Safety analysis of routing and planning of the transportation of dangerous goods by water transport

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Abstract. The transportation of dangerous goods makes up a substantial proportion of the world cargo turnover. The role of water transport in the transportation of such goods as the cheapest form of transport in international trade is also growing. Hazardous substances can be extremely harmful to both the environment and human health. Their leakage can lead to global catastrophes and damage caused by them can amount to millions of dollars. Nowadays one of the main problems of emergencies in water transport is a violation of the existing transportation rules, including the transportation of dangerous goods. In this paper their characteristics and classification are given on the basis of the considered existing normative documents (conventions and agreements) and the analysis of the existing system for the transportation of dangerous goods by water transport. The concept of “dangerous goods” is defined. The issues related to accidents, labeling of dangerous goods, training of service staff are considered. The issue of limits on sulfur oxides (SOx) in the exhaust gases of marine diesel engines is considered after the initial review of the current regulations for the carriage of dangerous goods by water. Possible risks arising in connection with the transportation of dangerous goods are presented.

1. Introduction

1.1 Transportation of dangerous goods

According to the Federal State Statistics Service [1], the total volume of cargo transported in Russia in 2019 was approximately 8,400 million tons. Recently, the increasing number of them is transported by water transport as the cheapest mode of transport in international trade. This method also provides faster transportation. In January and February 2021 alone, about 2,686 thousand tons of cargo were transported in Russia by sea, and 3865 thousand tons of goods were transported by inland waterways. Figure 1 shows statistics on the carriage of goods by water transport in Russia for the period from 2013 to 2020.

According to the latest data from the United Nations (UN), a significant increase in the share of the transport of dangerous goods occurs daily in the world cargo turnover [2]. It reaches about half of the total world cargo turnover [3]. Absolutely different types of transport are used every day for the transportation of such goods. In particular, water transport is used. A significant part of the transported dangerous goods in Russia is oil and oil products, as well as coal and coke, chemical and mineral fertilizers, etc. Figure 2 shows the structure of dangerous goods transportation by sea in Russia in 2019 [1].
At the same time, the modern rates of development of oil, chemical and energy industries require the provision of transportation of dangerous goods by all existing modes of transport [4, 5]. For the traffic of large consignments of such goods, water transport is most often used due to the good carrying capacity of ships. As a result, there is a sharp increase in the number of ships and terminals carrying out loading and unloading of dangerous goods. This, in turn, also leads to an inevitable increase in accidents on the routes of ships.

**Figure 1.** Statistics on the transportation of goods by water transport in Russia for the period from 2013 to 2020

**Figure 2.** Structure of transportation of dangerous goods by sea in Russia in 2019
1.2 Accident rate in the transportation of dangerous goods by water transport

Accident rate is a serious problem in the transportation of dangerous goods. Usually, accidents are provoked by the specific properties of goods themselves [6]. These properties include flammability, explosiveness, toxicity, etc. According to [7], on January 19, 2021, a Turkish ship “April” flying the Panamanian flag across the Kerch Strait had an incident involving the poisoning of six sailors. Chemicals were cited as one of the possible causes of poisoning. Ferrosilicon was transported on board April, which can emit poisonous gas if stored improperly.

It is reported [8] that in October 2020, an explosion occurred on board General Hazi Aslanov tanker in the Sea of Azov at the mouth of the Kerch Strait. The causes of the explosion are still unknown. The tanker went completely empty to Rostov-on-Don. One of the official reasons for the incident is considered to be an explosion of vapors of petroleum products. It is possible that the human factor could also be the cause. According to some experts, when transporting dangerous goods, the crew members of the tanker had to use explosion-proof electrical equipment, including explosion-proof portable radio sets. Perhaps the crew neglected this mandatory requirement.

When ships with dangerous goods get into accidents, economic losses are colossal [9]. The harm caused to the environment and human health is estimated in millions of dollars [10]. At the same time, a fairly long-term socio-ecological impact, such as long-term poisoning of flora and fauna, is in the nature of a catastrophe. In July 2020, the Japanese tanker MV Wakashio, transporting 4,000 tons of petroleum products on board, stumbled upon a coastal reef off the coast of Mauritius in the Indian Ocean. As a result, about 1000 tons of oil spilled out of the resulting hole. Scientists called this accident the worst environmental disaster that will negatively affect economy for decades [11]. Therefore, in all countries associated with transportation in the shipping transport industry, the task of the organization of the safety of transportation became a priority.

In Russia, the provision of safety of transportation is very difficult due to the wear and tear of a significant number of ships. In addition, the country retains rather low freight rates [12]. Low rates limit ship-owners. They can not pay due attention to preventive work, such as technical modernization of ships, training service staff, etc.

