ClassNK
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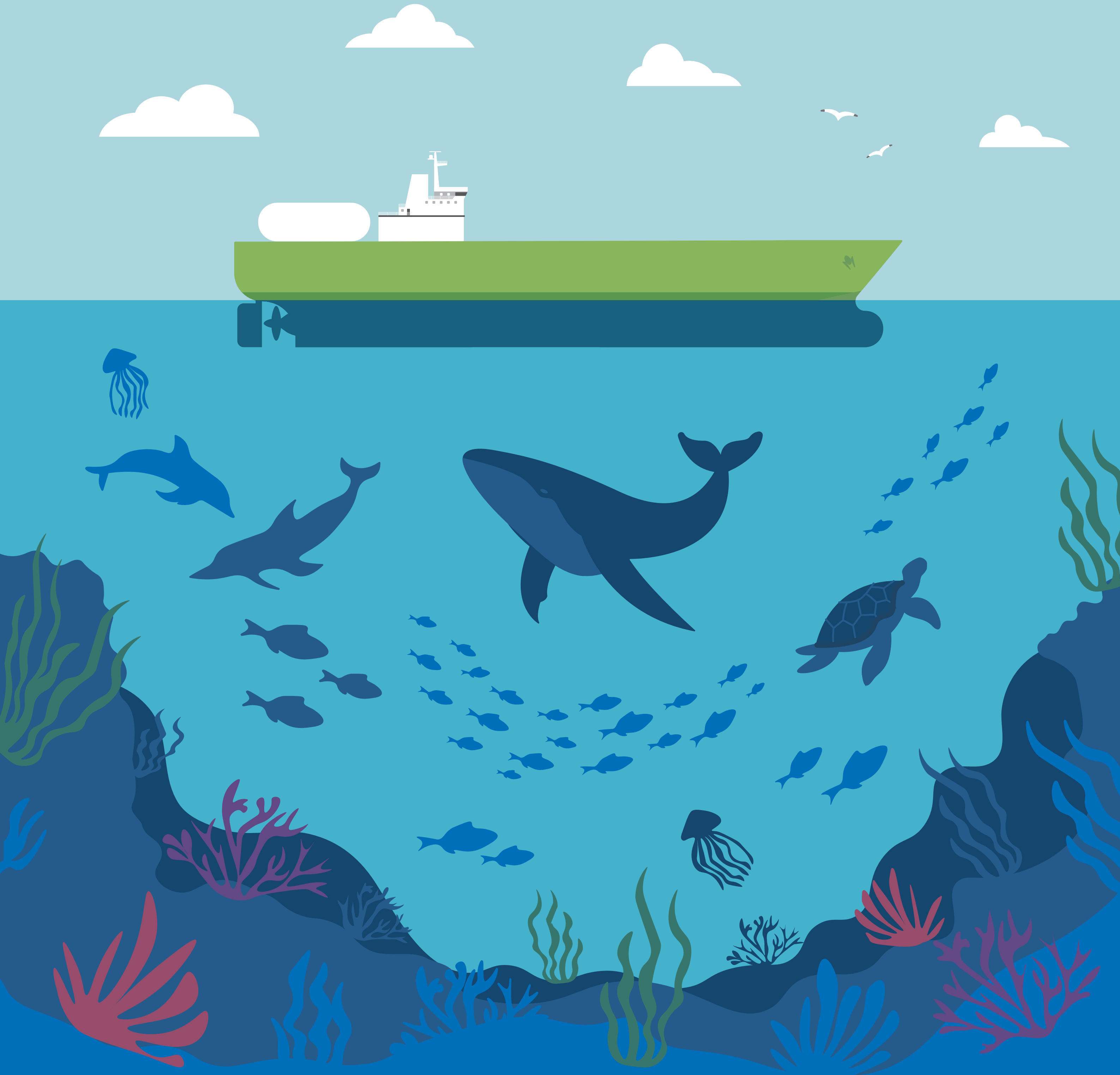
No.11 2025（Ⅰ）

Special Feature: Latest Technological Trends for Protection of the Marine Environment



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Since ammonia does not emit carbon dioxide (CO2) when burned, it is expected to be an important fuel for realizing net-zero GHG emissions by 2050, as announced by the IMO under its Strategy on Reduction of GHG from Shipping. In February 2025, the IMO issued Interim Guidelines for the Safety of Ships Using Ammonia as Fuel, specifying safety requirements when using ammonia as a fuel. This paper introduces the content of discussions in the IMO when developing the IMO Interim Guidelines, and the initiatives of ClassNK for practical application of ammonia-fueled ships.

As part of the trend toward the decarbonization of society, including the maritime sector, it is thought that different safety assessments from those in the past will be needed. Since decarbonization is progressing rapidly, it is also necessary to develop safety assessment techniques with a sense of urgency. As safety assessment techniques for responding to the use of alternative fuels by ships, and changes in the cargoes transported by ships, the Society prioritizes research on advanced and quantitative risk assessment and integrity evaluation techniques for cargo and fuel containment systems as core technologies.

This paper presents an overview of a study on estimation of the frequency of ammonia leaks in ammonia-fueled ships, ammonia gas diffusion experiments and advanced risk assessment techniques, which were introduced at the R&D Forum held in January 2025. As integrity evaluation techniques for cargo and fuel containment systems, the paper also introduces the condition of study and the results achieved in a study on an ammonia stress corrosion cracking (ammonia SCC) sensitivity evaluation method, and study on an evaluation technique for the liquefied oxygen (LOX) compatibility of materials.

Ammonia-fueled ships have been developed with the aim of reducing greenhouse gas emissions during operation. Due to concerns about the toxicity of ammonia, a risk assessment is required on ammonia at an accidental leakage. However, the leak frequency of the ammonia has not been obtained. In this article, we will explain the estimation methods and results on the leak frequency for each equipment on ammonia-fueled ships, using Bayesian estimation.

Technical Topics

The shipping industry is considering measures such as the adoption of alternative fuels and further improvements in energy efficiency to reduce greenhouse gas (GHG) emissions towards net-zero by around 2050. This paper focuses on how to operate the main engine in order to save fuel when encountering rough sea conditions. First, it explains the mechanism of fuel loss that may occur due to the operating limits of the main engine when facing rough weather. Next, it estimates the amount of fuel loss under various conditions. Finally, it presents methods for operating the main engine to save fuel during rough weather encounters.

In recent years, acquisition of ship AIS (Automatic Identification System) data has become easy, and it is now possible to grasp the movement of ships. AIS data are used in diverse fields, including estimation of the volume of maritime cargo transportation, analysis of environmental impacts, etc., and in industry, AIS data are also used to optimize ship operation. The Society has also developed highly accurate and transparent rules through the use of AIS data. As examples of the use of AIS, this paper introduces the results of analyses of the actual situation of ship operation, the features of ships calling in Tokyo Bay (Port of Tokyo) and changes in navigation routes in the Red Sea.

This article introduces recent topics discussed at International Maritime Organization (IMO). At this issue, a summary of the decisions taken at 82nd Marine Environment Protection Committee (MEPC 82) and 109th Maritime Safety Committee (MSC 109) is provided.

During calendar year 2024, ClassNK issued the 10 Guidelines shown in Table 1. This article presents the outlines of these Guidelines.

Prefatory Note

Introduction to the Special Feature on "Latest Technological Trends for Protection of the Marine Environment"

General Manager of Research Institute, Research and Development Division, ClassNK
Kinya ISHIBASHI

On the occasion of the publication of ClassNK Technical Journal No. 11, I would like to extend a warm welcome to all our readers.

ClassNK Technical Journal is a technical publicity journal which 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. The previous issue (ClassNK Technical Journal No. 10) reported the latest technological trends and the latest research and development results of the International Maritime Organization (IMO) and other organizations. As a new initiative, in January 2025, ClassNK held the ClassNK R&D Forum to provide opportunities for the creation of new collaboration such as joint research and also heard the various needs of members of the maritime industry and other stakeholders for services and R&D by ClassNK. Among topics related to the theme of the Forum, " Towards Safer and Environmentally Friendly Ships," this Special Feature summarizes presentations in two areas: reduction of underwater noise from ships and safe decarbonization.

In the early 2000s, there was growing interest in the effects of underwater noise on marine organisms and on underwater acoustic equipment used by the oil and gas industry in offshore oil field development. The IMO also discussed the reduction of underwater noise levels emitted from commercial vessels, and issued guidelines for the reduction of underwater noise on ships in 2014. However, the guidelines were not mandatory due to various issues in underwater noise measurement methods and noise reduction measures for large commercial vessels. Although the guidelines were not still mandatory as in 2023, the revised guidelines were adopted to enhance their effectiveness. In this issue, we outline the status of efforts by the IMO and other organizations to reduce underwater noise and the future actions taken by the Society. In addition, we have invited outside experts to contribute to the technologies related to "estimating and designing" and "measuring and evaluating" of underwater noise on ships, which will serve as the basis for future discussions, although the international trends regarding future regulations are uncertain.

The IMO has also established the ambitious goal of "aiming for net-zero emissions of GHG by around 2050 at the latest," and IMO/EU regulations accompanied by monetary charges are to be introduced. Since accelerated construction of alternative fuel ships that respond to those regulations is expected, ClassNK is developing "safe decarbonization" technologies related to the safety required in alternative fuel ships. This issue includes the latest information on the development of the IMO's Guidelines for the Safety of Ships using Ammonia as Fuel, the initiatives of ClassNK for practical application of alternative fuels, and a contribution by outside experts on the most recent techniques in methods for estimation of the frequency of ammonia leaks, which is necessary in quantitative risk assessments.

Until now, ClassNK has devoted its efforts to the creation of "good ships" as its highest-priority issue. In addition to that goal, 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, also including the viewpoints of “good management” and “good operation.”

In closing, we sincerely request the continuing understanding and support of all those concerned in future, as in the past.

Guidelines for Underwater Noise from Ships and Trends in the IMO, Etc.

Research Institute, Research and Development Division, ClassNK

1. INTRODUCTION

In January of this year, ClassNK (hereinafter, the Society) held the ClassNK R&D Forum (hereinafter, the Forum) to hear the various needs of persons in the maritime industry, etc. related to services and research and development, and to create opportunities for the creation of new collaborations such as joint research, etc. As a theme of presentations at the Forum, the Research Institute addressed the issue of underwater noise generated by ships, which has attracted heightened interest worldwide as a new environmental problem. This article summarizes the presentations on "Trends in Discussions on Reduction of Underwater Radiated Noise from Commercial Shipping in the IMO" and "Response to Guidelines for Underwater Noise from Ships."

This article presents an outline of the history of the establishment of the IMO's guidelines on underwater noise, the characteristics of underwater noise, trends in initiatives to reduce underwater noise from ships in each country, guidelines issued by the Society and other ship classification societies, technical issues for reduction of underwater noise from ships and the future initiatives of the Society.

2. HISTORY OF ESTABLISHMENT OF GUIDELINES ON UNDERWATER NOISE BY THE IMO

In the early 2000s, there was a growing concern about the impact of underwater noise on marine life and on marine acoustic equipment used by the oil and gas industry for subsea oil field development, etc. The IMO discussed the reduction of underwater noise levels emitted from commercial ships. At MEPC 58 held in 2008, the United States proposed the development of guidelines (MEPC 58/19) for underwater noise from ships due to propeller cavitation and engine vibration, including consideration of noise control measures at the design stage and improvement of operational procedures, but the guidelines were not obligatory due to various issues related to underwater noise measurement methods and noise control for large merchant ships. The first IMO Guideline for the Reduction of Underwater Noise from Shipping to Address Adverse Impacts on Marine Life (MEPC.1/Circ.833) [1] was approved at MEPC 66 held in 2014.

3. CHARACTERISTICS OF UNDERWATER NOISE

Underwater noise can be broadly divided into structural noise, which occurs when the vibration caused by the main engine, auxiliary engines, etc. installed in a ship propagates through the hull structure and is radiated from the hull shell plates, and propeller noise caused by fluid noise due to friction between the hull and a fluid, etc. or propeller cavitation (Photo 1) [2]. Propeller cavitation occurs by a process in which the pressure on the propeller blade surface decreases as the blade passes through the area near the hull where the flow is slow, generating a huge volume of cavitation bubbles locally, and the bubbles grow and then undergo a rebound action of compression and collapse. Wide bandwidth noise is generated when this occurs. In addition, because the propeller blades pass periodically, peaks at the harmonic components of the frequency of propeller blade passage (i.e., number of blades x rotational speed) are caused by fluctuations in the volume of cavitation.

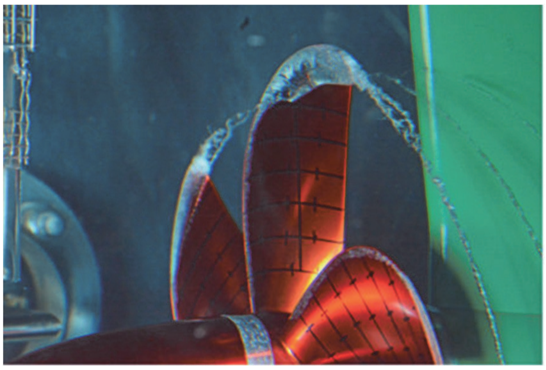

Photo 1　Cavitation caused by ship propeller (tank test)

Particularly in the case of large-scale blunt ships, which have a highly irregular stern flow and require a high-efficiency propeller, ship underwater noise caused by the propeller and radiated in the water is dominant. In the case of research ships, warships, and others in which low underwater noise itself is a performance requirement, it is possible to take countermeasures to reduce structural noise, for example by providing vibration-isolating mounts for the main engine, adopting electric propulsion, etc. However, the majority of ships built in Japan are large-scale blunt ships, in which the main engine and other engines, which have a large vibratory force, are mounted directly on the hull, and it would be difficult to take countermeasures such anti-vibration supports, etc. It should also be noted that the noise caused by the main engine, etc. becomes apparent if cavitation noise is reduced by decreasing the ship's speed.

In water, the sound at high frequencies of 1 000 Hz and higher attenuates greatly and does not travel long distances. However, much of the sound generated by ships is low frequency sound, so almost no attenuation effect in water can be expected. Because the speed of sound in water is affected by the water temperature, underwater sound generally tends to deviate toward the sea bottom due to the temperature distribution in oceans. The general propagation distance is considered to be several km to several 10 km. However, when the water temperature distribution and the sound velocity change with the water depth, there is a region in this distribution called a "sound channel" where the sound velocity reaches its minimum, depending on the season. Due to refraction, the sound waves do not radiate in the vertical direction, but approach a condition of diffusion within cylindrical coordinates. In this result, the sound waves can affect marine life even at great distances.

The effects of underwater noise from ships on marine life include changes in behavior and decreased auditory sensitivity of the organisms affected, and in extreme cases, underwater noise can damage the auditory organs and affect the habitat distribution area, migration routes, etc. As shown in Fig. 1, the frequencies at which various species are easily affected by underwater noise differ depending on the species [3].

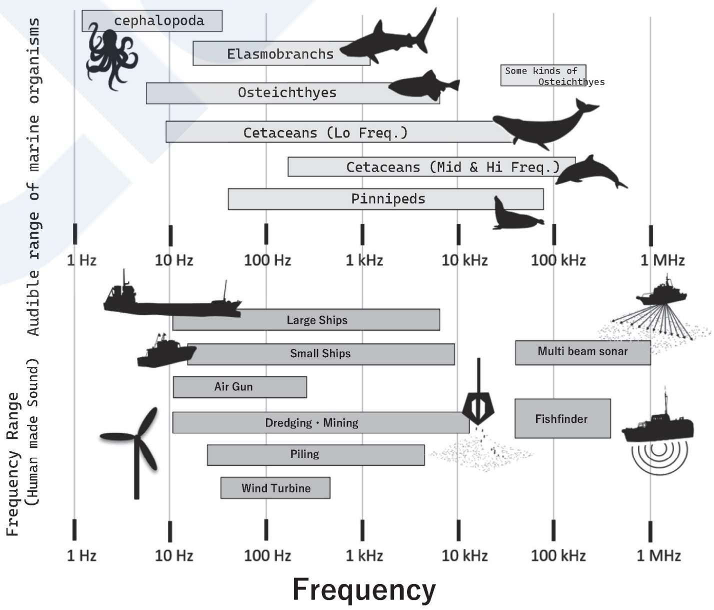

Fig. 1　Underwater noise and audible ranges of marine life

4. SHIP CLASSIFICATION SOCIETY GUIDELINES FOR UNDERWATER NOISE

Eight ship classification societies have issued guidelines for underwater noise from ships corresponding to the IMO Guidelines approved in 2014 (hereinafter, the 2014 Guidelines). ClassNK (the Society) issued “Guidelines for Underwater Noise from Ships (Edition 1.0)” in October 2023.

These Guidelines consist of six chapters covering design requirements, measurement of underwater noise, survey, etc., and appendices summarizing examples of underwater noise reduction measures, etc. As in the Guidelines issued by other ship classification societies, the ClassNK Guidelines contain provisions conforming to ISO 17208-1 and -2 for acoustic measurement and evaluation in deep seas, where the effect of sound reflection by the sea bottom is limited. the Society specifies that the water depth is to be 150 m or 1.5 times the ship’s length, whichever is greater (Fig. 2), and the position of the hydrophone array and the route of the target ship (Fig. 3), and notations (SUN-Controlled, SUN-Advanced) are affixed to the ship’s classification characters based on original standard noise levels (Table 1 and Fig. 4).

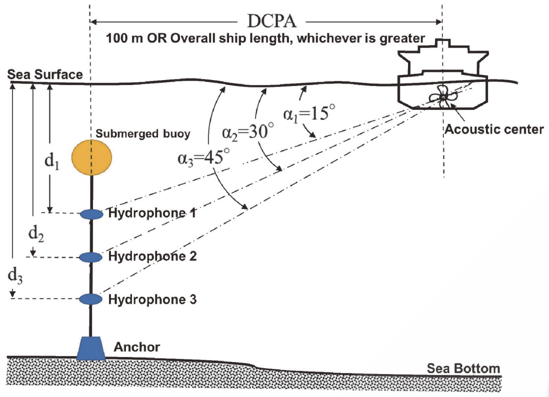

Fig. 2 Example of arrangement of bottom-mounted hydrophones

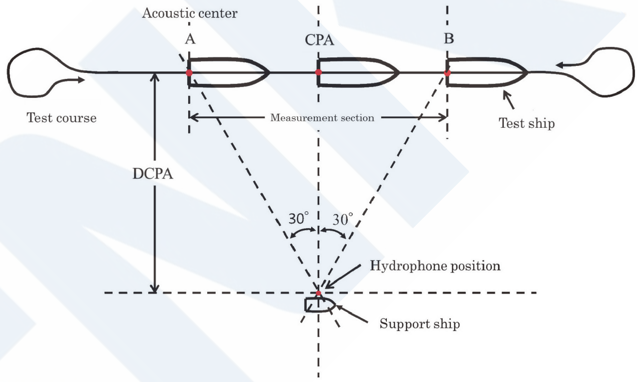

Fig. 3 Measurement configuration (test course, etc.)

Table 1 Reference noise levels (1/3 octave band)

Frequency	Critical sound pressure level (1/3 octave band) *dB* re 1μPa @1m			
f(*Hz*)	**SUN-Controlled**		**SUN-Advanced**	
20	175	SPL = 4.365 × LN(f) + 161.9	160	SPL = 4.365 × LN(f) + 146.9
50	179		164	
100	173	SPL= −8.288 × LN(f) + 211.3	158	SPL = −8.288 × LN(f) + 196.3
1,000	154		139	
10,000	135		120	

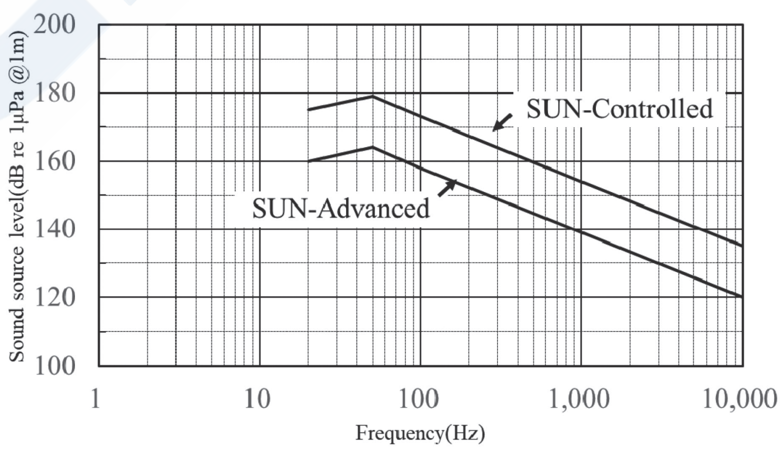

Fig. 4 Reference noise levels (1/3 octave band)

5. RESEARCH TRENDS, ETC. RELATED TO UNDERWATER NOISE FROM SHIPS AND DISCUSSIONS ON REVIEW OF THE IMO GUIDELINES

5.1 Trends in Research on Underwater Noise from Ships by Country

In the EU, two research projects related to underwater noise from ships, SATURN and PIAQUO, have been carried out.

SATURN is based on the perspective that environmental pollution by underwater radiated noise (URN) from ships may possibly interfere with communication, foraging and avoidance of predators by marine life, and consists of an interdisciplinary team centered on experts in bioacoustics. The purposes of the project comprise the following three items:

・To deepen understanding of the sources of URN and how they affect various marine species.
・To identify the effects of URN on marine ecosystems (including both short- and long-term effects).
・To develop solutions for mitigating these effects and reducing environmental pollution by URN.

The targets of research include measurement of the effects of URN from ships on marine life, development of standards and test methods for assessing those effects, and quantification of URN from commercial shipping and other types of ships, etc. As outcomes of this research, the project has published a report [4] on measurement of URN in shallow waters, which will be important for ensuring the effectiveness of URN management in the future, and a paper [5] showing that only a slight reduction in the speed of cargo ships greatly reduces the effects of noise on marine mammals.

PIAQUO is a project that began in 2019 with the aim of mitigating the impacts of noise caused by marine traffic on marine life by minimizing underwater noise pollution. This project centers on manufacturers, research institutes, etc. which conceive solutions that realize reductions in underwater noise. Companies [6] and others that develop and manufacture warships, sensors mounted on warships, etc. and have particularly strong expertise in underwater acoustics are also participating.

The main goals of the PIAQUO project are as follows:

・To develop improved propellers to reduce emissions of underwater radiated noise.
・To develop onboard systems for self-estimation of the level of URN generated in the surrounding environment and self-detection of cavitation in real time.
・To create a program targeting ship owners with the aim of raising awareness of reduction of emissions of URN, using a database that includes actual sound pollution data measured by acoustic buoys at sea.
・To create a mechanism for adjustment of marine traffic to the surrounding maritime ecosystem, by using real-time PAM (passive acoustic mapping) and AUV (autonomous underwater vehicles).
・To realize social implementation of decision-making tools for public institutions and private-sector stakeholders in order to address the problem of URN from ships.

The project has also presented a future image of underwater noise management which will integrate stationary buoys, shipboard systems and AUVs when these goals are achieved [7].

As outcomes of the project, evaluations of underwater noise from individual ships passing nearby by a stationary buoy installed in the Port of Genoa have already been carried out. The concept of the Noise Ship Index (NSI) was also developed by the project, and use of the NSI for tracking and recognition of the condition of URN, the condition of the progress of countermeasures, etc. as required by ship owners and managers is being considered [8].

In Canada, URN from ships calling at the Port of Vancouver is measured and evaluated on an ongoing basis. Reduction of ship URN is incentivized by the EcoAction Program [9], which gives preferential treatment such as reduction or exemption from the ship's harbor charges to quiet ships. When a ship classification society has assigned a notation indicating URN reduction measures, 75% of harbor charges will be reduced, the maximum rate of exemption available. In addition, the installation of propellers and other equipment manufactured by Japanese domestic manufacturers is also eligible for the exemption.

In Japan, the "Underwater Noise Countermeasures Study Project" has been underway since 2015 by the Japan Ship Technology Research Association (JSTRA) as part of "Survey Research on Ship Related Standards," a supported project of the Nippon Foundation. Various types of demonstration research are being carried out as part of this project. As one example, a study on the response behavior of humpback whales when ships pass was carried out by visual observation and acoustic measurement in the waters around Chichijima in the Ogasawara Islands, where regularly-scheduled passenger and cargo ships operate. As results of this study, it was suggested that it is difficult to think that exposure to the noise of the target ships caused damage of the auditory organs of the whales, and based on the results of an analysis of their behavior, it was not possible to obtain a clear conclusion that exposure to the ship noise had an adverse impact on their mode of life. A hydrophone array was also installed in the waters near Izu Oshima island, which has a water depth of approximately 300 m and is a navigation route for large merchant ships, and the underwater reflected noise levels from about 500 passing ships were acquired. The source levels were then obtained based on AIS information on the passing vessels and information on the seawater temperature distribution in the depth direction on the day of the measurement. That data has become the basic data for formulation of the reference noise levels of the Society's "Guidelines for Underwater Noise from Ships."

5.2 Discussions on Review of Guidelines for Underwater Noise

The 2014 Guidelines, once established, have not been adopted and implemented on a sufficient number of large merchant ships,, as well the accumulation of new technical innovations and scientific knowledge since that time, a new work program item (MEPC 75/14) proposed by Canada, Australia and the United States was discussed at MEPC 76 in 2021. In addition, 14 proposals were also submitted by a number of environmental groups and member countries, including European countries. As a result, a decision was made to begin a review of the existing 2014 Guidelines and deliberations on the subsequent action plan in the Sub-Committee on Ship Design and Construction (SDC). At the same time, a study on implementation of a global-scale project for mitigation of underwater noise from shipping (GloNoise Partnership) was also begun under the leadership of the IMO.

Following discussions over a 2-year period, the Revised Guidelines (MEPC.1/Circ.906; hereinafter, 2023 Guidelines) were adopted at MEPC 80 in 2023, targeting all commercial ships (cargo ships and passenger ships, new and existing ships) [10).

In addition, An "Experience-building phase (EBP)" until the end of 2026 was set, mainly to collect feedback on the Revised Guidelines, information related to best practice, and information for establishing mechanisms to realize noise reductions.

5.3 Overview of 2023 Guidelines

The largest change in the 2023 Guidelines was inclusion of provisions for the preparation of Underwater Radiated Noise (URN) Management Plans to ensure the effectiveness of reductions in underwater noise radiated from shipping. The main items described in those provisions are as follows.

- Setting of the baseline URN level (may be predicted or preferably measured)
- Setting of the target URN reduction level (can be gradually strengthened over a specified period)
- Description of URN reduction approaches, i.e., what technical and operational actions are to be taken by the ship
- Periodic monitoring and evaluation of the effects of URN reduction actions
- Roles of main parties related to the URN Management Plan

Under the 2014 Guidelines, the only stakeholders that made commitments to reduce URN were ship designers, manufacturers and operators. However, the 2023 Guidelines expanded the stakeholders as follows and specified their roles.

- Shipowners: Develop and implement the URN Management Plan.
- Shipbuilders: Design and build the ship to meet URN specifications.
- Ship operators: Operate the ship to meet URN targets and any additional regional requirements.
- Maritime authorities of the flag state: Take supportive actions in the form of incentives.
- Ship classification societies: Assist shipowners and builders through predictions of URN, URN measurement and testing in actual waters, certification, etc.

Workflow charts for implementing these provisions have been compiled by the IMO. An excerpt is shown in Fig. 5.

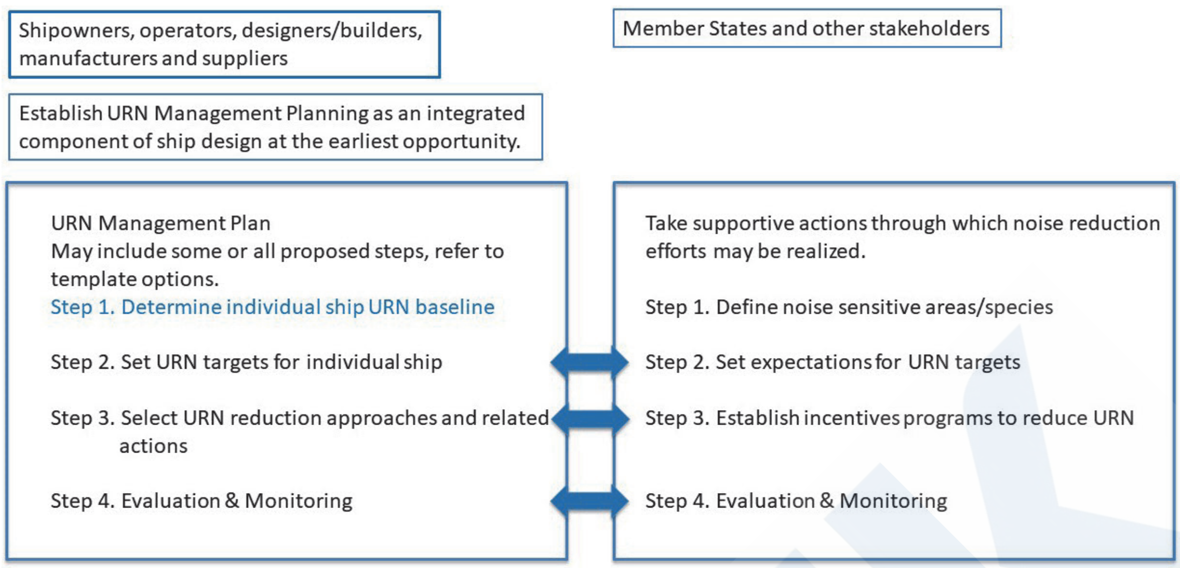

Fig. 5 Workflow chart of 2023 Guidelines (excerpt)

6. RESPONSE OF THE SOCIETY TO THE 2023 GUIDELINES

The 2023 Guidelines state that the role of ship classification societies is to “assist shipowners/builders through predictions, trials, relevant URN notations, certification, etc. as reasonable and practicable.” Classification societies are expected to participate in each of the Steps of URN Management Planning on the left side of Fig. 5. Here, Step 1 Determine the baseline URN of the individual ship, specifies that “The baseline URN is to be predicted or preferably actually measured under normal operating conditions using the standard equipment/engines.” The 2014 Guidelines followed the measurement method in ISO 17208-1, -2 for measurements in deep waters, where the effect of sea surface reflection, etc. is slight. However, examples of measurements of large merchant ships were limited, as there is no economic incentive due to the high cost of such measurements. In the future, it is considered likely that measurements will conform to the URN measurement method in shallow waters described in ISO 17208-3, which is reasonable and economically practicable. Formal approval of ISO 17208-3 is expected during 2025. However, there are issues related to measurement accuracy, such as elimination of the effect of sea surface reflection, calibration of the trial sea surface, etc. For a discussion of the technical issues related to URN measurement in shallow waters, please see “Measurement of Ship Noise in Shallow Water” in this issue of ClassNK Technical Journal.

Appendix 2 of the 2023 Guidelines presents the following items as types of computational models for optimization of ship design and technical URN reduction approaches.

1. Flow characteristics (fluid noise): Underwater radiated noise generated by cavitation, etc. can be predicted by techniques for analysis of flow field around the ship’s hull and propeller performance using CFD, etc.
2. Noise radiation (structural noise): URN originating from the main engine, etc. can be predicted by using analytical techniques such as FEM, BEM, SEA, etc.
3. Noise propagation in water: The effect of URN from a ship on the targeted marine species, etc. can be predicted by long-range sound propagation modelling methods such as ray theory, the normal mode method, etc.

Since these techniques are also in a region which is closely related to military applications, represented by anti-submarine warfare, care is considered necessary so as not to introduce excessive regulations for general commercial ships based on the advanced military technologies. The Society has carried out a study on a simple estimation method for flow characteristics in 1. above. For a commentary on the results of that research, please see “Development and Use of Ship Underwater Noise Prediction Tool for Preservation of the Marine Environment” in this issue.

Although the Society will also carry out work on each step of the URN Management Plan from Step 2 to Step 4 in the future, the basic concepts are as follows.

Step 2. Set desired values for target URN:

Since the reduction target from the baseline URN is specified by setting an absolute reduction value, a reduction ratio, or other values that conform to the rules of the classification society for underwater noise from ships, etc., the Society will collect and disseminate relevant information.

Step 3. Establish an incentive program for URN reduction:

The Guidelines specified that a design approach, operational technologies, or a combination of those approaches is to be identified and selected. The Society plans to study assigning notations to the classification characters of ships that install hull appendages, adopt optimum operational techniques, etc. for URN reduction.

Step 4. Evaluate and monitor effects:

The Guidelines specify periodic evaluations of the effectiveness of URN reduction approaches, and a response when necessary. Therefore, the Society will study certification of shipboard URN monitoring systems, standardization of hull cleaning, etc.

At present, there is a feeling that the eventual form of regulations on URN is still unclear. However, as a ship classification society, ClassNK will continue to deepen its dialogue with related stakeholders, develop methods, tools, etc. that are "reasonable and practicable," and endeavor to resolve the concerns of stakeholders regarding underwater radiated noise from shipping.

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Development and Application of Ship Underwater Radiated Noise Estimation Tool for Preservation of the Marine Environment

Koichiro SHIRAISHI*

1. INTRODUCTION

The effects of underwater radiated noise (URN) generated by commercial shipping on marine ecosystems have become important issues in the International Maritime Organization (IMO). At the 66th session of the Marine Environment Protection Committee (MEPC 66) held in April 2014, "GUIDELINES FOR THE REDUCTION OF UNDERWATER RADIATED NOISE FROM COMMERCIAL SHIPPING TO ADDRESS ADVERSE IMPACTS ON MARINE LIFE" (MEPC.1/Circ.833) was approved. While these Guidelines are not mandatory, they present directions for the reduction of underwater radiated noise (URN) in each of the stages of ship design, construction, operation and maintenance. Subsequently, a draft revision of the Guidelines was prepared at the 9th session of the Sub-Committee on Ship Design and Construction (SDC 9) in January 2023, and the draft revision was approved as "REVISED GUIDELINES FOR THE REDUCTION OF UNDERWATER RADIATED NOISE FROM SHIPPING TO ADDRESS ADVERSE IMPACTS ON MARINE LIFE" (MEPC.1/Circ.906) at MEPC 80 in July of the same year. The revised guidelines include new provisions related to the development of underwater radiated noise management plans (URN management planning). URN Management Plans consist of the elements of setting standard values and development of reduction targets for URN generated by ships, technical and operational reduction methods, and periodic monitoring and evaluation.

With this situation as background, the National Maritime Research Institute (NMRI) has been carrying out research on a simple estimation method for calculating the URN level of actual ships. Previous research has shown that the velocity effect of propeller cavitation noise of actual ships can be understood by an equation that combines Brown's formula and HOPE Light (a ship performance estimation program developed by the NMRI) [1]. To improve URN estimation accuracy, the cavitation area estimation method has also been enhanced[2]. The cavitation area has been estimated by numerical analysis while varying the main parameters such as the propeller rotational speed and advance coefficient, the cavitation number, etc., and a database has been constructed from the results. Based on this database, a practical cavitation area estimation chart (DB chart) has been prepared. The cavitation area was estimated using the DB chart, and the accuracy of the simplified estimation method has been improved by calculating the URN level using those values and Brown's formula.

This paper introduces the simplified estimation method for URN developed by the NMRI. Furthermore, it presents a comparison between the actual measurement results of URN emitted by a bulk carrier off the southern coast of Oshima Island and the estimated results obtained using the simplified estimation method, to evaluate the effectiveness of the proposed approach.

2. SIMPLIFIED ESTIMATION METHOD FOR UNDERWATER RADIATED NOISE

The proposed method calculates URN levels using Brown's formula, which is a simplified estimation formula for URN. The parameters required for Brown's formula are estimated using "HOPE Light," a hull form optimization program developed by NMRI [4]. AIS data from target ships are used as input data for HOPE Light. In the conventional method, the cavitation area had been estimated using the Burrill cavitation diagram [5], but because the Burrill diagram is primarily intended for high-speed vessels, the cavitation area tended to be underestimated when this method is applied to general merchant ships. Therefore, in the simplified estimation method, a "DB chart," which is a cavitation area estimation chart for general merchant ships, was newly constructed with the aim of improving the accuracy of estimations of the cavitation area by using this chart, and as a result, also improving the accuracy of the URN estimation method. The following sections explain the specific URN level estimation method.

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2.1 Brown's Formula

The proposed method estimates ship URN using Brown's formula [3]. Brown's formula, shown in Eq. (1), is an empirical formula derived from actual ship URN measurement results. The use of Brown's formula makes it possible to estimate the upper limit of the underwater sound pressure level (SPL) over a wide frequency range of approximately 100 Hz to 10 kHz based on the propeller rotational speed, propeller diameter, number of propeller blades (blade count), and the cavitation area.

$$SPL = 10\log\left(\frac{n^3 D_p^4 Z}{f^2}\right) + 10\log\left(\frac{A_c}{A_D}\right) + K \tag{1}$$

Where, SPL: underwater sound pressure level [dB], f: frequency [Hz], K: constant (propeller: K=163, thruster: K=170), n: propeller rotational speed [rps], D_p: propeller diameter [m], Z: number of propeller blades [–], A_C/A_D: cavitation area ratio [–], A_C: cavitation area [m^2] and A_D: propeller disc area [m^2].

In the proposed method, the parameter n and D_p necessary in Brown's formula are estimated using HOPE Light. An outline of HOPE Light is presented in the following section 2.2. The number of propeller blades was set to 4, and the cavitation area ratio A_C/A_D is estimated from the DB chart prepared using numerical calculations. An outline of the DB chart is presented in section 2.3.

2.2 HOPE Light

The parameters necessary for estimation of the URN level of a target ship were estimated by using "HOPE Light," a program for optimization of the hull form dimensions of ships developed by NMRI [4]. This program can obtain not only the propulsion performance of the target ship, but also the maneuverability, course stability and other operational performance characteristics of the ship. As one distinctive feature, it can also estimate the fuel consumption of the main engine, auxiliary engines, etc., suited to the target ship.

As the basic input for HOPE Light, the ship type and principal particulars are necessary. These input data can be obtained from the AIS data and the principal particulars database. The parameters necessary for Brown's formula, which is a simple estimation formula for URN level, are extracted from the calculation results obtained from HOPE Light. In the simplified estimation method, Excel sheets were prepared for the URN level estimations, and the URN levels were calculated through integration of these sheets and HOPE Light.

2.3 DB Chart

In the proposed URN estimation method, DB charts were newly developed for typical merchant ships. First, the propeller to be used as a standard is selected, and propeller groups are formed by revising its pitch and expanded blade area. The cavitation area for these propeller groups is calculated for various propeller loads and cavitation numbers, and DB charts are then constructed by arranging the cavitation area data obtained from the numerical calculations.

The cavitation area is estimated using the lift equivalent method [6]. The method used in calculations of the pressure distribution on the propeller blade surface during wake flow, which is necessary for application of the lift equivalent method, is the unsteady marine propeller performance calculation method [7, 8] based on the simplified surface panel method (SQCM: Source and Quasi-Continuous Method), which was developed by Kyushu University.

