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Special Feature: Latest GHG-Related Trends and NK Initiatives

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In the future, the use of alternative fuels will be indispensable for achieving net-zero GHG emissions in 2050. On the other hand, a wide range of alternative fuels are available for use by ships. Therefore, for appropriate selection of fuels, it is necessary to understand not only the technical aspects of alternative fuels, but also the issues related to those fuels as a whole, including fuel availability, cost projections, and other factors. To support this type of fuel selection, the Society issues “ClassNK Alternative Fuels Insight.” This paper presents an easy-to-understand overview of “ClassNK Alternative Fuels Insight.”

The 2023 IMO Strategy for the Reduction of GHG from Ships, which was adopted at MEPC80, set a new target of achieving net-zero GHG emissions by close to 2050, and also adopted guidelines for assessing the life cycle GHG intensity (GHG emissions per unit of energy) of marine fuels, incorporating consideration of GHG emissions in the total life cycle of marine fuels from production and transportation to use on shipboard (Well-to-Wake GHG emissions).This article presents a commentary, including the most recent information, on the IMO’s “Guidelines on the life cycle GHG intensity of marine fuels (LCA guidelines).”

To reduce GHG emissions from ships, the IMO has set a target of achieving net-zero GHG emissions from international shipping as soon as possible in this century. To achieve this goal, the maritime industry is actively grappling with the introduction of new technologies and alternative fuels. Against this background, this article explains the regulatory framework and examination system for alternative fuel ships and the trends in alternative fuel ships in which the Society is involved.

This paper is a follow-up report on “Studies on In-Engine Combustion of Low- and Zero-Carbon Fuels,” which appeared in ClassNK Technical Journal No. 7 (2023, pp. 71-80). In that paper, issues for combustion when using various alternative fuels and their solutions were described. This paper introduces the status of dual-fuel engines for marine use which are currently being developed as a solution to those issues. It can be said that the progress of those development efforts has sufficient momentum, both in Japan and in other countries.

Technical Topics

Prefatory Note

Introduction to the Special Feature on "Latest GHG-Related Trends and NK Initiatives"

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

On the occasion of the publication of ClassNK Technical Journal No. 10, 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 ClassNK available to a wider range of interested parties.

In the previous issue (ClassNK Technical Journal No. 9), we reported on guidelines to contribute to safer transportation of electric vehicles. These guidelines were issued as the first of their kind in the world, and we also covered fire-fighting technologies related to the guidelines, as well as the latest technological trends in launch vehicle recovery ships, among other topics.

In July 2023, IMO MEPC 80 (International Maritime Organization Committee for the Protection of the Marine Environment) adopted the ambitious goal of achieving "Net-zero GHG emissions by or around 2050". ClassNK has established the "ClassNK Transition Support Service" with the objective of providing comprehensive support for customers' smooth transition to Net-zero GHG emissions. In this issue, a special feature article, "Latest GHG-Related Trends and NK Initiatives", is published to provide customers with the latest information related to "Understanding Regulations" and "Alternative Fuel Support" as part of the support services that propose optimal GHG emission reduction solutions to meet their needs. In this special issue, regulations related to GHG emissions, characteristics of alternative fuels, supply chains, life cycle costs, and the status of responses to alternative fuels by marine engines are explained.

In recent years, the digitization of ships has rapidly advanced, and the risk of cyber-attacks has increased. In this issue, we outline the background and trends of cyber security regulations for ships as well as the efforts of ClassNK in relation to the Unified Requirement of the International Association of Classification Societies (hereinafter referred to as UR) E26 and E27, which are considered to be of high interest in the maritime industry and started to be applied are applicable to contract ships constructed on and after July 1 this year.

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

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

ClassNK Alternative Fuels Insight

Hiroyuki WATANABE*

1. INTRODUCTION

In July 2023, new greenhouse gas (GHG) emissions reduction targets for international shipping were announced with the aim of reaching “Net-zero GHG emissions by or around 2050.” This was a decisive turning point for international shipping, which made it clear that alternative fuels would be considered necessary in all international shipping in the future. Following this, international shipping embarked upon an era of large-scale fuel transition toward the year 2050.

On the other hand, a wide range of alternative fuels are available for use by ships. Owing to this diversity of fuels, which fuels are to be introduced at what timing, corresponding to the ship type and size, navigation routes, etc. will affect the maritime shipping business in the future. In order to study introduction, it is necessary to understand not only the technical aspects of alternative fuels, but also the general issues related to alternative fuels as a whole, including fuel availability, cost projections and other related factors.

To support this kind of fuel selection, ClassNK (hereinafter, the Society) issues “ClassNK Alternative Fuels Insight.” This publication introduces the minimum points that must be understood when introducing alternative fuels in the four steps of “Understanding regulations,” “Understanding trends,” “Understanding alternative fuels” and “Understanding costs.” This article presents an overview of “ClassNK Alternative Fuels Insight” to assist readers in understanding its content.

2. UNDERSTANDING REGULATIONS

2.1 GHG Emission Pricing

Why is it necessary to introduce alternative fuels? It is because GHG emissions from ships will be subject to GHG emission costs (GHG emission pricing) in the near future. The two main regulatory bodies that influence GHG emissions from international shipping, that is, International Maritime Organization (IMO) and the European Union (EU), announced respective GHG emission reduction targets of “net-zero GHG emissions by or around 2050” and “net-zero GHG emissions by 2050.” While the EU target is not limited to maritime shipping and is simply a target for the EU as a whole, EU policies that forcefully promote the realization of a decarbonized economy will also affect the trends in international shipping. To realize these GHG emission reduction targets, i.e., to realize net-zero GHG emissions in international shipping, not only the improvement of energy efficiency of ships, but also the use of lower GHG emissions than conventional fuel oil, or so-called alternative fuels, will be indispensable. On the other hand, because the price of alternative fuels is generally higher than that of conventional fuel oil, the use of alternative fuels will not progress unless the price gap between the two is closed. Therefore, the IMO and EU will introduce regulations that promote the use of alternative fuels, in other words, regulations that reduce demand for conventional fuel oil. This is so-called “carbon pricing,” and is intended to treat GHG emissions as a cost. The schedule for introduction of the IMO and EU regulations is as shown in Fig. 1. The IMO is targeting the introduction of regulations called “mid-term measures” in 2027, while the EU already introduced that type of regulations in 2024 as “EU-ETS for shipping,” and will introduce new regulations called “FuelEU Maritime” in 2025. Thus, pricing of GHG emissions will not wait.

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Fig. 1 Introduction schedule of GHG-related regulations

2.2 IMO Mid-Term Measures

In addition to the one large time constraint of "net-zero by 2050," the GHG emission reduction targets of the IMO also includes the "indicative checkpoints" of 2030 (20% to 30% reduction) and 2040 (70% to 80% reduction). The IMO will introduce regulations in accordance with this timeline to achieve GHG emissions reductions. The regulations introduced up to the present aiming at GHG emission reductions in the "short-term" span until 2030 are called "short-term measures" and focus mainly improvement of ship's energy efficiency. In contrast, the regulations to be introduced in the future, which aim at GHG emission reductions in the "mid-term" span until 2040, are called "mid-term measures," and as mentioned above, the focus of these mid-term measures is promoting the use of alternative fuels.

The methods for achieving the transition from conventional fuel oil based on the market mechanism by regulations that promote the use of alternative fuels, namely, pricing of GHG emissions, mainly include two methods: The first approach is simply levying fees for GHG emissions ("levying" system). In a levying system, the cost of the levy is equivalent to the amount of GHG emissions, irrespective of the type of fuel, so all fuels other than the zero-emission fuels can be subject to a cost burden. The second approach is regulation of the amount of GHG emissions per unit energy of the fuel, that is, regulation of the GHG intensity of the fuels (fuel GHG intensity system). Although the amount of fuel (weight-ton) necessary to move a ship 1 mile differs depending on the fuel, the amount of energy extracted in this process is the same for all types of fuels. Thus, by applying an index that shows "how much GHG was emitted when energy was extracted from the combustion of fuel," it becomes possible to compare the GHG emissions of each fuel equally. A typical unit of fuel GHG intensity is CO_{2eq}/MJ, where CO_{2eq} means CO_2 equivalent ($_{eq}$ is the abbreviation of equivalent). This unit is used to calculate the total amount of emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other GHGs with different warming effects by a single unit. Of course, even when calculating only CO_2, CO_{2eq} is sometimes used for convenience. MJ is a unit of energy and is the abbreviation of megajoule ("mega" means "million"). Returning to the discussion of regulations, regulations on GHG intensity are intended to limit fuel use exceeding a certain threshold by setting a uniform threshold for GHG intensity. Naturally, in implementing regulations, it would be possible to impose a compulsory limit forbidding fuel use exceeding the threshold, but realistically, implementation permits excess fuel use by asking for payment of a monetary penalty for fuel use that exceeds the threshold. In this kind of implementation, the GHG intensity system is substantially a levying system on excess GHG emissions that exceed a threshold. Moreover, since designated fuels with low GHG intensities can avoid penalties depending on how the threshold is set, not only zero-emission fuels, but also low-emission fuels have a competitive advantage in comparison with conventional fuel oil; this is a feature of fuel GHG intensity regulations. Because the relative GHG emission costs of various fuels is determined by what threshold level is set at what timing, this is the point at issue in policy discussions.

The IMO is engaged in discussions on the content of the mid-term measures toward introduction in and after 2027 along the lines of the two approaches described above. The issues in those discussions are the selection of the regulatory approach and the purpose of use of the levy income or penalty income collected by the IMO under the regulatory scheme. Candidates for the use of levy income and penalty income include refunds ("rebates") of fuel costs to ships that use high-cost alternative fuels, support for developing countries, and others.

2.3 EU Regional Regulations

The EU began introducing regulations that promote the use of alternative fuels ahead of similar efforts in the IMO. In 2024, the European Union Emission Trading System (EU-ETS) implemented by the EU was expanded to the maritime sector as "EU-

ETS for shipping." Emission trading systems are generally cap-and-trade systems that set GHG emission allowances in advance, and then allow to sell or buy ("trade") their surplus or shortage of GHG emissions. However, the most important feature of EU-ETS for shipping is that free emission allowances are not allocated to ships in advance. In other words, in EU-ETS for shipping, the ship's actual emissions are defined as a "shortage" of GHG emission allowances, and the ship must cover those emissions by purchasing GHG emission allowances. In this sense, EU-ETS for shipping is essentially a type of levy system. Furthermore, continuing from EU-ETS for shipping, "FuelEU Maritime" is a new regulation which will be introduced beginning in 2025. FuelEU Maritime is a GHG intensity regulations, as described above, and will impose monetary penalties on the use of fuels in excess of the GHG intensity threshold.

While both EU-ETS for shipping and FuelEU Maritime are ultimately regional regulations of the EU, as one feature of these regulations, their application is not limited to coastal vessels operating only in EU waters, but also include other vessels that call at ports in the EU. Thus, these policies clearly show the intention of the EU to influence international shipping. Therefore, fuel selection based on an accurate understanding of the provisions of these EU regulations is strategically important for all ships engaged in EU-related voyages. The Society issues FAQs in a question-and-answer format, presenting an overview of the EU regulations and summarizing the preparations and procedures necessary to ensure compliance with those regulations.

2.4 Increasing GHG Emission Costs

Up to this point, this paper has explained the general framework of the new regulations of the IMO and EU. However, what is the estimated cost burden that will be imposed by these GHG emission regulations? As one example, Fig. 2 shows an image of the increase in the regulatory cost burden, using a 14 000 TEU containership as an example among containerships which are considered to have particularly large fuel consumption. Because the provisions of the IMO's mid-term measures have not been finalized, here, this discussion assumes that provisions similar to those of FuelEU Maritime are adopted. Since the IMO regulations are not limited to EU-related voyages, but are applicable to the GHG emissions of all voyages worldwide, the cost burden will be large in comparison with that of EU-related regulations. As reference, the figure shows the fuel cost calculated based on the average annual fuel consumption (23 000 tons) of a 14 000 TEU containership assuming USD 522.60/ton (USD13.0/GJ) as the price of conventional fuel oil. As is clear from these results, it is possible that the regulatory cost will reach a level that far exceeds the fuel cost, depending on the provisions of the IMO's mid-term measures. Since the purpose of the new GHG emission regulations of the IMO and EU is to promote the use of alternative fuels, in other words, a changeover from conventional fuel oil, setting a level that closes the price gap between high-priced alternative fuels and low-priced conventional fuel oil is only natural.

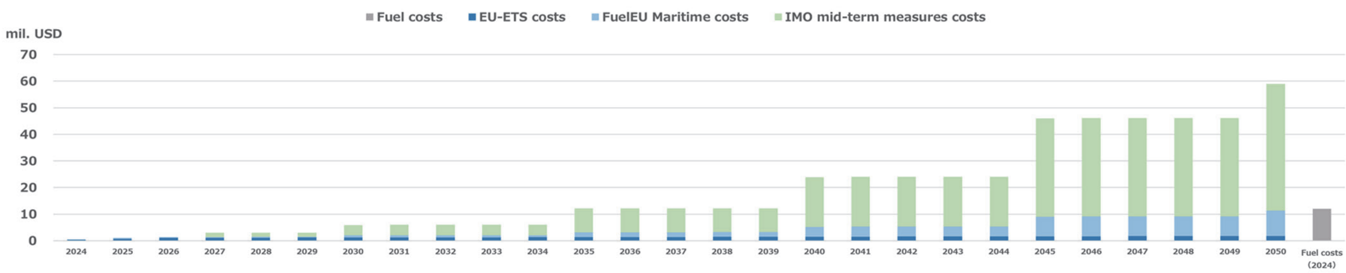

Fig. 2 Image of increasing GHG emission cost

3. UNDERSTANDING TRENDS

3.1 Trends in Adoption of Alternative Fuel Ships

After understanding GHG emission regulations, the next step is understanding trends in alternative fuels. Trends on the alternative fuel demand side impact the alternative fuel supply side, and both trends influence the availability and purchase price of alternative fuels.

In anticipation of future regulations, in international shipping, adoption of ships that can use alternative fuels is gradually increasing (hereinafter, these ships are called "alternative fuel ships"). This section and the following introduce the trends in the adoption of alternative fuel ships. It should be noted that the content introduced here is all based on information available at the end of June 2024. The subject of calculations of the total number of ships is ships with a gross tonnage of 5 000 tons and above, as these are the ships that will be subject to future IMO and EU GHG emission regulations. By limiting the subject ships to those having a gross tonnage of 5 000 tons and above, the intention is to accurately understand the trends in the vessels that will be subject to the regulations, and to accurately understand the effects of those regulations on the subject ships. The total numbers of alternative fuel ships do not include so-called alternative fuel-ready ships, which are either designed or already partially-equipped to use alternative fuels in the future. In actuality, alternative fuel-ready ships include a mix of various types, from ships in which only the design work for use of alternative fuels has been completed, to ships that are already partially-equipped for alternative fuels use. Because it would be difficult to accurately understand the possibility of converting these ships to alternative fuel ships, and also in order to avoid misunderstanding the trends in alternative fuel ships, those vessels are not included in the totals of alternative fuel ships. In addition, LNG carriers are not included in the total of LNG-fueled ships, which are one type of alternative fuel ship, because LNG carriers generally use cargo LNG as a fuel, and as a result, significant progress has already been made in the use of this alternative fuel in LNG carriers. Therefore, LNG carriers were excluded from the total number, and efforts were made to grasp the trends in the adoption of alternative fuels in ships other than LNG carriers.

3.2 Status of "Newbuilding" and "In Service" Alternative Fuel Ships

This section introduces the status of "newbuilding" and "in service" alternative fuel ships to date. Deliveries of alternative fuel ships increased rapidly from 2021 (Fig. 3). Compared with the 62 ships delivered in 2021, a total of 167 ships were delivered in 2023. By fuel, more than half were LNG-fueled ships. LNG fuel is superior to other alternative fuels in terms of development of infrastructure, fuel availability, purchase cost, etc. However, among ships scheduled for completion in and after 2024, methanol-fueled ships also have a significant share. Methanol fuel attracted attention as a result of orders for methanol-fueled ships placed by containership companies, as methanol is comparatively easy to handle onboard ships because it is a liquid at normal temperature and normal pressure. Looking at the total of alternative fuel ships scheduled for completion by 2026, when almost all orders in shipyards have been fixed, a cumulative total of 1 250 alternative fuel ships are forecast to be in service (Fig. 4).

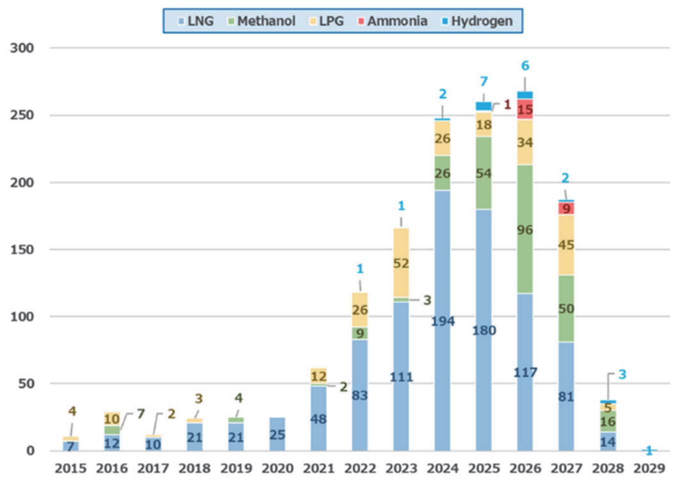

Fig. 3 Trend of newbuilding alternative fuel ships (totals by year)

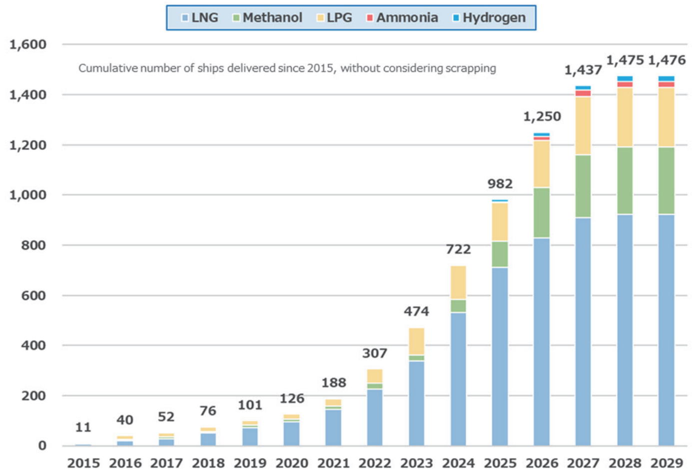

Fig. 4 Trend of in service alternative fuel ships (cumulative totals)

3.3 Trends in Shares of Alternative Fuel Ships

Although the number of alternative fuel ships is increasing continuously, what is their share in total international shipping? Fig. 5 shows the share of alternative fuel ships to all ships in service and their share in the orderbook. By number of ships, alternative fuel ships have a share of 1.7% of all ships in service, but have a share of 21.5% of the orderbook. Thus, adoption of alternative fuel ships is limited at present, but assuming full-scale enforcement of new GHG emission regulations in the future accompanying pricing of GHG emissions by the IMO and EU, rapid expansion of the adoption of alternative fuel ships can be expected in order to avoid the regulatory cost burden of continuing to use conventional fuel oil and the risk that the ships themselves may become "stranded assets."

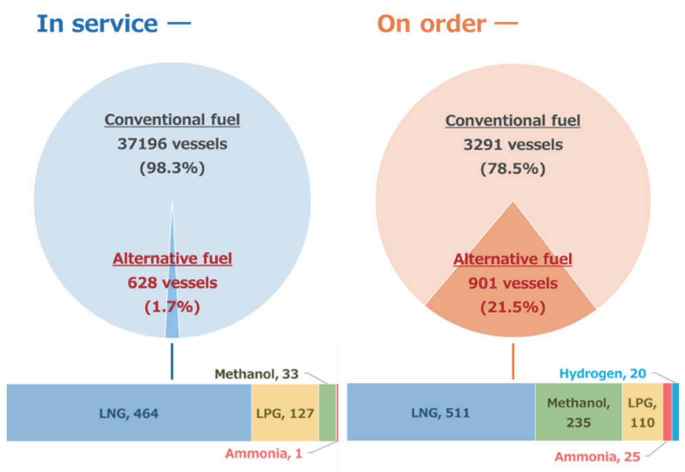

Fig. 5 Share of alternative fuel ships

3.4 Trends in "In Service" and "On Order" Alternative Fuel Ships (by Ship Type)

In order to understand the trends in alternative fuels, it is also important to understand the trends by ship type. Selection of fuel ships that go against the trends can be a high risk/high return investment. Looking at the trends by ship type, among all ships with the exception of LPG carriers, the largest number of ships in service is LNG-fueled ships (Fig. 6). In LPG carriers, adoption of LPG-fueled ships has expanded since the advent of LPG-fueled main engines. A certain number of in-service methanol-fueled ships can also be seen in the category of product/chemical tankers, because this category includes methanol carriers that transport methanol as a chemical product. Since some methanol carriers are equipped with methanol-fueled main engines which are capable of using methanol as a fuel, these vessels are methanol-fueled ships. Regarding alternative fuel ships on order, in comparison with the in-service status of alternative fuel ships, orders for methanol-fueled bulk carriers and vehicle carriers, and particularly containerships, are also increasing (Fig. 7). In addition, orders for ammonia-fueled ships can also be seen in some ship types.

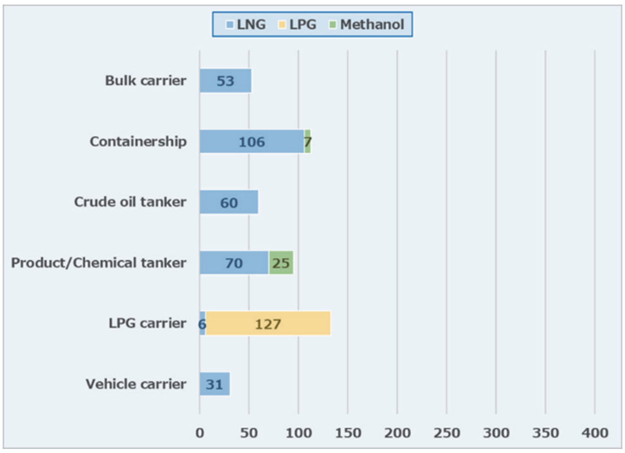

Fig. 6 Trends in alternative fuel ships in service (by ship type)

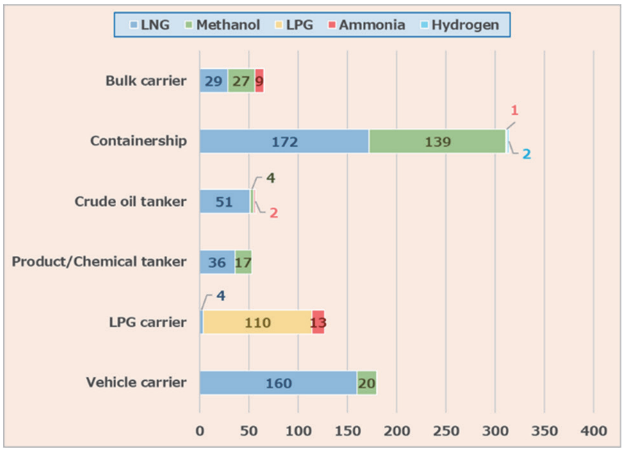

Fig. 7 Trends in alternative fuel ships on order (by ship type)

4. UNDERSTANDING ALTERNATIVE FUELS

4.1 Properties of Alternative Fuels

The step after understanding the trends in alternative fuels is understanding the alternative fuels themselves. It is only possible to select the most appropriate fuel after understanding not only their chemical characteristics as fuels, but also the differences in their emission factors as specified in regulations, costs, fuel supply-and-demand trends, etc. This section introduces the properties of each fuel. Table 1 presents a list summarizing the properties of the respective fuels.

Table 1 List of fuel properties (overview)

Fuel type	HFO	LNG (Methane)	LPG		Methanol	Ammonia	Hydrogen
			Propane	Butane			
TtW CO_2 emission [HFO = 1]	1	0.73	0.85	0.86	0.90	0	0
TtW GHG emission [HFO = 1]	1	0.82	0.85	0.86	0.92	0.04	0.01
Required to obtain the same amount of energy Fuel ton [HFO = 1]	1	0.84	0.87	0.88	2.02	2.16	0.34
In liquid form Fuel tank capacity [HFO = 1]	1	1.89	1.69	1.41	2.47	3.07	4.63
Flammability (Lower Explosive Limit)	0.7 vol%	5.0 vol%	2.1 vol%	1.8 vol%	6.0 vol%	15.0 vol%	4.0 vol%
Toxicity (TLV-TWA*)	-	-	-		200 ppm	25 ppm	-
Cyrogenic (Boiling point)	- (Liquid at normal temp.)	-161℃	-42℃	-0.5℃	- (Liquid at normal temp.)	-33℃	-253℃

The CO_2 emissions and GHG emissions in Table 1 were calculated based on the emission factors given in the FuelEU Maritime regulation of the EU. TtW is an abbreviation of Tank-to-Wake and means the emission when the fuel is used (burned) onboard a ship. Regarding CO_2 emissions, LNG (methane), LPG and methanol have limited CO_2 reduction effects, but substantial reductions can be expected with ammonia (NH_3) and hydrogen (H_2), as these fuels do not contain the carbon (C) which is the source of CO_2. As for GHG emissions, the GHG reduction effect of LNG is more limited than its CO_2 reduction effect because the regulations recognize the existence of "methane slip," i.e., discharges of unburned methane, when LNG (methane) is burned. Methane is a potent GHG, and is estimated to have a 30 times larger greenhouse effect than CO_2.

Due to differences in energy density per unit weight, the necessary weight (tons) of some alternative fuels is larger than that of conventional fuel oil (in Table 1, conventional fuel oil is listed as HFO). By weight ratio to HFO, an amount (tons) of methanol 2.02 times greater and an amount of ammonia 2.16 times greater than that of HFO is needed to obtain the same energy as HFO. Therefore, it should be noted that direct comparison of fuel prices based solely on a per-ton basis is misleading.

Since the volumetric energy density of alternative fuels is also different, the volume of fuel tanks for alternative fuels may also be larger than the volume for conventional fuel oil. In comparison with conventional fuel oil, the fuel tank size necessary to obtain the same energy as conventional fuel oil is 1.89 times that of conventional fuel oil for LNG, but is larger by 2.47 times for methanol, 3.07 times for ammonia and 4.63 times for hydrogen. This will depend on the design, but this increased fuel tank capacity may make lead to the reduction of cargo space; conversely, keeping the same fuel tank capacity or reducing tank capacity may require an increase in refueling when using alternative fuels.

Regarding combustibility, as a particular feature of ammonia, ammonia does not explode when its concentration in the atmosphere is not 15.0 vol% or more. This means it is less explosive than the other alternative fuels.

Where toxicity is concerned, both methanol and ammonia are toxic. In particular, ammonia is considered to have an adverse effect on human health in case of repeated exposure, even at comparatively low concentrations, and high toxicity is a concern.

4.2 Emission Factors of Alternative Fuels

When studying the introduction of alternative fuels, an accurate understanding of their respective emission factors is necessary. The emission factor is directly linked to the GHG emission cost. It is important to note that the emission factors used in each regulation may be different. Fig. 8 shows the emission factors per unit of energy for each fuel, calculated based on the emission factors given in the EU's FuelEU Maritime regulations. As noted above, in order to compare the GHG emissions of various fuels on an equal basis, the fuels must be compared per unit of energy, and not per unit of weight.

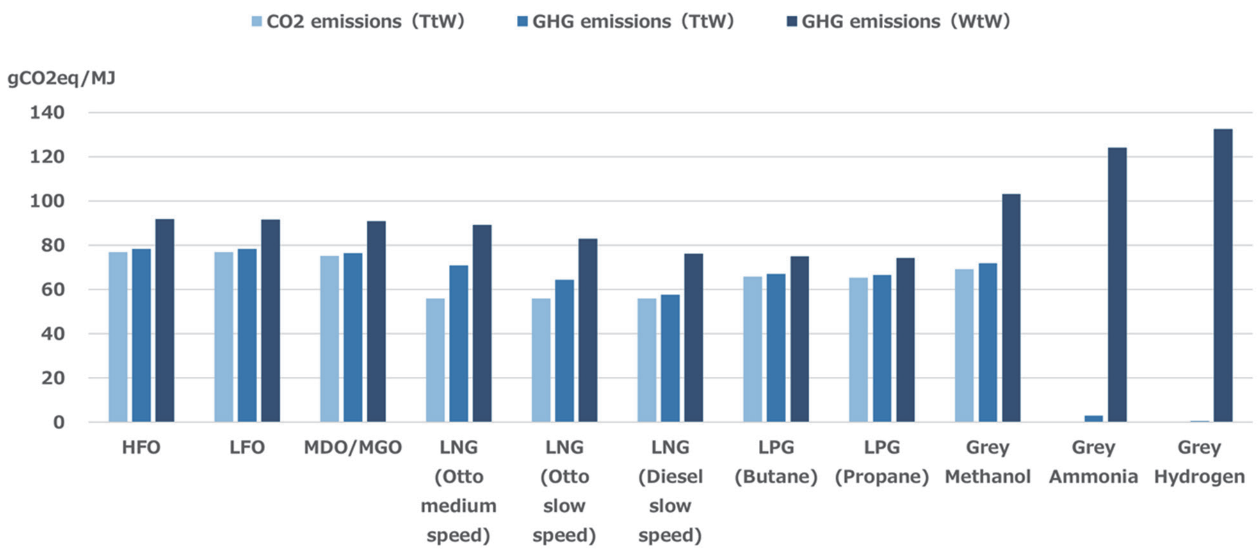

Fig. 8 Emissions per unit of energy

TtW is the abbreviation of Tank-to-Wake and means the emissions during use (during combustion) of the fuel onboard a ship. WtW is the abbreviation of Well-to-Wake and means the emissions during the entire lifecycle from production of the fuel until use (combustion) onboard a ship. In order to understand the GHG emission cost, in addition to the differences in the emission factors under various regulations, it is also important to recognize the scope of the emissions (TtW or WtW) that are the target of the regulations. For example, under EU-ETS for shipping, the target is CO_2 emissions in the TtW, and after 2026, GHG emissions in the TtW. However, the target of FuelEU Maritime is GHG emissions in the WtW. Moreover, there is a high possibility that the scope of the IMO's mid-term measures will also be GHG emissions in the WtW. However, this is undecided at present, and discussions on the emission factors to be used in the mid-term measures are continuing. Because the regulatory advantages and disadvantages of the various fuels differ greatly depending on the scope of the emissions, it is necessary to conduct a careful study of the fuel to be introduced and the timing of introduction, while considering these differences in the emission factors.

4.3 Alternative Fuel Costs

When studying the introduction of alternative fuels, understanding the cost of each alternative fuel is indispensable. Fig. 9 shows the projected costs of the various alternative fuels as of 2030, together with the production pathways. However, it is necessary to note that the cost will vary depending on actual supply and demand.

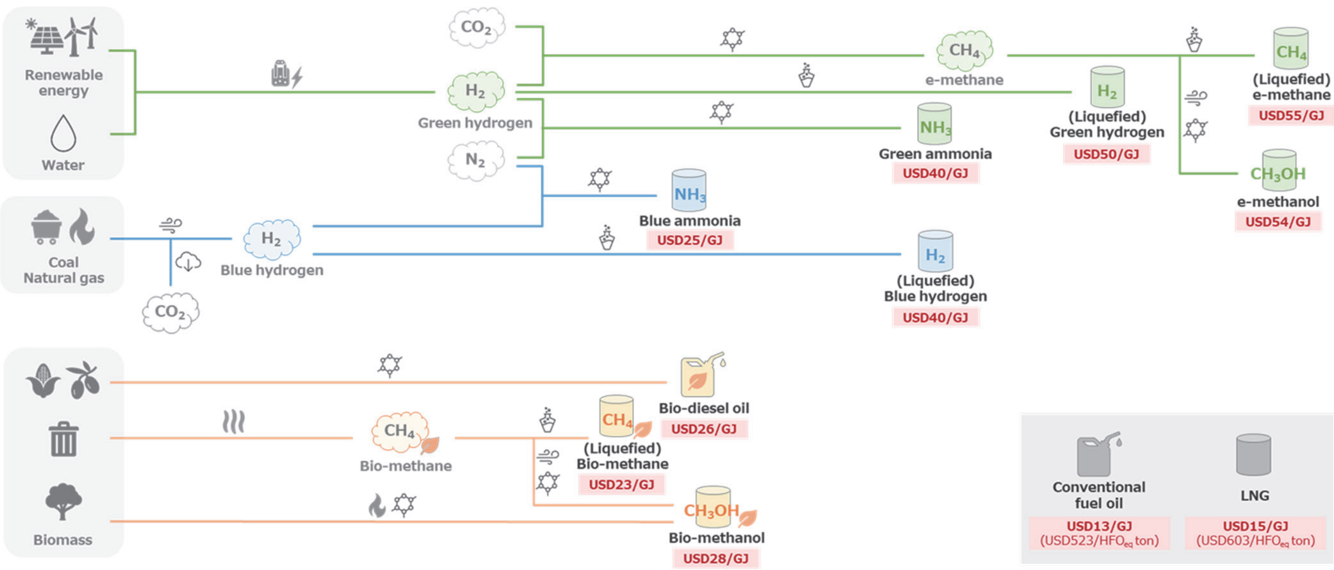

Fig. 9 Production pathways and costs of alternative fuels

With the exception of hydrogen, the alternative fuels that presumably will be used in international shipping are compounds of two or more chemical elements. Accordingly, the alternative fuels are basically produced by combining their component elements. Ammonia (NH_3) and hydrogen (H_2) are considered to be zero-emission fuels because they do not contain carbon and therefore do not emit CO_2. On the other hand, methane (CH_4), methanol (CH_3OH) and other compounds that contain carbon atoms emit CO_2 when burned. Limited to cases where these compounds are produced by capturing underlying carbon including CO_2 "from animal or vegetable materials (biomass)" or "by artificial recovery (direct air capture; DAC)" of the carbon that forms the base of the fuel, the CO_2 balance in the atmosphere is zero, and the fuels are regarded as carbon-neutral fuels. In other words, some type of carbon circulation is necessary.