2. Results

2.1 System of international regulation of the transportation of dangerous goods

The State standard GOST 19433-88 “Dangerous goods. Classification and labeling” ([13], Appendix 4, p. 30) defines: “Dangerous goods – substances, materials and products with properties, the manifestation of which in the transport process can lead to death, injury, poisoning, radiation, illness of people and animals, as well as to explosion, fire, damage to structures, vehicles, ships, characterized by the indicators and criteria given in this standard, transported in packaging, as well as in tank or in bulk in containers, vehicles and in bulk by water transport”.

Various systems, both national and international, govern the basic rules for the transportation of dangerous goods. Moreover, these systems are largely identical. The similarities relate both to the technical side of the issue of the organization of transportation and storage of cargo and to the issue of additional training for service staff. At the same time, the transportation of such goods requires particularly strict adherence to a clear organization, the implementation of a certain order of actions and control over transportation. For this purpose, in order to reduce the risks of the possibility of man-made disasters associated with the transportation, storage and use of dangerous goods, the need for strict regulation of the procedure for handling them among interested states and international organizations was identified.

According to [14], this need was formed back in the 1900s. As a result, over time, specific rules have been developed for most of the existing modes of transport. In accordance with these rules, the procedures for the classification of dangerous goods were determined, which included the conditions of their transportation, methods of loading, as well as requirements for organizations, training of service staff and special documentation provided in case of accidents. Nowadays, the system of
international regulation of the transportation of dangerous goods includes a large number of different regulatory documents (conventions and agreements). Figure 3 [15] shows the main international organizations within which the development of these documents is carried out.

Decryption of symbols [16] presented in figure 3:
- **UNO** – United Nations Organization;
- **ICAO** – International Civil Aviation Organization;
- **IMO** – International Marine Organization;
- **IAEA** – International Atomic Energy Agency;
- **IATA** – International Air Transport Association;
- **UNESC** – United Nations Economic and Social Council;
- **UN’s EC** – Economic Commission for Europe;
- **UIC** – Union Internationale des Chemis;
- **ORC** – Organisation for Railways Cooperation;
- **Sub-C TDG** – Sub-Committee on the Carriage of Dangerous Goods;
- **Sub-D GHS** – Subcommittee on the Globally Harmonized System of Classification and Labeling of Chemicals;
- **WP. 15** – Working Party on the Transport of Dangerous Goods;
- **WP. RID** – Working Party on the Transport of Dangerous Goods by Rail;
- **ICAO-TI** – Technical Instructions for the Safe Transport of Dangerous Goods by Air;
- **IATA DGR** – Dangerous goods regulations;
- **IMDG** – International Maritime Dangerous Goods;

Figure 3. International organizations involved in the development of regulatory documents for the transportation of dangerous goods
2. Legal environment for the transport of dangerous goods by water transport

The main document regulating the transportation of dangerous goods, as well as the organization of all intermediate operations with them (loading and unloading, storage, etc.), is the document “Recommendations for the transport of dangerous goods”. The recommendations are model rules developed by the UN dedicated committee of experts. The document is of a recommendatory nature. However, it was developed in the form of compulsory provisions. The main purpose is to use the list of recommendations as a basis for the formation of national and international transport regulations.

The working group of the Intergovernmental Maritime Consultative Organization (IMCO), later transformed into the Subcommittee on the Transport of Dangerous Goods, developed the International Code for the Carriage of Dangerous Goods by Sea (IMDGCODE) [17]. The IMDG Code was first presented at the IV Assembly of the International Maritime Organization (IMO, IMO) in 1965. Then Resolution A.81 (IV) entered into force. The Code is recommended for use in countries that have signed the International Convention for the Safety of Life at Sea (SOLAS).

IMO member countries adopted it as a basis for the development of national regulations for the transportation of dangerous goods by sea. Currently, the IMDG Code is a generally recognized international document. It also details such issues as cargo packaging, labeling, stowage, segregation, handling, emergency operation [18], etc. The carriage of dangerous goods by water transport is regulated by the International Convention for the Prevention of Pollution of the Seas from Ships (MARPOL). Subsequently, the European Agreement on the Carriage of Dangerous Goods by Inland Waterways (ADN) was prepared and entered into force. In contrast to the UN Model Regulations, all of these documents are mandatory for international transport of dangerous goods through the territories of states that have ratified the relevant conventions and agreements [18].