The MAU propeller is used as the prototype propeller for creation of the DB charts [9]. The number of propeller blades was set to 4. Twenty propeller groups were created by varying the propeller pitch ratio and the expanded blade area ratio. Three kinds of wake distributions were used: the JBC (Japan Bulk Carrier) [10], KCS (KRISO Container Ship) [11] and the KVLCC2 (KRISO Very Large Crude Carrier) [11] (KRISO: Korea Research Institute of Ships and Ocean Engineering). The wake distributions of these three ship types are shown in Figs. 1-3. The details of the DB charts are shown in Table 1. The cavitation area estimation charts were prepared by estimating the largest cavitation areas of the 20 propeller groups for these three types of wake distributions by varying the propeller loading and the cavitation number, and arranging the results. In this paper, for example, when the target propeller (MAU) has an expanded blade area ratio a_E= 0.6 and a pitch ratio H/D_P = 0.6, the propeller is denoted as MAU0606, and when the wake distribution is the JBC and the target propeller is MAU0606, the DB chart is denoted as JBC-MAU0606.

Table 1 Detail of cavitation area estimation charts

Item	Num. of items	Parameter
Propeller Blade	1	MAU
Expanded Blade Area Ratio (a_E)	4	0.4, 0.5, 0.6, 0.7
Pitch Ratio (H/D_P)	5	0.6, 0.7, 0.8, 0.9, 1.0
Wake Distribution	3	JBC, KCS, KVLCC2
Number of Charts	60	-

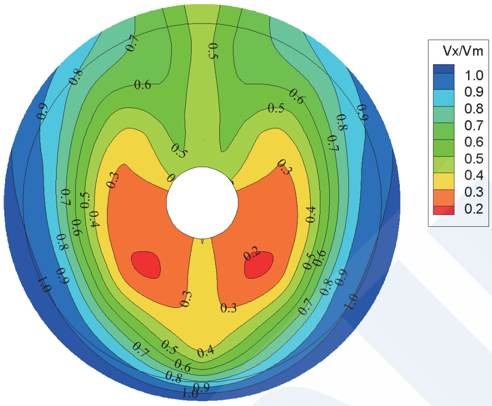

Fig. 1 Wake distribution of JBC

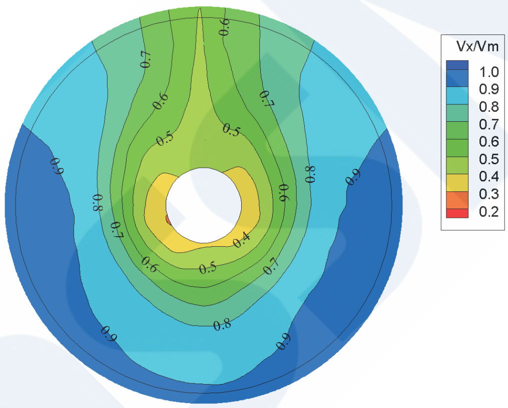

Fig. 2 Wake distribution of KCS

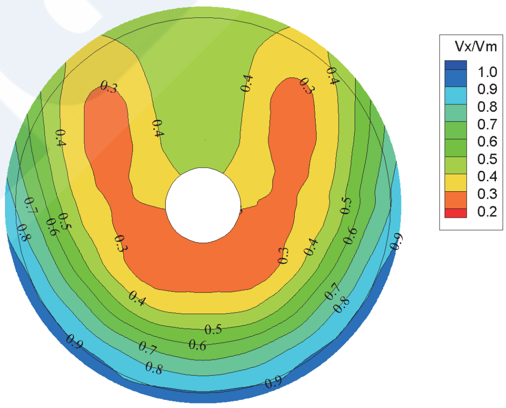

Fig. 3 Wake distribution of KVLCC2

As examples of the DB charts prepared in the simplified estimation method, the results of estimations of the cavitation areas of the following six types of propellers with the JBC wake distribution are shown in Figs. 4-9.

· Expanded blade area ratio series: JBC-MAU0506, JBC-MAU0606, JBC-MAU0706

· Pitch ratio series: JBC-MAU0607, JBC-MAU0608, JBC-MAU0609

Fig. 4 to Fig. 9 show the cavitation coefficient (cavitation number) $\sigma_{0.7R}$ on the *x*-axis and the propeller load τ_c on the *y*-

axis, and give the upper limit at which cavitation will not occur. $\sigma_{0.7R}$ and τ_c are expressed by Eq. (2) and Eq. (3), respectively. The circumferential velocity V_R at the 0.7 R position on the propeller radius is expressed by Eq. (4).

$$\sigma_{0.7R} = \frac{p - e}{1/2\rho V_R^2} \tag{2}$$

$$\tau_C = \frac{T}{1/2\rho A_P V_R^2} \tag{3}$$

$$V_R = \sqrt{V_A^2 + (0.7 D_P \pi n)^2} \tag{4}$$

Where, τ_c: propeller load [–], T: thrust [N], ρ: density of fluid [kg/m^3], A_p: projected area of propeller [m^2], V_A: propeller inflow velocity [m/s], V_R: circumferential velocity at propeller radius 0.7 R position [m/s], $\sigma_{0.7R}$: cavitation number (at 0.7 R position) [–], p: water pressure at propeller radius 0.7 R position [Pa], e: pressure of water vapor [Pa] and D_p: propeller diameter [m].

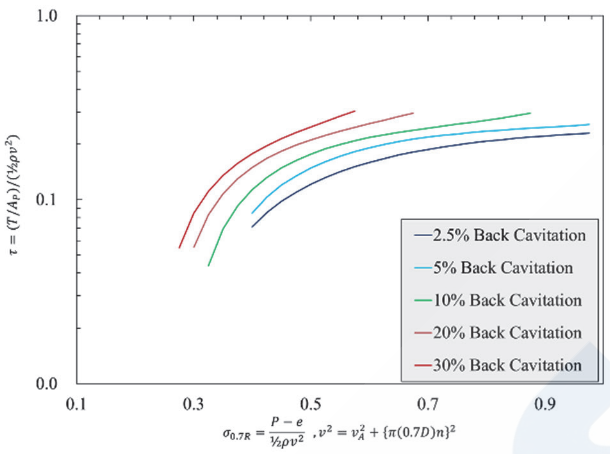

Fig. 4 Cavitation area estimation chart: JBC-MAU0506

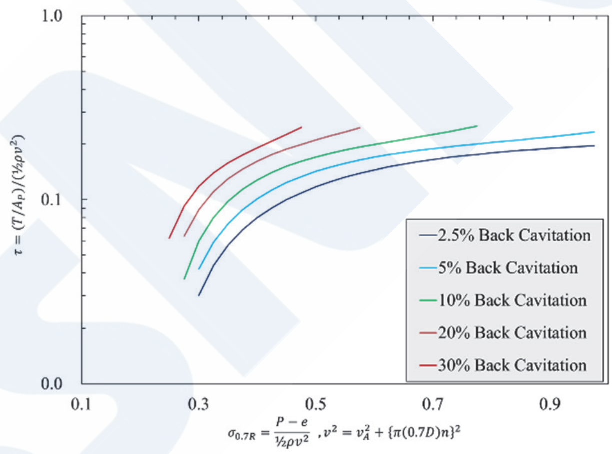

Fig. 5 Cavitation area estimation chart: JBC-MAU0606

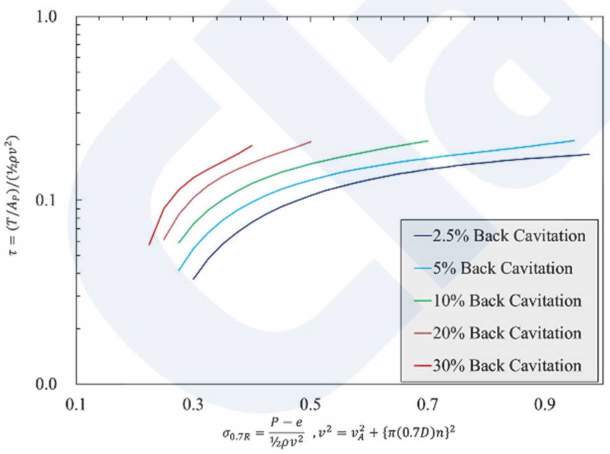

Fig. 6 Cavitation area estimation chart: JBC-MAU0706

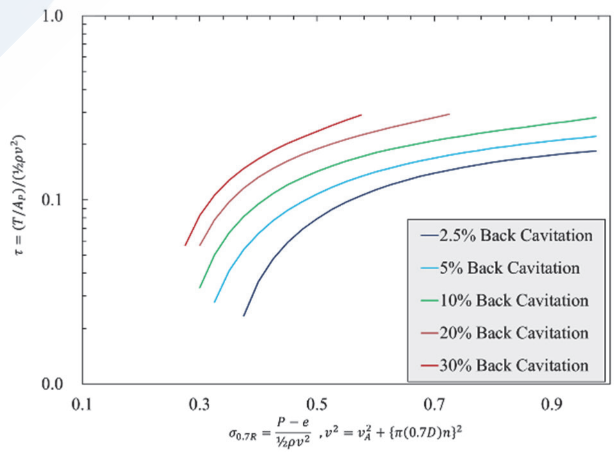

Fig. 7 Cavitation area estimation chart: JBC-MAU0607

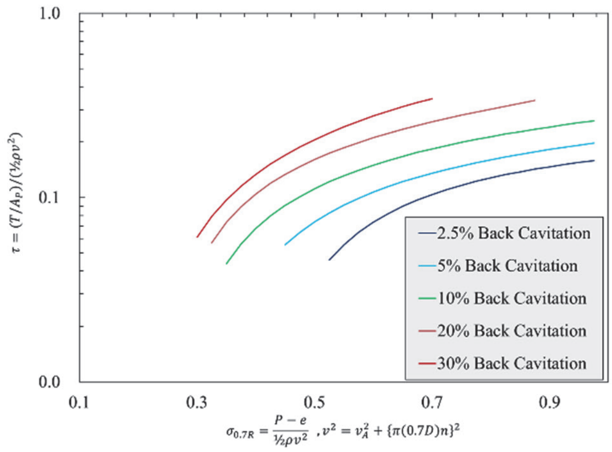

Fig. 8 Cavitation area estimation chart: JBC-MAU0608

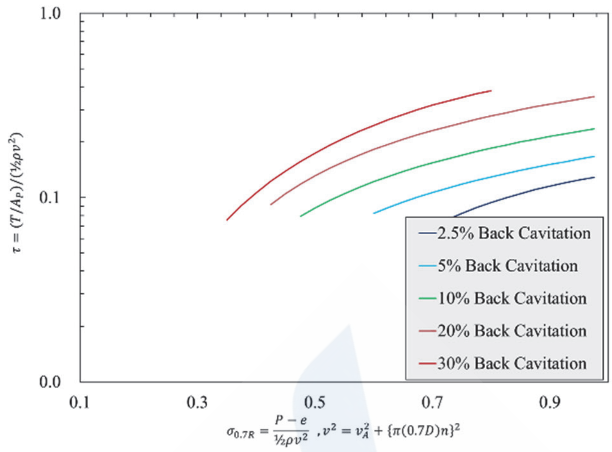

Fig. 9 Cavitation area estimation chart: JBC - MAU0609

2.4 Method of Implementation in URN Estimation Method

The DB charts described in section 2.3 were incorporated into HOPE Light, and a function for estimating the cavitation area from the DB charts was added. Specifically, in this system, the pitch ratio and expanded blade area ratio of the propeller of the target ship, which are output from HOPE Light, and the DB chart corresponding to the wake distribution of the target ship are searched. Then, based on the searched chart, the cavitation area corresponding to the propeller load and the cavitation number of the target ship output from HOPE Light is calculated. Finally, the URN level of the target ship is estimated by substituting that result (cavitation area) into Brown's formula.

3. VERIFICATION BY ACTUAL SHIP MEASUREMENT DATA

A comparative study with the URN data obtained by measurement of actual ships was conducted to verify the accuracy of the improved URN estimation method. The verification work related to the accuracy of the improved method was carried out by comparing the values of underwater radiated noise in the waters off the southern coast of Oshima Island, which were collected in the Underwater Noise Countermeasures Study Project in the past, and the calculated results obtained by this URN estimation method.

3.1 Outline of Actual Ship Measurements Off Southern Coast of Oshima Island

In the Underwater Noise Countermeasures Study Project, hydrophones were installed in the waters off the southern coast of Oshima Island, and URN data from ships sailing in the vicinity were collected. Using these actual ship measurement data, a comparative study between the URN estimation method adopted in the present research and the actual ship measurement data was conducted. The details of the actual ship measurement data are described in the paper by Sakai *et al.* [12]. The objective of the present analysis was actual ship measurement data for large ships with a length between perpendiculars L_{pp} of 100 m and longer. From the measurement data for these large ships, data where tidal current effects were limited and cruising speeds closely matched design speeds were selected. The following filtering conditions were applied:

・Data with a difference ≥1 kt between AIS speed over ground and speed through water were excluded due to significant tidal current effects.

・Data in which the ship's speed at the time of measurement was <30 % of its design speed were excluded as abnormal values.

Five bulk carriers were extracted from the selected actual ship measurement data, and the level of URN was estimated for each ship and compared with the actual ship measurement results. The principal particulars of the extracted target ships are shown in Table 2.

3.2 Comparison of Actual Ship Measurement Results and Estimation Results

Using the conventional and improved URN estimation methods, the URN levels of the actual ships were estimated for the target ships described in section 3.1, and the estimation results and actual ship measurement results were compared. Fig. 10 to Fig. 14 show the actual ship measurement results of the bulk carriers and the URN estimation results obtained by the conventional estimation method and improved estimation method. In these figures, the blue marker line shows the actual ship measurement results, the dark blue broken line shows the estimation results of the conventional method, and the red solid line shows the estimation results obtained by the improved method. From Fig. 10 to Fig. 14, compared with the conventional method, the estimated values of the URN level obtained with the improved method increased and approached the actual ship measurement values.

Table 2 Principal particulars and ship speeds of bulk carriers used for verification

No.	L_{pp} [m]	B[m]	D[m]	Vs[kt]
203	195	32	13	10
208	225	32	15	14
231	178	32	12	14
246	229	43	14	12
282	288	45	18	13

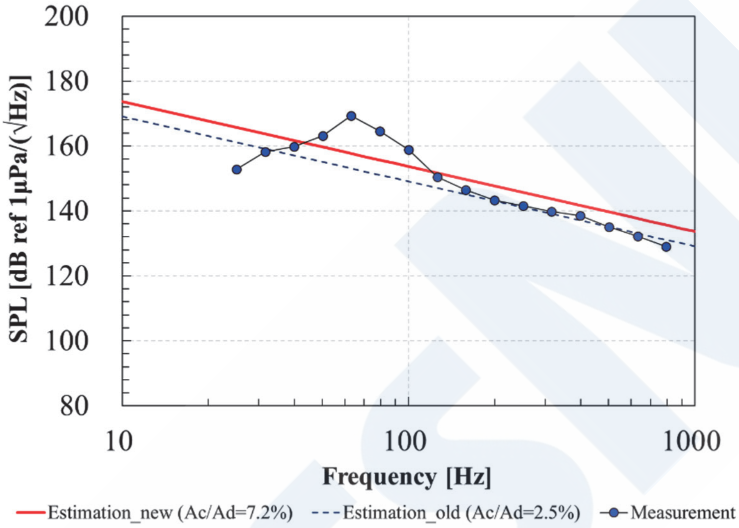

Fig. 10 The results of No.203 bulk carrier (L_{pp}=195m, Vs=10kt)

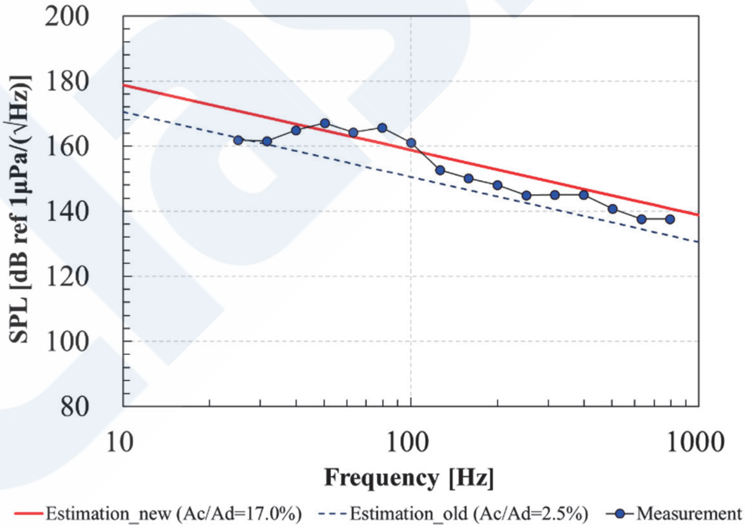

Fig. 11 The results of No.208 bulk carrier (L_{pp}=225m, Vs=14kt)

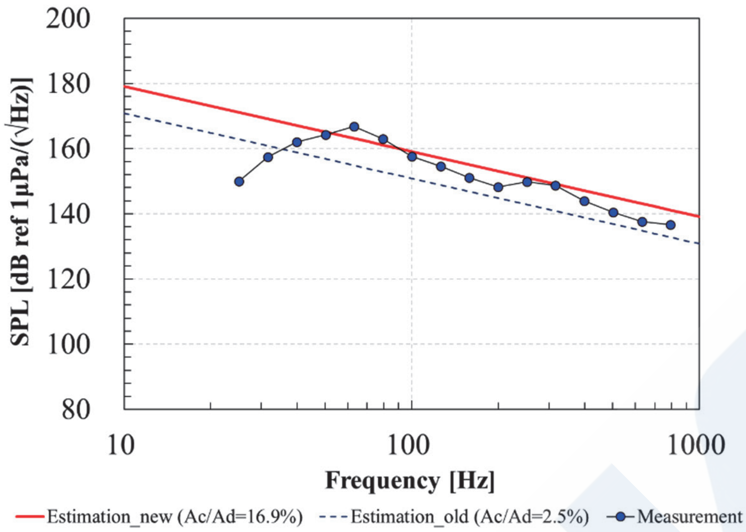

Fig. 12 The results of No.231 bulk carrier (L_{pp}=178m, Vs=14kt)

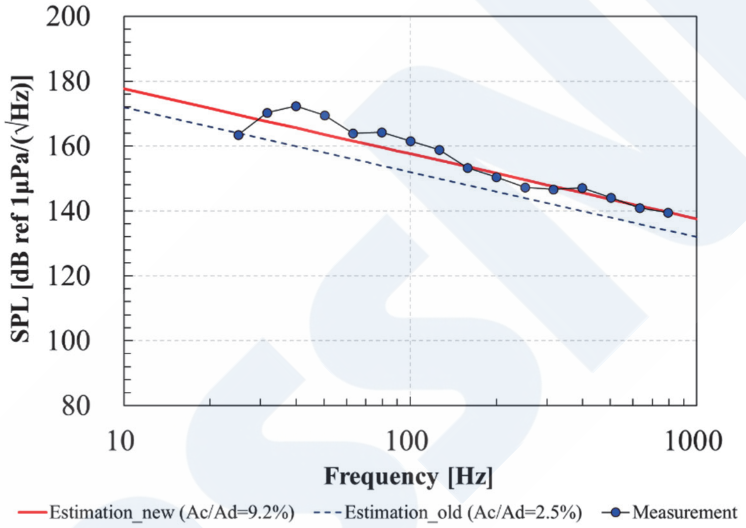

Fig. 13 The results of No.246 bulk carrier (L_{pp}=229m, Vs=12kt)

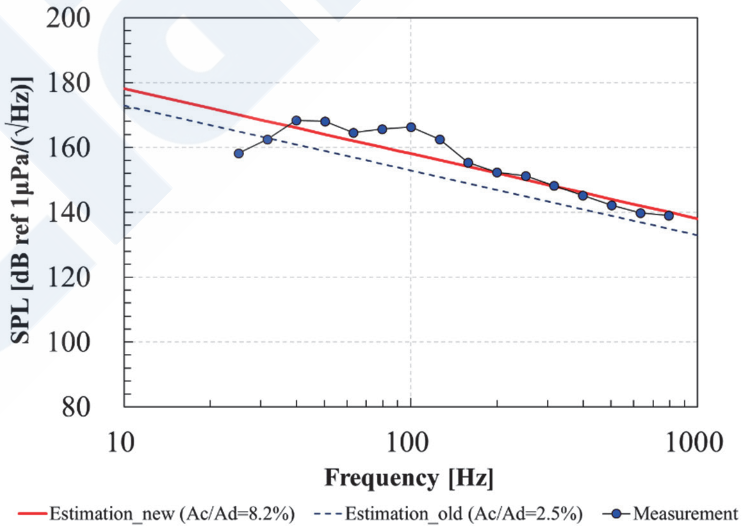

Fig. 14 The results of No.282 bulk carrier (L_{pp}=288m, Vs=13kt)

3.3 Discussion

To quantitatively evaluate the actual ship measurement results and estimated values by the URN estimation methods presented in section 3.2, the error between the two sets of results was evaluated. The RMSE (Root Mean Square Error) of the measurement results and the estimated values at the center frequencies of each 1/3 octave band was calculated, and the estimation accuracy was verified by comparing the RMSE of the conventional method and the improved method. The center frequencies in this evaluation are 25, 32, 40, 50, 63, 79, 100, 126, 158, 200, 251, 316, 398, 501, 631 and 794 [Hz]. Table 3 and Fig. 15 show the RMSE evaluation results for the bulk carriers. Compared with the RMSE of 7.0 [dB] of the conventional method, the RMSE of the improved method was 5.2 [dB], representing an accuracy improvement of approximately 1.8 [dB] (approximately 26 %). This result shows that the accuracy of the URN estimation method can be improved significantly by adopting the cavitation area estimation charts that consider the propeller geometry and wake distribution. As the main factor for the increased accuracy of the improved method, more accurate estimation of the cavitation area reflecting the propeller geometry is now possible by using cavitation area estimation charts that consider the propeller pitch ratio and expanded blade area ratio, as well as the wake distribution, resulting in enhanced accuracy in estimation of the cavitation area.

Table 3　Results of RMSE assessments of bulk carriers

No	L_{pp} [m]	*Vs*[kt]	*RMSE_old*[dB]	*RMSE_new*[dB]
203	195	10.2	6.6	6.2
208	225	13.5	6.6	4.6
231	178	14.0	6.9	6.9
246	229	11.7	7.6	3.4
282	288	13.1	7.4	4.7
		Average	7.0	5.2

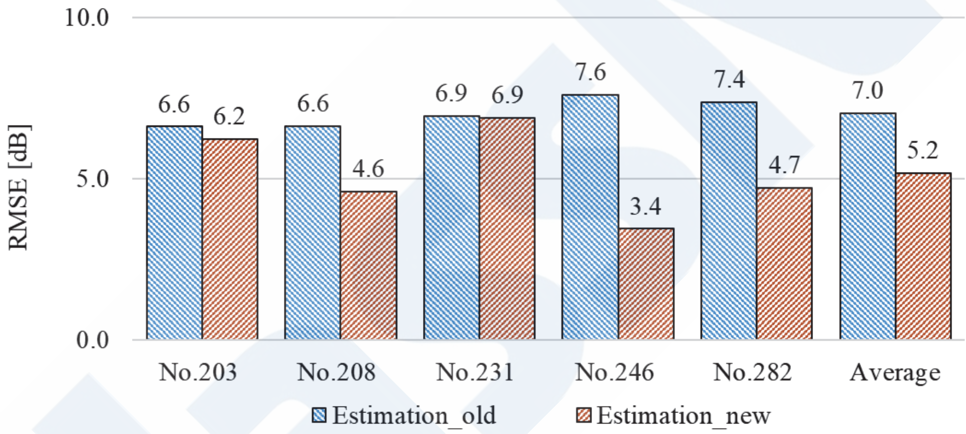

Fig. 15　Comparison of RMSEs for bulk carriers

4.　CONCLUSION

This paper has introduced the simplified estimation method for estimating URN levels of merchant vessels using design-stage information. The method constructs database (DB) charts for estimating cavitation areas of typical merchant ships and improves URN estimation accuracy by combining these charts with Brown's formula.

The key features and achievements of the proposed method are:

・Enhanced cavitation area estimation accuracy compared to conventional Burrill chart methods through the development of DB charts based on numerical calculations for merchant vessels.

・High-accuracy cavitation area estimation considering propeller geometry and stern wake distribution through the use of DB charts that account for propeller pitch ratio, expanded blade area ratio, and wake distribution.

・Validation through comparison with actual vessel measurement data obtained in waters off southern Oshima Island, demonstrating improved estimation accuracy for all five examined bulk carriers compared to the conventional method.

・Quantitative accuracy improvement shown by RMSE evaluation at 1/3 octave band center frequencies, where the average RMSE decreased from 7.0 dB (conventional method) to 5.2 dB (proposed method), representing approximately 26% improvement in estimation accuracy.

The proposed method is expected to serve as an effective tool for evaluating URN during ship design phases and developing

URN management plans in compliance with IMO guidelines.

ACKNOWLEDGEMENT

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Measurement of Ship Noise in Shallow Sea Area

Tomoki MURAYAMA*

1. INTRODUCTION

In July 2023, IMO/MEPC80 approved a revised version of the non-mandatory circular *Guidelines for the Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life,* which include provisions to assist shipowners with the development of underwater noise management plans. In line with this, in October 2023, ClassNK (hereinafter, the Society) issued new guidelines entitled "Guidelines for Underwater Noise from Ships (Edition 1.0) " (hereinafter, 2023 Guidelines)[*1]. In addition to measurement of underwater noise from ships in deep waters in accordance with the provisions of ISO 17208-2 specified in the 2023 Guidelines, the ISO is also drafting new provisions, ISO 17208-3, for shallow sea area, where measurement is easier, and an empirical evaluation of that measurement method is underway in the EU's Saturn Project.

Based on those moves, the Society is now studying a system that considers restrictions unique to Japan, for example, water depth and ocean currents, navigation routes, etc. This article introduces a portion of that study concerning ship noise measurement in Japan's coastal waters (shallow sea area).

2. NOISE MEASUREMENT IN THE 2023 GUIDELINES

The 2023 Guidelines present details of measurements of ship noise. The measurement conditions are arranged in simple terms in the following.

2.1 Measurement Points (Excerpted from 2023 Guidelines, Section 5.2)

The following two measurement points are specified.

(1) Water depth: 150 *m* or more, or more than 1.5 *times* the length of the ship, whichever is greater.

(2) Sea area where there is no traffic congestion.

* As the reason or setting these points, it can be understood that (1), the maximum wavelength of the generated frequency of noise is considered based on the size of the generation source, and (2), the intention is to ensure the safety of measurements and reduce the effects of background noise on measurements.

2.2 Measurement Conditions (Excerpted from 2023 Guidelines, Section 5.3)

The 2023 Guidelines specify the Beauford scale wind force, wave scale, main engine output, etc.

* It can be understood that the purpose is to grasp the magnitude of the signal levels of the measurement target and background noise during the measurement.

2.3 Measurement Procedure (Excerpted from 2023 Guidelines, Section 5.4)

The following procedure is described.

(1) Measurements are to be conducted by personnel familiar with the use of the equipment.

(2) Only personnel necessary for ship operation and measurement purposes are, in principle, to be allowed on board the ship during the measurement.

(3) Measurement sections are to be in the range of ±30 *degrees* from the center of the hydrophone array.

(4) The number of navigations and measurements is to be twice with the hydrophone array on the starboard side and the port side.

(5) The distance to the Closest point of Approach (DCPA) to the hydrophone array is to be 100 *m* or the ship's length, whichever is greater.

* Oki Electric Industry Co., Ltd.

*1 "Guidelines for Underwater Noise from Ships (Edition 1.0)" issued by ClassNK in October 2023.

(6) The hydrophones used in the measurements are to be omni-directional, and are to be the bottom-mounted type, the floating buoy type or the floating line type lowered from a support ship. Three hydrophones are to be used.

(7) The hydrophones are to be calibrated in advance.

(8) The frequency band is to be 10 *Hz* to 10 *kHz*.

Although the author attempted to extract the key points in the above, these requirements are specified in considerable detail. The following proposes a measurement environment for ship noise measurement in shallow sea area, considering the issues for measurements and their countermeasures, while utilizing these provided measurement parameters.

3. TWO METHODS CONSIDERING DIFFERENCES IN THE MEASUREMENT METHODS

Figs. 1 and 2 on the following page show the image of measurements by a floating type hydrophone array and a bottom-mounted type hydrophone array based on the provisions of the Guidelines presented in the above Chapter 2. When the hydrophones are arranged at relative angles of ±30° with respect to the ship being measured (target ship), the guidelines specify that the water depth is to be at least 1.5 times the ship's length. Therefore, assuming the ship's length is 100 m and the water depth is 150 m, a horizontal distance of 100 m from the CPA (Closest Point of Approach) to the measurement system at this time is necessary. Similarly, if the ship's length is 400 m, the required water depth is 600 m and the distance from the CPA to the receivers is 400 m. Considering the distance required to stabilize the ship's speed of movement toward the CPA and turn in order to measure the port side and starboard side, the sea area necessary in the measurement is assumed to be roughly several km^2.

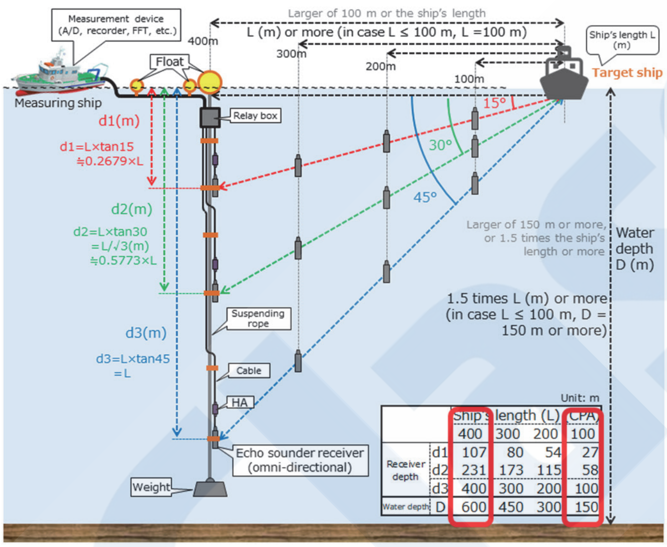


Fig. 1 Image of measurement by floating buoy type

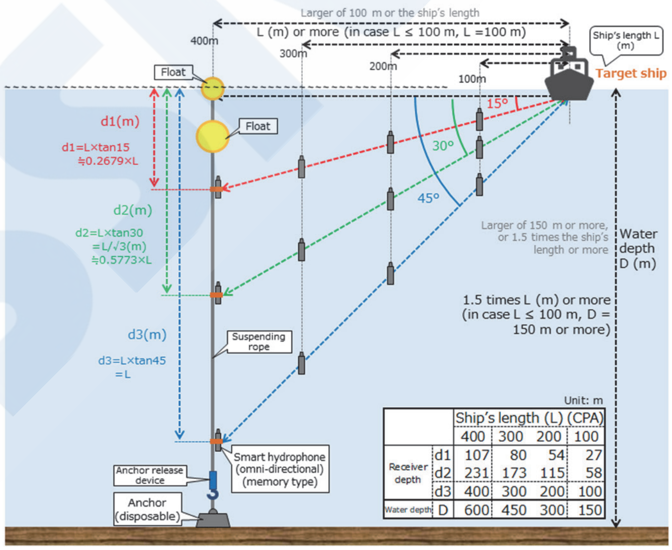


Fig. 2 Image of measurement by bottom-mounted type

With the bottom-mounted hydrophone method in Fig. 2, it would also be possible to use a measuring ship, as show in Fig. 1. However, permanent installation is preferrable considering the difficulty of setting and raising and recovering the hydrophone array, and it is more efficient to install optical fiber and electric cables, etc. to nearby land for the measurements and supply of electric power by wire, and carry out the measurements from a land-based measurement station. Since a mooring type array would be installed permanently at sea in this case, and may become an impediment to navigating ships, it would be necessary to restrict entry into the sea area concerned, inform other ships that may use those sea areas, install warning buoys, etc. Moreover, during measurements by either the floating type or the bottom-mounted type, it may also be necessary to deploy a warning vessel, etc., depending on the circumstances.

4. ISSUES IN ACOUSTIC MEASUREMENTS AND THEIR COUNTERMEASURES

4.1 Issue during Measurements

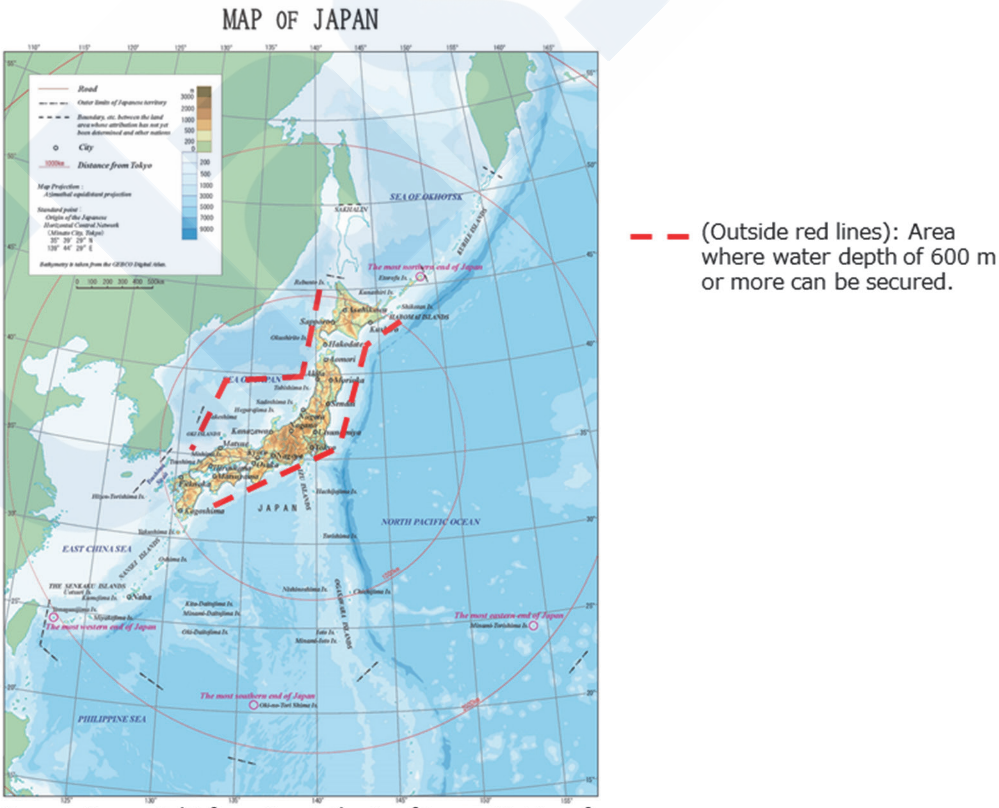
First, let us narrow the candidate sea areas to cases in which the required water depth of 600 m is secured purely for the ship length of 400 m, as described above. In Fig. 3 on the next page, the candidate areas in the seas around Japan are roughly outside the red dotted line. Although cases where ocean trenches exist nearby are excluded, sea areas where measurements are possible cannot be reached without traveling about 100 km from the coast. Moreover, even if the measurement point is reached, the cost of installing and maintaining a permanent bottom-mounted measurement array (shown in Chapter 3, Fig. 2) is easily expected to be enormous. The floating type (Chapter 3, Fig. 1) might be a possible method, but even if it is possible, it can easily be assumed that the cost would increase substantially, considering the entire process from traveling to the measurement area, setting the hydrophone array and preparation for the measurement to completion of the measurement.

This suggests that measurement of ship noise in accordance with the 2023 Guidelines might itself be possible by traveling to waters where the depth is greater than 600 m, but as described above, the measurement scale and the measurement term involved would be prohibitive. Thus, the first issue that can be assumed when envisioning practical use is the fact that "Measurement points are limited to locations that are distant and require excessive time and labor."

Conversely, let us consider what kind of location and timing of measurements would reduce the burden on ship owners in the operational aspect. First, as the timing of measurements, the time of new ship construction, or the time of maintenance (statutory survey) is considered favorable.

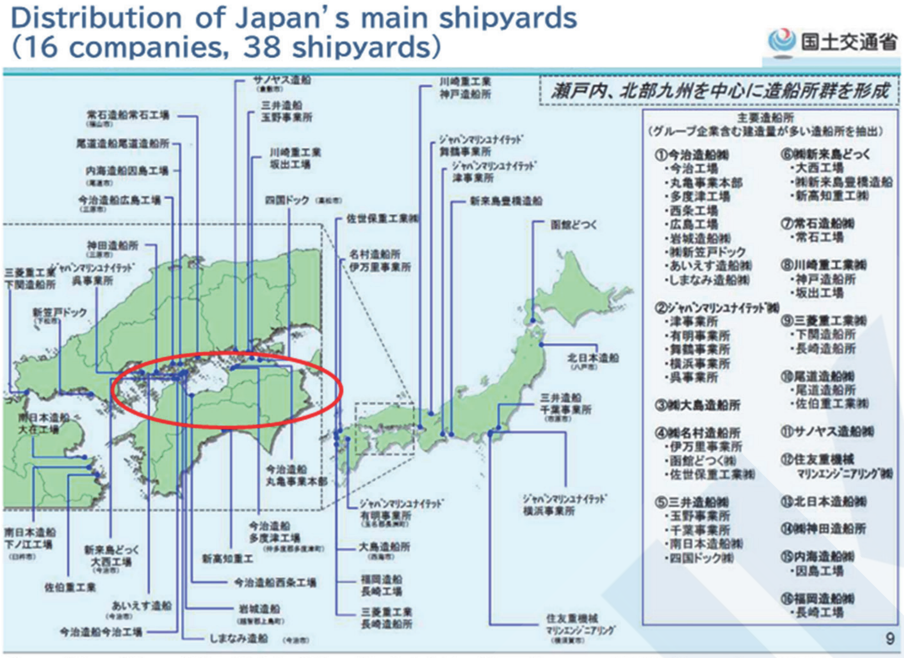
Next, regarding the location, measurement near the shipyard, if possible, would be preferrable, and the Seto Inland Sea, where Japan's main shipyards are concentrated, was assumed as the operating area. Therefore, let us begin the study of the measurement system based on these conditions. Fig. 4 on the next page shows the distribution of the main shipyards in Japan. If measurements of ship underwater noise are conducted during new building and maintenance (statutory survey), it would be desirable to be able to perform the measurements near these shipyards.

However, as the reader may know, it is difficult to secure even a water depth of 100 m in the Seto Inland Sea, much less the above-mentioned depth of 600 m.



