group note that it can be assumed that the ship had a carbon dioxide system installed, due to the owner and shipyard. However, it is not clear what type of firefighting equipment that was used to extinguish the fire.

3.22 Grande Costa D’Avario (2023)

The Grande Costa D’Avario is a con-ro ship (built in 2011) that caught fire at Port Newark Marine Terminal in New Jersey, USA on July 5, 2023, while loading used vehicles for export. Shoreside firefighters responded to the fire and the efforts were later expanded to include specialized teams. Two of the shoreside firefighters died in the initial effort and the fire continued to spread in the vehicle spaces before it was finally extinguished after six days. The 28 crew members were all evacuated without injury [56].

The ship has ro-ro spaces on its aft for loading vehicles and cargo spaces forward for loading containerized cargo. The ship loaded an unknown number of used vehicles in Port Newark that were bound for West Africa. The fire likely started in a vehicle space on deck 10 shortly after 09:00. The initial emergency call reported six or seven vehicles on

53 “AH SHIN”, <https://www.wkwebster.com>, published on February 13, 2023

54 Willmington, Rob, “Grimaldi vehicle carrier crew tackle car-deck fire off Spain”, www.lloydlist.com, published on February 20, 2023

55 “Fire on the car carrier Grande California”, www.informare.it, published on February 20, 2023

56 “Salvage Operation Clears Cargo from Grande Costa D’Avario”, The Maritime Executive, published on August 7, 2023

fire and the fire had spread upward to deck 12 by the time shoreside firefighters reached the ship at about 09:25. The crew aboard had already activated the ship's fixed fire suppression system before the shoreside firefighters arrived, but the type of system installed on the ship, or the effects have not been [at that time of the publication of the information] publicly communicated [57].

The cause of the fire is currently unknown. The US Coast Guard is leading an investigation into the incident with the National Transportation Safety Board (NTSB) and state and local authorities [57]. All vehicles were gasoline- or diesel-powered, there were no electric vehicles on board [58]. From the US Coast Guard Formal Investigation Hearings, it seems that a carbon dioxide system was installed in the ro-ro vehicle spaces [59]. Other information says that a door to the main space on deck 12 remained open during discharge, influencing the effectiveness of the system. The fire may have started in a vehicle used to push cargo on board and not in one of the vehicles that were supposed to be transported [60].

Comments: It seems that the carbon dioxide system was operated within 30 minutes after the start of the fire. The discharge was ineffective which could be because the spaces were not fully sealed and/or that the fire had spread to another fire zone prior discharge. No fire investigation report is yet available.

3.23 Fremantle Highway (2023)

The ship is a ro-ro vehicle carrier built in 2013. On July 25, 2023, a fire broke out in one of the ro-ro vehicle spaces whilst in the North Sea off the coast of the Netherlands. The ship was on route from Bremerhaven, Germany to Port Said in Egypt and from there to Singapore. The ship had departed from Bremerhaven and was at the coast of the Netherlands when the fire started on a ro-ro cargo deck around 21:30 before quickly spreading to other parts of the ship [61]. The crew were unable to extinguish the fire. One emergency tug from the Netherlands Coast Guard as well as one German emergency tug was involved in the firefighting. The use of water had to be limited due to a risk of the vessel becoming unstable and it took until August 1 before the fire was extinguished [62].

57 “New allegations regarding cause of Grande Costa d’Avario fire”, Professional Mariner, published on October 8, 2023

58 Hill, Brandyn, “Coast Guard Exhibit 01 - Facts of the Incident - Grande Costa D’Avario”, <https://www.dvidshub.net/video/910187/coast-guard-exhibit-01-facts-incident-grande-costa-davorio>, video dated 2024-01-10

59 <https://www.news.uscg.mil/News-by-Region/1st-District-Northeast/PADET-New-York/Grande-Costa-DAvario-Investigation/>

60 Parry, Wayne, “Investigative hearings open into cargo ship fire that killed 2 New Jersey firefighters”, <https://why.org/articles/nj-cargo-ship-fire-firefighter-deaths-investigative-hearings-open/>, published on January 10, 2024

61 Barlow-Brown, Tom, “Car Carrier Fire off Dutch Coast Leaves One Dead, Several Injured”, The Naval Architect – News, published on July 28, 2023

62 Buitendijk, Mariska, “Dutch Safety Board investigates emergency response Fremantle Highway”, <https://swzmaritime.nl/>, published on August 9, 2023

The ship was towed to the Eemshaven port in Netherlands, to reduce any risk of oil spills. Local media reported that the lower four of twelve decks on the ship are relatively undamaged, which is where the 1,000 salvageable vehicles (including battery electric vehicles) were located. However, the four uppermost decks were badly damaged [63].