Alternative fuels are broadly divided into three types, depending on the fuel production method. The first type is produced from green hydrogen extracted from water by using electricity derived from renewable energy. These are so-called e-fuel, which is an abbreviation of electrofuel. The second type is produced from gray hydrogen, which is extracted from fossil fuels, and the CO_2 emissions associated with production must be captured and stored. This type is called blue fuel. The third type is so-called biomass-derived fuel which is produced from carbon and hydrogen extracted from animal or vegetable materials (biomass).

The cost of alternative fuels is controlled by the cost of extracting hydrogen and/or carbon. The cost of extracting hydrogen from water using electricity generated by renewable energy is higher than the cost of extraction from fossil fuels, and extraction of carbon by direct air capture is more expensive than extraction from biomass. As a result, the cost of e-fuels produced from green hydrogen is the highest, and the cost of blue fuel and biomass-derived fuel is relatively low. However, in the case of biomass, there are resource-related constraints on the supply of biomass itself, so fuel availability requires particular attention.

4.4 Demand for Alternative Fuels

In this section, this paper will introduce demand for alternative fuels. Trends on the alternative fuel demand side affect the fuel supply side, and trends in supply and demand affect the availability and purchase price of alternative fuels.

4.4.1 Fuel Consumption in International Shipping

The first step toward understanding the demand outlook for alternative fuels is understanding the current consumption of alternative fuels in international shipping. Reporting of actual data on fuel consumption in international shipping by the IMO began in 2019. The IMO requires collection and reporting of data on the fuel consumption, etc. of ships with gross tonnages of 5 000 tons and above engaged in international voyages, which are the object of this system. When the Society calculated the total fuel consumption in international shipping based on the statistical values of the data released by the IMO [1], total fuel consumption (in 2023) was 216 million tons (by HFO conversion) (Table 2). In other words, to achieve net-zero CO_2 emissions in 2050, it will be necessary to replace 216 million tons of energy with alternative fuels in the coming years. While there may be increases and decreases due to future increases in maritime transport volume and improvement in energy efficiency, for example, converting all of this 216-million-tons of HFO to methanol would require 440 million tons of methanol, and conversion to ammonia would require 470 million tons of ammonia.

Table 2 Fuel consumption in international shipping (unit: tons)

	Heavy Fuel Oil (HFO)	Light Fuel Oil (LFO)	Diesel/Gas Oil (MDO/MGO)	LNG	LPG (Propane)	LPG (Butane)	Methanol	Ethanol	Other	Total (HFO eq)
2021 (28,171 ships) (1.25 bn GT)	109,169,447	64,479,128	25,732,999	12,623,121	34,973	2,028	13,031	4,849	170,501	217,710,495
2022 (28,834 ships) (1.29 bn GT)	116,576,283	57,077,835	28,285,802	10,950,408	88,774	16,673	35,523	10,890	226,739	218,339,992
2023 (28,620 ships) (1.30 bn GT)	130,441,745	40,416,174	26,600,016	12,890,011	192,405	49,887	93,876	4,137	428,263	215,833,384

4.4.2 Demand Outlook for Alternative Fuels

As mentioned above, the amount of alternative fuels necessary in international shipping in the future is huge, but realistically, supplies are gradually increasing, in line with the pace of increasing demand for alternative fuels. Fig. 10 shows the future outlook for the pace of increasing demand for alternative fuels based on the orderbooks for alternative fuel ships. This figure also includes demand for LNG fuel by LNG carriers. It is assumed that alternative fuel ships (dual-fueled ships) delivered after 2024 will use only alternative fuels, and use of a pilot fuel (conventional fuel oil) when using alternative fuels is not assumed. In other words, the demand outlook shown here is the maximum demand outlook for alternative fuels in international shipping. The actual amount of alternative fuel usage will be adjusted considering the price difference between alternative fuels and conventional fuel oil.

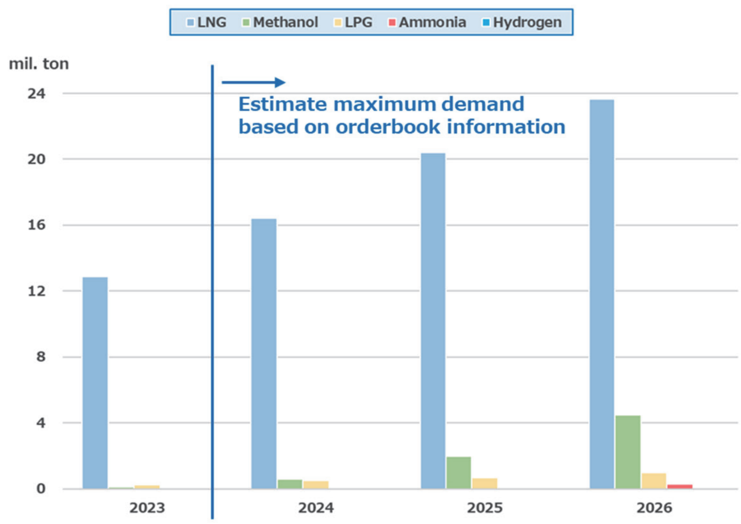

Fig. 10 Maximum demand outlook for alternative fuels

For LNG fuels, peak demand of 24 million tons in 2026 is forecast, based on mass delivery of LNG-fueled ships. Demand for methanol fuels is expected to peak at 4.5 million tons in 2026 as a result of successive deliveries of methanol-fueled ships, especially containerships. Peak demand for LPG fuel will be limited to 1 million tons in 2026, because the only type of ship that is currently expected to use LPG is LPG carriers. At present, the assumed demand for ammonia fuel and hydrogen fuel is limited, but increased demand is anticipated in the future when the development of ammonia- and hydrogen-fueled ships is complete.

4.5 Supply of Alternative Fuels

A stable supply of alternative fuels is indispensable for reducing GHG emissions from international shipping. This section introduces the future outlook for the production capacities of various fuels, which were calculated based on information in the Hydrogen Production Projects Database [2)] published in October 2023. This paper focuses on green hydrogen, green ammonia, green methanol and green methane. Green hydrogen is produced by electrolysis of water using electricity derived from renewable energy, and is a fuel with very low GHG emissions through the entire lifecycle from production through use (combustion) onboard ships. Similarly, green ammonia, green methanol and green methane produced from green hydrogen also have very low lifecycle GHG emissions or are carbon neutral. Because these kinds of green hydrogen-derived fuels will be cost-competitive under the future regulations of the IMO and EU, increasing demand is anticipated. However, since the fuel suppliers in the production projects tabulated here are not limited to the maritime shipping sector, it should be noted in advance that the supply outlook for international shipping is unclear.

4.5.1 Projected Production Capacity of Green Hydrogen

The projected production capacity of green hydrogen (all sectors) is total annual production of about 49 million tons (Fig. 11) in 2040, including the projects with the most delayed startup dates among those publicly announced. However, the actual feasibility of these projects is unclear, since the majority are currently in the conceptual or feasibility study stages. Fig. 12 shows the projected green hydrogen production capacity in 2040 by country/region. In addition to Europe, a certain number of projects are also planned for South America and Australia, which are considered to be suitable areas for green hydrogen production owing to their abundant renewable energy resources.

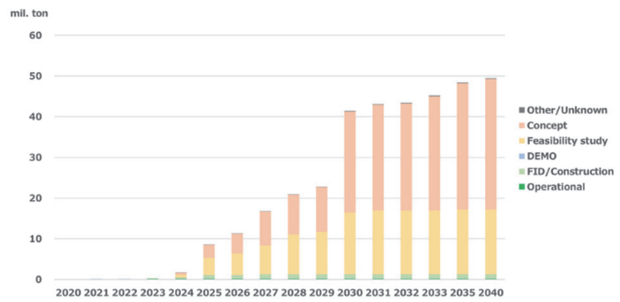

Fig. 11 Green hydrogen production capacity (by year)

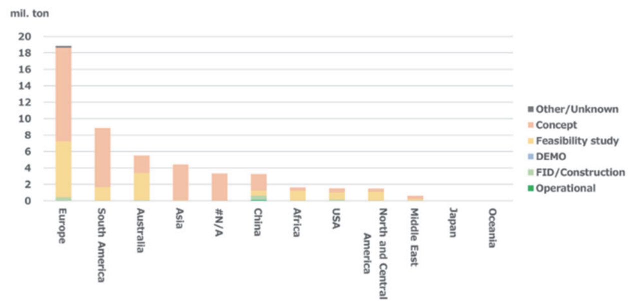

Fig. 12 Green hydrogen production capacity (by country/region)

4.5.2 Projected Production Capacity of Green Ammonia

The projected production capacity of green ammonia is a total annual production of about 220 million tons in 2043, including the projects with the most delayed startup dates among those publicly announced (Fig. 13). Comparatively large demand for ammonia is foreseen, as ammonia is expected to play the roles of an alternative fuel for coal-fired thermal power plants and use as a hydrogen carrier, and a large number of production projects are underway to meet that demand. However, since the majority of projects are still in the conceptual or feasibility study stages, their actual feasibility is unknown. Fig. 14 shows the projected green ammonia production capacity in 2043 by country/region. Many projects are located in Australia, Africa, etc.

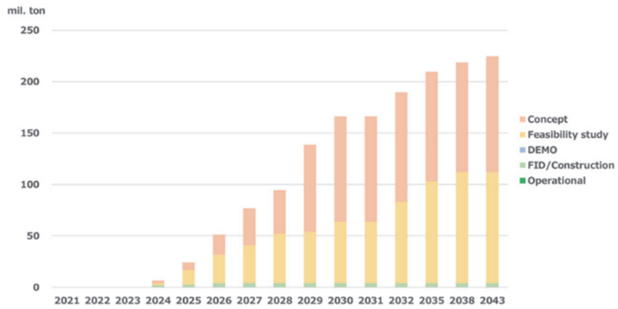

Fig. 13　Green ammonia production capacity (by year)

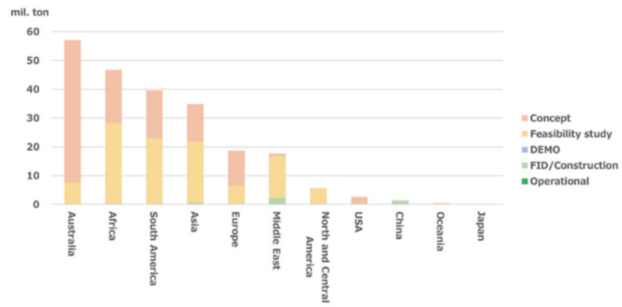

Fig. 14　Green ammonia production capacity (by country/region)

4.5.3　Projected Production Capacity of Green Methanol

The projected production capacity of green methanol is total annual production of about 5 million tons (Fig. 15) in 2030, including the projects with the most delayed startup dates among those publicly announced. Because the majority of projects are currently in the conceptual or feasibility study stages, their actual feasibility is unknown. Fig. 16 shows the projected production capacity of green methanol in 2030 by country/region. Many projects are located in Europe or the United States.

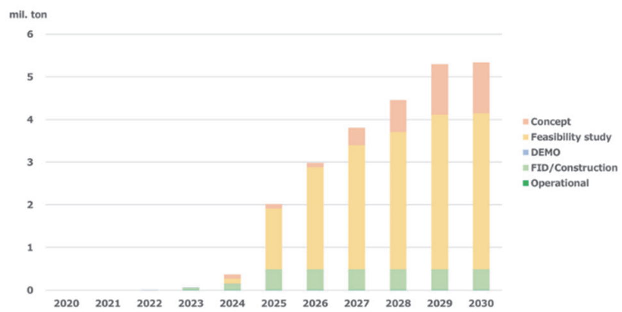

Fig. 15　Green methanol production capacity (by year)

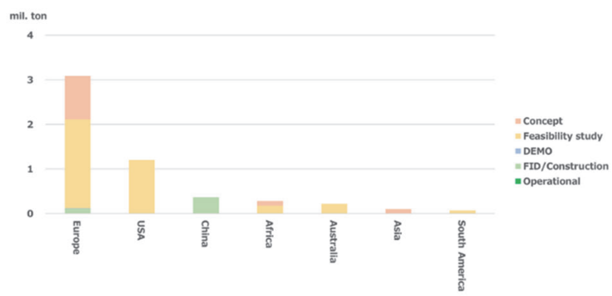

Fig. 16　Green methanol production capacity (by country/region)

4.5.4 Projected Production Capacity of Green Methane

The projected production capacity of green methane is total annual production of about 900 000 tons (Fig. 17) in 2030, including the projects with the most delayed startup dates among those publicly announced. Because the majority of projects are currently in the conceptual or feasibility study stages, their actual feasibility is unknown. Fig. 18 shows the projected production capacity of green methanol in 2030 by country/region. Many projects are located in Europe or the United States.

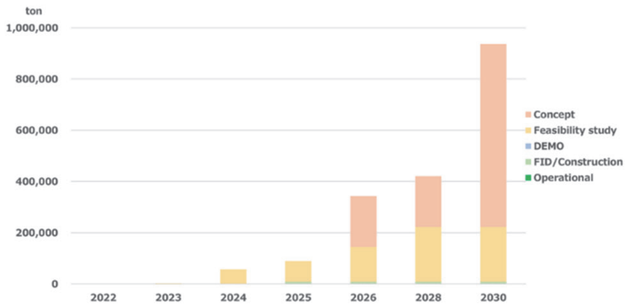

Fig. 17 Green methane production capacity (by year)

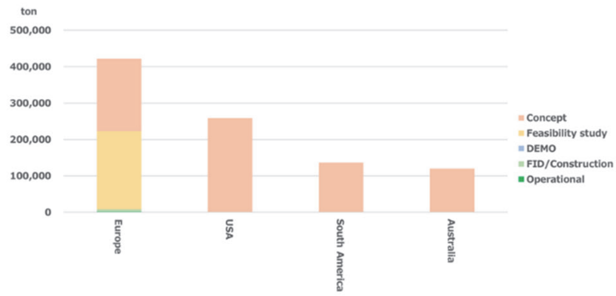

Fig. 18 Green methane production capacity (by country/region)

5. UNDERSTANDING COSTS

5.1 Cost Simulations

The final step is understanding the total cost of introducing alternative fuels. Although there are various ship-related costs, the costs that will be particularly affected by the introduction of alternative fuels are “Shipbuilding costs,” “Fuel costs” and “Regulatory costs.” As mentioned previously, future regulatory costs consist of the costs associated with the EU’s EU-ETS for shipping and FuelEU Marine and the IMO’s mid-term measures.

Introduction of alternative fuels will increase Shipbuilding costs and Fuel costs, but will decrease Regulatory costs. When introducing alternative fuels, it should be aimed for a timely transition from conventional fuel oil, based on a full discussion and sharing of the changes in the structure of these costs among stakeholders.

5.2 Example of Cost Simulation

The Society carries out cost simulations of the transition from conventional fuel ships to alternative fuel ships in order to support fuel selection. As an example of a simulation, this section introduces the results of a simulation of “Adoption of conventional fuel ship” vs. “Adoption of ammonia-fueled ship” for a 64 000 DWT bulk carrier.

Fig. 19 shows the results of a comparison of the total cost by year for the cases of “Adoption of conventional fuel ship” (vertical bars on left) and “Adoption of ammonia-fueled ship” (vertical bars on right). As costs, here, only “Shipbuilding costs,” “Fuel costs” and “Regulatory costs” are considered. Because the IMO’s mid-term measures have not been finalized, the simulation assumes the case in which regulatory provisions similar to those of FuelEU Maritime are adopted in the IMO’s mid-term measures. Assuming delivery of the ship in 2031 and a life of 20 years, i.e., until 2050, Shipbuilding costs are amortized over that 20-year period. As fuel prices, for the Conventional fuel ship, the price of Heavy Fuel Oil (HFO) is constant at USD 522.60/ton (USD 13.00/GJ) over the 20-year period, assuming that the Conventional fuel ship will use only HFO. The Ammonia-fueled ship is a dual-fuel ship and can use both HFO and e-ammonia. It is assumed that the price of e-ammonia will decrease linearly from USD 723.80/ton (USD 38.90/GJ) to USD 366.20/ton (USD 19.70/GJ) in 2050. Therefore, the fuel is selected so as to minimize the annual cost, considering the relative differences of "Regulatory cost of using HFO (continuously increasing)" and "Fuel cost of using e-ammonia (continuously decreasing)." On these assumptions, the annual cost of the Ammonia-fueled ship is reduced by continuing to use HFO until 2039 (Fig. 19). In other words, it is more advantageous to use HFO than expensive e-ammonia, even considering the regulatory costs of using HFO. Furthermore, from 2040, when the fuel cost of e-ammonia has decreased sufficiently, selection of e-ammonia results in a more decrease in annual costs than that of HFO.

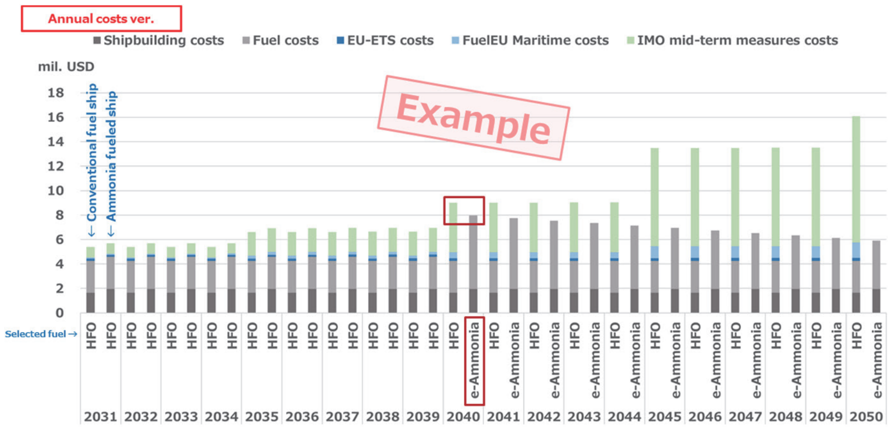

Fig. 19　Results of cost simulation (annual costs)

Fig. 20 shows the results of the simulation in Fig. 19 expressed as the cumulative total of the annual costs until 2050. When the results are expressed as cumulative costs, it is possible to understand when the crossover point between the cumulative costs of adopting the Conventional fuel ship and adopting the Ammonia-fueled ship occurs and its timing. Naturally, it is also possible to understand the difference between lifetime total costs. In this example, it can be understood that the cost difference between the adoption of Conventional fuel ship and the adoption of Ammonia-fueled ship is approximately USD 50 million over the 20-year life of the ship. This cost difference is large enough to purchase another bulk carrier of the same size, with change left over. Although the actual results will depend on the provisions of the IMO's mid-term measures and the various assumptions used in the simulation, it can be said that the results of this simulation suggest how heavy the cost burden of future regulations will be.

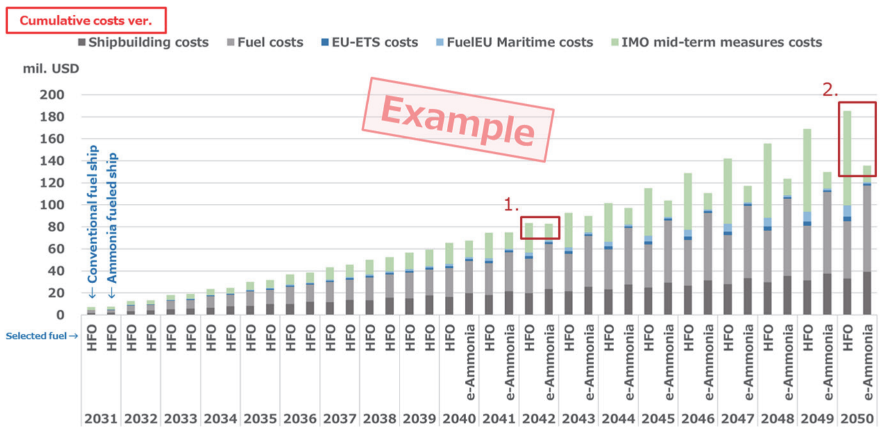

Fig. 20　Results of cost simulation (cumulative costs)

6.　CONCLUSION

To assist readers in understanding the contents of "ClassNK Alternative Fuels Insight," which is issued by ClassNK, this paper has introduced the trends in alternative fuels, as increased use of these fuels will be indispensable for responding to the future regulations of the IMO and EU. At present, the estimated supplies of alternative fuels are insufficient to meet the expected demand in international shipping. To further increase production of alternative fuels, it is essential to send clear signals of demand to the supply side. Naturally, promotion of the use of alternative fuels through regulatory mechanisms will be necessary for this, but demand creation by cooperation among various stakeholders, not limited to the maritime sector, are also essential. It is my sincere hope that this paper will be of assistance when studying initiatives to expand the use of alternative fuels in the shipping industry.

REFERENCES

1) Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2023)
2) IEA (2023), Hydrogen Production Projects Database

IMO Guidelines on Life Cycle GHG Intensity of Marine Fuels

Ryuji MIYAKE*

1. INTRODUCTION

As part of efforts to reduce GHG emissions, the International Maritime Organization (IMO) has focused on improvement of the energy efficiency of individual ships from the viewpoint of satisfying both GHG reduction and economic development and has implemented EEDI (Energy Efficiency Design Index) as a fuel consumption regulation for ship design and SEEMP (Ship Energy Efficiency Management Plan) as a fuel consumption regulation for ship operation since 2013. Furthermore, the IMO adopted Initial IMO GHG Strategy to reduce the GHG emissions from international shipping in 2018. As short-term measures of the GHG Strategy, EEXI (Energy Efficiency Existing Ship Index) and CII (Carbon Intensity Indicator) rating have been also begun since 2023. At MEPC 80 held in July 2023, the GHG Strategy was revised and set an enhanced common ambition to reach net-zero GHG emissions from international shipping by or around, i.e. close to 2050. While the Initial IMO GHG Strategy focused on only GHG emissions from onboard ships, referred to as Tank-to-Wake, as shown in Fig. 1, the revised IMO GHG Strategy considers GHG emissions over the whole life cycle of the fuel used by a ship, referred to as Well-to-Wake. Since GHG emissions from onboard ships are allocated to international shipping, but GHG emitted onshore during the production and distribution of marine fuel are allocated to the country, GHG emission regulations in the IMO such as EEDI/EEXI, DCS and CII ratings have so far focused only on CO_2 emitted from ships. On the other hand, even next generation fuels such as ammonia and hydrogen, e.g. hydrogen produced using electricity generated from fossil fuels, have higher GHG emissions during electricity generation and therefore have higher GHG emissions than heavy fuel oil over their whole life cycle, as shown in Fig. 2. Therefore, in the revised IMO GHG Strategy, the GHG reduction target was also changed the GHG emissions from ships to the whole life cycle of the fuels. In the European Union (EU), the FuelEU Maritime Regulation on the life cycle GHG intensity of marine fuels will come into force in 2025. In addition, the International Civil Aviation Organization (ICAO) adopted a long-term decarbonization target of achieving carbon neutrality across the whole life cycle by 2050 at the 41st ICAO General Assembly. With the IMO changing its GHG reduction target from onboard emissions to whole life cycle emissions, for example, fossil-based LNG fuel will improve onboard emissions by about 18-26% compared to heavy fuel oil, but only by about 10-17% compared to heavy fuel oil over its whole life cycle due to the impact of liquefaction, and the benefits are significantly reduced. In addition, to achieve net-zero emissions over the whole life cycle, all ships need to use blue or green fuel, which is highly dependent on the availability of blue or green fuel.

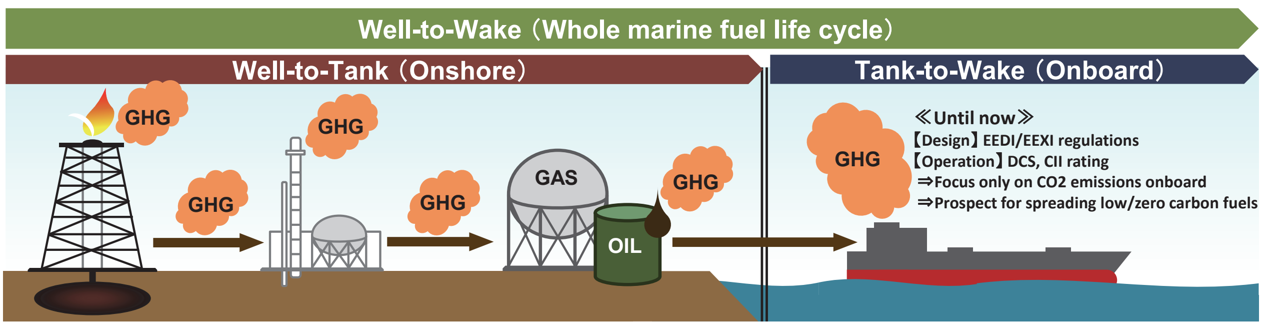

Fig. 1 Diagram of GHG emissions over the life cycle of marine fuels

With the reduction target in the revised IMO Strategy was changed from onboard emissions to the whole life cycle emissions reduction, IMO adopted the “GUIDELINES ON LIFE CYCLE GHG INTENSITY OF MARINE FUELS” [1] at MEPC 80 held in July 2023. On the other hand, as there were many issues in the Guidelines, a Correspondence Group (CG) on LCA of marine

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fuels was established, and discussions in the CG were made on the review of the data collection template for establishing default emission factors, examination of proposed default emission factors, carbon resulting from the LUC (Land-Use Change), methane leakage, credits from use of captured CO_2 as carbon stock to produce synthetic fuels, credits from onboard carbon capture and storage etc. At MEPC 81 held in March 2024, on the basis of the draft amendments [2] proposed by the CG, the amendments (the detailed evaluation method and quantification of parameters for GHG emissions from biofuel production, GHG intensity for electricity used during fuel production, evaluation method for onboard GHG emissions, etc.) to the Guidelines were made and adopted as the "2024 GUIDELINES ON LIFE CYCLE GHG INTENSITY OF MARINE FUELS" [3] (hereafter referred to as the "LCA Guidelines"). In this paper, the LCA Guidelines are explained with up-to-date information.

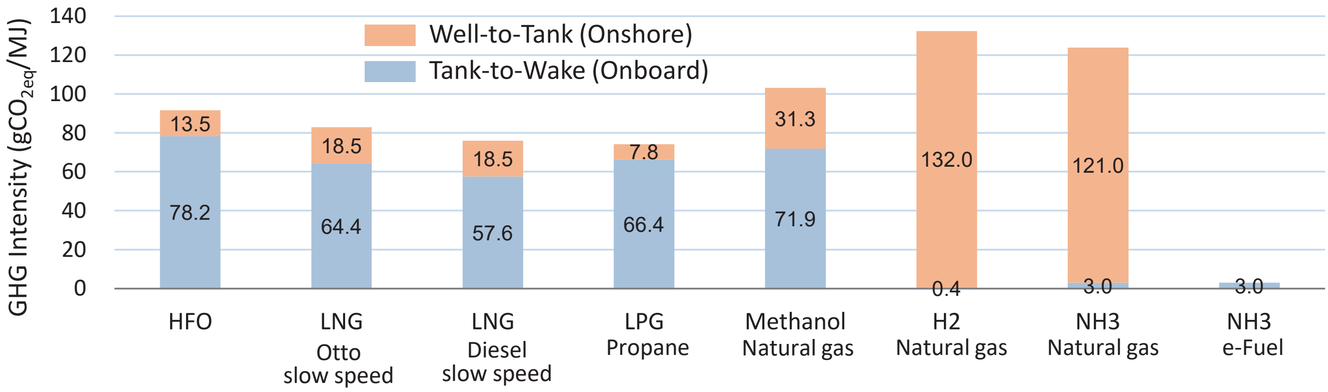

Fig. 2　Examples of GHG intensities of marine fuels [4]

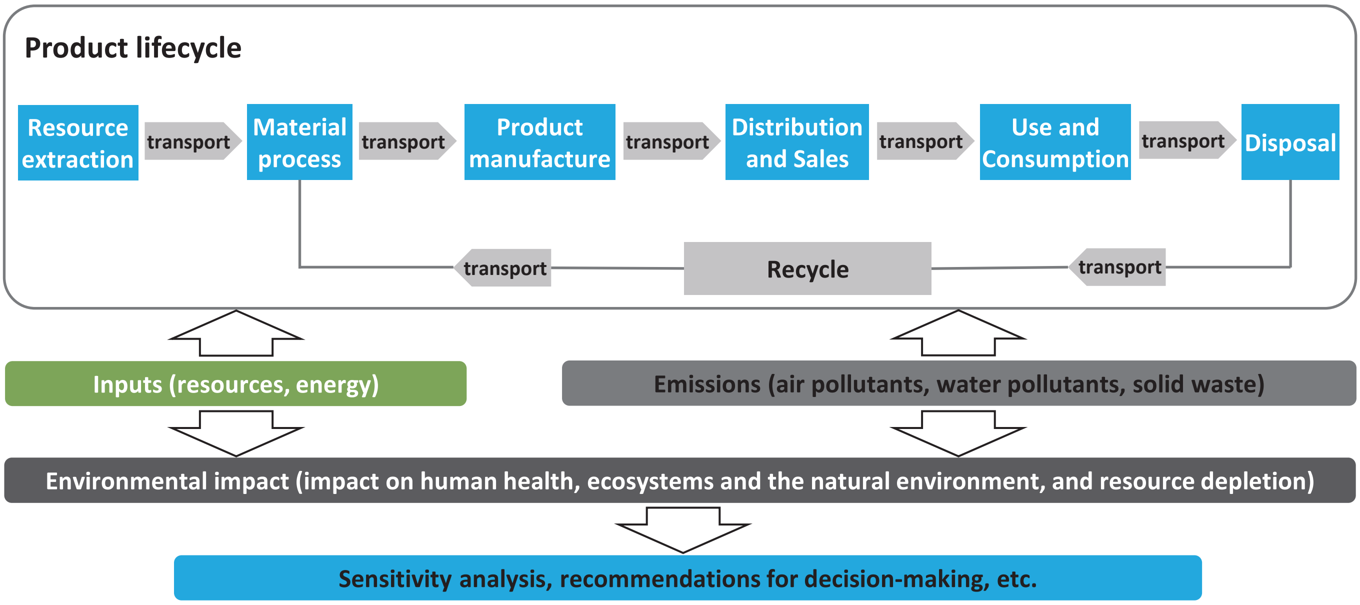

Fig. 3　Concept of Life Cycle Assessment (LCA) [5]

2. GUIDELINES ON LIFE CYCLE GHG INTENSITY OF MARINE FUELS

The LCA Guidelines consist of three main components: (i) a methodology for assessing GHG emissions throughout the whole life cycle of marine fuels from production to transport and onboard use; (ii) a theme/aspect of sustainable marine fuels on a life cycle basis (sustainability criteria); and (iii) verification and certification.

Life cycle assessment (LCA) is generally a method for quantitatively assessing the environmental impact of a product or service over its whole life cycle and has been standardized by the International Organization for Standardization (ISO). The details are as follows.

◇ LCA is a method that can provide scientific and objective evidence to support decision-making for environmental improvement, etc. by quantitatively grasping the amount of resource or energy input and the amount of various emissions at each stage in the whole life cycle of a product or service, from acquisition of feedstock to processing, distribution, use, disposal and recycling (inventory analysis), and further quantifying the various environmental impacts or impacts on resource or energy depletion that these have, etc. as much as possible (impact assessment).

◇ With the increase in the number of cases of life cycle assessment implementation, ISO decided that it would be desirable to establish a common basis for such assessments and standardized the assessment methodology. The methodology for conducting LCA is specified in ISO 14040:2006 and ISO 14044:2006, ISO 14040:2006 specifies the principles and framework for LCA and ISO 14044:2006 specifies the technical requirements and guidelines for LCA.

2.1 Assessment of GHG Emissions over Life Cycle of Marine Fuels

The LCA Guidelines define GHG emissions from feedstock extraction to processing, fuel production, transport and bunkering as Well-to-Tank, onboard GHG emissions as Tank-to-Wake, and GHG emissions over the whole life cycle as Well-to-Wake, as shown in Fig. 4. The GHG emissions over the whole life cycle are assessed by adding up the GHGs emitted in each process, and methane slip and N_2O are also considered. Furthermore, an assessment range (system boundary) is set according to the pathway, such as transport and storage of recovered CO_2, and the GHG intensity, i.e. the GHG emissions per unit of energy, is used to assess GHG emissions as shown in equation (1).