Source: Geospatial Information Authority of Japan, Ministry of Land, Infrastructure, Transport and Tourism (MLIT)

Fig. 3 Water depth in seas around Japan



From "Condition of the Shipbuilding Market," Maritime Bureau, MLIT, December 2017

Fig. 4　Distribution of main shipyards in Japan

In this connection, in the first place, although the 2023 Guidelines require a "water depth of 150 m or more, or 1.5 times the ship's length or more, whichever is greater," let us consider separating this restriction from the technical considerations. First, at a glance, the reason for assuming this in the 2023 Guidelines is that the object of measurement is frequencies of 10 Hz and higher. Since the speed of sound = frequency x wavelength, it seems possible that this might be derived by conversion to a single wavelength of 150 m at the frequency of 10 Hz. However, against the background of the modal theory of propagation, when considering propagation in the horizontal mode, horizontal propagation as such is considered possible even at a water depth of primary mode 37.5 m (= 1/4 wave length = 150 m/4 m). (The propagation cutoff frequency diagram is discussed later in this paper.)

As a second reason for assuming this requirement, since it is desirable to eliminate to effects of sea surface and sea bottom reflections during the measurement, it is possible that the aim was to reduce the effect of sea bottom reflection by lengthening the path route of the bottom reflected waves as much as possible to allow attenuation with distance. However, even if bottom-reflected waves are reduced by securing a certain water depth, it is easy to expect that the influence of interference, including the sea surface reflection route, will remain to a considerable extent if the measurements are made with a single device.

In any case, the second of the above-mentioned issues, that is, the effect of the sea surface and sea bottom reflections, is considered to be extremely large. In view of this, the second real issue for practical implementation is "Constructing a measurement method that minimizes the effect of sea surface and sea bottom reflections in shallow sea area in order to secure measurement locations as close to land as possible." (To restate the first issue initially assumed when envisioning practical use, "Measurement locations are limited to locations that are distant and require excessive time and labor.")

4.2　Proposal of Measurement Method for Shallow Sea Area

The following Fig. 5 shows the images of measurement by the floating buoy method (figures at left and top) and by the bottom-mounted method (right and bottom), assuming Japan's Seto Inland Sea (average water depth: 38 m) as a suitable location. Although it might appear that there is no change from the 2023 Guidelines except that the water depth is 38 m, careful examination shows that the number of hydrophones has been increased from 3 to 5 units. Why is it necessary to increase the number of hydrophones where the water depth is shallower? This reflects the results of a simulation to achieve the aim of "Reducing the effect of interference of sea surface and sea bottom reflected waves" as a measure to solve the above-mentioned problem by the measurement method proposed here. The following presents the results of the simulation and discussion of the influences of multiple wave paths.

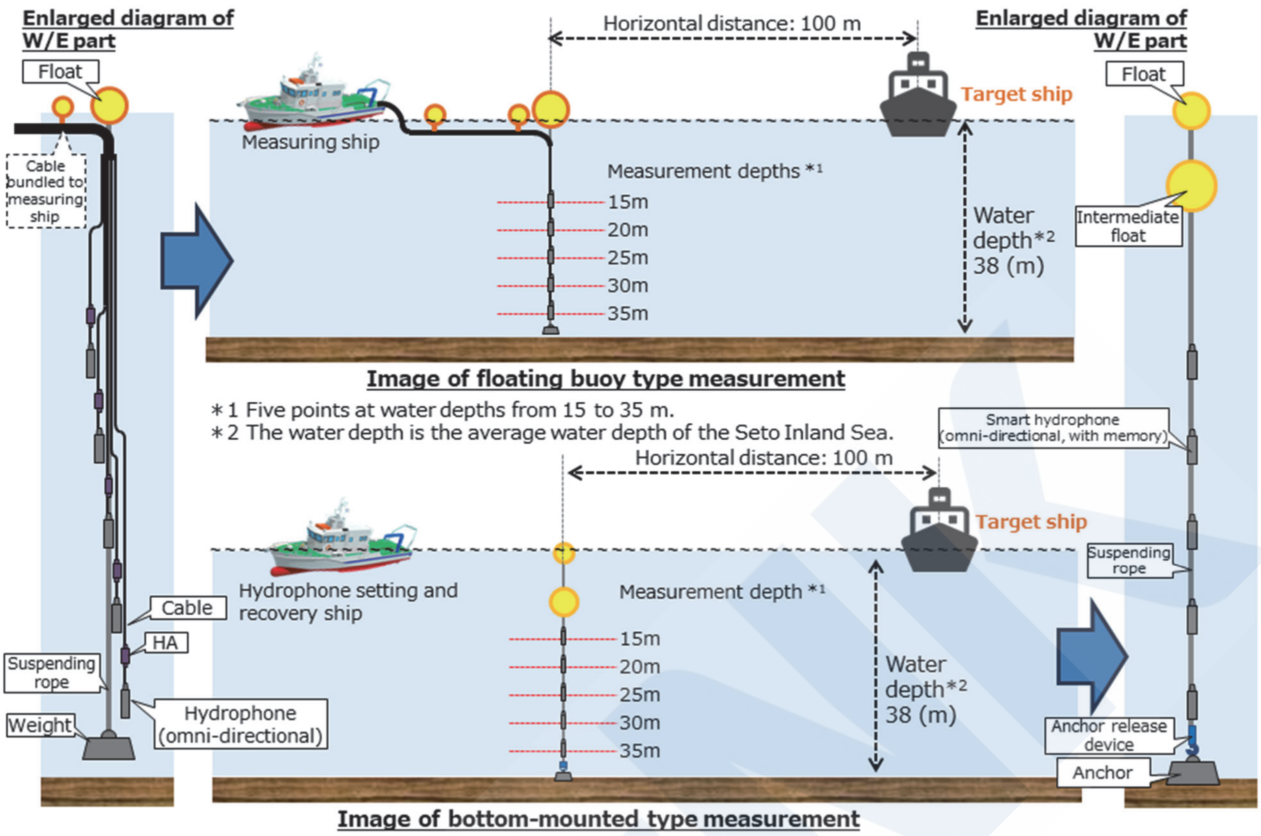


Fig. 5 Image of proposed measurement method for shallow sea area

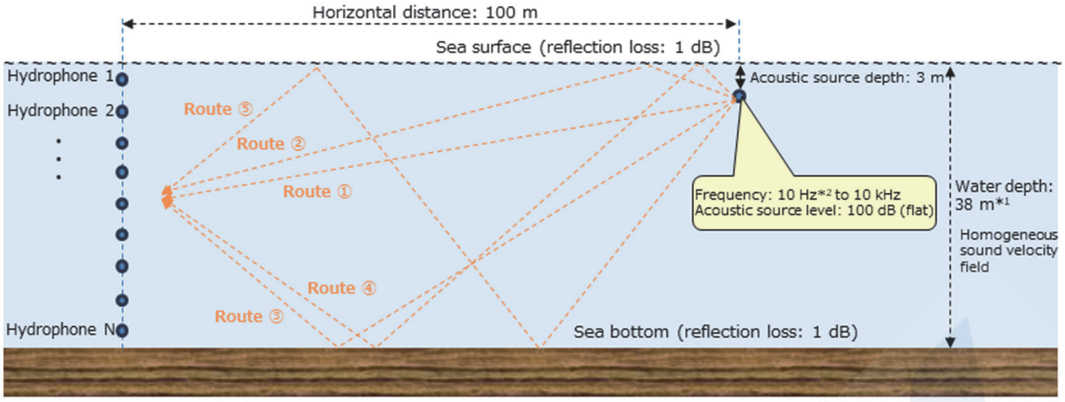
The simulation considered the water depth conditions in two sea areas. One was the average water depth of 38 m in the Seto Inland Sea, and the other was a water depth of 80 m, intended for the Bungo Channel waters, etc.

4.2.1 Study of Sea Area in Seto Inland Sea (Average Water Depth 38 m)

Fig. 6 shows the content of the simulation of acoustic wave interference under a multiple wave path environment in the Seto Inland Sea (average water depth: 38 m).

The figure shows the condition of multi-path interference at each water depth with fine division of the hydrophone water depth. The depth of the acoustic source is 3 m, and the interference results were calculated by considering the propagation condition to be spherical diffusion, for the 5 acoustic paths: ① Direct wave, ② sea surface single reflection route, ③ sea bottom single reflection route, ④ sea surface (forward) single reflection, sea bottom (back) single reflection route and ⑤ sea bottom (forward) single reflection, sea surface (back) single reflection route. Reflection loss was set a 1 dB for both sea surface and sea bottom reflection.

The small figure at the bottom right in Fig. 6 shows that the lower limit frequency (mentioned previously as an item to be discussed later) was achieved at the water depth of 38 m, even for 10 Hz, based on the cutoff frequency of a space enclosed by a rigid body (source: Fundamentals and Applications of Marine Acoustics).



＊1 Water depth: Average water depth of the Seto Inland Sea.
＊2 Lower limit frequency: Cutoff frequency of space enclosed by a rigid body (see figure below).

Number of reflections of routes ① to ⑤

	Surface reflection	Bottom reflection
Route ①	0	0
Route ②	1	0
Route ③	0	1
Route ④	1 (forward)	1 (back)
Route ⑤	1 (back)	1 (forward)

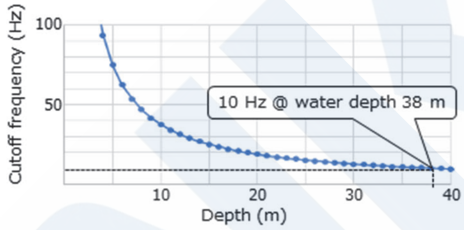


Fig. 6　Conditions of multi-path simulation (average water depth of Seto Inland Sea: 38 m)

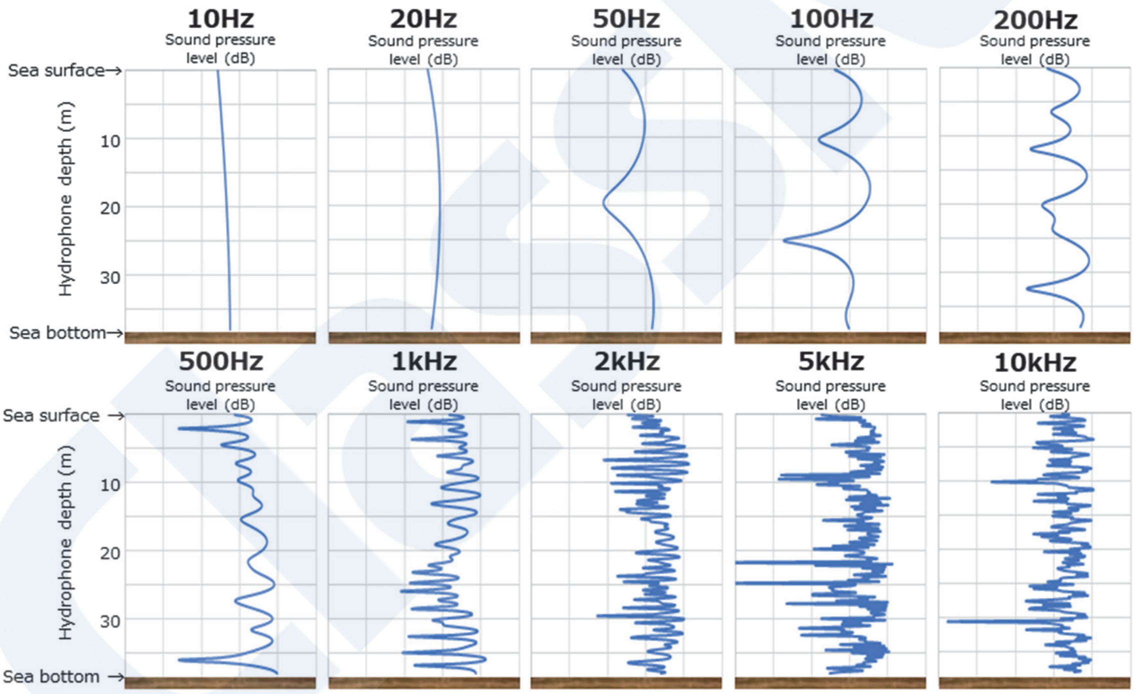


Fig. 7　Changes in level by multi-path interference by frequency at each hydrophone depth

Fig. 7 shows the results of the changes in the sound pressure level by addition of the multiple paths during fine division of the depth from the sea surface to the sea bottom when the hydrophone depth was plotted against frequency under the conditions in Fig. 6. From these results, the following two points can be mentioned: “① The amount of change differs with the frequency, but since the influence of interference varies due to the differences in the multi-path routes depending on the hydrophone depth, and large changes occur in the sound pressure level (although this also depends on the frequency), measurement with only one hydrophone is not desirable,” and② “Receiving the peaks and valleys of changes in the sound pressure level without differentiation by using multiple hydrophone and taking the average sound pressure level is a satisfactory method.”

Here, just to be sure, the principle of level fluctuation due to interference is presented.

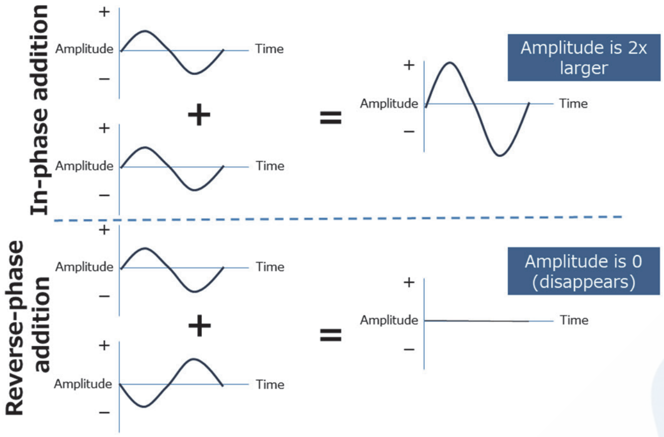


Fig. 8 Situation of in-phase addition and reverse-phase addition of 2 hydrophones

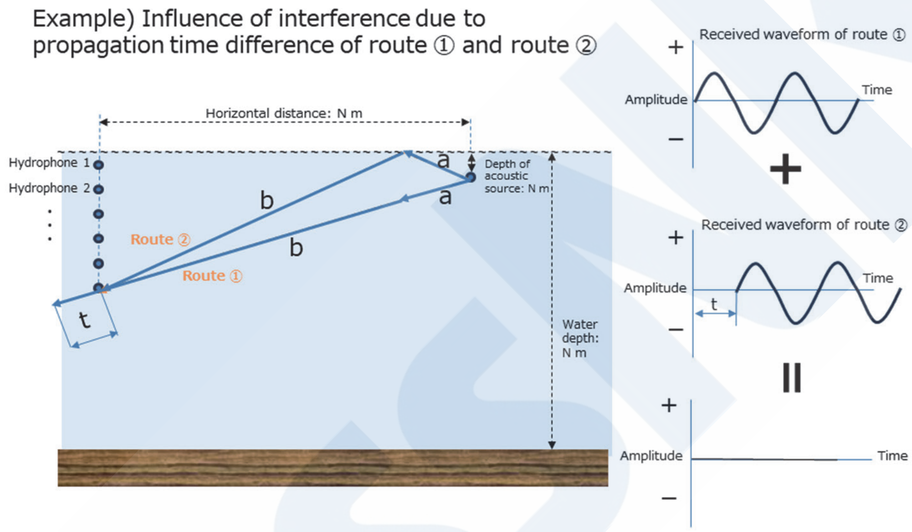


Fig. 9 Situation of addition of 2 waves with different routes
(case when delay time is equivalent to 1/2 of the wavelength, resulting in reverse-phase addition)

Fig. 8 shows extreme examples in which two waves interfere and (top) the sound pressure level after addition increases by 2 times, and (bottom) the waveforms are mutually cancelling and the amplitude becomes 0 (waves disappear).

Fig. 9 shows an example of the two waves in Fig. 8 with interference between a direct wave (route ①) and a sea surface-reflected wave (route ②). If the delay time t of the reflected wave is an integral multiple of the wavelength and the two waves are in phase, and excluding the attenuation of the sea surface reflected wave and attenuation of due to the route length, this is a case of perfect in-phase addition, and the sound pressure level doubles. Conversely, as an example of attenuation, if the delay time t of the reflected wave shifts further by the equivalent of 1/2 of the wavelength against the integral multiple of the wavelength, the two waves are mutually cancelling. Assuming there is no difference in the attenuation of the surface reflected wave and attenuation due to differences in the route length, the two waves have perfectly reversed phases, and the signals disappear due to mutual cancellation.

As a simple method for reducing the influence of these forms of interference, smoothing by using multiple hydrophones in the depth direction is effective.

(*As another measure for reducing the influence of sea bottom and sea surface reflection, use of a directional measurement array may be mentioned. However, particularly at low frequencies, it is difficult to obtain directivity because it is not possible to make an acoustic opening, and directivity requires a large increase in the system scale. Therefore, this paper considers smoothing operation using multiple hydrophones, as this is thought to be the simplest and most effective approach.)

Here, I would like to plot the fluctuations in the sound pressure levels of the hydrophones at each depth side-by-side (Fig. 7), consider “the disruption of the measurement results,” and propose examples of installation of the hydrophones in the depth direction. The situation of interference by frequency depending on the hydrophone installation depth is also shown again, plotted horizontally, in Fig. 10.

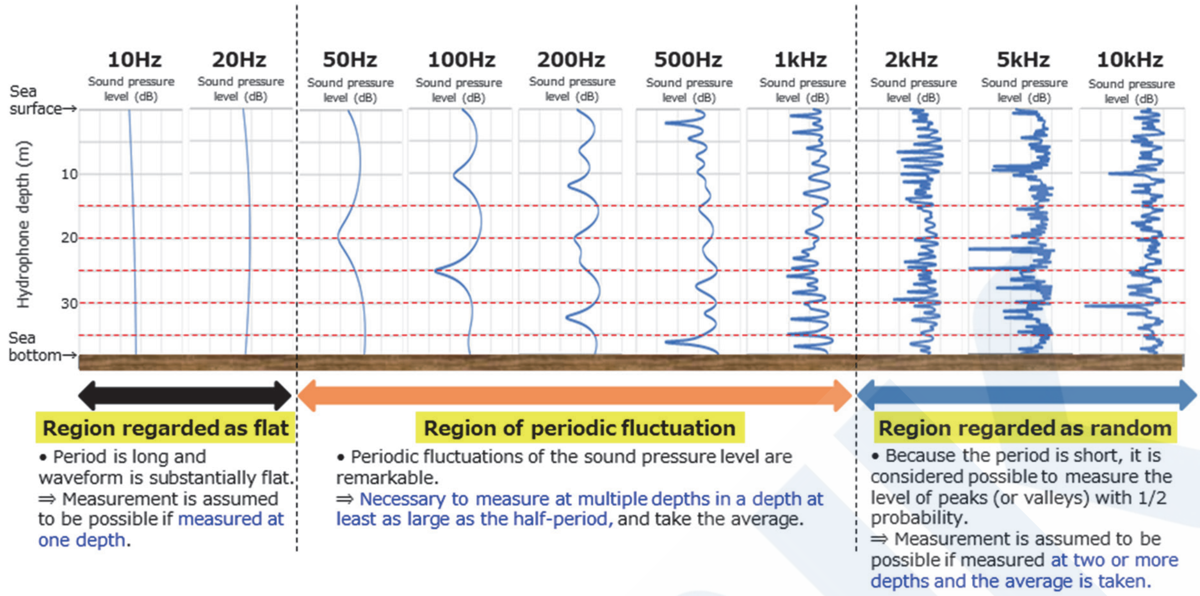


Fig. 10　Additional consideration of situation of sound pressure level fluctuations at each hydrophone setting depth by frequency (water depth of Seto Inland Sea: 38 m)

As can be seen in Fig. 10, at frequencies of 20 Hz and less, the period of the sound pressure level fluctuations due to interference is long, the waveform is substantially flat, and it is assumed the measurement is basically possible even at one depth. In the range from 50 Hz to about 1 kHz, periodic level fluctuations are considered to be remarkable, and it is considered necessary to carry out measurements by depth, using multiple hydrophones in a depth interval equal to or greater than the half-period, and take the average. At 2 kHz and above, the fluctuation period is short, and measurement is assumed to be possible if measurements are made at two or more depths and the average is taken.

To summarize the recommended number of hydrophones and set depths once again:

① The periods of the sound pressure level fluctuations in the depth direction are different, depending on the frequency, and can be divided into three regions.

② As a method for measuring the average level by using multiple hydrophones, the following conditions are deemed appropriate.

- Measurement depth zone: 15 m to 35 m (set so as to cover approximately the half-period in the results for 50 Hz)
- Number of hydrophones: 5 (set so as to cover multiple peaks and valleys in the results for 50 Hz to 500 Hz)

⇒ In the depth range from 15 m to 35 m, measurement at 5 points (15, 20, 25, 30, 35 m) is recommended (shown by the horizontal red dotted lines in Fig. 10)

In actuality, the ship being measured sails at a constant speed and passes across the CPA of the hydrophone array, but since a time measurement of plus/minus a few seconds is acquired while passing through the CPA, the average in the time direction is also added. Although the difference in the route equivalent to the ship’s traveling distance during these few seconds is small, it is considered to make an additional significant contribution to the average of the random path difference at frequencies of 2 kHz and above.

4.2.2　Study of Waters Equivalent to Bungo Channel Sea Area (Average Water Depth: 80 m)

Finally, a simulation was attempted with the water depth condition changed to 80 m, which is equivalent to the waters in the vicinity of the Bungo Channel. The setting conditions are shown in Fig. 11, and the situation of interference at each frequency and the recommended depths of the installed hydrophones are shown in Fig. 12.

Other than the water depth setting, the setting conditions are the same as those used above, including the 5 path routes. However, the cutoff frequency was also lowered to around 5 Hz, corresponding to the increased water depth.

As can be understood from Fig. 12, and was also the case with the water depth of 38 m, measurement with one hydrophone is not desirable because multi-path interference causes large fluctuations in the sound pressure level, depending on the hydrophone setting depth. As with the water depth of 38 m, it is advisable to measure the average sound pressure level by receiving the peaks and valleys of fluctuations in the sound pressure level with multiple hydrophones.

In considering the results in Fig. 12, which are similar to the results for the Seto Inland Sea (simulation for water depth of 38 m), the conclusions were essentially unchanged.

① The periods of sound pressure level fluctuations in the depth direction are different, depending on the frequency, and can be divided into three regions. This is the same as in the simulation for the Seto Inland Sea.

② As a method for measuring the average level by using multiple hydrophones, the following conditions are considered appropriate.

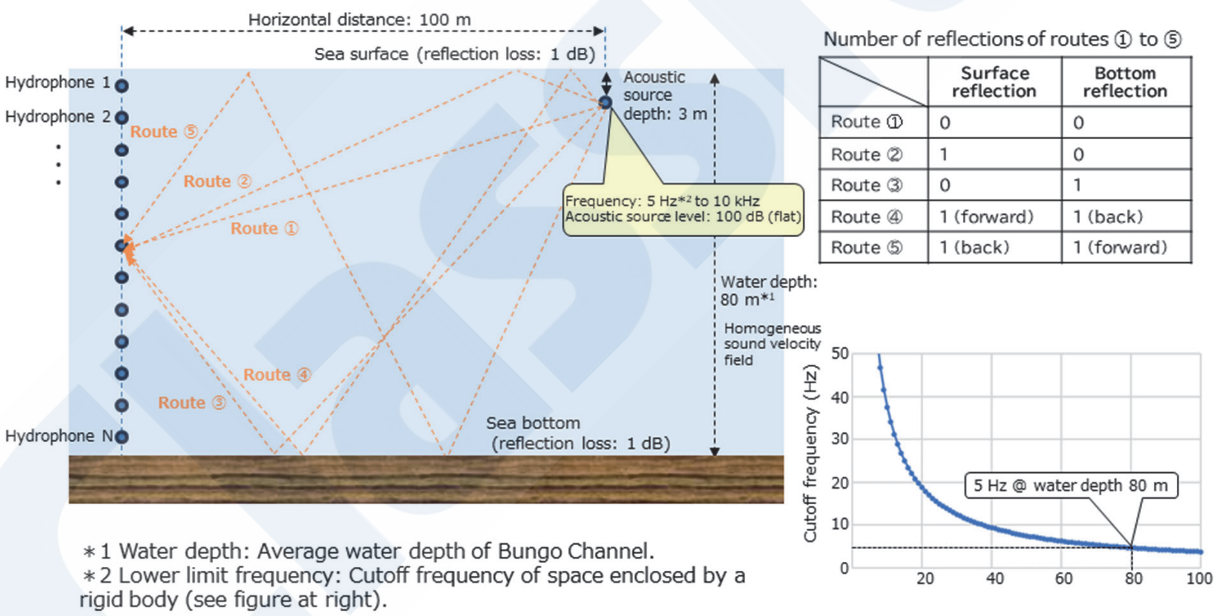
- Measurement depth zone: 30 m to 70 m (set so as to cover approximately the half-period in the results for 20 Hz)
- Number of hydrophones: 5 (set so as to cover multiple peaks and valleys in the results for 10 Hz to 200 Hz)

⇒ In the depth range from 15 m to 35 m, measurement at 5 points (15, 20, 25, 30, 35 m) (shown by the horizontal red dotted lines in Fig. 10)

As one difference from the case of the water depth of 38 m (Seto Inland Sea), the region regarded as random is broader.

Since measurement in the periodic fluctuation region requires 5 hydrophones, if the measurement depth is increased further, approaching the condition of the 2023 Guidelines, it is expected to approach to the average of 3 hydrophones.

As already discussed, if the 2023 Guidelines are followed faithfully, the appropriate measurement locations for securing the necessary water depth will be limited, a large-scale system will be required, and the burden on ship owners will also increase. In the future, the author believes that "the development of more concrete systems that enable measurements as easily as possible, in any location (with almost no restrictions)" will be an issue for continuing study, and would like to conclude this paper with a proposal for proceeding in the future.



	Surface reflection	Bottom reflection
Route ①	0	0
Route ②	1	0
Route ③	0	1
Route ④	1 (forward)	1 (back)
Route ⑤	1 (back)	1 (forward)

Fig. 11 Conditions of multi-path simulation (water depth in Bungo Channel area: 80 m)

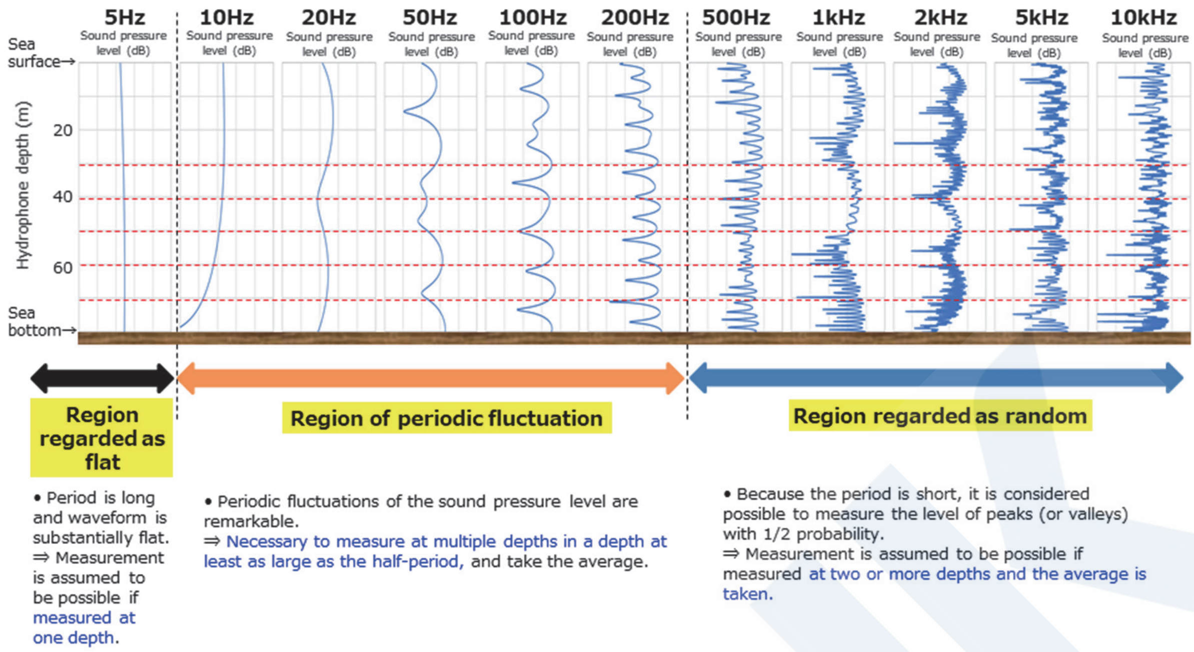


Fig. 12 Additional consideration of situation of sound pressure level change at each hydrophone setting depth by frequency (water depth in Bungo Channel area: 80 m)

5. PROPOSAL FOR PROCEEDING IN THE FUTURE

Considering the regulations on ship noise measurement expected in the future, methods that are suitable for Japan and can also reduce the burden on ship owners should be studied with all stakeholders in the maritime industry.

- ◆ Candidate measurement sites should be proposed, and if necessary, the parameters of simulations should be adjusted to represent a more realistic environment (water temperature, topography, water depth, etc.) corresponding to the conditions, in order to improve the accuracy of simulations.
- ◆ Based on actual data for real sea areas and simulation results, more concrete measurement systems should be constructed and proposed.
- ◆ The proposed systems should be materialized and measurements should be verified in actual seas areas as quickly as possible.

Recent Information on the Development of IMO Guidelines for the Safety of Ships Using Ammonia as Fuel and Initiatives of ClassNK for Practical Application of Ammonia-Fueled Ships

Technical Solution Department, Plan Approval and Technical Solution Division, ClassNK

1. INTRODUCTION

In recent years, with the strengthening of regulations to prevent air pollution and suppress global warming, the international shipping sector has actively conducted studies on the use of alternative fuels such as low-carbon fuels and decarbonized fuels, which have low environmental impacts, in place of petroleum fuels as fuels for next-generation ships.

At present, introduction of ships that use LNG, LPG, methanol/ethanol, etc. is continuing to expand in order to respond to SOx and NOx regulations. Although it is possible to reduce CO_2 emissions from ships that use conventional fuel oil by 10 % to 25 % by using these fuels, heightened expectations are placed on ammonia and hydrogen fuels, which do not contain carbon, to realize net-zero GHG emissions by or around 2050, which is the target level set by the International Maritime Organization (IMO) in its Strategy on Reduction of GHG Emissions from Shipping.

In these circumstances, the IMO issued Interim Guidelines for the Safety of Ships Using Ammonia as Fuel in February 2025, specifying safety requirements when using ammonia as a fuel for ships.

This paper introduces recent information on the development of the IMO's Guidelines for the Safety of Ships Using Ammonia as Fuel, and the initiatives of ClassNK (hereinafter, the Society) for practical application of ammonia-fueled ships.

2. STATUS OF DEVELOPMENT OF GUIDELINES FOR THE SAFETY OF SHIPS USING AMMONIA AS FUEL AT THE IMO

2.1 Status of Development of Safety Guidelines for Ammonia Fuel

At its meeting in September 2024, the 10th session of the Sub-Committee on Carriage of Cargoes and Containers (CCC10), a subordinate organization of the IMO's Maritime Safety Committee (MSC), finalized Draft Interim Guidelines for the Safety of Ships Using Ammonia as Fuel for ships other than liquefied gas carriers. Subsequently, the Guidelines finalized at CCC10 were approved at the 109th session of the Maritime Safety Committee (MSC109) in December 2024, and the IMO Interim Guidelines (MSC.1/Circ.1687) were issued in February 2025.

The details of discussions on the Guidelines in CCC10 will be explained in the following Chapter 3. The discussions on the provisions (i.e., specific provisions for achieving the functional requirements) of all chapters of the Guidelines were not completed at CCC10 due to time limitations. The items discussed at that meeting were mainly the goals and functional requirements of each chapter. While some of the specific provisions were discussed, other requirements were basically finalized by adding special requirements related to ammonia, referring to the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code). Ongoing reviews of the Guidelines in future sessions of Sub-Committee on Carriage of Cargoes and Containers based on appropriate information collection and technical discussions are planned.

2.2 Status of Development of Guidelines for the Safety of Liquefied Gases Carriers Using Ammonia as Fuel

In addition to the above-mentioned Guidelines for the Safety of Ships Using Ammonia as Fuel, the IMO is also currently developing safety guidelines for liquefied gas carriers using ammonia as fuel, to which the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) applies. A proposal for these guidelines was submitted in CCC10, and in the future, work related to the development of the Guidelines will be carried out by the Correspondence Group etc. The draft Guidelines are scheduled to be finalized in CCC11 in 2025.

3. COMMENTARY ON IMO GUIDELINES FOR THE SAFETY OF SHIPS USING AMMONIA AS FUEL

3.1 Discussions on Development of Guidelines for the Safety of Ships Using Ammonia as Fuel

This section presents an overview of the discussions on the Guidelines for the Safety of Ships Using Ammonia as Fuel (hereinafter, referred to as "the Guidelines") in CCC10. Based on the draft, the Guidelines were discussed in CCC10 from various viewpoints, including the scope of application, goals and functional requirements of the Guidelines, ship design and arrangement, the ammonia fuel containment system, prevention of exposure to toxicity, etc.

The Guidelines comprise Chapter 1 to Chapter 20. However, as mentioned above, due to time constraints, discussions on the provisions of each chapter of the Guidelines was not completed at CCC10. The discussions focused mainly the goals and functional requirements of each chapter, and the document was finalized by agreement on the goals and functional requirements. However, some provisions (e.g., Chapter 5 through Chapter 6, 6.9, Chapter 12bis) were discussed, and those provisions were included in the Guidelines. Other requirements were basically finalized by adding only special requirements related to ammonia, referring to the requirements of the IGF Code. A list of the chapters of the Guidelines and the status of the discussions are shown in Table 1.

Table 1 Composition of IMO Interim Guidelines and status of discussions on each chapter

Chapter No.	Chapter title	Goal	FR (Functional Requirements)	Provisions (specific requirements)
1	INTRODUCTION	Agreed at CCC9 (2024)		
2	GENERAL	Agreed at CCC9 (2024) + Agreed on remaining items		
3	GOAL AND FUNCTIONAL REQUIREMENTS	Agreed at CCC9 (2024) + Agreed on remaining items		
4	GENERAL PROVISIONS	Agreed at CCC9 (2024)		
5	SHIP DESIGN AND ARRANGEMENT	Agreed	Agreed	Agreed
6	FUEL CONTAINMENT SYSTEM	Agreed	Agreed	Partially agreed
7	MATERIAL AND GENERAL PIPE DESIGN	Agreed	Agreed	Partially agreed
8	BUNKERING	Agreed	Agreed	Partially agreed
9	FUEL SUPPLY TO CONSUMERS	Agreed	Agreed	Partially agreed
10	POWER GENERATION INCLUDING PROPULSION AND OTHER FUEL CONSUMERS	Agreed	Agreed	Agreed to refer to IGF Code
11	FIRE SAFETY	Agreed	Agreed	Agreed to refer to IGF Code
12	EXPLOSION PREVENTION	Agreed	Agreed	Agreed to refer to IGF Code
12bis	PREVENTION OF EXPOSURE TO TOXICITY	Agreed	Agreed	Agreed
13	VENTILATION	Agreed	Agreed	Agreed to refer to IGF Code
14	ELECTRICAL INSTALLATIONS	Agreed	Agreed	Agreed to refer to IGF Code
15	CONTROL, MONITORING AND SAFETY SYSTEMS	Agreed	Agreed	Partially agreed
16	MANUFACTURE, WORKMANSHIP AND TESTING	Agreed to excerpt Chapter 16, B-1 of IGF Code		
17	DRILLS AND EMERGENCY EXERCISES	Agreed	Agreed	Agreed to refer to IGF Code
18	OPERATION	Agreed	Agreed	Agreed to refer to IGF Code
19	TRAINING	Agreed	Agreed	Agreed to refer to IGF Code
20	PERSONNEL PROTECTION	Agreed	Agreed	Agreed to refer to IGF Code

*Chapter 12bis is a new chapter, but because consistency with the existing IGF Code was prioritized, this chapter was not assigned a new number.

Since sufficient discussions on the provisions of each chapter were not carried out, some members expressed opposition to finalizing the draft Interim Guidelines. However, since projects involving ships using ammonia as fuel are already in progress in various countries, and prompt issuance of the Guidelines is required, the majority favored finalizing the Guidelines, as a result, the Interim Guidelines were finalized at CCC10. Considering the "provisional status" of the Guidelines, the Introduction includes a note to the effect that the Guidelines "may not include specific provisions with details on how to achieve these functional requirements in all cases."

It was also agreed that the Interim Guidelines will be reviewed in the future after more detailed technical discussions and accumulation of information.

3.2 Overview of the IMO Guidelines for the Safety of Ships Using Ammonia as Fuel

This section introduces the main content of the discussions in the development of the IMO Guidelines for the Safety of Ships Using Ammonia as Fuel, and the provisions of the guidelines related to those points.

3.2.1 Application of the Guidelines

It was agreed that the scope of application of the Guidelines excludes liquefied gas carriers, which are subject to application of the IGC Code. As mentioned above in 2.2, preparation of separate safety guidelines for ships subject to the IGC Code is planned.

3.2.2 Prevention of Exposure to Toxicity (Classification of Toxic Areas and Toxic Spaces)

To limit the risk of direct exposure to ammonia for persons on board, it was agreed to classify the areas and spaces of a ship as "toxic areas" (areas in which ammonia is or may be expected to be present on the open deck) and "toxic spaces" (enclosed or semi-enclosed spaces in the ship where leakage of ammonia may occur) in order to arrange life-saving appliances, escapes routes, air intakes and outlets, openings for accommodations, etc. in safe areas. The related requirements are provided in the Guidelines.

"Toxic areas" are defined as areas where ammonia leaks may occur and the distance (range) from those areas is within 10 m of flanges, valves and other potential leakages sources in ammonia fuel piping systems and within 25 m of vent posts, etc. "Toxic spaces" are defined as the interiors of fuel storage equipment and enclosed or semi-enclosed spaces in which potential sources of release, such as single-walled piping containing fuel, are located. (also including the interiors of fuel tanks, fuel preparation rooms and secondary enclosures, and potential sources of leakage).

In toxic areas, in addition to the prescriptive distance requirements, the Guidelines also stipulate that a gas dispersion analysis should be carried out to demonstrate that an unacceptable ammonia concentration (220 ppm) will not exceed the normative distance and reach nontoxic areas such as the air intakes of accommodations, etc. The image of a toxic area is shown in Fig. 1.

