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Safe Maritime Transport of Electric Vehicles on PCTC

- Fire Safety HAZID

Executive Summary

Korean Register (KR) conducted a HAZID (Hazard Identification) analysis to assess key fire risks and related issues that could significantly impact fire safety on PCTCs during the transport and handling of electric vehicles (EVs). This analysis aimed to prevent EV fire incidents and minimize potential damage. Led by KR, the HAZID analysis involved experts from various fields, including PCTC operators, shipyards, and fire research institutes. Its purpose was to systematically identify potential hazards, risk scenarios, their causes and consequences, as well as existing safety measures and additional actions required to enhance safety. The analysis highlighted the need for the following measures:

First, a clear fire response strategy for EV fires on PCTCs should be established. Given the unique fire characteristics of lithium-ion batteries, it is expected that crew members alone will not be able to fully extinguish an EV fire. Therefore, the scope of external support from specialized firefighting personnel onshore must be carefully reviewed. Additionally, it is important to determine what fire response actions can be performed on board, considering the specific characteristics of the onboard fire suppression systems. Based on this, a comprehensive concept for EV fire response should be developed.

Second, collaboration among relevant stakeholders is necessary to mitigate the risk of EV fires on PCTCs. As global EV usage increases, the volume of EVs transported by sea will also rise, leading to higher fire risks. Currently, the IMO SSE Sub-Committee[1] is reviewing amendments to SOLAS requirements for EV fire safety during ship construction. Additionally, the IMO CCC Sub-Committee[2] is considering revisions to the IMDG Code[3], including restrictions on the State of Charge(SoC) of batteries during EV transportation. Once these regulatory amendments are finalized and implemented, they are expected to enhance the safety of EV transportation.

This report, based on discussions during the HAZID analysis, examines the characteristics of EV fires on PCTCs. It summarizes key factors in ship design, construction, and operations to reduce the fire risks and minimize damage. As such, this report is recommended as a foundational resource for developing fire response strategies to ensure the safe maritime transport of EVs.

1 IMO SSE Sub-Committee : IMO Sub-Committee on Ship System and Equipment

2 IMO CCC Sub-Committee : IMO Sub-Committee on Carriage of Cargoes and Containers

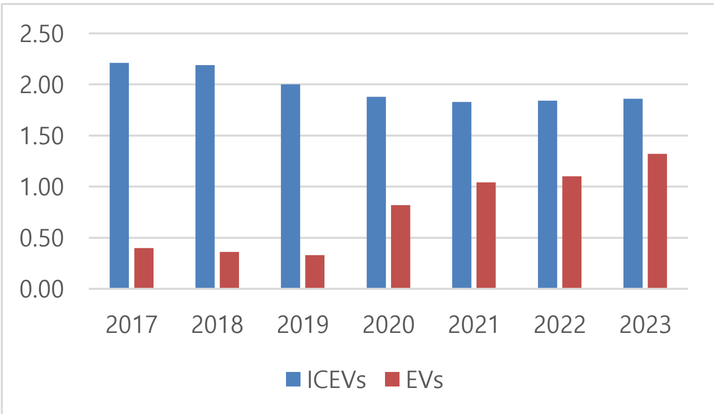
3 IMDG Code : International Maritime Dangerous Goods Code

1. Background

The intensification of global warming and the consequent worldwide climate changes have become major issues, prompting continued international efforts to address these challenges. In response, countries have adopted stricter regulations to reduce emissions from internal combustion engine vehicles (ICEVs) and are promoting the adoption of eco-friendly vehicles through policies such as EV subsidies. According to the Global EV Outlook 2024, published by the International Energy Agency (IEA), the share of EVs sales in total global new car sales has risen from less than 5% in 2020 to 9% in 2021, 14% in 2022, and 18% in 2023, with expectations that this figure will exceed 20% in 2024. As EV sales grow rapidly, the number of EVs being loaded and transported on PCTCs for import and export is also rising significantly.

As the EV market expands, reports of EV fires covered in the media. These reports often emphasize the obstacles in extinguishing EV fires, pointing out that they require a substantial amount of time and water, and in some cases, the affected EV must be submerged in a water tank for effective and complete extinguishment.

While EV fires are challenging to completely extinguish, it is important to recognize that EVs belong to a rapidly expanding industry, which draws more attention when such incidents occur. Statistics indicate that while the rate of EV fires in Korea is increasing, it remains approximately 30% lower than the rate of ICEV fires.