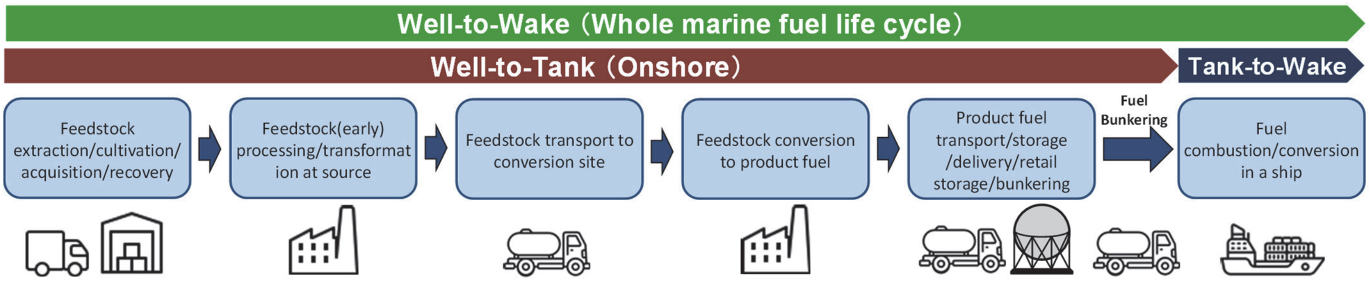

Fig. 4 An example of life cycle supply chains for marine fuels

$$GHG_{WtW} = GHG_{WtT} + GHG_{TtW} \quad (1)$$

GHG_{WtW}	$gCO_{2eq}/MJ_{(LCV)}$	GHG emissions per unit of energy over the whole life cycle of fuel from production to transport and onboard use
GHG_{WtT}	$gCO_{2eq}/MJ_{(LCV)}$	GHG emissions per unit of energy upstream of the fuel life cycle (e.g. extraction, processing, and transport of feedstock)
GHG_{TtW}	$gCO_{2eq}/MJ_{(LCV)}$	GHG emissions per unit of energy downstream of the fuel life cycle (onboard use)

2.2 Methods for Calculating GHG Intensity

In the LCA Guidelines, the GHG intensity of the Well-to-Tank, i.e. the GHG intensity on onshore, is calculated using equation (2), which calculates the GHG emitted from the extraction of feedstock to production, transport, and bunkering. However, emissions related to carbon stock changes caused by direct land-use change and soil carbon accumulation via improved agricultural management are assumed to be zero until a calculation method is established, and these cannot currently be considered. On the other hand, blue fuel with CCS can be considered, as the equation (2) considers CCS on onshore. Furthermore, GHG intensity of Tank-to-Wake, i.e. GHG intensity on board, is calculated using equation (3), which can also consider methane and N_2O emitted during fuel combustion, as well as methane leaked between the fuel tank and the engine. However, methane leaked between the fuel tank and the engine cannot currently be considered, as it is assumed to be zero until further technical work determines an appropriate factor. In onboard emissions, GHG reductions from biofuels can be considered, but synthetic fuels and onboard CCS cannot currently be considered, as their reductions are assumed to be zero until their treatment has been established.

$$GHG_{WtT} = e_{fecu} + e_l + e_p + e_{td} - e_{sca} - e_{ccs} \quad (2)$$

e_{fecu}	Emissions associated with the feedstock extraction/cultivation/acquisition/recovery	
e_l	Emissions (annualized emissions (over 20 years) from carbon stock changes caused by direct land-use change) **Pending further methodological guidance to be developed by the Organization, the value of parameter e_l should be set to zero.**	
e_p	Emissions associated with the feedstock processing and/or transformation at source and emissions associated with the conversion of the feedstock to the final fuel product, including electricity generation	
e_{td}	Emissions associated with the feedstock transport to conversion plant, and the emissions associated with the finished fuel transport and storage, local delivery, retail storage and bunkering	
e_{sca}	Emissions (annualized emission savings (over 20 years) from soil carbon accumulation via improved agricultural management) **Pending further methodological guidance to be developed by the Organization, the value of parameter e_{sca} should be set to zero.**	
e_{ccs}	Emissions credit from carbon capture and storage (e_{ccs}), that have not already been accounted for in e_p. This should properly account the avoided emissions through the capture and sequestration of emitted CO_2, related to the extraction, transport, processing and distribution of fuel (c_{sc}). From the above-mentioned emission credit, all the emissions resulting from the process of capturing (e_{cc}) and transporting (e_t) the CO_2 up to the final storage (including the emissions related to the injection, etc.) need to be deducted. This element should be calculated with the following formula: $e_{ccs} = c_{sc} - e_{cc} - e_t - e_{st} - e_x$	
	c_{sc}	Emissions credit equivalent to the net CO_2 captured and stored (long-term: 100 years)
	e_{cc}	Emissions associated with the process of capturing, compression and/or cooling and temporary storage of the CO_2
	e_t	Emissions associated with transport to a long-term storage site
	e_{st}	Any emissions associated with the process of storing (long-term: 100 years) the captured CO_2 (including fugitive emissions that may happen during long-term storage and/or the injection of CO_2 into the storage)
	e_x	Any additional emissions related to the CCS

$$GHG_{TtW} = \frac{1}{LCV}\left\{\begin{array}{l}\left(\left(1-\frac{1}{100}\left(C_{slip\_ship}+C_{fug}\right)\right)\times\left(C_{fCO_2}\times GWP_{CO_2}+C_{fCH_4}\times GWP_{CH_4}+C_{fN_2O}\times GWP_{N_2O}\right)\right)\\ +\left(\frac{1}{100}\left(C_{slip\_ship}+C_{fug}\right)\times C_{sfx}\times GWP_{fuelx}\right)-S_{Fc}\times e_c-\left[S_{Fccu}\times e_{ccu}\right]-\left[e_{OCCS}\right]\end{array}\right\} \quad (3)$$

C_{slip_ship}	Factor accounting for fuel (expressed in % of total fuel mass delivered to the ship) which escapes from the energy converter without being oxidized (including fuel that escapes from combustion chamber/oxidation process and from crankcase, as appropriate) $C_{slip\_ship} = C_{slip} * (1 - C_{fug}/100)$
C_{slip}	Factor accounting for fuel (expressed in % of total fuel mass consumed in the energy converter) which escapes from the energy converter without being oxidized (including fuel that escapes from combustion chamber/oxidation process and from crankcase, as appropriate)
C_{fug}	Factor accounting for the fuel (expressed in % of mass of the fuel delivered to the ship) which escapes between the tanks up to the energy converter which is leaked, vented or otherwise lost in the system **Pending further methodological guidance to be developed by the Organization to determine appropriate factor(s), the value of C_{fug} should be set to zero.**
C_{sfx}	Factor accounting for the share of GHG in the components of the fuel (expressed in g GHG/g fuel) Example: for LNG this value is 1
C_{fCO2}	CO_2 emission conversion factor (gCO_2/g fuel completely combusted) for emissions of the combustion and/or oxidation process of the fuel used by the ship
C_{fCH4}	CH_4 emission conversion factor (gCH_4/g fuel delivered to the ship) for emissions of the combustion and/or oxidation process of the fuel used by the ship For LNG/CNG fuel, the C_{slip_engine} is covering the role of C_{fCH4}, so C_{fCH4} is set to zero for these fuels.
C_{fN2O}	N_2O emission conversion factor (gN_2O/g fuel delivered to the ship) for emissions of the combustion and/or oxidation process of the fuel used by the ship
GWP_{CH4}	Global warming potential of CH_4 over 100 years (based on the fifth IPCC Assessment Report 5) : 28
GWP_{N2O}	Global warming potential of N_2O over 100 years (based on the fifth IPCC Assessment Report 5) : 265
GWP_{fuelx}	Global warming potential of GHG in the components of the fuel over 100 years (based on the fifth IPCC scientific Assessment Report)
LCV	Lower Calorific Value is the amount of heat that would be released by the complete combustion of a specified fuel
S_{Fc}	Carbon source factor to determine whether the emissions credits generated by biomass growth are accounted for in the calculation of the TtW value : 0 or 1
e_c	Emissions credits generated by biomass growth
S_{Fccu}	Carbon source factor to determine whether the emissions credits from the used captured CO_2 as carbon stock to produce synthetic fuels in the fuel production process are accounted for in the calculation of the TtW value : 0 or 1

e_{ccu}	Emission credits from the used captured CO_2 as carbon stock to produce synthetic fuels in the fuel production process and utilization (that was not accounted under e_{fecu} and e_p) **Pending further methodological guidance to be developed by the Organization, the value of the multiplication $S_{Fccu} \times e_{ccu}$ should be set to zero.**	
e_{occs}	Emission credit from carbon capture and storage (e_{occs}), where capture of CO_2 occurs onboard. This should properly account for the emissions avoided through the capture and sequestration of emitted CO_2, if CCS occurs on board. From the above-mentioned emission credit, all the emissions resulting from the process of capturing (e_{cc}), and transporting (e_t) the CO_2 up to the final storage (including the emissions related to the injection, etc.) need to be deducted. This element should be calculated with the following formula: **Pending further methodological guidance to be developed by the Organization, the value of e_{occs} should be set to zero.** $e_{occs} = c_{sc} - e_{cc} - e_t - e_{st} - e_x$	
	c_{sc}	Credit equivalent to the CO_2 captured and stored (long-term: 100 years)
	e_{cc}	Any emission associated with the process of capturing, compress and temporarily store on board the CO_2
	e_t	Emissions associated with transport to long-term storage site
	e_{st}	Any emission associated with the process of storing (long-term: 100 years) the captured CO_2 (including fugitive emissions that may happen during long-term storage and/or the injection of CO_2 into the storage)
	e_x	Any additional emission related to the CCS

2.3 Fuel Lifecycle Label (FLL)

The LCA Guidelines specify a technical tool called the Fuel Lifecycle Label, which collects and conveys the information relevant for the life cycle assessment of marine fuels and energy carriers (e.g. electricity for shore power) used for ship propulsion and power generation onboard and is used to assess the life cycle GHG emissions. The Fuel Lifecycle Label consists of five main parts, from Part A to Part E, as shown in Table 1.

Part A indicates information on fuel type, fuel pathway code, lower calorific value, fuel blend ratio and the WtT (upstream) GHG emission factor; Part B indicates information on reductions from biofuels and synthetic fuels; Part C indicates information on TtW (downstream) GHG emission factor from onboard emissions and engine type with and without consideration of biofuel and synthetic fuel reductions; Part D indicates the WtW GHG emission factor over the whole life cycle, and Part E indicates information on sustainability performance of the fuel.

Table 1 Fuel Lifecycle Label (FLL)

Part A-1	Part A-2	Part A-3	Part A-4	Part A-5
Fuel type (blend)	Fuel Pathway code	Lower Calorific Value (LCV, MJ/g)	Share in fuel blend ($\%MJ_{(LCV)}/MJ_{(LCV)}$)	WtT GHG emission factor (GWP100, $gCO_{2eq}/MJ_{(LCV)}$)

Part B-1	Part B-2
Emissions credits related to biogenic carbon source (e_c, in gCO_2 / g fuel based on GWP100)	Emissions credits related to source of captured carbon (e_{ccu}, in gCO_2 / g fuel based on GWP100)

Part C-1	Part C-2	Part C-3
TtW GHG intensity Value 1 (carbon source NOT taken into account): TtW GHG emission factor (GWP100, $gCO_{2eq}/MJ_{(LCV)}$)	TtW GHG intensity Value 2 (carbon source taken into account): TtW GHG emission factor (GWP100, $gCO_{2eq}/MJ_{(LCV)}$)	Energy Converter

Part D	Part E
WtW GHG emission factor (GWP100, $gCO_{2eq}/MJ_{(LCV)}$) Note: Part D = Part A-5 + Part C-2	Sustainability (Certification)

2.4 Fuel List with Fuel Pathway Codes

The LCA Guidelines classify fuel pathways according to the type of feedstock, origin, production method and energy used, with a total of 128 different fuel pathways specified. The representative fuels in the 128 different fuel pathways are shown in Table 2: Heavy Fuel Oil, LPG, LNG, Methanol, Hydrogen, Ammonia, Electricity and Wind propulsion.

Table 2 Examples of fuel list with fuel pathway codes

Order	Group	Fuel type	Feedstock structure		Conversion/Production process		Fuel Pathway Code
			Feedstock Type	Nature/Carbon Source	Process Type	Energy used in the process	
1	HFO (VLSFO)	Heavy Fuel Oil (ISO 8217 Grades RME, RMG and RMK, 0.10 < S ≤ 0.50%)	Crude Oil	Fossil	Standard refinery process	Grid mix electricity	HFO(VLSFO)_f_SR_gm
11	LPG	Liquefied Petroleum Gas (Propane)	Crude Oil	Fossil	Standard refinery process and liquefaction	Grid mix electricity	LPG(Propane)_f_SR_gm
31	LNG	Liquefied Natural Gas (Methane)	Natural Gas	Fossil	Standard LNG production including liquefaction	Grid mix electricity	LNG_f_SLP_gm
35	LNG	Liquefied Natural Gas (Methane)	$CO_2 + H_2$	CO_2: Fossil Point Source Carbon Capture H_2: Fossil Steam Methane Reformation	Methanation and liquefaction	Grid mix electricity	LNG_fCO2_fH2_M_gm
90	Methanol	Methanol	2nd and 3rd Gen. feedstock	Biogenic	Gasification of Biomass and Methanol Synthesis	Grid mix electricity	MeOH_b_G_MS_gm
110	Hydrogen	Hydrogen	Water + Electricity	Renewable	Dedicated Photovoltaic and/or Wind and/or other Electrolysis and liquefaction	Renewable electricity	LH2_EL_r_Liquefied
120	Ammonia	Ammonia	$N_2 + H_2$	N_2: separated with renewable electricity H_2: produced from renewable electricity	Haber Bosch process	Grid mix electricity	NH3_rN2_rH2_HB_gm
126	Electricity	Electricity		Fossil/Renewable	-	Grid mix electricity	Electricity_gm
128	Wind propulsion						

Table 3 Initial default emission factors per fuel pathway code

Order	Fuel type	Fuel Pathway Code	WtT GHG intensity (gCO_{2eq}/MJ)	LCV (MJ/g)	Energy Converter	$C_f CO_2$ (gCO_2/g fuel)	$C_f CH_4$ (gCH_4/g fuel)	$C_f N_2O$ (gN_2O/g fuel)	C_{slip}/C_{fug} (mass %)	e_c (gCO_{2eq}/g fuel)	TtW GHG intensity (gCO_2eq/MJ)	NOTE
1	Heavy Fuel Oil (ISO 8217 Grades RME, RMG and RMK, 0.10 < S ≤ 0.50%)	HFO(VLSFO)_f_SR_gm (Fossil)	**16.8**	0.0402	ALL Internal Combustion Engines (ICEs)	3.114	0.00005	0.00018				Resolution MEPC.364(79) Fourth IMO GHG study
2	Heavy Fuel Oil (ISO 8217 Grades RME, RMG and RMK exceeding 0.50% S)	HFO(HSHFO)_f_SR_gm (Fossil)	**14.1**	0.0402	ALL ICEs	3.114	0.00005	0.00018				Resolution MEPC.364(79) Fourth IMO GHG study
3	Light Fuel Oil (ISO 8217 Grades RMA, RMB and RMD maximum 0.10% S)	LFO(ULSFO)_f_SR_gm (Fossil)		0.0412	ALL ICEs	3.151	0.00005	0.00018				Resolution MEPC.364(79) Fourth IMO GHG study
4	Light Fuel Oil (ISO 8217 Grades RMA, RMB and RMD, 0.10 < S ≤ 0.50%)	LFO(VLSFO)_f_SR_gm (Fossil)		0.0412	ALL ICEs	3.151	0.00005	0.00018				Resolution MEPC.364(79) Fourth IMO GHG study
5	Marine Diesel/Gas Oil (ISO 8217 Grades DMX, DMA, DMZ and DMB maximum 0.10 % S)	MDO/MGO(ULSFO)_f_SR_gm (Fossil)	**17.7**	0.0427	ALL ICEs	3.206	0.00005	0.00018				Resolution MEPC.364(79) Fourth IMO GHG study
6	Marine Diesel/Gas Oil (ISO 8217 Grades DMX, DMA, DMZ and DMB, 0.10 < S ≤ 0.50%)	MDO/MGO(VLSFO)_f_SR_gm (Fossil)		0.0427	ALL ICEs	3.206	0.00005	0.00018				Resolution MEPC.364(79) Fourth IMO GHG study
11	LPG (Propane)	LPG(Propane)_f_SR_gm (Fossil)		0.0463	ALL ICEs	3.000	0.00005	0.00018				Resolution MEPC.364(79) Fourth IMO GHG study
21	LPG (Butane)	LPG(Butane)_f_SR_gm (Fossil)		0.0457	ALL ICEs	3.030	0.00005	0.00018				Resolution MEPC.364(79) Fourth IMO GHG study
31	LNG (Methane)	LNG_f_SLP_gm (Fossil)		0.0480	LNG Otto (dual fuel medium speed) LNG Otto (dual fuel slow speed)	2.750	0	0.00011	**3.5/-** **1.7/-**			Resolution MEPC.364(79) Fourth IMO GHG study

					LNG Diesel (dual fuel slow speed)				**0.15/-**			
					LBSI (Lean-Burn Spark-Ignited)				**2.6/-**			
					Steam Turbines and boilers				**0.01/-**			
33	LNG (Methane)	LNG_b_AD_gm (Biogenic)			LNG Otto (dual fuel medium speed)	2.750						
					LNG Otto (dual fuel slow speed)							
					LNG Diesel (dual fuel slow speed)							
					LBSI (Lean-Burn Spark-Ignited)							
					Steam Turbines and boilers							
62	Diesel (FAME)	FAME_b_TRE_gm_2ndgen (2nd Gen. feedstock)	**20.8**	0.0372	ALL ICEs							
77	Renewable Diesel (HVO)	HVO_b_HD_gm_2ndgen (2nd Gen. feedstock)	**14.9**	0.0440	ALL ICEs							
105	Hydrogen	H2_f_SMR_CCS_gm (Fossil)		0.1200	ALL ICEs	0						
					Fuel cell							
121	Ammonia	NH3_rN2_fH2_HB_gm (Renewal, Fossil)		0.0186	ALL ICEs	0						
					Fuel cell							

2.5 Provisions for Default and Actual Values

As the actual calculation/measurement of GHG intensities and various coefficients requires considerable time and effort, the LCA Guidelines allow the use of default values, which are set on the basis of representative and conservative assumptions. To establish the default values, GHG intensities and various coefficients are determined for each emission source for at least three different representative emission sources, and the upper (conservative) limit of these values is adopted as the default value. If a better value than the default value is desired, the actual value obtained according to the methodology specified in the LCA Guidelines may be used, subject to third-party certification. On the other hand, in the case of pure fossil fuels, actual values of GHG intensity are not permitted, so only default values are to be used. There are 128 different fuel pathways in the LCA Guidelines, but for fuels whose fuel pathways are not included in the LCA Guidelines, the actual values can be used if detailed information on the pathway is submitted, and third-party certification is obtained. Few default values have yet been established, and Table 3 shows the Well-to-Tank, i.e. upstream GHG intensities in red, but only five in total for fossil-based heavy fuel oil and biofuels, FAME and HVO. Furthermore, default values for methane slip have been established for different types of LNG engines, such as Otto cycle and high-pressure types, as shown in Table 3, but not yet for methane leaking from the fuel tank into the LNG engine or for N_2O generated by ammonia engines.

2.6 Sustainability Criteria for Marine Fuels

For marine fuels, sustainability also needs to be considered and the LCA Guidelines set out ten environmental themes or aspects, which are listed below. However, specific verification criteria have not been defined and will be discussed in the future. In addition, as a sustainable marine fuel, the LCA Guidelines specify lower GHG emissions than conventional marine fuels on a life cycle basis, but the ICAO CORSIA for international aviation requires a 10% reduction in GHG intensity compared to the reference fuel, while the EU Renewable Energy Directive (RED III) requires a 70% reduction (Renewable Fuels of Non-Biological Origin, Recycled Carbon Fuels) in GHG intensity compared to the reference fuel, which may become more stringent in the future.

1. GHG: Sustainable marine fuels generate lower GHG emissions than conventional marine fuels (energy-based weighted average of liquid petroleum products on 3 specific years of DCS data) on a life cycle basis.
2. Carbon source: Sustainable marine fuels do not increase GHG intensity from the use of fossil energy sources and the permanence of captured and stored carbon is ensured while also avoiding double counting across economic sectors.
3. Source of electricity/energy: Sustainable marine fuels requiring significant electricity input during WtT phase and electricity delivered directly to ships are produced by using electricity/energy from renewable, nuclear or biogenic sources, which are additional to current or long-standing demand levels, or by using surplus electricity during off-peak hours.

4. Carbon stock – direct land use change (DLUC): Sustainable marine fuels are not made from biomass obtained from land with high carbon stock; production of sustainable marine fuels minimizes emissions resulting from Direct Land Use Change.
5. Carbon stock – indirect land use change (ILUC): Cultivation of feedstock of sustainable marine fuels minimizes inducing negative changes in the use or management of land which occurs outside the product system being assessed.
6. Water: Production of sustainable marine fuels maintain or enhance water quality and availability.
7. Air: Production of sustainable marine fuels minimizes negative impacts on air quality.
8. Soil: Production of sustainable marine fuels maintain or enhance soil health.
9. Waste and chemicals: Production of sustainable marine fuels maintain or enhance responsible management of waste and use of chemicals.
10. Conservation: Production of sustainable marine fuels maintain or enhance biodiversity and ecosystems, or conservation services.

2.7 Verification and Certification

The LCA Guidelines specify that the Fuel Lifecycle Label (FLL) needs to be verified and certified by a third party, taking into account further guidance to be developed by the IMO.

- ✧ The verification and certification of Part A, Part B, Part C and Part E of the FLL may be carried out separately by different verification bodies. The verification and certification of Part D of the FLL needs to be based on the verified Part A, Part B and Part C.
- ✧ As long as Part A-1 to Part A-4 and Part C-3 of the FLL have been duly verified, the default emission factors contained in these guidelines can be consequently applied without further verification.
- ✧ In the case where lower emission factors are claimed compared to the default emission factors, the actual emission factors can be used only after the verification and certification by a third party, taking into account further guidance.

On the other hand, the LCA Guidelines specify that the verification and certification of individual parts of the FLL will use relevant certification schemes/standards recognized by the Committee, taking into account guidance to be developed by the IMO. The list of recognized certification schemes/standards will be publicly available and kept under review. In addition, it is specified that proposals to recognize international certification schemes/standards are submitted to the MEPC for consideration, and the framework, criteria and procedures leading to the recognition of certification schemes are implemented uniformly to guarantee the quality, reliability, and robustness of the IMO framework as a whole and to ensure a level playing field among certification schemes. However, as the LCA Guidelines do not specify details, guidance on certification schemes and third-party certification need to be developed in the future.

3. TERMS OF REFERENCE TO GESAMP WORKING GROUP ON LIFE CYCLE GHG INTENSITY OF MARINE FUELS

As mentioned above, there are still many issues in the LCA Guidelines, such as default values and certification methods, and as expertise is needed to resolve these issues, it was agreed at MEPC 81 held in March 2024 to newly establish a GESAMP working group on life cycle GHG intensity of marine fuels (GESAMP-LCA WG) under GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) and a Terms of Reference for the work was developed. The GESAMP-LCA WG is a group of experts to provide the best possible scientific and technical assessment of issues related to the implementation of the LCA Guidelines, and the Terms of Reference are as follows.

- ■ Methodological refinement of the emission quantification in the LCA Guidelines, with a view to ensuring the integrity of all information provided:
  - ✓ scientific review of the LCA methodology;
  - ✓ scientific review of the WtT GHG default emission factors of fuel production pathways and technologies;
  - ✓ scientific review of the TtW GHG default emission factors of fuel usage and onboard technologies (explicitly mentioning OCCS boundaries); and
  - ✓ sample calculations on LCA and reflecting the output into the existing FLL.
- ■ Sustainability themes/aspects:
  - ✓ refine and further explore indicators and metrics under the sustainability themes/aspects in the LCA Guidelines; and

- ✓ approaches to ILUC risk classification.
- ■ Methodological requirements of the LCA Guidelines with regard to certification:
  - ✓ provide external experience and further information for the development and/or identification of possible requirements for fuel pathway certification, including WtT and TtW actual values.

Note : GESAMP (the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) is independent group of experts set up already in 1969. It is currently co-sponsored by 10 UN agencies with an interest or mandate relating to the marine environment, and IMO provides the secretariat. Currently, GESAMP has nine active working groups, and the experts are all there as independent experts in their individual capacity. GESAMP working groups include, for example GESAMP WG 1 on the evaluation of hazardous substances carried by ship, and the working group on Review of applications for “active substances” to be used in ballast water management system (WG 34). To ensure independence, GESAMP selects the best expert for the task with maximum attention to gender and geographical balance. The author was one of the three coordinators of the Correspondence Group on LCA of marine fuels established at MEPC 80 held in July 2023, and was also selected as one of the 12 experts of the GESAMP-LCA WG.

4. NEW TERMS OF REFERENCE TO CORRESPONDENCE GROUP ON LCA OF MARINE FUELS

As the sustainability criteria for marine fuels does not specify other social and economic sustainability themes/aspects of marine fuels such as Land and Water Use Rights, Local and Social Development, Human and Labor Rights, Food Security etc., it was agreed at MEPC 81 held in March 2024 that the CG on LCA of marine fuels would consider them as new terms of reference and submit a report to MEPC 83 to be held in April 2025.

5. TERMS OF REFERENCE TO NEW CORRESPONDENCE GROUP ON MEASUREMENT AND VERIFICATION OF NON-CO_2 GHG EMISSIONS AND ONBOARD CARBON CAPTURE

At MEPC 81 held in March 2024, it was agreed to establish a new “Correspondence Group on measurement and verification of non-CO_2 GHG emissions and onboard carbon capture”, separate from the GESAMP-LCA WG and the CG on LCA of marine fuels, because further studies are needed on onboard emissions of methane (CH_4) and N_2O as well as onboard CCS when the LCA Guidelines are revised. The Terms of Reference are as follows.

- ■ With regard to tank-to-wake CH_4 and N_2O emissions:
  - ✓ consider how to develop a framework for the measurement and verification of actual tank-to-wake CH_4 and N_2O emission factors and C_{slip} value for energy converters;
  - ✓ consider how to develop a methodological framework for associated certification issues, in support of the application of the LCA Guidelines;
  - ✓ identify the relevant gaps in existing instruments, and propose recommendations, with a view to developing necessary regulatory or recommendatory instruments;
- ■ With regard to onboard carbon capture:
  - ✓ further consider issues related to onboard carbon capture, and develop a work plan on the development of a regulatory framework for the use of onboard carbon capture systems with the exception of matters related to accounting of CO_2 captured on board ships; and
- ■ With regard to reporting to the Committee:
  - ✓ submit a written report to MEPC 83 to be held in April 2025.

6. CONCLUDING REMARKS

The LCA Guidelines will be further discussed in the GESAMP-LCA WG, the CG on LCA of marine fuels and the CG on measurement and verification of non-CO_2 GHG emissions and onboard carbon capture. As one of the members of the GESAMP-LCA WG, the author would be happy to continue contributing to the study. In particular, as a certification expert, the author would be happy to contribute to the development of Guidance on certification schemes/third-party verification for marine fuels.

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Trends in Alternative Fuel Ships and Activity of the Society

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

1. INTRODUCTION

The International Maritime Organization (IMO) adopted new targets for greenhouse gas (GHG) reduction at the meeting of the Marine Environment Protection Committee (MEPC80) held in July 2023. Prior to MEPC80, the targets adopted in 2018 called for improvement of fuel efficiency by at least 40 % compared to 2008, to be achieved by 2030, and as reductions in GHG emissions, a reduction of total emissions by at least 50 % by 2050 and zero GHG emissions "as soon as possible in this century." In the new targets, IMO set goals of reducing GHG emissions by 70 to 80 % by 2040, aiming at "net-zero GHG emissions from international shipping close to 2050." (Fig. 1)

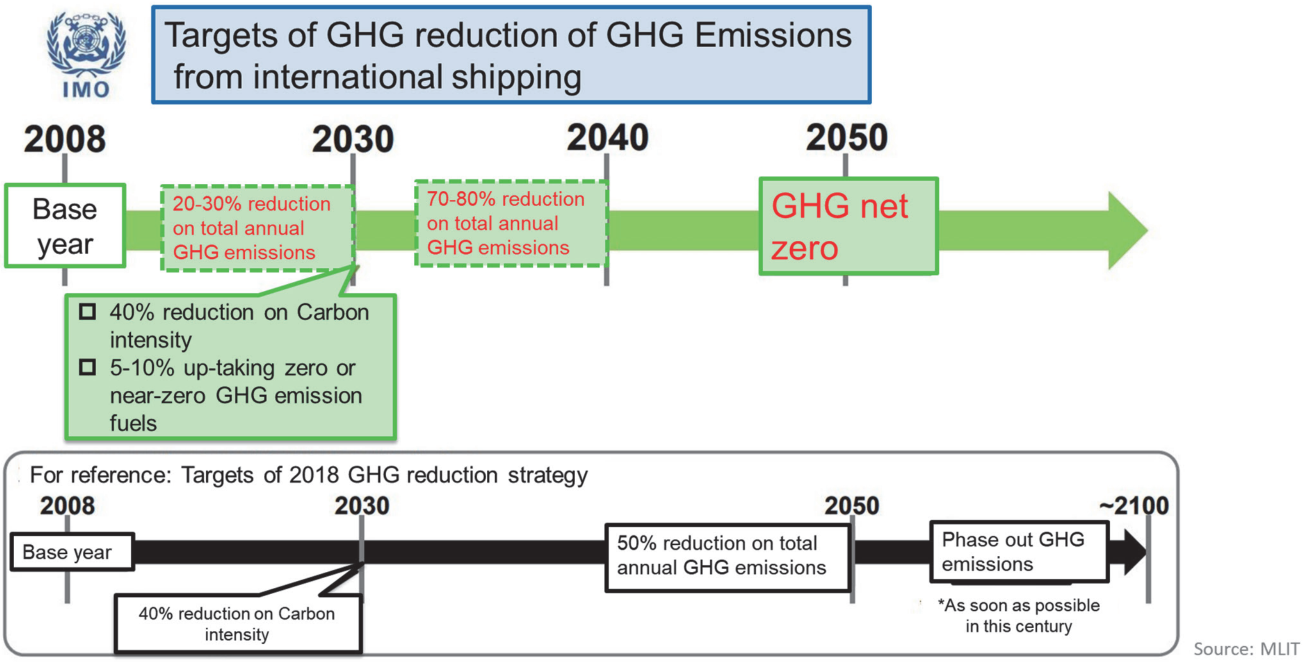

Fig. 1 Targets for reduction of GHG emissions from international shipping

Achievement of the target of IMO strategy for 2030 is considered possible by improving the energy efficiency of existing ships and newbuilding ships with high energy efficiency. However, to achieve the targets for reduction of GHG emissions from international shipping for 2040 and 2050, which are substantially more stringent than the previous 2018 targets, the use of GHG reduction technologies and low-carbon or zero-carbon alternative fuels is considered indispensable. Against this background, construction of ships that introduce low-carbon or zero-carbon alternative fuels is expected to increase, and in fact, many projects are being launched in Japan and other countries.

This report introduces the trends in alternative fuel ship and the initiatives of the Society.

2. ALTERNATIVE FUEL CERTIFICATION SCHEMES

As alternative fuels which are either already in use in shipping or can be assumed as alternative fuels, LNG, LPG, methanol, ammonia and hydrogen may be mentioned. Table 1 shows IMO and Society codes and guidelines for the alternative fuel ships and the related technologies.

Table 1　Codes and guidelines for alternative fuel ships and related technologies

<table>
<tr><th>Alternative fuel/ related technology</th><th>IMO code/guideline</th><th>ClassNK rules/guideline</th></tr>
<tr><td>LNG</td><td>IGF Code</td><td>Technical Rules and Guidance, Part GF, Ships Using Low Flashpoint fuels</td></tr>
<tr><td>Methanol</td><td>Interim Guidelines for Ships Using Methyl / Ethyl alcohol as Fuel (MSC.1/Circ.1621)</td><td rowspan="4">Guidelines for Ships Using Alternative Fuels (Edition 3.0) (Methyl/Ethyl Alcohol, LPG, Ammonia, Hydrogen) Aug. 2024</td></tr>
<tr><td>LPG</td><td>Interim Guidelines for the Safety of Ships Using LPG Fuels (MSC.1/Circ.1666)</td></tr>
<tr><td>Ammonia</td><td>Under development
(Finalized at Sept. 2024 CCC10 and will be adopted at MSC109 in December, 2024)</td></tr>
<tr><td>Hydrogen (as fuel)</td><td>Under development
(to be finalized at CCC11, Sept. 2025)</td></tr>
<tr><td>(Ships transporting liquefied hydrogen)</td><td>Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk (Res.MSC.420(97))</td><td>Guidelines for Liquefied Hydrogen Carriers (Edition 2.0) Sept. 2023</td></tr>
<tr><td>Fuel cells</td><td>Interim Guidelines for the Safety of Ships Using Fuel Cell Power Installations (MSC.1/Circ.1647)</td><td>Guidelines for Fuel Cell Power Systems on Ships (Edition 2.0) Sept. 2023</td></tr>
</table>

IMO has issued the IGF Code for LNG-fueled ships, and the Society has also issued Technical Rules and Guidance, Part GF (Ships Using Low Flashpoint Fuels), which corresponds to the IGF Code. For alternative fuels and related technologies other than LNG, IMO Guidelines for methanol, LPG, liquefied hydrogen carriers and ships using fuel cells have been issued, and the Society has also issued guidelines based on these IMO guidelines. Guidelines for ammonia fuel and hydrogen fuel are also under development in IMO, and the guideline for ammonia fuel was finalized at CCC10 in September, 2024, and will be adopted at MSC109 in December, 2024.

