ClassNK Technical Journal

No.9 2024（Ⅰ）

Special Feature: Initiatives for Vehicle Carrier Fires

ClassNK Technical Journal No.9 2024 (I)

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Recently, the development of AI systems has advanced in the maritime industry. Since AI, especially machine learning, learns patterns and rules from large amounts of data, it is required to carry out activities necessary to ensure quality while addressing the AI-specific challenges through the development process. Considering these points, the Society will summarize the items that developers of AI systems should consider during development in "Technical Guide for Utilizing AI System on Ships -Quality Control in the Development Process of AI System-". This paper introduces the contents of the Guide.

JAXA is studying a reusable launch vehicle as the next mainstay launch vehicle following the H3 Launch Vehicle. This initiative responds to the Roadmap for an Innovative Future Space Transportation System established under the leadership of Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) and will be developed with the aim of achieving a substantial cost reduction, targeting the first launch around 2030. This report presents a brief explanation of the status of study of an offshore launch vehicle recovery ship for recovery of reusable launch vehicles in offshore waters, and the results of a study of compliance with ship class rules which was carried out as joint research with the Society.

During calendar year 2023, ClassNK issued the 14 Guidelines shown in Table 1. This article presents the outlines of these Guidelines.

Prefatory Note

Introduction to the Special Feature on "Initiatives for Vehicle Carrier Fires"

General Manager of Research Institute, ClassNK
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On the occasion of the publication of ClassNK Technical Journal No. 9, I would like to extend a worm welcome to all our readers.

ClassNK Technical Journal is published with the aim of contributing to the progress of technology in the maritime industry by making information concerning the technological activities and research results of the Society available to a wider range of interested parties. Based on the adoption of the revised IMO Strategy on the Reduction of GHG Emissions from Ships at IMO MEPC80 (80^{th} Session of the Marine Environment Protection Committee of the International Maritime Organization) in July 2023, the previous issue (ClassNK Technical Journal No. 8) reported on moves to strengthen international regulations toward the achievement of higher emission reduction targets than in the past, related technological trends for achieving that goal, and recent research and development achievements.

Adoption of electric vehicles (EVs) in order to achieve carbon neutrality is increasing internationally, and as a result, marine transportation of EVs by Vehicle carriers is also increasing. Although there is statistical data showing that the occurrence probability of fires involving EVs is lower in comparison with gasoline-fueled vehicles, the situation after a fire occurs is different. Therefore, in order to contribute to safer transportation of EVs, the Society issued "Guidelines for the Safe Transportation of Electric Vehicles (Edition 1.0)."

This ClassNK Technical Journal No. 9 includes a Special Feature entitled "Initiatives for Vehicle Carrier Fires," which introduces the guidelines for the safe transportation of EVs and fire-extinguishing technology for Vehicle carriers. This issue also includes diverse articles and papers in connection with a launch vehicle recovery ship for reusable launch vehicles being developed by the Society together with the Japan Aerospace Exploration Agency (JAXA), recent technological activities in the Society and other topics.

Based on the needs of society and the industry, the Society will continue to grapple wholeheartedly with research and development which contribute to securing the safety of human life and property at sea, protecting the marine environment and creating innovations that lead society, and will strive to contribute to the further development of the maritime industry.

We sincerely request the understanding and support of all those concerned in the future, as in the past.

Safe Maritime Transportation of Electric Vehicles

– Characteristics of EV Fires and Guidelines for Response –

Yasuyoshi TARAO*

1. INTRODUCTION

In recent years, many electric vehicles (EVs) can be seen travelling around cities and towns. Because EVs use lithium-ion batteries (LIBs) as a drive power source and do not emit CO_2 while travelling, as gasoline-powered vehicles do, EVs are considered to be superior in environmental terms. The characteristics of LIBs include high energy density, high voltage and chargeability.

Fig. 1 is a graph of the number of registered EVs published by the International Energy Agency (IEA). Internationally, adoption of EVs to achieve carbon neutrality is increasing exponentially. Transportation of EVs by vehicle carriers, including existing vessels, has begun, and the share of EVs among all vehicles being transported is currently increasing. Among potential problems, if an abnormality occurs in the LIB used to power an EV or a fire breaks out from the battery, special response methods must be applied. It is also known that much time is required to extinguish fires once a fire breaks out from an LIB. Moreover, because the vehicles transported on vehicle carriers are loaded in the vehicle spaces (car decks) with minimal distance between them, there is a risk that the fire will spread to other adjacent vehicles, and it may be difficult to approach the burning vehicles to conduct fire-fighting operations. When a fire breaks out from an EV or spreads to other EVs, special measures must be implemented in the special environment of the vehicle space. Thus, one issue is whether fire-fighting operations can be carried out, considering the special characteristics of the vehicle spaces of vehicle carriers and the characteristics of the vehicle loading condition. In other words, a special response and guidelines are necessary for the safe transportation of EVs with LIBs by vehicle carriers.

This article provides a commentary on *"Guideline for the Safe Transportation of Electric Vehicles"* issued by ClassNK (hereinafter, referred to as "the Society") to contribute to the safe maritime transportation of EVs by vehicle carriers.

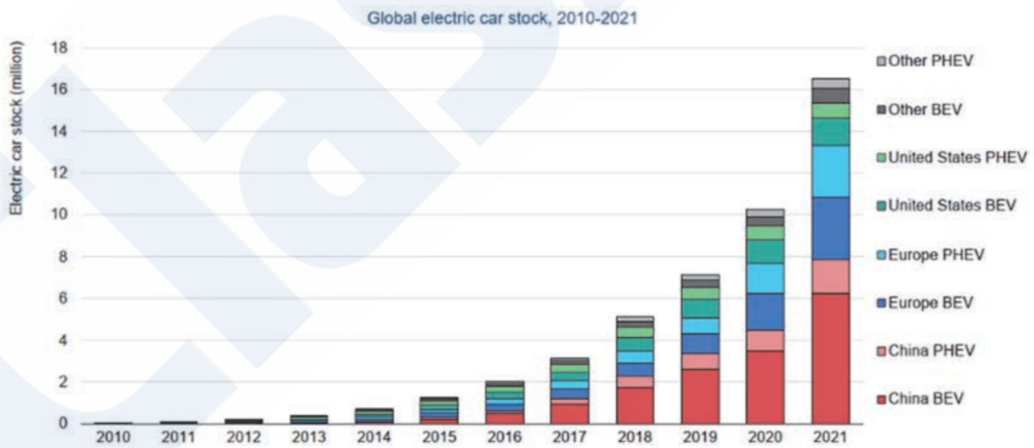

Fig. 1 Number of registered electric vehicles (EVs)[1)]

2. INITIATIVES OF THE SOCIETY

Based on the fire accidents involving vehicle carriers in recent years, the Society continuously studies fire safety measures, particularly when transporting EVs. What we wish to note here is that statistical data show that the risk of a fire occurring in an EV is low in comparison with gasoline-powered vehicles, and there are still no cases in which an EV was identified as the origin of a fire that caused a fire accident on a vehicle carrier.

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Nevertheless, unlike gasoline-powered vehicles, the power source for EVs is electricity stored in a secondary cell (LIB). If an internal short circuit occurs in an LIB, thermal runaway will begin, and a fire may break out. Moreover, once a fire occurs in an LIB, it is known that the fire is extremely difficult to extinguish.

Guidelines for responding to LIB fires on land already exists, but whether they can be implemented under the special environment of a ship is a major issue.

Therefore, in August 2023, the Society released *"Guideline for the Safe Transportation of Electric Vehicles (Edition 1.0)"* and *"List of Safety Measures for the Maritime Transportation of Electric Vehicles"* as guidelines for responding to EV fires, considering the special environment of ships and the characteristics of EV fires. It is our hope that those who own, operate or manage ships, and the shipyards, will study measures referring to these documents, and this will lead to a decrease in fire damage of vehicle carriers. From the following Chapter 3, this article will explain the details related to safe maritime transportation of EVs in concrete terms.

3. TECHNICAL EXPLANATION OF GUIDELINE FOR SAFE TRANSPORTATION OF ELECTRIC VEHICLES

3.1 Characteristics of Electric Vehicles and Characteristics of EV Fires

3.1.1 Electric Vehicles

Electric vehicles are vehicles that are powered by electricity. The types of vehicles that use electricity as a power source include pure electric vehicles (also called "battery electric vehicles" or BEVs), plugin hybrids and hybrid vehicles. In spite of differences in the types of batteries used in the respective vehicles and their systems and capacities, they can all be considered as types of EVs. However, it should be noted that the risk when a fire occurs is not completely the same because the types of battery cells and the capacities of the batteries are different.

Pure EVs have the largest battery capacity, and many use lithium-ion batteries. Many BEVs obtains the battery cells which are installed in a battery pack that extends under the entire floor of the vehicle, as shown in Fig. 2. From several 10s to several 1 000s of individual lithium (Li) ion cells may be installed in the battery pack, although the number differs depending on the type of vehicle and battery.

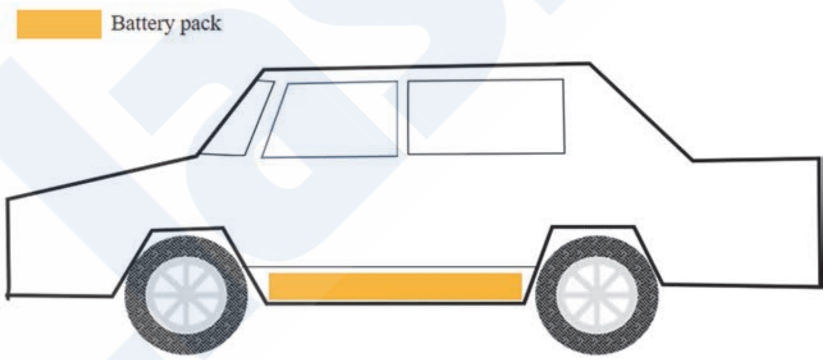

Fig. 2　Location of drive battery in an EV

3.1.2 Drive Batteries

At present, the lithium-ion battery is considered to be the only type of battery that has an energy density which makes it possible to install the power capacity necessary for vehicle travel at a practical level. LIBs achieve a high rated voltage and high energy density because electrolysis is less likely to be caused until a high potential (high voltage) due to the use of an organic solvent in the electrolyte. However, if electrolysis occurs and gasification takes place, the battery does not return to its original state. For this reason, various conditions, such as the input/output electricity, cell temperature are monitored [2)].

There are three types of LIB cells, the laminated type consisting of cells in sheet form, square shaped LIBs, and the familiar cylindrical type familiar in shape of dry-cell battery. Although the battery cells have various distinctive features, which type is used differs in each vehicle model, depending on the cruising range and whether a cooling device is necessary or not. As mentioned previously in EVs, a robust case which houses the lithium-ion cells, called a battery pack, is installed, and the total capacity of the battery ranges from 20 kWh to more than 100 kWh. The voltage is extremely high, at 300 V to 400 V.

3.1.3 Safety measures of EVs

The following safety measures are taken for the passengers of EVs equipped with high-voltage LIBs [3].

1) As measures to prevent electrical shock, the drive battery is installed in a location where passengers will not come into contact with the high-voltage battery or high-voltage components during a vehicle collision. The battery is protected by a robust case and high-voltage circuits are shut down in case of a collision.

2) To prevent thermal runaway, the current, voltage and temperature are monitored and controlled by a battery management system, and high-voltage circuits are shut down if an abnormality is detected.

Nevertheless, the author hopes that all concerned will understand that the safety measures for EVs are not limited to only those mentioned here, and the safety of EVs is increasing on a daily basis.

3.1.4 Characteristics of EV Fires

Because a heavy battery pack is installed in EVs, many composite resins, etc. are used to reduce vehicle body weight. It must also be noted that more combustible materials are used in EVs in comparison with conventional gasoline-powered vehicles.

In the event of an internal short circuit in the Li-ion cells, thermal runaway will occur. Fig. 3 shows an example of the process leading to thermal runaway of an LIB. This figure shows the experimental data for a cylindrical-type cell. The temperature of the battery cell in which the internal short-circuit occurred rises due to Joule heat generation. In this process, a chemical reaction between the negative electrode and the electrolyte and meltdown of the separator occur, finally resulting in an exothermal reaction with a temperature exceeding 1 000 °C. In these experimental results, the time to reach 1 000 °C was less than a mere 28 minutes.

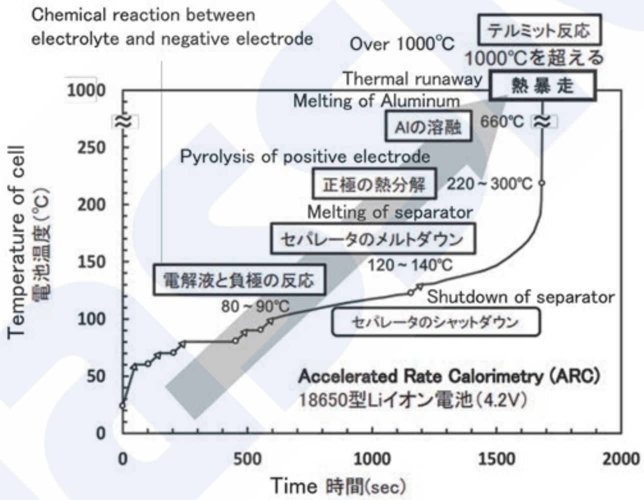

Fig. 3 Example of temperature and time to thermal runaway [4]

In addition, it must also be remembered that combustible gases are generated in the process that causes thermal runaway. The results of an analysis of the gases generated from LIBs revealed that the combustible gases include hydrocarbon gases such as methane and ethane, and hydrogen gas, among others [5]. Since this means that a combustible gas atmosphere may form in the EV loading space in vehicle carriers, attention must be paid to ignition and explosion.

Moreover, the gases generated in this process are not limited to combustible gases, but also include hydrogen fluoride (HF) as the toxic gas. HF, which is extremely harmful to human life and health, is formed by the reaction of water with the lithium hexafluorophosphate contained in the electrolyte of LIBs, or the process of pyrolysis of polyvinylidene DiFluoride, which is a binder [6]. The IDLH (**I**mmediate **D**angerous to **L**ife or **H**ealth) of hydrogen fluoride is 30 ppm, which is the upper concentration limit from which one could escape within 30 min. without a respirator and without experiencing any escape impairing or irreversible heald effects.

It is also necessary to bear in mind the danger of electrical shock. As mentioned above, high voltage LIBs, with voltages of 300 V to 400 V are used in EVs, but the risk of shock is minimal if water is sprayed on a cell where an internal short circuit has already occurred. However, considering the fact that EVs contain from several 10 to several 1 000 battery cells, and all of these cells have not necessarily suffered internal short circuits, it is important to remember that spraying water on battery cells where internal short circuits have not occurred can also cause electrical shock.

3.2 Guidelines for Responding to EV Fires

Up to this point, we have explained the characteristics of EV fires and points to note in this connection. The following explains how those concerned should respond to EV fires in concrete terms, considering the characteristics of EV fires, the environment in the vehicle spaces of vehicle carriers, and the condition of vehicle loading condition. Before explaining the individual items, please refer to Table 1, which arranges the scenarios leading up to a EV fire. Although also explained in section 3.1, thermal runaway occurs when a Li-ion cell in an EV suffers an internal short circuit. If thermal runaway occurs in a Li-ion cell, the temperature of the cell will rise due to Joule heat generation, the positive and negative electrodes will undergo pyrolysis, and the electrolyte will be vaporized, resulting in the generation of combustible gases. These gases are discharged outside the vehicle through the safety valve of the battery pack, and can be recognized as white smoke. There is a possibility that an explosive atmosphere may form in the vehicle space due to the discharge of combustible gases from the vehicle into the vehicle space. If the gas concentration reaches the Lower Explosive Limit (LEL) and ignition energy is provided by an ignition source, the gas will ignite, and an explosion and fire will occur. It is thought that the fire will ignite parts of the vehicle, and the EV itself will catch fire and begin to burn. In this case, there is a danger that the fire in that EV may then spread to adjacent vehicles, and fires may also occur in unexpected locations if combustible gases accumulate and catch fire at a location different from the burning vehicle. These events may cause the fire to spread through the vehicle loading space. The following explains the countermeasures that are thought to be effective, considering these fire scenarios.

3.2.1 Early Detection

One of the most important points when considering countermeasures for EV fires is early detection of vehicles in which a fire appears to be likely and vehicles that are actually on fire. Fig. 3 explained that the time from an internal short circuit to the final period of thermal runaway is extremely short. In other words, it is desirable to take action as early as possible to isolate vehicles in which a fire appears likely and to respond to burning vehicles. To solve these problems, as shown in Fig. 4, it is important to arrange the process leading to thermal runaway in an LIB by event, and to take effective action in each stage. These are classified in three phases, the “Temperature rise stage,” in which temperature rise is occurring in a battery cell where thermal runaway has occurred, “Combustible gas generation stage,” in which combustible gas is spewing from the battery pack, and the “Fire outbreak stage,” in which a fire actually occurs.

In the “Temperature rise stage,” one conceivable measure is to install a sensor capable of detecting temperature rise in cells near the battery. However, this involves numerous problems, such as how the signal for the temperature rise detected by the sensor is to be transmitted and received.

In the “Combustible gas generation stage,” detection of the combustible gases (HC gases and hydrogen) generated before a fire occurs is conceivable, but considering the total amount of combustible gases generated from an LIB, there are also many problems, such as what level of concentration the gas detector should be able to detect, and the possibility that the gases may spread due to the condition of ventilation in the vehicle space, making quick detection impossible.

Table 1 Scenario of fire spread in vehicle carrier

Fire escalation scenario				
Internal short circuit	Temperature rise	Emitting white vapour	Ignition to flammable gases Fire spread to vehicle parts	Fire escalation
				
Thermal runaway occur due to the trigger such as internal short circuit etc,.	Temperature of battery cell which is under thermal runaway rise.	Flammable gases and/or toxic gases are emitted and blowed off from safety valves due to the chemical reaction of battery cell.	Igniting to flammable gases and fire spread to the vehicle parts.	Flammable gas generate explosion gas atmosphere inside vehicle loading space and fire and/or explosion occur at unexpected space and fire escalation occur.

In the "Fire outbreak stage," flame detectors, heat detectors and smoke detectors are effective. However, if the flame detectors or heat detectors are not installed in locations where flames are visible or locations that receive radiant heat, they cannot fully demonstrate their functions. Therefore, installation of a remarkably large number of these detectors in the vehicle space is expected to be necessary. Furthermore, to ensure the maximum effect of smoke detectors, the smoke caused by a fire must be able to reach the detector in a timely manner. Since beams and girders are arranged in vehicle space ceiling and will restrict the flow of smoke, ingenuity is necessary when selecting the positions for installation of smoke detectors.

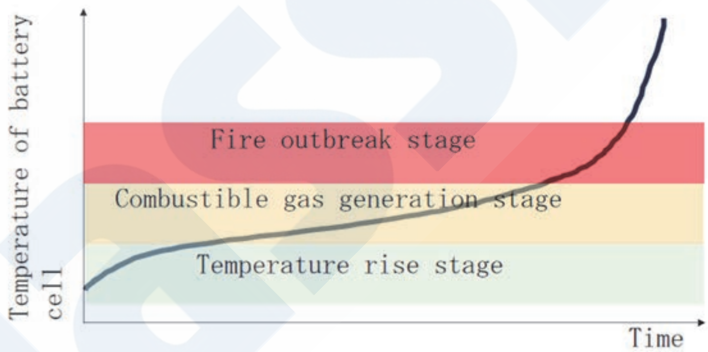

Fig. 4 Arrangement of events leading to thermal runaway of Li ion cell

Among current technologies, there is one product that demonstrates effectiveness in both the "Fire outbreak stage" and the "Combustible gas generation stage," namely, Closed Circuit Tele-Vision (CCTV). Because CCTV can recognize not only the black smoke when a fire breaks out, but also the white smoke of combustible gases as images, detection is possible from the "Combustible gas generation stage" by monitoring the vehicle space by CCTV. Fig. 5 shows a graphic representation of an image captured by a CCTV camera, which can be observed when a CCTV system is installed in a vehicle space. However, in addition to the very large number of CCTV cameras that must be installed for comprehensive monitoring of the vehicle space, full-time, image-by-image monitoring is not realistic. Adoption of a technology that recognizes smoke and issues alarms using AI-based image recognition technology is considered to be an effective solution to these problems.

Fig. 5 Appearance of vehicle captured by CCTV installed in vehicle space (image)

Up to this point, various countermeasures for early detection have been explained, but it is thought that issuance of alarms by the EV itself can also contribute to early detection. Because the battery management systems installed in EVs monitor the condition of the battery cells (temperature, voltage, etc.), it is thought that lighting the lights or honking the horn of the vehicle at a certain stage when temperature rise is detected in battery cells can make a large contribution to early detection of abnormal vehicles. The only technology capable of diagnosing abnormalities in an EV before they are visible from outside the vehicle is the battery management system installed in EVs.

3.2.2 Prevention of Secondary Fires

Concretely, the combustible gases generated from LIBs in the process of thermal runaway include hydrogen, HC gases, such as methane, ethane, propane, etc. The generated amounts of the respective gases differ depending on the type of positive electrode and negative electrode, the type and amount of electrolyte, and the charging rate [4]. If combustible gases are generated, there is concern that they may accumulate in the vehicle space and reach the LEL, and if an ignition source is present in the atmosphere and provides energy exceeding the minimum ignition energy, the gases will ignite, resulting in an explosion and fire. For example, when non-explosion-proof devices are installed in the space formed by beams and girders, as illustrated in Fig. 6, ignition and fire may occur if the accumulated combustible gases reach 100 % of LEL. Therefore, one effective measure is to determine where combustible gases may accumulate in vehicle spaces, and adopt a structure in which gases will not accumulate in the place.

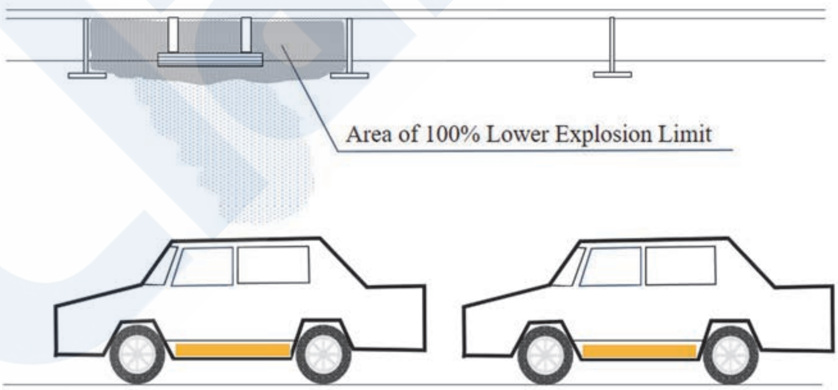

Fig. 6 Image of formation of explosive atmosphere in vehicle space

Classified broadly, the following two methods for preventing secondary fires in vehicle spaces are possible.

● Structure that makes it possible to discharge the combustible gases from the ship by ventilation so they will not form an explosive atmosphere, even if emitted from a vehicle, and prevents accumulation of gases in the vehicle space.

● Use of appropriate explosion-proof electrical devices in vehicle spaces so an explosive atmosphere will not ignite, even if formed.

Because combustible gases are emitted in the vehicle space during an emergency, the explosion-proof class of electrical devices has an explosion-proof structure suitable for use in Zone 2, as classified in IEC60079-10, and for gas vapor groups, temperature classes, gas vapor group IIC and temperature class T2 are appropriate, based on the results of an investigation of the types of gases generated during thermal runaway. It should be noted that these explosion-proof classes consider only the gas species generated from LIBs. The explosion-proof class required for other types of vehicles, such gasoline-powered vehicles, natural gas-powered vehicles, hydrogen vehicles, and vehicles carrying hazardous substances, etc., must be considered separately for each type of vehicle.

3.2.3 Prevention of Fire Spread

Because vehicles are loaded in vehicle carriers with a Door to Door spacing of 10 cm and Rear to Bumper spacing of 30 cm, it is easy to imagine that a fire which occurs in one vehicle will spread to adjacent vehicles by radiant heat during the fire. Therefore, after a fire occurs, it is extremely important to take fire-fighting action to isolate the burning vehicle from adjacent vehicles. Various means of preventing fire spread are conceivable, but two comparatively well-known methods are the water curtain and the fire blanket.

A water curtain is a curtain of water formed by water sprayed from nozzles, which can cut off the radiant heat generated by a burning vehicle. Although fixed water curtain systems exist, there is product that applies a portable-type called a water curtain hose, as shown in Fig. 7. Unlike fixed water curtain systems, the water curtain hose does not require fixed piping and nozzles, and holes with a special shape are provided in the fire hose. Because it can be placed in the location where the user wishes to form a water curtain depending on the condition of the vehicle space, it is considered to be one effective means of isolating burning vehicles.

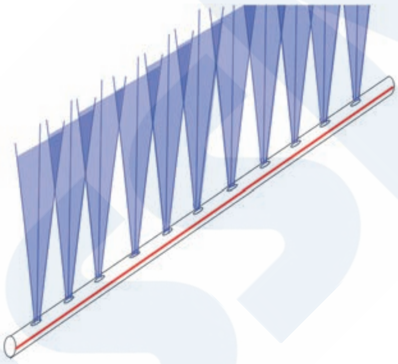

Fig. 7 Image of water curtain hose

A fire blanket is essentially a blanket which is used to enclose a burning vehicle and extinguish the fire by creating an oxygen-deficient condition inside the blanket. However, in the case of vehicle carriers, the fire may weaken, but it cannot be completely extinguished due to the presence of lashing holes. Although fire blankets are not suitable for extinguishing car fires on vehicle carriers, they can be used to prevent fire spread due to their excellent heat resistance. Fire blankets can be deployed even by two Society staff members, as demonstrated in Fig. 8, but considering the conditions in actual vehicle spaces, some ingenuity may be required when deploying fire blankets in a vehicle space.

Fig. 8 Fire blanket (photo courtesy of NIPPON TOKUSO CO., LTD.)

3.2.4 Fire-Fighting Procedures

What is important as a fire-fighting procedure for LIB fires is to understand the concept of “Burning out.” “Burning out” means that burnable fuel is no longer available and the fire burns out. For example, when a gas fire occurs, the gas will continue leaking after the fire has been extinguished, and if combustible gas fills the space and is reignited, this will cause an explosion. In this case, the fire-fighting procedure is to cut off the gas supply source and allow the remaining gas to burn up, without attempting to extinguish the fire immediately. In the meantime, efforts must be made to prevent the fire from spreading.

Battery fires are similar, in that the chemical reactions in a battery in which thermal runaway has occurred will continue until the potential difference between the electrodes is eliminated, and these reactions will continue to generate heat and gas, even if the fire from the battery is extinguished. Since it is not possible to cut off the supply of gas from the generation source, it is necessary to slow the chemical reactions by decreasing the temperature of the battery in which thermal runaway occurred, and to concentrate on continuing actions to prevent the fire from spreading to the surroundings until the chemical reactions are finished.

As one means of cooling the battery, releasing water from hydrants in the ship is effective. Because the EV batteries are arranged at the bottom of the vehicle, the battery itself cannot be cooled simply by spraying water from above the vehicle. Cooling the battery by releasing water from the vehicle bottom using a water fog applicator like that shown in Fig. 9, or directly cooling the cell by using a penetrating nozzle are effective. To prevent electrical shock, use of a penetrating nozzle is limited to cases where the nozzle can be inserted safely, at a position where it will not penetrate to a cell where internal short circuit has not occurred.

An important point when cooling a battery is the fact that the temperature will rise again, combustible gases will be generated, and the fire will be rekindled if cooling of a battery in which thermal runaway has occurred is stopped. Thus, it is also important to confirm each time that the temperature is not rising, even after battery cooling, by using a thermal camera, etc.

Fig. 9 Water fog applicator (excerpted from Marine Fire Fighting)

Although cooling the battery is extremely important, due to the high voltage of the battery, firefighters must be mindful of electrical shock when conducting fire-fighting operations. Experimental results show the necessary distance that a firefighter must take to avoid shock when using a solid stream or spraying water on an electrified grid [7]. Based on a water flowrate of 28.35 m^3/h and pressure of 0.21 MPa, a current value of 0 mA can be obtained when that distance is 11.5 ft (about 3.45 m) for a solid stream, 1.5 ft (about 0.45 m) for water spraying with an angle of 30°, and 0.5 ft (about 0.15 m) for a spray angle of 90°. In other words, when electrical shock is considered, these results show that it is important to use spraying.