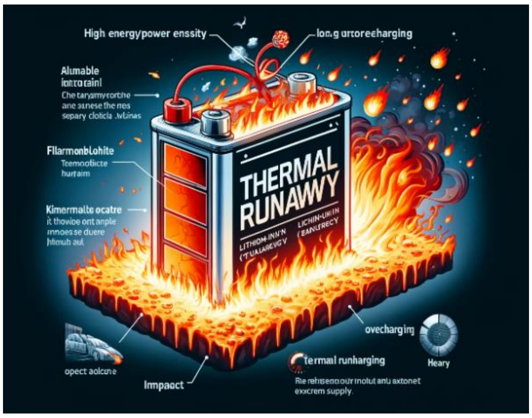
Number of fire incidents in Korea per 10,000 vehicles by vehicle type

〈Source : National Fire Agency〉

Nevertheless, the characteristics of EV fires differ significantly from those of traditional ICEVs. Once a fire occurs, it can lead to substantial property damage and even loss of life. Therefore, it is essential to understand and prepare for these unique risks to ensure safer maritime transport of EVs.

2. Overview of EV Fires on PCTC

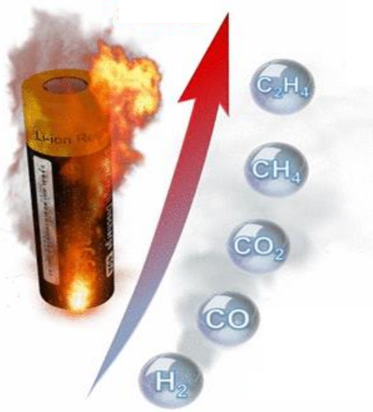
2.1 Characteristics of Lithium-Ion Battery Fires



While lithium-ion batteries, which powers EVs, offers numerous advantages-such as high energy density, long lifespan, and efficiency-their major drawback is the difficulty in extinguishing fires once they start. This challenge originates from a phenomenon known as "thermal runaway" in lithium-ion batteries, where the heat generated during a fire accelerates the battery's exothermic reactions, further increasing heat production. Thermal runaway can occur when the battery temperature rises due to impact, overheating, or overcharging. Once thermal runaway begins in a single cell, it can spread to adjacent cells, perpetuating the phenomenon. Particularly, once thermal runaway initiates, the fire can sustain itself through the release of heat, flammable materials, and oxygen from the battery itself, even without an external oxygen supply, potentially leading to an explosion.

Battery fires and thermal runaway are also closely related to the battery's SoC. A lower SoC significantly reduces the likelihood of thermal runaway, and in cases where the battery experiences failure and fire, it extends the time before thermal runaway begins. Specifically, when the SoC is below 30%, the possibility of thermal runaway is extremely low.

The off-gas emitted by lithium-ion batteries under abnormal conditions can be released at much lower temperatures (around 80°C) than the onset of thermal runaway. The composition of this gas varies depending on the battery's condition or the temperature during a fire and may contain oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and hydrogen fluoride (HF).



2.2 Characteristics of EV Fires on PCTC

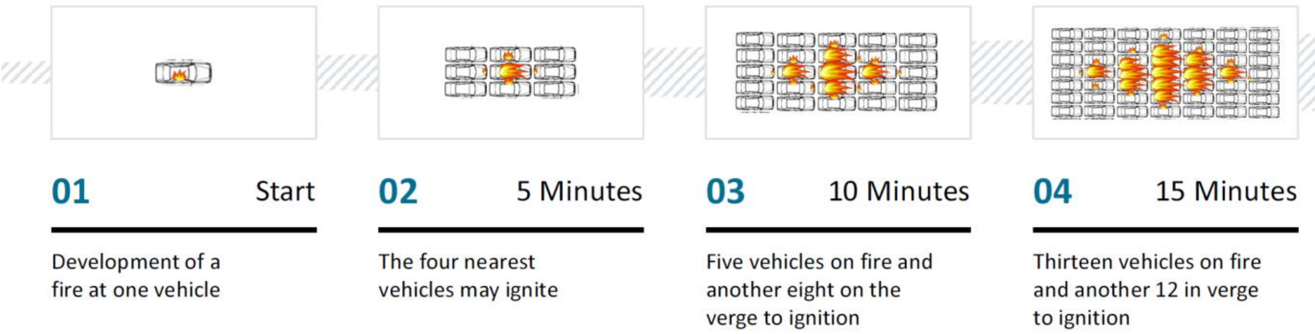
Fires involving EVs loaded onto PCTCs exhibit three key characteristics compared to fires in ICEVs : 'Release of battery off-gas (toxic and flammable)', 'Rapid spread of fire', and 'Prolonged fire suppression time'. Therefore, when responding to fires involving EVs on PCTCs, it is essential to consider these characteristics in the response strategy.