As described up to this point, the only alternative fuel for which IMO code has already been established is LNG. Other fuels are still in the Interim Guidelines stage, and codes have not yet been established. For fuels of this type, codes that allow application of alternative are provided in the IGF Code, IGC Code and SOLAS. (Fig. 2)

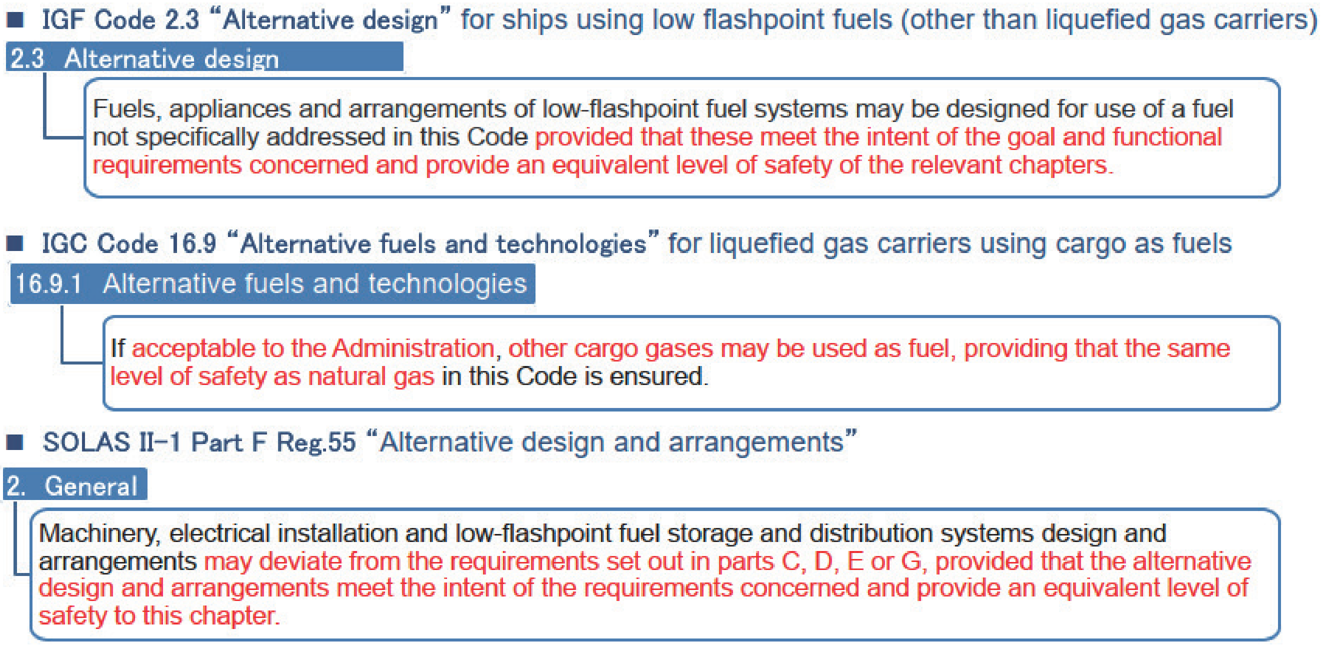

Fig. 2　Scheme of alternative design for alternative fuel ships

The IGF Code applies to ships other than liquefied gas carriers that use low flashpoint fuels with flashpoints of less than 60 °C. For example, this IGF Code also applies to ships that use hydrogen fuel, but at present, detailed requirements are only provided for LNG fuels.

Since similar detailed safety requirements have not been provided for hydrogen fuel, the use of hydrogen fuel can be approved by the Administration after confirming the same level of safety as that specified in the IGF Code, when the alternative design requirements of that code are applied.

When cargo gas is to be used as fuel by a liquefied ammonia carrier or liquefied hydrogen gas carrier, the IGC code which is applied also contains provisions for "Alternative fuels and technologies," and this allows the use of cargo gases other than methane as fuels with the approval of the Administration, on the condition that the same safety as that required for methane is ensured.

In the case of ammonia-fueled ships other than liquefied gas carriers, the provisions of "Alternative designs and arrangements" in SOLAS Chapter II-1 Part F, Regulation 55 apply. Use of ammonia fuel can be approved by the Administration, based on confirmation of safety equal to the provisions applied to existing ships of the same type.

For alternative fuels and alternative technologies without detailed application rules related to safety, it is necessary to ensure the same level of safety as that in the provisions applicable to existing ships, based on the existing rules that recognize the use of alternative designs, and finally, to obtain the approval from the Administration, that is, the flag state of the ship concerned.

3.　TRENDS OF VARIOUS TYPES OF ALTERNATIVE FUEL SHIPS

3.1　LNG-Fueled Ships

Among LNG-fueled ships classified by the Society, as of the end of August 2024, 15 were in service and the Society had received applications for classification for more the 60 other vessels. Many have already entered the shipbuilding stage at shipyards in various areas. The types of ships span a diverse range, including PCC, bulk carriers, containerships and chemical tankers, among others. In addition, the Society also performs Approval in Principle (AiP; approval of the basic ship design) for ammonia-ready LNG-fueled ships.

Fig. 3 LNG-fueled ship, M/V CENTURY HIGHWAY GREEN

3.2 LPG-Fueled Ships

As of the end of August 2024, 18 LPG-fueled ships classified by the Society were in service and applications for classification had been received for more than 10 others. Some ships had also reached the shipbuilding stage. As the ship type, all are LPG carriers which use the cargo LPG as fuel.

In view of the expected increase in demand for ammonia transportation, an increasing tendency can also be seen in specifications that enable loading of ammonia in addition to LPG. There is also an increasing tendency to perform conceptual design for use of the cargo ammonia as a fuel when ships are designed in order to acquire the Society's ammonia-ready ship class notation.

Fig. 4 LPG-fueled LPG/ammonia carrier, M/V PHOENIX HARMONIA

3.3 Methanol-Fueled Ships

As of the end of Augst 2024, 4 methanol-fueled ships classified by the Society were in service. In all cases, the ship type was chemical carrier, and the ships use cargo methanol as fuel.

In addition, shipbuilding projects involving coastal chemical tankers, bulk carriers and container carriers are increasing, and the Society is participating in risk assessments and responding to safety verifications and approvals by the Administration.

3.4 Ammonia-Fueled Ships

As of the end of August 2024, one ammonia-fueled ship classified by the Society had received class registration. This vessel is the tugboat “Sakigake.” Research and development were carried out by Nippon Yusen Kaisha and IHI Power Systems Co., Ltd., and the vessel was registered as an ammonia-fueled ship.

In addition to the start of construction projects for ammonia fuel-fired bulk carriers and liquefied gas carriers, to date, the Society has also issued AiP certificates for ammonia-fueled ships for car carriers, bulk carriers and VLGC, among others.

3.5 Hydrogen-Fueled Ships

A project aiming at application of hydrogen fuel to hydrogen carriers that will use cargo hydrogen as fuel is being carried out, and the Society is also participating in that initiative. There are also examples of practical application of hydrogen-fueled fuel cell ships that employ fuel cells using hydrogen to small-scale ships such as small ferries and others.

On the other hand, engines using hydrogen fuel are also under development, and in Japan, development projects aiming at realization of various types of hydrogen engines including a medium-speed, 4-stroke propulsion engine, a high-speed 4-stroke auxiliary engine, and a low-speed 2-stroke propulsion engine are underway, centering on engine manufacturers and persons with expert knowledge and experience. (Fig. 5)

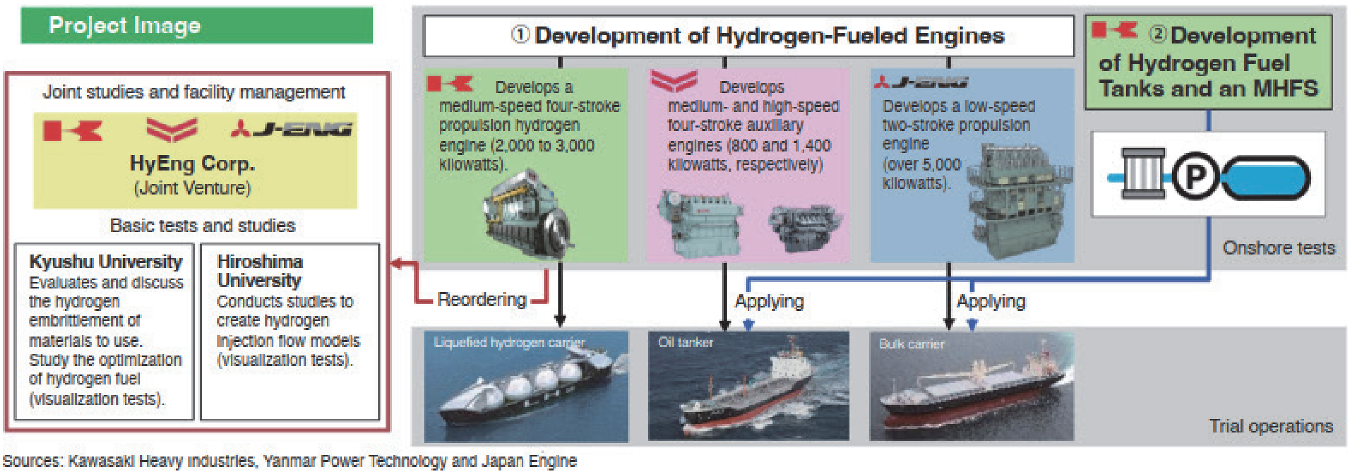

Fig. 5 System for development of engines using hydrogen fuel

3.6 Liquefied Hydrogen Carriers

As of the end of August 2024, one ship had received class registration as a liquefied hydrogen carrier. This was the “SUISO FRONTIER,” which was constructed by Kawasaki Heavy Industries, Ltd. and is the world’s first liquefied hydrogen carrier. The Society also issues AiP certificates for the cargo tanks, cargo transfer equipment, dual-fuel boilers, dual-fuel engines and other equipment of large-scale liquefied hydrogen carriers.

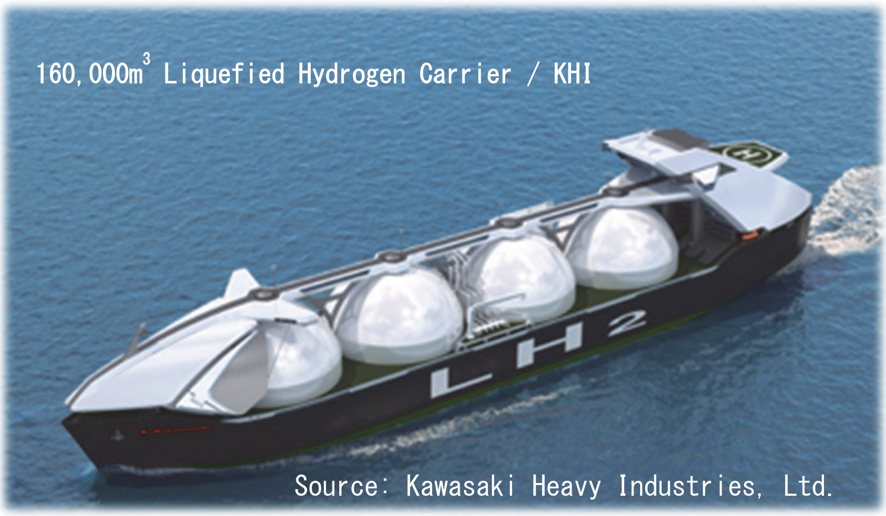

Fig. 6 Liquefied hydrogen carrier

3.7 Initiatives Related to Biofuels

In addition to a large number of trials of biofuels on ships classified by the Society, there are also actual results of vessels using liquid biomethane and biomethanol derived from livestock excreta. The Society has issued Technical Guidance for the use of biofuels. This Technical Guidance describes the features of biofuels and the conceivable problems when using them, efforts related to conventions (statutory requirements) on the use of biofuels as fuels, and the future potential of biofuels.

4. CONCLUSION

In order to achieve the GHG reduction targets of IMO, the use of new technologies toward the introduction of alternative fuels and zero-emission fuels will be indispensable.

The Society aims to contribute to the maritime industry by safety assessments and design certification of alternative designs, as well as support for their certification by flag states, etc., through cooperation with the industry and participation in various projects, and using the knowledge acquired, to contribute to the formulation of conventions and guidelines related to the safety of ships utilizing new technologies in IMO and other committees.

Trends in Development of Marine Dual Fuel Engines to Reduce GHG Emissions

Koji TAKASAKI*

1. INTRODUCTION

This paper is a follow-up to the author's previous paper "Studies on In-Engine Combustion of Low and Zero Carbon Fuels" in ClassNK Technical Report No. 7 published in 2023. Toward achievement of the IMO's target of "Net zero GHG emissions from international shipping in 2050," ClassNK Alternative Fuels Insight ("NK Insight") was published in 2024. This paper may be useful for understanding the steps in applying alternative fuels to international shipping described in the NK Insight.

As stated in NK Insight, there is an overwhelming shortage of alternative fuel production at present. However, in order to achieve the 2050 target, the development of marine engines that can use alternative fuels must be pursued now, with a view to increasing the scale of alternative fuel production in the future. Continuing from the previous paper, this paper describes the development of marine engines that use zero-emission (zero-carbon) and carbon-neutral fuels, including the progress made in Japan under the Green Innovation Fund Project for the Development of Next-Generation Ships (hereinafter, GI Fund) by the New Energy and Industrial Technology Development Organization (NEDO), and also touches on trends in development on the European side.

The definition of Dual Fuel engines in this paper is engines that can use both an alternative fuel and heavy fuel oil, and may operate on heavy fuel oil until the alternative fuel supply system is in place. For this purpose, sufficient capacity of heavy fuel oil tanks should be maintained on board. In addition, since the self-ignition properties of all possible alternative fuels are inferior to those of heavy fuel oil, a small amount of heavy fuel oil must be injected as pilot fuel for ignition in the cylinder. If the supply of alternative fuels is insufficient, it is possible to actively increase the amount of heavy fuel oil injected to create so-called "mixed combustion with an alternative fuel and heavy fuel oil."

2. ZERO-EMISSION FUELS AND CARBON-NEUTRAL FUELS

<u>Zero-emission fuels</u> include green hydrogen, which is produced by electrolyzing water with renewable electricity, and blue hydrogen, which can be made from fossil fuels, provided the CO_2 emitted during production is captured and stored. A project to produce hydrogen from Australian brown coal, which has a high water content, liquefy the hydrogen, and transport it to Japan is an example of the use of blue hydrogen. Ammonia (NH_3), which is synthesized from hydrogen and nitrogen, is also a zero-emission fuel.

<u>Carbon-neutral fuels</u> include the following. Biofuels emit CO_2 during combustion, but are zero-counted because they have absorbed CO_2 from the atmosphere before combustion. Synthetic methane and synthetic methanol were described in the previous paper, but it is expected that regulations will be enacted to allow zero-counting of CO_2 from ships using fuels synthesized from green or blue hydrogen and CO_2 recycled from land-based industries (in that case, the land side would have emitted the CO_2). The IMO begins discussions of this issue.

There is also the idea that, in the absence of actual supplies of such synthetic fuels, grey fuels (fossil natural gas or methanol made from fossil fuels) may be used for the time being, and then switched to green or blue ones as soon as they become available. This is explained below.

<u>Biofuels</u>: According to NK Insight, methane, LPG and methanol can be produced from bio-based sources in addition to the synthetic methods mentioned above. However, only biodiesel oil, which is also being tested and used at present, is discussed here. There are few combustion problems in engines when vegetable oil is processed to FAME (Fatty Acid Methyl Ester), which can be used by conventional heavy oil-fueled diesel engines as a drop-in, i.e., without changing the engine side settings. It can also be mixed with heavy fuel oil for bunkering. However, the amount of raw material is an issue. There is much opposition

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worldwide to the direct conversion of cooking oil into fuel, and at present the aviation industry is competing for waste cooking oil as a raw material.

For reference, the Maritime Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and ClassNK have revised the following guides on the handling of biofuels, respectively.

・Maritime Bureau, MLIT: Guidelines for handling biofuels, revised March 2024 [1)]

・ClassNK: Technical Guide for Using Biofuels (Edition 1.1), revised in April 2024 [2)]

Synthetic methane: Synthetic methane is a drop-in for existing LNG-fueled vessels, as methane is the main component of the natural gas currently in use. There is a view that fossil LNG-fueled vessels should be built at present and converted to synthetic methane as soon as it emerges.

Synthetic methanol: Methanol has the advantage of being a liquid at ambient temperature and pressure. Methanol engines require pilot fuel due to the higher self-ignition temperature of methanol, but once ignited, methanol shows better combustion characteristics than diesel oil. The low-speed, two-stroke methanol engine developed by MAN Energy Solutions (MAN) has already been in operation since 2016 as the main engine of methanol carriers.

The high cost of both synthetic methane and synthetic methanol is an issue due to the aforementioned production process, and according to NK Insight's “Production pathways and costs of alternative fuels (costs are projected as of 2030),” the cost of both is estimated to be 4.2 times higher than that of conventional heavy fuel oil.

Ammonia: Both low-speed, two-stroke and medium-speed, four-stroke engines are currently under development, as will be discussed later. NK Insight estimates the cost of green ammonia to be 3.1 times that of conventional heavy fuel oil and the cost of blue ammonia is 1.9 times higher. As mentioned above, a supply chain of green or blue ammonia is urgently needed, even if grey ammonia is allowed to be used at first.

The Maritime Bureau of MLIT has been holding meetings of an Ammonia Bunkering Guideline Study Committee since last year [3)] to implement safe and smooth bunkering of ammonia-fueled ships, and is giving sufficient consideration to measures against leakage, especially in view of the toxicity of ammonia.

Hydrogen: Hydrogen engines are also under development as both low-speed, two-stroke and medium-speed, four-stroke types, as discussed below. In comparison with conventional heavy fuel oil, NK Insight estimates the cost to be 3.8 times higher for liquefied green hydrogen and 3.1 times higher for liquefied blue hydrogen. As hydrogen is also relatively expensive compared to ammonia, reducing the cost of liquefaction is a challenge at present.

In addition, due to issues such as the capacity of on-board liquefied hydrogen tanks, the development of hydrogen engines under the GI Fund is initially planned for use on liquefied hydrogen carriers and for short sea shipping routes such as those between Japan and South East Asia.

Which of these alternative fuels will be the main one? Many research institutes around the world predict that all will remain in 2050. Against this background, this paper describes the development of methanol, ammonia and hydrogen combustion engines.

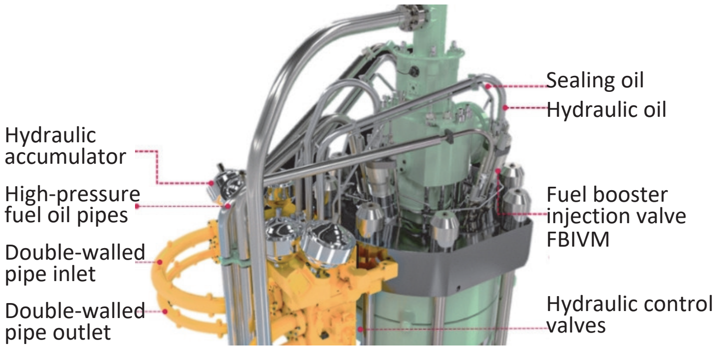


Fig. 1 MAN low-speed, two-stroke methanol engine G95ME-C10.5-LGIM (cylinder diameter: 950 mm), showing the cylinder cover section (courtesy of MAN ES)

Fig. 2 Single-cylinder test engine SCE920 (cylinder diameter: 920 mm) for WinGD's low-speed, two-stroke methanol engine development (courtesy of WinGD)

3. TRENDS IN THE DEVELOPMENT OF METHANOL (CH_3OH) DF ENGINES

3.1 Low-speed, Two-stroke Methanol Engines

To begin with, the diesel-type methanol engine will be described. Both MAN and WinGD are developing low-speed, two-stroke main engines of this type. The properties of methanol and diesel spray combustion were described in the previous paper. Methanol has a boiling point of 65 °C at ambient pressure and can be fed as a liquid to the engine at line pressure (1.3 MPa according to Mitsui E&S [4]), allowing normal diesel injection into the cylinder. However, as the calorific value per volume is approximately 40 % that of heavy fuel oil, a system that injects 2.5 times the volume is required to achieve the same output.

Methanol has a low flash point of 9 °C, but a high ignition point (self-ignition temperature) of 440 °C, requiring pilot injection of diesel oil for ignition in the cylinder. However, as shown in the previous paper, once ignited, it shows better combustion characteristics than gas oil. As mentioned above, low-speed, two-stroke engines developed by MAN are already in service and are technically at the stage of completion, and many orders have been placed recently, particularly for large containerships.

Fig. 1 shows the cylinder cover of an engine with a cylinder diameter of 950 mm developed as the main engine for large container vessels. The 'DF' features three pairs of methanol and heavy fuel oil injection nozzles. The orange part indicates the double-walled pipe section, which is provided as a countermeasure against leakage of low flash point, high toxicity methanol [5].

WinGD has also been conducting combustion rig tests and development work using a four-cylinder test engine (cylinder diameter: 500 mm) for alcohol (ethanol and methanol) fueled main engines since 2015. It is conducting verification with a single-cylinder test engine (Fig. 2, cylinder diameter: 920 mm), and plans operation tests of 10X92DF-M engines with ten cylinders of the same diameter for large containerships in the first quarter of 2025 [6].

3.2 Medium-speed, Four-stroke Methanol Engines

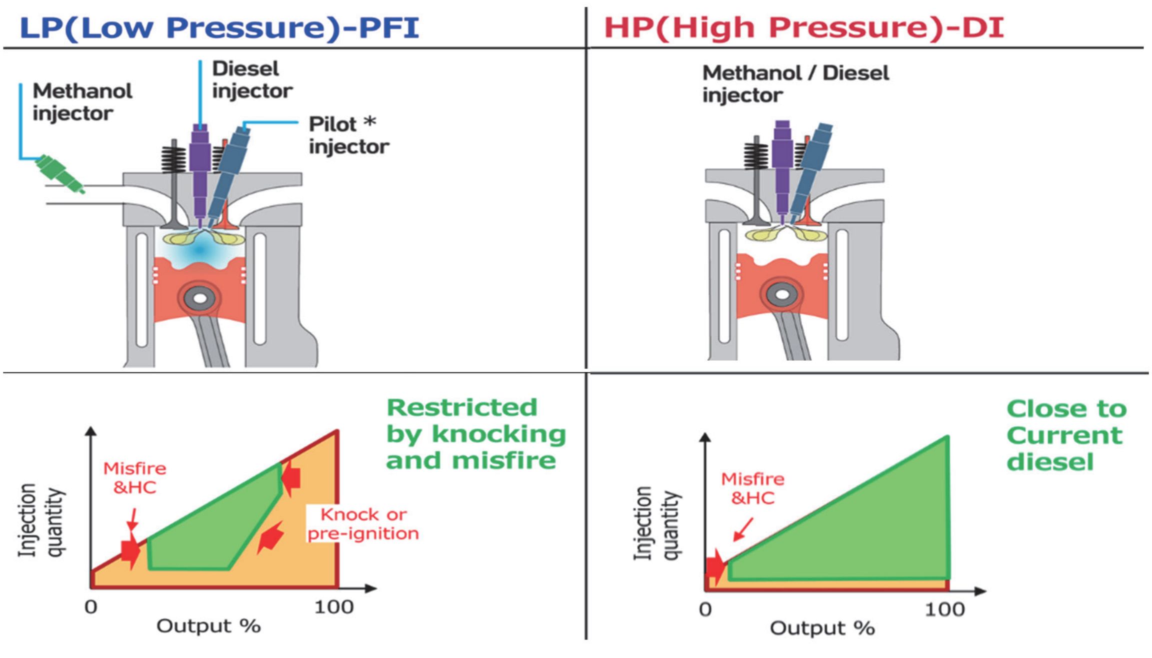


Fig. 3 Two combustion patterns for medium-speed, four-stroke methanol engines [7]

Medium-speed, four-stroke methanol engines are being developed for onboard generators or as main engines of small and medium-sized vessels. The combustion patterns of the diesel type and the Otto-cycle type are introduced here using Fig. 3.

In diesel-type combustion (right half of Fig. 3: HP (High-Pressure)-DI (Direct Injection)), high-pressure liquid methanol is injected into the high-pressure air compressed by the piston to create a spray combustion process. In addition to the injection system for diesel oil, a methanol injection system with an injection volume of 2.5 times that of diesel fuel is required, as already mentioned. The advantage of the diesel-type over the Otto-cycle type is that abnormal combustion such as knocking does not occur, so it is possible to aim for high output (high Pme: mean effective pressure) and high efficiency.

In Otto-cycle combustion (left-half of Fig. 3: LP(Low-Pressure)-PFI(Port Fuel Injection)), methanol is injected into the intake port, and the vaporized methanol and air mixture is compressed by the piston and then ignited by pilot injection to start flame propagation. The low-pressure injection system for the intake port is simpler and easier to retrofit than the diesel-type high-pressure injection system. However, as knocking, etc. may occur, the methanol percentage and the power range with methanol tend to be restricted, as shown in the diagram at the bottom left in Fig. 3 (the green and brown areas in the diagram are the methanol and diesel oil use ranges, respectively).

YANMAR POWER TECHNOLOGY CO., LTD. (YANMAR) and DAIHATSU DIESEL MFG. CO., LTD. (DAIHATSU DIESEL) in Japan have compared both combustion patterns using test engines and presented their results [7), 8)]. Both companies have also announced plans to launch engines compatible with methanol fuel in 2026.

HANSHIN DIESEL WORKS, LTD. has already developed a low-speed, four-stroke engine, LA28M, with a cylinder diameter of 280 mm. This engine is the diesel type and targets a methanol mono-fuel engine instead of DF. However, even when methanol is not used, redundancy is ensured by increasing the amount of marine diesel oil which is originally used for pilot use, making it possible to sail at the speed required by the classification [9)].

Furthermore, AKASAKA Diesels Limited is also developing a low-speed, four-stroke diesel-type methanol DF engine [10)], for which an electronically controlled common-rail methanol injection system will be applied.

On the European side, MAN has developed L21/31DF-M (cylinder diameter: 210 mm) and L27/38DF-M (cylinder diameter: 270 mm) engines with generator-set specifications by applying the Otto cycle type. MAN is also announcing that it will start offering retrofit packages for conversion of larger four-stroke conventional models to methanol DF [11)].

The Wartsila 32 (cylinder diameter: 320 mm) methanol engine applying the diesel type has already been developed and released by Wartsila, a pioneer in this field, and a method for converting conventionally-fueled vessels to methanol fuel has also been announced [12)].

In the case of diesel-type four-stroke engines, the fuel injection nozzle must be installed in the center of the cylinder head, unlike low-speed, two-stroke engines. For this reason, a fuel injection nozzle with multiple needle valves for methanol and diesel oil, respectively, in one nozzle body has been developed.

4. TRENDS IN THE DEVELOPMENT OF AMMONIA (NH_3) DF ENGINES

4.1 Low-speed, Two-stroke Ammonia Engines

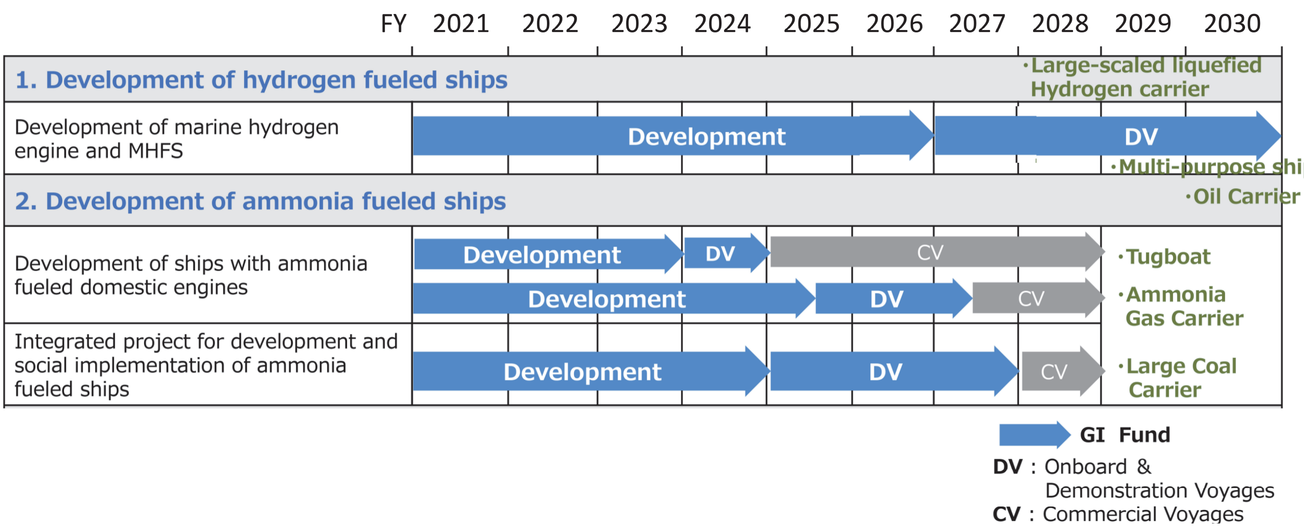


Fig. 4 A part of development schedule of the GI Fund Project for the Development of Next-Generation Ships [13)]

Ammonia-diesel injection types of low-speed, two-stroke main engines are being developed by three licensors, MAN, WinGD and Japan Engine Corporation (J-ENG). Since ammonia has a boiling point of -33 °C at ambient pressure, semi-cooled pressurized type or cooled type tanks are envisaged for onboard liquid storage. When fed into engines, liquid ammonia is further pressurized (according to Mitsui E&S, the line pressure is 8.3 MPa [4)]).

The aforementioned development schedule of the GI Fund is explained using Fig. 4 [13)]. The main engine of the bulk carrier to be built under the “Integrated project for development and social implementation of ammonia-fueled ships,” which is included in “Development of ammonia fueled ships,” will be a low-speed, two-stroke ammonia engine, 7S60-LGIA (seven cylinders, cylinder diameter: 600 mm), developed by MAN and built by Mitsui E&S. MAN has completed tests on one cylinder of the test engine (Fig. 5, cylinder diameter: 500 mm) and will conduct tests of all four cylinders burning ammonia.

In ammonia combustion, there has been a concern about emissions of N_2O, a greenhouse gas about 300 times more potent than CO_2. At present (August 2024), none of the above three companies has disclosed confirmed GHG emissions or environmental performance, but MAN has provided qualitative data (Fig. 5) from the one-cylinder test [4], according to which N_2O emissions are reportedly “very low.” However, because the unburnt ammonia emissions are higher than expected, reduction by reaction with NOx in the SCR is planned.