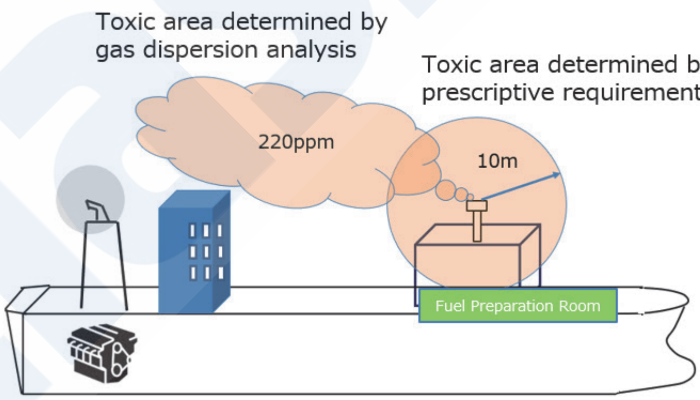


Fig. 1 Image of toxic area

3.2.3 Safe Havens

In preparation for potential ammonia leaks, it was agreed that "safe havens" capable of accommodating all persons on board the ship should be arranged in one or more enclosed spaces. The Guidelines stipulate that safe havens are to be arranged in locations that are essential for the ship's operation (e.g., the bridge and the engine control room), and are to be places where it is possible to maintain the environment within the space (e.g., spaces with a self-sustaining air supply), so that ammonia will not be flowed from outside.

3.2.4 Ammonia Exposure Limit and Activation of Alarms and Safety System

Discussions were held on the ammonia exposure limit and the thresholds for the activation of alarms and safety equipment. However, agreement on the exposure limit for persons on board was not reached, as there are differences in the work standards in each country, such as the available standards for exposure limits, the Acute Exposure Guideline Levels (AEGLs) and the National Institute for Occupational Safety and Health (NIOSH) exposure limit guidelines.

The activation levels for alarms and safety systems were also discussed, including the action to be taken in case ammonia liquid or vapor is detected in each space, and the threshold values for the concentration and the response when that concentration is detected were specified as follows.

- Visual alarms are to be provided at the entrance to toxic spaces, and the alarm setting value (activation level) is an ammonia concentration of 25 ppm in the space.
- When a gas concentration exceeding 110 ppm is detected, visual and audible alarms are activated in spaces where persons are present. Visual and audible alarms are given on the navigation bridge, in the continuously-manned central control station, and inside and outside the space where the leak is detected.
- When a gas concentration exceeding 220 ppm is detected, the safety system is activated.

3.2.5 Ammonia Releases

As a basic principle, it was agreed that direct releases of ammonia under the normal operating condition are not allowed. Under controllable conditions, it was agreed that the amount of releases should basically kept to the minimum by using the ammonia release mitigation system. It was also agreed that uncontrollable releases of ammonia are to be limited to catastrophic conditions such as activating of the pressure valve of a fuel tank, etc. In foreseeable and controllable events, the Guidelines specify that the ammonia concentration must be reduced to less than 110 ppm by the ammonia release mitigation system. As used here, releases due to “foreseeable and controllable events” mean gas bleeds from double-block bleed valves of the fuel piping system, releases from safety valves of the fuel piping system, releases of purging gas and discharge of drain from fuel pipes, and the like.

3.2.6 Ship Design and Arrangement

Regarding the ship design and arrangement, it was agreed that requirements are to be specified for each ammonia-related space and area, including fuel preparation rooms, tank connection spaces, bunkering stations, etc. From the viewpoint of preventing exposure to toxicity, the Guidelines stipulate that openings of escape routes and openings of accommodations shall not be arranged in toxic areas. The Guidelines also specify that engine rooms are allowed only in gas-safe machinery spaces, and the fuel pipes in engine rooms are to be protected by a gas-tight secondary enclosure.

3.2.7 Fuel Containment Equipment

In pressurized or semi-refrigerated, semi-pressurized ammonia storage, the danger of ammonia spewing out when a leak occurs in the ammonia containment system is a concern, whereas in the case of low temperature ammonia, the evaporation rate is extremely low, even if a leak occurs. For this reason, it was agreed that the development of the Guidelines should be preconditioned on storage at atmospheric pressure and in a fully-refrigerated condition. Thus, even though pressurized type and semi-refrigerated, semi-pressurized type ammonia storage are not described in the Guidelines, it was agreed that those storage methods are not prohibited, and they may be allowed based on alternative designs. In discussions on the tank pressure and temperature control, it was agreed that the temperature of the liquefied ammonia in fuel tanks is to be maintained at no more than -30 °C at all times.

3.3. Study Items Related to the Requirements of the Guidelines

As mentioned above in 3.1 and 3.2, although safety requirements for ammonia-fueled ships are provided in the IMO’s Interim Guidelines, there are many remaining points that were not discussed sufficiently because priority was given to finalizing the Guidelines. Therefore, in actual ship construction, it is considered necessary to adjust the safety requirements of the ship with the Administration on a case-by-case basis. For reference, this section describes the main items among those which the Society believes will require consultation with the Administration in actual ship construction. Because these items are related to the basic design, consultation as early as possible in the design stage is recommended.

3.3.1 Ammonia Temperature in Fuel Tanks

Section 6.9.1.1 of the Guidelines specifies that “The temperature of the liquefied ammonia in the fuel tanks should be maintained at a temperature of no more than -30°C at all times by means acceptable to the Administration.” The interpretation of “at all times” was discussed in the Working Group (WG) of CCC10. For example, since the temperature of the ammonia supplied during bunkering is approximately -33 °C, it can be assumed that the temperature will temporarily exceed -30 °C, even if the tanks are cooled down. Therefore, the CCC10 attempted to confirm whether this requirement is also applicable during bunkering. Although the conclusion was unclear, some Administrations also included the temperature during bunkering. On the other hand, assuming this requirement is to be achieved, it will be necessary to reduce the temperature of the ammonia which is actually supplied to an extremely low level. Thus, as a practical matter, it is assumed that the temperature of the ammonia will temporarily exceed -30 °C. As an additional issue, it is also necessary to confirm the meaning of "at all times" in this requirement with the Administrations, assuming abnormal conditions such as blackout, etc.

3.3.2 Pressurized or Semi-Refrigerated, Semi-Pressurized Ammonia Storage

In the development of the Guidelines, it was agreed that the Guidelines would be preconditioned on storage of ammonia at atmospheric pressure and in a fully-refrigerated condition. However, in the WG, there seemed to be many participating members who thought that pressurized or semi-refrigerated, semi-pressurized storage should be recognized. This is due to the fact these are recognized storage methods for liquefied gas carriers that current transport ammonia as a cargo, and the existing infrastructure facilities, which are expected to be candidates for infrastructure to supply ammonia fuel in the future, perform storage by the pressurization method or the semi-refrigerated, semi-pressurized method. Under these circumstances, how to establish the safety of the pressurization method and semi-refrigerated, semi-pressurized method is an issue. Three methods for demonstrating safety exist: a method using performance criteria, which are generally set based on the applicable rule, a method using specific risk assessment criteria, based on a relative comparison with the rule design ship risk (both shown in Fig. 2), and a comprehensive risk assessment using an allowable standard of total risk (Fig. 3). Although a detailed explanation will be omitted here, among these three methods, it is thought that the comprehensive risk assessment method should be used in demonstrating the safety of alternative designs for these requirements. When this method is used, it is essential to note that it is necessary to set the allowable risk standard, and it is necessary to decide this standard through consultation with the Administration. In actuality, there are no actual results of calculations of this type of risk for the refrigeration method, the semi-refrigerated, semi-pressurized method, or the pressurization method, and whether a risk standard agreeable to the ship operator and the Administration can be worked out is unknown. Therefore, we recommend that demonstrations of safety for these methods should be completed in the previous stages of basic design.

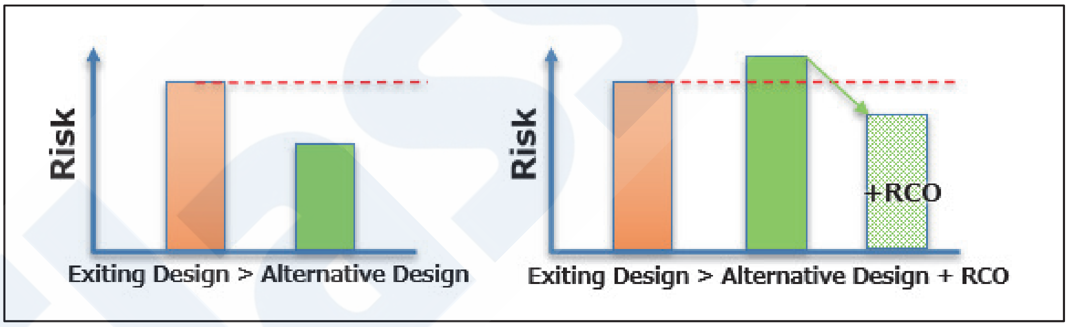


Fig. 2 Evaluation methods using specific risk assessment criteria

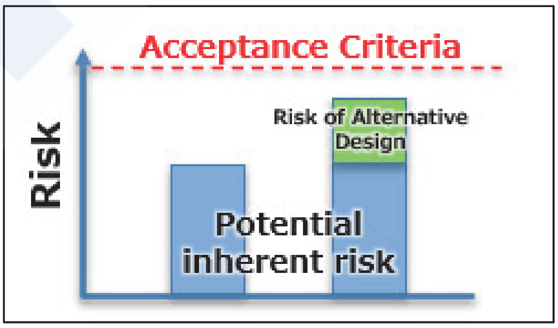


Fig. 3 Comprehensive risk assessment method

3.3.3 Foreseeable and Controllable Events

The WG in the CCC10 also conducted discussions on the question of whether leaks from piping, etc. are "foreseeable and controllable events." Some WG members asserted that, assuming leaks from pipes, etc. are foreseeable and controllable events, even leaked ammonia should not be discharged directly into the atmosphere, but should be discharged after treatment through the ammonia release mitigation system. On the other hand, there were also members who argued that even assuming leaks from pipes, etc. are foreseeable, they cannot be controlled leading to the conclusion that the Administration should decide whether the leaked ammonia must be treated or not when a leak accident occurs. Since whether leaked ammonia is treated or not will also affect the basic design, it is necessary to confirm the interpretation of this point with the Administration at an early timing. Since the Society assumes that leaked ammonia will be released into the atmosphere from a safe location as a precondition, we think that release via the ammonia release mitigation system is not necessarily required. Since a gas dispersion analysis is carried out in order to set toxic areas in either case, it is essential to decide whether to implement ammonia mitigation measures or not, considering the range and degree of the effect.

3.3.4 Gas Dispersion Analysis Methods

When carrying out a gas dispersion analysis, the analysis conditions have a large influence on the results. For example, in the dispersion analysis to set the toxic area, the range of the toxic area will differ greatly depending on how the wind direction and wind velocity are set. The setting of the leakage rate also has a large influence on the results. In the discussions in the WG of the CCC, there was an argument to the effect that the approval of the Administration should be obtained for the analysis conditions used in gas dispersion analyses by CFD analysis, etc. Generally, the analysis conditions in CFD analyses indicate boundary conditions such as Dirichlet conditions, Neumann conditions, wall conditions, etc., but it is necessary to bear in mind that the items discussed with the Administration are the conditions assumed in the above-mentioned analysis, rather than the general boundary conditions of a CFD analysis.

3.3.5 Fire Protection and Fire Fighting

The requirements related to fire protection and fire fighting in Chapter 11 of the Guidelines are specified to refer to Chapter 11 of the IGF Code. The fire protection and fire fighting requirements in Chapter 11 of the IGF Code were developed for LNG. However, the fire risk of ammonia is overwhelmingly lower than that of LNG, suggesting the possibility that the requirements of Chapter 11 of the IGF Code are excessive for ships which handle ammonia as a fuel. For example, the Society considers that a flammable atmosphere cannot be formed on an open deck from the range of ammonia combustion, which implies that fire protection and fire fighting requirements for open decks are not necessary, so these requirements are not contained in our Guidelines. Because Chapter 11 of the IMO Interim Guidelines was not discussed due to time constraints, the Society believes that this item should also be decided through consultation with the Administration.

4. FUTURE ACTIONS OF THE SOCIETY

The content of provisions (Chapter 5 to Chapter 6, 6.9, Chapter 12bis, etc.) in the IMO Interim Guidelines introduced in this paper which were discussed in detail in CCC10 are also planned for inclusion in Part C-1 of the ClassNK Guidelines for Ships using Alternative Fuels.

In future work to develop guidelines for liquefied gas carriers using ammonia fuel and revisions of Guidelines for the Safety of Ships Using Ammonia as Fuel, the Society also intends to contribute actively to the discussions using the results of survey studies carried out up to the present. In the future, the Society will continue to review its Guidelines regularly, considering the most recent status of discussions in the IMO and the rapid development of new technologies, and will work to develop guidelines that will be useful for developers.

REFERENCE

1) IMO, MSC.1/Circ.1687 INTERIM GUIDELINES FOR THE SAFETY OF SHIPS USING AMMONIA AS FUEL

Research to Develop Safety Assessment Measures of Alternative Fuel/New Cargo Transportation

Safety Assessment Section, Research Institute, Research and Development Division, ClassNK

1. INTRODUCTION

This paper presents an overview of the lecture "Safety Assessment of Alternative Fuel and New Cargo Transportation" at the ClassNK R&D Forum held on January 28, 2025. In addition to proposals of various alternative fuels for realizing zero emissions in shipping, the cargos which are transported are also changing, beginning with mass transportation of liquefied hydrogen for decarbonization in industry and society. Ship safety has been achieved over the long history of ships. This is backed by the fact that, until now, rules specifying the design requirements for ships based on new concepts were not always established before those ships were designed, but rather, rules were developed by accumulating knowledge through the design and approval processes of ships with new concepts. Today, however, when we are attempting to quickly achieve systems that have little record of actual use on ships, or have not been used heretofore, formulation of safety requirements with a sense of speed is also necessary in order to accelerate social implementation of these new systems.

Therefore, in addition to the conventional approach of developing safety requirements in cooperation with the front runner who is, so to speak, the "first penguin," ClassNK (hereinafter, the Society) has also adopted a proactive approach by strengthening its own research and development initiatives. As part of this, we are promoting research and development of "Advanced and quantitative risk assessment of alternative fuel ships" and "Integrity assessment techniques for cargo and fuel containment systems" as core techniques. As the reasons for selecting these two items, first, because risk assessments are required in the design of alternative fuel ships, quantification of risk assessments is necessary and indispensable for fostering a common recognition among diverse stakeholders, and secondly, although risk assessments consider the unlikely event of a leak, precisely for this reason, efforts to ensure than leaks do not occur in the first place were considered necessary. Research and development are being carried out based on these two approaches.

The research which the ClassNK Research Institute carries out based on the above-mentioned approaches spans a diverse range. However, due to the limited time available, we took up the following items in presentation at the R&D Forum.

Advanced and quantitative risk assessment of alternative fuel ships:

- Estimation of frequency of ammonia leaks in ammonia-fueled ships
- Ammonia gas diffusion tests
- Quantitative risk assessment methods and advanced risk assessment techniques for alternative fuel ships

Integrity assessment techniques for cargo and fuel storage facilities:

- Study of evaluation techniques for ammonia stress corrosion cracking sensitivity of materials
- Study of liquid oxygen (LOX) compatibility evaluation method for materials

In addition to these topics, in "Advanced and quantitative risk assessment of alternative fuel ships," we are also promoting Verification & Validation (V&V) of analysis of hydrogen fine droplet leak and diffusion tests and gas diffusion analysis, and in "Integrity assessment techniques for cargo and fuel storage facilities," we are conducting research on the fracture behavior of materials under cryogenic environments, evaluating the effects of post weld heat treatment (PWHT) on fracture toughness assuming liquefied CO_2 tanks, and studying the possibility of omitting large-scale tests by simulation of ductile fracture in materials for service at cryogenic temperature environments. The results will be incorporated successively in ClassNK Rules and Guidelines, and reports will be posted on the website of the ClassNK Research Institute. Persons with an interest in these issues are invited to refer to those sources.

This paper presents an outline of the research and development being carried out under "Advanced and quantitative risk assessment of alternative fuel ships" and "Integrity assessment techniques for cargo and fuel containment systems," followed by an explanation of the results of the five above-mentioned research projects, which were discussed at the R&D Forum, and the current condition of the projects.

2. ADVANCED/QUANTITATIVE RISK ASSESSMENT OF ALTERNATIVE FUEL SHIPS

As shown in Fig. 1, risk assessments are generally carried out by a flow that begins from identification of hazards. When a certain scenario has been selected, the risk can be found by evaluating the frequency of occurrence and the degree of effect, and then multiplying the effect of the hazard by its frequency. Therefore, for advanced and quantitative risk assessments, it is necessary to quantify the respective evaluations of the frequency of occurrence and degree of effect. Since quantitative risk assessments are not necessarily the general practice in the ship field, except in the case of HAZID, etc., it is also necessary to study an advanced and quantitative approach to the entire flow of risk assessments. For this reason, we are studying "Estimation of frequency of ammonia leaks in ammonia-fueled ships," "Ammonia gas diffusion tests" and "Quantification of risk assessments and Application of the process safety concept to alternative fuel ships," which will be explained in the next section.

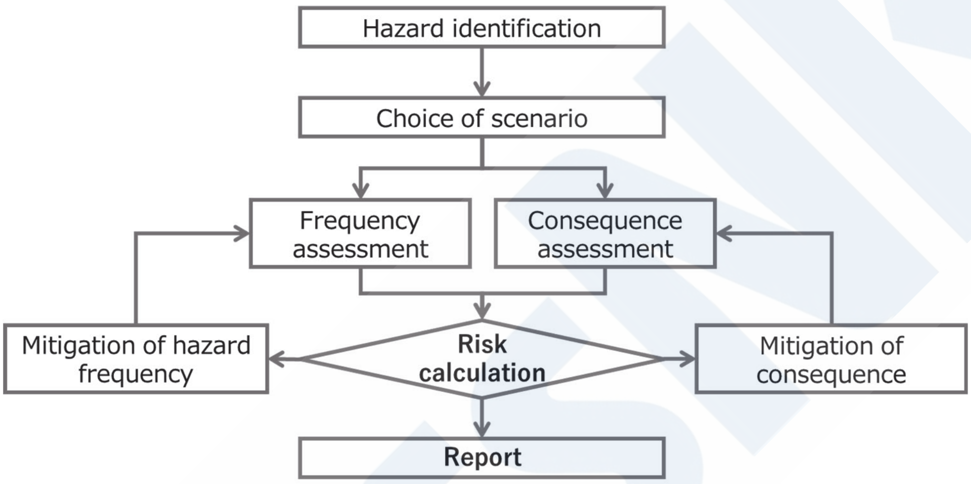


Fig. 1 Flow of risk assessment

2.1 Estimation of Frequency of Ammonia Leaks in Ammonia-Fueled Ships

The risk of alternative fuel ships originates from leaks of the fuel that is stored and used. Therefore, in performing a risk assessment of an alternative fuel ship, accurate estimation of the frequency of leaks is important. In hydrocarbon (petroleum, natural gas) plants, the scale and probability of leaks have been arranged based on an enormous amount of actual results to date, as seen, for example, in the IOGP Risk Assessment Directory [1)]. Past research on ammonia-fueled ships includes an example of a risk assessment for ammonia-fueled ships using the statistical value of leaks at hydrocarbon plants [2)] and an example that states to the effect that a conservative evaluation of the risk of ammonia-fueled ships is possible by using the IOGP frequency [3)].

However, because the properties of ammonia are different from those of hydrocarbons, and the hazards that occur are also different, it would be preferrable to apply the frequency of ammonia leaks in risk assessments of ammonia-fueled ships, but no statistical values are available for ammonia leaks. Therefore, we estimated the frequency of leaks from shipboard ammonia fuel equipment by using a limited database of ammonia leaks from land-based ammonia-using equipment by Bayesian updating, which is a technique that was used by the Sandia National Laboratories in the United States in a risk assessment of hydrogen stations [4)]. It may be noted that our research was carried out in cooperation with the Research Institute of Science for Safety and Sustainability of the National Institute of Advanced Industrial Science and Technology (hereinafter, AIST).

Since this research was presented at the Forum by Dr. Kojima of AIST, and submission of a peer-reviewed paper is still in the progress as of this writing (Feb. 2025), I will refrain from describing the details here. Although the results obtained in this research were based on various assumptions, because the results are the world's only estimated values for the frequency of leaks specifically for ammonia, this work is expected to be useful for securing the safety of ammonia fuel equipment, which still has a high degree of uncertainty.

2.2 Ammonia Gas Diffusion Test

In quantitatively evaluating the degree of effect in Fig. 1, evaluations of gas diffusion after a fuel leak are carried out on alternative fuel ships. Since it is impossible to carry out experiments for all cases, a plume model or other diffusion equation, or computational fluid dynamics (CFD) is generally used. Of course, it is desirable to examine the validity of these evaluation methods from the viewpoint of V&V.

In the V&V mentioned here, the purpose of the first V (Verification) is to determine whether the created numerical calculation correctly implements the conceptual model, and the purpose of the second V (Validation) is to determine whether that numerical calculation can correctly reproduce the phenomenon [5]. Here, it can be pointed out that many diffusion evaluations assuming ammonia-fueled ships have been carried out at the research level, but validation of those evaluations has not been carried out adequately.

Particularly in the case of Validation, experimental data are necessary as an object of comparison. However, the reliable ammonia gas leak diffusion tests are limited to Tan et al. (2017) [6], the RED SQUIRREL tests [7] and the Fladis Field Experiments [8], and in all cases, the object of those tests was diffusion behavior in an open space or in a wind tunnel. On the other hand, closed spaces where ammonia leaks may occur also exist in ammonia-fueled ships, for example, in the fuel preparation room, engine room, etc. Therefore, based on this background, ammonia leak and diffusion experiments were conducted in a closed space to contribute to validation of numerical analyses.

The experiment was carried out by releasing a mixed gas consisting of ammonia and nitrogen into an acrylic container with a volume of approximately 1 m^3 from the container bottom, as shown in Fig. 2. Although omitted in Fig. 2, the ammonia was discharged from the top of the container via a hose, and was detoxified before final release. As an additional safety measure, the maximum ammonia concentration in the ammonia-nitrogen mixed gas was at maximum 5 vol%.

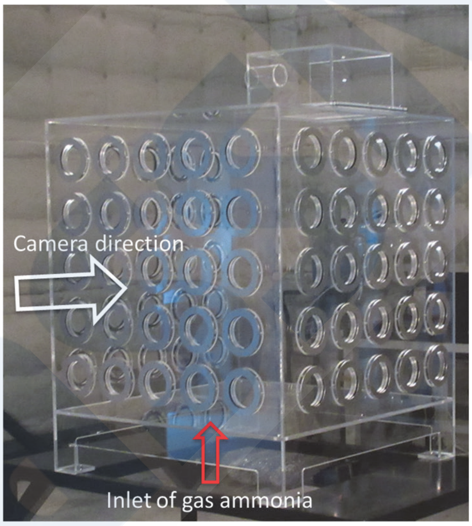


Fig. 2　Ammonia release space

The most important feature of this experiment was measurement of the ammonia concentration by 2-dimensional imaging by the Raman scattering method. For example, Tan et al. [6] used a contact-type gas concentration meter in measurements of the ammonia concentration. However, in small-scale experiments, the possibility that this kind of concentration meter itself may affect the flow field is a concern. Moreover, commercially-available ammonia gas detectors are not suitable for application in this type of experiment due to their long response time. Therefore, we adopted a system that makes it possible to evaluate the ammonia concentration of their entire region, without influencing the flow field (flow distribution), by using a laser Raman spectroscopy technique developed by the Shikoku Research Institute Inc. This technique has an extensive record of results with hydrogen, as described in detail in Asahi et al. (2021) [9]. In our experiment, quartz glass windows were inserted into the numerous round holes in the acrylic container shown in Fig. 2. This system makes it possible to photograph the laser light and the scattered light of the gas molecules during laser Raman spectroscopy. Ideally, a photography surface made entirely of quartz glass would be desirable, but considering the difficulty of manufacturing large-scale quartz glass, quartz glass was installed in the observation windows.

In this experiment, the scattered Raman light was photographed with a CCD camera in the direction indicated by “Direction of photography” in Fig. 2. Fig. 3 shows an example of an image of the ammonia concentration. Because this is the condition immediately after release of the ammonia started, high brightness (red contour) was observed near the release hole, and ammonia could not be detected in the upper part of the container, which is relatively far from the release hole. The measured luminescence here was converted to the concentration of ammonia by using the luminescence of a reference cell (compact vessel filled with ammonia of a known concentration). Fig. 4 shows an example of the transition of the measured ammonia concentration. It can be understood that that the transition of the concentration accompanying the start and end of ammonia release was successfully measured.

Future issues include improvement of measurement accuracy, installation of obstacles in the chamber, study of diverse methods of releasing the ammonia (e.g., pinhole release), and validation by comparison with a CFD analysis. Since no other attempts to measure the ammonia concentration in a closed space have been reported anywhere in the world, we plan to continue this research in cooperation with our joint research partners (Prof. Tomohiko Imamura of the Suwa University of Science and Prof. Emeritus Takeshi Shinoda of Kyushu University).

Fig. 3 Example of imaging of ammonia concentration

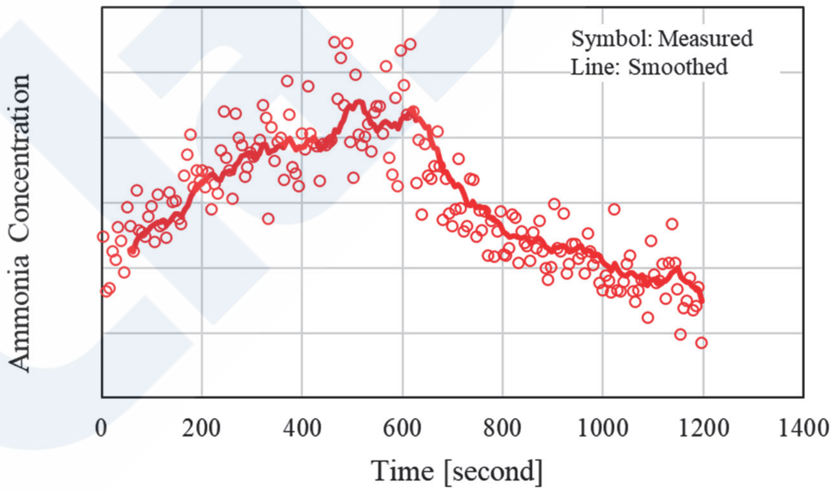


Fig. 4 Example of transition of ammonia concentration near ammonia jetting hole

2.3 Quantitative Risk Assessment and Advanced Risk Assessment Techniques for Alternative Fuel Ships

A risk assessment is required when designing an alternative fuel ship. Although HAZID or HAZOP is often conducted as the risk assessment, a risk assessment in the narrow sense (Quantitative Risk Assessment, QRA), like those carried out for hydrogen stations [10], is not the general practice in the maritime industry. Since visualization of the evaluated risk is simple with QRA, this approach easily fosters a common understanding among the stakeholders, and since quantitative evaluations of the effects of actions to reduce risks are possible, this approach is particularly suitable for risk assessments of systems with few actual results of use until now. On the other hand, there are few results of application to alternative fuel ships. Therefore, in this research, research and development were carried out to perform a QRA of a hydrogen-fueled model ship. Up to the present, HAZID, HAZOP and bow-tie analysis have been carried out for the same model ship. An example of the results of a bow-tie analysis is shown in Fig. 5.

Using these risk assessment results, research was carried out with the aim of using the risk assessment results not only in the QRA, but also in operation. As characteristic features of ships, the designer, operator and owner are different, and the crews assigned to ships also change with comparatively high frequency. Used ship sales are also the general rule, and in many cases, the ships are operated by different owners. Therefore, it is thought that management using the results of the risk assessment at the time of ship design, that is, the types of risks that exist for the ship and the actions that should be taken, will contribute to improved safety of alternative fuel ships, for which few records of actual use are available.

These studies are being carried out jointly with Associate Professor Yuichiro Izato of Yokohama National University.

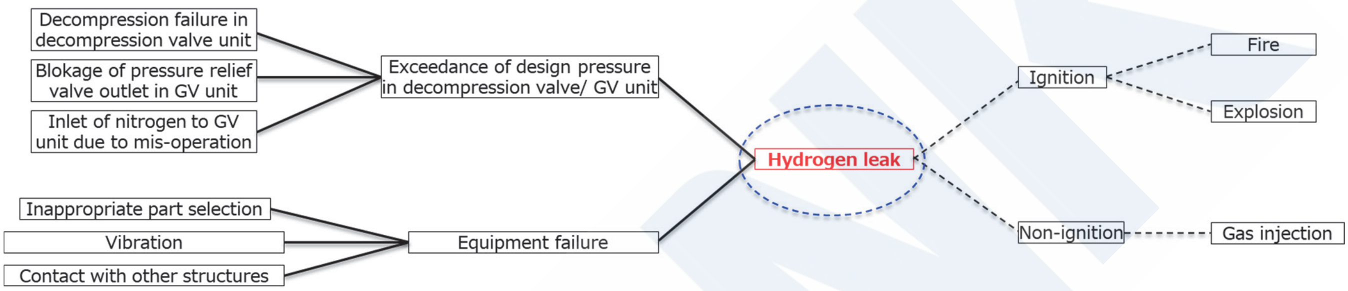


Fig. 5　Example of bow-tie analysis of hydrogen-fueled model ship

3.　PREVENTION OF CARGO AND FUEL CONTAINMENT SYSTEM DAMAGE

Although risk assessment is necessary in order to prepare a design that ensures the safety of the system as a whole, considering the unlikely event of a leak. On the other hand, however, leaks and damage are only treated statistically. That is, in systems for which no actual results exist, there is naturally a possibility of damage which has not been experienced in the past, and this type of damage itself cannot be prevented simply by a design based on a risk assessment. Therefore, in order to prevent damage of the fuel and cargo containment equipment itself, it is necessary to study techniques for evaluating the integrity of this equipment and countermeasures for events that may threaten that integrity. Until now, rules had been created based on damage that actually occurred, but in an era of technological innovation, proactive research and development, like that mentioned in chapter 1, is needed. The Society carries out research and development from the viewpoints of “Structural integrity” and “Material compatibility.”

In an assessment of structural integrity, accurate evaluations of the driving force that causes failure and the force of the resistance against failure are required. The following are examples of research carried out by the Society. Among these, as an example of a driving force that causes failure, a study of an evaluation method for ammonia stress corrosion cracking (SCC) of materials was reported at the Forum. Together with this, research and development for material compatibility with liquid oxygen (LOX), which can become a source of fire, was also reported at the Forum. In this chapter, the content of these two topic is introduced in sections 3.1 and 3.2, respectively.

3.1　Study of Evaluation Method for Ammonia Stress Corrosion Cracking Sensitivity of Materials

In storage and use of liquefied ammonia tanks, ammonia SCC is a cause of damage. At present, the countermeasures against ammonia SCC include limitation of the strength of the steel materials used, addition of water to the ammonia, post weld heat treatment (PWHT), etc., as specified in the IGC Code 17.12. However, since these measures are based on the knowledge up to the 1970s, this may be an obstacle to upscaling of ammonia transport ships and the spread of ammonia-fueled ships in the future. Therefore, the Society is studying methods for evaluating the possibility of using materials in ammonia storage, considering ammonia SCC.

Since ammonia SCC is a time-dependent fracture phenomenon, it is desirable to evaluate the ammonia SCC sensitivity of materials by an accelerated test. Since it is known that ammonia SCC sensitivity generally displays a correlation with the hardness of the material, experiments focusing on high strength steel materials were carried out in past research. However, in many cases, steel materials without such high yield stress, such as those used in ship tanks, were not evaluated. Therefore, the Society set test conditions referring to the research by Nakai et al. [11] in the 1980s, and verified whether cracking occurred or not in steel materials with a wide range of strength levels. These tests were conducted using the 4-point bending method.

Fig. 6 shows the condition of HT80 class steel after immersion for 2 weeks in ammonia with addition of 5% CO_2 and 1 000 ppm of oxygen, under the combined conditions of strain equivalent to the yield stress and application of a potential of 2.0 V vs Pt. It can be understood that remarkable cracking has occurred. In contrast, when the same test was carried out with steel having the lowest yield stress of 325 MPa under the standard, only fine cracks with a length of approximately 200 μm were observed. From these results, it was suggested that, under these test conditions, more significant results can be obtained in the ammonia SCC test with the steels currently in practical use, with the exception of mild steel.

On the other hand, Fig. 7 shows the result when the same HT80 class steel was immersed for 136 hours in the same experimental system. As this experiment shows, although cracks will still occur, they will be limited to minor length if the immersion time is short. In addition, no cracks occurred with the steel with the lowest yield stress of 325 MPa. Based on these facts, it can be said that setting an appropriate immersion period corresponding to the test conditions is necessary in order to evaluate the ammonia SCC sensitivity of materials.

Fig. 6　SCC fracture surface of HT80 (immersion time: 2 weeks)

Fig. 7　SCC fracture surface of HT80 (immersion time: 136 hours)

When conducting accelerated ammonia SCC tests, setting appropriate acceleration conditions is indispensable. While it is known that impurities, namely, oxygen, carbon dioxide and water, affect ammonia SCC, the mechanism responsible for changes in ammonia SCC behavior is not clear. In addition, corrosion reaction is also a contributing factor, and at present, the success rate in experiments is not necessarily high. Therefore, in the future, we plan to continue research with the aim of setting the conditions for stable experiments and confirming variations.

3.2　Study of Evaluation Method for Liquid Oxygen (LOX) Compatibility of Materials

Liquid hydrogen, which is expected to become an important zero-emission energy source in the future, is liquified under the cryogenic temperature of –253 °C. Since this temperature is lower than the liquefaction temperature of oxygen, oxygen in the air may possibly liquefy, depending on the state of thermal insulation. Therefore, Guidelines for Liquefied Hydrogen Carriers [12] published by ClassNK requires consideration of ignition risk due to liquified oxygen (LOX) when the air is cooled below its liquefaction temperature in single-failure scenarios. Specifically, it must be ensured that the generation of LOX does not pose a hazard, or that materials in contact with LOX are LOX compatible.

“LOX compatibility” refers to the ability of a material not to ignite upon mechanical impact when in contact with LOX. Although LOX compatibility assessment is specified in the ASTM code, until now, LOX compatibility assessments have mainly been used in the aerospace field, and have rarely become an issue in the maritime field. Therefore, the Society has accumulated experience and knowledge on LOX compatibility through collaborative research with Japan Aerospace Exploration Agency (JAXA).

In LOX compatibility tests, the assessment specimen is immersed in LOX and struck by way of a striker pin, as shown in Fig. 8. When there is no ignition or sign of ignition in the specimen, the tested material is considered to be LOX compatible. On the other hand, when ignition similar to that in Fig. 9 is observed, the material is considered to be incompatible with LOX. The forms of ignition vary; it can be relatively mild, as shown in Fig. 9, or it can be explosive, as classified as "Explosion" by Guo et al.[13]. Through the collaboration with JAXA, the Society has carried out experiments with six materials, carbon steel (SM400C), coated carbon steel, Al-Mg alloy (A5083-O), PEEK resin, insulation material (MLI) and an epoxy-based structural adhesive.

The experimental results obtained so far are presented in Table 1. The ASTM code stipulates an impact energy of 98 J, but in this study, 49 J and 25 J were also used to examine the sensitivity of LOX compatibility to impact energy, because the suitable impact energy for the maritime industry is still unclear. "Non-ignition" refers to a test condition in which ignition does not occur in 10 or more experiments. However, if even one trial in the multiple experiments results in ignition, that experimental condition is regarded as "Ignition." Although some scattering of the results was found, Table 1 shows that the LOX compatibility of various material displays dependency on the amount of the impact energy. This finding suggests that it may be possible to assess LOX compatibility based on the degree of the ignition factor to which the material is subjected.

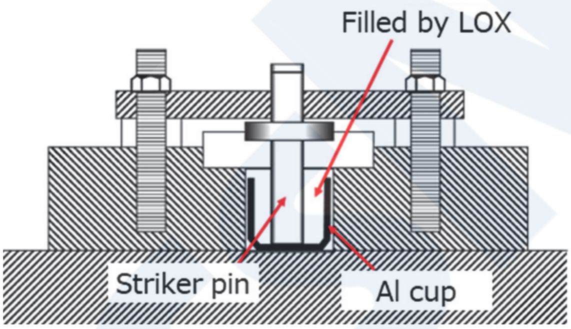


Fig. 8 LOX compatibility impact tester

Fig. 9 Result of LOX test

Table 1　Status of LOX compatibility test

Specimen	Impact energy [J]		
	98	49	25
SM400C	Non-ignition		
Coated SM400C	Ignition	Ignition	Non-ignition
A5083-O	Non-ignition		
PEEK resin	Ignition	Non-ignition	
Insulation material（MLI）	Ignition	Ignition	
Epoxy-based structural adhesive*	Ignition	Ignition	Ignition

Because LOX compatibility has been assessed in the aerospace field, it is valuable to investigate the assessment methodology and criteria suitable for the maritime field for reasonable onboard liquid hydrogen operation. This study has been carried out under a partnership with JAXA, and we aim to deepen this collaboration to improve the safety of liquid hydrogen usage.

4.　CONCLUSION

Decarbonization of the maritime industry is progressing rapidly, and design of alternative fuel ships and new cargo carriers is underway. On the other hand, safety requirements have been developed as an extension of the rules existing until now, or in a form that reflects the knowledge gained in the approval process of those designs. Depending on the case, there are also areas where design precedes the development of safety requirements. For this reason, proactive research and development is even more important. The Society promotes research and development by the two approaches of “Advanced and quantitative risk assessment of alternative fuel ships” and “Integrity assessment techniques for cargo and fuel containment systems,” and is accumulating the knowledge necessary to materialize and operate safe and efficient alternative fuel ships and new cargo carriers.

The Society carries out research and development in each of the stages of element technology research, establishment of safety requirements/rule development, and actual projects. ClassNK Research Institute is mainly involved in research and development in the stages of element technology research and establishment of safety requirements/rule development. However, together with providing advanced knowledge obtained through element technology research to actual projects, we are also building a research and development system based on organic cooperation by obtaining feedback on needs from actual projects. In addition, we are constructing cooperative systems with a diverse range of fields in order to acquire necessary knowledge, without being bound by the conventional field of naval architecture and ocean engineering, and with the aim of achieving timely research and development by maintaining and promoting these open innovation systems.

ACKNOWLEDGEMENT

Much of the research and development work of the Society is carried out through cooperation with universities, companies and research institutes. We wish to take this opportunity to thank all those concerned for their generous cooperation.

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Commentary on “Bayesian Estimation of Ammonia Leak Frequency for Risk Assessment of Ammonia-Fueled Vessels”

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1. INTRODUCTION

This article presents a commentary on the paper by Kojima et al. (2025) [1] mentioned in the title. For details and attached materials, please refer to the References. In particular, due to the limitations of space, we have omitted the methods of measuring the prior distribution and likelihood setting method and sensitivity analysis for the first updating, which are discussed in the following, and presented the parameters used in the estimation and the estimation results only for flanges as an example.