2.2.1 Release of battery off-gas (toxic and flammable)

As previously mentioned, when overheating and thermal runaway occur in lithium-ion batteries, various toxic and flammable gases are released. If a damaged lithium-ion battery comes into contact with water during firefighting, electrolysis can produce hydrogen and chlorine gases. This reaction occurs more rapidly when seawater is used compared to fresh water. Additionally, during an EV fire, the highly toxic gas hydrogen fluoride (HF), may be released. Therefore, it is essential for firefighters to wear appropriate protective gears and breathing apparatus when entering areas where an EV fire has occurred.

2.2.2 Rapid spread of fire

On a PCTC, where numerous vehicles are densely packed in limited space, a fire can easily spread to adjacent vehicles. In addition, the RoRo space may fill with smoke, reducing the visibility and making it difficult to access the burning vehicle due to the tight arrangement of the vehicles.



Fire Spread Rate to Adjacent Vehicles

〈 Source : SP Technical Research Institute of Sweden, 2016-12-12 ; 5P08059-1 〉

Fires involving EVs, in particular, spread more rapidly than those in ICEVs due to the characteristics of lithium-ion batteries. Fires originating in an EV's battery pack tend to spread horizontally, fueled by pressure and the release of flammable gases.

Flame Direction of ICEVs

- **ICEVs**

- The primary combustibles are equipment in the engine room, fuel and interior materials. Due to the upward movement of flames, the fire tends to spread vertically.

Flame Direction of EVs

<Source : Guide for Responding to EV Fires, National Fire Research Institute, 2023>

- **EVs**

- The primary combustibles are the high-voltage battery pack and interior materials. Fires within the battery back tend to spread horizontally due to pressure and the release of flammable gases.

2.2.3 Prolonged fire suppression time

When considering the fire safety of EVs loaded onto a PCTC, the most critical factor is the prolonged time required to extinguish an EV fire. The most effective method for extinguishing an EV battery fire is cooling to prevent the thermal runaway. However, due to the fact that EV batteries store an extensive amount of energy, complete extinguishment requires a substantial amount of water and time. Additionally, as EV batteries are installed in the bottom of the vehicle, the cooling effect from firefighting water application is relatively limited during a battery fire, which further extends the fire suppression time.

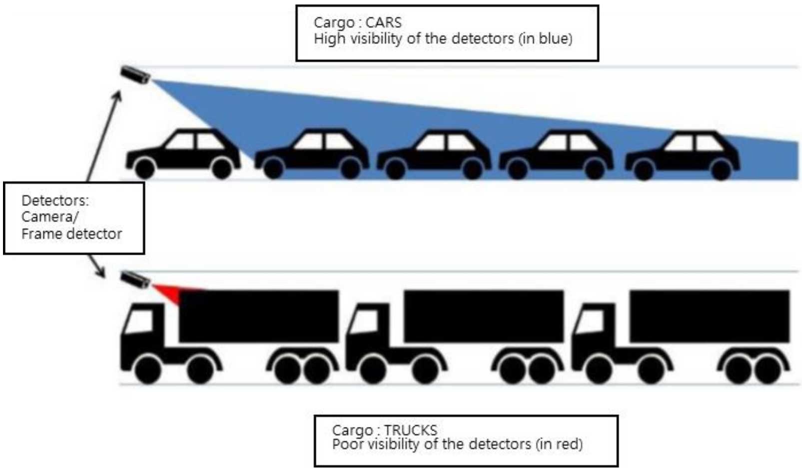
Moreover, even after the fire is extinguished, EVs carry risk of re-ignition. Batteries that were exposed to heat but not burn may still have the potential to reignite. As a result, it is crucial to always consider the possibility of re-ignition, even if the fire appears to be out.