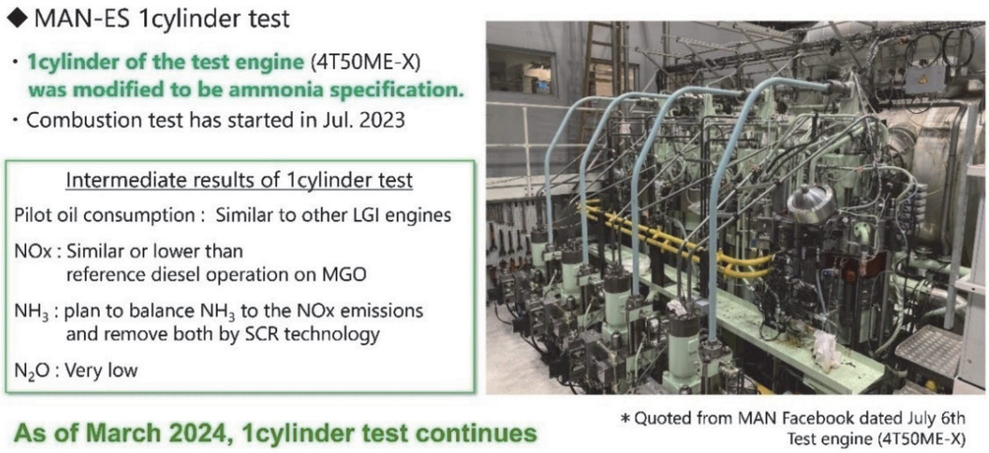


Fig. 5 MAN's one-cylinder ammonia operation test results [4]

Fig. 6 AFMGC: Ammonia-fueled medium gas carrier (projected figure) [14]

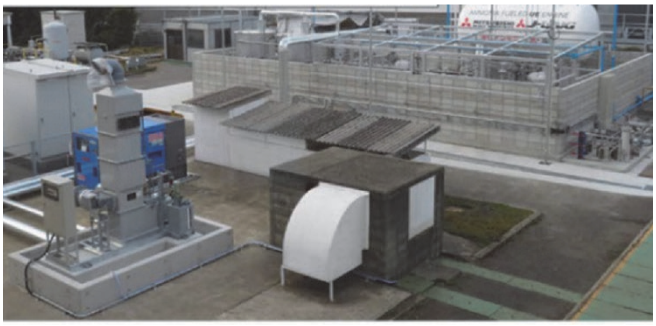



Fig. 7 J-ENG's single-cylinder ammonia test engine (left) and ammonia supply system (right) [15]

Next, “Development of ships with ammonia-fueled domestic engines,” in Fig. 4 is explained. In December 2023, Nippon Yusen Kabushiki Kaisha (NYK), Japan Engine Corporation (J-ENG), IHI Power Systems Co. and Nihon Shipyard Co., Ltd. signed a series of contracts to construct the world's first ammonia-fueled medium gas carrier (AFMGC) equipped with Japanese-made engines. The four companies have formed a consortium with ClassNK since being selected for the GI Fund project, and full-scale world-leading efforts to develop ships with ammonia-fueled domestic engines are now underway [14].

The background and objectives of the project include the following items:

(1) Contribute to the achievement of net-zero emissions in international shipping.

(2) Establish an ammonia value chain

(3) Strengthen Japan's maritime industry

(4) Establish international rules for the use of ammonia in marine applications.

Fig. 7 shows the single-cylinder engine currently being tested at J-ENG and its ammonia supply system [15]. The company conducted the world's first ammonia co-firing test operation on a low-speed, two-stroke engine.

WinGD is also developing a low-speed, two-stroke ammonia engine using a test engine (Fig. 8) [16] and plans to install the 6X52DF-A engine in the second quarter of 2025 as the main engine of an LPG/ammonia carrier to be built in Korea.

In this connection, Mitsubishi Shipbuilding Co., Ltd. is developing an ammonia fuel supply system and an ammonia treatment system, for which an AiP has been issued by ClassNK (April 2024) [17].

Fig. 8　WinGD’s low-speed, two-stroke, single cylinder test engine (cylinder diameter: 520 mm) (courtesy of WinGD)

Fig. 9　A-Tug “Sakigake” (main engine output: 1618 kW x 2 units) [19]

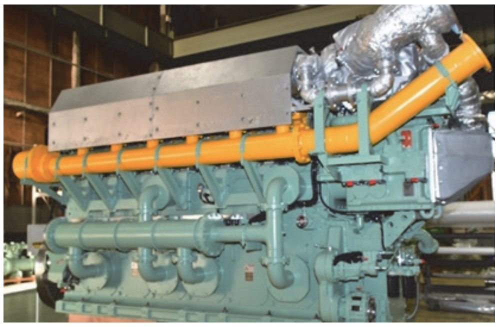


Fig. 10　Medium-speed, four-stroke 28ADF engine for A-Tug (power: 1618 kW/750 rpm/unit, D/S: 280/390 mm, 6 cylinders, Pme: 1.8 MPa) [18]

4.2　Medium-speed, Four-stroke Ammonia Engines

The tugboat for “Development of ships with ammonia-fueled domestic engines” in Fig. 4 is described below. IHI Power Systems has completed a medium-speed, four-stroke ammonia DF engine, which was developed for the main engine of an ammonia-fueled tugboat (Fig. 9: A-Tug). ClassNK issued the world's first classification approval for this engine as an ammonia-fueled marine engine in April 2024 [18]. The engine is currently being fitted to A-Tug, which is engaged in towing operations in Tokyo Bay for a three-month demonstration voyage [19].

This engine is shown in Fig. 10, and is the ammonia Otto cycle type. As with methanol engines of the same type, ammonia is fed into the intake pipe to form a mixture with air. The mixture is compressed by the piston and ignited by pilot diesel oil near TDC. In land-based tests, the fuel-ammonia mixing ratio was gradually increased to achieve a maximum mixing ratio of 95 % (pilot fuel: 5 % of heat). Its N_2O emission is reduced by an after-treatment system, and a GHG reduction rate of more than 90 % is achieved compared to operation with heavy fuel oil.

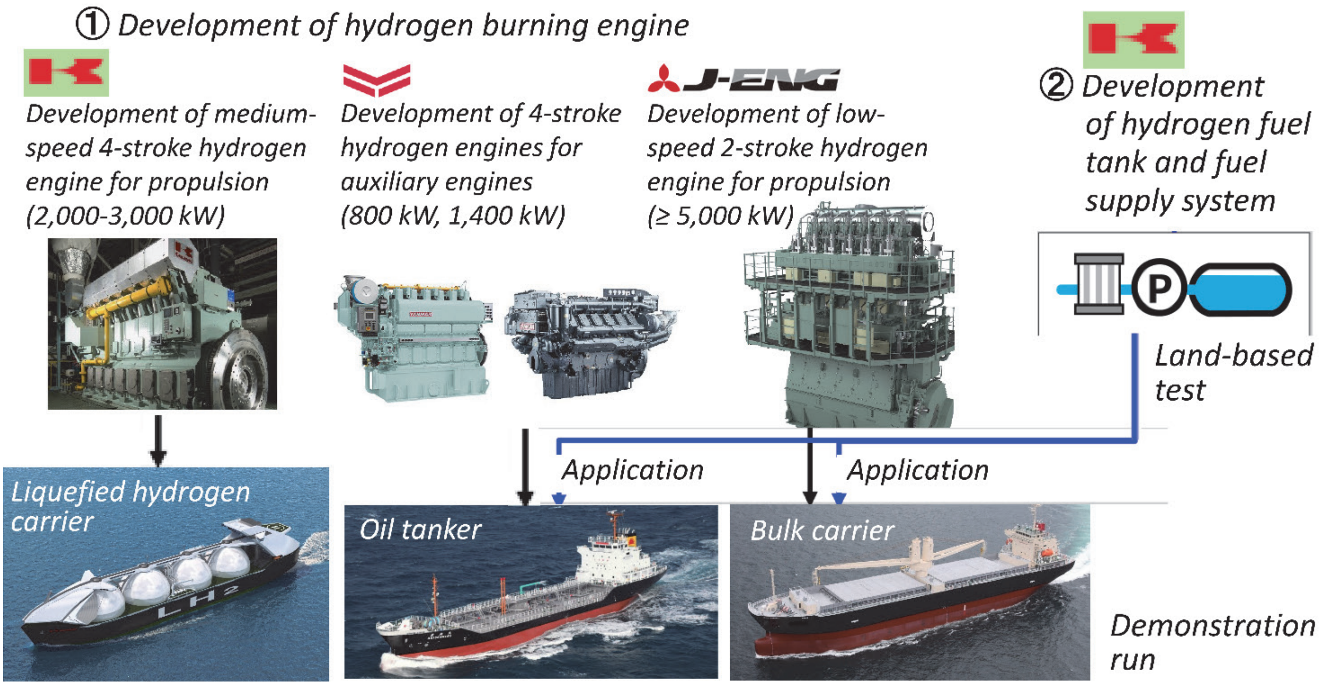
The company has also confirmed the ability to follow load fluctuations required for tugboats and zero ammonia leakage from the actual machine during operation and after shutdown. The company is currently developing an engine (cylinder diameter: 250 mm) for the aforementioned AFMGC’s generator.

YANMAR and DAIHATSU DIESEL are also testing ammonia combustion in single-cylinder engines [7), 8)]. Moreover, basic research is being conducted by the both companies with the aim of improving ammonia combustion by co-firing hydrogen. This will become practical once the technology for reforming of the ammonia to hydrogen on board is established.

In Europe, for example, Wartsila has already developed and started release of a W25 type (cylinder diameter: 250 mm) Otto-cycle type ammonia engine [20)]. As an example, the company has presented the provision of a package including parts from ammonia fuel gas supply to the exhaust gas treatment system, as well as a W25 engine, for a Platform Supply Vessel (PSV) retrofit [20)].

5. TRENDS IN THE DEVELOPMENT OF HYDROGEN DF ENGINES

This chapter explains R&D item 1 "Development of marine hydrogen engines and MHFS (Marine Hydrogen Fuel Systems)" in the development schedule of the GI Fund in Fig. 4.



Project Period: FY 2021-FY 2030 (10 years)

Source: Kawasaki Heavy Industries, Ltd., YANMAR POWER TECHNOLOGY CO., LTD. and Japan Engine Corporation

Fig. 11 Development of marine hydrogen engine and MHFS (Marine Hydrogen Fuel System) (NEDO website)

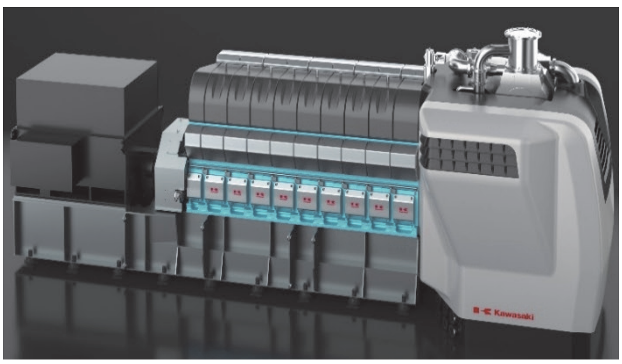


Fig. 12 Hydrogen-fueled DF generator engine (courtesy: Kawasaki Heavy Industries) [22)]

Fig. 13 Hydrogen-fueled multi-purpose vessel (17,500 DWT type) (Rendering) [24)]

Fig. 11 shows an overview of the development of marine hydrogen engines and the Marine Hydrogen Fuel System (MHFS). Kawasaki Heavy Industries' medium-speed, four-stroke hydrogen DF engine (Fig. 12) is scheduled for long-term demonstration as a generator engine of a large liquefied hydrogen carrier, with the aim of developing it as a main engine for propulsion. A basic design approval (AiP) was issued by ClassNK in November 2022 [21].

The hydrogen four-stroke engine in this project is the Otto cycle type, in which hydrogen is supplied at low pressure to the intake port to create a mixture with air. Kawasaki's engine uses exhaust gas recirculation as a technology to suppress abnormal combustion, aiming for a high hydrogen mixing ratio and high power. The hydrogen ratio has already reached 95 % (pilot diesel oil: 5 % of heat), and the output in the hydrogen mode of an eight-cylinder 8L30KG-HDF type (cylinder diameter: 300 mm) is 2.4 MW [22].

The development of four-stroke hydrogen engines as auxiliary engines, as shown in Fig. 11, is under the responsibility of YANMAR. A hydrogen combustion system with diesel micro-pilot ignition has been established through a hydrogen-mixed combustion demonstration test using a single-cylinder engine, and the target has been achieved. Apart from the GI Fund, the company is also developing a high-speed, four-stroke hydrogen engine for a hydrogen-fueled hybrid electric propulsion coastal tanker [23].

In relation to the development of J-ENG's low-speed, two-stroke hydrogen engines in Fig. 11, an AiP was issued by ClassNK in October 2023 for a parcel layout concept for a hydrogen-fueled multi-purpose ship (Fig. 13) by five companies, Mitsui O.S.K. Lines, Ltd., MOL Drybulk Ltd., Onomichi Dockyard Co., Ltd., Kawasaki Heavy Industries, Ltd. and J-ENG [24].

This J-ENG engine is a diesel-cycle type, where hydrogen is injected at high pressure (on the order of 30 MPa) into piston-compressed air. For this reason, Kawasaki developed the MHFS (Marine Hydrogen Fuel System), which supplies high-pressure hydrogen (gas) with less compression work by vaporizing hydrogen pressurized in the liquid phase beforehand. As part of the project, tests of the high-pressure hydrogen injection system are currently in progress by J-ENG, and data on hydrogen embrittlement of engine materials is also being analyzed in collaboration with a research institute [13].

DAIHATSU DIESEL and MITSUI E&S participated in MLIT's “Maritime Industry Intensive Cooperation Promotion Technology Development Support Project” (FY2021-2023) to develop the technology required for a propulsion system for ocean-going ships using hydrogen fuel.

DAIHATSU DIESEL visualized hydrogen combustion as basic research, and started tests using hydrogen supply systems and a single-cylinder engine (Otto cycle type, cylinder diameter: 230 mm, output: 200 kW/900 rpm) from April 2023. As a result, a 96 % GHG reduction (compared to diesel oil) and high output rate equivalent to a natural gas engine could be achieved [25].

MITSUI E&S and its licensor MAN tested hydrogen combustion by modifying one cylinder of the low-speed, two-stroke test engine 4S50ME-T (cylinder diameter: 500 mm, four cylinders, output: 7 MW/117 rpm) [26]. This is a diesel-cycle type based on the ME-GI natural gas engine. A 95 % hydrogen mixing ratio (remaining 5 %: pilot marine diesel oil) at full load operation and a stable combustion state equivalent to those of the other three cylinders operating with marine diesel oil could be obtained, and it was also confirmed that the high-pressure hydrogen required by the engine could be stably supplied from the hydrogen supply system.

In Europe, Wartsila is developing a four-stroke engine and is also working on technology to produce hydrogen from LNG by cracking on board.

A tugboat equipped with two medium-speed hydrogen and gas oil DF engines (power: 2000 kW/set), which was developed by Anglo Belgian Corporation and CMB.TECH, is in operation in the port of Antwerp-Brugge. The tugboat carries compressed hydrogen instead of liquefied hydrogen. In addition, a marine hydrogen mono-fuel engine is being developed [27]. In Japan, JPN H_2YDRO's hydrogen-fueled vessels also use the company's engines [28].

6. SUMMARY

The author described the combustion challenges and solutions for the use of each alternative fuel in the previous paper. This paper has introduced the situation where Dual Fuel engines for marine use are being developed with the challenges solved. Thus, it can be said that engine development has sufficient technological momentum at home and abroad. As mentioned at the outset, issues such as the scale of production of each alternative fuel, supply chain possibilities and costs remain, but it is desirable to perfect the technology, including safety aspects, and to develop human resources who can make use of it, so that they can respond immediately when these issues are resolved.

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Latest Trends in Ship Cybersecurity Regulations

— IACS UR E26/E27 and the Society's Initiatives —

Machinery Department, Plan Approval and Technical Solution Division, ClassNK
Management Systems & Maritime Training Certification Department, Business Assurance Division, ClassNK

1. INTRODUCTION

The rapid digitalization of ships in recent years has increased the risk of cyberattacks. The maritime industry is experiencing a sharp rise in damage caused by ransomware, and actual cyberattacks on ships have also been reported. In this context, ship cybersecurity has gained attention, and the International Association of Classification Societies (hereinafter referred to as IACS) has formulated IACS Unified Requirements (hereinafter referred to as UR) E26 and E27, which came into effect on July 1, 2024, for ships contracted for construction on or after that date. This paper outlines the background and trends in ship cybersecurity regulations, focusing on UR E26 and E27, as well as the Society's initiatives.

1.1 Cybersecurity Threats Surrounding Ships

Traditionally, ship systems such as navigation equipment, engine control systems, and cargo monitoring systems relied on physical connections and controls, and threats such as cyberattacks were not anticipated. However, with the introduction of IoT technology to improve operational efficiency and safety, and the recent launch of relatively inexpensive, high-capacity maritime Internet services such as Starlink provided by SpaceX in the United States and the adoption of automated navigation technology under development, there are an increasing number of cases of ship systems being interconnected via computers and the Internet. As a result, ship systems are increasingly exposed to cyberspace, and the risk of cyberattacks is becoming apparent.

According to statistics from the MTS-ISAC[*1], a maritime-focused cybersecurity information sharing and analysis organization in the United States, 15 % of all cyberattacks on the maritime sector in June 2024 were directed at ships. This clearly shows that cyberattacks on ships are definitely occurring and that the number of such attacks is on the rise.

In light of this situation, there is growing interest in cybersecurity in the maritime industry, and countermeasures are required for ships as well.

The specific cyberattack methods reported include ransomware hijacking of ship management systems, GPS spoofing[*2] to falsify location information, and phishing scams to steal crew members' personal information. Table 1 shows the main examples of such attacks.

Table 1 Examples of cyberattacks

2017 June: Maersk, a major shipping company, was hit by a cyberattack using ransomware called NotPetya, affecting its business locations worldwide. The attack disrupted the company's container shipping operations and is said to have caused hundreds of millions of dollars in losses.[3)]
2017 June: In the Black Sea, at least 20 ships experienced anomalies in their GPS receivers, showing their location to be about 32 km inland despite actually being at sea. This phenomenon is strongly suspected to be due to a GPS spoofing attack.[2)]
2019 May: According to the Marine Safety Information Bulletin issued by the U.S. Coast Guard (USCG), there have been reports of cases where emails were sent to ships from email addresses posing as PSC authorities in an attempt to extract confidential information contained in arrival notifications.[5)]
2023 January: The server of DNV's ship management software was attacked by ransomware, restricting access to online functions.[6)]

[*1] Abbreviation for Maritime Transportation System Information Sharing and Analysis Center (MTS-ISAC), an organization that shares and analyzes information on cybersecurity in the maritime field.
[*2] A type of cyberattack that misleads the position information of GPS receivers by transmitting fake GPS signals. There is a risk that this may disrupt the ship's course or cause a collision.

From past reported cases, it is clear that IT systems[*3] on ships are being targeted by cyberattacks such as ransomware and malware. On the other hand, the impact of cyberattacks on OT systems[*4] is still largely unknown, as details such as specific damage and attack methods are rarely made public. One reason for this is that if cybersecurity measures are inadequate, it is difficult to even notice that an attack has occurred. In addition, the risk of disclosing details of an attack could lead to damage to a company's reputation and loss of trust from business partners, as well as triggering further cyberattacks, which seems to be another reason why companies are hesitant to disclose information.

1.2 Trends in International Cybersecurity Countermeasures

In response to the increasing cybersecurity risks to ships, the International Maritime Organization (hereinafter referred to as IMO) and IACS are working to strengthen cybersecurity measures for ships.

1.2.1 IMO Initiatives

The IMO is progressively strengthening its efforts related to ship cybersecurity.

- ISPS Code

The ISPS Code (International Ship and Port Facility Security Code), adopted in 2004, focuses on physical security measures for ships and port facilities. While it does not directly require cybersecurity measures, it does require that the Ship Security Assessment (SSA) and Ship Security Plan (SSP) address vulnerabilities in computer-based systems and networks, and establish procedures for the protection of confidential information in electronic form. These are the foundation of cybersecurity measures. The ISPS Code is mandatory for Contracting Governments to the SOLAS Convention (International Convention for the Safety of Life at Sea).

- Resolution MSC.428(98)

Resolution MSC.428(98), adopted in 2017, recommends incorporating cyber risk management in a ship's Safety Management System (SMS). It requires that cyber risks be assessed in the same way as other risks in ship operations, and that appropriate measures be taken. This resolution is a recommendation, but many flag states have made it mandatory.

- GUIDELINES ON MARITIME CYBER RISK MANAGEMENT (MSC-FAL.1/Circ.3)

MSC-FAL.1/Circ.3, approved[*5] in 2017, supports the implementation of Resolution MSC.428(98). It provides specific recommendations on the roles, activities, and measures of shipping companies to assist ship operators and shipowners in implementing cyber risk management. It also refers to cybersecurity guidelines and standards issued by IACS, Baltic and International Maritime Council (hereinafter referred to as BIMCO), National Institute of Standards and Technology (hereinafter referred to as NIST)[*6], and others. While the GUIDELINES ON MARITIME CYBER RISK MANAGEMENT itself is not mandatory, it serves as a reference for ship operators and shipowners to establish and operate an effective cyber risk management system.

1.2.2 IACS Initiatives

IACS established the Cyber Systems Panel in 2016, where experts from each classification society gather to share information on the latest cybersecurity technologies and threats and discuss the development of unified rules.

- Twelve IACS Recommendations (hereinafter referred to as Rec.)

By November 2018, twelve Recs. had been published. These recommendations provide specific guidelines for ship cybersecurity measures, covering a wide range of areas which are recommended procedures for software maintenance of shipboard equipment and systems, recommendations concerning manual/local control capabilities for software dependent machinery systems, contingency plans for onboard computer based systems, network architectures, data assurance, the physical security of onboard computer based systems, the network security of onboard computer based systems, vessel system design, inventory lists of computer based systems, integration, remote update/access and communication and interfaces.

- Rec. No. 166

[*3] Abbreviation for Information Technology (IT) system, a system that collects, processes, stores and transmits data. On board ships, PCs for clerical work, etc. fall under this category.

[*4] Abbreviation for Operational Technology (OT) system, a system that monitors and controls physical processes and equipment. On board ships, systems such as navigation equipment, engine control systems, and cargo monitoring systems also fall under this category.

[*5] Regular updates are carried out, and MSC-FAL.1/Circ.3/Rev.2 was approved in 2022.

[*6] US government agency that conducts research and development on technology, measurement and standards. Also develops various guidelines and frameworks in the field of cybersecurity.

Prior to the development of UR E26 and E27, work was undertaken to consolidate the above twelve Recs. into one, and in May 2020, Rec. No. 166 was issued as a recommendation on cyber resilience. It summarizes the recommended cybersecurity measures for the construction and operation of new ships. It comprehensively shows the matters to be considered in each stage of ship design, construction, and operation, and specifically includes measures based on risk assessment, network separation, access control, system updates and crew education.

- UR E26 and E27

Based on the results of its previous efforts, IACS newly formulated two URs, E26 and E27, in April 2022, which stipulate requirements for cybersecurity. These are requirements for capabilities (hereinafter referred to as cyber resilience) to reduce the occurrence of cyber incidents due to cyberattacks, etc., to mitigate their impact, and to ensure early recovery in the event of an incident, based on the premise that cyberattacks will occur. UR E26 mainly stipulates the framework for cyber resilience of the entire ship, and UR E27 stipulates the security requirements for systems and equipment installed on board ships. The purpose of these is to realize ships with at least a minimum level of cyber resilience.

Initially, UR E26 and E27 were scheduled to come into force on January 1, 2024, but IACS revised UR E27 in September 2023 and UR E26 in November of the same year, based on feedback from the industry, clarification of inspection requirements, and limitations on the applicable ships. The revised versions of UR E26 and E27 came into effect on July 1, 2024 for ships for which construction contracts are concluded on or after that date.[*7]

2. OBJECTIVES AND OVERVIEW OF UR E26 AND E27 REQUIREMENTS

This chapter explains the objectives and overview of the UR E26 and E27 requirements. For details of the requirements, please refer to the Society's own guidelines, which are introduced in Chapter 3.

2.1 Relationship between UR E26 and E27

UR E26 stipulates a comprehensive framework for ensuring the cyber resilience of the entire ship, while UR E27 stipulates specific technical requirements for individual systems and equipment within the scope of UR E26. UR E26 also clarifies the cooperation and division of responsibilities among stakeholders, while UR E27 requires suppliers to ensure the security of computer based systems under their responsibility. (Fig. 1)

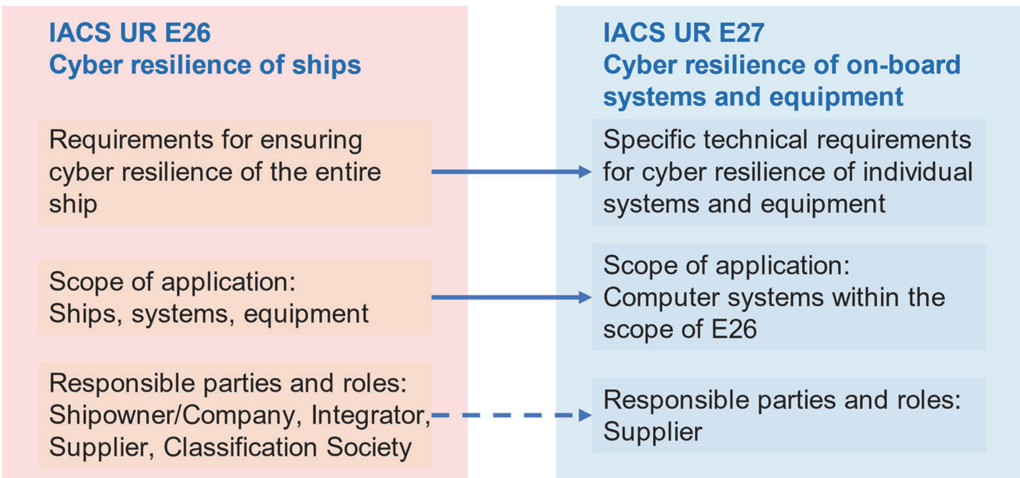

Fig. 1 Relationship of UR E26 and E27

2.2 Objectives and Overview of UR E26 Requirements

UR E26 is a rule that applies to the entire ship and mainly stipulates requirements related to shipyards (systems integrators) and shipowners. Specifically, it aims to safely integrate Operational Technology (OT) systems and Information Technology (IT) systems into the ship's network throughout the various stages of ship design, construction, commissioning, and operation, and stipulates requirements such as "Identify," "Protect," "Detect," "Respond" and "Recover."

[*7] The initial versions were withdrawn before the start of application.

2.2.1 UR E26 Objectives and the NIST Cybersecurity Framework

The requirements of UR E26 are organized and defined based on the five core elements of the NIST Cybersecurity Framework, referring to Rec. 166, guidelines from each classification society, BIMCO guidelines, NIST SP 800-53 and others. The objectives for each element are tailored to the specific characteristics of the ship so as to achieve the following goals (Fig. 2):

- Identify: To gain a comprehensive understanding of the ship's systems, the people involved, data, equipment, etc., and to identify and deepen the organizational understanding of cybersecurity risks.
- Protect: To implement measures to safeguard the ship from cyber incidents and to ensure the continuation of ship operations even in the event of an attack.
- Detect: To establish mechanisms for promptly detecting and identifying the signs of cyber incidents.
- Respond: To implement response measures to minimize damage in the event of detecting a cyber incident.
- Recover: To secure means for swift recovery and return to normal operation if ship functions are impaired due to a cyber incident.

Fig. 2 Five core elements of the NIST Cybersecurity Framework[4)]

2.2.2 Ships Subject to UR E26

The following ships, etc., are subject to UR E26:

- Passenger ships (including passenger high-speed craft) engaged in international voyages
- Cargo ships of 500 GT and upwards engaged in international voyages
- High speed craft of 500 GT and upwards engaged in international voyages
- Mobile offshore drilling units of 500 GT and upwards
- Self-propelled mobile offshore units engaged in construction (i.e., wind turbine installation, maintenance and repair, crane units, drilling tenders, accommodations, etc.)

Application to ships not engaged in international voyages and cargo ships of less than 500 GT is not mandatory.

2.2.3 Systems Subject to UR E26

UR E26 applies to onboard OT systems with the following functions, where the impact of a cyber incident could endanger human safety, the safety of the ship or the environment:

(a) Propulsion
(b) Steering
(c) Anchoring and mooring
(d) Electrical power generation and distribution
(e) Fire detection and extinguishing systems
(f) Bilge and ballast systems, loading computers
(g) Watertight integrity and flooding detection
(h) Lighting (e.g., emergency lights, low location lights, navigation lights, etc.)
(i) Any required safety system whose disruption or functional impairing may pose risks to ship operations (e.g., emergency shutdown systems, cargo safety systems, pressure vessel safety systems, gas detection systems, etc.)
(j) Navigational systems required by statutory regulations
(k) Internal and external communication systems required by class rules or statutory regulations

Furthermore, UR E26 stipulates that any IP-based communication interfaces connected to these OT systems are also to be within the scope of application. Therefore, systems and equipment other than the above OT systems may also be subject to UR E26.

2.2.4 Risk Assessment and Exemptions under UR E26

UR E26 states that if the systems integrator can demonstrate to the classification society that a system meets four criteria and considers three additional criteria, and the classification society approves, then that system can be excluded from the requirements of UR E26.

2.3 Overview and Objectives of UR E27 Requirements

UR E27 is a rule that applies to systems and equipment installed on board ships, and mainly stipulates requirements related to suppliers. Specifically, it defines the requirements for the cyber resilience of systems and equipment, the interface between onboard users and computer based systems, and the product development requirements for new products aiming to ensure cyber resilience at the product level.

2.3.1 Scope of Application of UR E27

UR E27 stipulates that it is applicable to computer based systems specified in UR E26 on ships subject to UR E26.

2.3.2 Security Capability Requirements of UR E27

UR E27 specifically defines the requirements for security capabilities to be implemented in systems. These requirements are based on IEC 62443-3-3, an international standard for the security of industrial automation and control systems, and some parts of it have been adopted. Specifically, 30 “required security capabilities” and 11 “additional required security capabilities” for computer based systems connected to untrustworthy networks are defined. These security capabilities are specific countermeasures that computer based systems should have, such as “authentication,” “access control,” “encryption” and “anti-malware.” By meeting these requirements, the risk of cyberattacks can be reduced, and the security of the system can be ensured.

2.3.3 Secure Development Lifecycle (SDLC) Requirements of UR E27

UR E27 defines requirements for the lifecycle related to the development and maintenance of secure products, and requires the introduction of a development process that considers security in the development of systems and equipment. Specifically, seven requirements are defined, such as “Controls for private keys,” “Security update documentation,” “Dependent component security update documentation,” “Security update delivery,” “Product defence in depth,” “Defence in depth measures expected in the environment” and “Security hardening guidelines.” This allows for the elimination of security vulnerabilities from the development stage, leading to the construction of more secure systems.

3. SOCIETY INITIATIVES AND SUPPORT FOR UR E26 AND E27

This is the first time that cybersecurity measures have been incorporated as mandatory requirements for newbuilding ships, and the impact is significant. Therefore, the Society has been working on prompt rulemaking and information dissemination. The Society has been providing information such as its own guidelines explaining the requirements of UR E26 and E27 for suppliers, shipyards and shipowners who need to comply with the requirements, interactive workshops with specific examples for compliance and explanatory videos.

3.1 Incorporation of UR E26 and E27 into the Society’s Rules

Following the issuance of UR E26 and E27, the Society incorporated these requirements into its rules. To incorporate the two URs into Part X and Part B of the Rules for the Survey and Construction of Steel Ships, as well as the “Guidance for the Approval and Type Approval of Materials and Equipment for Marine Use,” the Society held deliberations by an expert committee consisting of experts (December 2023) and the Technical Committee (January 2024), and issued a revised version on June 27, 2024.

Fig. 3 shows the structure of Part X of the Rules for the Survey and Construction of Steel Ships, which mainly stipulates the requirements of the two URs.

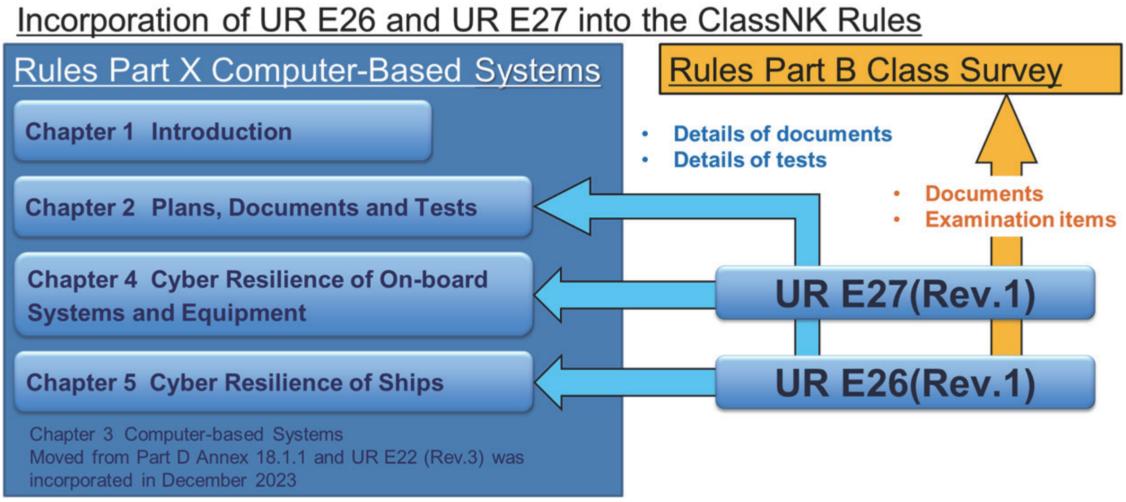

Fig. 3 Incorporation of UR E26 and E27 into the Society's Rules
(Structure of Part X of Rules for Steel Ships)

The Society has newly established provisions for "Approval of Use*8 of Systems and Equipment with Improved Cyber Resilience" in Chapter 10 of Part 7 of the "Guidance for the Approval and Type Approval of Materials and Equipment for Marine Use." This allows suppliers to obtain a certificate of approval for use in advance, certifying that equipment, etc., that meets the cybersecurity requirements complies with the regulations, before preparing for installation on board ships.