3.2.5 Fire-Fighting Operations

Here, the important points for fire-fighting operations will be explained. To secure safety when conducting fire-fighting operations, the basic principle is to confront the fire with at least two firefighters per team (two buddy system). Even if one firefighter encounters some kind of danger, the other may be able to respond in some cases. Moreover, even assuming one firefighter overlooks a dangerous situation, there is a low probability that two firefighters will fail to see it.

When a fire breaks out, smoke naturally occurs. Smoke is a gas consisting of a mixture of suspended solids (soot, fibers, dust), liquid particles (hydrocarbons and water) and gases (toxic gases including carbon monoxide, hydrogen cyanide, etc.), and is harmful to human life and health. In a space where a fire has broken out, smoke is generated and visibility becomes poor. This means it is important to disperse the smoke generated by the fire, that is, perform ventilation, before carrying out fire-fighting operations. Ventilation control is explained in detail in the next section. Visibility can be secured by removing the smoke from the space where the fire has occurred by ventilation. Securing visibility contributes to identification of the source of the fire, making it possible to take appropriate action, and also makes it possible to estimate the route of fire spread. Dispersing the smoke can also secure the safety of fire-fighters. That is to say, ventilation work is one of the most important activity of fire-fighting operations.

It is known that extinguishing battery fires requires an extremely long time because it is necessary to complete the cooling of the battery. Since the time that the breathing apparatuses for firefighters specified in the SOLAS Convention can be used generally limited to about 20 to 30 minutes, it is extremely important to provide breathing equipment that makes it possible to continue fire-fighting operations for longer periods, and to perform appropriate ventilation work to secure an environment in which fire-fighting operations can be conducted even without breathing equipment.

Proper drainage of the water used in actions to prevent fire spread and fire-fighting operations is also important. If proper water drainage is not possible because the scuppers are blocked by resins or other materials melted by the heat of the fire, there is a danger that the remaining water may affect the stability of the ship. Therefore, it is necessary to check each time that there is no blockage, and water can be drained properly from the scuppers during fire-fighting operations.

3.2.6 Ventilation Control

Although the previous section explained the importance of ventilation, many people advocate shutting down ventilation systems during fires to confine the fire because of concern that allowing fresh air to flow into the vehicle space by ventilation may cause the fire to spread. However, considering the amount of oxygen consumed by a few burning vehicles in a large space like vehicle spaces , the probability that an oxygen-deficient condition can be achieved in a vehicle space is low, rather, it is possible that allowing smoke to fill the space may create an even more dangerous situation. In order to conduct fire-fighting operations using fire hydrants, it is more important to effectively remove the smoke of the fire and secure a space where fire-fighting operations can be conducted. The purposes of smoke dispersal work can be summarized as follows:

1) To improve visibility for firefighters and facilitate identification of fire sources and persons who were unable to evacuate.
2) To reduce the danger of high temperature combustible gases and toxic gases by discharging such gases.
3) To reduce the possibility of flashovers and backdrafts.

The basic rule of ventilation is to create an air flow that provides easy access to the fire by firefighters, as shown in Fig. 10. However, there are places where air stagnates, depending on the arrangement of fans, positions of slopes and the opening direction of ventilation ducts. Since smoke cannot be dispersed effectively under such conditions, it is important to investigate the condition of ventilation in each ship and identify locations where air can easily stagnate. In places where air stagnates, forced ventilation using portable fans to enable effective smoke dispersal during a fire, or PPV(Positive Pressure Ventilation) in vehicle spaces for efficient smoke discharge are considered to be effective methods.

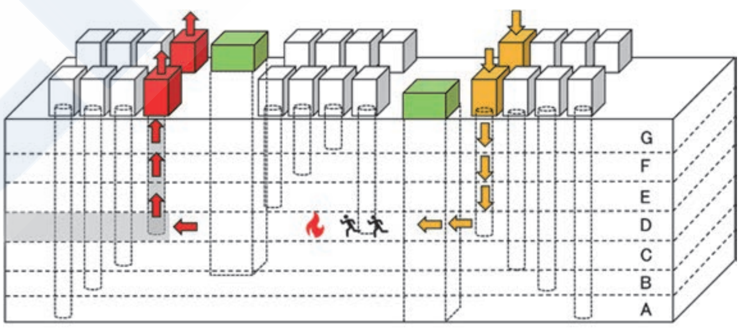

Fig. 10 Schematic diagram of ventilation system for vehicle space

3.2.7 Fixed Fire-Extinguishing Systems

As explained up to now, measures for early detection, prevention of fire spread, prevention of secondary fires and fire-fighting operations are extremely effective, but prompt activation of fixed fire-extinguishing systems is also one effective measure. The International Code for Fire Safety Systems (FSS Code) recognizes three types of fixed fire-extinguishing systems for installation in the vehicle spaces of vehicle carriers, namely, water-based fire-extinguishing systems, high-expansion foam fire-extinguishing systems, and carbon dioxide fire-extinguishing systems. Because installation of water-based systems is not realistic, high-expansion foam fire-extinguishing systems or carbon dioxide fire-extinguishing systems have become the mainstream in vehicle carriers. As a means of extinguishing fires, fixed fire-extinguishing systems are considered to be the last stronghold as a fire-fighting systems, but this appears slightly different when the object is an EV fire. Table 2 describes the effects of the respective fire-extinguishing systems in simple terms.

Table 2 Principle of fire-extinguishing by fixed fire-extinguishing systems

System	Principle of fire-extinguishing
High-expansion foam fire-extinguishing system	Extinguishes fire by the oxygen-deficient condition and cooling effect that result from covering the object of the fire in foam.
Carbon dioxide gas fire-extinguishing system	Extinguishes fire by reducing the oxygen concentration in the protected space to a level where continuing combustion becomes unsustainable.
Water-based fire-extinguishing system	Prevents generation of combustible vapor and makes continuing fire impossible by the cooling effect of water.

In thermal runaway of an electric vehicle LIB, combustion which require the oxygen occurs at the location of the fire, but the exothermic reaction of the battery is a chemical reaction which does not require oxygen. If the aim is to extinguish the flames of the fire, extinguishing the flame can be expected with any of the fixed fire-extinguishing systems shown in Table 2.

Although a water-based fire-extinguishing system cannot directly cool the EV battery because the battery is located under the vehicle, water itself is an extremely effective fire-extinguishing agent owing to its very high cooling effect, and the surrounding vehicles can be covered with a water film.

However, a cooling effect that will make the chemical reaction less severe may not necessarily be expected with high-expansion foam fire-extinguishing systems or carbon dioxide gas fire-extinguishing systems, which means it may be difficult to suppress a thermal runnway by slowing the chemical reaction simply by activating these fixed fire-extinguishing systems.

Concretely, if a high-expansion foam fire-extinguishing system is used, the foam will eventually disappear, and in this case, its smothering effect will be lost and the fire may reignite. On the other hand, the CO_2 gas used in carbon dioxide fire-extinguishing systems does not have an inherent cooling effect, and if there are openings in the protected space, the gas may leak out, allowing the oxygen concentration in the space to rise to a level where the fire can reignite.

Thus, it is necessary to understand what cannot be achieved even by a fixed fire-extinguishing system, and to study measures to compensate for those weaknesses. For example, in the case of a carbon dioxide fire-extinguishing system, this might mean sprinkling water from the carbon dioxide nozzles after the CO_2 gas has been released to provide a supplementary cooling effect.

Considering the possibility of prolonged fires, the number of times that the fire-extinguishing agent of a fire-extinguishing system can be applied is also an important factor. With high-expansion foam fire-extinguishing systems, it is possible to supply foam to the space repeatedly because ships are required to carry enough foam concentrate to fill protected spaces with foam 5 times. In comparison with high-expansion foam fire-extinguishing systems, if a carbon dioxide fire-extinguishing system is used, there is a high risk that the fire will break out again because carbon dioxide fire-extinguishing systems have only enough CO_2 gas to release into the space 1 time.

Because water-based fire-extinguishing systems use seawater, they have an inexhaustible supply of fire-extinguishing agent. However, there are high hurdles to installation of water-based systems in vehicle carriers, considering the arrangement and cost of the water feed pumps, nozzles, piping, etc.

3.2.8 Improvement of Operational Reliability of Fixed Fire-Extinguishing Systems

As described above, fixed fire-extinguishing systems, which are also called total flooding fire-extinguishing systems, are expected to have the effect of extinguishing or suppressing fires by filling the entire protected space with a fire-extinguishing agent. Since they are activated when it becomes impossible to suppress a fire through the stages of fire detection and initial fire-fighting, it is no exaggeration to say that they are the “last stronghold of fire-fighting.” If such important fire-fighting equipment cannot be activated in an emergency, there will be no choice but to evacuate the ship.

Since high-expansion foam fire-extinguishing systems use a very large number of sensors and devices to release high-expansion foam into the protected space, maintenance and management of that equipment are extremely important. For sensors, it is essential to take measures such as providing redundant sensor to ensure that the activation sequence will proceed smoothly, even if one of the sensors malfunctions.

Carbon dioxide fire-extinguishing systems are considered to have higher operational reliability than high-expansion foam fire-extinguishing systems because the CO_2 gas is released by the self-pressure in the tank when the discharge valve is opened.

Since the component elements of fixed fire-extinguishing systems differ depending on the type of system installed, understanding the sequences for activating the respective systems and identifying and strengthening the sensors and devices that are key components for releasing the fire-extinguishing agent in the protected space is one effective measure.

3.2.9 Other Considerations

As fire-fighting measures for vehicle carriers, this article has explained various facts from the viewpoint of ship equipment. However, it is also possible to avoid loading vehicles with a high risk of fire in the first place. At present, there are no indicators for judging whether a used EVs are in a dangerous condition based on the degree of deterioration of its LIB, but with future improvements in battery diagnosis technologies, it will become possible to exclude vehicles with a high risk of fire from vehicle carriers.

As one additional issue, it is not always possible to distinguish EVs from gasoline-powered vehicles. Even if someone actually witnesses a vehicle catching fire, appropriate action cannot be taken without knowing whether that vehicle is an EV or not. For example, actions such as clearly indicating where EVs are stowed in the Stowage plan and labeling or other identification of vehicles to indicate that they are EVs are considered effective.

3.2.10 Establishment of Fire-Fighting Tactics

It is important to establish the fire-fighting tactics of the response policy for EV fires, referring to the characteristics of EV fires and the points to note and response policy described up to this point.

When a fire actually breaks out, it is extremely difficult to consider various matters and take appropriate action on the spot. Therefore, it is important to compile a flowchart of fire-fighting tactics like that shown in Fig. 11, and to ensure that all crew members fully understand its content. It is also important to ensure that crew members physically master those procedures through regular training.

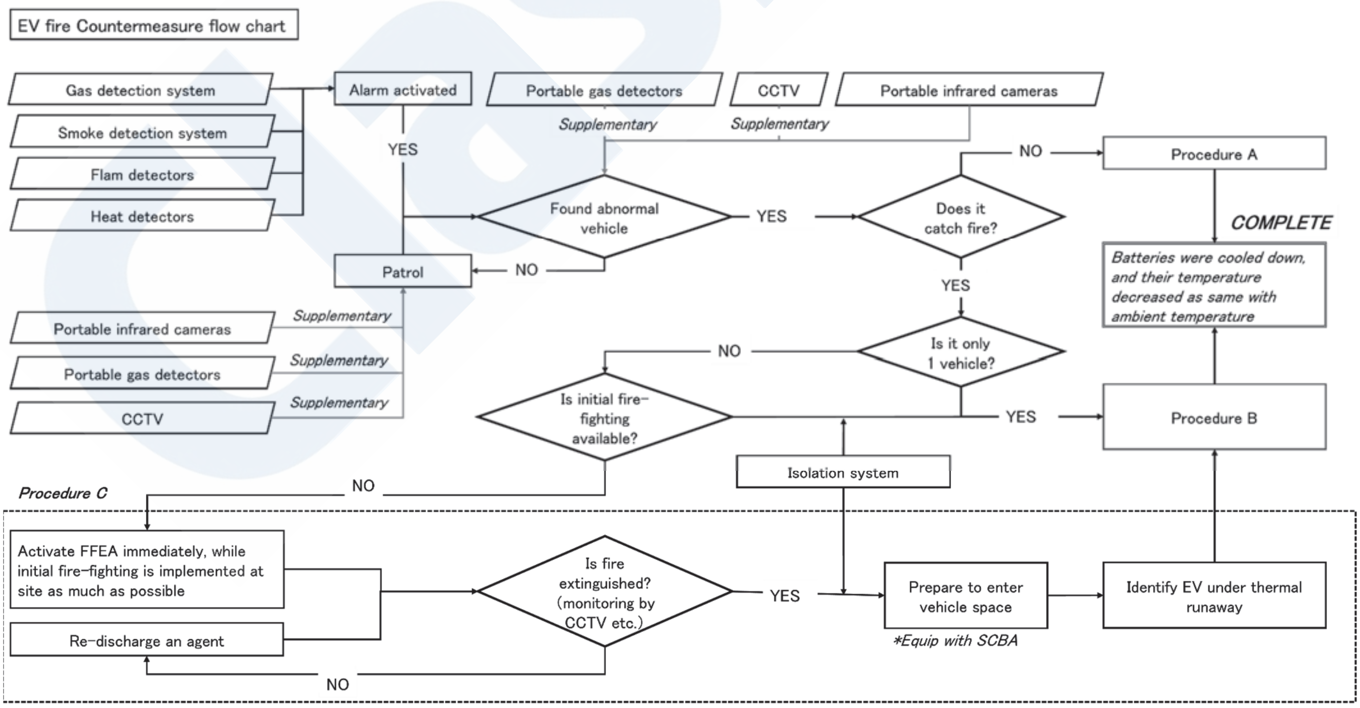

Fig. 11 Example of flowchart of fire-fighting tactics (image)

EV fires can be divided into an initial stage which is limited to only heat generation from the battery without the outbreak of a fire, a stage when a fire breaks out from a single vehicle, and a stage when fires occur in multiple vehicles. It is important to arrange the response policy corresponding to those respective stages.

3.2.11 Class Notation

Based on *"Guideline for the Safe Transportation of Electric Vehicles"* published by the Society in August of 2023, the notations shown in Table 3 can be affixed to the ship's classification characters, corresponding to the fire safety measures taken by the ship. For the following two reasons, the *Guideline* propose the types of measures that can be taken, but do not specify concrete equipment requirements.

The first reason is that it is of primary importance to understand the expected effects of various the fire safety measures and what equipment should be installed to achieve those effects, based on the purposes of the fire safety measures. Without that understanding, the system may fail to demonstrate its full effects in an emergency. Each company can best understand the purposes and importance of fire safety measures by studying those points, and this will contribute to reducing fire damage of vehicle carriers.

The second reason is because a wide range of effective technologies for EV fires is available worldwide, and technologies are also expected to be developed in the future. For this reason, the Society believes that restrictions should not be placed on the use of those technologies, and the kinds of element technologies necessary as fire measures should be conveyed by communication from the maritime industry to other industries.

It is our hope that the issuance of the *Guideline* will contribute to the development of extremely outstanding technologies and accelerated study of fire safety measures in each company.

4. FUTURE OUTLOOK AND ISSUES

The Society is promoting study of fire safety measures for vehicle carriers on an ongoing basis. We plan to refine and improve the *Guideline* based on the comments received since the publication of the *Guideline*. We also plan to continue to investigate technologies in the other industry which were not covered by studies prior to the publication of the *Guidelines*, and to study and update the kinds of effects that can be expected in fire safety measures by applying those technologies to ships.

In addition, the Society is promoting studies related to ship evacuation in the event of a fire. There may be situations where it is finally necessary to abandon ship, even if fire safety measures like those described in this article are taken on a vehicle carrier. First, we plan to conduct a risk assessment to identify the types of risks when evacuating a ship, and will then study measures for those risks that will enable the crew to safely reach lifeboats and evacuate, and reflect those results in a set of guideline.

5. RECENT TOPIC AT IMO AND INTERNATIONAL TRENDS

At present, the International Maritime Organization (IMO) has begun discussions on a revision of fire safety measures when transporting new energy vehicles, including electric vehicles, in the 10th Session of the Sub-Committee on Ship Systems and Equipment (SSE10), targeting completion in 2027. As future plans, the results of experiments conducted in each country and the views of experts concerning the characteristics of fires involving new energy vehicles will be compiled, and the systems and equipment to be required in an international convention will be studied.

Because ship owners in Japan operate a large number of vehicle carriers, even in terms of the total number of vessels in operation, we believe that Japan should actively submit safe and cost-effective measures for the transportation of EVs to the IMO, and make efforts to ensure that those measures will become the global standard.

Moreover, it is also necessary to actively exchange opinions with Japan's domestic automobile industry and take actions on this matter by the country as whole.

Table 3 Notation affixed to ship class characters for additional fire-fighting measures

Notation	Details
AFVC (FD) (EV)	**A**dditional **F**ire-fighting measures for **V**ehicle **C**arrier (**F**ire **D**etection) (**E**lectric **V**ehicle) Affixed to ships that have taken measures contributing to fire detection for vehicles with battery abnormalities.
AFVC (PS) (EV)	**A**dditional **F**ire-fighting measures for **V**ehicle **C**arrier (**P**revention of **S**econdary fire) (**E**lectric **V**ehicle) Affixed to ships that have taken measures related to prevention of secondary fires accompanying combustible gases generated by a battery fire.
AFVC (PFS) (EV)	**A**dditional **F**ire-fighting measures for **V**ehicle **C**arrier (**P**revention of **F**ire **S**pread) (**E**lectric **V**ehicle) Affixed to ships that have taken measures against the spread of a fire of a single vehicle.
AFVC (FF) (EV)	**A**dditional **F**ire-fighting measures for **V**ehicle **C**arrier (**F**ire **F**ighting) (**E**lectric **V**ehicle) Affixed to ships that have taken measures related to fire-fighting and extinguishment of electric vehicle fires.
AFVC (EFF) (EV)	**A**dditional **F**ire-fighting measures for **V**ehicle **C**arrier (**E**nhanced **F**ixed **F**ire-extinguishing system) (**E**lectric **V**ehicle) Affixed to ships that have taken measures to strengthen the capacity and improve the operational reliability of fixed fire-extinguishing systems.

6. CONCLUSION

This article has explained the characteristics and points to note concerning fires involving electric vehicles, and the fire safety measures based thereon. Persons who have studied the fire safety measures taken to reduce the damage during fires have a thorough knowledge of the use methods that make it possible to demonstrate their effects to the fullest possible extent. Ensuring that everyone understands the intentions and purposes of installing fire-extinguishing systems is the most necessary point for reducing fire accidents. If equipment requirements are specified once in an international convention or the Society's rules for ships, those concerned have a shallow understanding of the technical background for requiring that equipment, and there is a possibility that the equipment may not be able to demonstrate its full intrinsic effects. To ensure that the fire safety measures developed through repeated study over many years by persons involved in the maritime industry do not become a wasted things, the Society will continuously work to reduce fire accidents, and will provide timely information on effective methods and action guidelines for action during fires to stakeholders.

Finally, based on the fire safety measures for vehicle carriers developed independently by each company, it is our hope that all those concerned will make exhaustive efforts to ensure that the most effective and rational fire safety measures become the global standard.

ACKNOWLEDGEMENT

In preparing this article and *"Guideline for the Safe Transportation of Electric Vehicles"*, the author received the opinions of many persons in various industries, and also referred to various references in the literature. I wish to take this opportunity to thank all those concerned.

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High-Expansion Foam Fire-Extinguishing Systems for Pure Car and Truck Carriers

Susumu OTA*

1. INTRODUCTION

The answer to the question of whether a fire-extinguishing system can extinguish a certain kind of fire or not is: "It may or may not be able to." This is because fire is defined as uncontrolled combustion, and its characteristics are so diverse that the "same fire" cannot exist twice. As actual fires are not reproducible, the performance of a fire-extinguishing system is evaluated based on whether the system can extinguish a reproducible "test fire," rather than an actual fire. On the other hand, test fires for cargo spaces of Pure Car and Truck Carriers (PCTCs), have not been established internationally.

The characteristics of fires involving electric vehicles (EVs) are discussed in "Safe Maritime Transportation of Electric Vehicles – Characteristics of EV Fires and Guidelines for Response –" in this Special Feature. However, from the viewpoint of the effectiveness of high-expansion foam fire-extinguishing systems, the detailed knowledge on fires involving automobiles and fires involving EVs is not sufficient to discuss these two types of fires separately. Therefore, this article describes the currently-available information on the effectiveness of high-expansion foam fire-extinguishing systems against fires in the cargo spaces of PCTCs, without specializing in fires involving EVs.

In recent years, there have been some reports of casualties in which high-expansion foam fire-extinguishing systems were not successful in extinguishing fires in the cargo spaces of PCTCs equipped with such systems. The details of these casualties are unknown, including whether the ignition fuels were automobiles or not, and whether the high-expansion foam fire-extinguishing system activated or not. However, following such accidents, the Japan Ship Technology Research Association (JSTRA) established the "Advisory Committee on Prevention of the Recurrence of Fire Accidents in Car Carriers" with relevant domestic stakeholders, drawing upon information from two of these accidents that occurred in 2019. The committee studied safety measures based on the structures and specifications of the ships that suffered these accidents, actual accident information, etc., and compiled a report on "Improvement Measures for Effective Use of Fixed Foam Fire-Extinguishing Systems" in March 2021 for preventing the recurrence of similar accidents. Those results were reflected in a Notice [1)] of the Safety Policy Division of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). In addition, Kashiwa Tech Co., Ltd., a manufacturer of high-expansion foam fire-extinguishing systems, has been conducting experimental research to confirm the effectiveness of the equipment with the support of Nippon Kaiji Kyokai (ClassNK), etc. Moreover, there was also a possibility that fire-extinguishing foam was not supplied promptly to the cargo space in the above-mentioned accidents. Therefore, JSTRA also established a "Advisory Committee on Improvement of the Reliability of High-Expansion Foam Fire-Extinguishing Systems" in order to facilitate shipping companies in preparing better maintenance manuals, with the ultimate aim of enhancing the reliability of those systems. The following presents an overview of these research initiatives.

2. HIGH-EXPANSION FOAM FIRE-EXTINGUISHING SYSTEMS FOR CARGO SPACES OF PCTCS

2.1 Fixed Fire-Extinguishing Systems and Fireproof Structures

On a large number of PCTCs, the cargo spaces (car decks) are protected by high-expansion foam fire-extinguishing systems. Here, only cargo ships are assumed as PCTCs, and so-called Ro-Ro passenger ships are not discussed. In addition, as PCTCs generally do not have cargo spaces on exposed decks (weather decks), only enclosed cargo spaces are discussed in the following.

The previous Chapter II-2 of the annex to the SOLAS Convention had required fixed gas fire-extinguishing systems in the cargo spaces of PCTCs (ro-ro cargo spaces of cargo ships) [2)]. However, the comprehensive revision [3)] of Chapter II-2 of the annex to the SOLAS Convention, which entered into force on July 1, 2002, permitted the use of high-expansion foam fire-extinguishing systems instead of fixed gas fire-extinguishing systems [4)]. The International Code for Fire Safety Systems (FSS Code) [5)] was also

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adopted together with the comprehensive revision of the Convention. After that, as a result of the revision of the annex to the SOLAS Convention (including revision of Chapter II-2) [6], which entered into force on July 1, 2014, the cargo spaces of PCTCs, so-called "vehicle spaces," should be protected by one of the three types of fixed systems complying with the FSS Code [7], i.e., fixed gas fire-extinguishing systems, high-expansion foam fire-extinguishing systems or water-based fire-extinguishing systems.

The fixed gas fire-extinguishing systems used in the cargo spaces of PCTCs are carbon dioxide gas fire-extinguishing systems. In these systems, a volume of carbon dioxide gas equivalent to 45 % of the gross volume of the largest protected cargo space is required. Therefore, if a cargo space to be protected is excessively expanded, the required amount of carbon dioxide gas will no longer be realistic. Thus, it is necessary to divide the cargo space into multiple fire compartments. Fig. 1 shows an example of the fire protection structure of the cargo spaces of a ship using a carbon dioxide gas fire-extinguishing system, where A to G in the figure are fire compartments. In this example, one deck in 3 to 4 decks was made gastight, and bulkheads having openings with means of closure were provided near the mid-ship. To make the decks gastight, the lashing holes should also be made airtight.

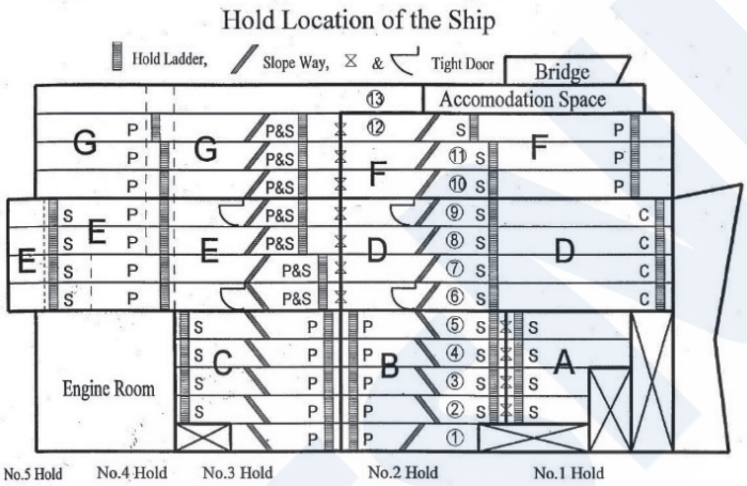

Fig. 1 Example of fire compartments in cargo space of PCTC

Previously, A-0 (A-zero) class fire integrity had been required for the fire-resisting divisions constituting a fire compartment. This means that steel structures can be used without thermal insulation for such fire-resisting divisions. However, since the above-mentioned revision of the SOLAS Convention that entered into force in 2014, A-30 class fire integrity has been required for such fire-resisting divisions. This means that thermal installation is required even for steel structures. For this reason, it is thought that high-expansion foam fire-extinguishing systems will be adopted widely as fixed fire-extinguishing systems in the future as well.

2.2 Performance Required for High-Expansion Foam Fire-Extinguishing Systems

The original FSS Code [5] prescribed foam fire-extinguishing systems, although not as systems for vehicle spaces, from the time of the comprehensive revision of Chapter II-2 of the annex to the SOLAS Convention. The major requirements, other than those for the properties of the foam (foam concentrate), were as follows:

- The nominal foam filling rate, i.e., the ratio of nominal foam production (the volume of foam produced per unit time) to the area expressed in m/min, should be 1 m/min or more.
- The quantity of foam concentrate available should be sufficient to produce a volume of foam equal to at least five times the volume of the largest protected space.

It should be noted that "Guidelines for the approval of alternative fixed water-based fire-fighting systems for special category spaces" [8] had also been referred to as a footnote to a regulation of the SOLAS Convention, but these Guidelines did not specifically mention high-expansion foam fire-extinguishing systems.

In advance of the revision of the SOLAS Convention that entered into force in 2014, Chapter 6 of the FSS Code, i.e., "Fixed foam fire-extinguishing systems," was also revised [9]. Since the revision of the FSS Code, it has been required that the foam-generating capacity should be adequate to fill the largest protected space within 10 minutes as the performance of high-expansion foam fire-extinguishing systems. The Guidelines, which is referred to in a footnote to the Code [10], also include provisions for fire tests, and in the tests, for example, the test fire is an oil spray fire having the heat release rate of 5.8 MW ± 0.6 MW plus fires in trays under (4 m^2) and on top (3 m^2) of the oil spray fire.