The ship's cargo was unloaded in the Eemshaven port, Netherlands. The operation to remove cars and debris from the ship was completed in beginning of September 2023. As many as 1,000 vehicles may have been removed, mostly from the lower decks of the ship and many looked undamaged while others were burnt and at least one caught fire on the dock afterwards. A preliminary survey and report say apparently the fire was not caused by electric vehicles. There were 498 electric vehicles and hybrids and a total of 3,784 vehicles including some heavy equipment on board the ship [64].

A recent report looking at the rescue operation to rescue the crew from the ship is highly critical of the efforts according to a Dutch newspaper. The analysis confirms earlier media reports that claimed that the responders were ill-prepared, slow to reach the ship, and disorganized in their efforts. The newspaper reports that the analysis shows that the initial wrong assessment of the seriousness delayed the rescue helicopter and that they had initially been prepared to fight the fire, not an evacuation. Ultimately, 16 crew members were rescued by two helicopters, another seven chose to jump into the ocean to be rescued by a Coast Guard boat. One of the crew members died from injuries sustained from the jump and hitting the water [65].

Comments: No information on the type of fixed fire-fighting system and if it was used was found in the references. Unconfirmed reports claims, however, that the ship had a high-expansion foam system.

63 Megan, Kelly, “EVs “in good condition” after Fremantle Highway ro-ro fire”, www.automotivevelogistics.media, published on August 22, 2023

64 “Salvage Completed on Fire-Damaged Car Carrier Fremantle Highway”, PM by The Maritime Executive, published on September 8, 2023

65 “Report Details “Confused and Chaotic” Rescue for North Sea Car Carrier Fire”, PM by The Maritime Executive, published on February 7, 2024

4 Fire suppression of lithium-ion batteries

Traditional search tools and engines were used to collect research reports on fire tests involving lithium-ion batteries. Some references describing fire suppression tests involving lithium-ion batteries were identified. The information is summarized in this chapter.

4.1 A review of fire-extinguishing agents for lithium-ion battery fires

Yuan et al. [66] have conducted a comprehensive review of the suitability of different fire-extinguishing agents on suppressing lithium-ion battery fires. The review, published in 2021, concludes that a fire-extinguishing agent developed for this type of fire will most likely need a high heat capacity, a high degree of wetting, a low viscosity, and a low electrical conductivity. Several agents are discussed and summarized in detail in the review. It is noted in the review that water-based fire-extinguishing agents possess high cooling capacity and fire re-ignition prevention performance. For carbon dioxide, it is concluded that the extinguishment efficiency highly depends on how sealed the enclosures are. The study also notes that some heat in the flame zone can be absorbed due to the evaporation and sublimation of carbon dioxide, which may help lower the temperature and further suppress the fire. However, the impact of these endothermic reactions on reducing the flame temperature appears to be minimal.

Comments: This study assumes that the fire suppression agent is applied directly towards the seat of fire. It is therefore not directly applicable for fixed total-flooding systems in a large vehicle space where the seat of the fire may be far away or shielded from direct application of the agent.

4.2 Experimental study comparing three different agents

Xu et al. [67] have conducted fire suppression tests on a single 94 Ah large-scale $\text{LiNi}_{0.5}\text{Co}_{0.2}\text{Mn}_{0.3}\text{O}_2/\text{graphite}$ cell. The nominal voltage was 4.2 V, and the cell size was 170 mm by 45 mm by 125 mm. Before tests, each cell was precycled several times and finally charged to 100 % state of charge (SoC). To ensure that the spray of the fire

66 Yuan, Shuai, Chang, Chang, Yan, Shuaishuai, Zhou, Pan, Qian, Xinming, Yuan, Mengqi, and Liu, Kai, "A review of fire-extinguishing agent on suppressing lithium-ion batteries fire", *Journal of Energy Chemistry*, 62, 262-280, 2021