3.2 Guidelines Explaining the Requirements of UR E26 and E27

First, the Society believes that it is necessary to have equipment that meets the cybersecurity requirements available in the market. Therefore, the Society issued its own guidelines "Guidelines on Cyber Resilience of Onboard Systems and Equipment" in November 2023 to explain UR E27, which stipulates the requirements for equipment.

Furthermore, in July, 2024, the Society issued its own guidelines "Guidelines on Cyber Resilience of Ships" to explain the requirements of UR E26. Fig. 4 shows each guideline and their structure.

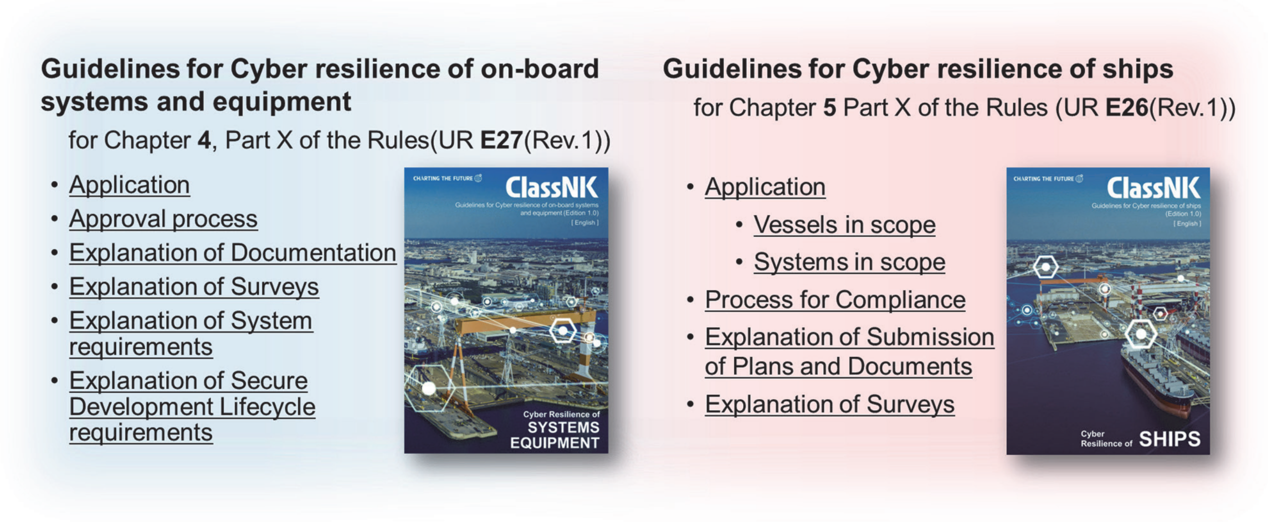

Fig. 4 Guidelines explaining the requirements of UR E26 and E27 and their structure

In particular, the Society aimed to make its two guidelines "easy to understand" as explanatory books by providing many examples that are not mentioned in the URs. For example, the Society provides specific examples of systems to which the cybersecurity requirements apply, such as engine control systems, steering system control systems, fixed CO_2 fire extinguishing

*8 For equipment, etc., for which the rules, etc. stipulate that the approval of the Society for it use must be obtained in advance, before preparing for installation onboard a ship, representative individual products are examined, tested and inspected in advance as stipulated in the Guidance, and the Society approves that the equipment conforms to the provisions.

systems and radars. Fig. 5 shows a part of these.

Propulsion

Engine control systems	Engine remote control systems
Main boiler control systems	CPP control systems
Electric propulsion control systems	FGSS control systems
Machinery alarm and monitoring systems (including data loggers)	Waterjet propulsion systems

Electrical power generation and **distribution**

Generator engine control systems (including power management systems)	Electric power converters (for electric propulsion ship)
Battery management systems (consisting of lithium-ion batteries with total capacities of 20 kWh or more, and associated equipment)	

Fig. 5 Examples of systems subject to application in the Guidelines

3.3 Portal Page

On its website, the Society provide explanatory videos and FAQs (which are updated regularly). All of these can be viewed on the portal page that aggregates information and materials related to UR E26/E27 on the website.
(https://www.classnk.or.jp/hp/en/activities/cybersecurity/ur-e26e27.html)

The portal page provides the following information and materials and is constantly being updated:

- Related rules
- Application forms for approval of use
- Guidelines
- FAQs
- Explanatory videos

3.4 ClassNK Academy

For those who wish to deepen their understanding in a more specialized manner, the Society has also established a new course on cyber resilience of onboard systems and equipment for developers and designers of marine equipment at the ClassNK Academy. In this course, the Society invites lecturers from the Control System Security Center (CSSC), which is a technology research association engaged in certification work for IEC 62443, an international standard for cybersecurity of industrial equipment and the basis of UR E27. The lecturers explain the basic concepts of the IEC standard, the security capabilities required by UR E27 and the secure development lifecycle.

4. CONCLUSION AND FUTURE PROSPECTS

In this paper, the Society introduced the ship cybersecurity regulations UR E26/E27 and the Society's own initiatives. The cybersecurity environment surrounding ships is changing every day, and the introduction of new technologies such as autonomous ships is expected to require further measures.

In the future, the digitalization and automation of ship operations will accelerate, and the use of cyberspace will advance. In addition to responding to URs and IMO guidelines, multifaceted security enhancements such as responding to automation and autonomy, collecting and sharing threat information, developing security personnel and utilizing new technologies are essential.

The Society's mission is to realize safe and sustainable shipping, and the Society considers improving the cyber resilience of ships to be an important element of that mission. The Society will continue to work with stakeholders to promote initiatives in this area.

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Investigation on Nonlinearity of Vertical Wave Bending Moment Based upon CFD

Kei SUGIMOTO*, Yuki YOSHIDA**

1. INTRODUCTION

Vertical wave bending moment is one critical factor in hull structure design, and appropriate consideration of this moment is essential. In classification society's rules, the Unified Requirements (URS11 and UR S11A) and Common Structural Rules (CSR) of the International Association of Classification Societies (IACS) specify the vertical wave bending moment, and formulate the maximum value (maximum hogging moment) and minimum value (maximum sagging moment) of the vertical bending moments that occur during the design life of the ship [1), 2), 3)]. In addition to the maximum expected value (e.g., value of the 10^{-8} probability of exceedance) obtained based on the linear theory, these formulae also take into account, either explicitly or implicitly, the nonlinear effects that occur under large wave heights, as well as the effects of maneuvering. Among these, focusing on nonlinear effects, nonlinear effects are formulated explicitly in UR S11A, which was developed in recent years, but these rules are limited to container ships, and in UR S11, which was developed prior to UR S11A, those effects are not clearly specified.

Various research results in connection with nonlinear effects have been reported. However, if those effects are classified in several levels, Computational Fluid Dynamics (CFD) is positioned as a "Fully Nonlinear" computational technique [4), 5)], and its effectiveness has been reported [6), 7), 8)], particularly in studies that consider slamming impact forces and green water loads, and in evaluations of whipping elastic vibration by coupled structural analysis. However, when estimating the 10^{-8} maximum expected value, it is necessary to perform calculations equivalent to 1 000 waves, even assuming that the expected value is roughly equal to the 10^{-3} maximum expected value in the most severe short-term sea state [9)]. Thus, from the viewpoint of computational time, it would be particularly difficult to apply this approach in applications that examine the nonlinear effects of diverse ships within a practical timeframe.

As methods that consider practicality and reduce computational costs, several techniques which estimate the wave profile that makes the largest contribution to responses have been proposed, and as one such methods, several design irregular wave methods have been proposed [10), 11), 12), 13)]. Dietz proposed the Most Likely Response waves (MLRW) for the estimation of the maximum expected value of the vertical wave bending moment of container ships, and showed that the results of a direct time-series calculation corresponding to the probability of exceedance and the results of a calculation using the MLRW are in good agreement [12)].

Therefore, in this research, trial calculations of the nonlinearity of vertical wave bending moments that can occur in the extreme sea states considered in hull structural design were carried out for a total of 55 ships by using CFD, which is an advanced analytical technique, and giving wave conditions for a design irregular wave MLRW, and the tendencies and other features of the obtained vertical bending moments were considered.

2. IACS UNIFIED REQUIREMENTS (UR)

2.1 IACS UR S11

In IACS UR S11 (Rev. 10, 2020) and IACS CSR B&T (2023), the vertical wave bending moments (hogging $M_{WV\text{-}Hog}$ and sagging ($M_{WV\text{-}Sag}$) are given by the following formulae [1), 2)]:

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** Rule Development Department, Research and Development Division, ClassNK
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$$M_{WV-Hog} = +190MCL^2BC_b \times 10^{-3} \quad (kN \cdot m)$$
$$M_{WV-Sag} = -110MCL^2B(C_b + 0.7) \times 10^{-3} \quad (kN \cdot m) \qquad (1)$$

where, L is the ship length, B is breadth, and C_b is the block coefficient. C is a coefficient specified corresponding to the length of the ship, and M is a distribution factor expressing the distribution along the ship length, and is 1.0 around midship.

The difference between the formulae for hogging and sagging occurs because the nonlinearity of sagging moment is considered. Accordingly, if it is assumed hypothetically that hogging is linear equivalent, this means that a nonlinear effect of 110 (C_b + 0.7) / (190 C_b) occurs in sagging moment.

2.2 IACS UR S11A

Next, among the said bending moments specified in IACS UR S11A (2015), those of the midship section are given by the following formulae [3)]:

$$M_{WV-Hog} = +1.5f_R L^3 C C_w \left(\frac{B}{L}\right)^{0.8} f_{NL-Hog} \quad (kN \cdot m)$$
$$M_{WV-Sag} = -1.5f_R L^3 C C_w \left(\frac{B}{L}\right)^{0.8} f_{NL-Sag} \quad (kN \cdot m) \qquad (2)$$

$$f_{NL-Hog} = 0.3\frac{C_b}{C_w}\sqrt{T}$$
$$f_{NL-Sag} = 4.5\frac{1+0.2f_{Bow}}{C_w\sqrt{C_b}L^{0.3}} \qquad (3)$$

where, C_W is waterplane area coefficient, and f_R is a factor related to the operational profile and is to be taken as 0.85. $f_{NL\text{-}Hog}$ and $f_{NL\text{-}Sag}$ are nonlinear correction factors for hogging and sagging moments, respectively, and depend on C_b, C_w, and T (scantling draught). In the case of sagging, the vertical bending moment is formulated including a bow flare shape coefficient (f_{Bow}) to take into account differences in the pressure-receiving area of the bow. With the exceptions of f_R and $f_{NL\text{-}Hog/Sag}$, the formulae are equivalent to the 10^{-8} values. In addition to the above, formulae are also provided for distribution of the vertical wave-induced bending moments along the ship's length. Although the product of formula (2) multiplied by 1.0 is considered for around midship, it is characteristic feature that the range is different for hogging and sagging.

3. TARGET SHIPS OF CALCULATIONS

The target ships of the calculations were a total of 55 vessels of various types, including bulk carriers, oil tankers, and container ships. Each vessel was modeled for the Full load condition and the Ballast condition (i.e., total of 110 models). Fig. 1 shows the principal particulars of the target ships. The plots of the red circles in Fig. 1 show CSR-applied ships, blue shows container ships, and the remainder indicate other types of ships. _slender and _blunt mean $C_b < 0.7$ and $C_b \geq 0.7$, respectively. It should be noted that the parameters C_b, C_W, and T, etc. in the figure are not values defined by the rules (i.e., not scantling draught-based values), but rather, the values used in the computational models. In the following, C_b, C_W, and T are different between Full load condition and Ballast condition.

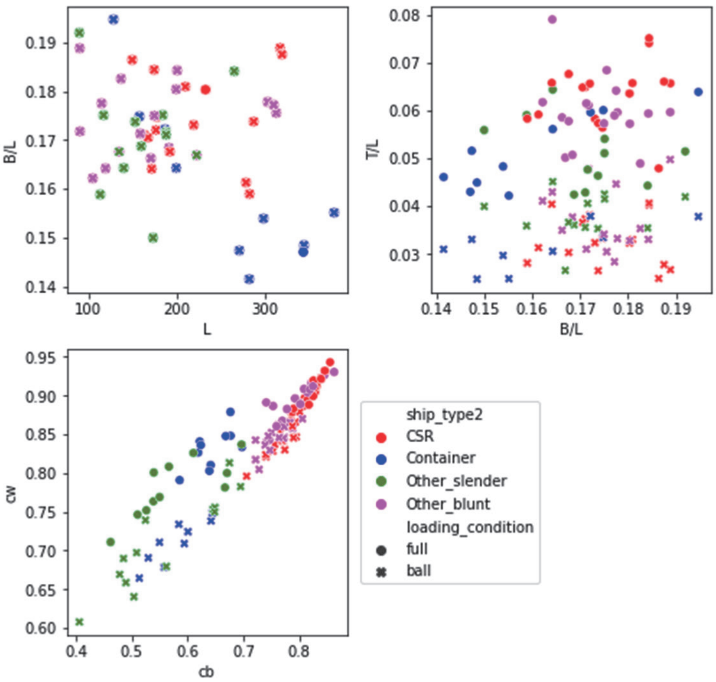


Fig. 1　Principle particular of target ships (circles: Full load condition, crosses: Ballast condition)

4.　NUMERICAL SIMULATIONS BY DESIGN IRREGULAR WAVE AND CFD

4.1　Analysis Program

In order to construct the dataset (Response Amplitude Operator, RAO, and phase difference) necessary in identification of the sea state conditions described in the following and creation of the design irregular wave, a linear load analysis program (3DPM.L) developed by the Society employing a 3-dimensional Green's function approach [14] was used. In the prepared design irregular wave MLRW, the commercial CFD program, Simcenter STAR-CCM+ 2210 [15], was used to reproduce vertical bending moments including nonlinear effects.

4.2　Flow

The flow shown in Fig. 2 was used in calculating the vertical bending moments in large waves height. In this study, we focused on reproduction of the vertical bending moments that occur under short-term sea state equivalents considered in the IACS UR described in Chapter 2.

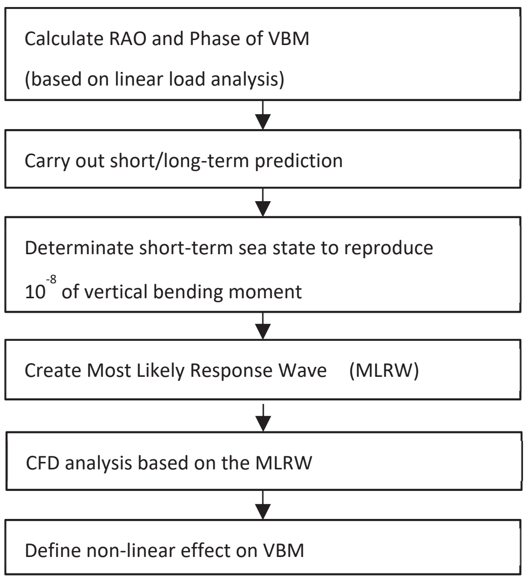


Fig. 2　Flowchart to reproduce vertical wave bending moment in extreme seas and define non-linear effect on the moment

4.3 Sea State Conditions Considered

As the sea state conditions, the North Atlantic wave spectrum and scatter diagram specified in IACS Recommendation No. 34 (2022) were used [16), 17)]. Based on the RAO of the vertical bending moments of the target ships obtained using that information and 3-DPM.L, the 10^{-8} values were found by statistical predictions for each ship, and the target values in the design irregular wave described below were set.

A ship speed of 5 knots was used in the calculations of RAO.

4.4 Design Irregular Wave

The vertical bending moment η (t) was associated with the wave ζ (t) according to formulae (4) and (5) based on the dataset of the RAO and the phase differences of the vertical bending moments obtained by the analysis by 3-DPM.L.

$$\zeta(t) = \sum_{n=1}^{N} a_{\zeta,n}^{e}\left[V_n \cos\left(-\omega_{e,n}t\right) + W_n \sin\left(-\omega_{e,n}t\right)\right] \quad (4)$$

$$\eta(t) = \sum_{n=1}^{N} a_{\eta,n}^{e}\left[V_n \cos\left(-\omega_{e,n}t + \theta_{\eta,n}^{e}\right) + W_n \sin\left(-\omega_{e,n}t + \theta_{\eta,n}^{e}\right)\right] \quad (5)$$

where, $a_{\zeta,n}^{e}$ is the wave amplitude, $a_{\eta,n}^{e}$ is the amplitude of the response, $\omega_{e,n}$ is frequency, $\theta_{\eta,n}^{e}$ is the phase difference of the response, V_n and W_n are random numbers that follow a standard normal distribution. The superscript e expresses the condition of encounter between the wave and the ship. The amplitudes of the wave and the response are expressed by $\sqrt{2S(\omega_{e,n})\Delta\omega_{e,n}}$ ($\Delta\omega_{e,n}$: difference of $\omega_{e,n}$) using their respective spectra $S(\omega_{e,n})$.

Next, the set of the Conditional Random Response Waves (CRRWs) which cause responses that satisfy the condition shown by formula (6) (magnitude of response at time $t = 0$: a_η, response: maximum or minimum, instantaneous frequency of response: ω_η) is obtained, and the MLRW is characterized by the average of the set.

$$\zeta(t)\ |_{a_\eta,\omega_\eta} \equiv \hat{E}\left[\zeta(t)\ \middle|\ \eta(0) = a_\eta, \dot{\eta}(0) = 0, \frac{\dot{\hat{\eta}}(0)}{\eta(0)} = \omega_\eta\right] \quad (6)$$

where, a_η is the magnitude of the targeted vertical bending moment, ω_η is the instantaneous frequency of the moment, $\hat{E}[\cdot|\cdot]$ is the conditional average, $\dot{\eta}(t)$ is the time derivative of the response, and $\hat{\eta}(t)$ is the Hilbert transform of the response. a_η is the value at midship section. ω_η is given by m_1/m_0 (m_n: n-th moment of the response spectrum). If m_n is the moment of a wave spectrum, this is a quantity which is equivalent to the mean wave angular frequency ($2\pi/T_{m01}$) [18)]. The analytical expressions of CRRW and MLRW are known when ω_η is given in this manner [12), 19), 20)]. The wave direction of MLRW in all the target ships was fixed as a head sea (180°).

As an example, Fig. 3 shows the associated wave $\zeta(t)$ (Fig. 3, top) and vertical bending moment $\eta(t)$ (bottom) for the hogging moment of a bulk carrier (hereinafter, BC-10) having L = abt. 290 m in the Full load condition. In the top part of the figure, the gray lines indicate a group 25 CRRW waves, the green line shows one wave in that group, and the red line shows the mean of the 25 waves. In the same figure, the blue line (MLRW) and the red line (mean of CRRW) diverge due to the limited number of CRRW waves. However, if the number of waves is increased sufficiently, the red line will converge with the blue line. In the obtained MLRW, a peak of the wave height exists at midship when $t = 0$. Therefore, the phases of the elementary waves in the wave spectrum of the MLRW were arranged using the encountered wave number, and the CFD simulation was started from the smooth water state. Furthermore, because the MLRWs at which hogging and sagging moments showed their largest values were those when the positive and negative wave height were transposed, two calculations were performed in the CFD analysis for those MLRWs.

4.5 Setting in CFD

On the assumption that fluids are incompressible, the Reynolds-averaged Navier-Stokes equation (RANS), which is the governing equation for flows, was discretized by the finite volume method. The advective term was discretized using a second-order accurate upwind difference scheme, and a backward difference scheme was used in time evolution. The Semi-Implicit Method for Pressure-Linked Equation (SIMPLE) algorithm was used as a solution for the discretization equations.

Considering a gas-liquid two-phase system consisting of air and seawater, the gas-liquid interface was obtained by using High Resolution Interface Capture (HRIC) [21], which is based on the Volume of Fluid (VOF) method.

The hull was assumed to be a rigid body, and the hull momentum was obtained by solving equations of motion for translation and rotation at the center of gravity. As the degrees of freedom of motion, only heave and pitch were considered, and others were fixed. Node movement of the fluid region surrounding the hull accompanying hull motion was performed by morphing, and the amount of node movement was determined based on Radial Basis Functions (RBF).

The MLRW was given as the inflow condition., and the Euler Overlay Method (EOM) [22] was used to prevent the influence of reflection of the wave at the interface of the computational region.

To perform calculations for a diverse range of ship types in a unified manner, the size of the computational region, mesh size, time step, etc. were given by the principal particulars of the ships (L, B, T, D (moulded depth)) and the sea state conditions (H_s (significant wave height), T_z (zero upcross wave period)).

Assuming the symmetry of the phenomena, only the half-breadth of the ships was modeled. The total number of cells was about 1 x 10^6 to 1.2 x 10^6. The simulations were begun from the smooth-water state and performed for an actual time of 50 to 70 seconds, until the peak of the wave height of the MLRW passed through the hull.

It may be noted that these settings were based on research by one of the authors [8], and the validity of the analysis results has been confirmed.

Fig. 4 shows a top view (deck direction) of the wave height distribution in the initial condition for the simulation of the hogging moment of BC-10 (Full load condition). The colors red, blue, and green indicate the wave peak, wave trough, and smooth water, respectively. White area in the center shows the ship. This figure shows a symmetrical representation of two sides of the vessel, but as noted above, the actual calculation was performed for only the half-breadth side.

Similarly, Fig. 5 shows the distribution of the VOF values of BC-10 in the initial condition as seen from the ship's breadth direction (side view) for a centerline section around the bow, together with the mesh diagram. Here, the colors light blue and white represent seawater and air, respectively.

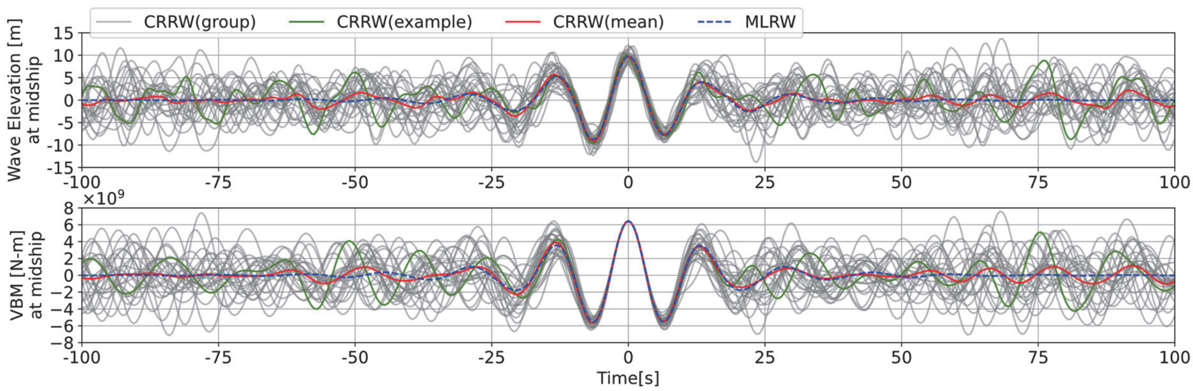


Fig. 3 An example of wave elevation and vertical bending moment in CRRW and MLRW (Bulk carrier, BC-10, Full load condition)

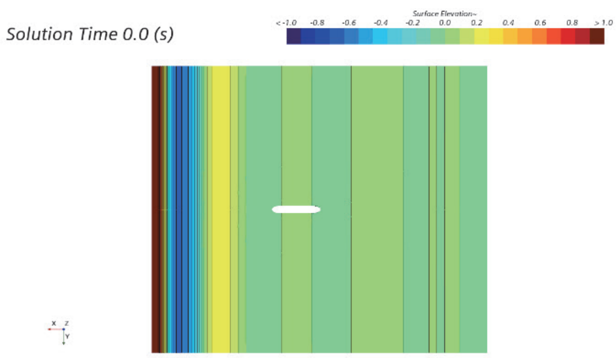


Fig. 4 Wave height distribution of BC-10 at initial condition (top view)

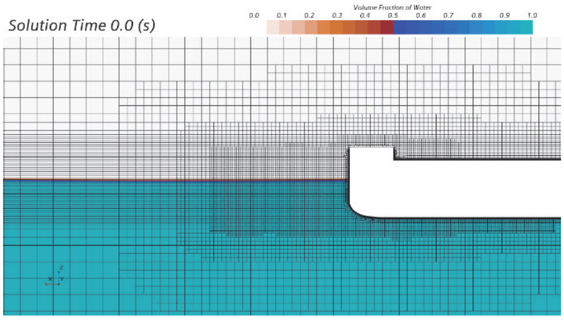


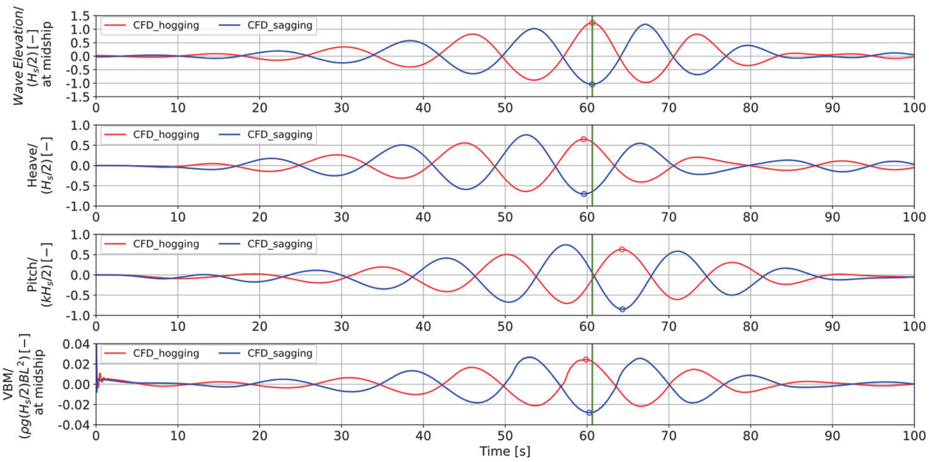
Fig. 5　VOF distribution of BC-10 with mesh diagram at initial condition (side view, near the bow)

5. SIMULATION RESULTS

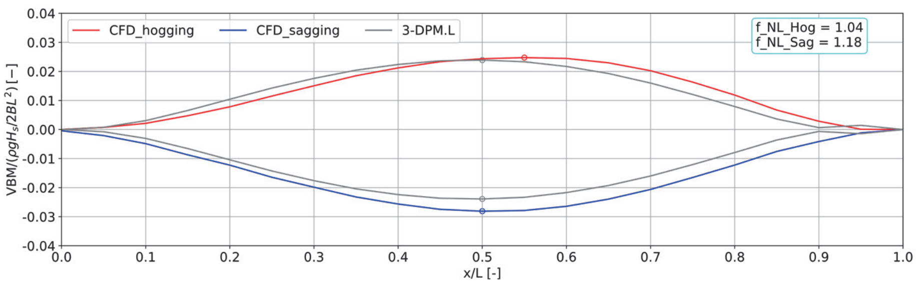
5.1 Time Series, Distribution, Etc. of Vertical Bending Moment

As an example of the CFD analysis results, Fig. 6 and Fig. 7 show the results for BC-10 in the Full load condition and the Ballast condition, respectively. In order from above, (a) in Figs. 6 and 7 shows the time history of the wave elevation at midship, heave motion, the pitch motion, and the vertical bending moment in the midship section. The red line means the analysis results when targeting the hogging moment, and the blue line shows the results when targeting the sagging moment. In this example, the maximum or minimum vertical bending moment occurs at around t = 60 (s). The times showing the maximum value (or minimum value) are indicated by the circles in the respective times series charts.

Fig. 6 (b) and Fig. 7 (b) show the distribution of the vertical bending moment along the ship length. Here, the value of the moment in each cross section is the maximum value (or minimum value) in the respective time series. The gray lines in these figures mean the distribution of vertical bending moment obtained by linear theory, and their differences can be regarded as the nonlinear effect that occurs in the vertical bending moment in large wave heights.

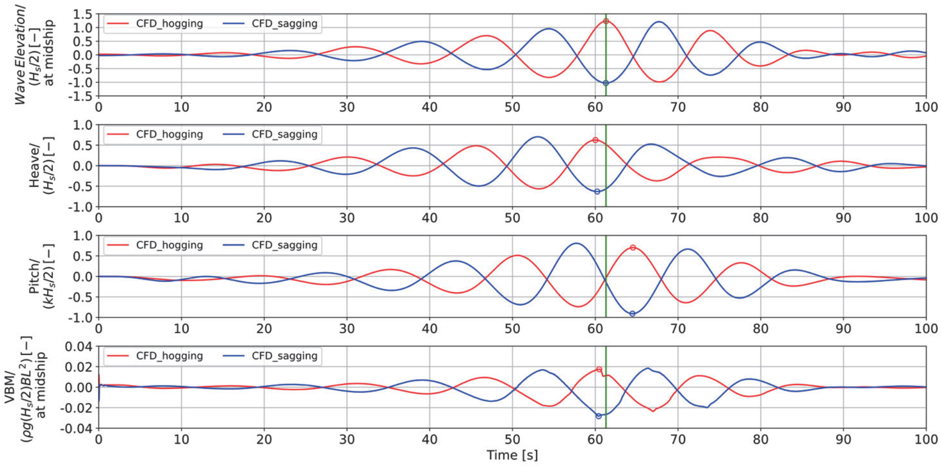


(a) CFD+MLRW, Time history of wave elevation, heave, pitch and vertical bending moment

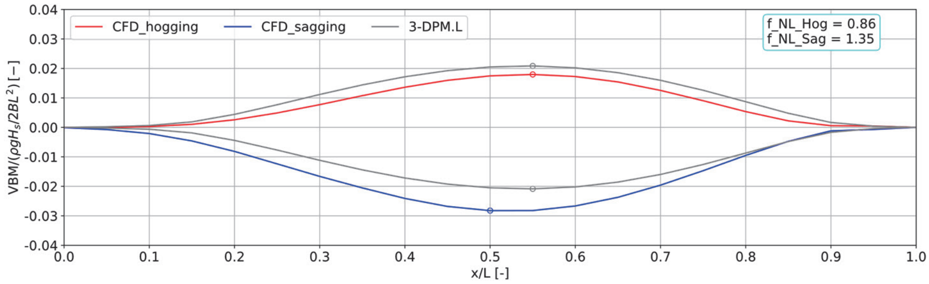


(b) CFD+MLRW, Vertical bending moment distribution along the ship length

Fig. 6　An example of CFD analysis result (Bulk carrier, BC-10, Full load condition)



(a) CFD+MLRW, Time history of wave elevation, heave, pitch and vertical bending moment



(b) CFD+MLRW, Vertical bending moment distribution along the ship length

Fig. 7 An example of CFD analysis result (Bulk carrier, BC-10, Ballast condition)

When the calculation results of the series of 55 ships (110 models) were compared, some cases showed remarkable differences in the tendency of the sagging moment, even in target ships with similar specifications. Since the results of the analysis on the effect of green water loads was suspected, a sensitivity analysis was carried out using the three forecastle shape models shown in Fig. 8 based on BC-10 (Full load condition), and the changes in the vertical bending moment were observed. Results are shown in Fig. 9. Fig. 10 shows the visualization of the green water condition in these analysis results.

The gray line in Fig. 10 indicates the relationship between the vertical bending moment based on linear theory and the probability of exceedance in the short-term sea state decided here. The red, blue, and green plots show the values of the vertical bending moments of the three forecastle shapes obtained by the CFD+MLRW analysis, and correspond to the colors in Fig. 8. Based on this, it could be understood that the sagging moment is reduced in the models in which green water acts more strongly, and it was also found that green water had no effect on hogging (although this is self-evident, because the forecastle is always exposed and green water does not act on it).

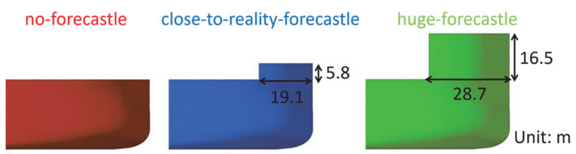


Fig. 8 Side view with assumed forecastle shape model based on BC-10

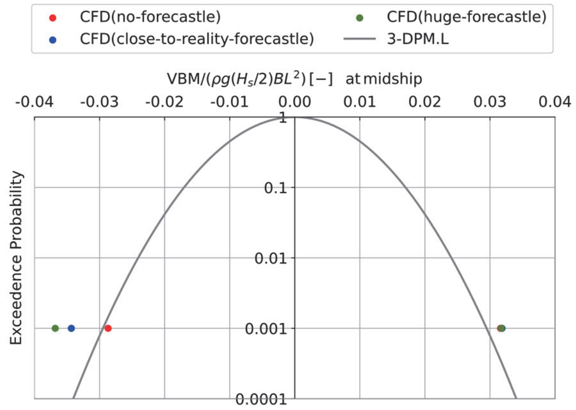


Fig. 9 The effect of with/without forecastle on vertical wave bending moment at midship (Bulk carrier, BC-10, Full load condition)

Fig. 10 Comparison of green water on deck at the time of maximum hogging and minimum sagging moment (Bulk carrier, BC-10, Full load condition)

Based on this discussion, the calculations of the respective models in this study were unified by modeling a forecastle close to that of the real vessel. Although green water occurred in some cases, depending on the ship's draught and freeboard, visual confirmation indicated that the amount of green water was small, and in the comparative study, etc. with the principal particulars described in the following, those conditions were not sufficient to lead to a different tendency from the others. Therefore, the authors judged that it was not necessary to consider virtual cases such as the huge-forecastle in the analysis presented below.