2.3 Types of High-Expansion Foam Fire-Extinguishing Systems

2.3.1 Types of Systems Prescribed in the FSS Code

Chapter 6 of the FSS Code contains provisions for the three types of high-expansion foam fire-extinguishing systems shown in Table 1, which are classified by the foam-generating method and the installation location of the foam generator. [11), 12)]

Table 1 Types of high-expansion foam fire-extinguishing systems

Foam-generating method	Foam generator installation location	Related section in Ch. 06 of the FSS Code
Inside air form system	Inside protected space	3.2
Outside air form system	Outside protected space	3.3
	Inside protected space	3.5

2.3.2 Inside Air Form System

As shown in Fig. 2, in this type of system, the foam solution, which is prepared by mixing the foam concentrate and water, is sprayed from the nozzle onto the foaming net to generate foam by drawing air from the surrounding space. It is called an "inside air" system because the air inside the protected space is used to generate the foam, where the foam generator is installed inside the protected space. Systems of this type are used in engine rooms and cargo oil pump rooms on ships.

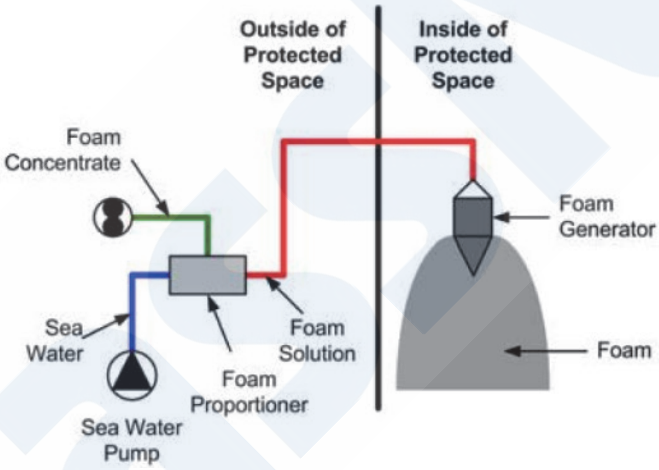

Fig. 2 Inside air form system

2.3.3 Outside Air Form System (Foam Generator: Outside Protected Space)

As shown in Fig. 3, in this type of system, foam is generated with air outside the protected space by using a mechanical fan, and the foam generator is installed outside the protected space. The foam generated at the foam generator is supplied to the protected space through a dedicated foam delivery duct. When the foam delivery duct becomes too long, the foam will collapse due to friction with the inner wall of the duct, so the length of the duct cannot be extended excessively. With the recent increase in the size of PCTCs, systems of this type of system became inefficient and are not adopted in PCTCs.

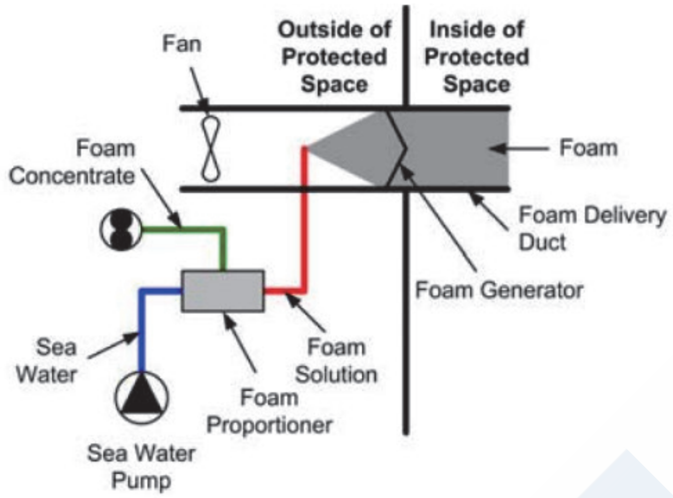

Fig. 3 Outside air form system (Foam generator: Outside protected space)

2.3.4 Outside Air Form System (Foam Generator: Inside Protected Space)

This type of system, foam is generated by the same method described in 2.3.3, where air is supplied to the foam generator from outside the protected space. As shown in Fig. 4, however, different from the above mentioned system, the foam generator is located inside the protected space. This type of system is generally adopted in the cargo spaces of PCTCs. In systems of this type, the loss of foam is minimal, even on large ships, because foam is generated inside the protected space, where air is supplied from the outside to the foam generator through a connecting duct by a mechanical fan.

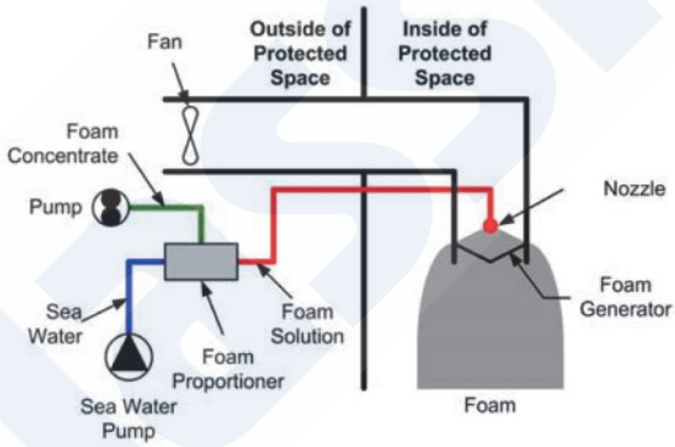

Fig. 4 Outside air form system (Foam generator: Inside protected space)

2.4 Fixed Fire-Extinguishing Systems and Response to Fire

The success or failure of fire-extinguishing activities is also related to the time from the outbreak of a fire to the start of fire-extinguishing. The fire-extinguishing system should, therefore, be activated as soon as possible.

The order of the actions when a fire occurs is sometimes expressed by the acronym “FIRE.” This means that the correct procedure is as follows: first, “Find” the fire; next, “Inform” nearby individuals, including notification; then “Restrict” the fire; and finally, “Extinguish” it. Among these, since “Restrict” includes cutting off of ventilation to the fire, the ship’s crew is trained to close openings when a fire is recognized in order to stop ventilation. In contrast to this, when using a high-expansion foam fire-extinguishing system in a cargo space of a PCTC, it is necessary to open specified ventilation ducts (including air vents). In this procedure, when a fire is recognized, the ventilation ducts are closed initially, and if initial fire-fighting attempts are unsuccessful and the high-expansion foam fire-extinguishing system needs to be activated, the specified ventilation ducts are then reopened. However, this procedure requires considerable time before the system can be activated. In this regard, it is recommended to skip the procedure for stopping ventilation in spaces protected by a high-expansion foam fire-extinguishing system. The aforementioned Notifice [1)] of the Safety Policy Division of MLIT also recommends skipping the procedure for closing the ventilation ducts (either by leaving the means of closures of ducts open or by automatic operation) in order to shorten the time until activation of the high-expansion foam fire-extinguishing system.

3. STUDY ON IMPROVEMENT OF THE RELIABILITY OF HIGH-EXPANSION FOAM FIRE-EXTINGUISHING SYSTEM OPERATION

The procedures indicated by the black circle symbol (●) in the following list are necessary before foam generation starts in the existing high-expansion foam fire-extinguishing systems with relatively low-level automation.

● Confirm the location and magnitude of the fire by the ship's crew.
● Check that all ventilation ducts to the space where foam is to be released are open.
● Press the "System standby button" on the "Control panel" (main or sub-control panel).
○ A "Foam discharge alarm" will sound automatically in the object space, and the "Ventilation fan" will stop.
● On the "Control panel," confirm that the "Water pressure lamp" and the "Foam concentrate pressure lamp" are flashing and the main power generator operation lamp is lighted.
● Press the operation button of the "Foam fire-extinguishing pump."
● Confirm that the operation lamp (green) of the Foam fire-extinguishing pump is lighted.
● Confirm that the "Water pressure normal" lamp is lighted, which means that the water pressure is raised.
○ Lamps showing that various valves such as the "Water supply valve" are open will also light automatically.
○ The "Foam concentrate pressure normal" lamp lights.
○ The "Foam discharge possible" lamp flashes.
● Check that there are no personnel in the space where foam is to be released.
● Press the "Foam discharge button."
○ The "Foam discharge" lamp lights.
○ The "Foam discharge valve" will open automatically, and the "Foam discharge valve open" lamp will light.
○ The ventilation-side openings of the "Foam damper" near the "Foam generator" on each deck will close automatically. When the air pathway to the "Foam generator" is formed, the "Foam damper open lamp" will light.
○ The "Air supply fan operation lamp" will light automatically.
⇒ "Release of foam" is started through the procedure up to this point.
(• After confirming that the fire is extinguished, press the "Stop button.")
(• Visually confirm that the foam has overflowed from the openings on the top space, and stop foam discharge.
⇒ If necessary, restart foam discharge.)

This complicated procedure cannot be executed correctly if even one switch malfunctions. Although more highly automated systems have become mainstream in recent years, the system will not function effectively if there are defects in individual parts, etc., even with progress in automation, which is similar to the case in the conventional systems. Furthermore, it is considered crucial to ensure the proper operation of the foam dampers, which are used to switch between ventilation modes for the holds and foam release. This is due to the possibility of dampers sticking and failing to operate smoothly if maintenance is poor, coupled with the difficulty of maintaining the foam damper itself. In recent years, these foam dampers have not been installed in the latest-model systems. In high-expansion foam fire-extinguishing systems, the typical procedure is to initially foam with fresh water to prevent damage to the cargo by the system's operation, and then switch to foaming using seawater. However, from the standpoint of reliability, shipping companies are exploring the use of seawater foaming from the initial stage. In any case, since maintenance is important and it is necessary to maintain manuals to be easily understood by ships' crew, JSTRA conducted research in FY 2023 and established guidelines for developing maintenance and inspection plans (to be published in the near future).

4. FIRE-EXTINGUISHING/SUPPRESSION EXPERIMENT ASSUMING FIRE OF SINGLE VEHICLE

4.1 Fire-Extinguishing/Suppression Experiment of Fire of Electric Vehicle

Kashiwa Tech, in cooperation with ClassNK and some shipping companies, carried out a fire-extinguishing experiment with an outside air-type high-expansion foam fire-extinguishing system using a battery electric vehicle (BEV) with a lithium ion battery (laminated type, 24 kWh) at the Japan Automobile Research Institute (JARI) on October 28, 2022 [12), 13), 14)]. The overall setup of the experiment is shown in Fig. 5. The BEV was covered with wire gauze, which was not permeable by the foam, and foam was supplied from the side (see Fig. 6). In the experiment, the BEV was burned for a time until the intensity of the fire was approximately constant (see Fig. 7), after which foam having a nominal expansion ratio of 900 was supplied at a nominal filling rate of 1 m/min (see Fig. 8). The fire of the BEV was extinguished under this condition (see Fig. 9).

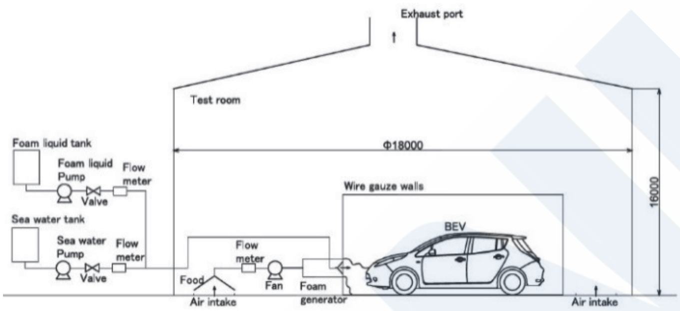

Fig. 5 Setup of experiment (overview)

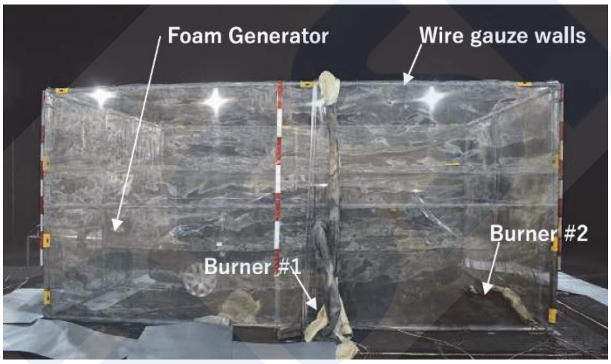

Fig. 6 BEV enclosed by wire gauze walls

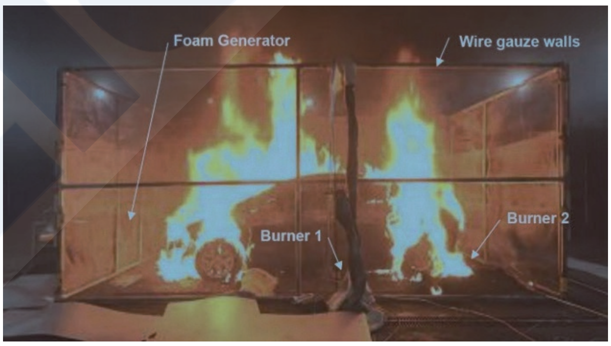

Fig. 7 Condition in burning period (before activation of fire-extinguishing system)

Fig. 8　Condition of BEV covered with foam

Fig. 9　BEV when wire gauze was removed after the fire

4.2　Fire-Extinguishing/Suppression Experiment with Test Fire Simulating Vehicle

Kashiwa Tech also conducted fire-extinguishing/suppression experiments using a test fire simulating one vehicle [15]. The fire-extinguishing limits of respective types of fire-extinguishing agents have been evaluated based on the relations between the fire-extinguishing agent supply rate (nominal foam filling rate) and time required for extinguishing (hereinafter, this relationship is called the “fire-extinguishing limit supply curve”) using wooden cribs and other standardized test fires. Following this practice, in this experiment, the time required to extinguish the fire was measured with different nominal foam filling rates, and fire-extinguishing limit supply curves were plotted.

The test fire consisted of three rectangular fire trays, each measuring 1.2 m^2, with a mock-up simulating an automobile covering the fire trays. The fire trays were filled with normal heptane, and the mock-up was made of perforated metal, which was impermeable to the fire-extinguishing foam but permeable to air, in order to achieve the required heat release rate (see Fig. 10). When the heat release rate was measured without fire-extinguishing, the average values with 1, 2 and 3 trays were 2.7 MW, 4.5 MW and 6.3 MW, respectively.

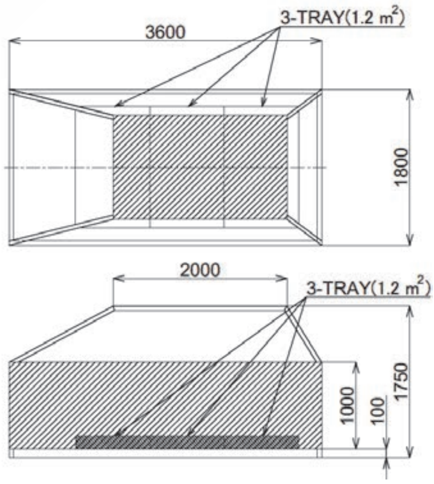

Fig. 10　Mockup of automobile (Roof: steel sheet, sides and floor: perforated metal)

In the experiments, the supply of the extinguishing foam was started after 1 minute of preliminary burning. When the foam was supplied and built up towards the front of the vehicle mockup, a flow of air from the back to the front of the vehicle mockup was formed, and the flames that had risen straight upward changed so as to burst out from the opening simulating the broken front windshield of the vehicle mockup. When the built-up foam reached the height of the windshield opening at the front of the vehicle mockup, the foam was blown away from the windshield opening by the air flow owing to the heat of the test fire. When the foam supply rate was sufficient to overcome this heat-induced air flow, the foam flowed into the interior of the vehicle mockup and covered the surface of the fire tray(s), and the fire could be extinguished or suppressed successfully. On the other hand, it was judged that fire-extinguishing/suppression was not possible when an equilibrium condition continued for several minutes, namely, when the heat-induced air flow was stronger than the foam supply rate and the foam could not flow into the vehicle mockup. The fire-extinguishing limit curves for the foam having an expansion ratio of 900 are shown in Fig. 11.

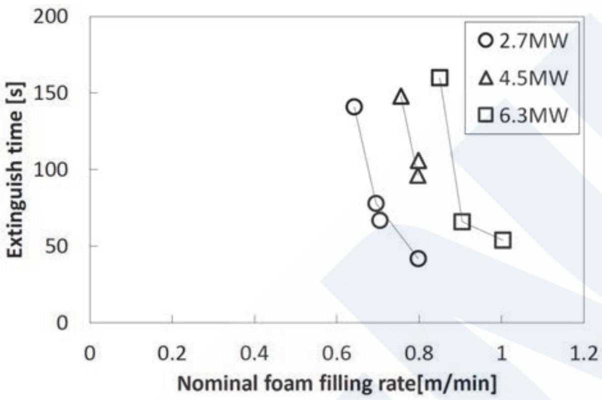

Fig. 11　Fire-extinguishing limit curves of high-expansion foam

Based on this figure, the nominal foam filling rate necessary to extinguish/suppress a one-vehicle fire, the heat release rate of which is roughly estimated as 4 MW, can be estimated to be about 0.72 m/min for the foam having the expansion ratio of 900. This implies that the fire-extinguishing systems of actual ships have a certain margin, taking into account that the systems are designed to achieve a nominal foam filling rate of at least 1 m/min. However, whether the nominal foam filling rate is sufficient to compensate for the loss of foam during spreading and build-up in the cargo space is considered to be a future subject.

5. PLAN FOR FIRE-EXTINGUISHING/SUPPRESSION EXPERIMENTS USING TEST FIRES ASSUMING MULTIPLE VEHICLES

Kashiwa Tech plans to conduct fire-extinguishing/suppression experiments using test fires and mockups of multiple vehicles in cooperation with ClassNK. The planned setup is shown in Fig. 12. These experiments aim to evaluate the effectiveness of high-expansion foam fire-extinguishing systems under conditions more closely simulating actual situations.

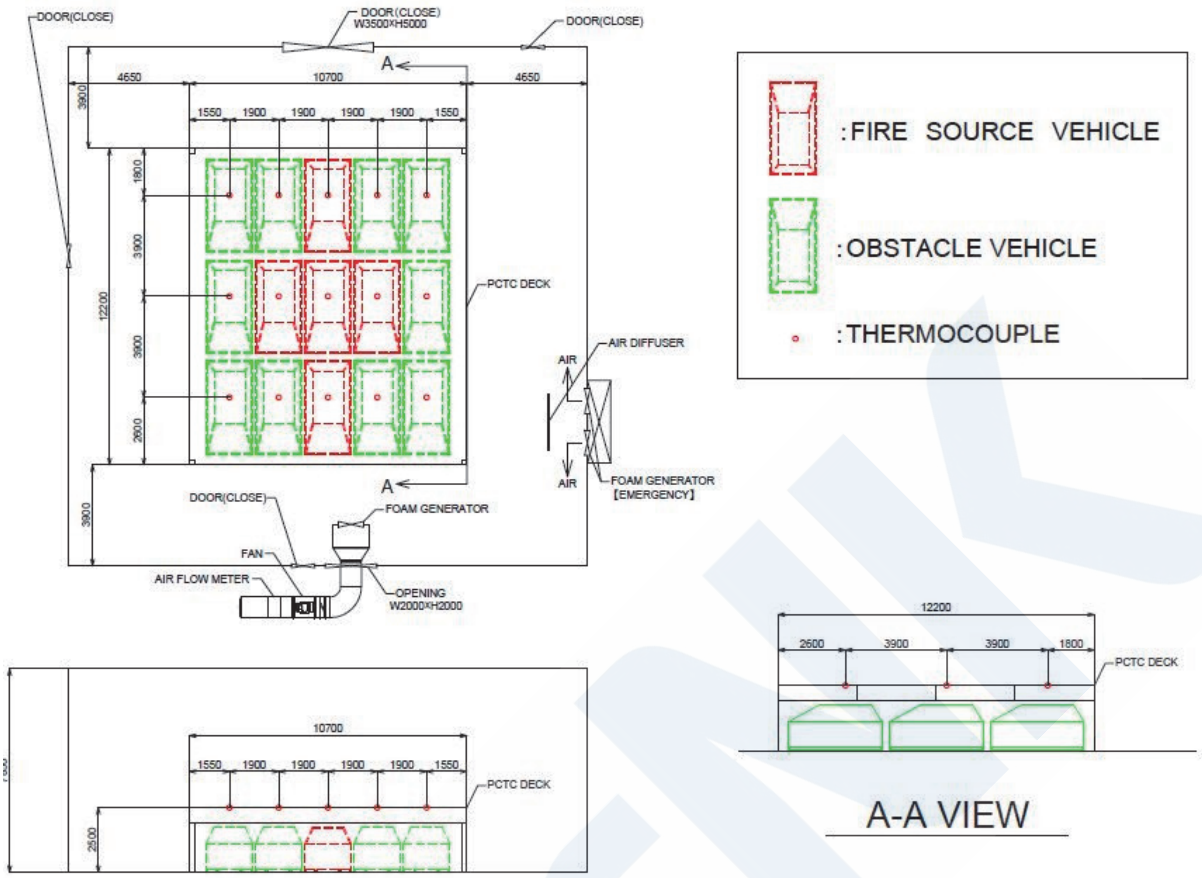

Fig. 12 Planned setup of fire-extinguishing experiment using a test fire assuming multiple vehicles

6. CONCLUSION

The timing of foam discharge in the cargo space where a fire has occurred has a dominant effect on whether fire extinguishing/suppression by high-expansion foam fire extinguishing systems is successful or not. Success, therefore, depends not only on the performance of the high-expansion foam fire-extinguishing system alone, but also on the fire detection capabilities and degree of automation of the ship as a whole. This includes securing the necessary electric power (starting power generators), preparation of ventilation equipment and ensuring operational suitability. Moreover, if all types of safety equipment, including the high-expansion foam fire-extinguishing system, are not adequately maintained and kept in a condition in which operation can start quickly, fire-extinguishing/suppression should not be expected. The author hopes that the results of the various research presented here will be utilized to enhance the fire safety of PCTCs in the future.

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Rational Estimation Method for Internal Pressure Due to Dry Bulk Cargo during Vertical Acceleration

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1. INTRODUCTION

In the transportation of dry bulk cargos such as iron ore powder, nickel ore, etc., not only the external pressure of waves, but also the internal pressure of the cargo caused by ship acceleration accompanying ship movement act on the hull. Due to friction between particles, dry bulk cargos have shear friction resistance and display complex behaviors. Unlike shipping containers and other solid cargos, dry bulk cargos show fluidity, but a change in the structural response has been suggested, in that the strain of double-bottom frame members in past measurements of actual ships was smaller than when dry bulk cargos were regarded as a liquid cargo [1].

The ClassNK *Rules for the Survey and Construction of Steel Ships*, *Part C* [1] specifies the loads acting on dry bulk cargos during vertical acceleration as shown in the following formulae (1) and (2) (Fig. 1). Formulae (1) and (2) were established based on estimation formulae for loads associated with liquid cargos, considering friction between particles and the inner surface of the hull. Although the results of past measurements of actual ships [2] and the results of model tests [3-5] suggested that the friction of the particles contributes to internal pressure by dry bulk cargos, rules were specified on the safe side in view of the remaining uncertainties concerning the mechanism and effects.

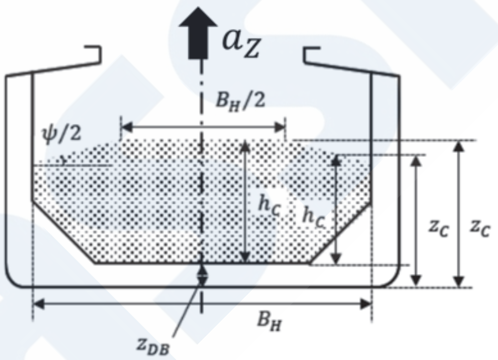


Fig. 1 Bulk cargo carrier [1]

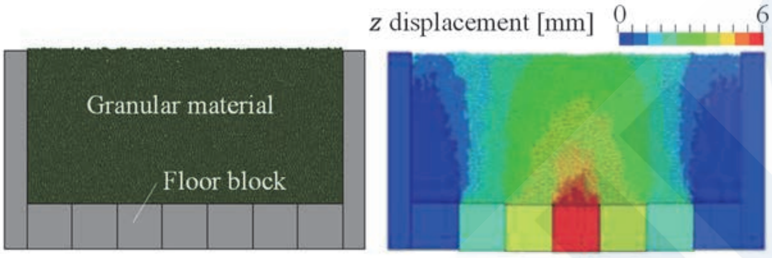
$$P = K_c \rho_c (g + a_z) h_c \qquad (1)$$

$$K_c = \cos^2\alpha + (1 - \sin\psi)\sin^2\alpha \qquad (2)$$

P: Pressure acting on a cargo hold loaded with dry bulk cargo,
K_c: Coefficient of static earth pressure,
ρ_c: Density of the dry bulk cargo (t/m^3),
g: Acceleration of gravity (m/s^2),
a_z: Vertical acceleration of ship (m/s^2),
h_c: Cargo loading height (m),
α: Inclination angle to the horizontal of the panel under consideration,
ψ: Angle of repose of the dry bulk cargo.

Based on the background outlined above, the Society conducted research on pressure due to dry bulk cargos. According to the research by the Society to date, it was suggested [9] that changes in the structural response are caused by a redistribution of loads called the “arching effect [6-8].” The arching effect is a phenomenon that is known in the civil engineering field.

As shown in Fig. 2 (a) (trapdoor experiment), the arching effect is a phenomenon that occurs on the descent of part of the region (called the “floor block” in the figure) supporting a dry bulk cargo, and an arch of particles is formed and the load is redistributed along that arch. The arching effect occurs by the following process: First, when the floor block descends, the particles in the area near the floor block located above the descending floor block also descend with the floor block, as shown in Fig. 2 (b), but more distant particles from the floor remain at the same height, without following the descending floor. The particles that do not descend form a particle arch, which is supported by the action of interparticle friction, and as a result, the load is redistributed toward the roots of the arch.



(a) Trapdoor apparatus (b) Contour of descent

Fig. 2 Arching effect in trapdoor experiment

However, because the arching effect in ships is different from that in civil engineering in the following respects, the Society carried out a basic experimental study and a study by numerical analysis.

(1) It is necessary to consider the interaction of changes in the deflection of a ship’s bottom plates accompanying ship motion and redistribution of the load by the arching effect.

(2) Ships are affected by repeated disturbances due to ship motion.

(3) The arching effect in a ship does not occurs in ground having an infinite extension, but rather, in a cargo loaded in the cargo holds, and thus is affected by the ship’s construction, including the double bottom structure, ship sides, etc.

This article reports the concept of an oscillation test using an elastic bottom plate, and a preliminary study by DEM-FEM coupled analysis carried out prior to the test.

2. APPROACH

As the approach of this paper, the principle of the numerical analysis and the experimental study will be explained.

2.1 DEM-FEM Coupled Analysis

As noted above, in order to study the arching effect that occurs in dry bulk cargos in a ship’s hold, it is necessary to perform a coupled analysis considering the interaction of the cargo and the ship. In this paper, we used a DEM-FEM coupled analysis in which the behavior of the material (i.e., cargo) particles is obtained by the discrete element method (DEM), and the deformation of the vessel is solved by the finite element method (FEM). The general-purpose software LS-DYNA was used in this analysis.

In DEM [10], the cargo particles are expressed by discrete elements in the form of rigid spheres, and an equation of motion is solved using the contact force between particles as an external force. The contact in the normal and tangential directions is formulated by a spring-dashpot model, and the contact force is calculated from the contraction of the spring, which corresponds to the contact between the elements. For the tangential direction, the frictional force based on Coulomb friction is used.

A bidirectional coupled analysis of the discrete elements and finite elements can be carried out by deformation of the finite elements by the load received from the discrete elements, followed by transmission of the contact force to the discrete elements in the next step.

Table 1 shows the values of the particle parameters used here. In a preliminary analysis [11], an angle of repose of 30.3° was measured as the angle at which the particles begin to move when a container filled with particles is inclined. In an analysis simulating the triaxial compression test, the internal friction angle was 20.0° and cohesion was 5.0 kPa.