67 Xu, Jiajia, Guo, Pengyu, Duan, Qiangling, Yu, Xinchun, Zhang, Lin, Liu, Yujun and Wang, Qingsong, "Experimental study of the effectiveness of three kinds of extinguishing agents on suppressing lithium-ion battery fires", *Applied Thermal Engineering*, Volume 171, 5 May 2020, 115076

extinguishing agents covered the fire, the discharge nozzle was positioned 300 mm above the cell. The tests were conducted in an explosion-proof chamber sized 0.8 m by 1.2 m by 1 m (0.96 m³). Three tests with different agents (carbon dioxide, HFC-227ea and water mist) and one reference test without any agent were conducted. The amount of extinguishing agent was 2 kg in all tests, i.e., an amount commonly used in portable fire extinguishers. It was concluded that the discharge of carbon dioxide, HFC-227ea and water mist prevented the combustion of the combustible gases and jet fire from the cell. Note: Another commercial name for HFC-227ea is FM-200. However, carbon dioxide and HFC-227ea did not completely suppress the fire, a flame was observed during the release of these two extinguishing agents, whilst the discharge of water mist effectively suppressed the fire. The surface temperature on one side of the cell was measured and water mist provided the best cooling effect, followed by HFC-227ea and carbon dioxide.

Comments: In these fire suppression tests the fire suppression agents were directed towards the battery cell from a relatively short distance. The reference does not describe the air tightness of the test chamber and whether the concentration of the gaseous agents was constant over a longer period of time.

4.3 Fire suppression tests using portable fire extinguishers

Ubaldi et al. [68] have conducted fire suppression tests using a single Kokam Superior Lithium Polymer Battery cell, with two different capacities (25 Ah and 40 Ah). Before being tested each cell was charged to 100 % SoC. The nominal voltage was 3.7 V, and the cells were sized 226 mm by 227 mm by 6.0 mm (25 A) and 226 mm by 227 mm by 9.1 mm (40 A). The tests took place in an open area with perimeter walls and a wire mesh ceiling to protect against the projection of solid fragments. The cell was positioned on a grating above a propane burner, with two thermocouples on the upper surface, opposite the burner. The tests were documented using a video camera and a thermal imaging camera.

Two portable water-based fire extinguishers (water mist and F500) and one portable gas (CO₂) fire extinguisher were used in the tests. Note: F500 is a commercial fire suppression agent that is mixed with water. The cell was heated until it ventilated and thermal runaway was observed. Thereafter the agent was applied. From the test results it is observed that the electrical capacity does not significantly influence the temperature at which venting and thermal runaway occurs. The number of applications, the cooling rate and temperature once the extinguishment was over were used as parameters to compare the different agents. The cooling rate was 36°C/min for F500, 31°C/min for water mist and 20°C/min for carbon dioxide, at the first application of agent. These values highlight the greater cooling efficiency of the water-based agents (i.e., water mist and F500) compared to a gaseous agent (CO₂).

68 Ubaldi S., Di Bari C., De Rosa A., Michele M., Russo P., “Investigation on Effective Fighting Technology for Lib Fire”, *Chemical Engineering Transactions*, 91, 505-510, DOI:10.3303/CET2291085, 2022

Comments: These fire suppression tests were conducted in an open space, preventing an extinguishing concentration to build up around the single battery cell under fire.

4.4 A review of lithium-ion battery fire suppression

Ghiji et al. [69] have conducted a literature review of lithium-ion battery fire suppression. The review covers water, foam, carbon dioxide and halon-based extinguishants. Regarding carbon dioxide it is concluded that it is not an ideal extinguishing agent for lithium-ion battery fires due its low cooling capacity. The review also refers to a study where the halogenated agent heptafluoropropane (commercial name HFC-227ea or FM-200) showed superior behavior in suppressing lithium-ion battery fires when compared to carbon dioxide and powder.

Comments: The referenced study is discussed in more detail subsequently, in Section 4.5.

4.5 Fire suppression tests of lithium-ion battery used for ships

Rao et al. [70] have conducted a series of fire tests in a test chamber to study the fire behavior of lithium-ion batteries and determined the effectiveness of three different fire extinguishing agents: the halogenated agent heptafluoropropane (commercial name HFC-227ea or FM-200), carbon dioxide and powder.