### 2.3 Classification of dangerous goods according to the IMDG Code

The first requirement for cargo is classification. Dangerous goods must be defined in accordance with the state standard GOST 19433-88 [13] and properly labeled. In accordance with the UN Recommendation for the carriage of such goods, the IMDG Code has developed its own classification of dangerous goods. It contains a breakdown of hazardous substances into nine classes [19, 20] (within the class, hazardous substances are grouped that have similar damage) depending on the properties and type of hazard (Table 1). Some of these classes are in turn subdivided into subclasses. Certain types of dangerous goods can belong to several of nine classes at once. Moreover, each of them must be marked with the appropriate marking. This classification has been defined for convenience. It is necessary to note that the numbering of classes and subclasses does not indicate the degree of hazard of goods.

| Class                          | Subclass                                                   | Example                      |
|-------------------------------|------------------------------------------------------------|------------------------------|
| Class 1: Explosive materials  | Subclass 1.1: Substances and articles with a mass explosion hazard | Explosives, ammunition, cartridges, gunpowder, rockets, pyrotechnics |
|                               | Subclass 1.2: Substances and articles which have a projection hazard but do not present a mass explosion hazard |                              |
|                               | Subclass 1.3: Substances and articles that have a fire hazard and either a minor explosion hazard or a minor |                              |
projection hazard, or both, but do not have a mass explosion hazard
Subclass 1.4: Substances and articles that do not pose a significant hazard
Subclass 1.5: Substances of very low sensitivity which have a mass explosion hazard
Subclass 1.6: Extremely insensitive articles that do not have a mass explosion hazard

Class 2: Gases, compressed, liquefied and dissolved under pressure
Subclass 2.1: Flammable gases
Subclass 2.2: Non-flammable non-toxic gases
Subclass 2.3: Toxic gases
Oxygen, propane, nitrogen, air, ammonia, chlorine
Oil, gasoline, oil, methanol, alcohol, kerosene

Class 3: Flammable liquids
Subclass 3.1: Flammable liquids with a low flash point and liquids having a closed cup flash point below -18 °C or having a flash point in combination with other hazardous properties than flammability
Subclass 3.2: Flammable liquids with a medium flash point – liquids with a flash point in a closed cup -18 °C to + 23 °C
Subclass 3.3: Flammable liquids with a high flash point – liquids with a flash point from + 23 °C to + 61 °C inclusive in a closed crucible

Class 4: Flammable solids; spontaneously combustible substances; substances that emit flammable gases in contact with water
Subclass 4.1: Flammable solids, self-reactive and solid desensitized explosives
Subclass 4.2: Autogenous substances
Subclass 4.3: Substances that emit flammable gases in contact with water
Sulfur, potassium, sodium, aluminum, coal, paper

Class 5: Oxidizing agents and organic peroxides
Subclass 5.1: Oxidizing agents
Subclass 5.2: Organic peroxides
Peroxide, nitrates, ammonium, chlorites

Class 6: Poisonous substances and infectious substances
Subclass 6.1: Toxic substances
Subclass 6.2: Infectious substances
Pesticides, infectious substances, drugs, cyanides, arsenic

Class 7: Radioactive materials

Class 8: Caustic and / or corrosive substances
Subclass 8.1: Acids
Subclass 8.2: Alkalis
Subclass 8.3: Various caustic and corrosive substances
Acid, alkali, mercury, paint

Class 9: Other dangerous substances
Subclass 9.1: Solid and liquid flammable substances and materials that do not belong to the 3rd and 4th classes by their properties, but under certain conditions can be dangerous in a fire relation (flammable liquids with a flash point from + 61 °C to
Dust, engines, asbestos, lithium batteries
Subclass 9.2: Substances that become caustic and corrosive under certain conditions

2.4 Labeling and packaging of dangerous goods

In accordance with the hazard class and the composition of the UN dangerous goods, a separate list was prepared – the List of dangerous substances. It includes over 3000 different items. Each hazardous substance in this list has a four-digit number. This number is also called the UN Hazardous Substances Identification Number. The number allows finding out the exact name of the transported dangerous substance.

Dangerous goods and vessels must additionally be labeled in accordance with international rules and established norms. To indicate the special properties of dangerous goods, the so-called danger label system is used. The symbols in the form of a diamond with a schematic designation of the product are applied to the product itself with dangerous goods or to its packaging. The system is based on the classification of dangerous goods (Table 1).

Dangerous goods, due to their properties, require specialized packaging. Properly selected, reliable packaging avoids harm to the environment and human health. Packaging must comply with all regulations and specifications for the transport of dangerous goods. The main properties of packaging are its reliability, strength and safety. Without fail, packaging excludes spillage or leakage of the substance. In addition, the material from which it is made should not interact with dangerous goods and do not lead to a violation of the integrity of the package.