Reducing greenhouse gases (GHG) is an urgent global challenge, and requires industrial activities in harmony with the environment. Maritime transportation is not an exception to this trend. Although the International Maritime Organization (IMO) initially aimed to achieve zero emissions in ocean-going vessels by 2100 [2], this target was moved up to 2050 in 2023 [3]. Historically, heavy oil was the main fuel used in ocean-going vessels, but in recent years, the use of alternative fuels such as liquefied natural gas (LNG), methanol, etc. has increased, as these fuels have low GHG emissions [4].

Ammonia is positioned as a decarbonization fuel for the transition period to a hydrogen society in the “Green Growth Strategy through Achieving Carbon Neutrality in 2050” [5] developed by Japan’s Ministry of Economy, Trade and Industry in cooperation with related ministries and agencies. Use of ammonia fuel in vessels is also continuing to attract increasing attention as one feasible option [6, 7, 8]. Compared with the above-mentioned LNG, methanol and other alternative fuels, ammonia has the advantage of a high gravimetric and volumetric energy density and is compatible with the existing storage and transport infrastructure [10], which supports annual global production of 150 million tons in 2019 [9]. Ammonia is also practical in terms of its physical properties, as it is easily liquefied at atmospheric pressure and has a narrow flammability range. By 2050, ammonia is projected to comprise approximately 44 % of total vessel fuel demand [3], accounting 30 % of total ammonia demand [8]. On the other hand, ammonia is a toxic substance and can irritate the eyes and damage the respiratory tract at a certain exposure level [11]. In addition, it may also cause stress corrosion cracking in materials such as high-strength steel, zinc, copper and brass [12].

The International Convention for the Safety of Life at Sea (SOLAS) [13] requires a risk assessment for vessel design of vessels using alternative fuels, regardless of the type of liquefied gas fuel to be used. An assessment of the risk during usage, storage and bunkering (fuel supply) in both ports and offshore environments is necessary.

Quantitative risk assessment (QRA) is a representative assessment methodin which the consequence of an event (damage an event might cause) and the probability (frequency or likelihood of that event) are estimated (referred to hereinafter as “consequence assessment” and “frequency assessment,” respectively), and the mathematical product of the two estimates is quantified as the risk [14]. Many examples of risk assessments for LNG-fueled vessels have been reported, including examples of assessment of the engine room [15] and LNG floating production, storage and offloading systems [16], various types of vessels, such as LNG-fueled tankers, including full-bore events [17] and LNG-fueled ore and bulk carriers [18]. The primary sources of information such as the leakage frequency and accident probability, occurrence rate, etc. used in these examples are the Health and Safety Executive (HSE) Hydrocarbon Releases System (HCR) in the UK [19, 20], the Guidelines for Quantitative Risk Assessment (so-called “Purple Book”) [21] of the Committee for the Prevention of Disasters (CPR) in the Netherlands and the database of the International Association of Oil and Gas Producers (IOGP) [22, 23]. However, it must be noted that these information sources are not specific to LNG or ammonia.

Although the number of risk assessments for ammonia is limited in comparison with LNG, QRAs for ammonia fuel have also been carried out in recent years. Since accidents and the spread of ammonia during bunkering of ammonia fuel are a particularly large concern, several risk assessments for port and harbor areas are available [24, 25]. However, as one issue in these assessments, the consequence assessment is carried out based on the characteristics of ammonia, but in the frequency assessment, the

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component-specific leak frequencies (LFs for each type of component equipment) are estimated based on data for LNG or hydrocarbon fuels. Thus, QRAs that adequately reflect the unique characteristics of incidents involving ammonia leaks are limited.

Moon et al. [26] estimated the potential leak frequency of the ammonia fuel supply system by analyzing the data on ammonia leak incidents in tankers transporting liquid ammonia. Based on a comparison of the estimated LFs for ammonia and the IOGP frequency data, they concluded that IOGP frequency data can be used in risk assessments of ammonia-fueled vessels. However, they also noted the limitations of their dataset due to the lack of leakage frequency data by leak size and component type. Since increased use of ammonia-fueled vessels is anticipated, accurate, reliable QRAs are expected to be required. Therefore, it was suggested that component-specific LFs that are applicable to QRAs for ammonia-fueled vessels will be indispensable.

Based on these issues, in our research, we estimated the leak size-specific and component-specific leak frequencies (hereinafter, LFs) of ammonia leaks considering the characteristics of ammonia and the characteristics of the component equipment used in ammonia-fueled vessels. Fig. 1 shows the framework for estimating the LFs of ammonia-fueled vessels. First, we developed a Bayesian model based on the methodologies of LaChance et al. [27], Groth et al. [28] and Kihara et al. [29]. For the first updating, we incorporated the leak frequency data for LNG-fueled vessels obtained from Davies and Fort [30]. However, for the second updating, we prepared component-specific LFs for ammonia-using facilities by analyzing 18 945 accident cases spanning a period of 57 years in the Japanese High Pressure Gas Accident Cases database (HPGAC) [31], and used these LFs as the likelihood of accidents. The component-specific leak frequency (LF) in ammonia-fueled vessels was estimated as the result of the second updating. A sensitivity analysis of the likelihood was also conducted to examine the indeterminacy of the results.

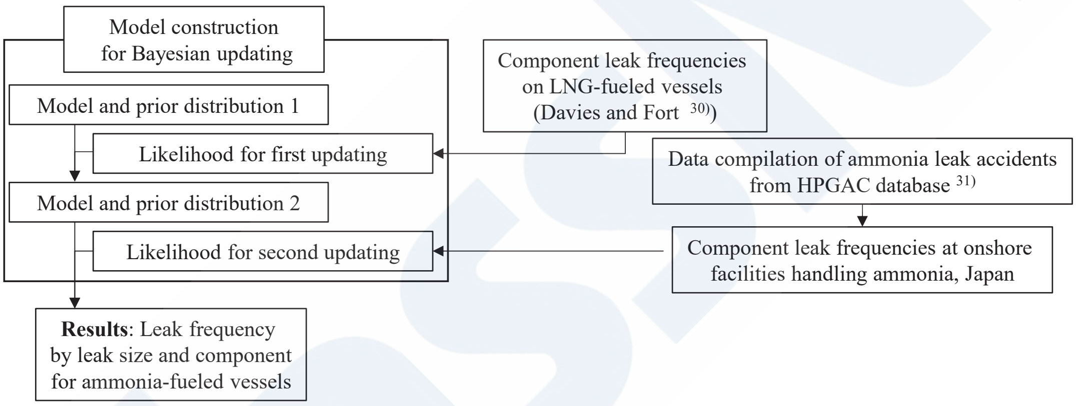

Fig. 1 Framework for estimating ammonia leak frequency from ammonia-fueled vessels

2. METHODOLOGY

2.1 Bayesian Theorem

The basic formula derived from the Bayesian theorem is expressed as shown in (1) [29].

$$\textit{Posterior distribution} \propto \textit{Likelihood x Prior distribution} \qquad (1)$$

The posterior distribution is proportional to the product of the likelihood and the prior distribution. The prior distribution can be derived from objective information or assumed based on subjective information such as the experience or judgment of experts. It is sometimes uniformly distributed as a non-informative distribution. The posterior distribution can be estimated by incorporating new evidence or data as the likelihood. A new posterior distribution is then calculated by using this posterior distribution as the new prior distribution and incorporating supplementary accumulated data. This iterative process is known as Bayesian updating.

As strengths of Bayesian updating, it is possible to combine data from multiple information sources and reliability is enhanced by continuously incorporating new evidence and data. For these reasons, Bayesian updating is utilized to derive probability distributions with a certain level of objectivity and reproducibility, even in fields where prediction by empirical models is difficult and the data tends to be insufficient, as in the case of fuel ammonia.

2.2 Construction and Implementation of the Hierarchical Bayesian Model Using FLA

In this paper, we referred to the component-specific LF estimation model for leaks in hydrogen fueling facilities developed by the Sandia National Laboratory (SNL model) in the United States [27), 28)].

First, the concepts of this model will be organized. The SNL model begins from the assumption that a linear relationship exists between the leak frequency (LF; unit: /year) and the logarithm of the fractional leak area (FLA). The FLA represents the ratio of a leak area to the cross-sectional area of equipment such as piping, etc. This assumption is consistent with the intuitive feeling that the frequency of large-area leaks is low, and conversely, small leaks occur with a higher frequency. The concept of the FLA is derived based on the results of an analysis of accident data from the chemical processing, compressed gas, nuclear power plant and offshore petroleum industries, and a similar tendency has also been confirmed in other past research (e.g., Spouge [32)], IOGP [22)]).

The model equation can be simplified to (3) by taking the logarithms of both sides of (2), and further simplified to (4) by substituting a constant for the intercept of (3) and changing the logarithm base. The size of the FLAs shown in Table 1 can be understood intuitively because the FLA output is converted to negative integers (-4, -3, -2, -1, 0) by changing the base. Next, the SNL model assumed that the logarithm of $LF(I)$, where I represents the size of leaks divided into the five categories shown in Table 1, follows the normal distribution expressed by (5).

The leak size was categorized as described here because the leak sizes reported in the information sources of the data for incorporation in the model were not consistent. That is, when handling the leak size continuously, the database frequently contains only one accident of a certain leak size. As a result, the probability data used as the likelihood cannot be prepared and Bayesian estimation becomes impossible. To avoid this situation, we collected accident cases where it was possible to judge the size of a similar leak and created a procedure for calculating the LF for that size. Considering the diversity of the contents of accident reports, the authors strongly recognized the necessity of this categorization procedure, even in the leak size classification work carried out in 2.6.2.

Returning to the description of the model equation, when the logarithm of $LF(I)$ follows the normal distribution in (5), (2) can be written as the logarithmic linear model in (6) having an intercept α_1 and a slope α_2. At this time, a natural conjugate distribution (conjugate prior distribution) is set for α_1, α_2 and ${\sigma^2}_{LF(I)}$, which are the parameters used in the estimations in (5) and (6), and (7) and (8) are assumed to have a normal distribution, while an inverse gamma distribution is assumed for (9). That is, we assumed a hierarchical Bayesian model where $\mu_{LF(I)}$ has a distribution in which α_1 and α_2 are variables, and furthermore, α_1 and α_2 also have respective distributions.

The LFs of components can be estimated by using this procedure by converting various combinations of the component cross-sectional areas (pipe diameters) and leak sizes derived from accident data to FLA, and incorporating the FLA in a Bayesian model. Here, we constructed a model for estimating the leak frequency distribution in ammonia-fueled vessels by incorporating the LFs of components used in ammonia facilities. Although the SNL model used WinBUGS [33)] as the tool for Bayesian updating, we used the R package jagsUI [34)].

$$LF = A_1 \times FLA^{A_2} \tag{2}$$

$$\ln LF = \log A_1 + A_2 \cdot \ln FLA \tag{3}$$

$$\ln LF = \alpha_1 + \alpha_2 \cdot \log_{10} FLA \tag{4}$$

$$\ln\left(LF(I)\right) \sim \ Normal\left(\mu_{LF(I)}, {\sigma^2}_{LF(I)}\right) \tag{5}$$

$$\mu_{LF(I)} = \alpha_1 + \alpha_2 \cdot \log_{10} FLA_I \tag{6}$$

$$\alpha_1 \sim \ Normal\left(\mu_{\alpha_1}, {\sigma^2}_{\alpha_1}\right) \tag{7}$$

$$\alpha_2 \sim \ Normal\left(\mu_{\alpha_2}, {\sigma^2}_{\alpha_2}\right) \tag{8}$$

$${\sigma^2}_{LF(I)} \sim \ InvGamma(a_I, b_I) \tag{9}$$

I: leak size (Table 1);
$LF(I)$: component leak frequency at leak size I;
A_1, A_2: parameters for the FLA;
α_1, α_2: intercept and slope parameters for the exponential function $\log_{10} FLA$ and μ_{LF}, respectively;
$\mu_{\alpha_1}, {\sigma^2}_{\alpha_1}$: mean and variance of the normal distribution for α_1, respectively;

μ_{α_2}, $\sigma^2{}_{\alpha_2}$: mean and variance of normal distribution for α_2, respectively;
$\mu_{LF(I)}$: mean of the recorded leak frequency;
$\sigma^2{}_{LF(I)}$: variance of the recorded leak frequency; and
a_I, b_I: shape and scale parameters of the inverse gamma distribution for $\sigma^2{}_{LF(I)}$, respectively.

Table 1 Coefficients corresponding to the categories of leak size and FLA

Leak size (I)		FLA[a]
1	Very small	0.0001
2	Minor	0.001
3	Medium	0.01
4	Major	0.1
5	Rupture	1

[a] FLA: Fractional Leak Area. The ratio of the leak area to the total cross-sectional flow area of the equipment (pipe). For example, the leak category "very small" refer to a leak area that is 0.0001 (= 0.01 %) of the total flow area.

2.3 Target Components of Leak Frequency Estimation

Table 2 shows the categories of the components for the prior distribution and the two likelihoods for the first and second updating required in the estimation reported in the respective sources referenced in this study. In this paper, the targets of the estimations of leak frequency were limited to components for which information was available in all three information sources, namely, Flanges, Joints, Pipes, Valves (actuated) and Valves (manual). For compressors, Davies and Fort [30] categorize the centrifugal type and reciprocating type separately, but LaChance et al. [27] and Japan's High Pressure Gas Accident Cases database (HPGAC database) [31] do not distinguish between the two types. Therefore, Compressors were excluded, considering the mechanical differences between the two types.

Table 2 Categories of components reported in each data source and their correspondence

Components in LaChance et al. [27] as prior distribution	Components in Davies and Fort [30] as likelihood for first updating	Component in HPGAC database [31] as likelihood for second updating
Flanges	**Flanges**	**Flanges**
Joints	**Instrument connections [a]**	**Joints**
Pipes	**Pipes**	**Pipes**
Valves	**Valves (actuated)**	**Valves**
	Valves (manual)	
Compressors	Compressors (centrifugal)	Compressors
	Compressors (reciprocating)	
Cylinders		
Filters		
Hoses		Hoses
	Pressure vessel	
	Refrigerated ambient pressure vessel	
Instruments	-	Others [b]

*Blank spaces indicate components that were not reported in the source.
[a] Davies and Fort [30] noted that "Instrument connections include flanges within the given release frequency." In the following, these are denoted as "Joints" unless specially noted otherwise.
[b] "Others" include Storage tanks, Heat exchangers, Pumps, Chillers, Measuring Instruments, etc.

2.4 Prior Distribution

The LFs used in the prior distribution of the first updating were the LFs of general components [27] estimated from accident data in various fields, including chemical processing, compressed gas, nuclear power plants, offshore petroleum, etc.

2.5 Likelihood for the First Updating: LFs from LNG Fueling Systems in Davies and Fort [30)]

In the first updating, the LFs from LNG fueling systems estimated by Davies and Fort [30)] were converted to correspond to the FLAs in Table 1, and the results were incorporated in the likelihood. These LFs are referenced in the risk assessment guidelines for LNG-fueled vessels (IGF Code) [35)] and are considered to have a certain degree of reliability.

2.6 Likelihood for the Second Updating: Likelihood Estimated from the HPGAC Database [31)]

2.6.1 Extraction of Ammonia Leak Accident Cases at Facilities Using Ammonia by Leak Size

Since ammonia-fueled vessels are currently in the research and design stage, accident cases and an accident database are still lacking. In this situation, use of data from onshore ammonia production and consumption facilities as alternative data has been suggested [12)]. In this paper, the leak frequency for the likelihood in the second updating was estimated from leak accident cases involving ammonia at onshore facilities in Japan, referring to the above-mentioned HPGAC database [31)], which is managed by the High Pressure Gas Safety Institute of Japan.

The HPGAC database contains 18 945 accident records spanning the period from 1965 to 2022. Businesses that handle high pressure gases, including ammonia, are required to report accidents under Japan’s High Pressure Gas Safety Act. These reports contain a total of 28 fields for each accident, including identifying information, the time and location of the accident, the number of injuries and fatalities, the substance involved, the characteristics of the leak or blowout (degree, component involved, etc.), the cause and an overview of the accident[*1].

From these 18 945 accident cases, 927 cases containing the word “ammonia” in the “Substance” field or “Accident overview” field were extracted. Next, 610 records[*2] related to ammonia refrigeration were excluded from the 927 cases. Those cases were excluded because refrigeration systems circulate ammonia in a closed loop, and do not produce or consume ammonia [36)], and their characteristics are considered to be different from those of combustion systems which continuously supply and consume ammonia. The remaining 317 cases were limited to the components selected as the evaluation targets in Table 2, i.e., Flanges, Joints, Pipes and Valves. As a result, the dataset was narrowed to 215 cases.

2.6.2 Categorization of the Leak Size of Ammonia Leak Accidents

The sizes of the leaks in the 215 cases obtained were determined following the flowchart in Fig. 2. First, in cases where it was possible to calculate the FLA directly from the degree or place of the leak, the leak size was set corresponding to that FLA. Next, accidents that could be judged easily from descriptors in the accident overview were classified as “Rupture” or “Very small.” For example, accidents with descriptors such as “fracture,” “disconnection” or “rupture” were classified as “Rupture,” while those described by terms such as “negligible,” “keep normal operation” or “steady operation” were classified as “Very small.” In accidents where the leak rate could be estimated from the description in the overview or information concerning the leak, the leak size was classified according to that flow rate. For other cases, two researchers estimated the leak size separately. When the two estimates agreed, that leak size was used, and when the estimates did not coincide, the leak size was determined through consultation. It was possible to categorize the leak size for 109 cases by the procedure up to this point.

Since the remaining 106 cases contained little or none of the information necessary for classifying the leak size, those cases were distributed proportionally based on the number of accident cases classified as Very small, Minor, Medium and Major up to this point. Rupture was not included in this proportional distribution because detailed information is generally available for large accidents classified as Rupture, while other accidents are described briefly. Very small was included in the distribution considering the possibility that some very small leaks might have been undetected or unreported. The results obtained are shown in Table 3, which provides a breakdown of the number of ammonia leak accidents before and after the proportional distribution.

[*1] However, complete reports including all fields were only available for 28 cases (0.1 %) of the 18 945 cases.

[*2] Cases in which the “type of industry,” “facility category” or “accident overview” field in the accident report contained the terms “refrigeration,” “freezing,” “ice making,” “food,” “fishing” or “fisheries” were excluded.

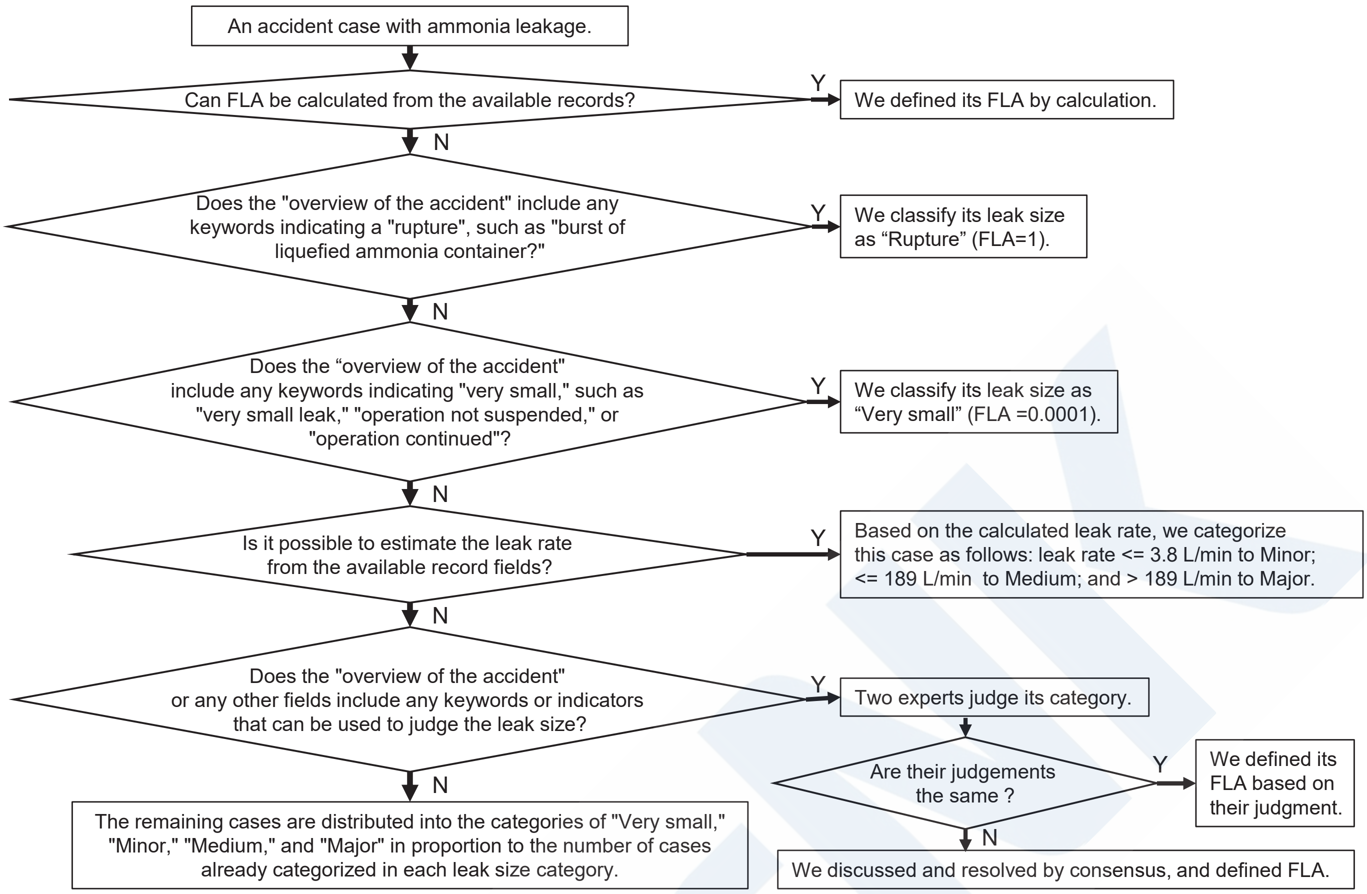

Fig. 2　Flowchart for determining leak size of ammonia leak accidents obtained from HPGAC database

Table 3　Component-specific number of ammonia leak accident cases by leak size

Component	Number of accidents by leak size						
		Very small	Minor	Medium	Major	Rupture	Unknown
Flanges	Before proportional distribution	14	1	1	0	1	18
	After proportional distribution	30	2	2	0	1	

2.6.3　Conversion from Number of Accident Cases to Accident Frequency (Likelihood)

In order to estimate the annual leak frequency (annual LF) per unit length (per meter for pipes) from the number of accidents by leak size estimated in 2.6.2, the number of leak cases after proportional distribution in Table 3 was divided by the total number of components (component count) and the total operational time of the component concerned. The total component count is estimated by multiplying the number of facilities by the average number of components in a facility.

$$LF(I)_j = \frac{LC(I)_j}{Period \times N_F \times N_{C,j}} \tag{10}$$

$LF(I)_j$ (cases/year/number): annual LF per unit (per meter in pipes) for component j in leak size category I

$LC(I)_j$ (cases): number of ammonia leak accidents for component j in leak size category I

$Period$ (years): total operational time, assumed to be 57 years from the period of the HPGAC database (1965 to 2022)

N_F (facilities): total number of ammonia-related facilities in Japan

$N_{C,j}$ (number/facilities): number of components per ammonia-related facility for component j in Japan

The total number of ammonia-related facilities (N_F) and the number of component j per ammonia-related facility ($N_{C,j}$) were estimated based on the information in the respective references, as these numbers were not available from the HPGAC database or the statistics tabulated by trade associations or the government.

For N_F, Suzuki [37] reported that the number of general facilities handling Class I gases (which include ammonia) under Japan’s High Pressure Gas Safety Act was 12 428 as of March 1996 and 21 438 as of March 2015. Based on the discussion in 2.6.1, the ratio of ammonia-related accidents (927) to all accidents (18 945) is 4.9 % (= 927/18 945), and when limited to non-refrigeration ammonia accidents (317), the ratio is 1.7 % (317/18 945). Based on these calculations, the number of ammonia-related facilities is considered to be in the range from 211 (≒12 428 x 1.7 %) to 1 050 (≒21 438 x 4.9 %). Therefore, the “most likely” number of ammonia-related facilities N_F from 1965 to 2022 was estimated to be 500.

The number of components per facility $N_{C,j}$ for component j was estimated referring to the number of components per facility for estimation of the leak frequency of hydrogen gas set by Japan’s National Institute of Advanced Industrial Science and Technology (AIST) [38]. That reference assumed that compressed natural gas (CNG) facilities are representative of high pressure gas facilities and gasoline fueling stations are representative of facilities handling hazardous substances, and used the typical component counts of the respective facilities in estimation of the leak frequency of hydrogen gas. Based on the same thinking, in this paper, the component count was estimated on the assumption that ammonia facilities are similar to CNG stations. As a result, the numbers of component j per facility ($N_{C,j}$) were Flanges = 10, Pipes = 48, Joints = 40 and Valves = 8.

The LFs estimated from these results are shown in Table 4. The range of the LFs was from 10^{-5} to 10^{-4}, and showed a lower tendency that of the LFs of LNG-fueled vessels.

Table 4 Leak frequency (likelihood) of flanges in ammonia facilities estimated from HPGAC database

FLA	Leak frequency, LF (/year)
0.0001	1.05E-04
0.001	7.02E-06
0.01	7.02E-06
0.1	Not available
1	3.51E-06

2.6.4 Sensitivity Analysis: Study of the Effect of Assumptions for LFs Based on the HPGAC Database on Estimation Results

The proportional distribution method, which was applied to accidents when the leak size was “Unknown,” and the estimation methods for N_F and $N_{C,j}$ discussed in sections 2.6.1 to 2.6.3 include subjective judgments and assumptions. Therefore, a sensitivity analysis was conducted as an effective technique [39] for understanding how the judgments and assumptions applied to the data affect the estimation results. In this paper, the values adopted up to now were assumed to represent the case with the highest validity (“most likely” case). The results obtained under different assumptions were compared with those values, and the difference was considered. We also conducted a sensitivity analysis of the effect on the analysis results when the LFs reported by Davies and Fort [30] were converted to FLAs, but the effect was slight. For details, please refer to the reference.

In the sensitivity analysis for the proportional distribution of accidents with an “Unknown” leak size in section 2.6.2, accidents with “Unknown” leak sizes were distributed proportionally to Very small to Rupture, Minor to Major, and Minor to Rupture, and the LFs were estimated based on those distributions and compared with the results for the proportional distribution to Very small to Major (“most likely” case).

Regarding the number of ammonia-related facilities N_F in Japan, in section 2.6.3, N_F = 500 was adopted based on the estimated range of approximately 211 to 1 050. Referring to this estimated range, in the sensitivity analysis, 100 was adopted as the N_F for the Lower bound case, and 1 000 was adopted for the Upper bound case (Table 5). In the sensitivity analysis for the number of components per facility $N_{C,j}$, the $N_{C,j}$ adopted as alternative cases were set referring to the values for CNG fueling stations and gasoline fuelling stations (Table 6).

Combining the three cases in Table 5 and the three case in Table 6, the five cases in Table 7 were set for the sensitivity analysis.

Table 5 Total number of facilities (N_F) in Japan in each case

Parameter	Lower bound	Most likely	Upper bound
N_F (facility): total number of ammonia-handling facilities.	100	500	1,000

Table 6 Number of components per facility ($N_{C,j}$) in each case

Parameter	Component (j)	Lower bound	Most likely	Upper bound
$N_{C,j}$ (number/facility): number of components per facility for component j.	Flanges	5	10	48

Table 7 Five cases used in sensitivity analysis for estimation of LFs of flanges in ammonia-handling facilities

Case No.	1	2	3	4	5
Cases of N_F	Most likely	Lower bound	Upper bound	Most likely	Most likely
Cases of $N_{C,j}$	Most likely	Most likely	Most likely	Lower bound	Upper bound
FLA					
0.0001	1.1E-04	5.3E-03	5.3E-05	2.1E-04	2.1E-05
0.001	7.0E-06	3.5E-04	3.5E-06	1.4E-05	1.4E-06
0.01	7.0E-06	3.5E-04	3.5E-06	1.4E-05	1.4E-06
0.1	NA	NA	NA	NA	NA
1	3.5E-06	1.8E-04	1.8E-06	7.0E-06	7.0E-07

3. RESULTS

3.1 Estimation Results of LF by Leak Size in Ammonia-Fueled Ships

Rhat, which is an indicator for diagnosis of convergence in Bayesian updating, was less than 1.1 for all parameters in all cases. Convergence and its plot were also confirmed, indicating that valid solutions were obtained in all cases, including the sensitivity analysis.

The results of the leak frequency estimation for ammonia-fueled vessels are shown in Fig. 3. The values of the plots and the confidence intervals are given in the Supplementary material of this paper. Compared with the LFs of LNG-fueled vessel, at the first updating (shown by the black dots/black lines in Fig. 3), the LFs of the ammonia-fueled vessels at the second updating (shown by the red dots/red lines) were relatively lower. This means that, when the LFs for LNG-fueled vessels are used in a QRA for ammonia-fueled vessels, the quantitative risk of the latter is overestimated by a factor of 1 to 10 times. In this case, it was suggested that a safer (more conservative) assessment result is obtained, but on the other hand, stricter risk management and more expensive measures may be required. The reason for this difference in the LFs will be considered in Chapter 4.

Regarding the confidence interval of the LFs, the 90 % uncertainty interval (spanning the 5^{th} to 95^{th} percentiles of the mean) was within a range of about 1/10 to 10 times the mean. This confidence interval represents the uncertainty that invariably accompanies estimation results, and must be considered when making risk assessments.

Comparing the LF estimation results for actuated (automatic) valves and manual valves, in the first updating, the LFs of manual valves were approximately 10 times higher than those of actuated valves, reflecting the fact that the LF (likelihood) of leaks in manual valves was roughly 10 times higher than that of actuated values in the report by Davies and Fort [30)]. However, at the second updating, the same likelihood obtained from the HPGAC database was used for both types of vessels, and substantially the same LF estimation results were obtained, in spite of the difference in the prior distributions. These results were obtained because the LF estimation results (LF distribution) are determined by a limited number of data points and the inflexible linear model defined by (3). Although an immediate response to these issues will be difficult, it may be possible to obtain results that more accurately reflect the characteristics of accidents in each component by enhancing the accident database or applying more flexible modelling approach (e.g., Kaneko and Yuzui [40)]).

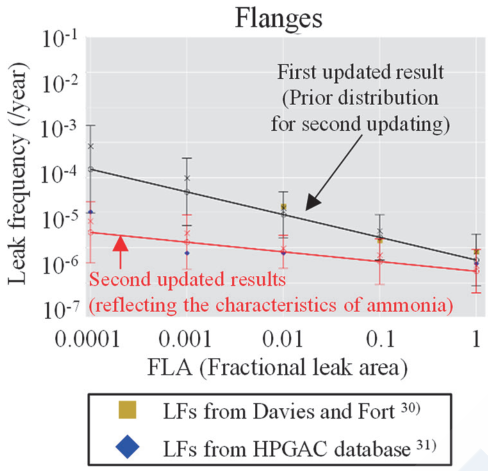

Fig. 3 Results of LF estimation for ammonia-fueled vessels

3.2 Results of Sensitivity Analysis

This section discusses the results of the sensitivity analysis for the likelihood in the second update, using Flanges as an example, as in the discussion until now (Fig. 4, Fig. 5). The results for other components can be found in the Supplemental material.

First, we will discuss the sensitivity analysis results of the proportional distribution method for accidents for which the leak size is “Unknown.” In the Very small to Major case adopted as the “most likely” approach, the LF estimation results for ammonia-fueled vessels showed that LF decreased as the leak size increased. Although this tendency was also the same for Minor to Major and Very small to Rupture, the slopes of the LFs were more moderate. However, Minor to Rupture showed a positive slope, which was a counterintuitive result, as the leak frequency became larger as the leak size increased. In addition, while there were differences in the 90 % confidence interval depending on the leak size and the component, the difference in the estimated mean was within the range of 1/10 to 10 times the mean. As a result, it can be concluded that Very small to Major gave a distribution which is suitable for the most conservative assessment.

Next, we will discuss the sensitivity analysis results for the number of ammonia facilities N_F and the number of components per facility $N_{C,j}$, as shown in Fig. 5. Since the only difference in the five graphs in Fig. 5 is these two parameters, which are both in the denominator in (10), and the likelihood (LF) increases or decreases in (10) independent of the leak size category, the five estimation results (straight red lines) in Fig. 5 have substantially identical slopes, and only the intercept (LF on the *y*-axis) is different. Regarding the mean of the estimated LF distribution, when compared against the “Most likely and Most likely” case (upper left), the values for the other cases are within a range of roughly 1/10 to 10 times of that case. The difference in the means is particularly wide depending on the assumption N_F, indicating that the influence of N_F was larger than that of the proportional distribution method for Unknown cases described above. With the exception of the Lower bound case of N_F, the results of the mean LF estimations of the Lower bound and the Upper bound for almost all components and leak sizes were generally within the confidence interval of the Most likely case. As a reason for the deviation of the Lower bound case of N_F, it is suggested that the setting of N_F = 100 was excessively small. The value of 100 was set because the lower end of the range of ammonia-related accidents was 211 (12 428 facilities x 1.7 %), and experts judged this good number as a boundary line.

Although assumptions always contain a certain bias, the distribution of the leak frequency estimated as the most likely case is considered to be within an acceptable range, even with limited information.

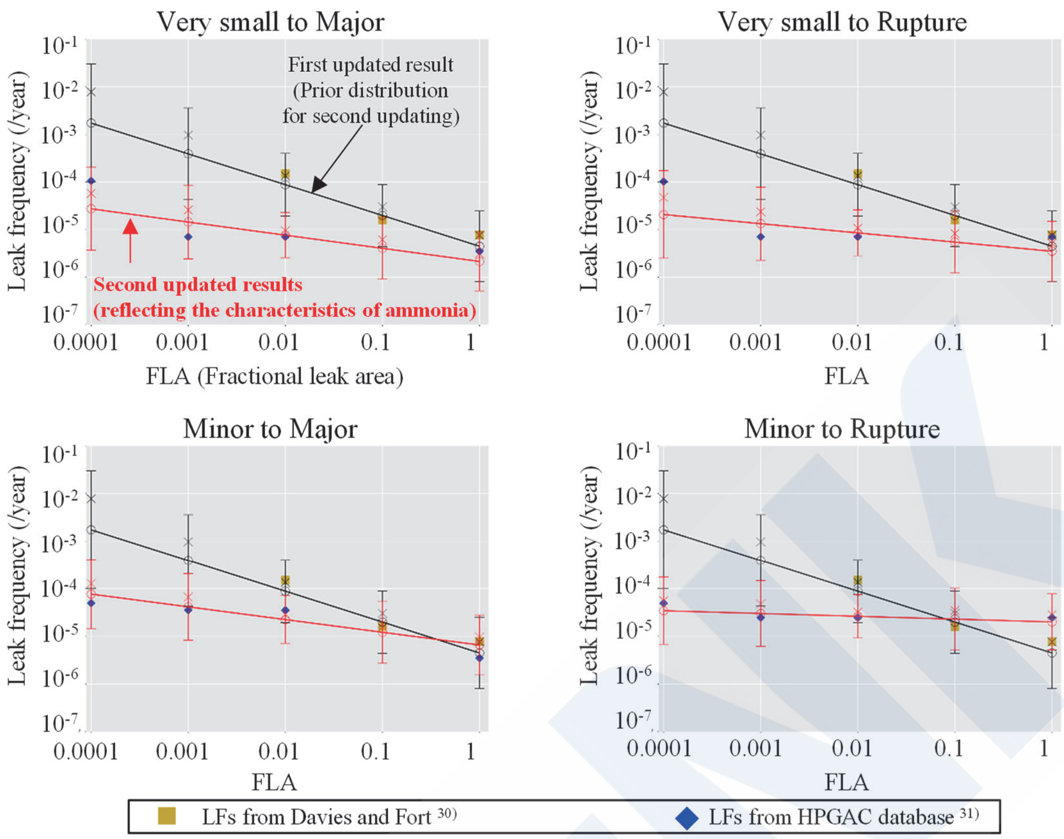

Fig. 4 Results of sensitivity analysis for proportional distribution of cases with "Unknown" leak size

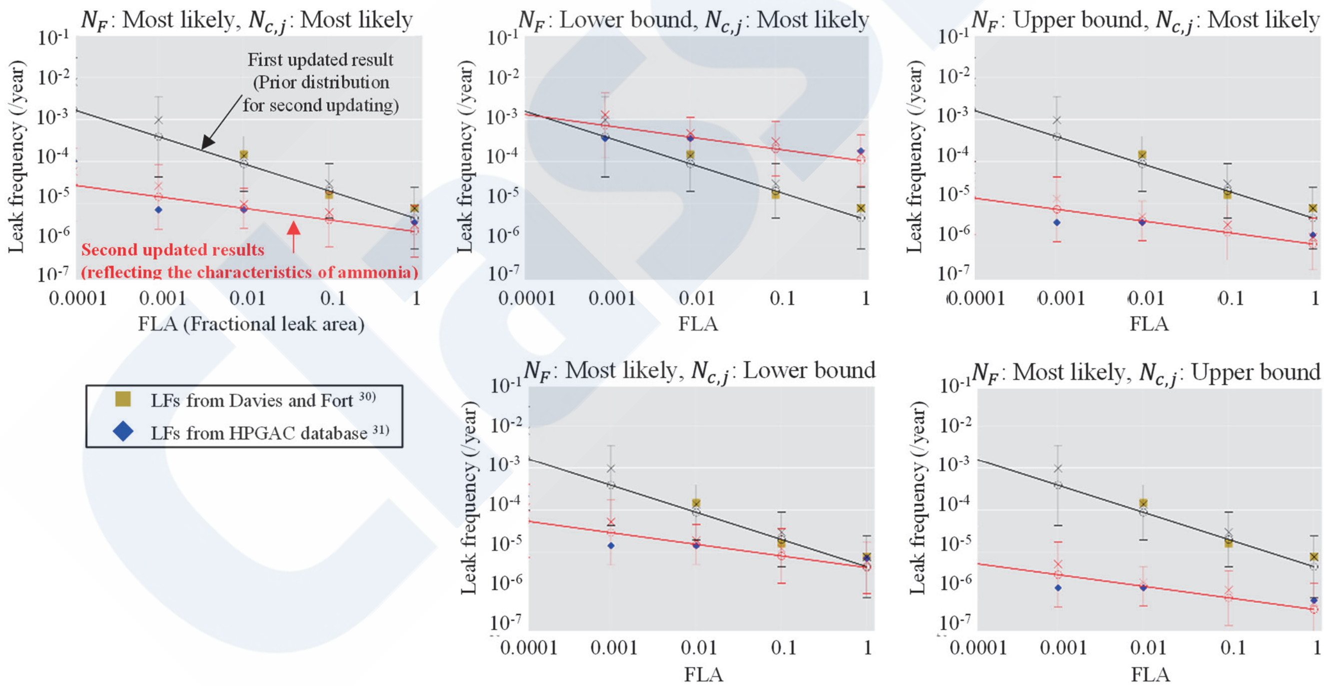

Fig. 5 Result of sensitivity analysis for number of facilities handling ammonia and number of components per facility

4. DISCUSSION

4.1 Comparison of Leak Frequencies of Ammonia-Fueled Ships and Other-Fueled Ships

In this research, the component-level leak frequency LF of ammonia-fueled vessels was estimated, and the results were compared with the estimation results reported by Moon et al. [26]. It should be noted that a direct comparison was difficult due to the limited amount of research reflecting the unique characteristics of accidents involving ammonia in the leak frequency, other than the above-mentioned study. Moon et al. [26] estimated that the system-level leak frequency of an ammonia-fueled vessel as a whole is 2.40 x 10^{-2}, which is equivalent to 77 % of LF of a conventional LPG tanker (3.10 x 10^{-2}). Because the system-level LF of the total vessel is not estimated in the present research, a direct comparison is not possible, but comparing the LF of ammonia-fueled vessels and the component-level LF of LNG-fueled vessels used as the likelihood, the tendency was similar. It is thought that the LF of ammonia-fueled vessel is lower than that of LNG-fueled vessel because comparatively strict controls are applied to ammonia, since ammonia, unlike hydrocarbon fuels, is both flammable and toxic. On the other hand, the difference in the LFs of LNG-fueled vessels and the ammonia-fueled vessels estimated by the authors was larger than the 77 % reported by Moon et al. [26]. In explaining this difference, it may be noted that Moon et al. [26] derived their results for both fuels from data sources for maritime accidents, while our results were larger because we compared the likelihoods derived from onshore systems and LFs derived from offshore systems.