The test chamber was made from steel sheets and measured 900 mm by 750 mm by 600 mm (H), i.e., it had a volume of 0.4 m³. Two nozzle inlets on the right wall allowed agents to be discharged from a fire extinguisher into the chamber through pipelines. Several pressure relief openings were installed in the walls.

The fire tests were conducted using lithium iron phosphate power batteries from a single manufacturer. The battery cell was sized 213 mm by 142 mm by 67 mm (H), had a shell of plastics, a nominal capacity of 100 Ah and a nominal voltage of 3.2 V. The relief valve outlet of each battery cell was closed by plastic welding and a two-component adhesive before testing. The cell type is typically used in battery systems on ships. Ignition was undertaken by a liquefied petroleum gas (LPG) burner, which was centered towards the bottom of the battery used in the tests.

69 Ghiji, Mohammadmahdi, Novozhilov, Vasily, Moinuddin, Khalid, Joseph, Paul, Burch, Ian, Suendermann, Brigitta and Gamble, Grant, “A Review of Lithium-Ion Battery Fire Suppression”, *Energies* 2020, 13, 5117

70 Rao, Hui, Huang, Zhaoxia, Zhang, Hui and Xiao, Shuming, “Study of fire tests and fire safety measures on lithium-ion battery used on ships”, *The 3rd International Conference on Transportation Information and Safety*, June 25 – June 28, 2015, Wuhan, P. R. China

Initially, free-burn tests were conducted with the battery to document the fire growth and flame spread. These tests were conducted both outdoors (unlimited amount of air) and inside the test chamber (restricted amount of air). When tested outdoors, the battery cell never reached a stage of thermal runaway, in opposite to the tests inside the test chamber. Then fire suppression tests were conducted. The required quantity of each extinguishing agent was calculated according to the relevant requirements for ships. The extinguishing agent was discharged into the test chamber when the battery electrolyte participated in the fire, which exhibited a rapid growth rate.

When using carbon dioxide, the battery underwent thermal runaway and then re-ignited during the first test. This was probably due to a few air supplies through the pressure relief openings on the walls. In the second test, the battery re-ignited as well, after being brought out from the test chamber. When using the superfine powder, the battery underwent thermal runaway in the first test and in the second test, the battery not only underwent thermal runaway, but it also exploded. When testing heptafluoropropane, the battery did not re-ignite, explode, or undergo thermal runaway in any of the two test tests.

In summary, it was concluded that heptafluoropropane was the most effective agent in controlling the battery fires and suppressing the thermal runaway reactions. For carbon dioxide, the effect of oxygen dilution primarily contributes to extinguishment to some extent, but the efficiency of extinguishment and cooling are significantly lower than heptafluoropropane. Carbon dioxide did not prevent battery thermal runaway reactions: consequently, once a battery is exposed to fresh air, it may re-ignite even if the thermal runaway reactions have finished completely (as observed in the second test). For the superfine powder agent, the solid particle surface plays an important role in suppressing the chain-branching combustion reaction, contributing to the extinguishment of battery fires. However, the thermal runaway reactions were not prevented. Consequently, a large amount of heat accumulated rapidly in the limited space of the test chamber, resulting in the explosion of the battery in the second test.

Based on the test analysis, fire safety measures for lithium-ion battery rooms on ships were recommended. The measures included a recommendation that a heptafluoropropane fire extinguishing system shall be installed in the battery room. If carbon dioxide is used, procedures shall be established for ensuring an adequate cooling time. The door to the room should not be opened until after an extended time, to account for the possibility of re-ignition or explosion.

Comments: These fire suppression tests remind of the conditions expected in a ro-ro vehicle space in that the test chamber supposedly allowed a design concentration of the fire suppression agent to build up.

4.6 Fire suppression tests using perfluorohexanone

Liang et al. [71] have evaluated the efficiency of perfluorohexanone (commercial name Novec 1230 or FK-5-1-12) for suppression of lithium-ion battery fire at different ambient (or rather agent) temperatures.