Table 1 Physical properties of particles

Property	Value
Coefficient of friction between discrete elements	0.25
Coefficient of friction between discrete elements and shells	0.25
Radius of discrete elements (mm)	3.0
Young's modulus of discrete elements (MPa)	71600
Poisson's ratio of discrete elements	0.23
Density of discrete elements (t/mm^3)	7.6×10^{-9}

2.2 Experimental Study

2.2.1 Oscillation Apparatus

As joint research with the Institute of Industrial Science (IIS), the University of Tokyo, an oscillation experiment using an elastic bottom plate was carried out to evaluate the arching effect with respect to vertical motion. This paper introduces the concept of the test apparatus. A duralumin plate with a thickness of 1.0 mm was used as the bottom plate to enable adequate deflection while avoiding plastic deformation during oscillation. So as not to impede the deformation of the bottom plate, the bottom plate deformation was measured by using a sheet-type electromagnetic pressure sensor having a 40.0 mm square pressure-receiving surface area and a thickness of 0.45 mm.

Although earth pressure gauges or load cells are frequently used in conventional earth pressure measurements, there was concern that those devices might affect the deformation of the bottom plate. The sheet-type sensor was considered appropriate for use in this test apparatus, as it is lightweight and thin, and the sensor itself can deform together with the bottom plate.

Since there are very few examples of measurement of earth pressure during vertical motion with an elastic bottom plate, the trapdoor experiment described in section 2.2.2 was performed prior to the experiment with the above-mentioned apparatus.

2.2.2 Trapdoor Experiment

Because studies of the arching effect in the civil engineering field are normally carried out by discrete dropping of the bottom plate, continuous descent of the bottom plate, like the motion that occurs during deflection of the inner bottom plate of a ship, has not been studied. Therefore, prior to the oscillation test using the above-mentioned apparatus, the effect of the descent shape on the arching effect was examined using a trapdoor test device.

The trapdoor experiment was conducted at the Institute of Industrial Science, the University of Tokyo. Because this paper will only present an outline of the test, the reader should refer to Hirano et al. (2023) [12] for details.

The test setup is shown in Fig. 3. Rigid aluminum blocks are arranged at the bottom of the device and are lowered by motor drive. The amount of descent of the respective blocks is 6.0 mm in the center (Fig. 4, Nos. 11-15), 4.0 mm in the two adjoining areas (Fig. 4, Nos. 6-10 and 16-20) and 2.0 mm at the two edges (Fig. 4, Nos. 1-5 and 21-25). The load was measured using load cells arranged under the blocks.

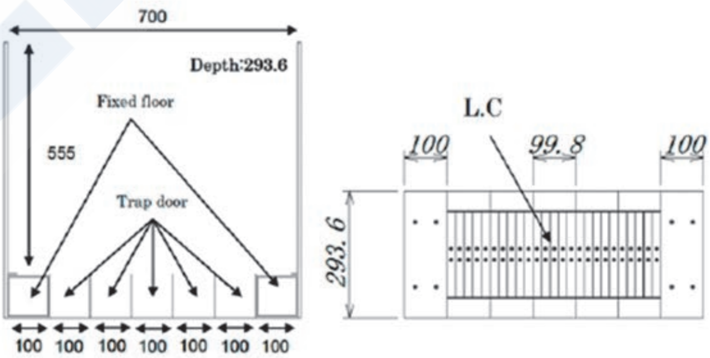


Fig. 3 Setup of trapdoor experiment [11]

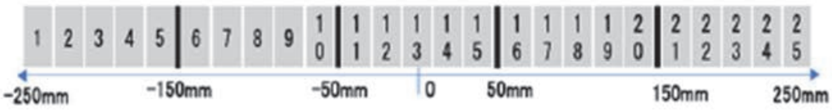


Fig. 4　Load evaluation points in trapdoor experiment [11)]

Fig. 5 shows the time history of load changes with respect to the descent of the center block. In the central area, the load decreases rapidly corresponding to block descent. In the two adjoining blocks, the load increases until descent of around 2.0 mm, but then begins to decrease, and the load at the two edges increases gradually. As shown in the load distribution in Fig. 6, no difference in the load due to displacement can be seen in the initial stage, but after descent, the arching effect can be seen, and it was found that the distribution profile depends on the final state. In addition, a condition in which the load increases near the block boundary could also be seen.

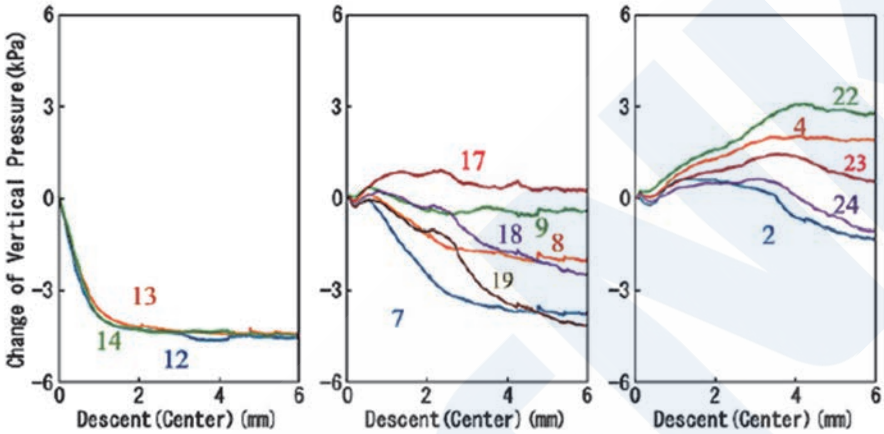


Fig. 5　Time history of load in trapdoor experiment (Case C) [12)]

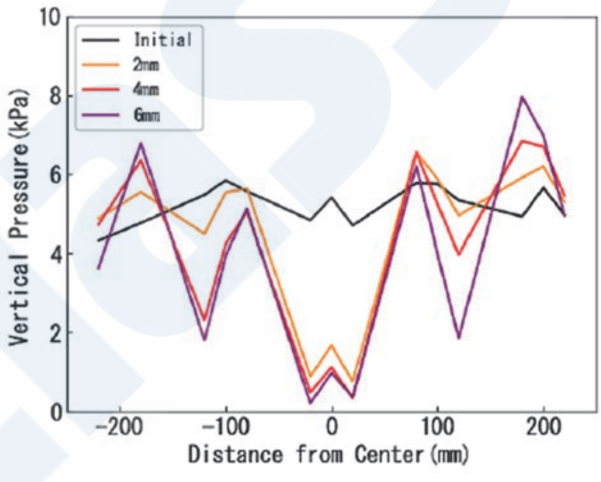


Fig. 6　Load distribution in trapdoor experiment (Case C) [12)]

In addition to the above study, the factors in the arch forming conditions were also investigated. When the cargo loading height h_c was changed in order to investigate the relationship between the cargo loading height h_c and breadth B, an arch was formed when $hc/B \geq 0.40$. With small grain diameters, it was suggested that an arch with a wide breadth is formed by very slight displacement. In addition, the pressure measured by the load cells and the sheet-type sensor were compared, and no large differences between the two were observed. Therefore, we plan to conduct ongoing research on measurement of dynamic response using the oscillation test.

3. DEM-FEM COUPLED ANALYSIS

A condition similar to the deformation of a ship inner bottom plate could be confirmed in the trapdoor experiment described above, although a discrete dropping condition was used in that experiment. An arch also formed above the descending blocks in a separate DEM analysis simulating the trapdoor experiment, confirming that redistribution of the load occurs. This chapter introduces the results of a verification of the arching effect with the elastic bottom plate in which a DEM-FEM coupled analysis was used.

3.1 Arching Effect in Elastic Bottom Plate

With the trapdoor experiment apparatus, an arch is formed when the rigid blocks are forcibly displaced. In a ship, on the other hand, deformation of the bottom plate occurs due to loading from the cargo accompanying ship motion. To consider this interaction, a DEM-FEM coupled analysis was carried out using a vessel with an elastic bottom plate. Because this paper is limited to an outline, please refer to Yanagimoto et al. (2022) [9] for details.

The analysis model is shown in Fig. 7. Because this is a quasi two-dimensional model in which a very short length of the hold was extracted, rigid walls were provided fore and aft as boundary conditions for continuity, and the friction coefficient between the fore and aft walls and particles was set at 0. The walls were assumed to be rigid bodies, and the inner bottom plate was modeled as an elastic body.

First, after self-weight was loaded and the model stabilized, acceleration a_z in the vertical upward direction was applied to the rigid part of the vessel, causing motion in one direction. a_z was set at 0.3 times the acceleration of gravity g.

Fig. 7 Load evaluation points of bottom plate [9]

The load distribution is shown in Fig. 8. In this figure, the load is calculated as the force ratio, that is, the pressure in the region being evaluated to the average pressure of the entire bottom plate. In the case of the highest arching effect, the average value of the force ratio acting on the bottom plate was 0.85 times at the vessel center (Fig. 8, ⑤⑥), which forms the inner side of the arch, while a force ratio of 1.2 times acted at the ends of the arch (Fig. 8, ①⑩).

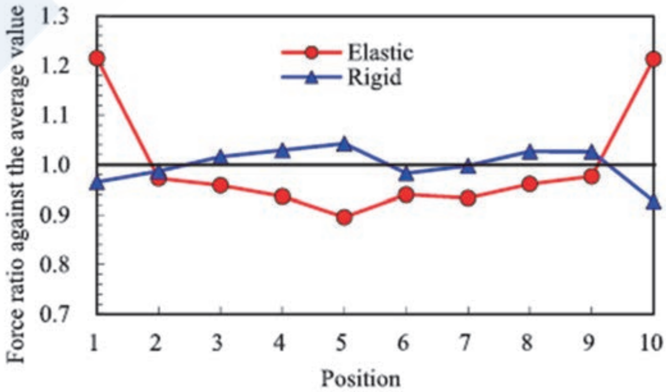


Fig. 8 Load distribution in bottom plate [9]

The ratio of the cargo loading height h_c and vessel breadth B also showed a tendency close to that of the trapdoor experiment in section 2.2.2, as an arch formed when $h_c/B \geq 0.33$. As h_c/B decreases, the arching effect becomes smaller. It was also found that there were no differences when the cargo particle radius was 1.5, 2.0 or 3.0 mm, and the Young's modulus and Poisson's ratio of the bottom plate had no effect on the arching effect.

3.2 Effect of Nonuniform Rigidity of Bottom Plate

In the trapdoor experiment, an arch was formed due to discrete deformation by the rigid blocks, and concentration of the load to the areas near the fixed block boundary could be seen. On the other hand, load concentration in the inner side of the arch was not observed in the elastic bottom plate model in section 3.1. Although a simplified bottom plate had been used in section 3.1, actual ship bottom plates display complex deformation, which includes not only the overall deformation of the total breadth region of the hold, but also superimposed local deformation between girders. Therefore, in this chapter, the influence of the arching effect caused by local deformation on the arching effect due to overall deformation was investigated.

Fig. 9 shows the analysis model, in which elastic shell elements simulating a double bottom and girders were added to the inner bottom plate. Here, a_z was increased monotonously up to 0.15 times the acceleration of gravity g (a_z=0.15 g). The particle parameters and other conditions were the same as those in section 3.1.

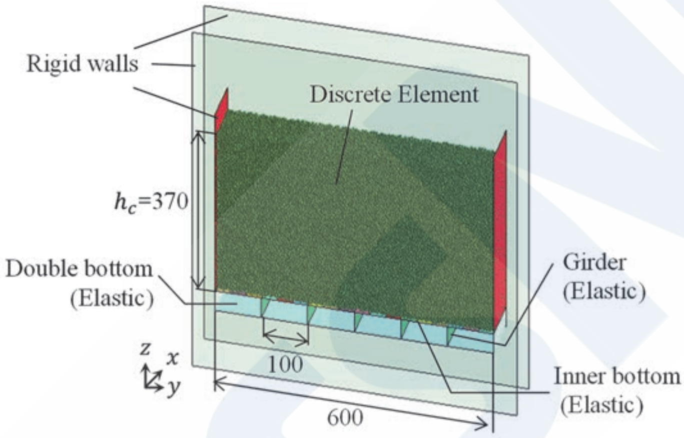


Fig. 9 Model with girders

The analysis results are presented in the following. Fig. 10 shows the contour of force chain at a_z=0.15 g. "Force chain" refers to a visualization technique which shows the force in the direction of principal stress acting on a particle obtained from the contact force with surrounding elements [13]. A large force chain means there is continuity in the magnitude and the direction of principal stress to nearby particles. From Fig. 10, it can be understood that an arch having the same span as the breadth of the ship's hold is formed, and small arches straddling the girders are also formed on the inner side of the arch spanning the hold breadth.

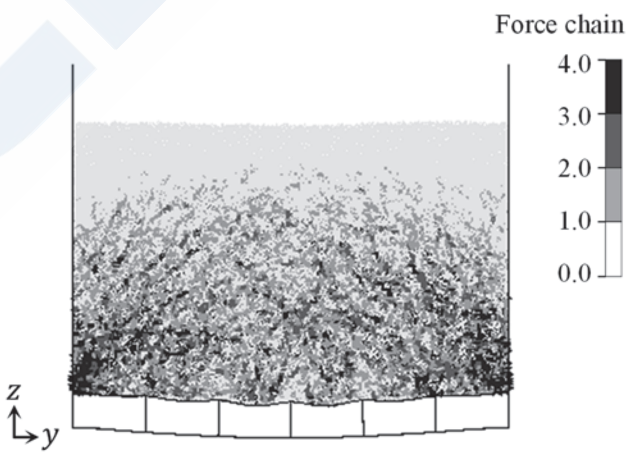


Fig. 10 Contour of force chain

As shown in Fig. 11, deflection occurred in the shape of superimposed overall deformation and local deformation. At the midpoints between girders, the increment of deflection due to dynamic loads is small, and it is thought that local arches were formed with the midpoints as the roots of the arches. In the load distribution in Fig. 12, the loads are concentrated at the midpoints between the girders, which are thought to be the positions of the roots of the local arches, rather than directly above the girders. This is consistent with an estimation based on the force chain and the deflection of the bottom plate.

In addition, in the load distribution in Fig. 12, it is suggested that the effects of the load distribution by the total arch and the distribution by the local arches are superimposed. Thus, it can be conjectured that arching effects occur and are manifested in a superimposed state, even in complex shapes like those of actual ship structures.

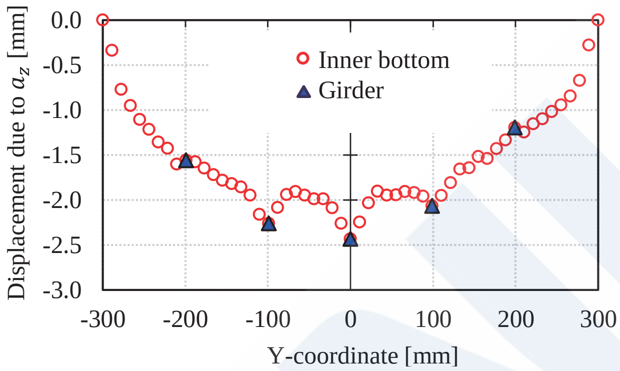


Fig. 11 Increment of deflection caused by vertical acceleration a_z

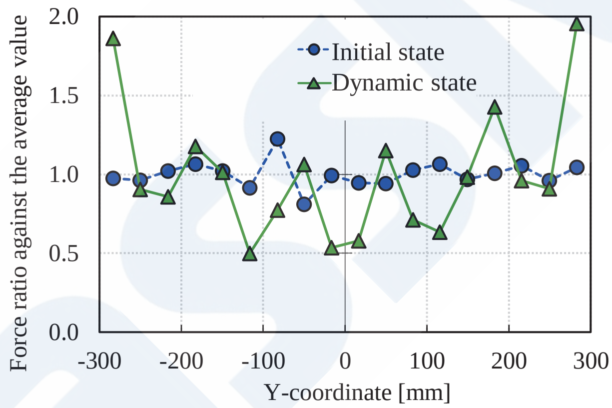


Fig. 12 Load distribution

3.3 Effect of Aspect Ratio of Bottom Plate in 3-Dimensional Vessel

Up to the previous section, this paper has introduced the results of an evaluation of the arching effect in the 2-dimensional state when a section with a very short length was extracted. However, longitudinal deflection also occurs in actual inner bottom plates. This suggests the possibility that the arch is formed not only in the transverse direction, but also in the longitudinal direction, which may influence the load distribution. Therefore, the arching effect caused by 3-dimensional deformation of the bottom plate was investigated using the vessel shown in Fig. 13.

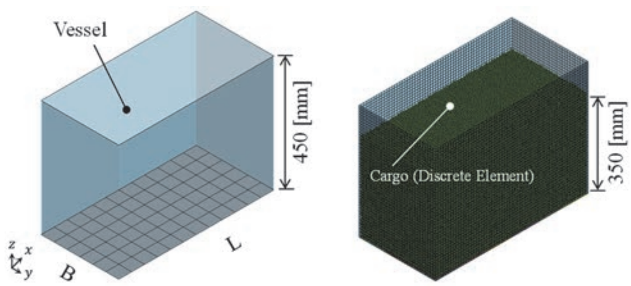


Fig. 13 3-dimensional model

Based on the fact that the ratio of the cargo loading height h_c and vessel breadth B contributes to the conditions for arch formation and arch descent, the relationship between the aspect ratio of the bottom plate and the load distribution is evaluated when the ratio of the length of the vessel bottom plate L and the bottom plate aspect ratio L/B was varied from 1.0 to 2.0, as shown in Fig. 14. As excitation, unidirectional vertical acceleration increasing monotonously up to a_z=0.3 g was applied. The side walls were modeled using rigid shell elements, and the bottom plate was modeled using elastic shell elements.

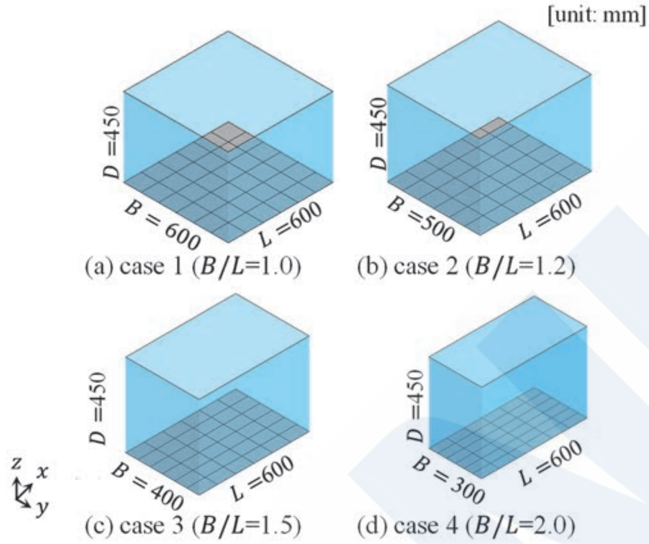


Fig. 14　FE models of cases examined

As the distribution of the dynamic loads in Cases 1 to 4 with different vessel bottom plate aspect ratios L/B at a_z=0.3 g, Fig. 15 shows the distribution in the vessel longitudinal L direction, and Fig. 16 shows the distribution in the vessel transverse B direction. In all cases, the distribution has been normalized by the average values.

In the longitudinal distributions shown in Fig. 15, the load at the center is lower than the average value in all cases. At the edges, the load in Case 1 (square bottom plate) is larger than the average value, while in the other cases, the load is close to the average.

In the transverse distributions shown in Fig. 16, the load at the center is lower than the average value in all cases. At the edges, however, the load is larger than the average value, indicating that the load is concentrated at the edges. In Case 1 with the square bottom plate, the load is approximately the same in the transverse direction, but in the other cases (Cases 2-4), in which the aspect ratio exceeds 1.0, larger loads act in the transverse direction. In addition, the load concentration at the transverse edges increases as the aspect ratio L/B becomes larger, that is, as the bottom plate becomes longer and narrower.

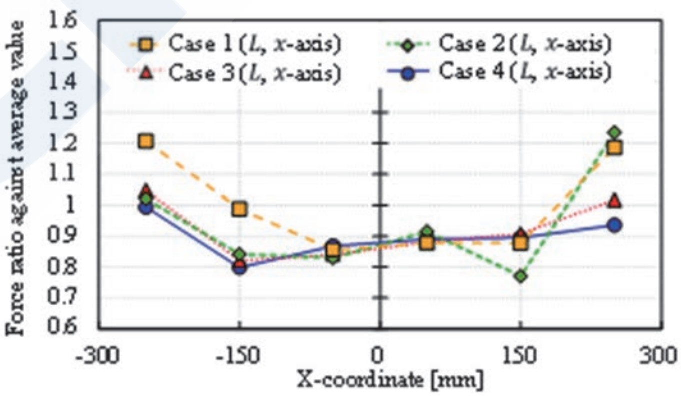


Fig. 15　Load distributions in vessel longitudinal L direction in Cases 1 to 4 with different vessel bottom plate aspect ratios L/B (a_z=0.3 g)

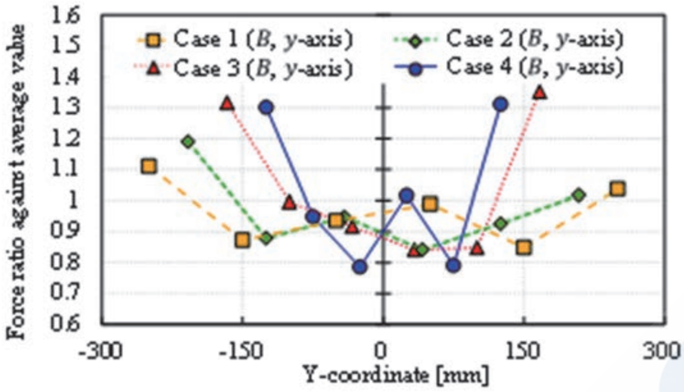


Fig. 16 Load distributions in vessel transverse *B* direction in Cases 1 to 4 with different vessel bottom plate aspect ratios *L*/*B* (a_z=0.3 *g*)

The cause of the differences in the strength of the arching effect depending on the aspect ratio is considered as follows: A schematic diagram of the arch structure is shown in Fig. 17. When an arch supports a load, in addition to a vertical reaction force, a horizontal reaction force *H* also occurs at the two ends of the arch [14, 15].

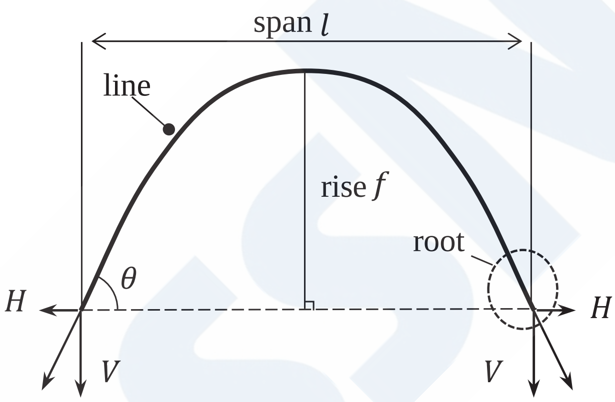


Fig. 17 Arch structure

This horizontal reaction force is supported by the side walls or the particles on the outer side of the arch. Fig. 19 shows the results of an investigation of the pressures ($p_L^{lateral}$: lateral pressure on sidewall at root of arch in lengthwise direction, $p_B^{lateral}$: lateral pressure on sidewall at root of arch in breadthwise direction, $p_L^{vertical}$: vertical pressure on bottom plate at arch root in lengthwise direction, $p_B^{vertical}$: vertical pressure on bottom plate at arch root in breadthwise direction) when a_z=0.3 *g* in the region shown in Fig. 18. According to Fig. 19, the lateral pressure is roughly the same in both directions, independent of the aspect ratio, but as the aspect ratio becomes larger, the loads positioned on the roots of the arch in the direction of the short side become larger. This appears to occur because, assuming the same horizontal reaction force acts, the longitudinal arch, which has a smaller arch breadth relative to the arch length, largely supports the vertical reaction force. This tendency is the same as the tendency of the result that, at the same h_c, a small vessel breadth displayed a stronger arching effect in an experiment using a trapdoor model in previous research [8].

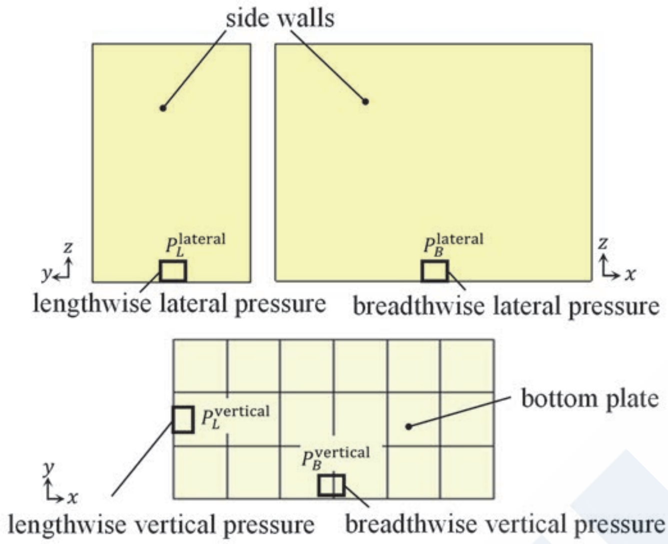


Fig. 18　Load measurement regions of sidewall and bottom plate

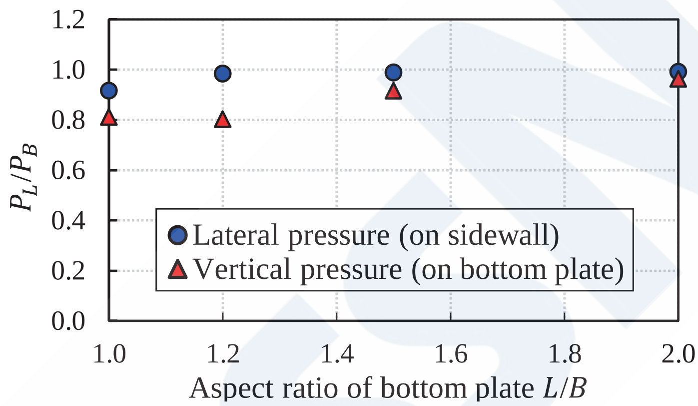


Fig. 19　Relationship of bottom plate aspect ratio and ratio of loads in short and long side directions

4.　CONCLUSION AND FUTURE OUTLOOK

Although it had been pointed out that dry bulk cargos generate smaller loads that those caused by liquid cargos under the same vertical acceleration of a ship, the mechanism had not been clarified. Therefore, the Society carried out research to elucidate this issue.

Based on a survey of the literature and the results of analyses in previous research, the difference between dry bulk cargos and liquids was considered to be due to the arching effect that occurs in dry bulk cargos. Since the interaction of the motion of the cargo particles and deformation of the ship's bottom plate should be taken into account, an evaluation was conducted by an oscillation experiment using a vessel with an elastic bottom plate and DEM-FEM coupled analysis. This paper has introduced those studies, which were carried out as the first steps toward solving this practical problem.

The studies described in this paper clarified the facts that the ratio of the cargo loading height and the vessel breadth has an influence on the arching effect, the arching effects due to local deformation and overall deformation are superimposed in the case of a bottom plate with nonuniform rigidity, and the aspect ratio of the bottom plate also has an effect.

Because more rational structural design is expected to be possible by considering the arching effect, the authors plan to conduct model tests in connection with dynamic response and study the conditions for arch formation and collapse on a continuing basis, with the aim of providing feedback to the Society's *Rules for the Survey and Construction of Steel Ships*.

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Quality Control in the Development Process of AI System on Ships

Hideki MIYAJIMA*

1. INTRODUCTION

Recently, the development of AI systems has advanced in the maritime industry. For example, a situation awareness support system [1) 2) 3)] using image recognition technology has been developed, and research and demonstration experiments [4) 5) 6)] on autonomous navigation AI that performs collision avoidance and automated berthing and unberthing have been carried out. At present, AI is mainly used to support seafarers or is in the research stage, but in the future, it is considered that AI systems installed on ships will be utilized in a way that is directly connected to safety.

This type of AI uses machine learning technology that learns patterns and rules from data. In addition, deep learning, which has attracted much attention recently, has shown high performance by learning complex models with large amounts of data. However, such AI has black box problem, and it is difficult for humans to understand how an AI system arrives at its conclusions. Also, AI system may output results that were not intended by the developer.