4.2 Qualitative Discussion of Elements Influencing the Uncertainty of Leak Frequency Estimation

As noted in section 4.1, the previous research is inadequate for a full discussion of whether the leak frequency estimated in this paper is overestimated or underestimated. Here, however, we will arrange the elements that influence the uncertainty of LF estimations within the range possible.

First, as already discussed, the likelihood incorporated in the second Bayesian updating reflects the condition of operation and control of onshore ammonia facilities in Japan extracted from the HPGAC database. Because this database includes accidents dating from 1965, the use of the LFs estimated in this paper may result in a QRAs on the safe side, considering the progress of materials science, construction technology, and operation and management up to the present in 2025. On the other hand, in comparison with onshore systems, the external loads acting on offshore systems are generally larger, and since this element is not considered in the LF, the QRA may be on the dangerous side.

Thus, because only the likelihoods from the HPGAC database were used in this study, there are several elements that could not be considered, and this is a problem. As described in Chapter 1, since accidents involving ammonia have not been arranged systematically in existing databases, some type of ingenuity is required when incorporating the data in a Bayesian estimation. In this connection, although LaChance et al. [27] incorporated the likelihoods obtained from multiple databases as the data point cloud, some cases showed expanded 90 % confidence interval when the data point cloud were widely dispersed. This point must also be noted.

Reporting bias should also be considered. Mulcahy et al. [39] pointed out that the estimated results may diverge from the actual condition because the leak frequency of very small leak sizes is difficult to detect and report. They also noted that the results of predictions of the leak frequency should be interpreted cautiously, as extrapolations to small leaks may contain bias, and the direction of that bias is not clear; this suggests that simply adding additional data may not reduce uncertainty.

4.3 Correspondence of Definitions of Components

When referring to the leak frequencies estimated in this paper, it is important to consider the nominal meaning and the actual situation of the component parts. As mentioned in connection with Table 2, the indicated range of components may differ depending on the source.

Although Joint, Flange and Instrumental connection are similar terms, there are presumably cases where these terms indicate different components. In fact, when we referred to the Japanese HPGAC database, we were unable to differentiate these terms based solely on the information provided in the database. Likewise, Davies and Fort [30] noted that “Instrument connections include flanges within the given release frequency,” suggesting a similar difficulty exists in this case.

Judgments in safety assessments of pipes also differ depending on whether the pipe is single-walled or double-walled. In Japan, the High Pressure Gas Safety Act requires that double-walled pipes be used for pipes handling toxic substances, including ammonia, but permits single-walled pipes if measures have been taken to prevent the diffusion of leaked gas. Since most facilities have taken preventive measures, single-walled piping is generally used. Based on this background, we assumed that all pipes in the HPGAC database are single-walled. Similarly, in Davies and Fort [30], after mentioning the number of walls of pipes, they also suggested that single-walled pipes are generally used. Therefore, we adopted assumptions consistent with that observation as a methodology.

4.4 Applicability of Estimated Leak Frequency

It is possible to update QRAs [24, 25] by using the leak frequences derived to date from hydrocarbon fuels [20, 22] by LFs that reflect the unique characteristics of accidents involving ammonia estimated in this paper. This makes it possible to support QRAs for ammonia-fueled vessels that better reflect the characteristics of ammonia. Since the leak frequencies for ammonia-fueled vessels estimated in this research represent an initial study with the aim of reflecting the distinctive characteristics of ammonia leak accidents, significant improvement of the accuracy and reliability in the coming decades is a realistic possibility.

5. CONCLUSION

In this research, we constructed a Bayesian updating model and proposed a component-specific estimation method of leak frequencies for various types of components (Flanges, Joints, Pipes, Valves) in ammonia-fueled vessels, even though only limited data is currently available. In particular, the likelihoods used in the second Bayesian updating phase was estimated based on accident cases in onshore ammonia facilities in Japan, and the unique characteristics of ammonia were reflected by incorporating the results in the Bayesian updating model. Uncertainties regarding the estimated leak frequencies were considered through a process of comparing the LFs of ammonia-fueled vessels and LNG-fueled vessels in a sensitivity analysis and the previous research, and arranging the characteristics of ammonia-related accidents in a database of accident cases as the likelihood for the second updating phase. The estimation results obtained in this process indicated that the leak frequency of ammonia-fueled vessels is lower than that of existing LNG-fueled vessels, reflecting the stricter control of ammonia. Since the proposed approach utilizes estimated leak size-specific and component-specific leak frequencies, this approach is considered suitable for integration into quantitative risk management frameworks, supporting regulatory compliance, and enhancing operational safety standards for ammonia-fueled vessels.

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Revealing a Fuel-Saving Tip for Main Engine Operation in Rough Sea Conditions

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1. INTRODUCTION

The target of achieving net-zero GHG emissions from global shipping by around 2050 was set by the International Maritime Organization (IMO) in 2023. To reach this target, a range of solutions have been implemented or are under consideration by the shipping industry. These efforts include the adoption of alternative marine fuels and further improvements in energy efficiency. Among these measures, energy saving will remain essential, even after the adoption of carbon-free or carbon-neutral fuels, due to the forecasted significantly higher prices of these candidate fuels compared to current heavy fuel oil (HFO). Energy efficiency improvements can be achieved through the application of energy-saving devices and/or operational optimization. Operational optimization is easier to implement, as it typically does not require hardware changes.

This paper specifically focuses on how to operate the main engine to save fuel during severe weather conditions. Section 2 provides a general description of the main engine and ship behavior in various sea conditions. Section 3 explains the concept of MAMES (Maximum Attainable Main Engine Speed) in certain weather conditions. Section 4 estimates the amount of potential wasted fuel if the main engine is not properly operated. Section 5 outlines methods to save fuel. Finally, section 6 summarizes the conclusions.

2. MAIN ENGINE AND SHIP BEHAVIOR IN VARIOUS SEA CONDITIONS

When a ship encounters severe sea conditions, it requires more main engine power to maintain a certain speed. Fig. 1 conceptually illustrates the relationship between main engine power, ship speed, and engine speed for an imaginary Panamax bulk carrier with a main engine output of 10,000 kW at 80 rpm. On the left of Fig. 1, curves in different colors indicate the relationship between ship speed and required main engine power for various sea conditions, represented in terms of wave height. On the right of Fig. 1, curves in different colors show the relationship between engine speed and main engine power for different sea conditions. These curves were calculated based on the propeller characteristic curves for each sea condition. Normally, a ship operates with a setting main engine (propeller) speed. As sea conditions change from calm to rough, the ship's speed-power operating point shifts, as indicated by the dashed lines on the left for different setting engine speeds.

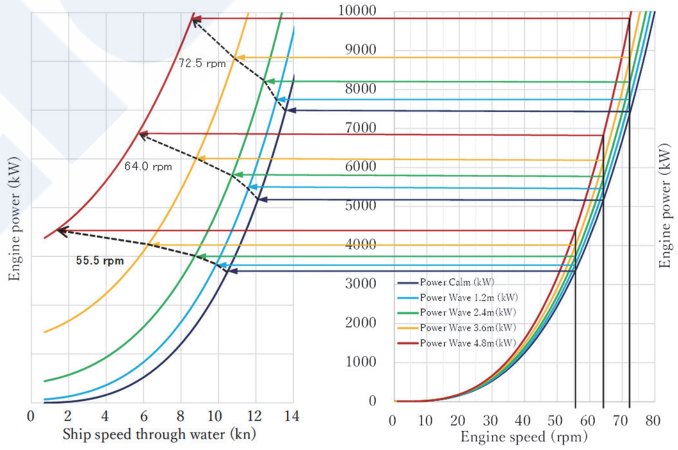

Fig. 1 Conceptual relationship between main engine power, ship speed, and engine speed for an imaginary Panamax bulk carrier

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This general behavior aligns closely with the measured data. Fig. 2 shows the measured data of a 200 m long general cargo ship over a period of 3 years by P. Gupta et al. [1] Each sample is obtained by averaging over a 15-minute period. The original data were pre-processed by removing samples during ship acceleration or deceleration to ensure the ship was in a quasi-steady state.

Although the samples in Fig. 2 appear to scatter over a wide area, some samples are concentrated and aligned along several lines slanting upward to the left. These lines suggest that certain engine speeds were more frequently chosen for the ship's operation, as explained in Fig. 1.

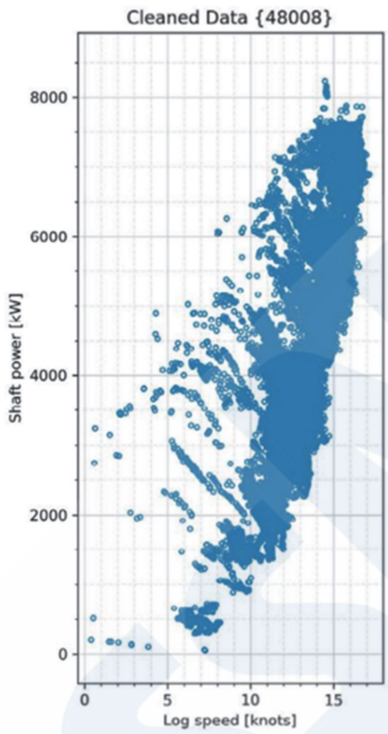

Fig. 2　Measured data of a 200 m long general cargo ship over a period of 3 years, reproduced from P. Gupta et al. [1]

3.　MAXIMUM ATTAINABLE MAIN ENGINE SPEED (MAMES)

One might think that the main engine can deliver whatever torque is needed to maintain a commanded speed, but this is not always the case. There is a limit to the torque that the main engine can generate at a given speed to avoid overloading. This limit is enforced by restricting the amount of fuel injected into the cylinders per cycle. The fuel injection amount per cycle is the dominant factor that determines torque through the fuel's calorific value, combustion efficiency, mechanical linkage mechanisms, and other factors, and can be simplistically treated as being in proportion to the generated torque. Therefore, the fuel injection limit essentially corresponds to the torque limit for each rotational speed. Traditionally, the amount of fuel injected per cycle is controlled by a component called the fuel rack in the fuel injection pump, which is why it is commonly referred to as the fuel rack limiter. The fuel rack limiter is shown as a dashed red line on the right side of Fig. 3. If a propeller loading curve intersects with the limiter line, then, theoretically, the propeller (and the main engine) can never be accelerated beyond the intersection point due to insufficient driving torque from the engine to overcome the propeller loading torque. In other words, the intersection point represents the maximum attainable main engine speed (MAMES).

In terms of propeller loading, the most severe case is called bollard pull, which occurs when the hull is stationary, as shown by the dashed black line on the right side of Fig. 3. While determining the exact power required in a bollard pull condition is difficult, a heavy running factor of 15-20% relative to the light propeller curve is commonly used. In Fig. 3, a factor of 20% is adopted [2]. In the bollard pull situation, the MAMES will be significantly lower than for most normal propeller loadings, even in heavy weather, as shown on the right side of Fig. 3.

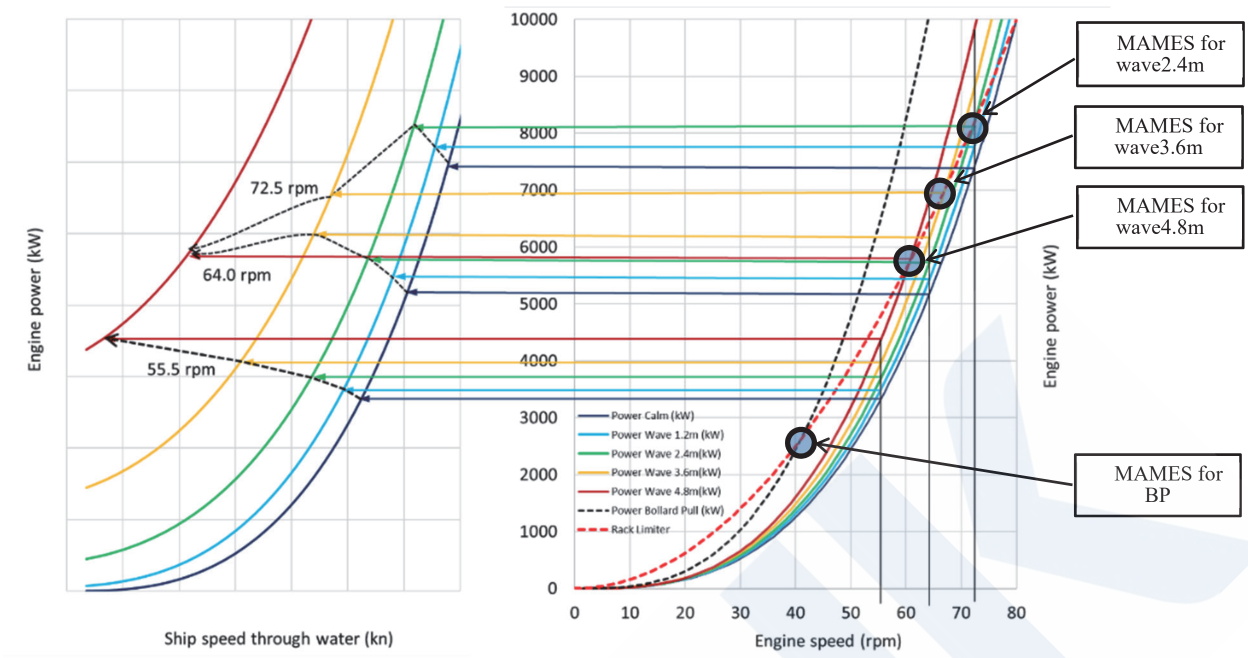

Fig. 3 Conceptual explanation of propulsion power limited by maximum attainable main engine speed

As the maximum available power is also limited by the torque limit for a given engine speed, the attainable ship speed will also be limited according to the available power. This is shown on the left side of Fig. 3 for the commanded engine speeds of 64.0 rpm and 72.5 rpm when encountering waves of significant heights greater than 3.6 m and 2.4 m, respectively. This phenomenon is also visible in Fig. 2. Samples that initially aligned with a nearly straight line slanting upward to the left began to turn downward to the left as they approached the left edges of the sampling area.

Measured data from a Panamax bulk carrier also shows the same trend, as shown in Fig. 4 [3]. For confidentiality reasons, the data were normalized by dividing them by the values at the maximum continuous rating (MCR). Additionally, the log speed was normalized by the service speed. Similar normalizations were also applied in Figs. 6, 7, and 8. The measured data were concentrated along a nearly straight line slanting upward to the left when the main engine output was between 0.2 and 0.3. This indicates that the ship was frequently operated at a specific commanded engine speed below the MAMES. As the main engine output increased to the range of 0.4 to 0.6, some operating points in the left area began to show flattened or downward slanting patterns. These patterns indicated that the main engine torque limit had been reached, as the left area corresponds to high wave conditions.

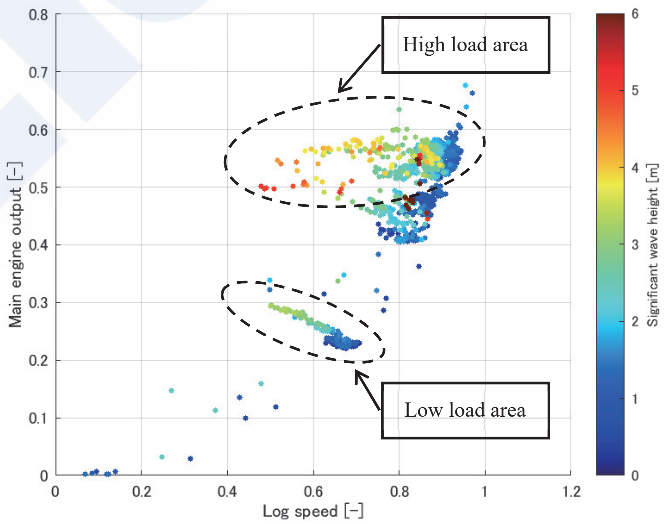

Fig. 4 Measured data showing the relationship between main engine power and ship speed of a Panamax bulk carrier

4. FUEL WASTE DUE TO ENGINE SPEED GAP

The commanded engine speed is used by the main engine governor to determine the target fuel rack position [4]. If the current engine speed is below the commanded engine speed, the governor will increase the fuel mass per cycle until the commanded engine speed is achieved. However, if the commanded engine speed exceeds the MAMES, it can never be reached due to the fuel rack limiter (torque limit). This means that the additional fuel corresponding to the difference between the MAMES and the commanded engine speed is wasted (see Fig. 5).

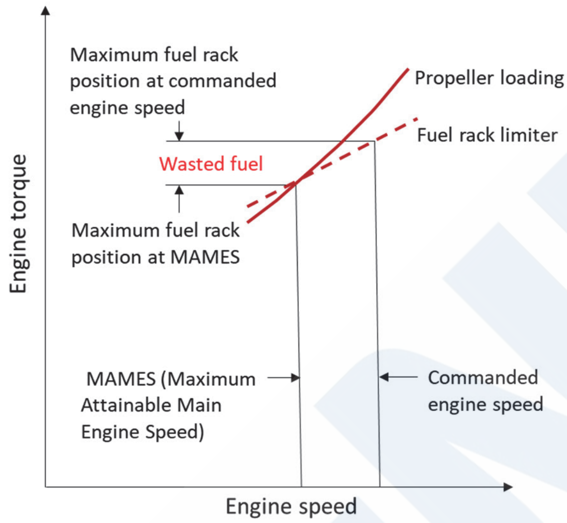

Fig. 5 Conceptual explanation of fuel waste due to engine speed gap

In real ship operation, ships are expected to encounter situations where the commanded engine speed cannot be achieved due to severe weather conditions. Fig. 6 illustrates the plot of engine speed against commanded engine speed for a Panamax bulk carrier over a 70-day voyage. The colors indicate the fuel rack position or significant wave height. In this case, the engine speed fell short of the commanded speed by up to just below 3 rpm. The speed gap was observed when the engine speed command ratio (relative to the speed at maximum continuous rating) was 0.79 and around 0.85.

An interesting observation from the left side of Fig. 6 is that whenever the engine speed falls short of the commanded speed, the injected fuel mass per cycle (fuel rack position) increases, regardless of how high the commanded speed is. This occurs because when the engine governor detects the speed gap, it increases the fuel mass flow to accelerate the engine and close the gap, as mentioned at the beginning of this section. When closing the speed gap becomes impossible, the fuel rack remains high, leading to fuel waste.

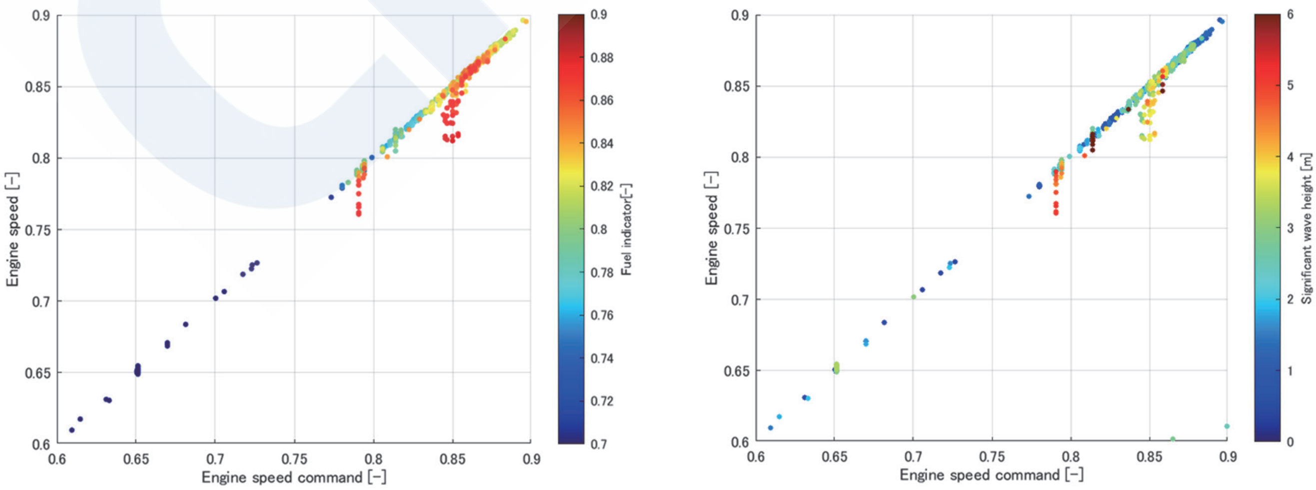

Fig. 6 Plot of obtained engine speed versus the commanded engine speed of a Panamax bulk carrier (left: fuel indicator; right: significant wave height)

Using the same voyage data as mentioned above, Fig. 7 shows the fuel indicator (fuel rack) against the commanded engine speed, with colors depicting the significant wave height. Fig. 7 demonstrates that when the engine speed command ratio is 0.79 and around 0.85, where speed gaps occur, the fuel indicator rises well beyond the values obtained in the main engine shop test.

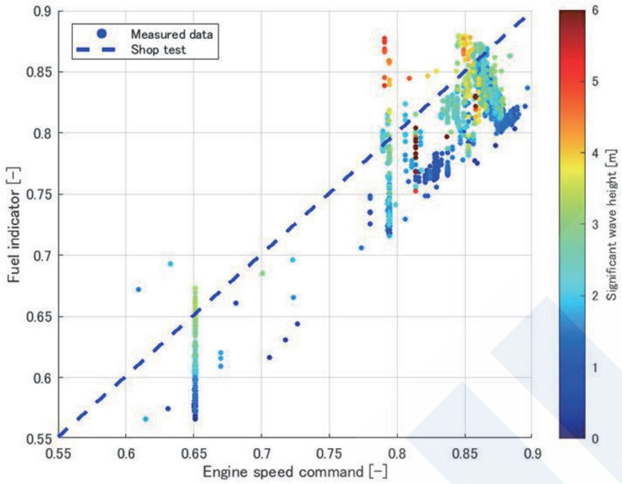

Fig. 7 Fuel indicator (fuel rack) versus commanded engine speed of a Panamax bulk carrier

The amount of fuel wasted depends on where the MAMES is located and how large the speed gap is. As ships age, the MAMES tends to shift to a lower position due to increased fouling on both the hull and propeller, as well as other factors that reduce propulsion efficiency. Therefore, a higher percentage of fuel waste would be expected due to higher probability of the speed gap existing as ships age.

Table 1 shows an estimation of wasted fuel for an imaginary main engine of 10,000 kW at 80 rpm, considering different MAMES and speed gaps. The leftmost column, N/NMCR, shows the MAMES relative to the speed at MCR. It is clear that as the speed gap grows, the wasted fuel increases. Similarly, as the MAMES increases, the wasted fuel increases in absolute terms but decreases in percentage terms. The rows highlighted in yellow indicate MAMES ratios of 0.79 and 0.85, where the real Panamax bulk carrier experienced a speed gap. At these MAMES ratios, if a speed gap of 3 rpm occurs, fuel waste of 9.8% and 9.0% is expected, which corresponds to a fuel waste of 1,943 and 2,260 kg per day, respectively.

Table 1 Potential fuel savings for an engine of 10,000 kW at 80 rpm

N/N_{MCR}	Load (%)	Speed gap (1 rpm)		Speed gap (2 rpm)		Speed gap (3 rpm)	
		Wasted fuel (kg/day)	Wasted fuel (%)	Wasted fuel (kg/day)	Wasted fuel (%)	Wasted fuel (kg/day)	Wasted fuel (%)
0.70	34	504	3.6	1,017	7.3	1,540	11.0
0.71	36	522	3.5	1,054	7.1	1,594	10.8
0.73	38	541	3.5	1,091	7.0	1,650	10.6
0.74	40	559	3.4	1,128	6.9	1,707	10.4
0.75	42	579	3.4	1,167	6.8	1,764	10.3
0.76	44	598	3.3	1,206	6.7	1,823	10.1
0.78	47	618	3.3	1,245	6.6	1,882	9.9
0.79	49	638	3.2	1,285	6.4	1,943	9.8
0.80	51	658	3.1	1,326	6.3	2,004	9.6
0.81	54	679	3.1	1,367	6.2	2,067	9.4
0.83	56	699	3.1	1,410	6.2	2,130	9.3
0.84	59	721	3.0	1,452	6.1	2,194	9.2
0.85	61	742	3.0	1,496	6.0	2,260	9.0
0.86	64	764	2.9	1,540	5.9	2,326	8.9
0.88	67	787	2.9	1,584	5.8	2,393	8.8
0.89	70	809	2.8	1,629	5.7	2,461	8.6
0.90	73	832	2.8	1,675	5.6	2,530	8.5

Fig. 8 shows time histories of measured data from a single voyage of a Panamax bulk carrier. The area framed in red indicates where the speed gap arose. The histories clearly show that the commanded engine speed was deliberately lowered, likely in response to worsening weather conditions, particularly after encountering beam seas with significant wave heights greater than 4 meters. However, even after lowering the commanded engine speed, a difference of approximately 2.5 rpm persisted for about 8 hours, with the maximum speed difference observed during this period.

The actual fuel loss for this Panamax bulk carrier was estimated using the fuel indicator shown in Fig. 8. The fuel loss was calculated based on the difference in the fuel indicator for two cases: when the difference between the commanded and actual engine speed was at its maximum (approximately 2.5 rpm) and when there was no difference, while maintaining a constant commanded engine speed. The estimated fuel loss is 2,286 kg/day, representing 12.2%.

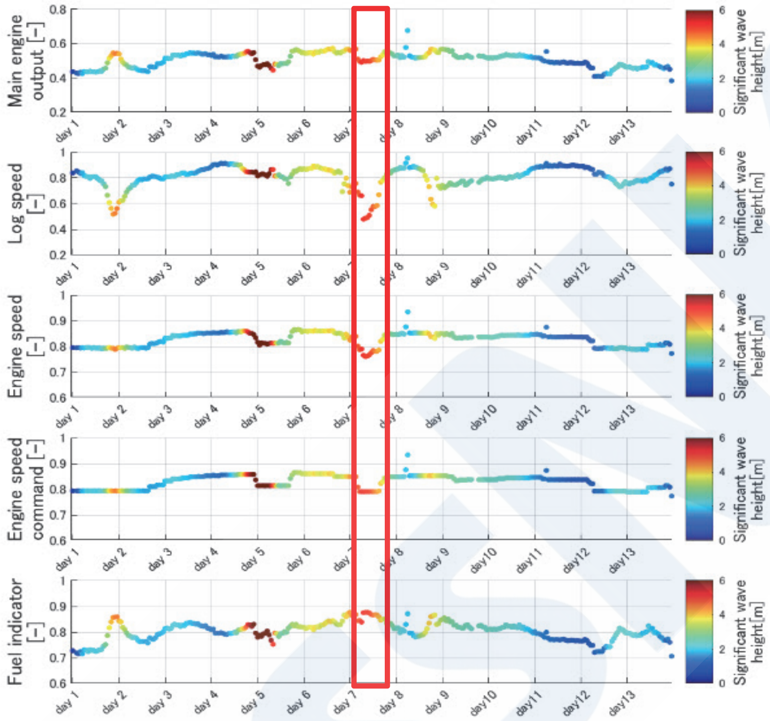

Fig. 8 Time histories of measured data from a Panamax bulk carrier

Fuel loss due to the speed gap over an extended period, such as one year or a ship's lifespan, significantly depends on the probability of encountering weather conditions severe enough to cause the engine speed gap. Table 2 presents the total hours and their ratio to the entire voyage time during which the significant wave height exceeds 4.5 m on each route over the course of a year. It also includes the estimated wasted fuel mass and cost, assuming a constant speed gap of 2.5 rpm during those periods.

Representative routes for a Panamax bulk carrier were selected based on past Automatic Identification System (AIS) data, shown in Fig. 9. In the analysis, the threshold wave height that causes the speed gap was set at 4.5 m, according to measured data from the Panamax bulk carrier. The wave data used for analyzing encountered sea conditions along each route is derived from the ERA5 wave hindcast, provided by ECMWF. The sea conditions encountered over a one-year period were estimated by considering the effect of weather routing to avoid heavy weather, based on statistical data regarding sea conditions along each route and past operational records [5), 6)]. Furthermore, the ship's operational rate was assumed to be 0.8, and the price of VLSFO (Very Low Sulphur Fuel Oil) was assumed to be 600 USD per metric ton.

Table 2 indicates that, over the course of a year, the probability of encountering waves exceeding the threshold is 81 hours on the Asia-Australia route, 901 hours on the Asia-US West Coast route, and 1,196 hours on the US East Coast-Europe route. Furthermore, if a speed gap of 2.5 rpm were continuously maintained during periods when the encountered wave height exceeded 4.5 m on each route, the estimated wasted fuel would range from 8 to 114 MT, with the corresponding cost ranging from 5,000 to 71,000 USD. However, it should be noted that the speed gap can vary depending on the operation of the main engine as well as the sea conditions. Thus, the actual values of the wasted fuel can also change accordingly.

Table 2 Estimated total hours and their ratio to total voyage time in which the significant wave height exceeds 4.5 m on each route over the course of a year, along with the estimated wasted fuel and its cost assuming a constant speed gap of 2.5 rpm during those periods

Route	Time (h)	Time ratio (%)	Wasted Fuel (MT)	Wasted Fuel cost (USD)
Asia-Australia	81	0.9	8	5,000
Asia-US West Coast	901	10.3	86	54,000
US East Coast-Europe	1,196	13.7	114	71,000

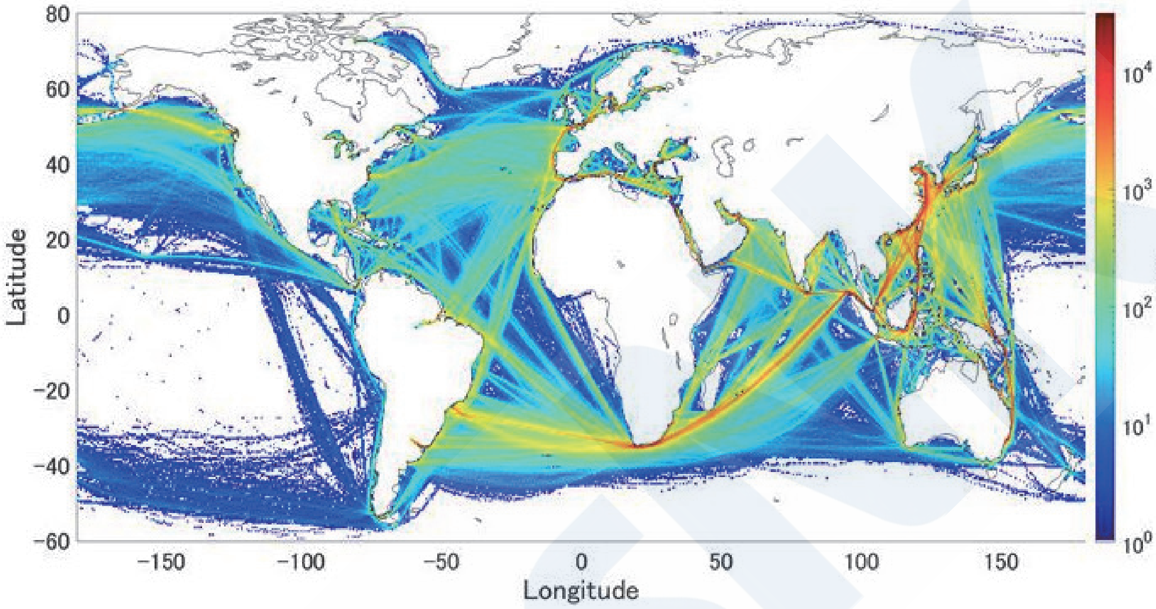

Fig. 9 Routes of Panamax bulk carriers based on AIS Data (2022-2023)

Apart from the economic perspective, safety implications are also important. As the engine continuously tries to fill the speed gap, it is forced to remain in a constant state of acceleration. In this acceleration state, due to the inertia of the turbocharger rotor, the air-fuel ratio tends to be lower than in steady-state conditions. A low air-fuel ratio can cause incomplete combustion and may momentarily result in a high density of smoke. Incomplete combustion particles (soot) in the exhaust gas will adhere to the turbine blades. This, in turn, can cause an imbalance, leading to vibration and rapid wear of the rotor and bearings (see Fig. 10) [7), 8)].


Fig. 10 Turbocharger components fouling with soot - Turbine blades (left) and turbine nozzles (right)

5. TIP FOR FUEL-SAVING MAIN ENGINE OPERATION IN ROUGH SEA CONDITIONS

There seems to be a common practice in the shipping industry to lower the main engine speed when encountering rough seas [9]. However, how much the speed of the main engine should be reduced is usually left to the individual ship crew's experience. In some cases, although the engine speed has been lowered by several rpm, the actual speed remained below the commanded speed for hours. These facts suggest that the speed gaps may have gone unnoticed by the crew. Thus, it is desirable to monitor the difference between the actual engine speed and the commanded speed. If the speed gap persists, the commanded speed should be gradually lowered until the gap disappears. Shipping companies are highly encouraged to review their fleet's past voyage data, if available. If main engine speed gaps are found in the past data, the crew should be instructed to check for any speed gaps onboard their ships and take appropriate action.

6. CONCLUSIONS

When ships encounter rough sea conditions, a main engine speed gap can occur between the obtained speed and the commanded speed, which may last for hours until the weather improves sufficiently for the main engine to close the gap. This phenomenon was confirmed by onboard measurements of a Panamax bulk carrier, and the mechanism behind it was theoretically analyzed and explained. A prolonged speed gap leads to waste of fuel. Depending on the main engine running speed and the size of the gap, the wasted fuel can be as high as 10% of the fuel consumed under normal conditions without the speed gap. The speed gap can also cause incomplete combustion, leading to turbine blades and nozzles fouling with soot. Fouling of the turbine components, in turn, causes rotor imbalance, which leads to vibration and rapid wear of the rotor and bearings.

By properly adjusting the main engine speed order in heavy weather conditions, a significant amount of fuel can be saved. In addition to the economic benefits, eliminating the speed gap reduces the likelihood of turbocharger failures and damage to other components exposed to exhaust gases.

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Introduction of Examples of the Use of AIS Data

Rei MIRATSU*

1. INTRODUCTION

In recent years, it has become possible to grasp information on the movement of ships, which had been difficult with conventional techniques, by acquiring Automatic Identification System (AIS) information by satellites, etc. AIS is a system for exchanging navigation information between ships operating at sea. With the increased number of satellite launches in recent years, it has become possible to acquire AIS signals from ships worldwide, and the range of uses of this data is expanding year by year. As examples of past research on AIS, a review paper on AIS data by Wada et al. [1] summarized examples of research on estimation of the volume of maritime cargo transportation, analysis and prediction of the condition of the maritime shipping market, prediction of demand for ship construction, analysis of the environmental impacts of ship operation, application to the cruise sector, and analysis of shipping networks and their changes over time, highlighting the diverse range of objects of research utilizing AIS data. As shown in Fig. 1, there is an increasing trend in the number of papers on ship AIS, and research on big data on marine logistics, which has become available in recent years, is being carried out from various angles.

Many initiatives to optimize ship operation by utilizing AIS data are also underway in industry. One example is the platform “Blue Visby Solution,” which uses digital technology to optimize the arrival time of ships at their destinations [2]. Blue Visby Solution attempts to reduce CO_2 emissions by providing the optimum sailing speed considering the position and heading of ships heading toward the same port by using AIS data in addition to information on congestion in ports and the weather. It has been suggested that this technique has the potential to reduce CO_2 emissions by an average of 16%.

ClassNK (hereinafter, the Society) also has a record of actual results of utilizing AIS data in the development of ship rules. In the comprehensive revision of Rules and Guidance for the Construction and Survey of Steel Ships, Part C, which enables safer and more rational design of ship hull structures and strength evaluations, and the revision of Guidelines for Container Stowage and Securing Arrangements, AIS data and wave statistics were used to rationalize the design loads of ships [3), 4)]. In comparison with conventional rules based on empirical rules and limited information, the development of rules with high accuracy and transparency was achieved by using quantitative data showing the actual situation of operation of real ships.

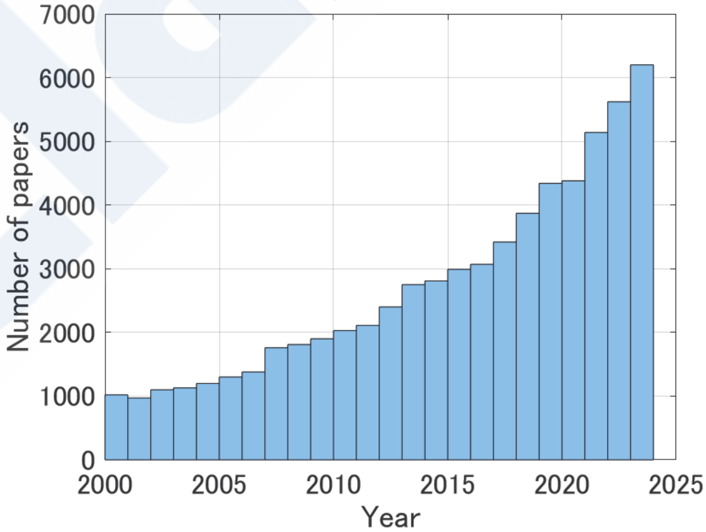

Fig. 1 Transition of the number of papers on ship AIS (source: Google Scholar)

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As described above, the regions of use of AIS data in academic research and industry are expanding, and the Society is also acquiring global AIS data and utilizing that data in the development of various services, beginning with rule development. The purpose of this paper is to introduce concrete examples of the use of AIS data and provide information widely to stakeholders involved in the maritime industry. As the overall composition, Chapter 2 presents an overview of AIS, Chapter 3 introduces examples of the results of analyses of the actual condition of ship operation by ship type and size, the characteristics of ships calling in Port of Tokyo, and the changes in navigation routes accompanying the deterioration of the situation in the Red Sea, and Chapter 4 presents the concluding remarks.