5.2 Nonlinear Effect Coefficient and Sensitivity of Principal Particulars

In this study, the nonlinear effect of large wave heights on the vertical bending moments were defined by the formulae shown below, and are discussed in the following.

$$
\begin{aligned}
f_{NL-Hog} &\equiv \frac{M_{WV-Hog-max}^{CFD}}{M_{WV-Hog-max}^{lienar}} = \frac{\max_{0\le x/L\le 1} M_{WV-Hog}^{CFD}(x/L)}{\max_{0\le x/L\le 1} M_{WV-Hog}^{linear}(x/L)} \\
f_{NL-Sag} &\equiv \frac{M_{WV-Sag-min}^{CFD}}{M_{WV-Sag-min}^{linear}} = \frac{\min_{0\le x/L\le 1} M_{WV-Sag}^{CFD}(x/L)}{\min_{0\le x/L\le 1} M_{WV-Sag}^{linear}(x/L)}
\end{aligned}
\quad (7)
$$

where, $M_{WV-Hog-max}^{CFD}$ means the maximum value of the vertical bending moment (hogging) in the all transverse section obtained by the CFD analysis, and $M_{WV-Hog-max}^{linear}$ means the maximum value of the said moment in the all transverse section obtained by linear theory. Although the transverse section that displays the maximum value is around midship in both cases, the two are not necessarily the same. When the subscript *min* is used, the term means sagging moment (minimum value).

Fig. 11 shows the relationship between the nonlinear effect coefficient for hogging, f_{NL-Hog}, and the principal particulars of the ships, and Fig. 12 shows the relationship between the nonlinear effect coefficient for sagging, f_{NL-Sag}, and the principal particulars of the ships. Based on these figures, it was suggested that the sensitivity for ship length L and breadth B is low, and sensitivity for the block coefficient C_b and the waterplane area coefficient C_w tends to be high. In addition, the results also confirmed that the hogging moment has the sensitivity by the draught T. Regarding the bow flare shape coefficient f_{Bow}, which is included in the nonlinear effect coefficient for the sagging moment in IACS UR S11A, a certain tendency could be observed in the container ships (see the blue plots in Fig. 12), but no clear trends could be seen in the other ships.

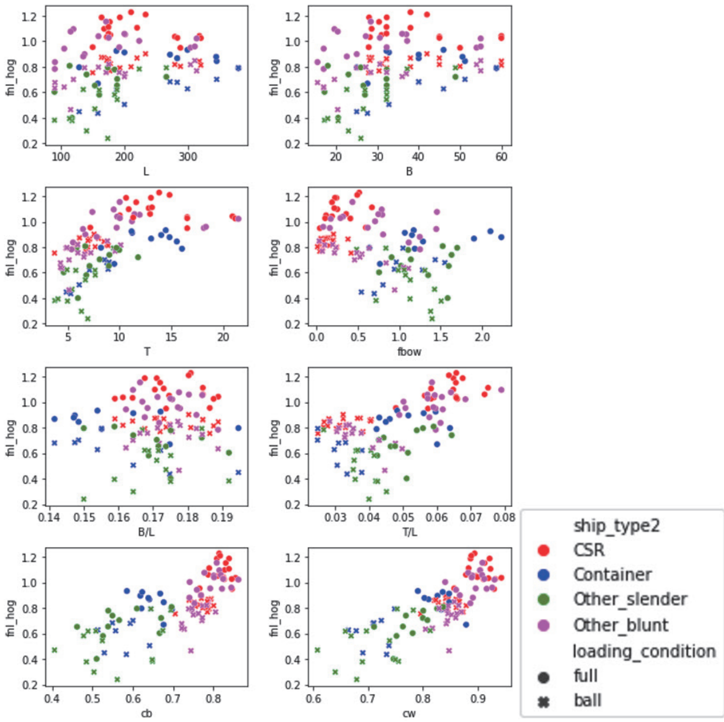


Fig. 11　Sensitivity of non-linear effect coefficient to principal particulars of ships, hogging moment

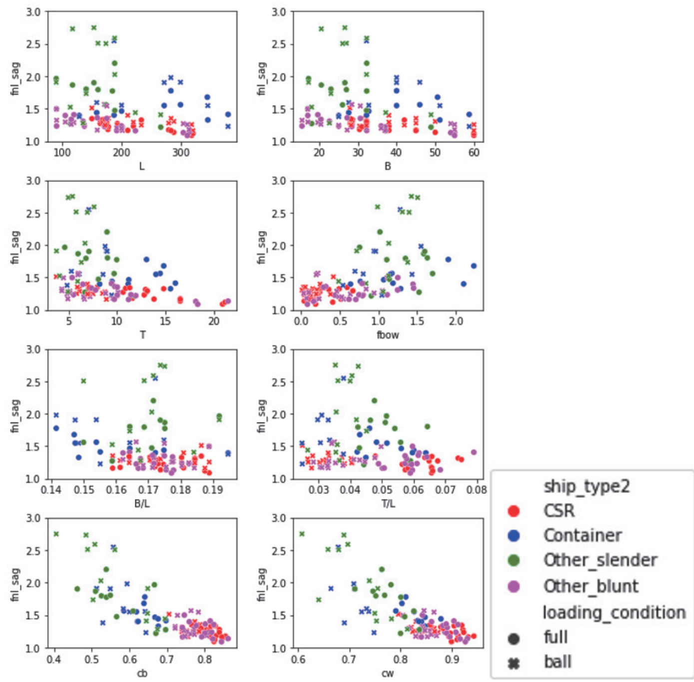


Fig. 12　Sensitivity of non-linear effect coefficient to principal particulars of ships, sagging moment

5.3 Relationship between Hogging and Sagging

Fig. 13 shows the relationship between f_{NL-Hog} and f_{NL-Sag}. From the figure, the nonlinear effect is relatively small in blunt ships, and in the Full load condition, values around 1.0 were obtained in hogging and around 1.2 were obtained in sagging. In the Ballast condition, a value of around 0.8 was obtained in hogging, and a value approximately the same or very slightly larger than that in Full load condition was obtained in sagging. In slender ships, which includes container ships, it was found that the nonlinear effect in hogging was small in comparison with blunt ships, while the nonlinear effect in sagging was became relatively large.

As reference, Fig. 14 shows a comparison of the results of calculations in connection with the nonlinear effect coefficient given in a Technical background document [23] for UR S11A, which has been published by the IACS, and the results of the research presented in this paper, in the same format.

The data in Fig. 14 (b) are not CFD results, but are the results of a program based on the 3-dimensional Green's function approach, which considers nonlinearity. However, in terms of macroscopic tendencies, there are no large differences between those results and the results of this study.

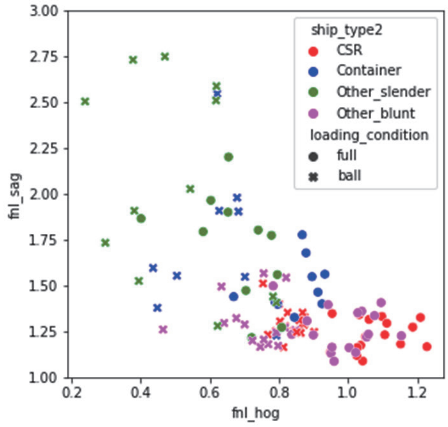
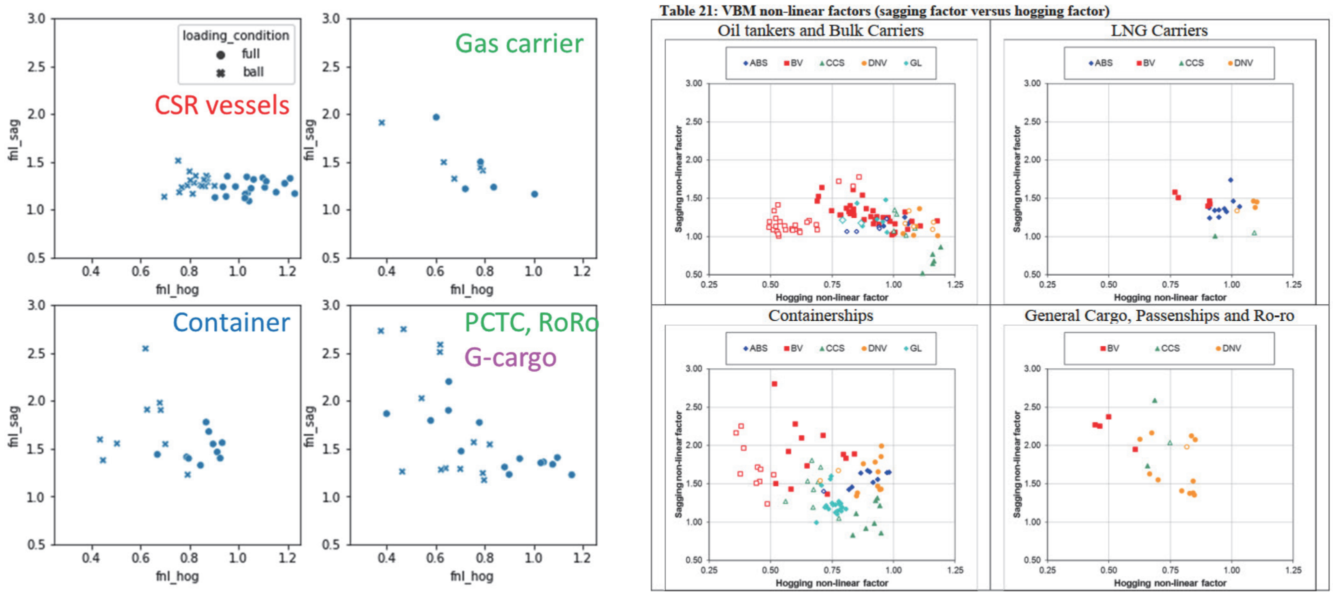


Fig. 13 Relationship between f_{NL-Hog} and f_{NL-Sag}



(a) Based on CFD+MLRW (same as Fig. 9) (b) According to an IACS document

Fig. 14 Comparison with a past investigation regarding relationship between f_{NL-Hog} and f_{NL-Sag}

Finally, Fig. 15 shows the relationship between the nonlinear effect coefficients specified in the said UR and the nonlinear effect coefficients based on the results of this study as reference. As noted in Chapter 3, the values of C_b, C_w, and T are values in the loaded condition, and the x-axis (i.e., UR values) also shows the same condition. In addition, the upper and lower limits specified in the UR are not considered in the figure. Accordingly, this is not a strict comparison with the UR. However, from the figures, it can be thought that an approximately good correlation exists between the two. Since it is presumed that codes which consider nonlinearity based on potential theory, such as the Strip method and the 3-dimensional Green's function approach, frequently consider the nonlinearity of the Froude-Krylov force and the nonlinearity of the restoring force, which are generally considered to be dominant to nonlinear effects, the correlation shown in Fig. 15 may suggest that the effect on the nonlinearity of the vertical bending moment is small except in the case of those two components.

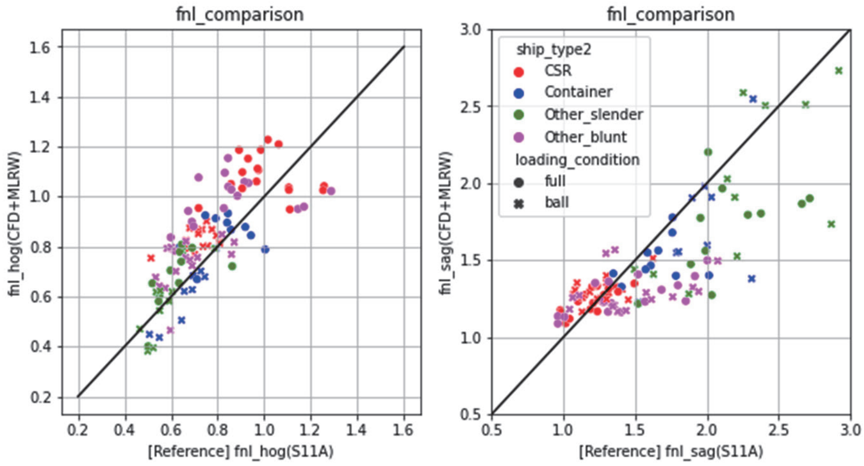


Fig. 15 Comparison with non-linear factor specified in IACS UR S11A (as reference), (left): hogging, (right): sagging.

6. CONCLUSION

In this study, simulations of the nonlinearity of the vertical wave bending moments that can occur in the extreme sea states considered in hull structural design were carried out for a total of 55 ships by using the advanced analytical technique CFD and giving the wave conditions by a design irregular wave.

In the trial calculation process, it was found that green sea loads are a phenomenon that suppresses the sagging moment. Therefore, modeling based on a forecastle shape close to that of the real ships was deemed essential when performing trial calculations of this phenomenon, and the simulation models were unified in that manner.

Based on the nonlinear effect coefficient defined here, the respective nonlinear effect coefficients that occur in the hogging and sagging moments were analyzed. Differences in the tendencies of blunt ships and slender ships and sensitivity to the principal particulars of the ships were observed. In addition to high tendencies with respect to C_b and C_w, a good correlation between the coefficients specified in the existing standard (IACS UR S11A) and these macroscopic tendencies was confirmed.

However, this study is ultimately only a trial calculation, and is not a comprehensive analysis of the nonlinearity that occurs in vertical bending moments. Further study is considered necessary in order to establish nonlinear effect coefficients for appropriate structural design. Examples of the issues that require further examination include study of the nonlinear effects that occur under conditions other than short-term sea states under the same calculation conditions as in this study, consideration of the nonlinear effects in following seas, and verification not only by numerical simulations for limited time domains such as MLRW, but also by a full simulation (i.e., reproduction of approximately 1 000 waves) of short-term sea states. The results of that kind of study may show that a different definition of the nonlinear effect coefficients defined in this study is appropriate. Furthermore, although linear theory was outside the scope of this study, a comprehensive study that includes terms corresponding to linear theory is also considered necessary.

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Initial Deflection Measurement of Continuous Plates in Actual Ships Using 3D Laser Scanner *1

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Daisuke SHIOMITSU**, Fuminori YANAGIMOTO**, Kinya ISHIBASHI**

1. INTRODUCTION

When stiffeners are attached to plating by fillet welding, hungry-horse initial deflection is induced in the plate between the stiffeners due to thermal shrinkage. This initial deflection is an uncertain factor that significantly affects the buckling and ultimate strength of the stiffened panel structure. To investigate the characteristics of this initial deflection in welding, measurements of actual ships have been conducted for many years [1-4)]. Contact-type displacement meters were used in those measurements, but because shape measurement is time-consuming, a sufficient volume of data has not been accumulated. Furthermore, the component of initial deflection that affects the buckling of the plate is the antisymmetric component with the stiffener. Therefore, the initial deflections of two adjacent rectangular plates are required in order to analyze this antisymmetric initial deflection, but the available data are minimal [4)].

Recently, 3D laser scanners have been used to measure the shapes of structures [5)], and one of the authors demonstrated the effectiveness of measuring the initial deflections of a box girder test specimen using a 3D laser scanner [6)]. In this study, we apply a 3D laser scanner to measure the initial deflection of actual ships and investigate its applicability. The obtained initial deflection measurement data are analyzed to examine the correlation of the initial deflection components of two adjacent rectangular plates. Additionally, the statistical model of the initial deflection proposed in our previous studies [7-9)] is extended to consider the correlation between adjacent plates.

2. MEASUREMENT OF INITIAL DEFLECTION

2.1 Measurement Targets

The initial deflection measurements were conducted at the Marugame Headquarters of Imabari Shipbuilding Co., Ltd. in 2023. The measured ships were a 64,000 DWT bulk carrier and a 5,800 TEU container ship. For the 64,000 DWT bulk carrier, the initial deflection of the side shell and bottom plating were measured, while for the 5,800 TEU container ship, the side shell and longitudinal bulkhead were measured.

2.2 Measurement Equipment

The 3D laser scanner Focus3D X130 manufactured by FARO Technologies Inc. was used in the measurements. This is a portable 3D laser scanner that measures surrounding objects as three-dimensional point cloud data. The measurement ranging error in the specification sheet is ± 2 mm.

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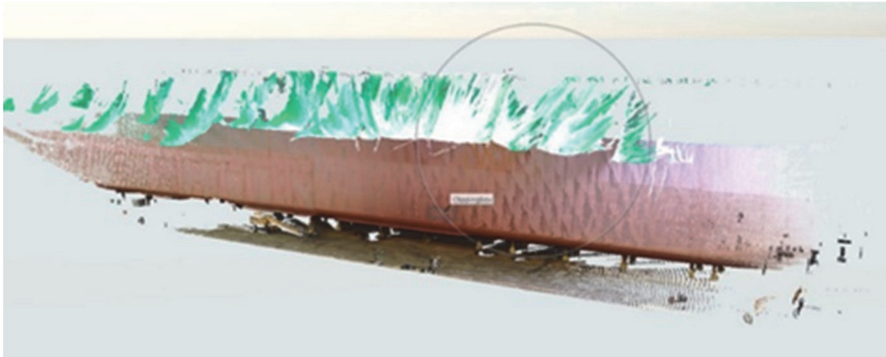

Fig. 1 Example of point cloud data of the ship side

2.3 Point Cloud Visualization

The point cloud data measured by the 3D laser scanner were visualized by using the software application FARO SCENE. Fig. 1 shows the visualized point cloud of the side of the 64,000 DWT bulk carrier. The target rectangular plates were extracted from this point cloud, the dispersion of the point cloud was checked, and the feasibility of analyzing the initial deflection was determined.

For the bottom of the bulk carrier, measurements of hull blocks on foundations were carried out with the laser scanner placed on the ground. However, due to the short distance between the scanner and the measurement target, the laser incidence angle increased at positions further from the scanner, which prevented accurate measurement of the initial deflection shape of the plates. For the side of the container ship, because measurements were carried out from the dockside, the distance between the measurement target and the scanner was long, resulting in significant dispersion in the point cloud.

In this study, the side shell of the bilge hopper tanks of the bulk carrier and the longitudinal bulkheads of the container ship, which could be measured accurately, were used for the initial deflection analysis. For the side of the bulk carrier, 21 pairs of adjacent rectangular plates, totaling 42 rectangular plates, were analyzed. For the longitudinal bulkheads of the container ship, 4 sets of 3 adjacent rectangular plates and 4 pairs of 2 adjacent rectangular plates, totaling 20 rectangular plates, were analyzed.

3. ANALYSIS OF INITIAL DEFLECTION

3.1 Analysis Method

The point cloud data measured by the 3D laser scanner was analyzed based on our previous study [6]. As an example, the analysis process using the point cloud data of a block of the 64,000 DWT bulk carrier is explained here. First, the measured point cloud data is processed using FARO SCENE to extract the target rectangular plate. In this stage, the coordinate axes depend on the direction in which the 3D laser scanner is placed, so a coordinate transformation should be performed to align each axis of the orthogonal coordinate system with the longitudinal, transverse, and out-plane directions of the plate. This coordinate transformation is performed by principal component analysis. This means that the first principal component axis with the maximum variance is oriented toward the longitudinal direction, the second principal component axis with the next largest variance is oriented toward the transverse direction, and the third principal component is oriented toward the out-plane direction. A result of the coordinate transformation is shown in Fig. 2. Next, the component analysis of the initial deflection is performed by fitting the deflection modes w_1 to w_5 shown in Fig. 3. w_1 represents the slope of the plane, w_2 represents the twisting mode, w_3 and w_4 represent the overall deflection modes in the longitudinal and transverse directions, respectively, and w_5 represents a local deflection mode indicating the hungry-horse shape, which is the subject of interest in this study. The following equations express these deflection modes:

$$w_1 = c_0 + c_1 x + c_2 y \tag{1}$$

$$w_2 = c_3 xy \tag{2}$$

$$w_3 = \sum_{j=1}^{m_s} \left(\frac{x}{a} B_j + \frac{a-x}{a} C_j \right) \sin \frac{j\pi y}{b} \tag{3}$$

$$w_4 = \sum_{i=1}^{n_s} \left(\frac{y}{b} D_i + \frac{b-y}{b} E_i \right) \sin \frac{i\pi x}{a} \tag{4}$$

$$w_5 = \sum_{i=1}^{m_p} \sum_{j=1}^{n_p} A_{ij} \sin \frac{i\pi x}{a} \sin \frac{j\pi y}{b} \tag{5}$$

where a is the length of the rectangular plate, and b is the width. m_s, n_s, m_p, and n_p are the number of terms considered for each deflection mode. In this study, $m_s = 1$, $n_s = 1, m_p = 11$, and $n_p = 3$ are assumed. c_0, c_1, c_2, c_3, B_j, C_j, D_i, E_i, and A_{ij} are the regression coefficients of each component, and A_{ij} represents the amplitude of the deflection component with i half waves in the longitudinal direction and j half waves in the transverse direction.

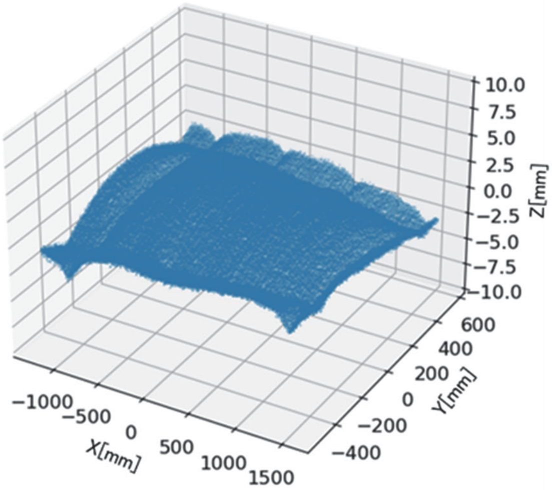

Fig. 2 Point cloud data after coordinate transformation

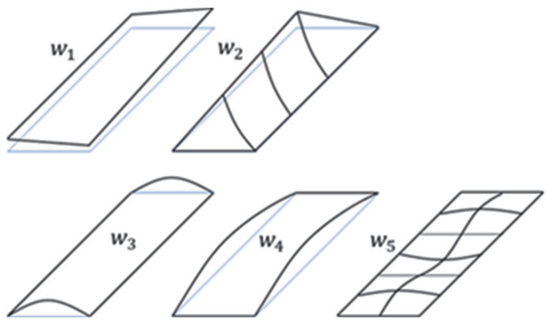

Fig. 3 Superposition of deflection modes

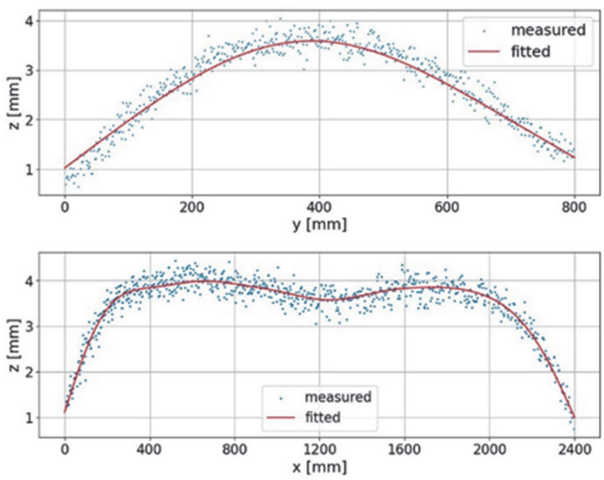

Fig. 4 Measured point cloud and fitted curves

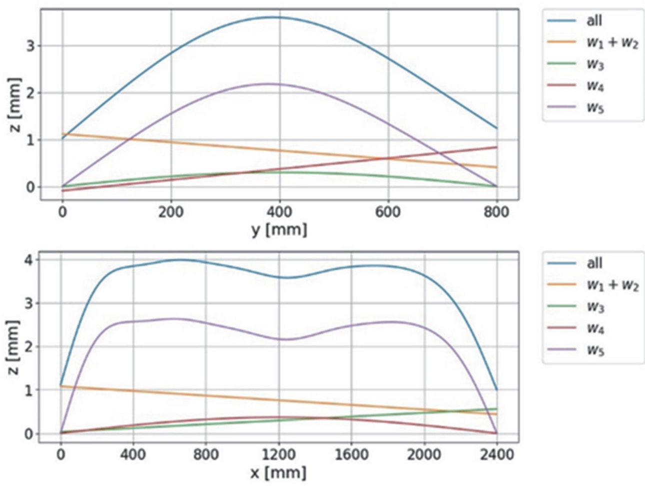

Fig. 5 Mode decomposition of initial deflection

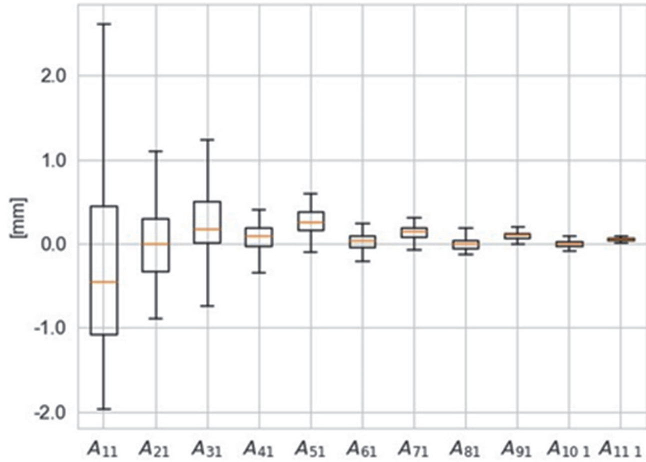

Fig. 6 Initial deflection components

Fig. 4 shows the measured point cloud and the initial deflection curve fitted to the point cloud. Fitting to the point cloud is performed using the least squares method. The x direction is the longitudinal direction of the rectangular plate, the y direction is the transverse direction, and the z direction is the direction in which the stiffeners stand. The fitted curves show the deflection curves along the centerlines of the plate, and the fitted curve generally passes through the center of the point cloud. Fig. 5 shows the result of the component decomposition of the initial deflection. For the target rectangular plate, it is clear that the local deflection mode w_5 is dominant. This series of analyses, from the coordinate transformation to decomposition, is performed for the 62 plates.

3.2 Analysis Results for Single Rectangular Plates

Fig. 6 shows the box plot of A_{i1} $(i = 1$ to $11)$. It can be seen that the mean values and variances of the odd half-wave components such as A_{11}, A_{31}, A_{51} are larger and more dominant than those of the even half-wave components. However, compared to past measurement results [2)], a certain number of plates have negative A_{11}. This is because the overall deflection w_4 is predominant in these plates, which results in the negative direction of the local deflection w_5, as shown in Fig. 7. In other plates, A_{31} and A_{51} are predominant because they have deflection peaks near both ends, leading to the negative A_{11}, as shown in Fig. 8. Further investigation is required to clarify the reason why these initial deflections were induced in the fabrication process.

Fig. 9 shows the relationship between the maximum deflection of the rectangular plate and $\beta^2 t$. β is the slenderness ratio parameter of the plate, expressed as $b/t\sqrt{\sigma_Y/E}$, where b is the width of the plate, t is the thickness of the plate, σ_Y is yield stress, and E is Young's modulus. In addition to the measurement results obtained in this study, past measurement results [2), 4)] are also shown. The closed dots in the figure represent the results of this study. The straight lines in the figure represent the levels for the maximum initial deflection derived by Smith et al. [10)] based on measurements of the initial deflections of actual ships. $0.025\beta^2 t$, $0.1\beta^2 t$, and $0.3\beta^2 t$ were derived as Slight, Average, and Severe deflection, respectively. The maximum values of the initial deflections measured in this study are generally scattered around Slight, and the past measurement results show the same trend.

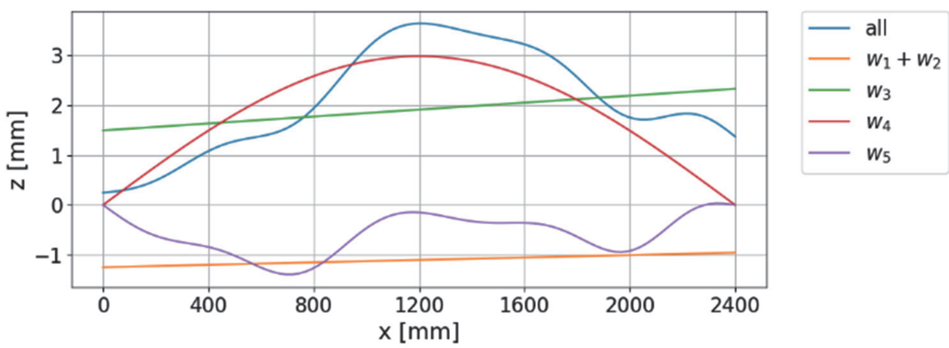

Fig. 7 Initial deflection with predominant overall deflection

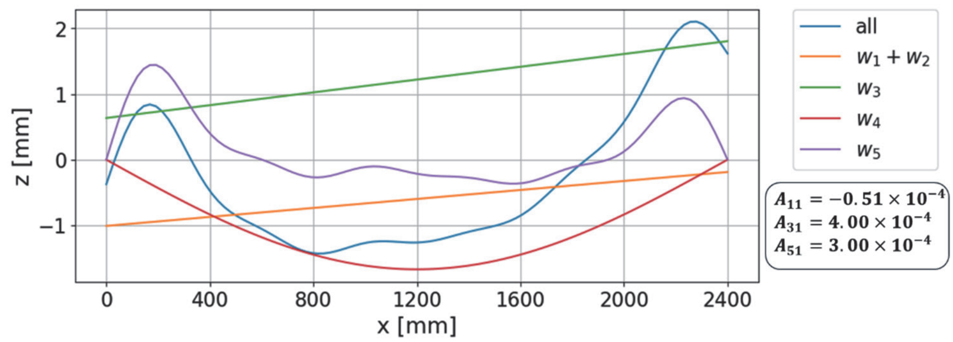

Fig. 8 Initial deflection with two peaks near both ends

3.3 Analysis Results for Adjacent Rectangular Plates

The correlation of the initial deflection between two adjacent rectangular plates is investigated. In addition to the data from the measurements in this study, the data from a 46,000 DWT bulk carrier with the positional relationship of the measured rectangular plates is analyzed.

The two adjacent rectangular plates are referred to as plate P and plate Q. Fig. 10 shows the relationship of A_{11} between plate P and plate Q. The horizontal axis A_{11}^P is one half-wave deflection of plate P, while the vertical axis A_{11}^Q is one half-wave deflection of plate Q. The data are generally distributed along the diagonal line, indicating a positive correlation in A_{11}. The correlation coefficient is 0.62.

Fig. 11 shows the histogram of ΔA_{11}, that is, the difference between A_{11} of the two adjacent plates P and Q. The solid line in the figure represents a fitting normal distribution whose mean is set to zero. The estimated value of the standard deviation is 1.24. It is noted that the KS test is performed and the p-value is above the significance level of 0.05, indicating that the normal distribution hypothesis for A_{11} is not rejected.

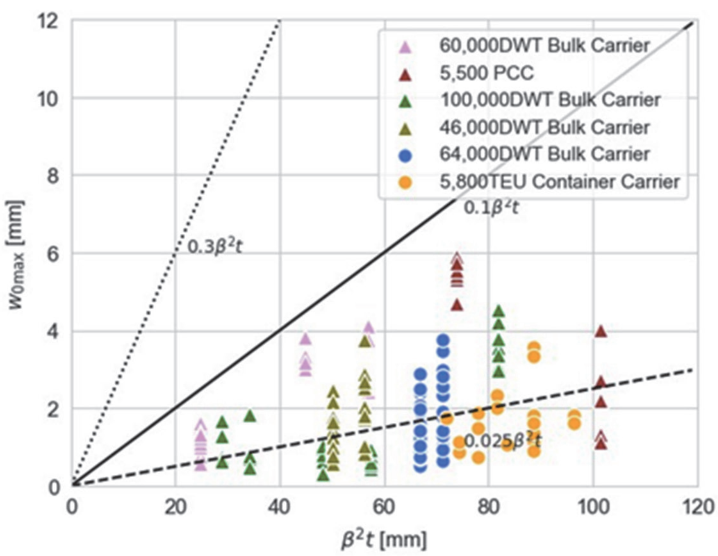

Fig. 9 Maximum values of initial deflection

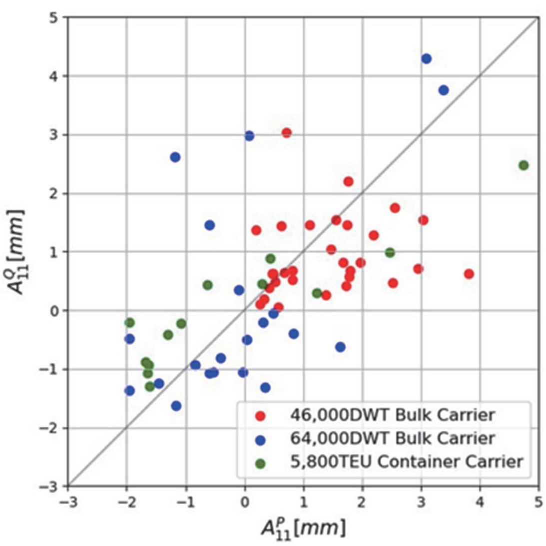

Fig. 10 Comparison of A_{11} of adjacent plates

Next, the maximum deflections of the two adjacent rectangular plates are taken as $w_{\max}^P$ and $w_{\max}^Q$, and $\alpha = w_{\max}^Q / w_{\max}^P (w_{\max}^P > w_{\max}^Q)$, the ratio of the maximum initial deflections, is calculated. Fig. 12 shows the histogram of the initial deflection ratio α. The distribution of α roughly follows a uniform distribution. The average value of α obtained from both the current measurement and the previous measurement of the 46,000 DWT bulk carrier is almost the same, and its value is approximately 0.64.