A commercial, prismatic lithium iron phosphate battery cell was used in the fire suppression tests. The battery cell was sized 173 mm by 71 mm by 200 mm (H) and had a nominal capacity and voltage of 271 Ah and 3.2 V, respectively. The weight was about 5.2 kg, and it was charged to 100 % SOC. An external electric heating plate of 500 W was utilized to trigger battery thermal runaway.

The battery cell was positioned inside a standard lithium-ion battery box with a size of 1060 mm by 660 mm by 250 mm (H). When the battery cell ignited, the power of the heating plate was stopped, and the battery cell was allowed to burn for 3 min before the fire suppression system was manually activated. An open flame was introduced at the opening of the battery test box every 3 min, to verify any fire re-ignition.

Three fire suppression tests at normal temperature, low temperature (-40 °C) and high temperature (85 °C), respectively, were conducted. The temperatures refer to the temperature of the agent and agent storage device. The time from the start of discharge of the agent until extinguishment of the open fire was 11 s, 14 s and 9 s, respectively. Fire re-ignition did not occur in any of the tests.

Comments: The fact that the battery cell was positioned inside a small test compartment likely allowed a certain hold time of the agent that helped preventing re-ignition of fire.

71 Liang, Chuang, Jin, Kaiqiang, Liu, Pengjie, Wang, Chengdong, Xu, Jiajia, Li, Huang and Wang, Qingsong, “The Efficiency of Perfluorohexanone on Suppressing Lithium-Ion Battery Fire and Its Device Development”, *Fire Technology*, 59, 1283–1301, 2023, <https://doi.org/10.1007/s10694-023-01365-z>

5 Discussion

This chapter provide a discussion regarding the use and effectiveness of carbon dioxide and experiences from fire actual fires on board ro-ro vehicle carriers.

5.1 The use of carbon dioxide systems

Carbon dioxide systems are commonly used on board ships to protect machinery spaces and cargo spaces due to its chemical and physical properties, because the systems do not require electricity and the relatively low cost. To suppress or extinguish a fire it needs to displace oxygen at a level that is acutely hazardous for humans. As it must be ensured that no person is left in the protected space and as it need to be sealed closed, the time to discharge the system in case of fire is often around 20-30 minutes.

For vehicle spaces and ro-ro spaces which are not special category spaces, the quantity of carbon dioxide available shall be at least sufficient to give a minimum volume of free gas equal to 45 % of the gross volume of the largest cargo space capable of being sealed, and the arrangements shall be such as to ensure that at least two thirds of the gas required for the relevant space shall be introduced within 10 minutes. For safety reasons, carbon dioxide systems are prohibited to be used for the protection of special category spaces, i.e., spaces which passengers can access.

5.2 The experience from actual fires

5.2.1 The use and performance of the fixed carbon dioxide systems

In total, 22 severe fires were identified starting in the ro-ro vehicle space on ro-ro vehicle carriers in the years 2013 – 2023. For eight (36 %) of the incidents, fire investigation reports were publicly available, providing relatively detailed information of the actual ship and the timeline of the fire event. For the other fourteen fires (64 %), no fire investigation reports were found. By combining information from different public media sources, a general understanding of these fourteen fire incidents could be made. However, the information from public media sources is often too limited to draw any far-reaching conclusions.

Eight of the 22 (36 %) fires started during loading of vehicles. For all these fires, the shoreside fire department assisted during firefighting operations and helped evacuate crew members. The remaining fourteen fires (64 %) started during transport.

In ten of the 22 fires the information that was found verifies that the carbon dioxide system was used. The documented effectiveness of carbon dioxide systems is thereby based on a total of ten fires:

- Fire suppression or extinguishment performance was documented in **five** of the ten (50 %) cases, with varying degrees of fire damage:
 - The fire on board Golden Fan in 2013 started during loading. The system was discharged 27 minutes after the first observation of smoke. No structural

damages were reported other than some areas of coatings affected by the fire and the heat. A total of eight vehicles were damaged, two were burned and six others affected by the flames and the heat.