When considering AI systems from a quality assurance perspective, it is not easy to evaluate whether AI can perform as expected because AI with a mechanism in which its behavior is determined inductively by learning based on data. Furthermore, continuous learning is carried out in many cases so that the AI can follow changes in the surrounding situation even after development. Therefore, development considering the life cycle from design to operation is required. In the development of AI systems, it is important that activities to ensure quality, which varies depending on the purpose and use, are carried out throughout the development process. Considering such appropriate activities will lead to consideration of specific evaluation methods for AI systems.

Based on the development process and the importance of ensuring quality of AI systems, in order to ensure that AI systems developed under appropriate quality control are used in the maritime industry, Nippon Kaiji Kyokai (ClassNK, hereinafter, the Society) plan to develop "Technical Guide for Utilizing AI System on Ships -Quality Control in the Development Process of AI System-." The items that AI system developers should consider during development will be described in this Guide. Therefore, as an introduction to this Guide, this paper presents an overview of AI and describes an approach for integrated development and operation. In addition, as an information that will be helpful when organizing the development process of AI systems in the maritime industry in the future, this paper introduces the development process organized in "Machine Learning Quality Management Guideline."

2. ARTIFICIAL INTELLIGENCE

2.1 What Is AI?

The term AI was proposed at the Dartmouth Conference in 1956, and various studies have been conducted since then. Although various discussions have considered the definition of AI, there is no established definition, and it is understood as a broad concept such as "Programs that works in a manner similar to human thought processes, or information processing and technology that humans perceive as intelligent." [7)]

Although AI includes various technologies such as exploration and inference algorithms and expert systems, the center of the recent AI boom is machine learning. Machine learning is one of the methods for analyzing data, in which a mechanism corresponding to human learning is realized by computers. Based on the calculation method (algorithm), the computer can discover patterns and rules from input data (training data), and by applying those patterns and rules to new data, it is possible to identify and predict new data.

Deep learning is one of the methods of machine learning, and has attracted special attention as the method that triggered the

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recent AI boom. Deep learning uses a neural network that emulates the mechanism of nerve cells in the human brain, and a feature of deep learning is that it has a multi-layered structure of that neural network.

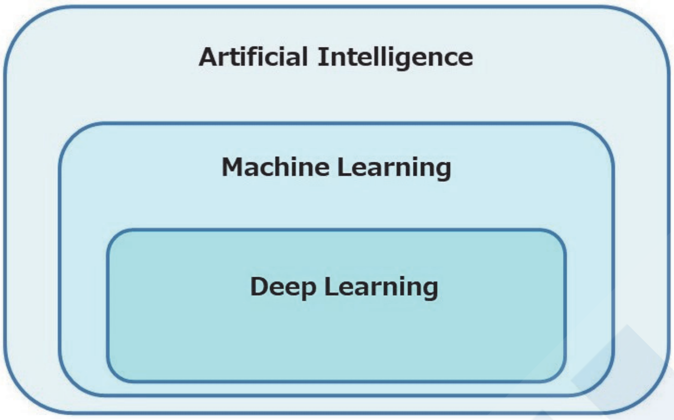

Fig. 1 Relationship between AI, machine learning and deep learning [7)]

2.2 Deep Learning

The neural network of deep learning consists of an input layer, an intermediate layer and an output layer. Features are extracted from the input data through calculations within the neural network, and the results of processing are output. The parameters for performing calculations of the neural network are optimized based on the data, and this process is called learning.

Deep learning achieves more accurate results than conventional methods in various fields by adopting a multi-layered network and learning with a large amount of data. There are various types of network structures, such as Convolutional Neural Networks (CNN) specialized in image recognition, Recurrent Neural Networks (RNN) used in processing time series data, text data, *etc*., generative AI which generates new data from a given data set, and so on, which are used depending on the purpose.

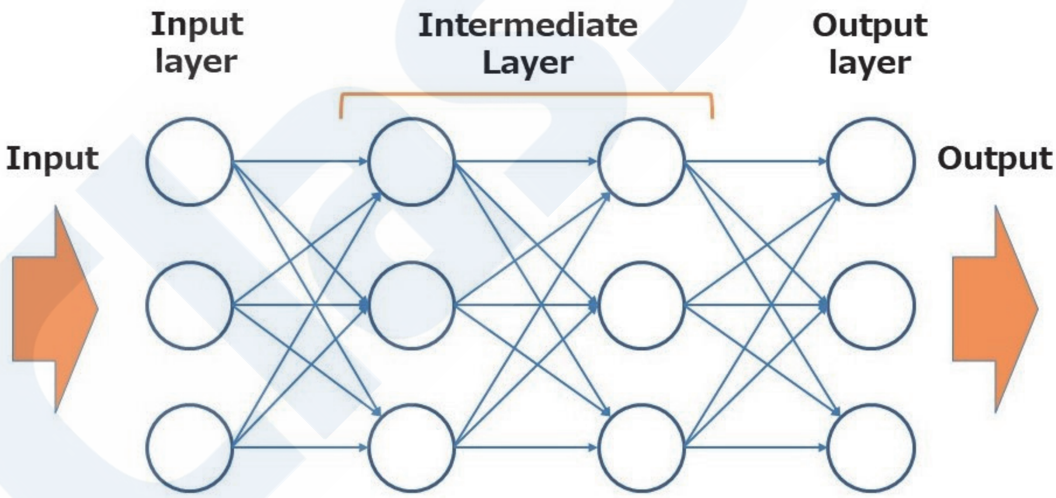

Fig. 2 Deep learning mechanism [8)]

2.3 Challenges of AI

AI based on machine learning can make predictions with high accuracy and is applied to a wide range of fields such as natural language processing, speech recognition, image recognition and content generation. On the other hand, since AI is learning based on a large amount of data and basically makes inferences probabilistically, it is necessary to deal with the following problems specific to AI.

2.3.1 Quality and Quantity of Data

Since AI learns based on data, the quality and quantity of the data are important for achieving the expected performance. For example, AI may not be expected to be accurate enough when past patterns do not apply to the data, the factors that serve as judgment criteria are not included in the data or the amount of data is small. Imbalanced data may also introduce errors in the inference results that the model outputs. Therefore, it is necessary to ensure that the data are adequate in terms of both quality and quantity. When developing an AI system, it is important to thoroughly analyze the problem to be solved, clarify the purpose, use environment and conditions, and then consider the quality and quantity of the data.

2.3.2 Computing Resources and Costs

Extensive data acquisition and annotation are extremely time-consuming. Large storage is also required to store and efficiently use big data. In addition, since a large amount of computational resources is required to train AI models, especially deep learning models, the time required for training must also be considered. Therefore, it is necessary to prepare a sufficient development system and environment.

2.3.3 Drift [9)]

In machine learning, a phenomenon called "drift" occurs in which the accuracy of predictions by the AI model decays over time. There are two main types of drift. With data drift, there is a discrepancy in the distribution of the data during training and the data during operation, such as seasonal changes and changes in trends. Conceptual drift refers to drift in which the relationship between the input data and the correct labels changes compared to when the model was trained, for example, when a new data feature appears. To deal with such drift, even after the development of AI systems, it is necessary to monitor changes in performance and the operating environment and to retrain the AI model periodically.

2.3.4 Probabilistic Behavior

AI basically makes probabilistic inferences but does not make decisions. It is also important to note that a phenomenon called "hallucination" [10)] occurs in generative AI, where AI generates information that is not based on reality. When developing an AI system, it is important to carry out activities to ensure that stakeholders fully understand these characteristics of AI, and to consider appropriate goals and operational procedures.

2.3.5 Black Box Problem

Machine learning models, especially deep learning, have a large number of parameters and a very complex structure. It is difficult for humans to understand how an AI system arrives at its conclusions, and the content of AI is essentially a black box. Although this kind of AI can perform prediction and recognition with high accuracy, the concern that "a system that cannot explain the basis of outputs cannot be used" may lead to distrust of the AI system, and may become a factor inhibiting its introduction. Therefore, it is important to carry out activities to gain the understanding from stakeholders, verify operational procedures considering the black box problem, and study the use of AI that can be explained rather than black box AI. XAI is attracting attention as a solution.

2.3.6 Difficulty of Evaluation

AI that learns based on data cannot explicitly relate its internal design and implementation to a defined specification, and it is difficult to review the internal design and implementation and evaluate quality. In addition, AI technology is advancing rapidly, and there are also various ways to utilize it. Therefore, it is important to clarify the objectives to be achieved in the whole system and the elements required in the AI system, and to consider the evaluation method according to the target AI system.

2.3.7 Differences in Risk by Utilization Method

The extent to which AI risks need to be considered varies greatly depending on how the AI system is used. For example, AI system is used in daily life, for example, in translation, chatbots and speech recognition, may have no risks which are paid attention. On the other hand, in the case of AI systems that are directly linked to safety, such as autonomous driving and autonomous ship navigation, safety and reliability should be carefully considered.

The AI Act, which is a European regulation on AI that was proposed by the European Commission on April 21, 2021, adopts a risk-based approach, establishing 4 risk levels and prescribing requirements and regulations according to each risk [11)]. This approach is useful for developing AI systems. It is important to grasp the risks of AI systems through risk assessment and to ensure safety by taking appropriate control measures.

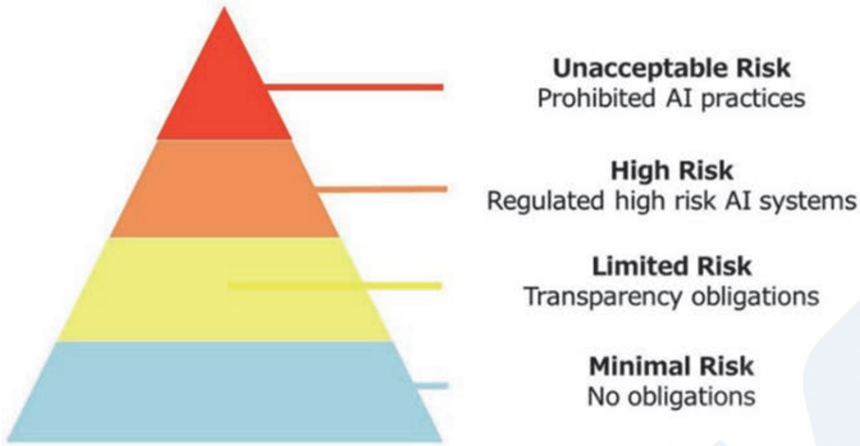

Fig. 3　Pyramid of risks in EU AI Act [12)]

2.3.8　Security [13)]

When developing AI systems, in addition to the conventional IT and system security viewpoints, it is also necessary to consider attacks targeting training data and AI models as security problems specific to AI. Attacks on AI models include the following. When developing AI systems, it is necessary to carry out a risk assessment and take countermeasures against attacks.

・Poisoning Attack

A type of attack in which the training data or AI model is manipulated in some way to cause the system to output results not intended by the AI model developer.

・Evasion Attack

Addition of noise to inference data can lead to incorrect inferences by AI models. When the added noise is small, a human may not be able to distinguish the difference from the original data. A kind of attack to discover such small noise is called an "evasion attack," and data with small added noise is called an "adversarial example."

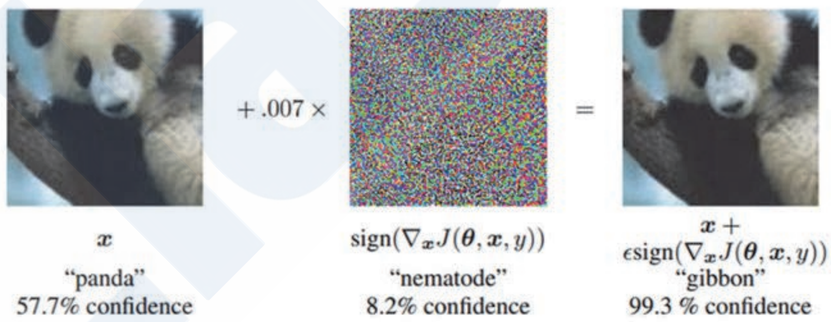

Fig. 4　Example of an adversarial example of a panda recognized as a gibbon [14)]

When developing AI systems, it is necessary to address these challenges through activities in the development process.

3.　APPROACH FOR INTEGRATED DEVELOPMENT AND OPERATION

In general, AI systems are developed by repeatedly learning and evaluating models based on data to achieve the expected performance. The performance of the developed AI system is also monitored even after it is introduced into the real environment, and continuous evaluation and learning are performed to cope with changes in data trends caused by changes in the surrounding environment such as drift, and to improve accuracy using newly acquired data. Therefore, in the development of AI systems, an approach for integrated development and operation [15) 16)] is often adopted, in which quality is maintained and improved by repeating learning with newly acquired data so that performance approaches the expected result more closely. Considering these points, the Guide will organize the approach of the AI system from the beginning of development to the end of operation as shown in Fig. 5.

Since the actual development flow varies depending on the developer and the system to be developed, a general approach considering various AI systems is shown here. In the development of AI systems, through each phase of such an approach, it is required to carry out the activities necessary to ensure quality while addressing the aforementioned AI-specific challenges. Therefore, the items to be considered during development in each phase will be described in the Guide.

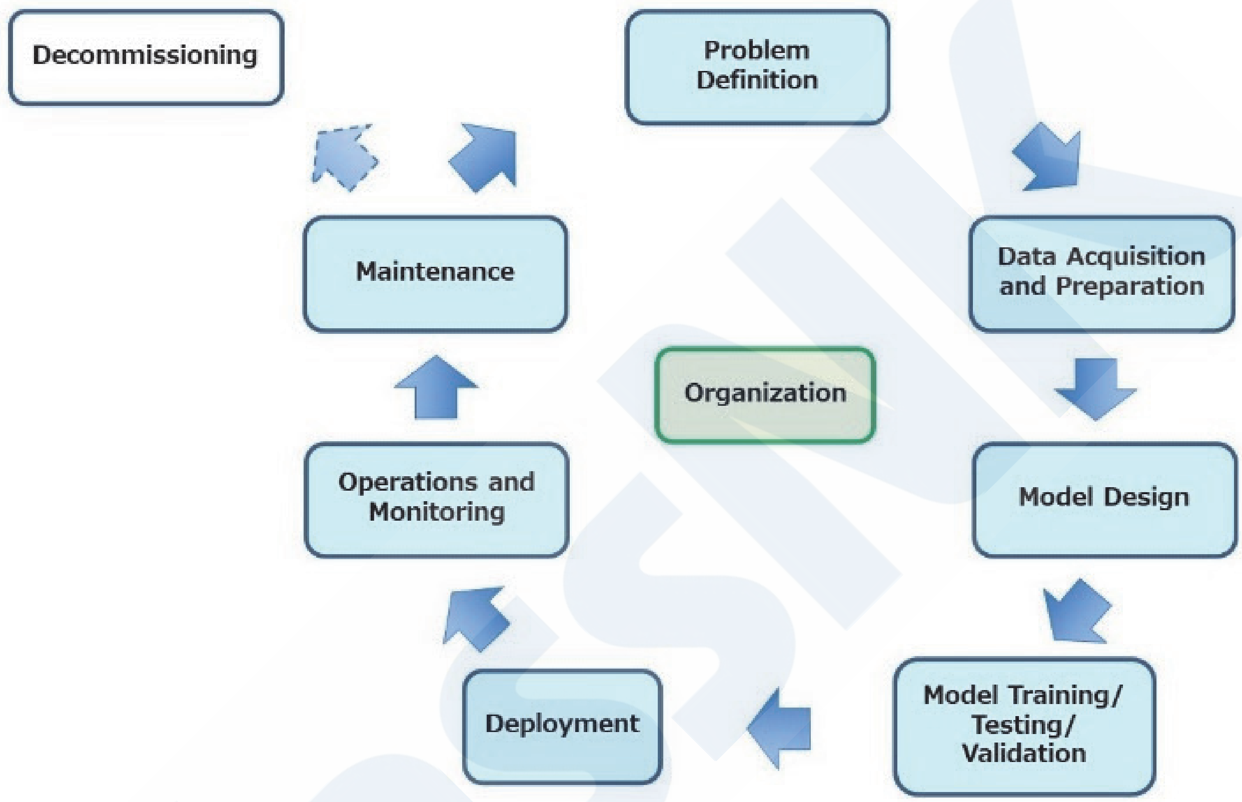

Fig. 5 Approach for integrated development and operation

In the development of an AI system, the development system and the development environment are also important, and since they are related to the whole approach, they are placed at the center of the organization.

0) Organization
   Factors related to the ability of the organization involved in the development and operation necessary for the successful development of the AI system.
1) Problem Definition
   The phase in which the problems to be solved by the AI system are identified and the necessary considerations are made to proceed with the development.
2) Data Acquisition and Preparation
   The phase in which data are acquired and preprocessed for use in training the AI model.
3) Model Design
   The phase in which the overall approach of development is defined and the AI model is designed based on the objectives, requirements and available data defined in the Problem Definition.
4) Model Training/Testing/Validation
   The phase in which the AI model is trained and verified to function as expected.
5) Deployment
   The phase in which the AI system is integrated with existing systems, processes, products and services so as to function

in a real-world environment.

6) Operations and Monitoring
The phase in which the AI system is operated in the real-world environment and is continuously monitored to ensure that the expected performance is being achieved.

7) Maintenance
The phase in which maintenance and system and model updates are performed as needed.

8) Decommissioning
The phase in which the operation results of the AI system are evaluated, and the operation of the AI system is terminated when the AI system is no longer needed or when another effective solution is developed.

4. ORGANIZING THE DEVELOPMENT PROCESS IN THE "MACHINE LEARNING QUALITY MANAGEMENT GUIDELINE"

As mentioned above, the approach for integrated development and operation can be used universally regardless of the target, and it is assumed that quality will be improved by continuously repeating learning. When this approach is applied to AI systems installed on ships, it must be reduced to a form suitable for the development process of the maritime industry. This paper introduces the development process modeled in "Machine Learning Quality Management Guidelines" as an idea which can be used in such cases.

In the development of an AI systems, the quality of the AI system is ensured through the approach which integrates development and operation described above. On the other hand, since AI learning depends on data, it is difficult to predict the deliverables in the early stage of development, and differences in understanding tend to occur between the developer and user. Therefore, PoC (Proof of Concept) is often performed when developing AI systems. PoC is a verification process that shows the feasibility of new concepts and ideas. In addition, even after an AI system is developed and introduced into a real environment, learning using newly acquired data is performed continuously to maintain and improve accuracy.

In the "Machine Learning Quality Management Guidelines" published by Japan's National Institute of Advanced Industrial Science and Technology, the development process of such general AI systems is divided into three stages, as shown in Fig. 6: "Proof of Concept stage," "Iterative development stage" and "DevOps and cont. training stage." it is important in the maritime industry to verify new technologies in advance of introduction and at the completion of development, and to confirm changes after the start of operation. Thus, it can be thought that the development stages described in the Guidelines are highly compatible with the maritime industry.

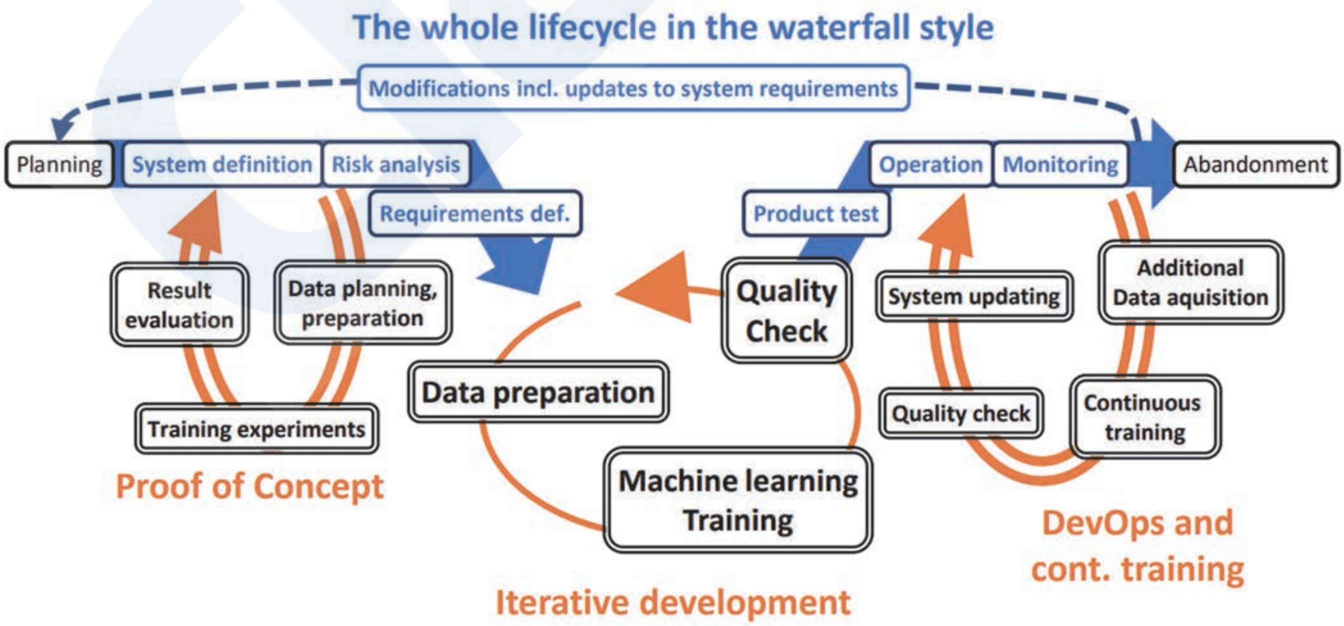

Fig. 6 Development process in "Machine Learning Quality Management Guideline" [15)]

5. CONCLUSION

Regarding "Technical Guide for Utilizing AI System on Ships -Quality Control in the Development Process of AI System-," which is under development, this paper has presented an overview of AI and described an approach for integrated development and operation. As a reference when applying this approach to the development process of the maritime industry, the development process in "Machine Learning Quality Management Guideline" was also introduced. Since the contents of the two guidelines can be used universally regardless of the application of the AI system, it will be necessary to arrange them in a form suitable for the development process in the maritime industry in future.

In the development of AI systems in the maritime industry, there will be cases where "people in the maritime industry develop AI systems" and cases where "companies responsible for AI system development develop AI system for the maritime industry." For the former, it is necessary to understand the AI system development process, and for the latter, it is necessary to understand the development process of the maritime industry. The Guide will strive to provide information that will provide insights in both cases. It is our hope that these contents will contribute to the development of AI systems in the maritime industry.

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Research and Development of Launch Vehicle Recovery Ship and Response to Ship Class Rules

Yuji KADO*

1. PURPOSE AND BACKGROUND

The Japan Aerospace Exploration Agency (JAXA) is studying a “Mainstay Launch Vehicle Development Space Transportation System” (hereinafter, “reusable launch vehicle”), which is being developed aiming at substantial cost reduction, targeting the first launch around 2030, to secure the development and success of Japan’s space development missions. This report presents a brief outline of the status of study of an offshore launch vehicle recovery ship (hereinafter, recovery ship) for recovery of reusable launch vehicles in offshore waters. It should be noted that development of the reusable launch vehicle has only begun, and the specifications, launch site and other matters related to reusable launch vehicle described in the following are proposals which are under study. Likewise, the recovery ship has not been finalized, and is also still in the stage of identification of functional requirements and tradeoffs among multiple types of vessels. This paper was prepared by adding Chapter 5, “Initiatives for Risk Assessment of the Recovery Ship” to a paper contributed to the *Journal of the Japan Institute of Marine Engineering* [1].

2. POSITIONING OF JAPAN’S REUSABLE LAUNCH VEHICLE

2.1 Japan’s “Roadmap for a Space Transportation System”

Space development and utilization, beginning with satellites, is now an indispensable part of the infrastructure that supports the lives of the Japanese people and socioeconomic and security activities, including weather observation, positioning, satellite communications, etc.

Securing the independence of the space transportation system, which is a means of transporting satellites into space, has become the basis of Japan’s space policy as the core infrastructure for accessing outer space.

Based on a recognition of the situation and awareness of the problems in the intensifying competitive environment in the space transportation market of recent years, the Space Utilization Subcommittee of Japan’s Ministry of Education, Culture, Sports, Science and Technology (MEXT) has also decided to realize an innovative future space transportation system which achieves a fundamental cost reduction through technical innovation by the early 2040s, with the aims of securing the independence of Japan’s space transportation system, ensuring its international competitiveness, and encouraging industrial development, and laid out the basic concepts for establishing a phased plan and route (roadmap) for reaching that goal [2]. Based on that thinking, MEXT established a Roadmap for an Innovative Future Space Transportation System [3] [4].

In the Roadmap, the content concerning reusable launch vehicles is summarized as follows:

• To respond to governmental missions such as security, disaster prevention, deep space exploration, etc., the national government will promote the development of a “mainstay launch vehicle development space transportation system (reusable launch vehicle)” which will achieve a substantial cost reduction (target: approximately 1/2 the cost of the H3 rocket), aiming at the first launch around 2030.

• JAXA will identify the necessary element technologies through a dialogue with private-sector companies, and will acquire the element technologies through joint government-private sector research.

• The government and JAXA will study the specifications of flight test sites and vehicle recovery measures and maintenance methods supporting reuse, assuming that private companies will also use the facilities in tests. Flight test site maintenance and operational data, etc. will also be provided to private companies, and the government will study the necessary response to portions related to institutional issues in cooperation with the organizations concerned.

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2.2 Overall Concept of Reusable Launch Vehicle in JAXA

The overall outline of the operation process in study by JAXA toward realization of a reusable launch vehicle is shown in the following A) to D) (Fig. 1).

A) The reusable launch vehicle is launched from a launch site in Japan. After the first stage separates from the second stage, it decelerates through a process of attitude reversal and inertial flight, and lands on a platform installed on a recovery ship.

B) When the first-stage rocket has landed on the recovery ship, the fuselage of the launch vehicle is fixed stably to the ship by fixing devices installed on the ship. Measures to ensure safety are taken by removing the propellant, oxidant, etc. from the tanks. Because all the tasks from landing to securing safety must be performed without human intervention, the crew will move to a support ship (described in section 2.3) which is standing by near the recovery ship and perform the recovery work by remote operation. After confirming safety, the crew will return to the recovery ship and perform work from shipboard.

C) The recovery ship, with the first-stage secured on board, sails to the quay of a land-based inspection and maintenance facility. After the ship reaches the quay, the first-stage rocket is unloaded by a crane.

D) The first-stage rocket is transferred to the inspection and maintenance site, and the maintenance necessary for reuse is performed. When maintenance has been completed, the first-stage rocket is moved to the launch site, and the launch operation in the above A) is carried out. Thereafter, reuse of the launch vehicle is accomplished by repeating steps A) to D).