It is common to assume the initial deflection shape in ultimate strength analyses of stiffened panel structures, and the ultimate strength of a continuous panel is influenced by the antisymmetric component across the stiffener. These results suggest that the maximum initial deflection of plate P is estimated from Fig. 7 and an initial deflection 0.64 times larger than the maximum deflection of plate P is applied to the adjacent plate Q. This enables an ultimate strength analysis considering the correlation of the initial deflection between the two adjacent rectangular plates.

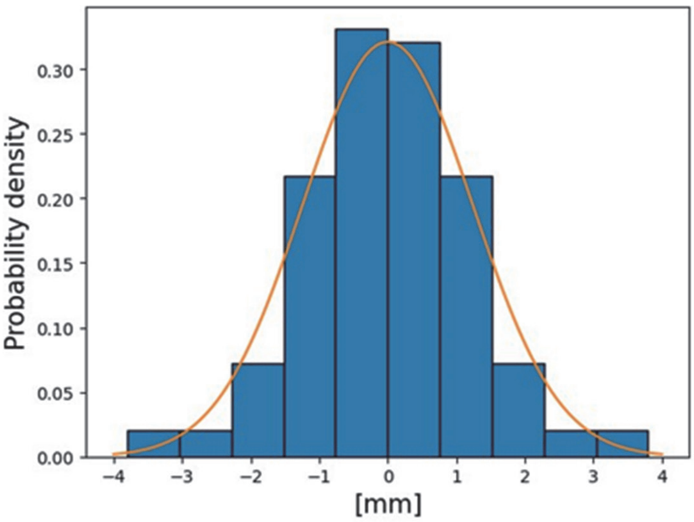

Fig. 11 Histogram of ΔA_{11} and a fitted normal distribution

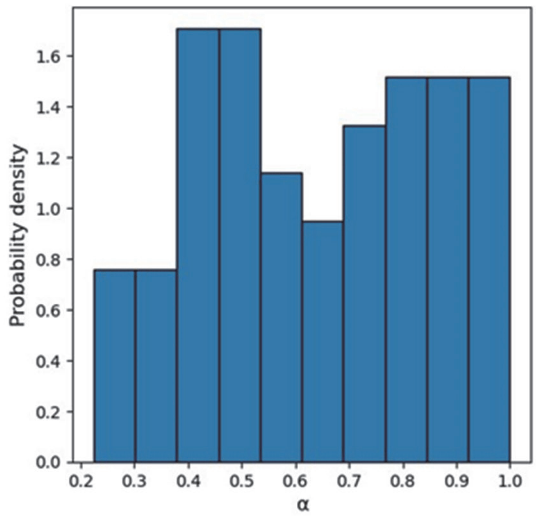

Fig. 12 Histogram of the initial deflection ratio α

4. A STATISTICAL MODEL OF INITIAL DEFLECTION SHAPES CONSIDERING THE CORRELATION OF ADJACENT PANELS

4.1 A Statistical Model for a Single Rectangular Plate

One of the authors proposed a statistical model for predicting the initial deflection shape of a single rectangular plate [7-9]. In that model, the probability density function of the initial deflection amplitude $\boldsymbol{A}$ is represented as

$$p(\boldsymbol{A}) = \frac{1}{\sqrt{(2\pi)^{11}|\boldsymbol{\Sigma}|}} \exp\left\{-\frac{1}{2}(\boldsymbol{A}-\boldsymbol{\mu})^T \boldsymbol{\Sigma}^{-1}(\boldsymbol{A}-\boldsymbol{\mu})\right\} \tag{6}$$

$$\boldsymbol{\mu} = \boldsymbol{c_0} + \boldsymbol{c_1}\left(\frac{b}{t^2}\right) + \boldsymbol{c_2}\left(\frac{b}{t^2}\right)^2 \tag{7}$$

The amplitude $\boldsymbol{A}$ is a vector with the initial deflection amplitudes $A_{i1}(i = 1 \text{ to } 11)$. This model assumes that the initial deflection amplitudes follow a multivariate normal distribution, where the mean $\boldsymbol{\mu}$ is expressed as a quadratic function of the explanatory variable b/t^2. $\boldsymbol{\Sigma}$ is an 11×11 covariance matrix, b is the plate width, t is the plate thickness, and $\boldsymbol{c_0}, \boldsymbol{c_1}$, and $\boldsymbol{c_2}$ are vectors of regression coefficients, each with 11 components. The explanatory variable b/t^2 is derived from an existing study on the angular deformation of bead-welded plates [11]. This statistical model uses Bayesian statistics to estimate the posterior distributions of the parameters $\boldsymbol{c_0}, \boldsymbol{c_1}, \boldsymbol{c_2}$, and $\boldsymbol{\Sigma}$. In this study, the expected values of the posterior distributions (EAP) of $\boldsymbol{c_0}, \boldsymbol{c_1}, \boldsymbol{c_2}$, and $\boldsymbol{\Sigma}$ are used as representative values, and the probability density function of the initial deflection of a single rectangular plate is calculated by equations (6) and (7).

4.2 Consideration of Correlation of Adjacent Panels

The statistical model of a single rectangular plate described above in 4.1. is extended to consider the correlation between adjacent plates. The initial deflection components of two adjacent rectangular plates, P and Q, are represented as $\boldsymbol{A^P} = (A_{11}^P, A_{21}^P \cdots, A_{11\ 1}^P)$ and $\boldsymbol{A^Q} = (A_{11}^Q, A_{21}^Q \cdots, A_{11\ 1}^Q)$. The joint probability density distribution of $\boldsymbol{A^P}$ and $\boldsymbol{A^Q}$ is proposed as

$$p(\boldsymbol{A^P}, \boldsymbol{A^Q}) = \&p\left(\boldsymbol{A_o^Q}|A_{11}^Q\right)p\left(A_{11}^Q|A_{11}^P\right)p(\boldsymbol{A^P}) \tag{8}$$

$p(\boldsymbol{A^P})$ is the probability density function of the initial deflection components of rectangular plate P given by equation (6), and $p\left(A_{11}^Q|A_{11}^P\right)$ represents the conditional probability density function of the one half-wave component of plate Q given the one half-wave component of plate P. From the results in Fig. 9, assuming that the difference between the one half-wave components $A_{11}^{P} - A_{11}^{Q}$ follows a normal distribution with a mean of zero and a standard deviation of σ_d, it can be expressed as

$$p\left(A_{11}^{Q} | A_{11}^{P}\right) = \frac{1}{\sqrt{2\pi}\sigma_d} \exp\left\{-\frac{\left(A_{11}^{Q} - A_{11}^{P}\right)^2}{2\sigma_d^2}\right\} \tag{9}$$

Finally, $p\left(\boldsymbol{A_o^Q} | A_{11}^{Q}\right)$ represents the conditional probability density function of the other components $\boldsymbol{A_o^Q} = \left(A_{21}^{Q} - A_{11\ 1}^{Q}\right)$ given A_{11}^{Q}. Assuming $\boldsymbol{A^Q}$ follows the multivariate normal distribution of equation (6), the conditional distribution is also derived as a multivariate normal distribution:

$$p\left(\boldsymbol{A_o^Q} | A_{11}^{Q}\right) = \frac{1}{\sqrt{(2\pi)^{10}\left|\boldsymbol{\Sigma_{o|1}}\right|}} \exp\left\{-\frac{\left(\boldsymbol{A_o^Q} - \boldsymbol{\mu_{o|1}}\right)^T \boldsymbol{\Sigma_{o|1}^{-1}}\left(\boldsymbol{A_o^Q} - \boldsymbol{\mu_{o|1}}\right)}{2}\right\} \tag{10}$$

where, $\boldsymbol{\mu_{o|1}}, \boldsymbol{\Sigma_{o|1}}$ are calculated as

$$\begin{aligned} \boldsymbol{\mu_{o|1}} &= \boldsymbol{\mu_o} + \frac{A_{11}^{Q} - \mu_1}{\sigma_1^2}\boldsymbol{\sigma_{o1}} \\ \boldsymbol{\Sigma_{o|1}} &= \boldsymbol{\Sigma_{oo}} - \frac{\boldsymbol{\sigma_{o1}}\boldsymbol{\sigma_{o1}^T}}{\sigma_1^2} \end{aligned} \tag{11}$$

$\boldsymbol{\mu_o}$ is a vector with the 2nd to 11th components of $\boldsymbol{\mu}$, σ_1^2 is an entry in the first row and the first column of $\boldsymbol{\Sigma}$, $\boldsymbol{\Sigma_{oo}}$ is a 10×10 matrix extracted from the 2nd to 11th rows and columns of $\boldsymbol{\Sigma}$, and $\boldsymbol{\sigma_{o1}}$ is a vector extracted from the 2nd to 11th rows of the first column of $\boldsymbol{\Sigma}$. Therefore, they are expressed as

$$\begin{aligned} \boldsymbol{\mu} &= \begin{pmatrix} \mu_1 \\ \boldsymbol{\mu_o} \end{pmatrix} \\ \boldsymbol{\Sigma} &= \begin{bmatrix} \sigma_1^2 & \boldsymbol{\sigma_{1o}} \\ \boldsymbol{\sigma_{o1}} & \boldsymbol{\Sigma_{oo}} \end{bmatrix} \end{aligned} \tag{12}$$

Fig. 13 shows the initial deflection shapes of two adjacent plates sampled from the proposed statistical model. Three samples are shown, with the solid line representing rectangular plate P and the dashed line representing rectangular plate Q. By combining the proposed model with the finite element method, it is possible to conduct a Monte Carlo analysis of the ultimate strength of continuous panels with initial deflection.

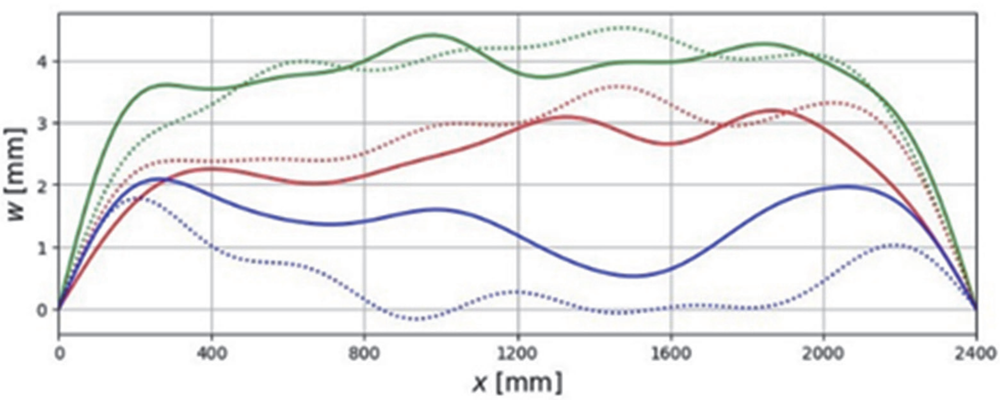

Fig. 13 Sampled initial deflections of adjacent plates

5. CONCLUSION

In this study, the initial deflection shapes of actual ships are measured using a 3D laser scanner, and its applicability is examined. The obtained measurement data are used to analyze the initial deflection components of rectangular plates and to investigate the correlation of the initial deflection components between adjacent plates that affect the buckling and ultimate strength of continuous stiffened panels. A statistical model of the initial deflection of two adjacent plates is developed by extending the existing model of a single rectangular plate. The conclusions are as follows:

1) If the positional relationship between the 3D laser scanner and the measurement target is appropriate, the 3D laser scanner can measure the initial deflection of multiple rectangular plates.
2) There is a positive correlation in the initial deflection amplitudes with the one-half wave between two adjacent rectangular plates. The average value of the ratio of the maximum initial deflection is approximately 0.64.
3) The proposed statistical model can sample initial deflection shapes considering the correlation between adjacent panels.

The initial deflection characteristics measured by the 3D laser scanner are in qualitative agreement with existing measured data, except that a certain number of plates have a negative one half-wave component. Further investigation is needed in this regard.

ACKNOWLEDGMENT

We would like to express our gratitude to Imabari Shipbuilding Co., Ltd. and Nihon Shipyard Co., Ltd for their cooperation in the measurement of the initial deflections.

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Recent Topics at IMO

― Outline of Discussion at IMO Committees ―

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 80th Marine Environment Protection Committee (MEPC 80) held in July 2023 and 107th Maritime Safety Committee (MSC 107) held in June 2023 was provided.

This article provides a summary of the decisions taken at 81st Marine Environment Protection Committee (MEPC 81) held from 18 to 22 March 2024 and 108th Maritime Safety Committee (MSC 108) held from 15 to 24 May 2024 as below.

2. OUTCOMES OF MEPC 81

2.1 Greenhouse Gases (GHG)

At MEPC 80 held in July 2023, the 2023 IMO Strategy on Reduction of GHG Emissions from Ships (2023 IMO GHG Strategy) was adopted, reinforcing the levels of ambition for reducing GHG emissions from international shipping. At this session at MEPC 81, measures already in force such as the Data Collection System for fuel oil consumption of ships (IMO DCS), Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) regulations were reviewed along with discussions on mid-term measures and lifecycle assessments of marine fuels with an aim to achieve the reinforced levels of ambition.

2.1.1 Review of Data Collection System for Fuel Oil Consumption of Ships

The IMO DCS, under which operational data such as fuel oil consumption has been collected and reported since 2019, has been under review since 2022 to improve the items to be reported and the granularity of reported data. At MEPC 80, draft amendments to Appendix IX of MARPOL Annex VI were approved for amending/adding the items required to be reported in the IMO DCS.

At this session, the draft amendments approved at MEPC 80 were adopted to introduce the new items to be additionally reported such as total fuel oil consumption per combustion systems and total fuel oil consumption while the ship is not under way. (See Section 2.4.1 below for details.)

In addition, following the discussions on the definitions of the terms and measurements methods for the new items to be reported, the relevant amendments to the “Guidelines for the Development of a Ship Energy Efficiency Management Plan (SEEMP)” and “Guidelines for Administration Verification of Ship Fuel Oil Consumption Data and Operational Carbon Intensity” were adopted, along with the details of “total transport work” calculated based on actual cargo carried during a voyage, etc.

2.1.2 Power Limitations in EEXI Regulations

At this session, to facilitate the compliance with the EEXI regulations which started from 2023, the “Guidelines on the Shaft/Engine Power Limitation System to Comply with the EEXI Requirements and Use of a Power Reserve” were reviewed.

As a result, clarifications were made in the guidelines to allow pre-emptive un-limiting of the Shaft Power Limitation (SHaPoLi) or Engine Power Limitation (EPL) system under certain scenarios which may endanger the safe navigation of the ship, and also new functional requirements were added for SHaPoLi systems, the control of which is independent from the engine automation.

2.1.3 Heavy Load Carriers

The amendments for the Unified Interpretations to MARPOL Annex VI were approved, defining heavy load carriers which are exempted from the application of Energy Efficiency Design Index (EEDI), EEXI and CII regulations.

2.1.4 Mid-Term Measures for Reduction of GHG

As mid-term measures to achieve the GHG reduction targets in international shipping, a basket of candidate measures, comprised of both a technical element and an economic element, is being developed as set out in the 2023 IMO GHG Strategy. Various measures have been proposed so far, such as: for a technical element, a goal-based marine fuel standard regulating the phased reduction of GHG intensity (GHG Fuel Standard); and for an economic element, posing a levy against GHG emissions (Universal Mandatory GHG Levy) and a combination of posing a fee to ships operating on fossil fuels and rebating revenues to ships operating on zero-emission fuels (feebate), etc.

The work plan in Table 1 has been agreed for developing mid-term measures, aiming for entry into force by 2027:

Table 1 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 this session, as a result of an exchange of views on the basket candidate of measures, the IMO net-zero framework was agreed, illustrating an outline of amendments to be considered, such as attained GHG fuel intensity and distribution of revenue etc. The IMO Member States and International Organizations were then invited to continue with discussions towards finalizing mid-term measures on the basis of the IMO net-zero framework.

Furthermore, the progress of the CIA was reported by the leading organizations of the tasks such as UNCTAD, where the final reports are to be submitted by MEPC 82. In addition, it was also agreed to organize an expert workshop prior to MEPC 82 to facilitate the understanding of preliminary findings of the CIA.

2.1.5 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, the LCA Guidelines were adopted, which provides a general framework on the calculation method of GHG emission intensity (GHG emitted per unit energy) throughout the lifecycle of the fuel: from feedstock extraction/ cultivation to fuel production, distribution and fuel utilization onboard a ship. At the Correspondence Group, which was established at the previous session, discussions were made on the review of the data collection template for establishing default emission factors, examination of proposed default emission factors, leakage of carbon and methane resulting from the LUC (Land-Use Change), credits from use of captured CO2 as carbon stock to produce synthetic fuels, credits from onboard carbon capture and storage etc.

At this session, on the basis of the draft amendments proposed by the Correspondence Group, the amendments (the detailed evaluation method and quantification of parameters for emissions from biofuel production, GHG emission intensity for electricity used during fuel production, evaluation method for GHG emissions onboard ships, etc.) to the LCA Guidelines were made and adopted as the 2024 LCA Guidelines. Furthermore, as the issues investigated at the Correspondence Group were diverse and required expertise, it was agreed to establish a new Working Group on the Life Cycle GHG Intensity of Marine Fuels under GESAMP to pursue discussions along with its Terms of Reference.

2.1.6 Measurement and Verification of Non-CO2 GHG and Onboard Carbon Capture Systems

When methane and ammonia are used as fuel oil, there are concerns with methane slips and formation of nitrous oxides causing impact on global warming. Thus, measurement and verification of non-CO2 (methane, nitrous oxides and other) GHG are being discussed in the context of further development of the LCA Guidelines.

Furthermore, there have been initiatives undertaken to develop onboard carbon capture (OCC) technologies for reducing GHG emissions by segregating and capturing CO2 from exhaust gases onboard ships.

At this session, it was agreed to establish a Correspondence Group to proceed with discussions on the following topics:

- Regulatory framework for the measurement and verification of non-CO2 GHG etc.
- Work plan for developing regulatory framework for OCC technologies.

2.2 BWM Convention

2.2.1 Review of BWM Convention

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 at its previous session approved the Convention Review Plan (CRP) which comprises the list of issues that need to be finalized.

The requirements in the current Convention were reviewed by the relevant Correspondence Group, and this session endorsed the list identifying items that need to be amended within the BWM Convention, BWMS Code and relevant guidelines and guidance. The aforementioned list comprises survey aspects such as sampling and analysis of ballast water to confirm the treatment capacity and discharge concentration of active substances during intermediate and renewal surveys, in addition to commissioning tests, to ensure appropriate installation and effective operation etc. In addition, it was further agreed to reestablish the Correspondence Group for pursuing the topics that require further discussions.

2.2.2 Ballast Water Management in Ships Operating in Challenging Water Quality

There has been continuing discussions at MEPC regarding ballasting operations at ports with challenging water quality (CWQ), where continuous operation of ballast water treatment systems (BWMS) becomes difficult due to issues such as excessive turbidity of ambient water preventing UV transmittance for sufficient disinfection, too low of salinity for proper operation, or particles in water causing filter to get clogged frequently.

At this session, an Interim Guidance on the Application of the BWM Convention to Ships Operating in Challenging Water Quality Conditions was adopted. The interim guidance provides operational guidance such as determination of CWQ, bypass procedures for ballasting operations at ports with CWQ and decontaminating procedures of ballast tanks after the bypassed ballasting operation. The interim guidance will be kept under review for further improvements.

2.2.3 Temporary Storage of Treated Sewage and/or Grey Water

Discharge of treated sewage and grey water has been prohibited in certain ports, which led to discussions for developing guidance for temporary storage of treated sewage and/or grey water to ballast tanks in such ports.

At this session, the Guidance for the Temporary Storage of Treated Sewage and/or Grey Water in Ballast Water Tanks was approved. The guidance sets out the standards such as for flushing tanks after temporary storage, for implementing the relevant procedures in Ballast Water Management Plans (BWMP) and for recording in the Ballast Water Record Book (BWRB).

2.3 Air Pollution Prevention

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

Regulation 13 of MARPOL Annex VI specifies the NOx emission standards for marine diesel engines installed on board ships. Regulation 13.6 designates the North American area, the US Caribbean Sea area, the Baltic Sea area and the North Sea area as Emission Control Areas (ECA), in which the NOx Tier III emission limit is applied.

Regulation 14 of MARPOL Annex VI sets out control measures to reduce emissions of SOx and PM from ships, where the sulphur content in fuel oil used has been generally limited to 0.50% since 2020. Regulation 14.3 designates the North American area, the US Caribbean Sea area, the Baltic Sea area, the North Sea area and the Mediterranean Sea area as ECA, in which the sulphur content in fuel oil used is further limited to 0.10%.

At this session, proposals were submitted to newly designate Canadian Arctic Waters and Norwegian Sea as ECA. As a result, draft amendments to MARPOL Annex VI were approved, adding these areas to ECA.

Assuming the adoption of the draft amendments at MEPC 82, it is expected that the sulphur content in fuel oil used for ships operating in these ECA will be limited to 0.10% at the earliest from March 2027. Furthermore, the NOx Tier III emission limit will be applied to ships in Table 2 operating in these ECA.

Table 2 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

2.3.2 Effectiveness of Measures against NOx Reduction Regulations

While Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) systems are often chosen as solutions for complying with NOx regulations, the effectiveness of such systems are being questioned for cases such as when ships operate under low loads in ECA, where the exhaust gas temperature becomes low or auxiliary control device (ACD) becomes activated and hence the system is prevented from functioning properly. In this regard, it was proposed to examine the way forward to improve the effectiveness of the NOx regulations as well as its application for ships operating in ECA based on the date of keel laid.

At this session, shortcomings of the current NOx regulations such as above were identified, and it was agreed to continue the discussion at MEPC 82.

2.3.3 Measures to Enhance the Safety of Ships Relating to the Use of Fuel Oil

Triggered by the control measures to reduce emissions of SOx and PM, further measures to enhance the safety of ships related to the use of fuel oil have been discussed. The 107th session of the Maritime Safety Committee (MSC 107) held in June 2023 approved and further requested MEPC to approve the draft joint MSC-MEPC guidelines for taking fuel oil samples during bunkering based on the existing guidelines (Res. MEPC.182(59)) in order to establish a unified sampling regime under both the SOLAS and MARPOL Conventions.

At this session, the draft joint guidelines were reviewed to align the terminologies between the guidelines and the MARPOL Convention etc., and the amended draft joint guidelines were subsequently approved. The draft revised guidelines were further approved by MSC 108 and published as an MSC-MEPC Circular (see also 3.3.2(6) below).

2.4 Amendments to Mandatory Instruments

2.4.1 Review of Data Collection System for Fuel Oil Consumption of Ships

The amendments to Appendix IX of MARPOL Annex VI were adopted, including the amendments and additions to the following items required to be reported in the DCS. The amendments will enter into force on 1 August 2025.

1. Total fuel oil consumption per combustion systems (main engines, auxiliary engines/generators and oil-fired boilers);
2. Total fuel oil consumption while the ship is not under way;
3. Laden distance travelled (on a voluntary basis);
4. Transport work;
5. Total amount of on-shore power supplied; and
6. Category of Innovative energy efficiency technologies.

The Parties were further invited to consider early application of the amended data collection provisions from 1 January 2025.

2.4.2 Revision of the Requirements of Bunker Delivery Note for Low-Flashpoint Fuels and Gas Fuels

The amendments to MARPOL Annex VI were adopted, which clarify the requirements for onboard storage and minimum information of BDN for low-flashpoint fuels and gas fuels. The amendments will enter into force on 1 August 2025.

2.4.3 Ballast Water Record Books in Electronic Record Book Format

The amendments to the Regulations A-1 and B-2 of the BWM Convention were adopted, which include the reference to “the Guidelines for the Use of Electronic Record Books under the BWM Convention” adopted at MEPC 80. The amendments will enter into force on 1 October 2025.

3. OUTCOMES OF MSC 108

3.1 Adopted Mandatory Requirements

Mandatory requirements were adopted at MSC 108 as follows:

(1) Amendments to SOLAS regulation II-1/3-4

Amendments to SOLAS regulation II-1/3-4 to require emergency towing arrangements on ships, other than tankers, of not less than 20,000GT were adopted. In addition, guidelines specifying specific requirements for the arrangement are under consideration by the Sub-Committee on Ship Design and Construction (SDC) with a target completion in 2025.

(2) Amendments to IGF Code

Amendments to IGF Code regarding redundancy of pressure relief valves for liquefied gas fuel tanks, 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. In addition, the MSC circular to invite a voluntary early implementation of 4.2.2, 8.4.1 through 8.4.3 of the amendments was also released. Note that the following requirements apply also to existing ships;

1. An emergency release system (ERS) or equivalent means shall be provided for bunkering manifold, unless installed on the bunkering supply side of the bunkering line. In cases where connections other than a dry-disconnect/connect coupling are used, a bunkering arrangement risk assessment are required, and the fuel handling manual shall include documentation that special consideration was granted under 8.4.2 of IGF Code;
2. The portable dry powder extinguisher shall be provided in the fuel preparation room not later than the first survey on or after 1 January 2026. (11.6.2); and
3. Regarding the written agreement on bunkering transfer procedures, items such as transfer pressure and temperature are added (18.4.1).

(3) Amendments to International Code for the Safe Carriage of Grain in Bulk (Grain Code) (resolution MSC.23(59))

Amendments to Grain Code, to add new loading condition of specially suitable compartments, partly filled in way of the hatch opening, with ends untrimmed, were adopted.

(4) Amendments to LSA Code

The following amendments to LSA Code and recommendation on testing of life-saving appliances (resolution MSC.81(70)) were adopted;

1. In-water performance requirement for lifejackets;
2. Requirements for single fall and hook systems with on-load release capability which is used for lifeboat launched by a fall or falls, except a free-fall lifeboat; and
3. Requirements for lifeboats to limit the minimum and maximum lowering speed of fully loaded survival craft and rescue boats.

(5) Amendments to SOLAS chapter II-2 and FSS Code

The following amendments to SOLAS chapter II-2 and FSS Code on fire safety of ro-ro passenger ships, etc. were adopted;

1. Fire safety requirements on new/existing ro-ro passenger ships mainly shown as below;
   - Fixed fire detection and fire alarm systems;
   - Video monitoring in ro-ro spaces;
   - Arrangement of openings in ro-ro and special category spaces;
   - Arrangement of weather decks;
   - Water monitors for protection of weather deck;
   - Linear heat detectors; and
   - Visual and audible fire signals
2. Amendments to SOLAS regulation II-2/7.5.5 concerning fire detection within control stations and cargo control rooms of cargo ships.

3.2 Approved Mandatory Requirements

The following mandatory requirements were approved at this session and are expected to be adopted at MSC 109 to be held in December 2024.

(1) Amendments to IGF Code

Amendments to IGF Code regarding minimum distance from bottom for suction well, etc. were approved as a part of the task for amendments to the IGF Code and development of guidelines for alternative fuels and related technologies.

(2) Amendments to IGC Code

Amendments to the IGC Code to make cargos identified as toxic products conditionally usable as fuel, in view of the launch of ammonia-fueled vessels. It was also agreed that this amendment would be effective 18 months after adoption by MSC 109 and to invite a voluntary early implementation at that time.

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

The following unified interpretations (UIs), guidelines, guidance and etc. were approved during MSC 108.

3.3.1 UIs

(1) Amendments to unified interpretations of SOLAS chapters II-1 and XII, of the technical provisions for means of access for inspections (resolution MSC.158(78)) and of the performance standards for water level detectors on bulk carriers and single hold cargo ships other than bulk carriers (resolution MSC.188(79)) (MSC.1/Circ.1572/Rev.1)

Amendments to unified interpretation to;

1. clarify the intervals and records for permanent means of access; and
2. amended title and application to meet the revised performance standards for water level detectors on ships subject to SOLAS regulations II-1/25, II-1/25-1 and XII/12 as well as bulk carrier (Resolution MSC. 188 (79)/Rev.2).

(2) Unified interpretation of SOLAS regulation XV/5.1 and paragraph 3.5 of part 1 of the International Code of Safety for Ships Carrying Industrial Personnel (IP Code) on the harmonization of the Industrial Personnel Safety Certificate with SOLAS safety certificates

Unified interpretation of SOLAS regulation XV/5.1 and paragraph 3.5 of part 1 of the IP Code to harmonize the Industrial Personnel Safety Certificate with various SOLAS safety certificates, in terms of their validity or date of endorsement.

(3) Unified interpretation of Code on noise levels on board ships

Unified interpretation of section 2.1 and 2.2 of the Code to clarify requirements for the calibration of the sound level meter and its field calibrator.

(4) Amendments to unified interpretations of SOLAS regulations II-2/9 and II-2/13 (MSC.1/Circ.1511)

Amendments to unified interpretations of SOLAS regulations II-2/9 and II-2/13 (MSC.1/Circ.1511) to include steering gear spaces as “safe position” for the purpose of escape from the lower part of machinery spaces through a continuous fire shelter.

3.3.2 Guidelines and Guidance etc.

(1) Amendments to revised guidelines on the application of high manganese austenitic steel for cryogenic service (MSC.1/Circ.1599/Rev.2)

Amendments to revised guidelines on the application of high manganese austenitic steel for cryogenic service (MSC.1/Circ.1599/Rev.2) to qualify high manganese austenitic steel for ammonia service and to add compatibility test requirements for ammonia service.

(2) Amendments to revised guidelines for the acceptance of alternative metallic materials for cryogenic service in ships carrying liquefied gases in bulk and ships using gases or other low-flashpoint fuels (MSC.1/Circ.1622)

Amendments to revised guidelines for the acceptance of alternative metallic materials for cryogenic service in ships carrying liquefied gases in bulk and ships using gases or other low-flashpoint fuels (MSC.1/Circ.1622) to add compatibility test requirements for ammonia service.

(3) Interim guidelines for use of LPG cargo as fuel

Interim guidelines for use of LPG cargo as fuel, as a part of the task for amendments to the IGF Code and development of guidelines for alternative fuels and related technologies.

(4) Revised interim recommendations for carriage of liquefied hydrogen in bulk (resolution MSC.420(97))

Revised interim recommendations for carriage of liquefied hydrogen in bulk, including the addition of cargo containment systems of independent cargo tanks using insulation materials and hydrogen gas in the inner insulation spaces.

(5) Amendments to revised guidelines on alternative design and arrangements for SOLAS chapters II-1 and III (MSC.1/Circ.1212/Rev.1)

Amendments to revised guidelines on alternative design and arrangements for SOLAS chapters II-1 and III (MSC.1/Circ.1212/Rev.1) to add the goals, functional requirements and expected performance criteria for alternative design and arrangements for SOLAS chapter II-1, Part C, D and E.

(6) Guidelines for the sampling of fuel oil for determination of compliance with MARPOL Annex VI and SOLAS Chapter II-2

Guidelines for taking fuel oil samples during bunkering in order to establish a unified sampling regime under both the SOLAS and MARPOL Conventions.

3.4 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).

At this session, based on the report by the correspondence group and the meeting outcome arranged by the related working group, non-mandatory MASS Code mainly on goal and functional requirements for items such as safety, operation, security, etc. has been considered. As a result, it was agreed to establish a correspondence group, and hold an intersessional working group meeting in September 2024 to proceed the work on development of the non-mandatory MASS Code. As a future work plan, it was agreed to finalize and adopt the non-mandatory MASS Code at MSC 110 scheduled to be held in June 2025, thereafter, to proceed the development of a mandatory MASS Code with a view to adoption by 2030(entry into force on 1 January 2032).

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

At the previous session, 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.

At this session, based on the report by the correspondence group, the work to update the list of new technologies and alternative fuels was progressed by the related working group, and it was decided that a correspondence group would continue to be established and work would proceed.

3.6 Cyber Risk Management

In view of the growing importance of cyber security on board ships and the need for security risk countermeasures, the non-mandatory resolution MSC.428(98) on cyber risk management in the Safety Management System (SMS) has been developed. Additionally, the Guidelines on Maritime Cyber Risk Management (MSC-FAL.1/Circ.3/Rev.2) have been developed.

At the previous session, it was agreed to carry out a review of the Guidelines in light of the increased use of cyber-connected systems in recent years.

At this session, a draft amendment to the Guidelines were approved that adds more maritime-specific functional requirements to be considered from organization, people, process and technological aspects based on the widely-recognized international and industry standards. The draft amendment to the guidelines will be approved by subsequent Facilitation Committee (FAL) and published as an MSC-FAL Circular.

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