2.5 Cargo Transport Unit Inspection Program

The next stage of the provision of the safety of the transportation of dangerous goods by water transport is to inspect the packed goods and documentation (declaration on the transportation of dangerous goods, IMDG Code rules, a list with the name and description of the goods, waybill, etc.) by shipping companies. This audit was initiated by the IMO. The main purpose is to apply the controls of the safety management system in order to determine the effectiveness of the current system. On the basis of the IMO recommendations, states have been advised to implement inspection programs for cargo transport units transporting dangerous goods and to report on the results of these inspections.

Inspection is an important aspect of control measures to ensure compliance with the IMDG Code. The results of the inspection are reported annually to IMO. However, the implementation of verification is not always implemented in the current practice of shipping. According to the IMO summary report for 2004 [21], a total of 7,300 cargo transport units were inspected. 1928 of them had defects. This is approximately 26.4%. In most cases, non-compliance with the requirements of the IMDG Code was due to the lack of training of service staff.

2.6 Service staff

It is necessary to note that the successful application of conventions, agreements and rules that determine the norms for the transportation of dangerous goods largely depends on their understanding by the service staff and their perception of possible risks. In this regard, each shipping company pays special attention to the issues of specialized crew training. The ship's service staff must undergo appropriate training and obtain supporting documents [12]. This is applied to river and sea transportation of dangerous goods.

For example, IMO previously developed a special training course program on dangerous goods. The main purpose of the course is to help the crew of ships understand and comply with the rules for the transportation of dangerous goods. The program included the following topics: classification of goods, their packaging, shipping procedures, loading and sorting, etc.
In general, training courses and seminars are more focused on the identification of security and safety issues and only later on the solution of these issues. Particular attention is also paid to the proper stowage and security of dangerous goods on board ships.

Significant difficulties in the provision of safety of transportation of dangerous goods can be caused by an unfavorable situation within a crew. Potential incidents of bullying often have serious consequences for the physical and emotional health of service staff. This leads to the decrease in motivation and the increase in morbidity and also poses a risk to the work of crew. At the same time, the presence of dangerous cargo on board the vessel introduces an additional threat. These situations can lead to negative consequences, primarily for shipping companies. An unfavorable environment within a crew affects working conditions and the potential occurrence of organizational, economic and legal consequences.

In this regard the attention to this problem in maritime shipping by international organizations increased recently. The International Transport Workers' Federation (ITF) and the International Chamber of Shipping (ICS) have drafted an amendment “Guidelines for the Elimination Harassment and Bullying on Board Ships”. This amendment addresses the issues of preserving the health of seamen and aims to eradicate bullying on board ships. This will improve the working conditions of the service staff and increase the efficiency of work and the level of safety.

2.7 Control over the reduction of emissions of sulfur oxides

However dangerous goods are not the only ones that are extremely harmful to the environment and human health. Water transport is one of the largest sources of sulfur oxides (SOX) pollution and carbon emissions on the planet. Water transport accounts for about 15% of oil consumed by the transport sector. Vessels consume about 5 million barrels of oil per day. This is approximately 8% of all products produced by oil refineries [22]. Most ships use fuels that contain 3,500 times more sulfur than automotive diesel. A Morgan Stanley study [23] states that sulfur oxide emissions from a single cruise ship are comparable to those of 380 million cars. At the same time they cause ocean acidification, damage to crops, and even extreme weather changes. Changes in weather are associated with the occurrence of thunderstorms along the shipping routes with the highest traffic volumes.

Controlling SOx emissions will improve air quality. It also will have a positive impact on human health and protect the environment [24].

In order to reduce harmful emissions of sulfur oxides from the marine industry and reduce the negative impact on human health and the environment, the IMO 2020 regulation came into force in 2020. It requires ships outside the established emission control zones to use fuels with a sulfur content of less than 0.5%. This is 86% less than the previous rule for sulfur content in fuel of 3.5% [25].

There are three ways to comply with the IMO 2020 standards:
1. The installation of scrubbers;
2. The transition to liquefied natural gas as fuel;
3. The use of clean fuel.

All three methods will entail high costs for shipping companies. One of the options for meeting the IMO 2020 standards is the use of an exhaust gas cleaning system (scrubbers) for their desulfurization. The functions of the scrubber differ depending on the type of scrubber. The main task is the use of sea or fresh water using a solution of caustic soda or a similar action of other chemicals to flush sulfur oxides from the exhaust gas [26]. Today there are more than 60,000 vessels in service that are subject to the IMO 2020 requirements. Only 3,000 vessels of them have been retrofitted with scrubbers capable of absorbing SOx emissions. Scrubbers require a large initial investment and a fairly long installation time. The system costs from $2.5 million and takes six to nine months to install. Larger vessels may require multiple scrubbers, which increases costs.