- The fire on board Courage in 2015 started when on route. The system was discharged 35 minutes after the first smoke alarm. The fire was extinguished by the operation of the fixed carbon dioxide system. No persons were injured but based on the extent of fire damage, the owner of the ship decided to scrap it.
- The fire on board Honor in 2017 started when on route. The system was discharged about 37 minutes after the first fire alarm. It was concluded that the crew's appropriate and effective use of the carbon dioxide system, along with boundary cooling, likely prevented the spread of the fire and reduced the damage. Still, the fire resulted in extensive damage.
- The fire on board Mignon in 2018 started when on route. The system was discharged 26 minutes after the fire alarm was triggered. After two hours, a couple of crew members checked whether the extinguishing attempt had been successful. No fire could be found, but fire-damaged cars on the deck with the fire and structural damage on the deck above were observed. It was also found that the fire had caused damage to electrical wiring and hydraulics.
- The fire on board Platinum Ray in 2019 started while the ship was loading new cars. The carbon dioxide system was discharged approximately 2,5 hours after the fire started and it seems that it had a good effect. Personnel from the shoreside fire department entered the affected decks and extinguished the remaining fires with fire hoses. Five hours after its start, the fire was fully extinguished. A total of 30 cars on the first deck (where it was believed that the fire started) and 31 cars on the second deck were destroyed, but 2,102 cars were saved from destruction.

For all these five incidents, the fire damage was extensive, with the exception of the fire on board Golden Fan. The damages on Courage and Honor were so extensive that the ships were scrapped.

- In **five** of the ten (50 %) cases, it is clear that the system failed to suppress or fully extinguish the fire:
 - The fire on board Silver Sky in 2016 started during loading. After closing of the stern ramp, the carbon dioxide system was released. Approximately 30 minutes later, a second release of the remaining carbon dioxide was made but problems occurred due to leakage of the main valve and the fire was not extinguished. Carbon dioxide from an on-shore supply was used to eventually stop the fire, three days after its start. Fire damage was extensive.
 - The fire on board Auto Banner in 2018 started during loading and was not extinguished, as the space was not sealed and because agent was unintentionally discharged into the engine room, reducing the agent concentration in the ro-ro vehicle space with the actual fire. Fire damage was extensive.
 - The fire was suppressed on board Grande America (when on route) in 2019 by the discharge in the ro-ro vehicle space but another fire in cargo containers positioned on the weather deck forced the crew to abandon the ship. The fire started when on route. All crew members and the only passenger were rescued by HMS Argyll while the Grande America, that was completely on fire, drifted away and eventually sank.

- During the fire on board Höegh Xiamen in 2020 that started during loading operations. The carbon dioxide system was operated but the fire was not extinguished or at least the fire continued to spread to the fire zone above. The fire burned for over a week and resulted in a total loss of the ship and its cargo of used vehicles.
- In the Grande Costa D'Avorio fire in 2023 the system was operated but seems to have been ineffective, maybe as the space was not sufficiently sealed (loading operations). It seems that the carbon dioxide system was operated within 30 minutes after the start of the fire. The discharge was ineffective which could be because the spaces were not fully sealed and/or that the fire had spread to another fire zone prior discharge. Two of the shoreside firefighters died in the initial effort and the fire continued to spread in the vehicle spaces before it was finally extinguished after six days.

For the majority of the five cases listed above where fire suppression or extinguishment failed, the fires started during loading operations, i.e., when the doors and ramps were open.

The effectiveness of carbon dioxide in an actual fire relies on fast fire detection, evacuation of the space, prompt closure of external and internal ramps and doors as well as closure of the ventilation system and associated hatches. Thereafter, the system needs to be discharged into the space with the fire. If this chain of events takes too long (combined with the long discharge time), the fire has time to grow large and may even spread to adjacent spaces or even to other fire zones, either through openings or through conduction of heat. A secondary fire can occur much later than the initial fire due to residual heat and as carbon dioxide systems are normally designed for one single discharge there is no spare capacity for this scenario.

For the remaining eleven of the 22 fires, publicly available information is lacking to conclude if a carbon dioxide system was installed and, in that case, whether it was used. In one of these cases, the fire on board Ah Shin in 2023, it seems that the system was used but no information on its effectiveness was documented. In another case, the fire on board Asian Empire in 2014, unconfirmed reports claims that the system was activated but the fire was not extinguished. In two other incidents, the fires on board Felicity Ace and Fremantle Highway in 2023, high-expansion foam systems were installed. The system failed to operate in the fire on board Felicity Ace when used which may be one reason why the fire resulted in a total loss of the ship. No public information on the use of the high-expansion foam system on Fremantle Highway was available. It is also likely that a high-expansion foam was installed on Sincerity Ace.