3. Recommendations based on HAZID - Shipbuilding and Design

3.1. Fire detection

3.1.1 CCTV

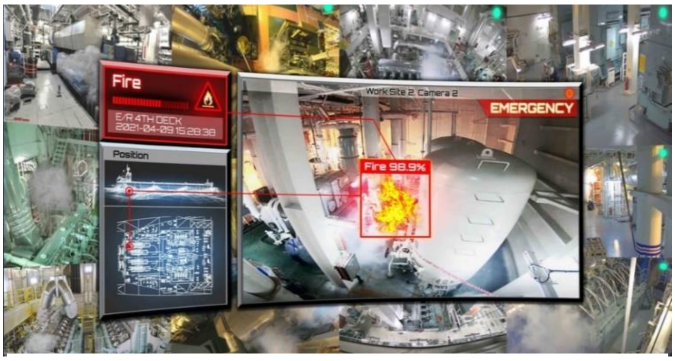
Using CCTV cameras to monitor the RoRo space allows for early detection of abnormal situations, such as fires. Smoke generated by battery malfunctions can be quickly identified, allowing for a rapid response. However, to accurately detect fires, ship's crew should continuously monitor the CCTV. Additionally, the space between the loaded vehicles and the ceiling is generally very narrow, which can create many shadow areas, making monitoring with CCTV cameras challenging. Furthermore, installing enough CCTV cameras to monitor all 7,500 vehicles typically loaded onto a PCTC may be challenging in practice. Given these challenges, it would be more effective to install rotating CCTV cameras to minimize unmonitored areas.



CCTV monitoring & Shadow Area *<Source : FIRESAFE II Report>*

3.1.2 AI-based Video Fire Detection System with CCTV

AI-based video fire detection systems leverage deep learning algorithms and sophisticated image processing technology to detect abnormal smoke or fire captured by CCTV cameras. This advanced system triggers alarms and simultaneously enables crew members to visually inspect affected areas through monitors. Its key advantages lie in detecting fires more quickly and across larger areas compared to conventional fire detectors, which only activate when smoke reaches their sensors. The system is compatible with existing CCTV infrastructure. For areas like RoRo spaces where CCTV is already installed, upgrading is straightforward- only a processing unit capable of generating alarms through video recognition needs to be additionally installed to implement the functionality. The versatility of AI-based CCTV makes it an effective solution for rapid fire detection not only in RoRo spaces but also in various high-risk areas such as engine rooms and cargo holds on container



AI-based Video Fire Detection System *<Source : HD KSOE>*

ships. While SOLAS does not currently recognize this method as an official fire detection device, it is under active consideration by the IMO SSE Sub-committee in 2024. This ongoing evaluation suggest that SOLAS may recognize AI-based video fire systems in the future.

3.1.3 Off-gas Detection

EV batteries can release off-gases when their temperatures rise abnormally. The composition of released gases varies depending on severity of the battery's temperature anomaly. These emissions may include hydrocarbons, carbon monoxide, oxygen, and toxic substances like hydrogen fluoride. Swift detection of these off-gases, which result from abnormal temperature rises, serves as an early warning system. This enables rapid identification of and response to potential fire hazards. When designing an off-gas detection system, careful consideration must be given to the volume of off-gas emitted by the battery and the strategic placement of detectors to ensure comprehensive monitoring.

3.2 Fire Extinguishment

3.2.1 Fixed CO2 Fire-extinguishing System

Fixed CO2 systems are one of the most used fixed fire-extinguishing systems in PCTCs. They operate by sealing off the affected area where the fire has occurred and releasing CO2 to lower the oxygen concentration, thereby suppressing the fire. However, EVs can generate oxygen during combustion, potentially compromising the effectiveness of this CO2 system. Additionally, CO2 systems are typically designed to be used once, as only enough CO2 for a single activation is stored onboard, meaning they cannot be deployed again if a fire reignites. To improve the effectiveness of CO2 systems in responding to EV fires, it would be helpful to store additional CO2 onboard, ideally enough for at least two deployments. The effectiveness of CO2 systems depends on the space where CO2 is released being well-sealed from the outside. During typical ship operations, all openings except the ventilation ducts are closed, so for CO2 use, it would be sufficient to close the ventilation ducts. However, during vehicle loading and unloading, the ramps connecting the ship to the shore remain open, which can render CO2 systems ineffective. In such scenarios, specialized firefighting support from shore-based teams becomes necessary for effective fire response.