2. OVERVIEW OF AIS

The main purposes of AIS are to prevent collisions between ships, obtain information on ships in transit and their cargoes, and support ship operation control work. Based on Chapter V of the SOLAS Convention (International Convention for the Safety of Life at Sea), which took effect in 2002, the IMO (International Maritime Organization) required that all ships that meet certain standards carry and operate AIS equipment. This requirement is applicable to all ships with a gross tonnage of 300 tons or more which are engaged in international voyages, all ships with a gross tonnage of 500 tons or more which are not engaged in international voyages, and all passenger ships irrespective of size [5)]. ITU-R M.1371 is adopted as the technical grounds, and IEC 61993-2 Ed. 1 is adopted as the equipment standard. As navigation equipment with upward compatibility, in recent years, the introduction of VDES (VHF Data Exchange System), which has a higher data transmission capacity, in addition to the AIS function, has been discussed in the IMO.

The radio waves of the AIS devices carried on ships have a horizontal range of 60 to 80 km. Initially, AIS signals were received by other ships and by ground stations, but since AIS signals reach a vertical altitude of 400 to 500 km, signals can also be acquired by satellites. With the increase in satellite launches from 2008 onward, it is now possible to capture AIS signals from ships operating in open seas [6)].

Fig. 2 shows the representative type of information that can be obtained by AIS. In addition to static information such as the identification numbers, etc. of navigating ships, this information includes dynamic information such as the ship position, speed, course, etc. Additionally, voyage-related information, such as the ship's draft and destination, can also be obtained. Fig. 3 shows an example of visualization of the information obtained by AIS in combination with data on the sea states. In this figure, the color represents the size of the significant wave height. The figures show information on the positions of ships under the two conditions of calm sea (top) and rough sea (bottom). In a calm sea state, ships basically sail the Great Circle route, which is the shortest route to their destination, but in rough sea states, ships are clearly avoiding the low pressure area near the center of the figure, where the significant wave height is 15 meter class. Thus, the sea states encountered by ships worldwide and the actual situation of navigation can be understood by using AIS and sea-state data. As described in the previous chapter, the Society used these data on encountered sea states in rule development [3), 4)].

Dynamic information	Static information	Voyage related information
• Latitude/Longitude	• MMSI/IMO number	• Draught
• Time	• Name	• Destination
• Headings	• Dimensions	• Estimated time of arrival (ETA)
• Speed over ground	• Type of ship	• Dangerous Cargo (Type)
• Course over ground	• Location of positioning system's antenna	• Route planning

Fig. 2 Information obtainable from AIS (Examples)

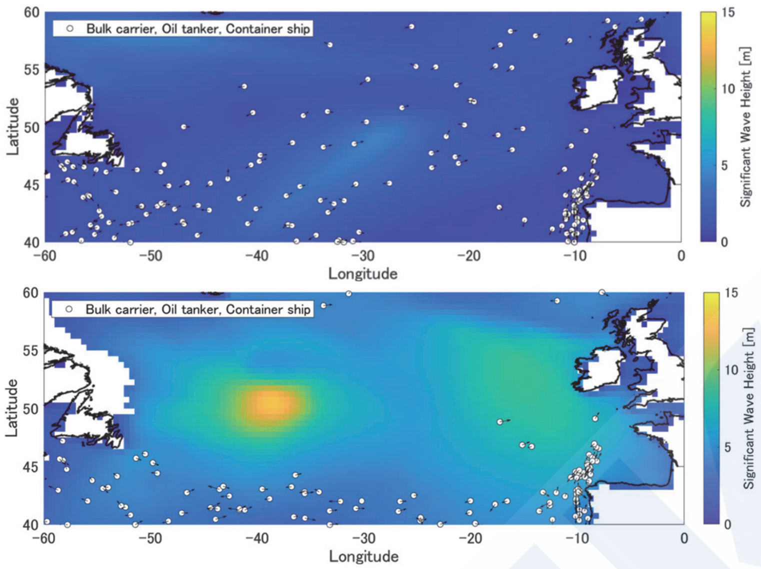


Fig. 3　Positions of ships in North Atlantic Ocean (top: calm sea state, bottom: rough sea state)

3.　INTRODUCTION OF EXAMPLES OF USE OF AIS DATA

This paper introduces the results of three analyses using the worldwide AIS data provided by Kpler and the Clarkson ship database. The period of the AIS data used here is from January 1, 2022 to December 31, 2024. Data preprocessed in 3 hour time periods were used.

3.1　Actual Situation of Navigation by Ship Type and Size

It is possible to capture ship navigation routes by ship type and size by using AIS data. Fig. 4 and Fig. 5 show the tracks of containerships and bulk carriers each by ship size, respectively. The object period is 2022 to 2024, and ship speeds of 2 knots or less have been excluded. Darker colors indicate a high frequency of voyages. For example, in Fig. 4, containerships with sizes of less than 3 000 TEU sailed in a wide range of coastal areas, whereas a large proportion of voyages by large containerships of more than 17 000 TEU were on Asia-Europe routes. Comparing containerships of the 8 000 to 11 999 TEU class and those of the 12 000 to 16 999 TEU class, a relatively large number of voyages by the former were on the North Atlantic Ocean route. Among the bulk carriers in Fig. 5, voyages by ships of both sizes were distributed uniformly worldwide, but voyages by VLOC (Very Large Ore Carriers) and Cape-size vessels with DWT (deadweight tonnage: tonnage of the cargo) of 100 000 DWT or more were concentrated on Asia-Brazil routes, showing the tracks of vessels transporting South American iron ore to Asia.

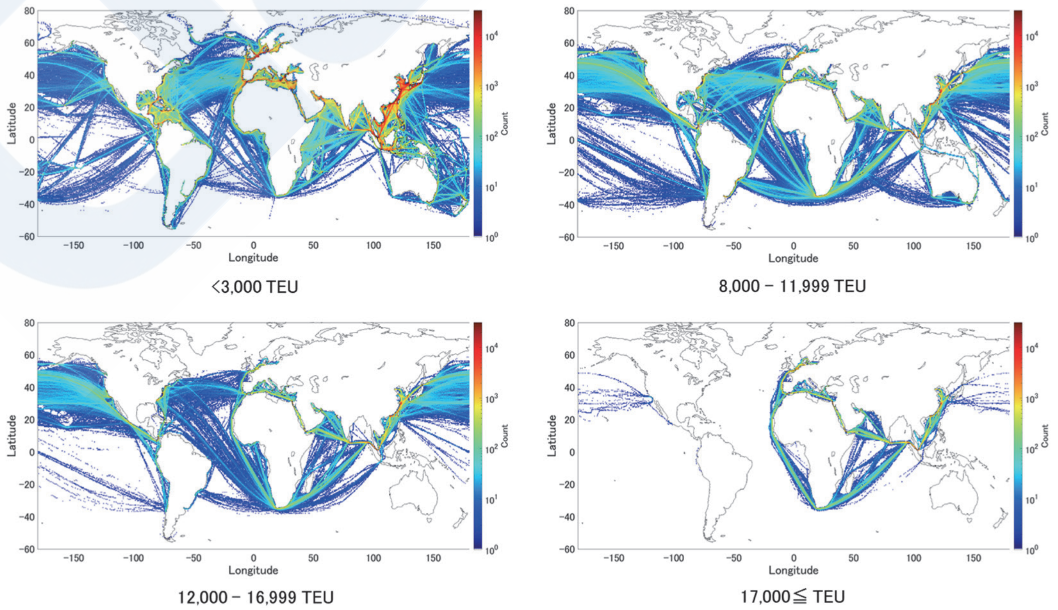


Fig. 4　Track charts of containerships by size (2022-2024)

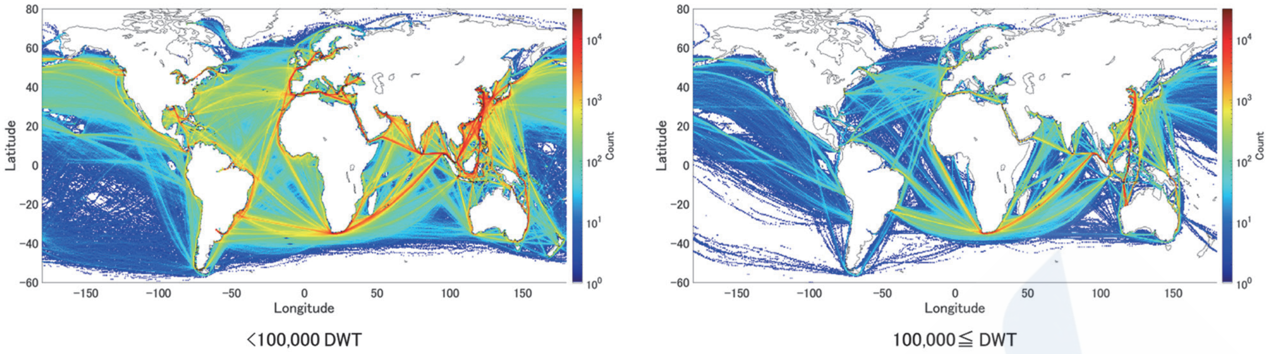
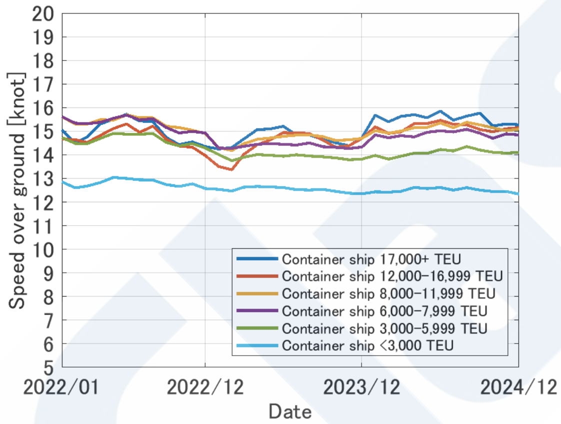


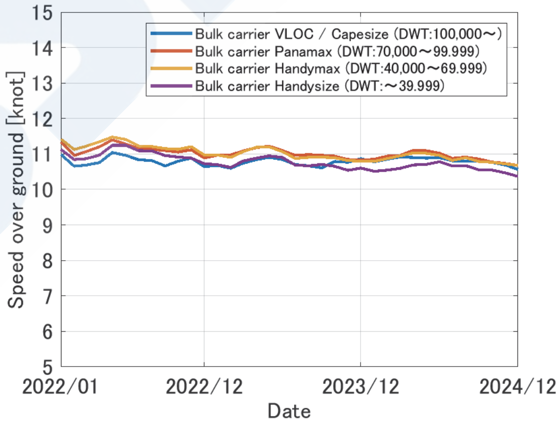
Fig. 5　Track charts of bulk carriers by size (2022-2024)

Fig. 6 shows the transition (average values) of the ship speed over ground for each month by ship type and size. Here, LNG carriers and vehicle carriers are not classified by size, and speeds of 2 knots or less are excluded from the calculations of the average values.

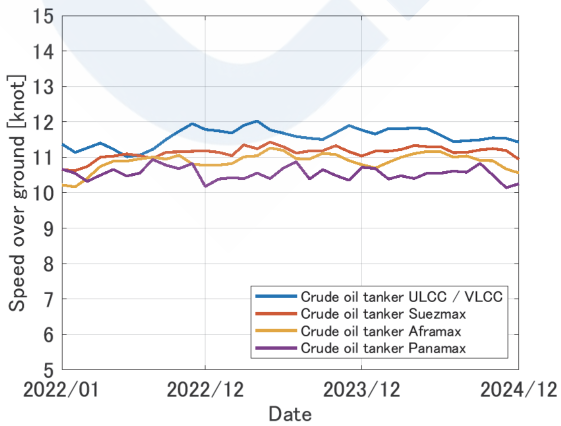
The speed of containerships with sizes of 6 000 TEU class and larger decreased from September 2022 to February 2023. This is presumed to be the result of a certain reduction in ship speed accompanying slack supply and demand for shipping due to a sharp decline in the movement of goods [7]. However, the average ship speed increased from around November 2023. Although this will be discussed in more detail in section 3.3 below, it is conjectured that some containerships avoided the Red Sea due to deterioration of the situation in those waters, and the average ship speed increased due to the longer cruising distance via the Cape of Good Hope. Among other types of ships, the average speed was generally flat or tended to decrease slightly.



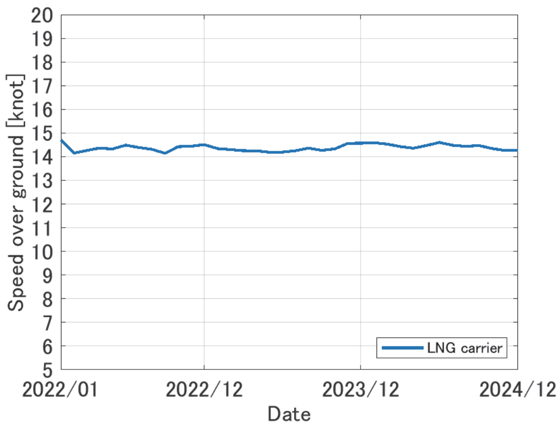
Containerships



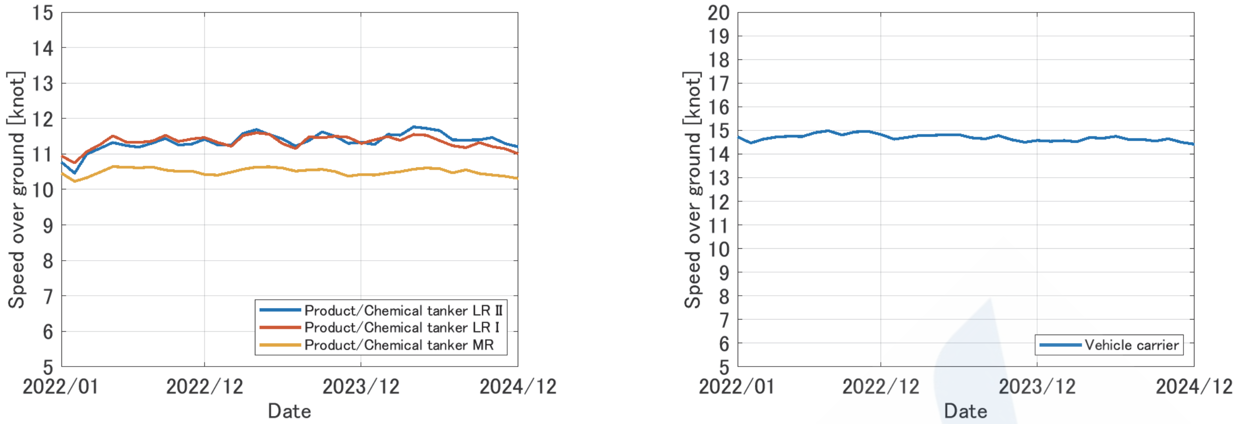
Bulk carriers



Crude oil tankers



LNG carriers



Product and chemical tankers　　Vehicle carriers

Fig. 6　Transition of average ship speed by ship type

3.2　Information on Ocean-going Ships Calling at Ports of Tokyo

Information on the ships that call at a specified port can be grasped by combining the AIS data and Clarkson's ship database. As one example, this paper introduces information on ships calling at the Port of Tokyo. In this paper, ships with a speed of 2 knots or less for 6 continuous hours in the area shown in dark blue in Fig. 7 are regarded to calling at the port. The object of this analysis is ocean-going ships, and the totals indicate the number cases where the port of call before/after calling at the Port of Tokyo was outside of Japan.

Fig. 8 shows the number of calls in Port of Tokyo in 2023 by ship type. In order, the largest number of calls was by containerships (4 343), general cargo ships (1 681) and Ro-Ro ships (1 256). According to the Tokyo Metropolitan Government's Bureau of Port and Harbor, there were 4 753 calls by ocean-going containerships in 2023. From this, it can be understood that the results of this analysis identified approximately 91% of the total number [8].

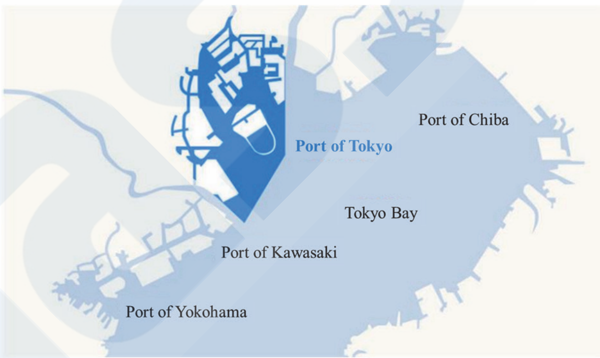


Fig. 7　Location of Port of Tokyo (source: Bureau of Port and Harbor, Tokyo Metropolitan Government)

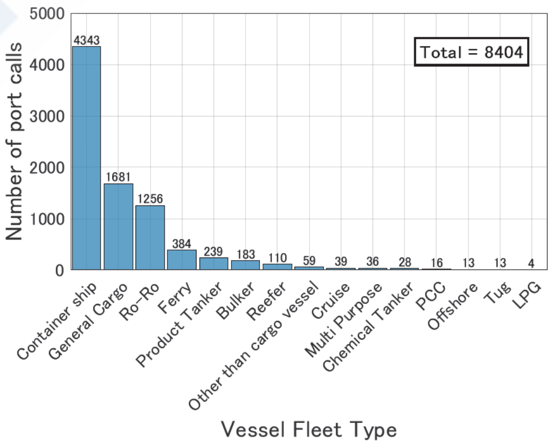


Fig. 8　Number of calls at Port of Tokyo by ship type (2023)

Fig. 9 shows the statistical values for the departure country/region, destination country/region, type of fuel (main engine), length overall, owner's nationality and the flag state of ships calling at the Port of Tokyo. By combining the AIS data and Clarkson database, it is also possible to understand the main engine fuel, the principal particulars of the ships, the owner's nationality and the flag state of ships calling at the Port of Tokyo. In order, the departure and destination country/regions are China, Korea and Taiwan, and China has particularly large share. In almost all cases, the fuel type of the main engine is intermediate fuel oil (IFO). By expanding these analyses to ports throughout the world, it would be possible, for example, to understand how frequently dual fuel vessels call at ports. However, since it is difficult to judge what fuels dual fuel vessels are actually using from the AIS data, it is necessary to examine the AIS data in combination with another database.

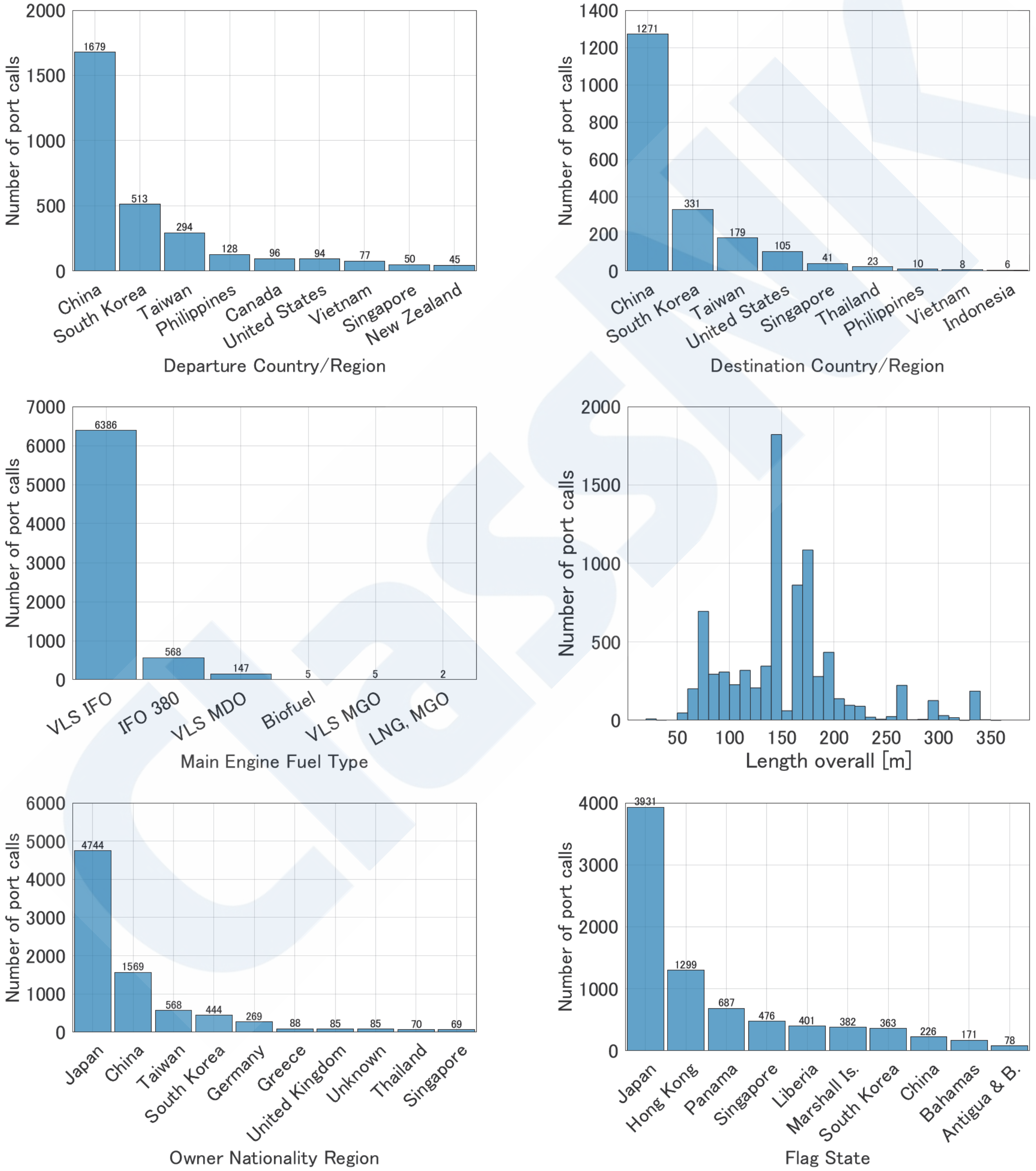


Fig. 9　Information on ships called at Port of Tokyo (2023)

3.3 Changes in Route of Voyages with Deterioration of Situation in the Red Sea

Deterioration of the geopolitical situation in the Red Sea region is one critical issue for international shipping. To make a quantitative analysis of the impact of avoidance of the Red Sea route, in this section, we analyzed not only the macroscopic changes in the number of vessels using the Red Sea route, but also the moves by ship type and nationality of the owner and management company. Using the AIS data, the number of ships sailing even one time in the region of the Red Sea and the Cape of Good Hope (shown by the blue circles in Fig. 10) was counted. Here, the Red Sea area is defined as a radius of 2° (approximately 220 km) from the center coordinates, and the Cape of Good Hope area is defined as a radius of 4° (approximately 440 km) from the center coordinates.

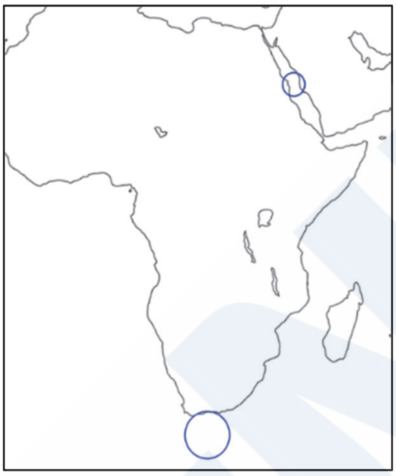


Fig. 10 Areas where ship is judged to sail through Red Sea or Cape of Good Hope

From Fig. 11, a large decrease in ships selecting the Red Sea route and a large increase in ships selecting the Cape of Good Hope route can be seen accompanying the deterioration of the situation in the Red Sea from November 2023. The number of ships sailing the Red Sea route decreased to less than half accompanying the worsening of the Red Sea situation, while the number sailing by way of the Cape of Good Hope increased rapidly from around January 2024, and ships using this route more than doubled from the number in 2023. Fig. 12 shows that the speed of containerships using the Red Sea route decreased after November 2023, and the speed of ships using the Cape of Good Hope route increased. As the reason for this increase in the average speed of ships sailing the Cape of Good Hope route, it is inferred that the ship speed was increased to keep the ships' schedules because the change from the Red Sea route to the Cape of Good Hope route required an additional voyage time of 2 weeks.

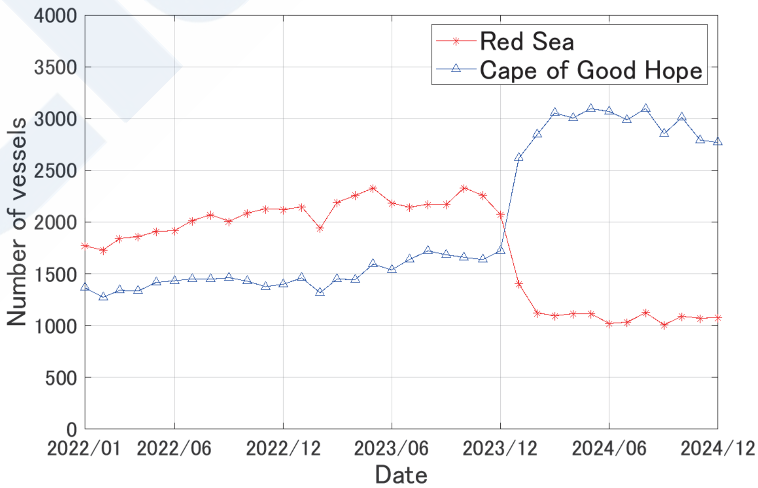


Fig. 11 Number of vessels sailing Red Sea and Cape of Good Hope routes (by month)

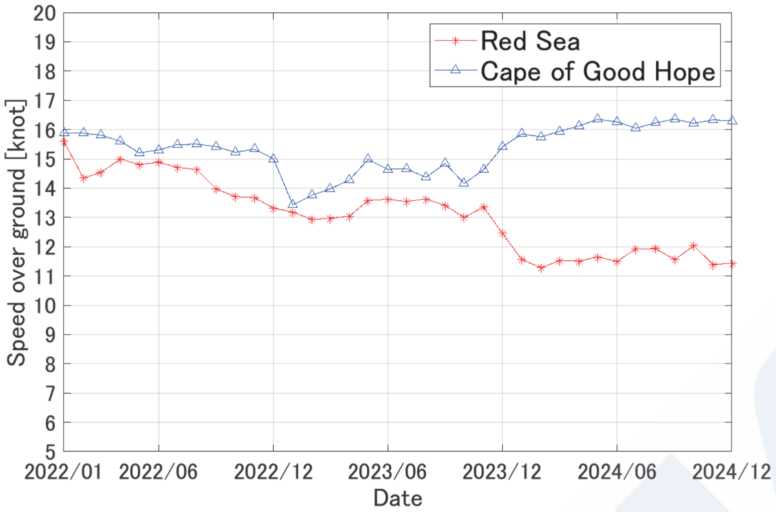


Fig. 12　Average speed of containerships sailing Red Sea and Cape of Good Hope routes (by month)

Next, the attributes of vessels sailing the Red Sea and Cape of Good Hope routes in months before and after (Sept. 2023 and Sept. 2024) the deterioration of the situation in the Red Sea were analyzed.

Fig. 13 shows the number of vessels by ship type of the ships sailing the Red Sea route and the Cape of Good Hope route. For all types of ships, the number of ships sailing the Red Sea decreased, while the number sailing the Cape of Good Hope increased, and these tendencies were particularly remarkable for containerships, LNG carriers and LPG carriers. It may also be noted that no remarkable difference was seen in the total number of ships using the two routes before and after the deterioration of the Red Sea situation.

Fig. 14 and Fig. 15 show a summary of the ships sailing the Red Sea and Cape of Good Hope routes by the nationality/region of the owner and the ship management company, respectively. In the Red Sea, Japanese, Norwegian and Korean ship owners and ship management companies in Singapore, Japan and Korea showed a tendency to avoid the Red Sea route. On the other hand, on the Cape of Good Hope route, the number of vessels of all ship owners and management companies increased, but this increase was particularly large in the case of the Japanese, Norwegian and Korean ship owners and ship management companies in Singapore, Japan, Korea, etc., which showed a remarkable tendency to avoid the Red Sea. It is suggested that this tendency occurred because many of the ships that avoided voyages through the Red Sea sailed by way of the Cape of Good Hope.

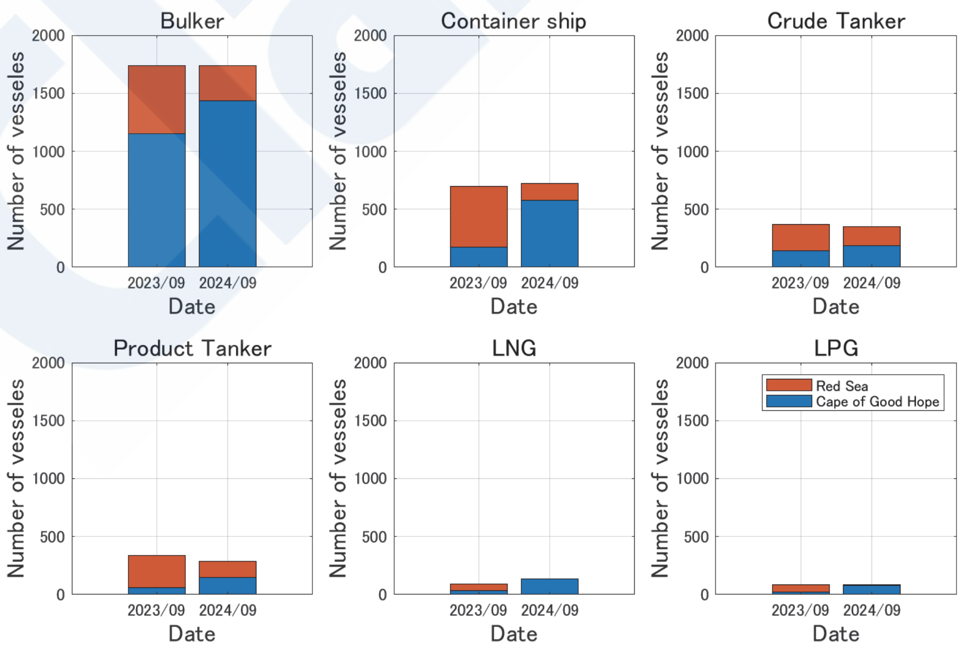


Fig. 13　Statistics by ship type for ships sailing Red Sea and Cape of Good Hope routes
(orange: Red Sea, blue: Cape of Good Hope)

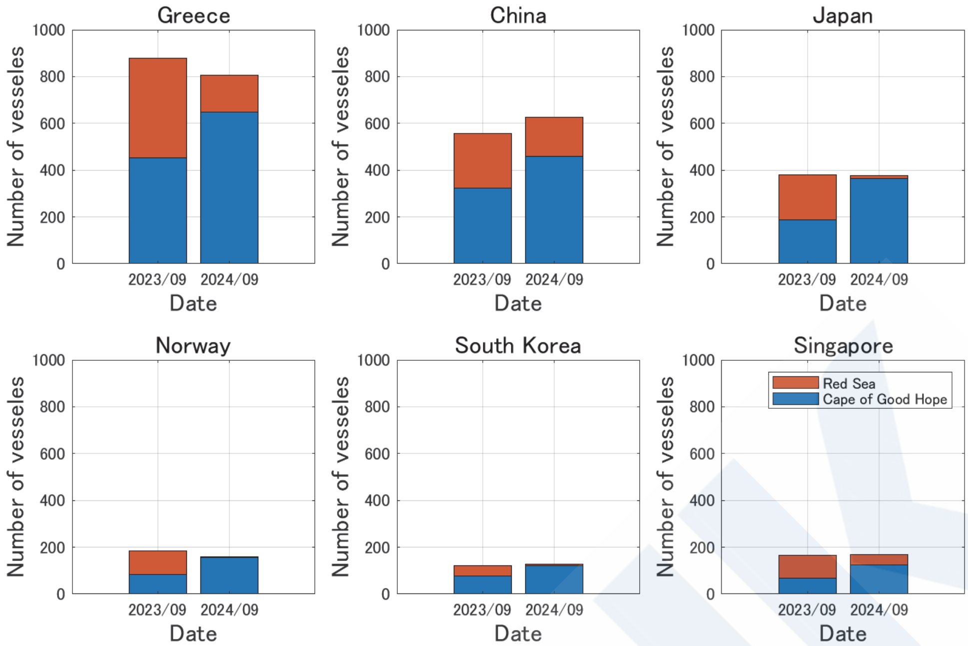


Fig. 14 Statistics by ship owner's nationality/region for ships sailing Red Sea and Cape of Good Hope routes (orange: Red Sea, blue: Cape of Good Hope)

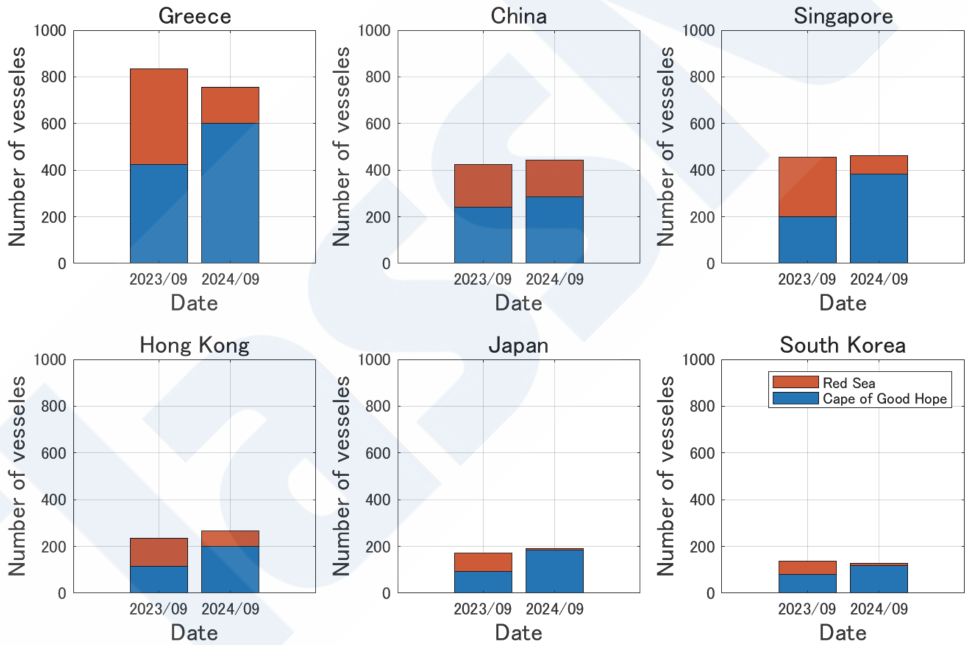


Fig. 15 Statistics by ship management company's nationality/region for ships sailing Red Sea and Cape of Good Hope routes (orange: Red Sea, blue: Cape of Good Hope)

4. CONCLUSION

As examples of the uses of AIS data, this paper introduced the results of analyses of the condition of voyages by ship type and size, information on ocean-going ships calling in Port of Tokyo, and changes in the root of voyages accompanied by the deterioration of the situation in the Red Sea. The Society acquired AIS data for ships registered with the Society after 2015 and all ships after 2022, and used the data mainly in rule development and ship classification services. Because AIS data are also expected to be used in diverse applications other than the development of services of the Society, in the future, we plan to summarize and publish the information obtained from AIS data periodically, based on the needs of those involved in the maritime industry.

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External Affairs Department, Research and Development Division, ClassNK

1. INTRODUCTION

This article introduces recent topics discussed at International Maritime Organization (IMO). At the previous issue, a summary of the topics discussed at 81st Marine Environment Protection Committee (MEPC 81) held in March 2024 and 108th Maritime Safety Committee (MSC 108) held in May 2024 was provided.

This article provides a summary of the decisions taken at 82nd Marine Environment Protection Committee (MEPC 82) held from 30 September to 4 October 2024 and 109th Maritime Safety Committee (MSC 109) held from 2 to 6 December 2024 as below.

2. OUTCOMES OF MEPC 82

2.1 Greenhouse Gases (GHG)

Reduction of greenhouse gas (GHG) emissions to address global warming is a universal challenge, and the measures to reduce GHG emissions from international shipping have been deliberated at IMO. Such measures introduced at the IMO so far include the regulation of Energy Efficiency Design/Existing Ship Index (EEDI/EEXI), retaining of the Ship Energy Efficiency Management Plan (SEEMP) onboard, and reporting annual fuel oil consumption data in the IMO Data Collection System (IMO DCS) and its Carbon Intensity Indicator (CII) rating. At MEPC 80 held in July 2023, the 2023 IMO Strategy on Reduction of GHG Emissions from Ships (2023 IMO GHG Strategy) was adopted, establishing the IMO's reinforced levels of ambition (see table below) and proposed measures for GHG reduction, to lead further discussions with an aim to accomplish the goals of GHG reduction from international shipping.

Table 1 Levels of Ambition Adopted at MEPC 80

Target year	Levels of ambition and indicative checkpoints (as of 2023)
2030	• To reduce CO2 emissions per transport work by at least 40% (compared to 2008) • To reduce total annual GHG emissions by at least 20% (striving for 30%) (compared to 2008) • Uptake of zero GHG emission fuels etc. to represent at least 5% of the energy used (striving for 10%)
2040	• To reduce total annual GHG emissions by at least 70% (striving for 80%) (compared to 2008)
2050	• To reach net-zero GHG emissions by or around 2050 at the latest

At this session, MEPC 82 held continued discussions on developing mid-term measures for reduction of GHG along with various topics such as the review of short-term measures (namely EEXI and CII), further operationalization of the Guidelines for Life Cycle GHG Intensity of Marine Fuels, etc.

2.1.1 Mid-Term Measures for Reduction of GHG

2023 IMO GHG Strategy sets out that, as mid-term measures for achieving the GHG reduction targets for international shipping, a basket of candidate mid-term measures should be developed comprising both a "technical element", which is a goal-based marine fuel standard regulating the phased reduction of the marine fuel's GHG emission per unit energy (i.e. GHG intensity), and an "economic element", which is based on a maritime GHG emission pricing mechanism.