5.2.2 Initial fire cause and/or location

Some information about the likely fire causes or the initial location of the fire is available in the referred documentation:

- The fire on board Golden Fan in 2013 started in the electrical system in one of the vehicles.
- The fire on board Courage in 2015 started due to electrical arcing in the automatic braking system module of a used passenger car.
- The fire on board Silver Sky in 2016 probably started in a used camper van.

- The fire on board Honor in 2017 started due to an electrical fault in the starter motor solenoid in a used passenger car.
- The fire on board Mignon in 2018 started due to a short circuit in the starter motor of a used passenger car.
- The fire on board Auto Banner in 2018 started during loading and smoke appeared from the engine compartment of a used car, but the exact cause could not be determined.
- The fires on board Grande America in 2019 and Grande Europa in 2019 may be due to arson.
- The fire on board Höegh Xiamen in 2020 was likely caused by an electrical arc or component fault in one of the used vehicles.
- The fire on board Felicity Ace in 2023 was described by a crew member as having started in a new production electric vehicle.
- The fire on board Grande Costa D’Avario in 2023 may have started in a vehicle used to push cargo on board and not in one of the vehicles that were supposed to be transported.

From the ten fires listed above, it can be noted that five of the fires occurred due to electrical fire causes (including short circuit) in used cars. This indicates that the 12 V battery was not disconnected, contrary to common practice.

5.3 Fire suppression of lithium-ion battery fires using carbon dioxide

The information that was found in this study indicates that carbon dioxide is not an ideal agent for the extinguishment of lithium-ion battery fires. A certain degree of fire suppression may be possible, but as soon as the concentration of carbon dioxide decreases (if air is entering the space or if it is not sufficiently sealed), fire re-ignition may occur.

Halogenated agents seem to be more efficient than carbon dioxide for fire suppression of lithium-ion battery fires. However, for the protection of ro-ro vehicle spaces, it is recognized that other gaseous agents may not be advantageous. Halogenated agents used in fixed systems in for example machinery spaces and cargo pump-rooms [72, 73] require noticeably short, in the order of 10 seconds, discharge times which would be impossible for the large quantities required in ro-ro vehicle spaces. Another critical issue is that fluorochemical specialty gases are used in halogenated fire suppression agents which will likely be classified as per- and polyfluoroalkyl substances (PFAS) [74]. This could result

72 IMO MSC/Circ. 848, “Revised Guidelines for the Approval of Equivalent Fixed Gas Fire-Extinguishing Systems as Referred to in SOLAS 74, for Machinery Spaces and Cargo Pump-Rooms”, 1998

73 IMO MSC.1/Circ.1267, “Amendments to Revised Guidelines for the Approval of Equivalent Fixed Gas Fire-Extinguishing Systems, as Referred to in SOLAS 74, for Machinery Spaces and Cargo Pump-Rooms (MSC/Circ. 848)”, 2008

74 “Report on Critical Per- and Polyfluoroalkyl Substance Uses”, Office of the Assistant Secretary of Defense for Energy, Installations, and Environment, Office of the Assistant Secretary of Defense for Industrial Base Policy, August 2023

in future restriction legislation on their use. It is also noted that one of the commonly used halogenated fire suppression agents, FM-200 (also known as HFC-227ea or heptafluoropropane), is being phased down in production as part of a recent Environmental Protection Agency (EPA) rule to reduce the production of greenhouse gases leading to global warming. It requires that the net U.S. production of HFCs is reduced to 15 % of the baseline levels in a stepwise manner over the course of 15 years (2022 - 2036). The overall reduction in the net production of HFCs will result in a reduction of FM-200 availability [75]. Some basic differences between application methods and fire extinguishing agents have been tested and documented in *Lion Fire: Extinguishment and mitigation of fires in Li-ion batteries at sea* [76].