3.2.2 Fixed High-expansion Foam Fire-extinguishing System

Fixed high-expansion foam systems are another type of fixed fire-extinguishing systems commonly used in PCTCs, alongside the fixed CO2 system. It operates by covering the fire-affected area with foam, providing cooling and suffocation effects to extinguish the fire. However, foam can breakdown when exposed to high temperatures for extended periods, and it cannot halt thermal runaway in EV batteries. To address these challenges, additional foam discharges may be necessary to maximally suppress thermal runaway and prevent re-ignition. The foam concentrate required to be stored onboard should be sufficient for at least five discharges, allowing for system reactivation if needed to control re-ignition and suppress further fire development. The foam system's effectiveness also relies on covering the fire space with foam, making proper sealing of the space essential, similar to the CO2 system. As discussed earlier regarding the CO2 system, using this system during loading and unloading operations in port may be challenging due to the open ramps. In such scenarios, fire response through support from specialized shore-based firefighting teams becomes necessary for effective fire control.

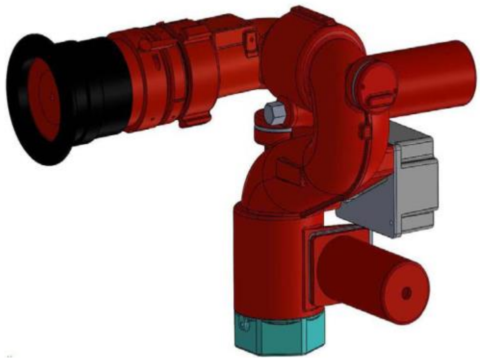
Test for fixed high-expansion foam system *<Source : IMO SSE 9/INF.4>*

3.2.3 Fixed Water Spray System

Fixed water spray systems can be installed in the RoRo space as an effective fixed fire-extinguishing system. These systems help extinguish and cool vehicles on fire by continuously spraying water from nozzles installed on the ceiling of the RoRo space, without requiring crew member access. As continuous cooling of the battery is the most effective method for extinguishing battery fires, using seawater to continuously spray and cool the burning vehicle can provide significant fire suppression. This makes it potentially the most effective fixed fire-extinguishing system for battery fires among those allowed in RoRo space under SOLAS regulations, which include CO2, Foam, and Water Spray systems. However, the implementation of these systems in PTCTs faces several challenges. Typical PCTCs consist of multiple RoRo decks (usually 12 decks), with liftable decks applied to adjust the height of these decks. Installing a fixed water spray system that meets SOLAS requirements on all RoRo decks would significantly increase costs compared to other fixed fire-extinguishing systems. In addition, installing water supply piping on the ceiling of the liftable decks presents considerable practical challenges. As a result, there are very few examples of fixed water spray systems being installed on PCTCs, despite their potential effectiveness in combating battery fires.

3.2.4 Remote-operated Fixed Fire Monitor

Remote-operated fixed fire monitors involve installing controllable fire-fighting devices on both sides of the vehicle decks to address fires within the RoRo space. This system allows crew members to safely respond to vehicle fires without directly entering the fire-affected area, as the monitors can be operated from a distance to continuously spray water. The monitors are mounted in a swiveling configuration, enabling precise aiming at the fire's location. Crew members can operate these monitors remotely while observe the area through CCTV cameras from a secure position. However, installing these remote-operated fire monitors along the entire length of the ship on all vehicle decks may significantly increase system installation costs. Additionally, when planning the installation of monitors, it is essential to consider that their presence might interfere with the vehicle storage area, potentially reducing the number of vehicles that can be loaded.



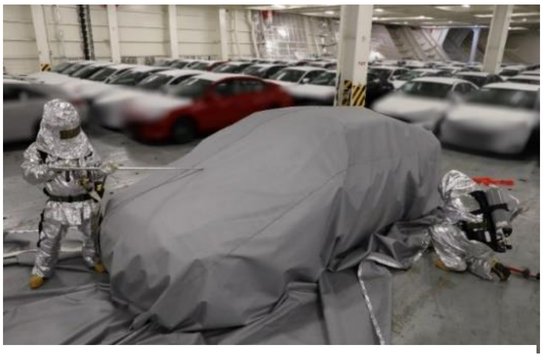
Remote-operated fixed fire monitor

3.2.5 Underbody Water Spray Equipment

Underbody water spray equipment offers a targeted approach to address EV battery fires. This system directly applies water to the battery pack installed beneath the vehicle, providing several key advantages. This method can effectively delay thermal runaway propagation or extinguish the fire through direct battery cooling. To implement this system, it should be connected to onboard fire hoses, so the connector must be compatible with theses hoses. However, the system requires crew members to directly access the burning vehicle, which can be challenging in densely packed Roro space. Consequently, a clear strategy and thorough training are necessary for effective deployment.