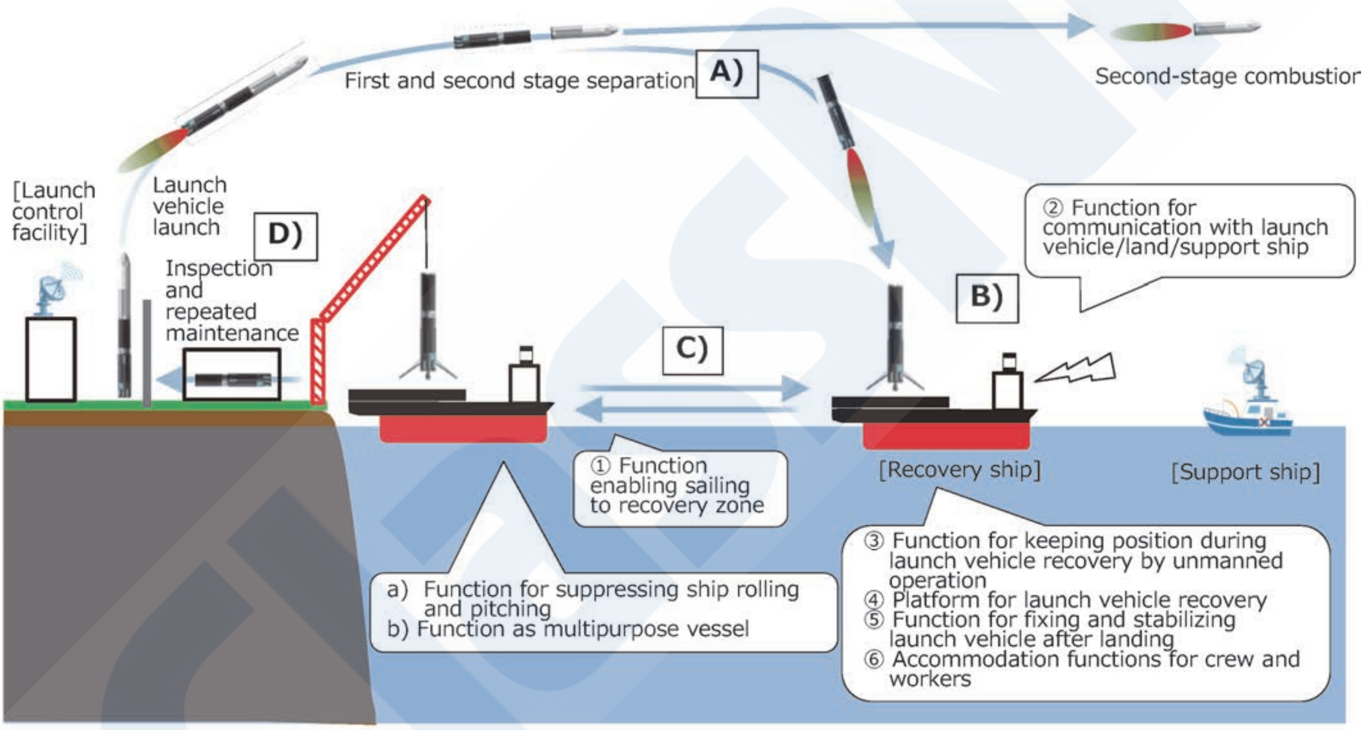

Fig. 1 Offshore recovery process by recovery ship (draft)

2.3 Candidate Recovery Zones

Locations for the reusable launch vehicle launch complex are currently under study. Although there are several candidates, the following are the results of a study assuming JAXA's Tanegashima Space Center is used. Since the Tanegashima Space Center already has equipment and infrastructure for use with the current mainstay launch vehicle, it is expected to be possible to reduce the cost of refitting facilities for use with the reusable launch vehicle by reusing the existing facilities. Moreover, it is also necessary to select the launch vehicle recovery zones considering the safety of Japan and neighboring countries. Assuming hypothetically that geostationary or earth exploration satellites are launched from the Tanegashima Space Center, the probable launch vehicle recovery areas are the waters east to southeast to south of Japan (Fig. 2). In case of earth-orbiting satellites, the candidate area is the waters southwest of Japan.

Considering the safety of the crew in the unlikely event of an explosion or fire, unmanned operation is required in launch vehicle recovery. Therefore, JAXA is studying a proposal to operate by a two-ship system consisting of a recovery ship and a support ship. As the division of roles, it is assumed that the recovery ship will be responsible for recovering the launch vehicle, ensuring safety, and transporting the launch vehicle. The support ship will be used for evacuation of the crew and remote operation of the recovery ship during launch vehicle recovery, and for tracking and control of the launch vehicle.

3. PREVIOUS EXAMPLE OF RECOVERY SHIP AND ISSUES SPECIFIC TO JAPAN

3.1 Previous Example (SpaceX)

The efforts of the American company SpaceX may be mentioned as an example of reusable launch vehicles and recovery ships [6]. The company conducts offshore recovery missions using the Falcon 9 rocket, which is equipped with 9 Merlin engines (Fig. 3), and as of April 2024, it had conducted a series of 271 launches, of which 267 missions were successful (success rate: 98.5%). Offshore recovery is performed by using a ship called an Autonomous Spaceport Drone Ship (ASDS), which is an improved barge that is capable of autonomous navigation. To date, SpaceX has constructed and is using four of these drone ships (Fig. 4). Since it is generally difficult for barges to put out to sea on long voyages due to their low freeboard height and international rules governing the autonomous operation of ships have not yet been established, it is thought that these vessels will operate within a range where special approval can be obtained from the United States government. Launch vehicle recovery is performed by unmanned operation, and control during recovery is performed by a support ship anchored nearby [7] (Fig. 5). Although the waters where launch vehicles are recovered differ depending on the mission, launch vehicle recovery is performed approximately 300 to 1 200 km off the coast of Florida.

3.2 Items to Be Considered in Japanese Recovery Ship

The situations of the United States (SpaceX) and Japan were compared, and the items that require special consideration are shown below.

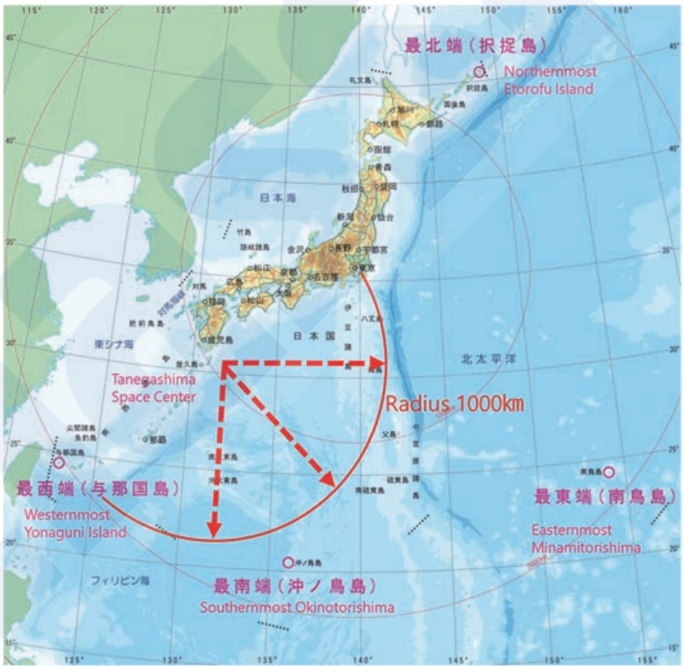

Fig. 2 Launch vehicle recovery area (proposed) (background figure [5])

Fig. 3　SpaceX Falcon 9 rocket [6)]

Fig. 4　SpaceX recovery ship (ASDS) [7)]

Fig. 5　SpaceX support ship (Go-Quest) [8)]

① Since the waters are comparatively calm off Florida, where SpaceX recovers launch vehicles, recovery is considered possible even with ships such as barges. In contrast, a ship with excellent seaworthiness in open water is needed in the seas around Japan, where heavy weather (wind and waves) may occur, depending on the season. Thus, it is necessary to adopt a large-scale ship which is not prone to pitching and rolling in swells at sea, or to use a general ship equipped with stabilizers (anti-rolling devices).
② SpaceX conducts launches of Starlink satellites [9)], etc. on a continuing basis, and therefore has stable, long-term opportunities for launches. Accordingly, it is possible to use a dedicated recovery ship, which is only used in launch vehicle recovery. On the other hand, opportunities for launch vehicle launches by JAXA are currently limited to a few times each year, so it will be necessary to consider maintenance management of the ship during periods when no launches are scheduled.

4. DEVELOPMENT CONCEPT OF RECOVERY SHIP

4.1 Required Functions of Recovery Ship

The functions required in the recovery ship in order to realize the overall concept of the reusable launch vehicle described above in section 2.2 were arranged as follows (Fig. 1).

(1) Basic functional requirements

① Function that enables sailing to the recovery zone
② Function for communication with the launch vehicle, land and the support ship
③ Function for keeping the ship's position in unmanned operation during launch vehicle recovery
④ Platform for launch vehicle recovery
⑤ Function for fixing/ensuring the safety of the launch vehicle after it lands
⑥ Accommodation function (living quarters) for the crew and other workers

(2) Functional requirements considering conditions specific to Japan

(a) Function for suppressing ship motion (stabilizers)
(b) Function as a multipurpose ship (conceivable possibilities include a dredging function [10), 11)], oil-spill recovery function, [10), 11)], hospital ship function, etc.)

4.2 Example of Recovery Ship Concept

JAXA is currently studying the trade-offs of ships that can realize the required functions. This section presents an example of the concept of a multipurpose ship which has functions such as transportation of hospital containers, etc. in addition to offshore recovery of launch vehicles, based on a combined dredging-and-oil recovery ship [10), 11)] (Fig. 6).

This ship was studied independently by the author, separate from the reusable launch vehicle plan in JAXA. If further study is to be carried out in the future, it will be necessary to study of its feasibility in terms of both ship rules, feasibility in terms of structural considerations, etc. in cooperation with shipbuilders and other related parties.

The following describes the features of this ship, corresponding to the required functions ① to ⑥ and (a) and (b) in section 4.1.

(1) A general ship is adopted to enable smooth sailing to the recovery zone (function ①). An azimuth-type thruster (full 360° horizontal rotation) is adopted, and the ship's position is maintained during launch vehicle recovery by using the thruster and the bow thrusters (function ③).

(2) During recovery, the recovery deck (11.5 (m) x 50 (m)) is mounted on the two sides of the ship's stern section, and an area of 50 (m) x 50 (m), which is necessary in launch vehicle recovery, is secured (function ④). During ordinary operation, the deck is stored on land so it does not hinder conventional ship operation. The equipment for fixing and ensuring the safety of the launch vehicle after landing is arranged near the recovery deck (function ⑤).

(3) The living quarters and the launch vehicle recovery deck are arranged in the ship's bow and stern areas, respectively (function ⑥). Visibility in the forward direction is secured by arranging the living quarters in the bow area. A gangway that allows vehicles to enter and leave the ship is provided on the port side of the living quarters, and a vehicle passage and parking area are provided under the living quarters. This improves accessibility by workers and when delivering launch vehicle and satellite equipment, which occurs frequently during launch vehicle maintenance work. Antennas for communication with the launch vehicle and support ship, etc. are installed on the weather deck above the living quarters (function ②).

(4) Anti-motion devices are mounted on the upper level of the living quarters, and the sides of the living quarters are sloped to reduce of the effect of crosswinds. A two-level structure with a space in the ship under the recovery deck of the hull is adopted so that crosswinds which strike the deck can pass through the space, thereby reducing rolling of the ship (function (a)).

(5) For multipurpose use, the ship has a dredging function (function (b)). A hopper door is arranged at the bottom of the dredged material tank. Side drag-type drag arms are adopted and arranged on both sides of the ship. To reduce the effect on the ship's trim condition when dredged material is discharged from the hopper door, the dredge material tank is arranged in the center of the ship. Furthermore, as an idea for reducing the damage to the living quarters in the unlikely event of a launch vehicle fire, the dredging tank is arranged between the launch vehicle recovery site and the living quarters. In case of a fire, the dredging pump is used in fire-fighting. During launch vehicle recovery, the ship's motion characteristics are controlled by loading the dredging tank with seawater.

(6) A large-scale portal crane is installed on the ship. This crane can be used as a multipurpose device, for example, for mounting the launch vehicle recovery deck, transferring the recovered launch vehicle to the quaywall, moving hospital-ship containers [12), 13)], etc.(function (b)).

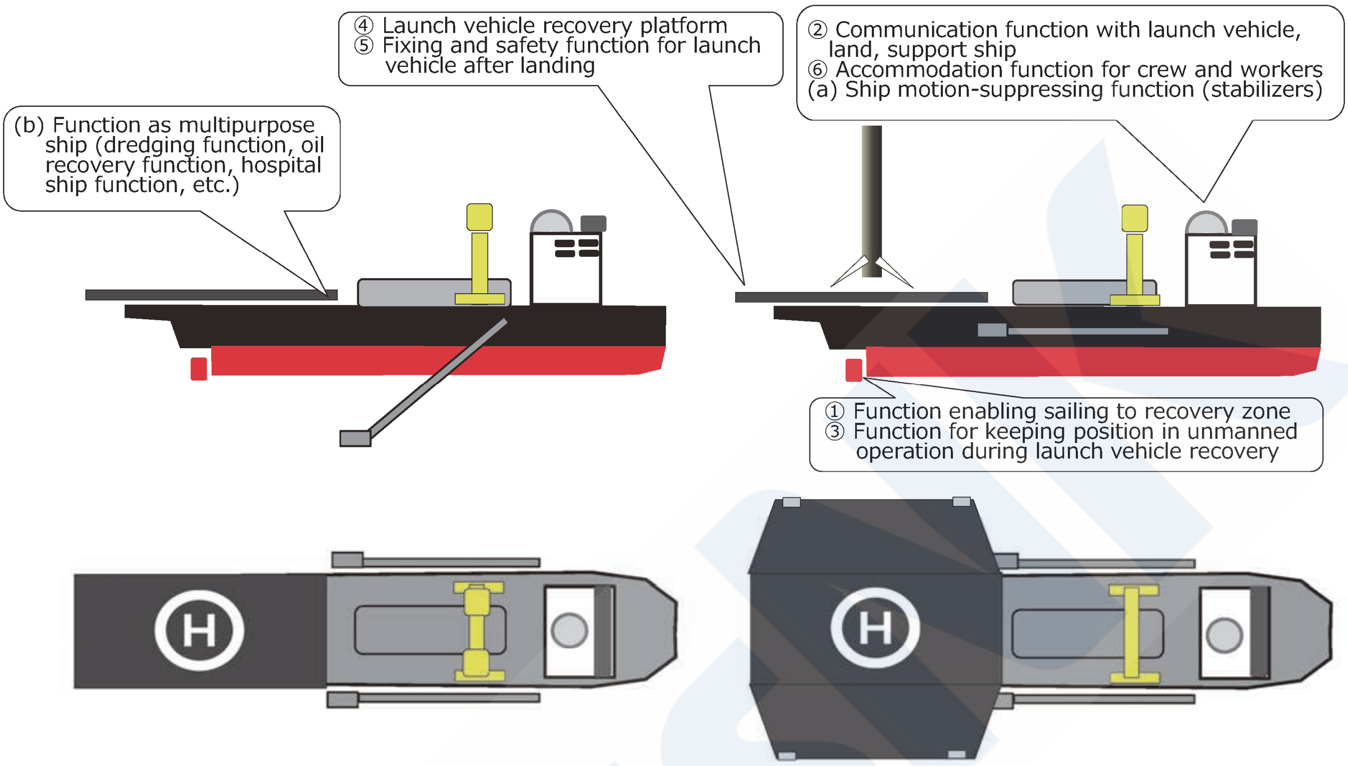

Fig. 6 Conceptual diagram of offshore recovery ship
(Left: during dredging, right: during launch vehicle recovery)

5. INITIATIVES FOR RISK ASSESSMENT OF RECOVERY SHIP

5.1 Policy of Initiatives

According to a book [14)] analyzing the cancellation of development of a Japanese-made regional jet, and the success of a small jet aircraft developed by an automobile manufacturer, the difference in the response to type approval has been pointed out as one perspective. As reasons for the success of the small jet, it was noted that the auto maker set up a base in the United States to carry out the procedures for type approval from the start, and deepened its technology exchanges with the US aircraft industry.

Because ships constructed by research and development institutes in Japan such as the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), etc. receive approval from the ClassNK, JAXA is also planning to receive type approval from ClassNK for the first launch vehicle recovery ship to be constructed. To ensure approval by the Society, JAXA has adopted a policy of deepening technology exchanges with the Society from the start of development, and conducting research and development and risk assessment at the same time in parallel.

Table 1 Ship class rules and related regulations considered objects of study

NK Technical Rules and Guidance	1	Part A GENERAL RULES
	2	Part B CLASS SURVEYS
	3	Part C HULL CONSTRUCTION AND EQUIPMENT
	4	Part U INTACT STABILITY
	5	Part V LOAD LINES
	6	Part W NAVIGATION BRIDGE VISIBILITY
	7	Part D MACHINERY INSTALLATIONS
	8	Part GF SHIPS USING LOW-FLASHPOINT FUELS
	9	Part H ELECTRICAL INSTALLATIONS
	10	Part K MATERIALS
	11	Part L EQUIPMENT
	12	Part M WELDING
	13	Part N SHIPS CARRYING LIQUEFIED GASES IN BULK
	14	Part S SHIPS CARRYING DANGEROUS CHEMICALS IN BULK
	15	Part I SHIPS OPERATING IN POLAR WATERS, POLAR CLASS SHIPS AND ICE CLASS SHIPS
	16	Part O WORK-SHIPS
	17	Part P MOBILE OFFSHORE DRILLING UNITS AND SPECIAL PURPOSE BARGES
	18	Part R FIRE PROTECTION, DETECTION AND EXTINCTION
	19	Regulations for the Classification and Registry of Ships / Guidance
	20	Conditions of Service for Classification of Ships and Registration of Installations
	21	Regulations for the Issue of Statutory Certificates
	22	Rules for the Audit and Registration of Safety Management Systems / Guidance
	23	Rules for Safety Management Systems of Ships Not Engaged in International Voyages or Having Gross Tonnage of Less Than 500 Tons / Guidance
	24	Rules for the Audit and Registration of Ship Security Management Systems / Guidance
	25	Rules for the Inspection and Registration of Maritime Labour Systems / Guidance
	26	Rules for Inspection and Testing of Ship's Fittings
	27	Rules for Approval of Manufacturers and Service Suppliers
	28	Rules for Marine Pollution Prevention Systems / Guidance
	29	Rules for Safety Equipment / Guidance
	30	Rules for Radio Installations / Guidance
	31	Rules for Living Quarter Sanitation Equipment / Guidance
	32	Rules for Anti-Fouling Systems on Ships / Guidance
	33	Rules for Ballast Water Management Installations / Guidance
	34	Rules for Cargo Refrigerating Installations / Guidance
	35	Rules for Cargo Handling Appliances / Guidance
	36	Rules for Diving Systems / Guidance
	37	Rules for Navigation Bridge Systems / Guidance
	38	Rules for Preventive Machinery Maintenance Systems / Guidance
	39	Rules for Integrated Fire Control Systems
	40	Rules for Hull Monitoring Systems
	41	Rules for High Speed Craft / Guidance
	42	Rules for the Survey and Construction of Passenger Ships / Guidance
	43	Rules for the Survey and Construction of Ships of Fibreglass Reinforced Plastics / Guidance
	44	Rules for Marine Engine Emission Verification
	45	Guidance for the Approval and Type Approval of Materials and Equipment for Marine Use

International conventions	1	MARPOL
	2	FSS code
	3	LSA code
	4	COLREG
	5	SPS Code (Code of Safety for Special Purpose Ships)
	6	IP Code (International Code of Safety for Ships Carrying Industrial Personnel)
	7	MODU Code (Code for the Construction and Equipment of Mobile Offshore Drilling Units)
	8	IMSBC Code (International Maritime Solid Bulk Cargoes Code)
	9	IMDG Code (International Maritime Dangerous Goods Code
	10	Polar Code (International Code for Ships Operating in Polar Waters)
	11	IBC Code (International Bulk Chemical Code)
	12	IGC code
	13	IGF code

Japanese laws	1	Ship Safety Law
	2	Regulations for the Carriage and Storage of Dangerous Goods in Ship
	3	Act on Prevention of Marine Pollution and Maritime Disaster
	4	Special Standards and Interim Standards
Others (Currently no regulations exist, but additional study is required)	1	Additional requirements for hospital ships
	2	Additional requirements for autonomous navigation ships
	3	Safety requirements related to launch vehicle recovery ships (requirements for fire-extinguishing and heat-resistant deck, etc.)

ロケット安全要求	1	JMR-001C System Safety Standard (*1)
	2	JERG-1-007 Safety Regulation for Launch Site Operation (*1)
	3	JERG-1-006 Launch Vehicle Development Safety Technical Standard (*1)
	4	NPR8715.3 NASA Procedual Requirements NASA General Program Requirements Chapter 2, System Safety
	5	MIL-STD-882 Department of Defense Standard Practice for System Safety

(*1) See https://sma.jaxa.jp/techdoc.html

5.2 Survey of Ship Class Rules

(1) Purpose

Among the objects of study, assuming the combined dredging-and-launch vehicle recovery ship described in section 4.2, the applicable rules in case functions such as a dredging ship, hospital ship, etc. are to be added, and the issues and measures for obtaining approval under those rules, were arranged. The investigation of the rules on the rocket side was also carried out at the same time in parallel, and the total image of the applicable rules was arranged.

(2) Results of study

Table 1 shows the overall image of the rules that were the object of this study. It was found that a response to the ship class rules is possible by responding in accordance with the design and construction plan. However, if the ship type is changed thereafter, a response beginning from confirmation of the applicable rules is necessary. Furthermore, as items which must be confirmed after the specification and operation of the launch vehicle are finalized, several other issues were also found, as outlined below.

① In case offshore recovery of launch vehicles is to be performed by unmanned operation, it is necessary to determine whether unmanned operation limited to keeping the ship at a fixed position is sufficient, or fully-autonomous operation is required.

② It was found that advance training for JAXA and manufacturer’s staff members will be necessary if they are to embark on recovery voyages on the recovery ship. Referring to the example of ships owned by JAMSTEC, it is also necessary for JAXA to prepare a training manual.

③ If the multipurpose launch vehicle recovery ship is to be used as a hospital ship, a substantial increase in construction costs is possible if medical activities are to be carried out onboard, as the ship’s specification will be similar to that of a passenger vessel.

④ In the future, study as a total launch vehicle system (launch vehicle + ship) will be necessary. In the future, in parallel with work to clarify the specifications of the launch vehicle at that time, it will also be necessary to arrange the rules on the launch vehicle side again through consultation with the JAXA Launch Safety Group, etc.

⑤ It is necessary to arrange the relationship between the environment at the time of launch vehicle landing (shock, heat, combustible gases) and pressure vessels carried on the ship. A detailed study of launch vehicle-related hazardous substances (launch vehicle fuel, liquid oxygen, hydrazine, etc.) loaded on the ship is also necessary, including methods of handing those substances.

6. FUTURE ISSUES

6.1 Study on Feasibility of Recovery Ship

Since the ship is currently in the conceptual stage, as noted in section 3.2, a feasibility study in cooperation with shipbuilding engineers is necessary. A large number of studies will be required, such as study of the type of ship to reduce ship motion during launch vehicle recovery, the strength design and heat resistance design of the launch vehicle recovery deck, etc. On the other hand, technical study for launch vehicle recovery is also needed. This study also includes numerous items, for example, study of a function for safely securing the launch vehicle, a function for ensuring safety, a function for unmanned operation, etc.

In addition, it is necessary to assess the life cycle cost (LCC) aspect of the ship. Although use in dredging, launch vehicle transportation, as a hospital ship, etc. have been proposed as applications when the ship is not being used in launch vehicle recovery, these were only mentioned as possibilities. Since use as a multipurpose ship has the demerit that the ship’s structure and operation become more complicated, it is possible that a ship with more narrowly-focused functions may be a better option, considering the actual operation costs and the desires of the company that will operate the ship.

6.2 Use as a Platform for Solving Space- and Ship-Related Problems

To realize a launch vehicle recovery ship, the cooperation of both space technology and ship and marine technology is essential. By developing the appeal possessed by space technology and the high technological capabilities of ship technology in combination, it may be possible to use the launch vehicle recovery ship as a platform for solving the problems faced by the respective industries.

According to the literature [16], the problems for the ship industry include maintenance of government ships and the development and popularization of gas-fueled ships for realizing carbon neutrality. Demonstration of autonomous operation technologies [17] and efforts such as ICT dredging [18] are also progressing. By utilizing the launch vehicle recovery ship as a platform for demonstrations of those technologies, the ship will become a platform that appeals to an even larger number of the nation’s citizens, and can be expected to broaden public understanding of the ship industry.

In the space industry, further improvements in performance and reliability and lower costs are demanded in response to intensifying competition involving venture companies in recent years. Because SpaceX in the United States has already applied reusable launch vehicles practically and has a proven track record with this technology, it will not be sufficient if JAXA simply continues efforts along an extension of conventional lines; if it does so, there is concern that the differences between JAXA and various other countries will grow wider. From this viewpoint, it is necessary to utilize the recovery ship in various applications so as to create new business opportunities and increase total profitability.

In Japan, many industries have high technological capabilities, including the shipbuilding and marine equipment industries and the shipping industry. Taking advantage of Japan's technological superiority and cultural background, we hope to create new ideas through discussions with various industries.

ACKNOWLEDGEMENT

The study in connection with ship class rules reported here is the result of the joint research project "Survey of Ship Class Rules for Multipurpose Use of Launch vehicle Recovery Ship" of ClassNK and JAXA. The author wishes to express his gratitude for the contributions of all those concerned.

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Overview of Guidelines Issued by ClassNK during CY 2023

Research Institute, Research and Development Division

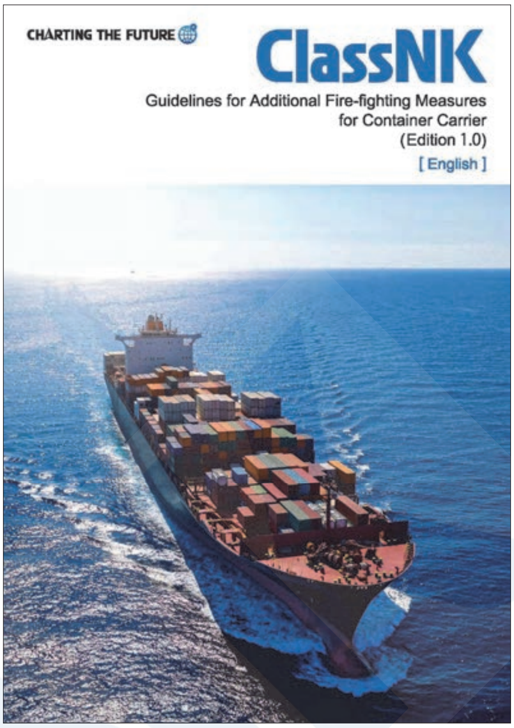
During calendar year 2023, ClassNK issued the 14 Guidelines shown in Table 1. This article presents the outlines of these Guidelines.

Table 1 Guidelines issued during CY 2023

Title	Languages	Date of issue	Contact
Guidelines for Additional Fire-fighting Measures for Container Carrier (Edition 1.0)	Japanese/ English	April 2023	Rule Development Dept.
Guidelines for Wind-Assisted Propulsion Systems for Ships (Edition 2.0)	Japanese/ English	April 2023	Technical Solution Dept.
Guidelines for Container Stowage and Securing Arrangements (Edition 3.1)	Japanese/ English	April 2023	Research Institute
Guidelines on Preventive Measures against Parametric Rolling (Edition 1.0)	Japanese/ English	April 2023	Research Institute
Guidelines for Electronic Logbooks (Edition 1.0)	Japanese/ English	May 2023	Rule Development Dept.
Guidelines for Direct Load Analysis and Strength Assessment (Edition 3.0)	Japanese/ English	June 2023	Rule Development Dept.
Guidelines for Shipboard CO_2 Capture and Storage Systems (Edition 1.1)	Japanese/ English	June 2023	Rule Development Dept.
Guideline for the Safe Transportation of Electric Vehicles (Edition 1.0)	Japanese/ English	August 2023	Material and Equipment Dept.

Title	Languages	Date of issue	Contact
Guidelines for Liquefied Hydrogen Carriers (Edition 2.0)	Japanese/ English	August 2023	Technical Solution Dept.
Guidelines for Fuel Cell Power Systems On Board Ships (Second Edition)	Japanese/ English	September 2023	Technical Solution Dept.
Guidelines for the Inventory of Hazardous Materials (Ver. 5.00)	Japanese/ English	October 2023	Ship Management Systems Dept.
Guidelines for Underwater Noise from Ships (Edition 1.0)	Japanese/ English	October 2023	Machinery Dept.
Guidelines for Cyber resilience of on-board systems and equipment (Edition 1.0)	Japanese/ English	November 2023	Maritime Education and Training Certification Dept., Machinery Dept.
Technical Guide for Using Biofuels (Edition 1.1)	Japanese/ English	December 2023	Machinery Dept.