The following work plan was previously agreed at MEPC 80 for developing mid-term measures, aiming for entry into force by 2027:

Table 2　Work plan for developing mid-term measures

Timeline	Work Item
2023-2024	Conduct a comprehensive impact assessment (CIA) to assess potential impacts towards various countries and international shipping posed by combinations of respective basket of measures, and finalize the mid-term measures
2025	Approval and adoption of the mid-term measures
2027	Entry into force of the mid-term measures

At the previous session, the "IMO net-zero framework" was agreed, illustrating an outline of regulatory amendments to be considered, and the IMO Member States and international organizations were then invited to continue with discussions towards finalizing mid-term measures on the basis of the framework.

Furthermore, the results from the CIA, which was conducted by organizations such as UNCTAD etc., were submitted as reports to this session in order to take into account the corresponding results in developing the proposed basket of candidate measures.

At this session, the various points of discussion regarding mid-term measures were consolidated as text options for relevant regulations; however, the Committee was not able to finalize the draft mid-term measures. Many unresolved topics still remain, such as calculating methods of GHG emissions on the life cycle basis, the level of GHG intensity and pricing regulations to be set out, and management and distribution of revenues collected through the pricing mechanism. Further discussions will continue with the aim to adopt mid-term measures within 2027.

Regarding the results from the CIA, a number of delegations expressed concerns that the impacts to States from transportation cost perspectives, in particular on essential food commodities, have not been properly assessed. Thus, it was agreed to carry out further work on assessing consequential impacts in terms of food security.

2.1.2　Review of Short-Term Measures for Reduction of GHG

MARPOL Convention Annex VI prescribes that a review of the EEXI (Energy Efficiency Existing Ship Index) and CII rating regulations, introduced by IMO as short-term measures, shall be completed by 1 January 2026 to assess their effectiveness.

In addition, it was agreed to investigate the effectiveness of the CII rating regulations in terms of a number of proposals submitted by Member States and international organizations, addressing concerns such as ship sizes and operational conditions both positively and/or negatively affecting the CII rating.

At this session, initial analysis on the available data and proposals from Member States and international organizations was conducted in order to proceed with the review of the short-term measures. This session also developed a consolidated list of challenges and gaps in the short-term measures, which will be used as the base document for subsequent discussions at the relevant Correspondence Group and Intersessional Working Group.

2.1.3　Operationalization of the Guidelines on Life Cycle GHG Intensity of Marine Fuels

For low/zero-carbon fuels, such as hydrogen, ammonia and biomass-based fuels which are expected to become more widely used in the future to decarbonize ships, it has been recognized that GHG emissions during manufacturing and distribution processes of these fuels should be taken into account. It is also recognized that GHG other than CO2, such as methane (CH4) and nitrous oxide (N2O), may cause significant impact on global warming.

At the previous session, amendments were made to the LCA Guidelines adopted at MEPC 80 and were adopted as the 2024 LCA Guidelines, and it was also agreed that further investigations will be pursued by the Working Group on the Life Cycle GHG Intensity of Marine Fuels (GESAMP-LCA WG) newly established under GESAMP so as to seek their scientific review and advice.

At this session, Member States and international organizations were invited to submit proposals for default emission factors in order to allow the GESAMP-LCA WG to review default emission factors for each fuel. Also, Member States and international organizations were further invited to propose a certification framework for sustainable fuels to MEPC for consideration by GESAMP-LCA WG in developing a fuel certification scheme.

2.1.4　Guidance for Collecting Data in IMO DCS

At the previous session, the amendments to MARPOL Annex VI Appendix IX were adopted, including the amendments and additions to the items required to be reported in the IMO DCS, such as total fuel oil consumption per combustion systems and actual transport work. These amendments will enter into force on 1 August 2025, but the Parties are further invited to consider early application of the amendments from 1 January 2025.

However, having noted that the data reported to IMO is collected annually per calendar year, it was pointed out that the data collected before and after the date of entry into force may contain data in an inconsistent format.

At this session, in order to allow data reporting in a consistent format throughout the year 2025, a guidance was approved, which essentially allows that data collection according to the amended data format may be commenced from 1 January 2026 for existing ships. It was also confirmed that the guidance does not preclude a voluntary early application of the amendments. Also refer to ClassNK Technical Information TEC-1339 for detailed application schedule and procedures etc.

2.1.5 Initiation of the Fifth IMO GHG Study

IMO periodically conducts a study, providing estimates such as GHG emissions from international shipping. The most recent study was the Fourth IMO GHG Study published in 2020, which presents the emission statistics between 2012 and 2018 and also GHG emission per transport work. It is to be noted that the GHG emission considered in the Study is only associated with onboard (Tank-to-Wake) emissions.

The 17th session of Intersessional Working Group on Reduction of GHG (ISWG-GHG 17), held immediately before this MEPC session, initiated the consideration of Fifth IMO GHG Study by discussing its Terms of Reference. During the discussions, some comments were made, such as: not only the GHG emissions in 2008, which essentially is considered as the baseline for emissions from international shipping, but also carbon concentration in fuels should be determined; and GHG emissions should be calculated on the Well-to-Wake basis.

It was then agreed at this session to continue with detailed discussions on the Terms of Reference of the Fifth IMO GHG Study at the next session, taking into account the views shared and comments raised at this session.

2.2 BWM Convention

2.2.1 Modifications to Ballast Water Management Systems (BWMS) with Existing Type Approval

There have been cases reported, where type-approved BWMS are modified or have their model changed after their installation, such as when the system is found no longer compliant with the Regulation D-2 of the Ballast Water Management (BWM) Convention due to various consequences. Such modifications and changes comprise not only removal of filters but also changes made in UV transmittance system and dosage of active substances. Given that varying approaches are being taken by Member States on whether new type approval should be necessary after such modifications or changes, the industry suggested aligning the views in this regard.

At this session, the amended Guidance for Administrations on the Type Approval Process for Ballast Water Management Systems (MEPC.2/Circ.43/Rev.2) was approved, listing detailed examples of BWMS components and providing guidance on when a new type approval should be necessary or not.

2.2.2 Review of BWM Convention

The Correspondence Group on Review of the BWM Convention reported to this session the progress of its work being undertaken since MEPC 80 and held further in-person discussions. The Correspondence Group will continue its work, which will further be reported to MEPC 83.

When BWM Convention entered into force in 2017, it was agreed to monitor the application and to review the effectiveness of the Convention through the experience building phase (EBP), and MEPC 80 approved the Convention Review Plan (CRP) which comprises the list of issues that need to be finalized. MEPC 81 further endorsed the list identifying items that need to be amended within the BWM Convention, BWMS Code and relevant guidelines and guidance, based on the review undertaken by the Correspondence Group.

At this session, the following topics were discussed with an aim to establish common understanding to facilitate further work by the Correspondence Group:

- BWMS maintenance procedures;
- Standardization of BWMS data logs and export files;
- Relationship between BWMS testing conditions and treatment rated capacity (TRC);
- BWMS test duration;
- Test water conditions; and
- Type of analysis of ballast water discharges during surveys.

It was also concluded that the Correspondence Group will not proceed with the consideration of the proposal for regulating disinfection by-products (DBPs) in discharges from BWMS that make uses of active substances, given that the matter is not mature enough for consideration.

2.3 Others

2.3.1 Ship Recycling Convention

To conduct dismantling of ships in a safe manner and under appropriate management without environmental pollution, the Ship Recycling Convention (formally "the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, 2009", a.k.a. "the Hong Kong Convention") will enter into force on 26 June 2025, where the Convention will apply to all ships of 500 GT or over flying the flag of a ratified Party (see ClassNK Technical Information TEC-1311). On the other hand, the Basel Convention which entered into force in 1992 (and its 1995 amendment) prohibits all transboundary movements to particular States of hazardous wastes covered by the Convention that are intended for final disposal.

At the previous session, concerns were raised where ships compliant to the Ship Recycling Convention may not proceed with the final voyage due to the Basel Convention; therefore, the interplay between the Conventions was further investigated.

At this session, the provisional IMO guidance was approved, clarifying that States that are Parties to both the Ship Recycling Convention and the Basel Convention should consider notifying the Secretariat of the Basel Convention so as to express that the States understand that the provisions of the Basel Convention should not affect the transboundary movements that take place pursuant to the Ship Recycling Convention. Member States and IMO Secretariat were also encouraged to continue sharing relevant information towards the implementation of the Ship Recycling Convention.

2.4 Amendments to Mandatory Instruments

2.4.1 Addition of Nitrogen Oxides (NOx), Sulphur Oxides (SOx) and Particulate Matter (PM) Emission Control Areas (ECA)

Amendments to MARPOL Annex VI were adopted, designating Canadian Arctic area and Norwegian Sea area as ECA and also including detailed dates relevant to the ship's construction into the Form of the Supplement to IAPP Certificate. The amendments will enter into force on 1 March 2026.

The sulphur content in fuel oil used for ships operating in these ECA will be limited to 0.10% from 1 March 2027. Furthermore, the NOx Tier III emission limit will be applied to the following ships operating in these ECA:

Table 3 Application of NOx Tier III limitations

Canadian Arctic ECA	• Ships the keels of which are laid or that are at a similar stage of construction on or after 1 January 2025
Norwegian Sea ECA	• Ships for which the building contract is placed on or after 1 March 2026 • In the absence of a building contract, ships the keels of which are laid or which are at a similar stage of construction on or after 1 September 2026 • Ships delivered on or after 1 March 2030

3. OUTCOMES OF MSC 109

3.1 Adopted Mandatory Requirements

Mandatory requirements were adopted at MSC 109 as follows:

(1) Amendments to IGC Code

Amendments to chapter 16 of the IGC Code to make cargos identified as toxic products conditionally usable as fuel, in view of the launch of ammonia-fuelled vessels were adopted. In addition, the MSC circular to invite a voluntary early implementation of the amendments was also released.

(2) Amendments to IGF Code

Amendments to IGF Code regarding suction wells installed in fuel tanks, pressure relief valves of piping system, segregation and insulation of boundary of accommodation spaces and others facing the fuel tanks, hazardous area etc. were adopted as a part of the task for amendments to the IGF Code and development of guidelines for alternative fuels and related technologies.

3.2 Approved Mandatory Requirements

The following mandatory requirements were approved at this session and are expected to be adopted at MSC 110 to be held in June 2025.

(1) Amendments to HSC Code

Amendments to 1994 HSC Code and 2000 HSC Code regarding the numbers of lifejackets for infants and adults weighing up to 140 kg.

(2) Amendments to IGC Code

Amendments to Chapter 1 to 5, 8 to 13 and 15 to 19 of the IGC Code regarding the filling limit, requirements of using cargo other than LNG as a fuel, special requirements for carbon dioxide, etc.

(3) Amendments to SOLAS regulation II-1

Amendments to SOLAS regulation II-1/56 to include gaseous fuels irrespective of flashpoint in application of IGF Code in addition to low-flashpoint fuels.

3.3 Approval of Unified Interpretations (UIs), Guidelines and Guidance etc.

The following unified interpretations (UIs), guidelines, guidance and etc. were approved during MSC 109.

3.3.1 UIs

(1) Unified interpretation of SOLAS regulation III/20.8.4 and 20.11, and resolution MSC.402(96)

Unified interpretation of SOLAS regulation III/20.8.4 and 20.11 to clarify that SOLAS regulation III/20.11 and resolution MSC.402(96) should also be applicable to inflated rescue boats

(2) Unified interpretation of SOLAS regulation II-2/4.5.6.1 and 20.11, and paragraph 3.1.2, 3.1.4 and 3.5.3 of the IBC Code

Unified interpretation of SOLAS regulation II-2/4.5.6.1 and 20.11, and paragraph 3.1.2, 3.1.4 and 3.5.3 of the IBC Code regarding gas-freeing air-supply piping system located outside of the cargo area

(3) Unified interpretation of SOLAS regulation II-2

1. Unified interpretation of SOLAS regulation II-2/4.5.3.2.2 and 11.6.3.2 clarifying the secondary means of venting cargo tanks; and
2. Unified interpretation of SOLAS regulation II-2/11.4.1 regarding the definition of crowns for machinery spaces of category A

(4) Unified interpretation of SOLAS regulation II-1

Unified interpretation of SOLAS regulation II-1/26.2 regarding the reliability of single essential propulsion components

3.3.2 Guidelines and Guidance etc.

(1) Revised standards for the design, testing and locating of devices to prevent the passage of flame into cargo tanks in tankers

Amendments to standards for the design, testing and locating of devices to prevent the passage of flame into cargo tanks in tankers (MSC.1/Circ.677) to incorporate the previous amendment made (MSC.1/Circ.1324) and updating references.

(2) Interim guidelines for ships using ammonia as fuel

Interim guidelines for ships using ammonia as fuel, as a part of the task for amendments to the IGF Code and development of guidelines for alternative fuels and related technologies. The interim guidelines do not address ships using ammonia cargo as fuel.

3.4 Goal-based Standards (GBS)

GBS, as stipulated in SOLAS II-1/3-10, is applied to oil tankers and bulk carriers of 150m in length and above. Design and construction of these ships shall comply with rules deemed as compliant with GBS.

Further, GBS requires maintenance of verification to the rules as conforming to the goals and functional requirements of GBS based on the GBS Verification Guidelines (MSC.454(100)).

At this session, the GBS audit report and actions taken by the IACS for the 2022 amendments to IACS Recommendation No.34 (Rec.34/Rev.2), which provides wave scatter diagram to be used as the basis for the IACS Common Structural Rules (CSR) were considered, and it was agreed to add more detailed information about the wave data.

3.5 Consideration of Requirements for Maritime Autonomous Surface Ships (MASS)

In the recent development of MASS, it has been discussed at MSC on an international instrument of MASS (MASS Code). Non-mandatory MASS Code mainly on goal and functional requirements for items such as safety, operation, security, etc. is currently under consideration.

At this session, based on the report by the intersessional working group (ISWG) meeting held in September 2024, chapters of Risk Assessment (Chapter 7), Connectivity (Chapter 12), and Remote Operations (Chapter 18) were finalized. In addition, the future work plan was reviewed, and it was agreed that an intersessional working group meeting will be held in the second half of 2025, and that the non-mandatory MASS Code will be finalized at MSC 111, scheduled for 2026. There will be no changes regarding the schedule for mandatory MASS Code, i.e. it will be considered after the development of the non-mandatory MASS Code, with a view to adoption by 2030.

At this time, the structure of the non-mandatory MASS Code will be as follows.

Part 1: Introduction (purpose and application of the code)

Part 2: Main principles for MASS and MASS functions (certificate and survey, approval process, risk assessment, operational context, human element, etc.)

Part 3: Goals, functional requirements and expected performance (stipulating for each item such as safety of navigation and remote operations)

3.6 A Safety Regulatory Framework to Support the Reduction of GHG Emissions From Ships Using New Technologies and Alternative Fuels

At MSC 107, identification and updating a list of new technologies and alternative fuels to reduce greenhouse gas (GHG) emissions and their technical assessment, as well as a review of safety obstacles and gaps in the current IMO instruments that may impede the use of the alternative fuel or new technology, were initiated. The correspondence group is working to update the list and is supposed to report to MSC 110.

In addition, it was proposed that the IGF Code should also apply to gaseous fuels irrespective of flashpoint by the Sub-Committee on Carriage of Cargoes and Containers held in September 2024 (CCC 10). At this session, amendments to SOLAS II-1/56 to apply the IGF code to all gaseous fuels, not just low-flashpoint fuels, was approved. It is expected to be adopted at MSC 110.

3.7 Cyber Risk Management

In view of the growing importance of cyber security on board ships and the need for security risk countermeasures, Resolution MSC.428(98) on maritime cyber risk management and the non-mandatory guidelines (MSC-FAL.1/Circ.3/Rev.2) for reference in the implementation of this resolution have been developed.

At the previous session, a draft amendment to the guidelines in light of the increased use of cyber-connected systems in recent years were agreed. The draft amendment to the guidelines were further approved by subsequent 49th session of the Facilitation Committee (FAL 49) and published as an MSC-FAL Circular (MSC-FAL.1/Circ.3/Rev.3).

At this session, it was agreed to the need to further develop cybersecurity standards for ships and port facilities as next steps to enhance maritime cybersecurity and also agreed to extend the target completion of the output on this agenda item to year 2026 to further discussion.

Overview of Guidelines Issued by ClassNK during CY 2024

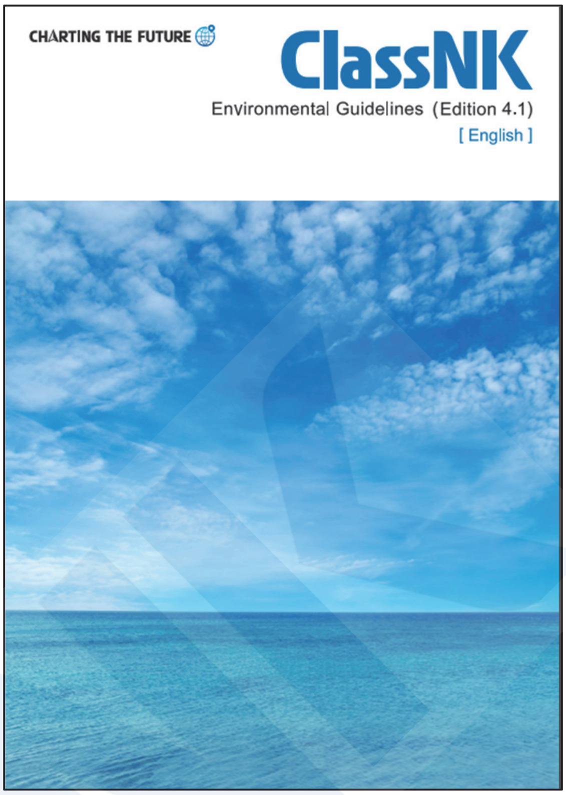
Research Institute, Research and Development Division, ClassNK

During calendar year 2024, ClassNK issued the 9 Guidelines shown in Table 1. This article presents the outlines of these Guidelines.

Table 1 Guidelines issued during CY 2024

Title	Languages	Date of issue	Contact
Environmental Guidelines (Edition 4.1)	Japanese/ English	February 2024	Rule Development Dept.
Guidelines for Open-top Ships (Edition 1.0)	Japanese/ English	March 2024	Rule Development Dept.
Guidelines for Ships Using Alternative Fuels (Edition 3.0)	Japanese/ English	July 2024	Technical Solution Dept.
Guidelines for Wind-Assisted Propulsion Systems for Ships (Edition 2.1)	Japanese/ English	July 2024	Technical Solution Dept.
Guidelines for Offshore Access Systems (Edition 1.0)	Japanese/ English	July 2024	Rule Development Dept.
Guidelines for Cyber resilience of ships (Edition 1.0)	Japanese/ English	July 2024	Machinery Dept.
Guidelines for Liquefied Hydrogen Carriers (Edition 3.0)	Japanese/ English	September 2024	Technical Solution Dept.
Guidelines for Excellent Living and Working Environment (Edition 1.1)	Japanese/ English	October 2024	Rule Development Dept.
Guideline for the Safe Transportation of Electric Vehicles (Edition 2.0)	Japanese/ English	December 2024	Material and Equipment Dept.

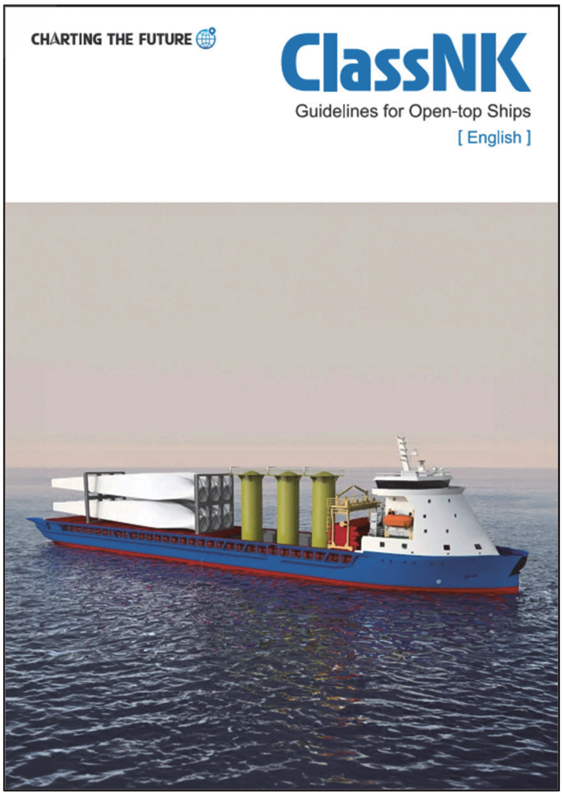
Environmental Guidelines (Edition 4.1)



All industries are engaged in global efforts to address environmental problems, and the maritime industry is no exception. The industry is also responding to heightened awareness of corporate social responsibility (CSR) and Sustainable Development Goals (SDGs) through initiatives (environmental measures) that not only meet but exceed the minimum requirements of international conventions in diverse fields such as prevention of marine pollution and air pollution. The Society first issued “Environmental Guidelines” in 2008, establishing a system under which environmental measures applied to ships are indicated as notations affixed to the ship classification characters. Since that time, the Guidelines have been revised several times in line with reviews of the related provisions. Edition 4.0 (2021) also established a new certification service that recognizes ships which have taken advanced environmental measures.

Among recent global warming measures, Edition 4.1 establishes new efforts for “green steel,” which has attracted interest in many industries, beginning with the steel industry, as well as construction and automobiles, that is, steel products produced using technologies that substantially reduce or realize zero CO_2 emissions in all or part of the steel manufacturing processes (a total of processes from raw materials to steel making), when this green steel is used in the ship hull structure, etc., and the installation of equipment for recovery of microplastics (marine plastic waste with a length < 5 mm), which is feared to have adverse impacts on marine life.

Guidelines for Open-top Ships (Edition 1.0)

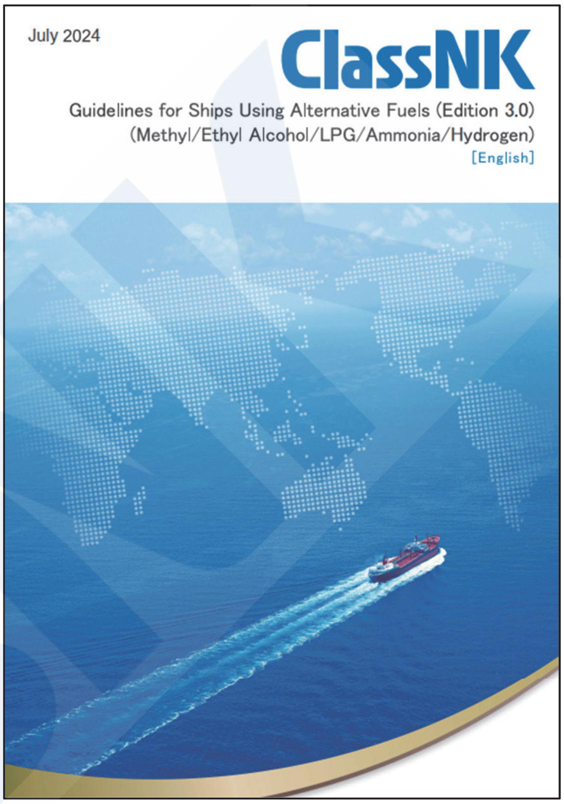


In recent years, there has been an increasing demand for the transport of large cargoes such as offshore wind power generation equipment without hatch covers on container carriers and general cargo ships.

The IMO adopted the guidelines “Interim Guidelines for Open-top Containerships” (IMO circular MSC/Circ.608/Rev.1) in July 1994 to serve as its guideline for “open-top” containerships (i.e. container carriers with cargo holds not fitted with hatch covers) and it specifies requirements for model test procedures, hold bilge dewatering systems, fire-protection and other matters related to such ships.

Therefore, based on the aforementioned IMO guideline and its own knowledge and experience, the Society developed its “Guidelines for Open-top Ships” (hereinafter referred to as “the Guidelines”) to provide requirements related to the transport of cargoes on open-top ships. The Guidelines cover not only container carriers but also extend the original scope of IMO guideline to include general cargo ships and other cargo ships. The Guidelines stipulate procedures for model tests and other requirements for such ships, and make it clear the application of its requirements is contingent upon obtaining Flag Administration approval for an exemption to relevant international conventions applicable to such ships.

Guidelines for Ships Using Alternative Fuels (Edition 3.0)

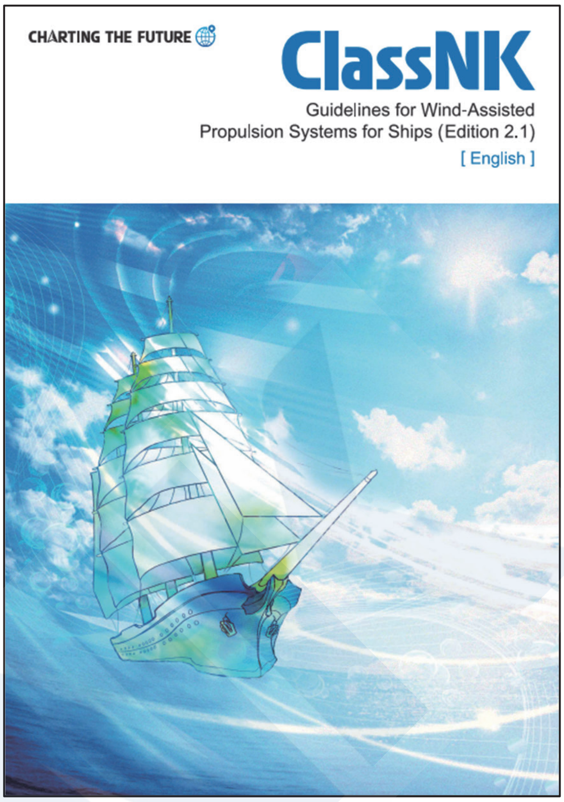


The first edition of these guidelines was published in 2021. Since then, the guidelines have been revised based on the implementation of the guideline on actual ships or added alternative fuel types, and the third edition (August 2024) has been published. In this edition, the safety requirement for hydrogen fuel was newly added and the safety requirement for ammonia fuel was partially revised.

Hydrogen and ammonia fuel are attracting attention as fuels with high GHG reduction effects on ships. However, the safety requirements for hydrogen and ammonia fuel are not specified in the international conventions or codes developed by the International Maritime Organization (herein after IMO). As of August 2024, when the third edition of these guidelines was published, the IMO interim guidelines were under development. Therefore, we, ClassNK, publish the edition of these guidelines to provide a certain safety level for ships introducing hydrogen and ammonia fuel.

In the future, the IMO plans to finalize the Interim Guidelines for ammonia fuel at the end of 2024 and the one for hydrogen fuel at the end of 2025, then our guidelines will be revised in accordance with the IMO interim guidelines.

Guidelines for Wind-Assisted Propulsion Systems for Ships (Edition 2.1)



Currently, as a solution for responding to the EEXI regulations and CII rating, and fuel costs reduction, the implementation of Wind-Assisted Propulsion Systems (herein after WAPS) is accelerating.

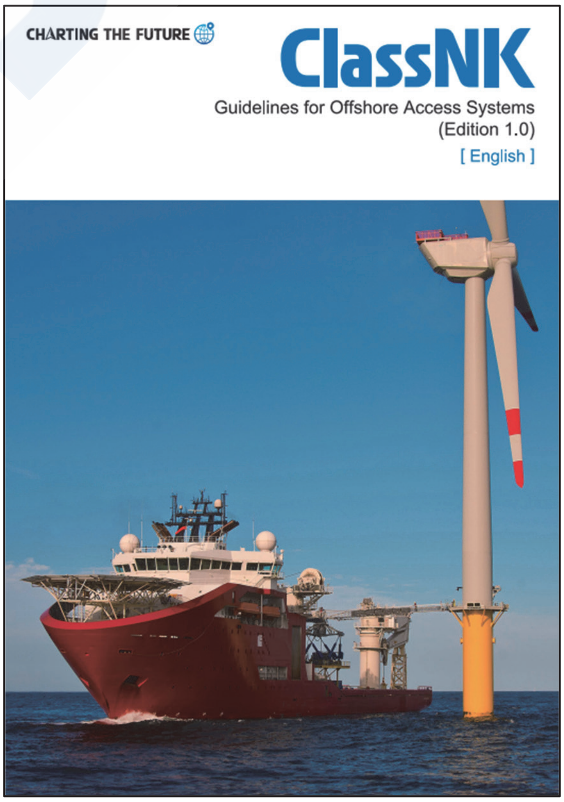
The safety of ships is guaranteed by international conventions, domestic laws, related regulations, etc., but there are still no conventions applicable to WAPS.

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.

Since then, reflecting the insights obtained from involvement in the actual installation projects, the guidelines are updated to the 2.1 edition (July 2024). In this edition, the guidelines now provide a comprehensive overview of the points to be considered in designing WAPS and their installation on ships to “update reference rules (Part X of the NK Rules)” and “clarify the classification and refinement of requirements.”

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 Offshore Access Systems (Edition 1.0)



As countries around the world have increased their use of renewable energy in recent years, the use of offshore power generation facilities has, mainly in Europe, become one of the main approaches being adopted. The implementation of programs for maintaining such facilities have already entered into service, and special ships have been introduced to support the maintenance and management of those facilities intended to operate for long periods of time. Such ships are typically provided with personnel transfer arrangements to ensure safe and efficient access for workers involved in maintenance and management operations from ships to offshore facilities.

The *International Code of Safety for Ships Carrying Industrial Personnel* (hereinafter referred to as the “IP Code”) adopted by the IMO Maritime Safety Committee at its 106th session (MSC 106) in November 2022 entered into force in July 2024. Although the IP Code specifies general requirements for ships manned by industrial personnel (all persons transported or accommodated on board for the purpose of offshore industrial activities performed on board other ships, offshore facilities or both), the design, construction, testing and installation of personnel transfer arrangements are subject to the requirements of the various individual classification societies.

This Guidelines specifies ClassNK's requirements for surveys of personnel transfer arrangements not only during their manufacture and installation but also periodical surveys to verify the continued compliance of such arrangements. Furthermore, this Guidelines also specifies that ships equipped with personnel transfer arrangements complying with its requirements may have their classification characters be affixed with notation corresponding to the classification of their personnel transfer arrangements.

Guidelines for Cyber resilience of ships (Edition 1.0)

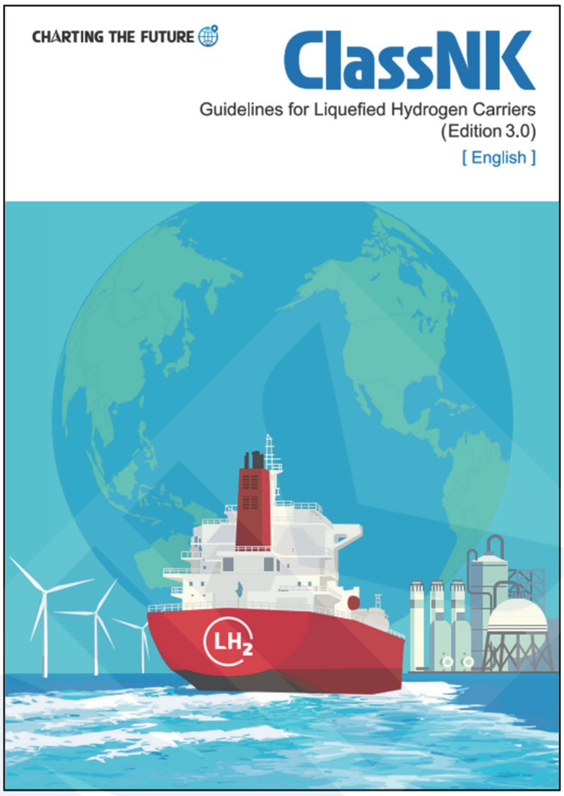
In recent years, maritime systems have shifted from traditional physical connections and controls to digital interconnections via computers and the internet. As a result, the risk of cyber-attacks has increased. In the event of such an attack, there could be impacts on the safety of life and property at sea, as well as on the prevention of pollution of the marine environment.

In response to these developments, IACS issued two Unified Requirements—UR E26 and UR E27—in April 2022, establishing the necessary measures to ensure cyber resilience: the ability to withstand, respond to, and recover from cyber incidents.

Of these, UR E26 specifies requirements for ships. ClassNK has incorporated these requirements into *Chapter 5, Part X of the Rules for the Survey and Construction of Steel Ships*. These rules apply to ships registered with ClassNK, for which the contract for construction is dated on or after 1 July 2024.

The guidelines are primarily intended for shipowners and shipyards (as integrators) and aim to provide a clear and practical explanation of the cyber resilience requirements specified in Chapter 5, Part X. They consist of five chapters: Overview, Application, Process, Submission of Plans and Documents, and Survey.

Guidelines for Liquefied Hydrogen Carriers (Edition 3.0)

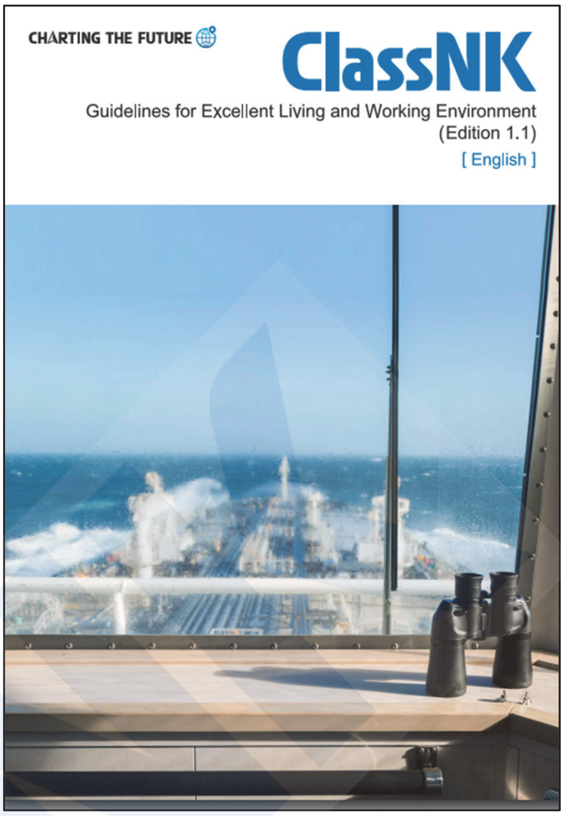


To construct a supply chain for hydrogen, which is expected to be a clean energy source in a decarbonized society, the development of liquefied hydrogen carriers that enable large-scale and efficient transportation is progressing actively.

IMO has worked on establishing safety requirements for liquefied hydrogen carriers with an extremely low cargo temperature of minus 253 degrees Celsius, and “Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk” was adopted in 2016. Subsequent development of liquefied hydrogen carriers led to the construction project of a larger-scale liquefied hydrogen carrier with cargo containment systems of different designs from a prototype liquefied hydrogen carrier. In response to this, the revision of the interim recommendations has been considered in IMO since 2021 and adopted at MSC 108 in May 2024.

In light of this situation, ClassNK has updated its “Guidelines for Liquefied Hydrogen Carriers” as edition 3.0, reflecting the changes in the interim recommendations and the knowledge gained through related projects. In this update, new safety requirements for cargo containment systems with different designs from an existing prototype liquefied hydrogen carrier were added, and the guidelines’ structure was reformed in anticipation of a future expansion of the applicable scope. Furthermore, to clarify the selection criteria for metallic materials suitable for liquid hydrogen carriers, an annex of guidance for the selection of metallic materials for hydrogen equipment was also newly implemented.

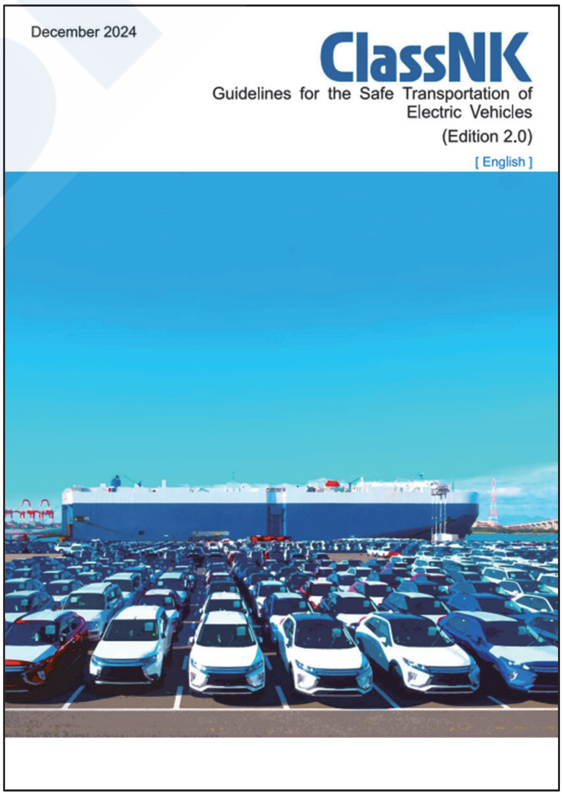
Guidelines for Excellent Living and Working Environment (Edition 1.1)



In moves related to the labor environment for seafarers working on ships, the Maritime Labour Convention (MLC, 2006) entered into force in 2013, and efforts to improve the labor environment are being made internationally. To make ships an attractive workplace for seafarers, ships that put more effort into improvement of the living environment and working environment than required under the MLC have appeared in recent years. To identify ships that make such efforts, “Guidelines for Excellent Living and Working Environment” was issued in 2022, making it possible to affix the notation Excellent Living and Working environment (abbreviation: ELW) to the ship’s classification characters.

Among efforts to improve the working environment, in response to the increase in ships that install hydroponic equipment that can cultivate vegetables, etc. almost automatically in living quarters, and provide meals that include fresh vegetables, etc. to seafarers, Edition 1.1 was revised so that notation to this effect can be affixed to the classification characters of ships equipped with such systems.

Guidelines for the Safe Transportation of Electric Vehicles (Edition 2.0)



Accompanying a large increase in the number of registered electric vehicles (EVs) worldwide, the number of EVs transported by car carriers is also expected to increase. Since the driving force for an EV is the electric energy stored in a lithium ion battery (LIB), when a fire breaks out from the LIB, or the LIB catches fire from another source, a different response from that used with gasoline automobiles is necessary to extinguish the fire. In August 2023, the Society issued “Guidelines for the Safe Transportation of Electric Vehicles,” which described the characteristics and points to note when an EV fire occurs, and presented the key points surrounding fire safety measures that are considered to be effective. Assuming the case where a fire breaks out from an automobile storage area of a car carrier, the Guidelines were revised as Edition 2.0 in 2024, focusing on where risks exist for safe evacuation of the crew from the ship, and what conceivable countermeasures are available. The risks that exist in car carriers are different from those of other ships because, unlike other types of ships, the living quarters and lifesaving equipment are located above the automobile storage areas. In order to discuss the risks and countermeasures, a risk assessment incorporating the opinions of related persons in Japan was carried out and summarized in a risk assessment report, and the risk assessment report was also published simultaneously with the revised Guidelines. Ships that take actions that are considered effective can affix a notation to that effect to the ship’s classification characters.

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