Underbody Water Spray Equipment *<Source : Guide for Responding to EV Fires, National Fire Research Institute, 2023>*

3.2.6 Fire Blanket

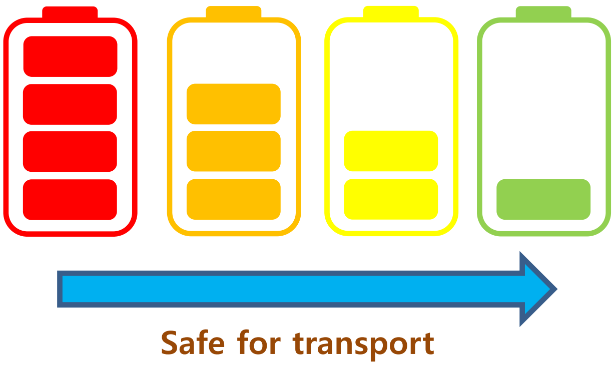


Fire Blanket *<Source : Hyundai Glovis>*

Fire blankets stored in the RoRo space can be used to prevent fire spread. Early detection of abnormal conditions such as fire or smoke, coupled with prompt use of fire blankets, can help contain the fire and prevent it from spreading to adjacent vehicles, thus averting major incidents. However, the unique characteristics of PCTC RoRo spaces, including lashing belts and lashing holes, make it challenging to fully isolate vehicles with fire blankets and effectively prevent oxygen ingress. In addition, while fire blankets are effective for extinguishing fires in ICEVs, they are less practical for EV batteries fires, which generate oxygen during combustion. Moreover, similar to underbody water spray equipment, as crew members must directly access the burning vehicle to deploy them, the use of fire blankets in tightly packed RoRo spaces poses significant challenges. Therefore, when storing and using them on ships, it is crucial to establish a clear strategy for the effective use of fire blankets. This strategy should be accompanied by comprehensive training to ensure crew members can practically utilize this equipment.

4. Recommendations based on HAZID - Operation

4.1 Limitation on EV Battery SoC



Controlling the SoC limit for EVs being loaded is one of the most critical factors in reducing fire risk during the maritime transport. As previously discussed, when the SoC is below 30%, the likelihood of thermal runaway is significantly reduced. Currently, EVs transported by ships typically have an SoC of up to 50%. Lowering the SoC limit for vehicles being loaded and transported on ships would further enhance safety during transport. However, implementing this change requires cooperation from vehicle manufacturers. Regulations regarding SoC limits for EVs transported by ships are under discussion at the IMO CCC meetings, in relation to amendments to the IMDG Code. If these regulations become mandatory, they are expected to have a significant positive impact on the safety of maritime transport for EVs.

4.2 Avoiding the Loading of EVs on the Uppermost Deck

When navigating in high-temperature regions, such as the equatorial zone, the temperature on the uppermost deck of a ship can exceed 80°C due to intense solar radiation. Such extreme temperatures pose significant risks to EV battery cells, increasing the likelihood of cell malfunctions and fire hazards. While it is possible to operate ventilation fans intensively in the RoRo space,

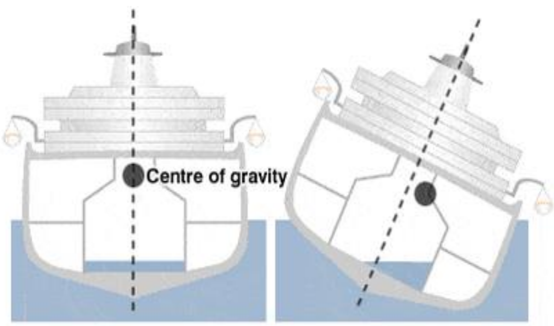
significant temperature reduction is unlikely, even with increased fan operation, when crossing high-temperature regions. Therefore, to prevent EVs from being continuously exposed to high temperatures during maritime transport, it is recommended to avoid loading EVs on the uppermost deck of the ship when navigating through these areas.