Guidelines for Additional Fire-fighting Measures for Container Carrier (Edition 1.0)

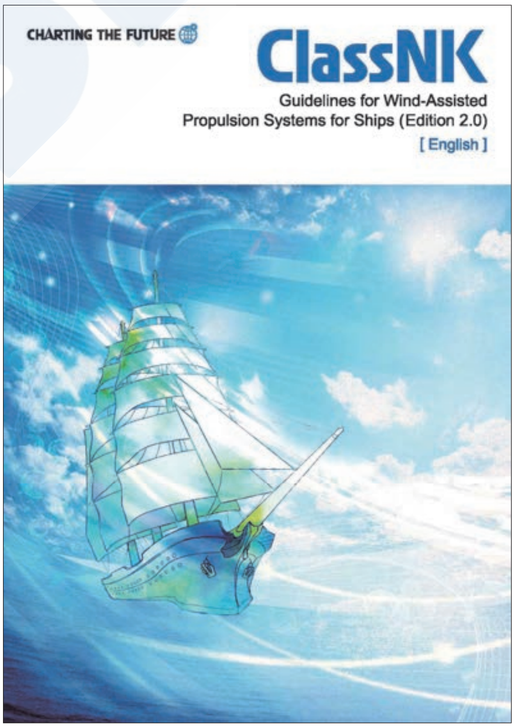


Accompanying the larger scale of container carriers in recent years, conventions have been revised to improve fire safety, but because multiple large fire accidents are still occurring, a review of international rules to further improve safety is under discussion in the IMO.

At MSC103 in May 2021, the IMO approved a new work plan to establish new requirements for fire safety measures on container carriers. In this plan, discussions on revision of the related requirements are to be completed by 2025, targeting issuance in January 2028.

There are also moves to respond voluntarily, in advance of discussions in the IMO, by some ship owners and ship management companies that operate container carriers. Therefore, the Society took the initiative in evaluating additional fire-fighting measures and issued “Guidelines for Additional Fire-fighting Measures for Container Carriers” to enable class notation representing those fire-fighting measures to the ship’s character of classification.

Guidelines for Wind-Assisted Propulsion Systems for Ships (Edition 2.0)



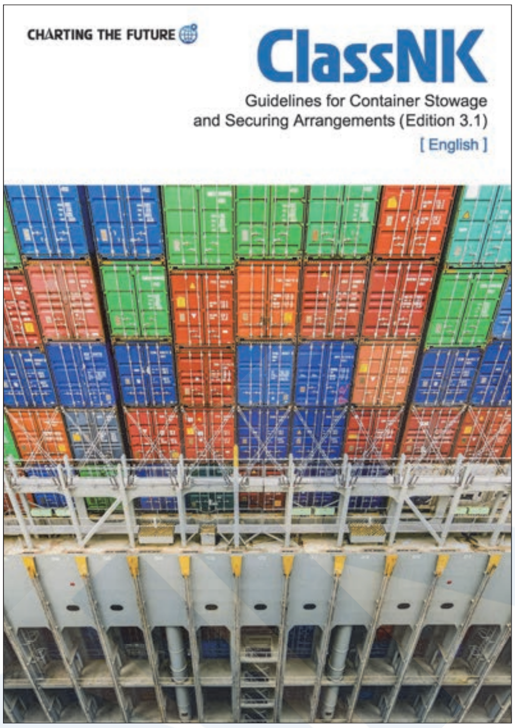
The safety of ships is guaranteed by international conventions, domestic laws, related regulations, etc., there are still no conventions applicable to Wind-Assisted Propulsion Systems (WAPS).

Therefore, ClassNK published the first edition of “Guidelines for Wind-Assisted Propulsion Systems for Ships” in 2019 and has performed drawing examinations and surveys related to the actual installation projects.

Reflecting the insights obtained from involvement in the actual installation projects, the guidelines are updated significantly to the second edition. The overall structure of the guidelines has been revised and organized into three parts: "Wind-Assisted Propulsion Systems", "Base Ships", and "Surveys", and requirements have been refined and clarified. The guidelines now provide a comprehensive overview of the points to be considered in designing WAPS and their installation on ships.

Also, the Guidelines will be successive updates planned, at the stage when actual results and knowledge concerning the adoption of WAPS have been accumulated.

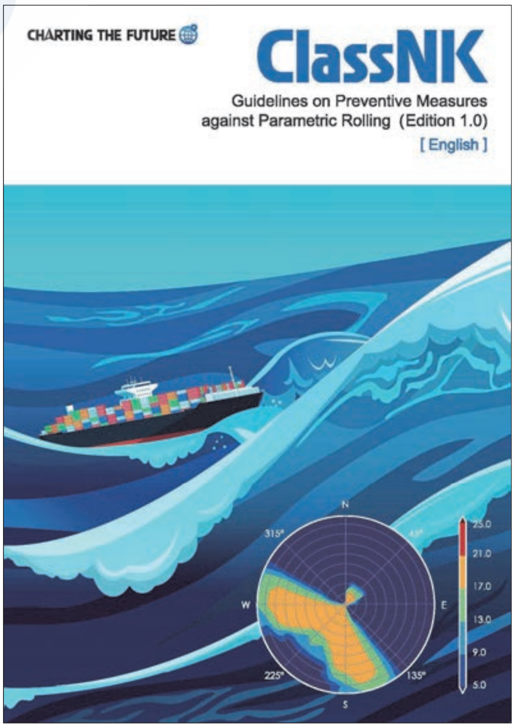
Guidelines for Container Stowage and Securing Arrangements (Edition 3.1)



To transport many containers at one time, container carriers are loaded with a large number of container stacks not only in holds, but also on deck. Container stacks are secured with securing devices, beginning with lashing rods that can withstand the loads associated with ship motion. Evaluations to determine whether the forces generated in containers and securing devices by ship motion exceed the allowable values are called “container securing strength calculations.”

Those calculations comprise evaluation of the design load and evaluation of lashing system deformation, including the lashing rods. In the Guidelines, design loads were revised by incorporating the results of the full revision of Part C in evaluations of ship motion and acceleration. In design load calculations, the Guidelines specified the use of encountered sea surface condition, considering ship behavior to avoid rough weather by weather routing, etc., based on the route and season. For evaluations of lashing system deformation, a solver that can perform calculations faithful to the phenomena with high speed and high accuracy was developed and is specified in the Guidelines. These revisions are expected to achieve safer and more economical maritime container transportation.

Guidelines on Preventive Measures against Parametric Rolling (Edition 1.0)



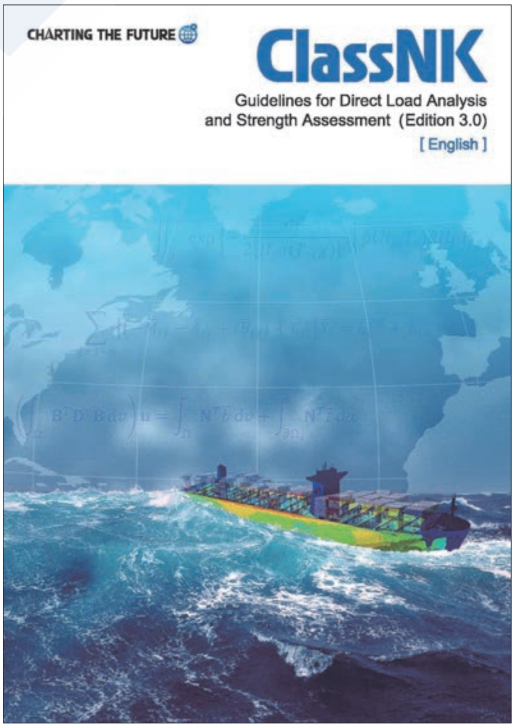
Parametric rolling, unlike synchronous rolling, is a rolling phenomenon caused by temporal changes in a ship’s righting moment, and can occur in a head sea or oblique sea. It occurs easily in fine ships such as containerships and car carriers. Particularly in recent years, cargo collapse accidents that are thought to have been caused by excessive rolling due to parametric rolling have occurred in large-scale containerships.

To promote wider use of measures to avoid and prevent excessive rolling due to parametric rolling, these Guidelines summarize the types of effective measures, functional requirements to be applied, and class notations to implement appropriate measures. Basic precautions for avoiding parametric rolling and the procedures for preparation of polar charts showing the parametric rolling region are also described.

Guidelines for Electronic Logbooks (Edition 1.0)

With recent progress in digital technology and digital devices such as tablets, various information that has been confirmed in paper form until now is being digitized, accelerating the overall transition to paperless business operations in society. Electronic logbooks describing important matters related to ship operation have also attracted attention in the maritime industry, and amendments allowing the use of electronic media for the record books for oil and ozone layer depleting substances required in the MARPOL Convention were adopted in May 2019. Since electronic logbooks have many advantages, not limited to the environmental aspect of paperless operation, but also in lightening the crew's recordkeeping workload by automatic inputting of data from nautical instruments and improving the quality of the contents of records, digitization is expected to spread to items other than the logbooks stipulated in the MARPOL Convention in the future. Against this background, the Society released these Guidelines, which summarize the general specifications for data retention and record management for electronic logbooks, as an approach for approving electronic logbooks used voluntarily on ships.

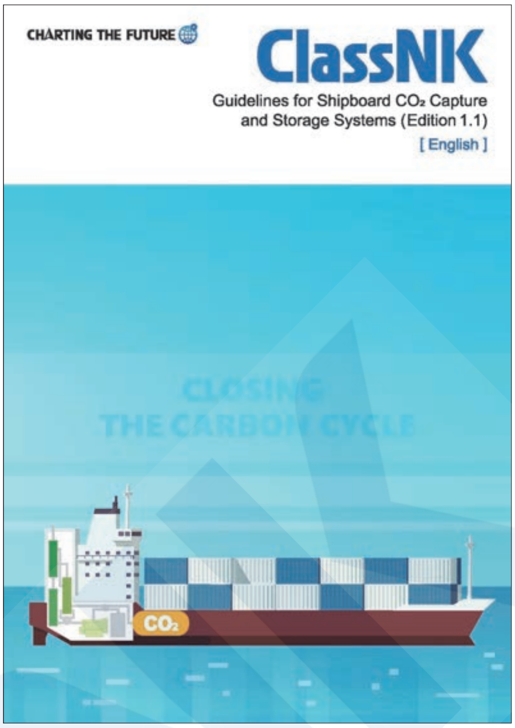
Guidelines for Direct Load Analysis and Strength Assessment (Edition 3.0)



"Guidelines for Direct Load Analysis and Strength Assessment Edition 1.0" specified the technique and related requirements of "Direct Load and Structural Analysis" for performing a structural analysis based on a direct load analysis that directly simulates the wave loads acting on a ship, and a ship structural strength assessment that accurately grasps the characteristics of the target ship. In 2022, the requirements for Direct Load and Structural Analysis were reviewed based on newly revised concepts related to structural strength assessment in Part C of *Rules for the Survey and Construction of Steel Ships* (released in July 2022), and Edition 2.0 was released.

At the end of 2022, Rev. 2 of IACS Recommendation No. 34 was released, specifying sea conditions in the North Atlantic analyzed using new technology. (IACS Recommendations are not compulsory.) Based on that revision, the Society recently released Edition 3.0, adding a summary of points to note when performing strength assessments based on the said sea conditions as reference.

Guidelines for Shipboard CO_2 Capture and Storage Systems (Edition 1.1)

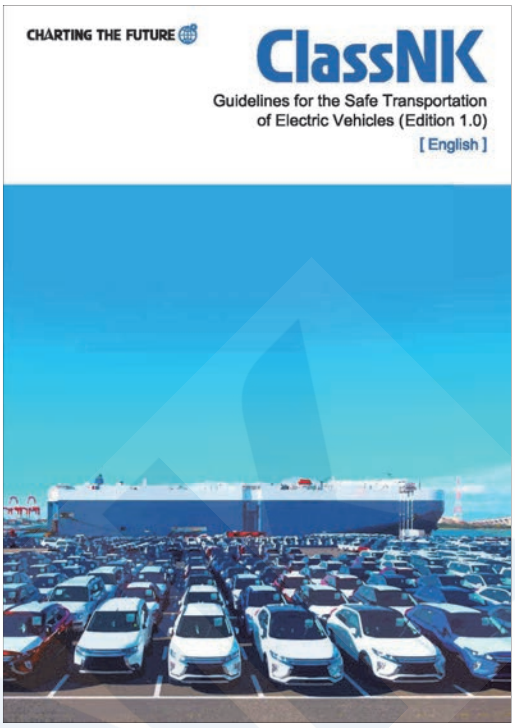


In recent years, ever stronger efforts have been made to reduce greenhouse gas (GHG) emissions from ships in the shipping industry. In particular, there is growing interest in shipboard CO_2 capture as a technology for reducing emissions of carbon dioxide (CO_2), which is said to have the largest impact among GHG.

Therefore, "Guidelines for Shipboard CO_2 Capture and Storage" was issued in April 2023 (Edition 1.0), summarizing the general concepts of CO_2 capture and storage systems (SCCS), safety requirements, the class notation equipped with SCCS, and the survey requirements for smooth Society approval of the installation of SCCS expected in the future, together with an Appendix on the additional energy requirements of SCCS, etc. Subsequently, the Guidelines were revised to clarify some content of the Appendix, and were released as Edition 1.1 in June of the same year.

The Guidelines specify the safety requirements for SCCS in two parts, Chapter 2, "CO_2 Capture Systems and Associated Equipment," and Chapter 3, "CO_2 Storage Systems and Associated Equipment." The content of Chapter 4, "Class Notation," allows a flexible response to the actual situation by providing class notations that can be differentiated according to the installation condition of the respective equipment on ships, and class notations for cases where design was carried out envisioning future installation. The Appendix provides useful information for SCCS design, including a simple calculation method for the size of CO_2 absorber units, calculation of the additional energy required to operate the SCCS, the capacity of liquefied CO_2 storage tanks, etc.

Guidelines for the Safe Transportation of Electric Vehicles (Edition 1.0)



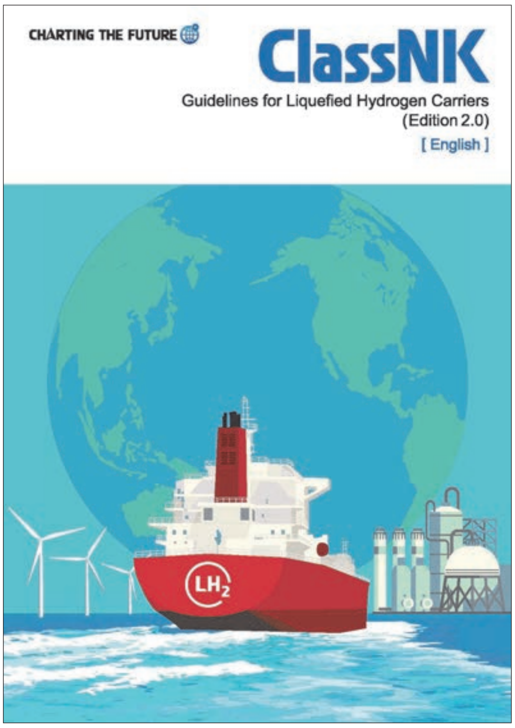
Accompanying the large increase in registered electric vehicles (EVs) worldwide, an increase in the number of EVs transported by car carriers is also foreseen. Since EVs are powered by electric energy stored in a lithium ion battery (LIB), if a fire breaks out from an LIB or fire spreads to an LIB, fire-fighting measures different from those used with gasoline-powered vehicles are necessary to extinguish EV fires.

The IMO has also begun discussions on fire safety measures for ships transporting new energy vehicles, including EVs, but those discussions are expected to extend over several years before rules are established.

On the other hand, since maritime transportation of EVs has already begun, ship companies are voluntarily studying and implementing fire safety measures.

Under these circumstances, the Society arranged the features and points to note concerning fires of EVs and issued “Guidelines for the Safe Transportation of Electric Vehicles,” showing the points which require attention in the fire-safety measures that are considered effective. This framework also allows voluntary assessment of fire measures by ship companies so that notations to the effect that a ship has taken measures that are considered effective can be affixed to the ship’s character of classification.

Guidelines for Liquefied Hydrogen Carriers (Edition 2.0)

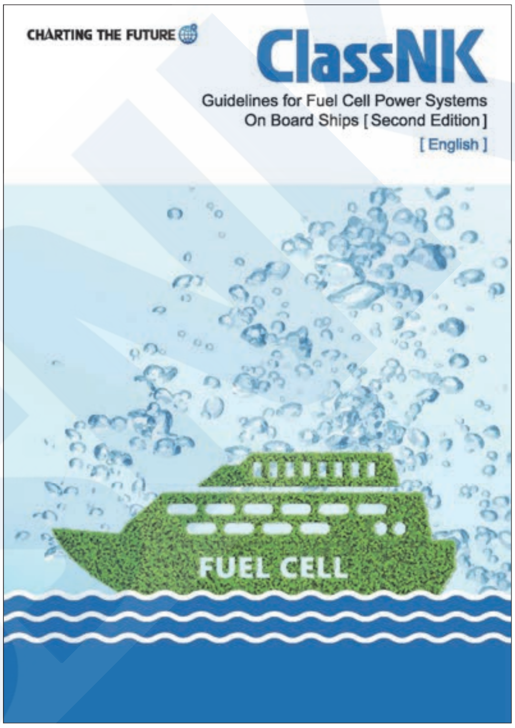


To construct a supply chain for hydrogen, which is expected to be a clean energy source in a decarbonized society, the development of liquefied hydrogen carriers that enable large-scale and efficient transportation is progressing actively.

IMO has worked on establishing safety requirements for liquefied hydrogen carriers that must keep cargo at an extremely low temperature of minus 253 degrees Celsius, and "Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk" was adopted in 2016. Based on the interim recommendations, ClassNK’s "Guidelines for Liquefied Hydrogen Carriers" published in 2017 set out specific requirements in consideration of related international standards and ClassNK’s R&D outcome. A design review and survey of the world's first liquefied hydrogen carrier, "Suiso Frontier," was based on these guidelines.

Incorporating insights from experience with the ship and reviews of other concepts currently under development, ClassNK has updated the guidelines to Edition 2.0. In this update, specific requirements were refined for clarity and rationality, and two sets of guidance assisting the process of risk assessment required for each project and the exploration of measures against potential hazards have been added, enhancing the practicality of the guidelines.

Guidelines for Fuel Cell Power Systems On Board Ships (Second Edition)

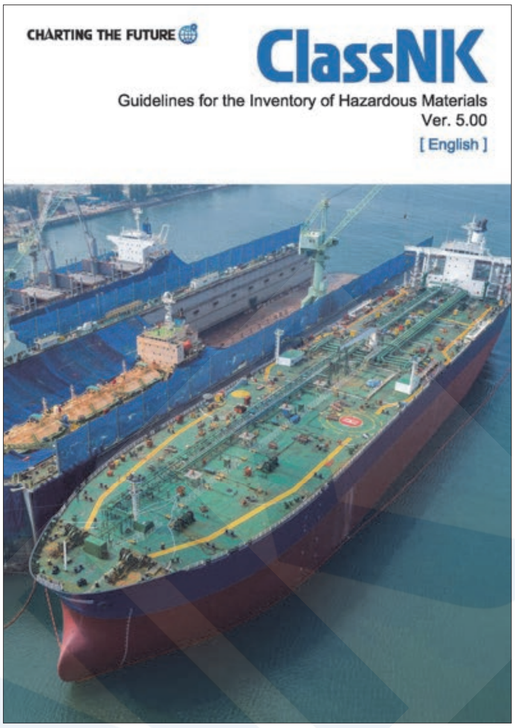


Fuel cells are power systems that use electrical energy obtained from the chemical reaction between hydrogen and oxygen. Notably, they do not emit CO_2 during electricity generation, positioning them as a potential solution to help reduce GHG emissions from shipping.

On the other hand, the use of fuel cells entails handling hydrogen, which has many physical properties distinct from conventional fuel gases. To ensure safety, it is critical to take sufficient measures. Discussions are currently underway at the IMO to amend the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code) to include provisions specific to fuel cells. At MSC105, the interim Guidelines for the safety of ships using fuel cell power installations were approved.

In this recent update, ClassNK has incorporated the contents of the IMO Interim Guidelines into its "Guidelines for Fuel Cell Power Systems On Board Ships (Second Edition)." These guidelines outline the latest safety measures for installing fuel cell power in vessels, including design principles for related equipment, fire safety, electrical systems, control, monitoring, and safety systems. The guidelines also set out requirements for a class notation for vessels that meet these provisions. Moreover, an annex detailing the examination requirements for fuel cell power systems, based on relevant IEC standards and regulations, has been added.

Guidelines for the Inventory of Hazardous Materials (Ver. 5.00)



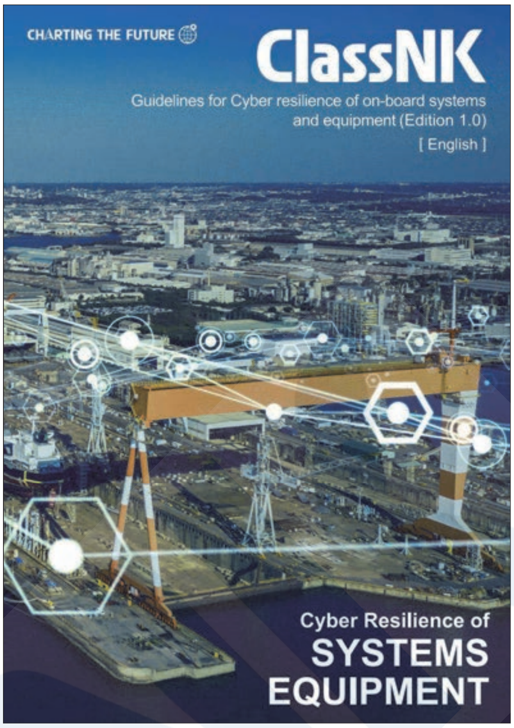
With regard to Inventory of Hazardous Materials (IHM) required on Ship Recycling Convention, which will enter into force on 26 June 2025, RESOLUTION MEPC.379(80) "2023 GUIDELINE FOR THE DEVELOPMENT OF THE INVENTORY OF HAZARDOUS MATERIALS" have been adopted at MEPC80 in July 2023 as amendment to RESOLUTION MEPC.269(68). RESOLUTION MEPC.379(80) has been issued adding cybutryne to hazardous materials to be listed in the Inventory of Hazardous Materials (IHM) with respect to the restriction of the use of cybutryne as anti-fouling system (AFS) since January 2023 on AFS Convention. "Guidelines for the Inventory of Hazardous Materials (Ver.4.00)", issued in October 2019, has been updated as Ver.5.00 reflecting RESOLUTION MEPC.379(80).

Guidelines for Underwater Noise from Ships (Edition 1.0)

In the early 2000s, stranding accidents of marine organisms such as dolphins and whales, which are assumed to be caused by underwater noise, occurred frequently, and research on the effect of underwater noise of ships on marine organisms was conducted. As a result of these investigations, the momentum for the introduction of underwater noise regulation increased internationally, and the International Maritime Organization (IMO) conducted activities for the introduction of underwater noise regulation, and adopted the non-mandatory guideline in March 2014. Since then, discussions to improve its effectiveness have increased, and a revised guideline was approved in July last year, including the preparation of a underwater noise management plan. In order to respond to such international trends, we have issued a guideline. This guideline specifies design requirements for underwater noise reduction, provisions for underwater noise measurement in accordance with ISO17208, and standards for assigning classification codes based on the results.

A brief explanation of the ClassNK Guidelines is presented at the end of this article.

Guidelines for Cyber resilience of on-board systems and equipment (Edition 1.0)



With the advent of IoT technologies in shipboard systems, the risk of ships falling victim to cyber-attacks is increasing. These attacks not only jeopardize the safety and reliability of ships but also pose a direct threat to human life and property at sea and the marine environment.

Therefore, IACS has studied the measures necessary to ensure the cybersecurity of ships. In April 2022, it issued new UR E26 and UR E27, which set out the measures as requirements. UR E26 covers ships, and UR E27 covers on-board systems and equipment. ClassNK has incorporated these into Part X of the *Rules for the Survey and Construction of Steel Ships* and will apply to ships contracted for construction on or after 1 July 2024.

The Guidelines are intended to assist manufacturers of marine systems and equipment, who are suppliers, intended to be covered by Chapter 4 of Part X incorporating UR E27. To this end, the Guidelines explain the technical details of cyber security and the Society's approval process..

Technical Guide for Using Biofuels (Edition 1.1)

Amid the growing momentum toward fuel transition for decarbonization, biofuels are gaining attention as carbon neutral fuels as feedstock plants absorb CO_2 from the atmosphere during their growth, and as drop-in fuels usable in place of petroleum fuels without major modifications to existing marine diesel engines or machinery. However, there are concerns about the potential risks associated with long-term use due to their limited practical experience and non-establishment of unified standards as marine fuel oils as of 2023.

The technical guide outlines the characteristics of biofuels, the potential issues arising from differences compared to conventional petroleum fuels, and precautions for safe use, such as measures related to machinery or against sludge. It also covers the stipulations and interpretations for biofuels under NOx and GHG reduction regulations, as well as future scenario for biofuels. In addition, it supplementally includes a hearing report on biofuel usage in Indonesia, as well as FAQ that is frequently asked from customers.

A brief explanation of the Technical Guide is presented at the end of this article.

Overview of Guidelines for Underwater Noise from Ships

Hirobumi KANEKO, Hikaru KAMIIRISA*

1. INTRODUCTION

In the first half of the 2000s, beaching incidents involving dolphins, whales and other forms of marine life occurred frequently. Because this phenomenon may be associated with underwater noise, research on the effects of underwater noise radiated by ships on marine life was carried out. The results of those studies heightened international momentum toward the introduction of underwater noise regulations. There were also moves in the International Maritime Organization (IMO) to introduce underwater noise regulations, and the non-mandatory guideline, Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life (MEPC.1/Circ. 833), was adopted by the 66th session of the IMO's Marine Environment Protection Committee (MEPC66) held in March 2014. Based on the direction formulated by the 76th session of the Committee (MEPC76) in March 2021, the work of reviewing and revising the Guidelines was begun, and the revised version of the Guidelines for the Reduction of Underwater Noise was approved at MEPC80 in July 2023. Based on these moves, ClassNK issued its own Guidelines for Underwater Noise from Ships (Edition 1.0) (hereinafter, referred to as the Guidelines) in October 2023.

This paper presents a technical overview of the relatively unfamiliar subject of underwater noise in the field of large-scale ocean-going commercial ships.

2. UNDERWATER NOISE

The main cause of underwater noise is the propellers and machinery and equipment installed on ships, and its level varies depending on the ship's hull form, structure and operating conditions, etc. In many cases, underwater noise is caused by propeller cavitation. Particularly in the case of large full type ships that require high-efficiency propellers and have highly nonuniform or non-homogeneous wake fields, it is thought that the underwater noise of the ship caused by propeller cavitation and radiated in the surrounding water is the dominant factor.

In this connection, the term "underwater noise level" means the sound pressure level (*dB*) given by the following equation.

$$L_p = 10\log\left(\frac{p}{p_0}\right)^2 \qquad (dB)$$

L_p: Sound pressure level, p_0: Reference sound pressure (= $1\mu Pa$)

The sound pressure level is converted to the level at a distance of 1 *m* from the noise source.

3. OVERVIEW OF THE *GUIDELINES*

The *Guidelines* comprise six chapters covering general provisions, submission of plans and documents, surveys, design requirements, underwater noise measurement, maintenance and operation. Among these, this paper presents a brief explanation of the design requirements and underwater noise measurement.

3.1 Design Requirements

This chapter of the *Guidelines* specifies the design requirements for underwater noise measurements for the ship hull, propellers, main and auxiliary engines, etc.

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3.1.1 Hull

To suppress cavitation, ship hull forms are to be designed so that the wake fields are as homogeneous as possible, the hull and propeller designs are to be adapted to each other, hull structures are to be optimized to reduce solid-borne noise and the excitation response of the hull, underwater noise reduction measures are to be harmonized with technical measures to reduce greenhouse gas (GHG) emissions, etc.

3.1.2 Propellers

The provisions for propellers include optimization of propeller load fluctuations in a wake flow designed to be as uniform as possible in order to reduce cavitation under normal operating conditions, model testing at cavitation test facilities using equipment such as a cavitation tunnel for optimizing propeller design, etc.

3.1.3 Main and Auxiliary Engines

Measures include appropriate vibration control measures such as resilient mounts, damping balancing, structural damping, etc. for equipment installed on board ships such as refrigeration plants, air compressors, etc., appropriate arrangement of onboard equipment, and optimization of foundation structures.

3.2 Underwater Noise Measurement

The *Guidelines* provides for acoustic measurement and evaluation in deep waters conforming to ISO 17208, where the effects of seabed acoustic reflection are limited.