Water or water mist may effectively suppress fires in lithium-ion batteries. However, in order to be efficient, direct application towards the seat of the fire is required. In battery electric passenger cars, the battery pack is typically integrated with the bottom of the car, making direct application of water from over-head sprinklers or nozzles in a ro-ro vehicle space virtually impossible. In the European Union funded LASH FIRE project [77], design and installation guidelines for *supplementary* automatic water-based fire sprinkler systems were developed for cargo spaces on ro-ro vehicle carriers protected by fixed carbon dioxide systems. An important design feature is that the system automatically activates at an early stage of a fire. With automatic sprinklers, only the sprinklers closest to a fire will activate by the heat which will limit the water flow rate. This would allow more time to fight the fire manually or to safely evacuate. Obviously, water need to be drained from the decks to avoid ship stability issues. If being kept under control by water sprinklers, the carbon dioxide system can be discharged when the fire is controlled to one or a few vehicles, rather than when it has escalated [78]. 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 with actual conditions on board was undertaken in the LASH FIRE project [79]. The overall conclusion from the tests was that a fire in an electric vehicle does not seem to be more challenging for the water spray system design used in ro-ro cargo and special category spaces than a fire in a gasoline-fuelled vehicle of comparable size. Full fire extinguishment of vehicle fires is typically not possible with an

75 MSIB 06-22: “FM-200 fire extinguishing agent phasedown”, Marine Safety Information Bulletins, United States Coast Guard, November 17, 2022

76 “Lion Fire: Extinguishment and mitigation of fires in Li-ion batteries at sea”, RISE Report 2018:77, RISE Research Institutes of Sweden, Borås 2018

77 <https://lashfire.eu/> (accessed on August 28, 2024)

78 Arvidson, Magnus and Westlund, Örjan, “The Development of Automatic Sprinkler System Concepts for Maritime Vehicle Carriers”, Fire Technology, 2024, <https://doi.org/10.1007/s10694-024-01563-3>, 2024

79 Arvidson, Magnus and Westlund, Örjan, “Water spray fire suppression tests comparing gasoline-fuelled and battery electric vehicles”, Fire Technology, 2023, <https://doi.org/10.1007/s10694-023-01473-w>

over-head deluge water spray system. When the application of water is intentionally stopped, resources should be available to undertake manual firefighting efforts.

6 Conclusions

During the 11-year period from 2013 to 2023, at least 22 severe fires started in the cargo space of ro-ro vehicle carriers, as identified in this report. Eight fires started while the ship was at port and the rest while at sea. Additional severe fires have occurred on ro-ro passenger (ro-pax) ships, but these fires were not documented in the report as their main fixed fire extinguishing system is generally water based.

In eleven (50 %) of the 22 fires the information that was found verifies that the fixed carbon dioxide system was used. In five of these verified incidents, the fire was suppressed or extinguished, in five of the incidents the fire was not suppressed nor extinguished and in one case information about the performance is lacking. The time to discharge the system in case of fire is often long, typically in the order of 30 minutes. This may explain why the fire damage can be extensive even though the fires were extinguished. For the cases when fire was not extinguished, a long delay time combined with the fact that the space was not sufficiently sealed may explain the failure. Residual heat and the risk of secondary fires due to heat transfer to adjacent spaces and inadequate fire insulation remain concerns. For the majority of these unsuccessful cases, the fires started during loading operations, i.e., when the doors and ramps are open. Electrical failure is a common fire causes (including short circuit) in used cars onboard. One probably started in a new production electric vehicle. Otherwise, no fires in electric vehicles were documented.

There are few fire suppression tests with lithium-ion batteries and carbon dioxide in scientific literature. Small-scale tests include handheld/portable fire extinguishers and not fixed, total-flooding systems. The hold time has not been significantly tested based on the results found in this study.

The identified studies indicates that full fire extinguishment of lithium-ion battery fires may not be possible with carbon dioxide. The halogenated fire suppression agents used in the tests seem more efficient than carbon dioxide, but this conclusion is largely due to the fact that it is what has been compared. Halogenated agents are, however, not suitable for the protection of ro-ro vehicle spaces, due to very short discharge time requirements as well as current and expected environmental restrictions on their use.

While carbon dioxide may not extinguish and cool down a battery cell effectively to prevent thermal runaway propagation, it may reduce the risk of fire spreading to nearby vehicles or spaces. This has not been investigated and is part of the upcoming objectives in the COFFEE project.

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