4.3 Designation of Dedicated EV Loading Area

EVs and ICEVs exhibit different fire characteristics, necessitating distinct fire response strategies. Designating a separate loading area for EVs, distinct from that for ICEVs, may improve fire response effectiveness. However, creating and managing a dedicated EV loading area can present operational challenges during loading and unloading. Additionally, with the anticipated continuous increase in demand for EV transportation, designating and maintaining a specific area solely for EVs is expected to become increasingly difficult in the future. Consequently, when developing fire response strategies for the RoRo space, it is necessary to consider scenarios where EVs and ICEVs are mixed in the same loading area.

4.4 Precaution for Water-based Fire Fighting

When a large amount of water is used for an extended period to extinguish a fire in the RoRo space, there is a risk that the water used for firefighting may accumulate inside the ship if not properly drained. This accumulation can lead to a serious loss of the vessel's stability due to the free surface effect[4]. Therefore, when using water for fire fighting in the RoRo space, it is crucial to ensure that the drainage system in the space remains open, allowing the water to be discharged overboard



Free Surface Effect

[4] Free Surface Effect : A condition where the ship's stability is reduced by the movement of liquid in partially filed tanks or compartments, caused by ship's rolling and pitching motions.

smoothly. Consequently, the ship's fire response manual should include procedures to maintain stability during water-based firefighting operations, such as keeping the drainage system open clear, operating the bilge system to manage the accumulated water, and taking other actions necessary to maintain the ship's stability.

4.5 Fire Response Strategies and Training

It is important to develop onboard a manual detailing considerations for transporting EVs and response strategies for fire incidents on ships. This manual should ensure the safe transportation of EVs and effective fire response. The manual should include procedures for fire suppression, taking into account the potential spread of a fire. In particular, fires in RoRo space can rapidly spread if not addressed early, necessitating the prompt activation of fixed fire-extinguishing systems, which should be clearly detailed in the manual. Additionally, due to the unique fire characteristics of lithium-ion batteries, fully extinguishing EV fires on board may be challenging. Therefore, the manual should also outline strategies for coordinating with shore-based specialized firefighting teams, detailing the level of support needed for various fire scenarios. Furthermore, the manual should establish different response strategies for various fire scenarios.

- Fire Incident During Maritime Transport

When an EV fire occurs during maritime transportation, where support from shore-based specialized firefighting teams is difficult to obtain, a well-driven strategies should be established to prevent the spread of the fire while ensuring the safety of the crew. If a fire or abnormal signs are detected early in a vehicle, the crew may attempt initial fire response actions. However, if these initial efforts fail and the crew cannot safely approach the fire, a strategy should be in place to activate the ship's fixed fire-extinguishing systems without delay to prevent the fire from spreading throughout the vessel. Although the fixed CO2 or foam fire-extinguishing systems installed on the ship may not be able to fully stop the thermal runaway of the battery, their timely[5] use can be crucial in preventing the fire from spreading across the entire vessel, thereby helping to avoid severe casualties or the total loss of the ship.

[5] According to SSE 10/16 ("Fire Safety on board PCTC/PCC ships," submitted by Germany, etc.), it is generally recommended that the time between fire alarm activation and the operation of the fixed fire-extinguishing system on a PCTC should be within 14 minutes.

- **Fire Incident During Cargo Loading and Unloading**

In the event of a fire during loading and unloading operations while the ship is in port, it is crucial to receive prompt support from shore-based specialized firefighting teams. As such, the fire response strategy in port should be developed in coordination with these shore-based firefighting teams.

Even during loading and unloading operations, the fixed fire-extinguishing systems installed on the ship may be considered for use. However, since both crew members and shore-based firefighting personnel might be present in the affected area, it is essential to ensure that everyone has evacuated the space before activating the system. A challenge during loading and unloading operations is that the ramps used for vehicle movement are typically open, which makes it difficult to completely seal off the affected space. As a result, the effectiveness of the fixed fire-extinguishing systems may be reduced.

While preventing EV fires is most essential due to the difficulty of fully extinguishing them once they start, being prepared for such incidents is equally crucial. Regular inspections and maintenance should ensure that the fire detection and extinguishing systems on the ship are fully operational. Additionally, the crew members should be well-versed in the features of these systems and trained in their operation. With these measures in place, a quick and effective response can be achieved even if a fire occurs.