3.2.1 Measurement site

Measurement site are to be selected in sea areas where the water depth is 150 m or more or more than 1.5 times the length of the ship, whichever is greater, and there is no traffic congestion.

3.2.2 Measurement Conditions

Measurements are, in principle, to be taken with the ship fully loaded during sea trials, under marine and meteorological conditions which will not affect the measurements at a BF scale of 4 or less and sea state of 2 or less, with engine power of 85 % of normal output.

3.2.3 Measurement Procedure

The Distance to the Closest Point of Approach (DCPA) to the hydrophones is to be 100 m or the ship's length, whichever is greater. The tolerance of DCPA is not specified. The hydrophones used in the measurement are to omni-directional, and 3 hydrophones of the bottom-mounted type, floating buoy type, or a floating line system from a supporting vessel are to be used. Fig. 1 shows an example of the arrangement in the case of the bottom-mounted type.

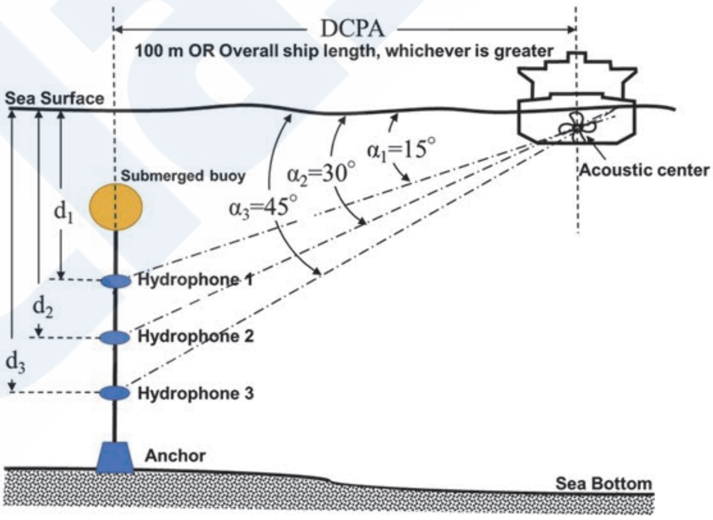

Fig. 1 Example of arrangement of bottom-mounted hydrophones

The measurement sections are to be the range of ±30 degrees from the center of the hydrophone, and the number of navigations and measurements is to be two times, with the hydrophone on the starboard side and the port side. Fig. 2 shows an example of the underwater noise measurement configuration in the test course.

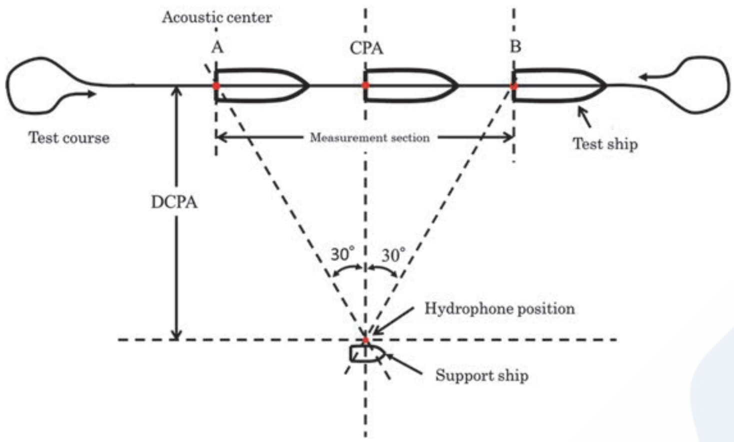

Fig. 2　Measurement configuration(test course and other matters)

3.2.4　Analysis Method

Narrow band spectrum analysis (every 1 Hz) and one-third octave band analysis are to be performed. The *Guidelines* also include provisions for processing of background noise, distance correction, correction of seabed reflection, etc.

3.2.5　Evaluation Criteria

The notation *Silent Underwater Noise-X* (abbreviated *SUN-X*) is noted to the class characters of ships adopting special measures for noise reduction in accordance with the *Guidelines*. *X* is based on the results of the Izu-Oshima underwater noise test conducted in cooperation with the Japan Ship Technology Research Association, and the notations *Silent Underwater Noise-Controlled* (*SUN-C*) and *Silent Underwater Noise-Advanced* (*SUN-A*) are noted in accordance with the determined reference noise levels(Fig. 3). For the detailed numerical values, please refer to the *Guidelines*.

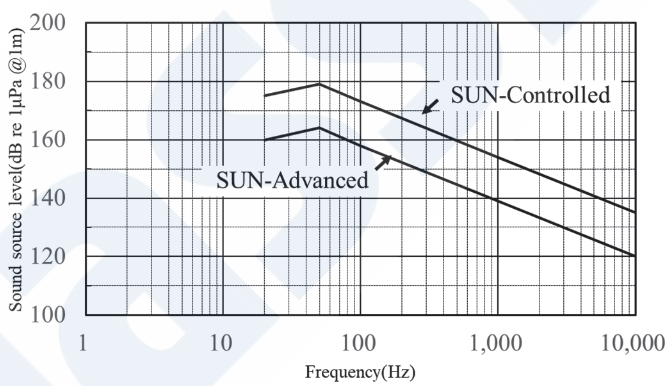

Fig. 3　Reference noise levels (1/3 octave band)

4.　CONCLUSION

In recent years, underwater noise radiated from ships has also been considered one type of environmental pollution in the United States and Europe. This article has presented an overview of the ClassNK *Guidelines for Underwater Noise from Ships* (*Edition 1.0*), which corresponds to international regulatory moves to address this problem. It is our hope that this paper will contribute to resources for study by all stakeholders.

Discussions toward the next stage, including preparation of noise management plans by various types of ships to ensure the effectiveness of underwater noise reduction efforts, are already underway in the IMO. ClassNK will update the *Guidelines* when necessary, depending on developments in the IMO, and will also provide the corresponding services, etc. to clients.

Biofuel Oils as Marine Fuels

Takuya TOKURA*

1. INTRODUCTION

The trend toward decarbonization has accelerated worldwide in recent years due to concerns about global warming. Initiatives for decarbonization are also progressing in the maritime industry, and biofuel oils, which make it possible to reduce GHG emissions, are attracting attention for use in the existing oil-fueled ships as well as new oil-fueled ships that will likely continue to be built for some time. This paper presents a partial introduction to how biofuel oils will be used as marine fuels.

2. NEEDS FOR BIOFUEL OIL

In the International Maritime Organization (IMO), the 80th Session of the Marine Environment Protection Committee (MEPC 80) adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships in July 2023, which set a target of net-zero GHG emissions in international shipping by around 2050 at the latest. To achieve this target, a changeover from the conventional petroleum-derived fuel to alternative fuels is being considered, with a particular focus on hydrogen and ammonia, which do not emit CO_2 when used.

However, in order to achieve widespread adoption of these alternative fuels, many issues must be addressed, including development of the requisite technologies, construction of fuel supply chains, training of seamen and establishment of a regulatory framework. Considerable time will be required until alternative fuels are adopted, but today's rapidly-advancing global warming will not wait for adoption. Isn't there any means of reducing GHG emissions from existing ships fueled with petroleum-derived fuel oil?

One answer to that question is biofuel oils, which can be used without requiring significant modifications for ship machinery equipment.

2.1 GHG Emission Reduction by Biofuel Oils

The term "biofuel oil" refers mainly to SVO (Straight Vegetable Oil), FAME (Fatty Acid Methyl Ester), and HVO (Hydrotreated Vegetable Oil). SVO is extracted from the fruits and seeds of plants, while FAME and HVO are produced using SVO as a raw material. Like petroleum-derived fuels, all these biofuel oils emit CO_2 when used on ships. However, since the plants absorb CO_2 in the growth process, biofuel oils can be considered to have smaller GHG emissions than petroleum-derived fuels if evaluated by the CO_2 balance in the total process from production and transportation to consumption (use in fuel consumption machinery, such as diesel engines), that is, Well-to-Wake CO_2.

2.2 Motivation for Using Biofuel Oils

At present, ARA (abbreviation of Amsterdam-Rotterdam-Antwerp), Singapore supply bio-blend fuel oils, which are marine fuel oils made from biofuel oils and petroleum-derived fuel oils. In order to evaluate their GHG reduction effect, many bio-blend fuel oil suppliers have obtained ISCC EU Certification (a certification scheme that shows compliance with the requirements of the EU Renewable Energy Directive (EU RED II) for sustainable biofuel production).

The bio-blend fuel oils already in distribution at ARA are a blend of FAME and VLSFO (Very Low Sulfur Fuel Oil, an oil residue with a sulfur content of 0.5 mass%) with a ratio of 30 : 70 (commonly known as Bio-VLSFO), and a blend of FAME and MGO (abbreviation of Marine Gas Oil, indicates light oil) with a ratio of 30 : 70 (commonly called Bio-MGO or Bio-DMA). These fuels are termed B30. In Singapore, the biofuel already distributed is a blend of FAME and VLSFO with a ratio of 24 : 76, and is termed B24.

In this connection, do you know the supply price of the above-mentioned B30 bio-blend fuel oil? At the end of 2023, B30 was trading at a price more than about 1.5 times higher than that of VLSFO, and clearly lacked economic rationality, even

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though it is environmentally friendly. This suggests that the motivation for using this bio-blend fuel oil, in spite of its high cost, may be due to GHG emission regulations.

In particular, the emission trading system in the EU (EU-ETS) was also applied to the maritime industry beginning in January 2024, and requires verification of GHG emissions on voyages in which a ship calls on a port in the EU by an accredited verifier such as a ship classification society, etc., purchase of EU allowances (EUA) by the shipping company equivalent to those GHG emissions, and surrender (payment) of the EUAs to the Administering Authority. The penalties for non-conformance are severe; for example, if a shipping company forgets to report to the Administering Authority or otherwise fails to surrender the required amount of EUAs for 2 consecutive years or longer, it may be refused entry into ports in the EU/EEA member states [1)].

To address this, one readily available method for reducing GHG emissions in order to meet these requirements is slow steaming (ship speed reduction) to reduce fuel consumption. Because fuel consumption is generally proportional to the square of speed, reducing a ship's speed by half will theoretically reduce fuel consumption to one-quarter. For this reason, many ships choose to operate slow steaming. However, it is difficult for the ships such as container carriers and car carriers to do this, because it is important to keep a set schedule. Therefore, the operators of these kinds of ships have expressed needs for bio-blend fuel oils, according to some surveys [2)].

A Japanese version of the GHG emission trading system, GX-ETS, will begin in 2026, and in response, there are also expected to be domestic needs for bio-blend fuel oils in Japan.

3. PROPERTY CHARACTERISTICS OF BIO-BLEND FUEL OILS

When considering the use of bio-blend fuel oils as marine fuels, it is important to be aware of their characteristics. This chapter introduces the characteristics of the two base materials: biofuel oils, namely, their high pour point and easy oxidation (only for SVO and FAME), and VLSFO, specifically, the variations in physical properties of VLSFO, which is a petroleum-derived fuel [3) 4)].

3.1 Characteristics of Biofuel Oils

As mentioned previously, biofuel oils are categorized as SVO, FAME, and HVO:

- SVO: Straight Vegetable Oil
  Mainly vegetable oil (includes UCO: Used Cooking Oil, i.e., waste cooking oil after use).
- FAME: Fatty Acid Methyl Ester
  Methyl ester-treated vegetable oil (produced by the reaction of SVO and methanol in the presence of an alkali catalyst).
- HVO: Hydrotreated Vegetable Oil
  Hydrotreated vegetable oil (produced by the reaction of SVO and hydrogen in the presence of a catalyst under high temperature and high pressure).

Fig. 1 shows photographs of these biofuel oil samples.

Although the mass of all the samples is the same (6 g), SVO has a smaller volume than the other two samples, and its color is also darker. By contrast, HVO has the largest volume and is almost colorless and transparent, while FAME has intermediate characteristics between the two. These characteristics of FAME are thought to occur because its molecular mass and density decrease due to methyl ester treatment in the production process, and as a result, its volume per unit mass increases in comparison with SVO, and its light transmittance increases in comparison with SVO because the impurities are removed in the treatment process. In the case of HVO, in addition to removal of impurities in the production process, the density of HVO decreases due to the smaller molecular mass and elimination of oxygen atoms by hydrogenation treatment, and as a result, its volume per unit mass is larger than that of FAME. The light transmittance of HVO is also increased by the elimination of unsaturated bonds in molecules by hydrogenation treatment, in addition to the removal of impurities by refining.

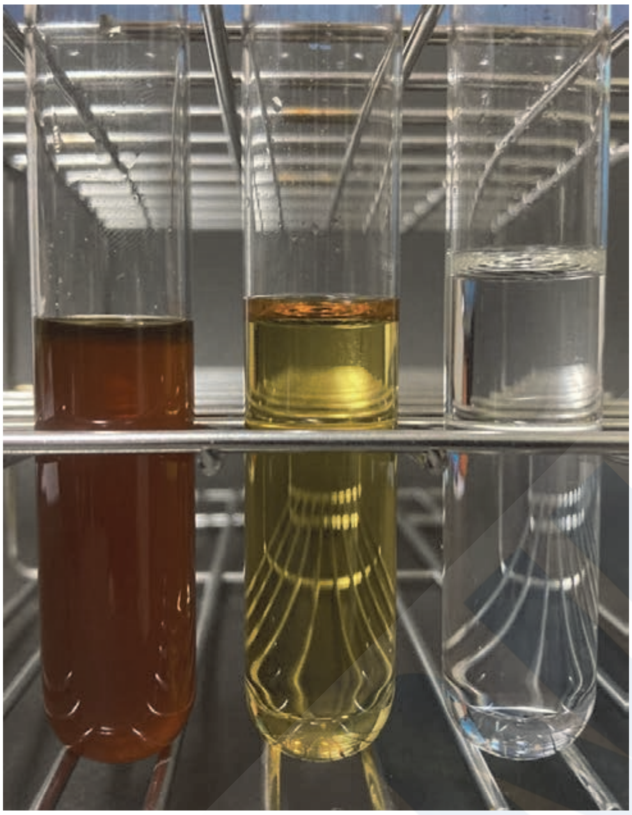

Fig. 1 Samples of biofuel oils
(all samples, 6g; from the left, SVO (UCO: Used Cooking Oil), FAME (UCOME: Used Cooking Oil Methyl Ester), and HVO)

Among these oils, HVO has properties similar to those of the distillate fuel oil such as MGO because the properties of vegetable oils (Oxygen atoms and unsaturated bonds in molecules) are eliminated by hydrogenation treatment.

On the other hand, SVO and FAME have a tendency to react readily with oxygen, which is a characteristic of vegetable oils. The easy oxidation of SVO and FAME is caused by the presence of carbon-carbon double bonds in their molecular structures. Therefore, if oxidation proceeds, lower fatty acids such as formic acid, acetic acid, etc. are eventually formed. Although these are weakly acidic, a corrosive environment for metals may form if they dissolve and concentrate in the drain water that accumulates at the bottom of a fuel tank. Additionally, both SVO and FAME are polar substances, and their polarity becomes stronger as oxidation proceeds. This polarity can cause swelling and strength reduction of nitrile rubber used in the seal parts of machinery.

In actuality, it may be possible to slow the oxidation reaction by adding an oxidation inhibitor (antioxidant) or mixing these biofuel oils with a petroleum-derived fuel. Nevertheless, when using SVO or FAME as a base material of the bio-blend fuel oil, the user should recognize the possibility that the above-mentioned phenomena may occur.

One characteristic related to all of these fuels, SVO, FAME and HVO, is low temperature fluidity. Although the fact that the molecular structures of SVO and FAME include carbon-carbon double bonds was noted above, if the oil contains few of the double bonds, oxidation tends to become more slowly, but the pour point (i.e., the temperature at which a substance loses its fluidity and solidifies) tends to become higher. The pour point of HVO will also increase if isomerization treatment to increase fluidity is not performed. Considering the possibility to lose its fluidity and solidify even at room temperature, users should be aware that the possibility of a high pour point is also a characteristic of bio-blend fuel oils.

3.2 Characteristics of VLSFO

Why introduce the characteristics of a petroleum-derived fuel? This is taken up here because the properties required in petroleum-derived fuels changed substantially as a result of strengthening of global regulations 4 years ago. In 2020, the regulations limiting the Sulphur content of marine fuels for ships were strengthened under the MARPOL Convention. To comply with those new regulations, many ships stopped using the High Sulfur Fuel Oil (HSFO; sulfur content: 3.5 mass%) until that time and began using VLSFO (sulfur content: 0.5 mass%).

Fig. 2 shows the property data for HSFO and VLSFO collected by the Society. It can be understood that the kinematic viscosity and density of VLSFO are significantly lower than those of HSFO. Fig. 3 shows the frequency distribution of each kinematic viscosity in Fig. 2.

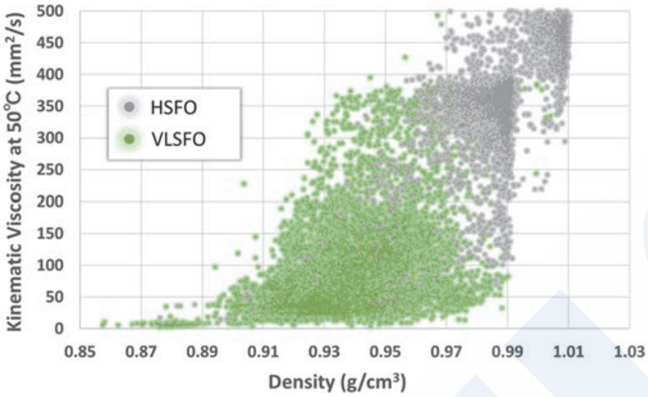

Fig. 2　Density-kinematic viscosity distribution of HSFO and VLSFO

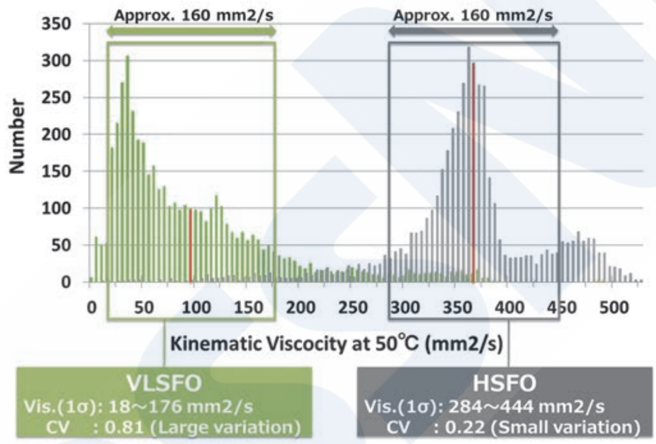

Fig. 3　Frequency distribution of each kinematic viscosity of HSFO and VLSFO

Approximately 70% of the kinematic viscosity values of both HSFO and VLSFO are distributed in a range of 160 mm^2/s, centering on the average value (this range represents ±1 standard deviation (±1σ) from the average). At a glance, there appears to be no difference in the variation. However, because the coefficient of variation (CV), which shows the variation of data, is 0.22 for HSFO but 0.81 for VLSFO, it can be understood that the variation of the kinematic viscosity of VLSFO is large. (In general, the value of CV is judged to be extremely large if the value exceeds 1.)

The variation of kinematic viscosity significantly impacts the work involved in operating a ship's machinery plant. ships have at least 4 heaters for fuel oil heating in the engine room, as well as piping trace heaters to maintain the fuel oil temperature in the fuel oil piping. The fuel oil is heated by maintaining a delicate heating balance of these multiple fuel oil heating devices. Because the temperature control of the individual devices is not linked, adjustments in the setting temperatures of the individual heater must be made by the crew. This is because of the complexity of the work, which includes trial-and-error adjustment of each of the heaters in order to find a new temperature balance when the heating temperature of the fuel oil changes significantly.

Marine heavy fuel oil must be heated to reduce its kinematic viscosity, which is too high to be used in ship's machinery plant. For example, the kinematic viscosity at the diesel engine inlet must be reduced to approximately 12 mm^2/s. Fig. 4 shows the heating temperature ranges for adjustment of HSFO and VLSFO to 12 mm^2/s for the kinematic viscosity range shown in Fig. 3.

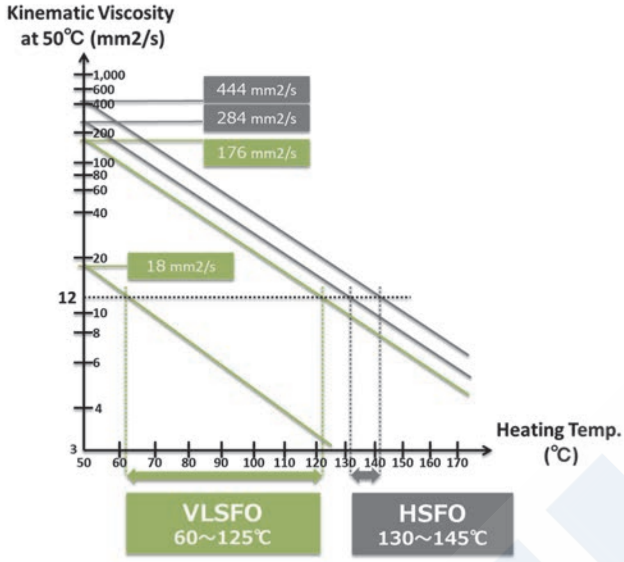

Fig. 4 Heating temperature ranges for HSFO and VLSFO

Although the heating temperature range of HSFO is narrow, at about 130 °C to 145 °C, the range for VLSFO is wide, from 60 °C to 125 °C. Thus, significant change in the heating temperature may be necessary when using VLSFO. Improper adjustment of the fuel oil heating temperature may result in problems in diesel engine operation due to abnormal combustion. Additionally, depending on the stability and pour point of VLSFO, asphaltene sludge may form in the fuel oil if heating is excessive, and wax sludge may form if heating is insufficient. If these types of sludge clog a filter, it will be impossible to adequately supply of fuel oil to the fuel consumption machineries, affecting its operation. Therefore, it is necessary to recognize that VLSFO requires careful temperature adjustment as one of its characteristic features.

4. MEASURES FOR USE OF BIO-BLEND FUEL OILS

Safety is the highest priority for ships. If a maritime accident occurs due to ship trouble, it not only endangers the lives of the seamen operating the ship, but also may have incalculable effects, such as marine pollution from an oil spill and disruption of maritime logistics due to the blockage of sea lanes.

To date, there have been no reports of trouble in actual ships using bio-blend fuel oils on a short- to medium-term basis. However, the risks of long-term use of the bio-blend fuel oils blended with SVO and FAME are unknown. Therefore, the following sections introduce responses for ship machinery for long-term use, measures for avoiding troublesome fuels, and measures for fuel storage and use [3].

4.1 Measures for Ship machinery

For long-term use of bio-blend fuel oils, the measures for each machinery consist mainly of countermeasures against the swelling of rubber and the corrosion of metals, which are characteristic problems mainly in the cases of SVO and FAME. The objects of these measures include seal parts made from nitrile rubber and metal parts in which a corrosive environment can occur. As measures for engines, boilers, purifiers, pumps, valves, filters and other machinery used to handle fuel oil, we recommend informing the respective manufacturers of the properties of the bio-blend fuel oil which the ship plans to use, the assumed fuel storage period, etc., and studying exchanges of parts and the length of the storage period based on the advice of the manufacturer concerned.

4.2 Measures for Avoiding Troublesome Fuels

The main measure for reducing the risk of using the fuel oils that may cause trouble is confirmation of fuel quality in accordance with ISO 8217, which is for conventional petroleum-derived fuel oils. If HVO which is equivalent to the distillate fuel oil such as MGO is used as a base material, conformance with ISO 8217 is considered sufficient. However, if SVO or FAME is to be used, in addition to conformance with the standard, it is also important to confirm the oxidation stability of the fuel, as the current ISO 8217 standard does not include provisions for evaluation of the ease of oxidation (oxidation stability). For this purpose, we recommend using the Rancimat method, which is specified in EN 14112, EN 15751, and other standards for automotive biofuels. In the Rancimat method, oxidation stability is evaluated by measuring the percentage of lower fatty acids generated in an aqueous solution by oxidation of SVO or FAME. If this test is performed a few days before bunkering, it may be possible to reduce the risk of purchasing bio-blend fuel oil that might cause problems, particularly when metal corrosion is a concern. Even if the above measures for machinery are considered sufficient, because machinery consists of metal components, this measure is important to minimize corrosion factors.

4.3 Measures for Fuel Storage and Use

During storage, oxidative degradation over time is unavoidable; that is, even assuming fuel oil of a certain quality is purchased, it will not maintain that quality permanently. This means it is important to consume bio-blend fuel oils in the short term. However, due to the operating conditions of ships, long-term storage may be unavoidable in some cases. Therefore, it is important to suppress oxidation during storage. According to Arrhenius's law, the rate of deterioration double when the storage temperature increases by 10 °C. For this reason, proper temperature control is recommended when using a bio-blend fuel oil containing the base materials such as SVO or FAME, which oxidize more easily than HVO, MGO, and VLSFO. The fuel oil heating temperature should not be excessive, as this will accelerate oxidation, and should not be reduced to the pour point to prevent solidification. (Another possible countermeasure to suppress oxidation is the addition of an oxidation inhibitor to the fuel oil.)

Suppression of microbial sludge is also important. Temperatures in the range of approximately 0 °C to 40 °C are a suitable environment for microorganisms, and if the three factors of temperature, a source of nutrition (hydrocarbons) and water are all present, mold, bacteria, yeast, actinomyces, and the like may propagate at the boundary between the fuel oil and water, resulting in the formation of slime-like or seaweed-like sludge. If this sludge blocks a fuel line filter, it will be impossible to provide an adequate supply of fuel oil to the oi consumption machinery. In addition, there is also a possibility that water in fuel tanks may create a corrosive environment for metals due to concentration of the water-soluble fatty acids formed by oxidation of SVO or FAME. Therefore, frequent removal of the drain water that accumulates at the bottom of fuel oil tanks in the engine room is recommended. (Another possible countermeasure for microbial sludge is the addition of a fungicide to the fuel oil to suppress microbial growth.)

4.4 Summary of Use Countermeasures

When using bio-blend fuel oil, it is important to pay attention to fuel oil temperature control, particularly as a countermeasure against variations in kinematic viscosity.

Moreover, because flow rate of fuel oil drain discharged from the various machinery is not large, there is a possibility that bio-blend fuel oil may accumulate in drain discharge lines for a long period of time, and forming a corrosive environment as oxidation proceeds. Since it is difficult to prevent this, we recommend checking the fuel oil drain lines of all machinery more carefully than before to enable early detection of corrosion.

5. CONCLUSION

The air transportation industry, like the maritime shipping industry, operates over long distances and is now studying SAF (Sustainable Aviation Fuel) using SVO as a raw material. Because both ships and aircraft have historically depended on oil fuels, which are easy to handle, liquid at ambient temperatures and pressures, and have high energy density, making the transition away from oil fuels not straightforward.

Although both bio-blend fuel oil and SAF are more expensive than petroleum-derived fuel oil and are expected to reduce GHG emissions, their supply is limited due to the availability of the raw material, SVO, making it difficult to secure the quantities needed by both industries. Consequently, the extent to which bio-blend fuel oils will be distributed in the maritime shipping industry remain uncertain. Furthermore, the primary motivation for using bio-blend fuel oil is international and regional regulations, and depending on the regulations and the price of bio-blend fuel oils, it may be more economically rational to bear the cost of purchasing GHG emissions allowances rather than reducing GHG emissions.

This potential conflict with the original intent of the regulations, which is to reduce GHG emissions, further contributes to the uncertainty in the distribution of bio-blend fuel oils.

Nevertheless, bio-blend fuel oils remain a limited means of reducing GHG emissions for the existing oil-fueled ships as well as new oil-fueled ships that will likely continue to be built for some time. Monitoring future regulatory developments and trends in the price of bio-blend fuel oils, advance preparations should be made envisioning long-term use, also assuming the possibility of full-scale distribution of bio-blend fuel oils.

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ClassNK Technical Journal

No.9 (2024 (Ⅰ))

Published by: Nippon Kaiji Kyokai (ClassNK) Research Institute

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July 2024