The second option is to switch to liquefied natural gas. There are currently only 300 vessels operating on liquefied natural gas. The transition to its use is especially difficult. This is explained by the need to install a different type of marine engine, which has special conditions for placement on board the vessel and requires additional training of service staff. These factors make the second option
for the implementation of the IMO 2020 standard even more expensive, complex and impractical in the short term.

This leaves approximately 57,000 ships, or about 97% of the total number of ships [25], for which a switch to cleaner fuel would be a reasonable short-term solution. For example marine gas oil (MGO) or very low sulfur fuel oil (VLSFO). This is also a rather expensive solution, but it is fully justified for today.

2.8 Risks of transportation of dangerous goods by water transport

The transportation of dangerous goods is associated with high risks. It has already been noted that the release of hazardous substances can pose a serious threat to the environment, and in extreme cases can lead to unusually large-scale disasters [27, 28]. The general increase in the number of transportation of such goods by water transport leads to the increase in the risk of accidents. At the same time, the risk management system should not only reduce the negative impact on the environment and society, but also take into account possible economic consequences. The specificity of this type of transport is that the elimination of the consequences of accidents is much more difficult than in a similar situation on land. The competition among shipping companies, which prioritize minimizing transport costs and shortening transportation times, does not contribute to the organization of safe transportation. According to ship-owners, the conventions and agreements aimed to improve water safety are too numerous and significantly limit their capabilities. Therefore, it is necessary to increase awareness of the need to comply with the rules and pay special attention to the countries interested [29] in the issues of transport safety.

2.9 The analysis of risks of transportation of dangerous goods by water transport

The detailed analysis of possible risks is required for effective planning and management of water transport [30], the prevention of accidents and mitigation of their consequences [19]. According to [31], “risk analysis in the transport of dangerous goods can be defined as the process of identifying hazards and assessing the risk for people involved or not participating in the technological process, vehicles, goods, structures, the environment, and other objects”. In this case, it is necessary to take into account the main characteristics of transportation. These include the average of the hazardous transported substances, the type of packaging, traffic conditions, time of day and weather in the geographic regions involved in the transport [32]. In addition, there are factors that depend on the service staff (e.g., age, experience) and on the operations carried out during transport [32]. Figure 5 shows a functional model for the development of risk in the transportation of dangerous goods by water transport.

According to this model, it is possible to determine the primary sources of risk occurrence – the possible causes of accidents. The presented causes of accidents bring the process of transportation of dangerous goods by water transport into an unstable state [31].

Based on the result of the risk analysis, information about its possible frequency of occurrence and possible consequences will be obtained. A significant drawback of existing modern risk assessment methods is that the probability of an event occurrence is considered separately from its possible consequences. This fact does not fully provide information on the degree of hazard of a substance. Thus, the dangerous substance is separated from a specific type of transport, route, etc.

The results of the risk analysis are used in the future to make decisions on the choice of a safe technology for the transportation of dangerous goods. At the same time, the complexity of the analysis in the process of the transportation of such goods by water transport is explained by the fact that an emergency situation can occur at absolutely any point on the route of the vessel. Moreover, the same events can lead to completely different consequences.

2.10 The ways to reduce the risk during the transportation of dangerous goods by water transport

Transport activity is associated with high risks to human life, environmental safety and economic sustainability [33]. The establishment of acceptable risk limits, assessment of their actual levels and
The analysis of the cost-benefit of proposed security measures are all designed to help the process of risk management and mitigation. The following basic actions are determined to limit the harmful effects that may arise during the transportation of dangerous goods by water transport:

- the analysis of the risk of a major accident in relation to specific terrain conditions;
- the determination of the main components of the assessed risk;
- the development of a specific methodology for risk assessment;
- the development of an action plan to reduce the risk of accidents and to limit adverse consequences.

Figure 5. Functional model of risk development in the transportation of dangerous goods

The ways to reduce the risk during the transportation of dangerous goods by water transport include:

- the exclusion of the primary sources of risk;
- the distribution of duties among staff with appropriate competence and qualifications;
- timely and correct maintenance of accompanying documentation (declaration on the carriage of dangerous goods, consignment note, etc.);
- the assessment of current activities and associated potential risks to ensure the safety of
transportation;
  • a clear statement of the safety measures on board;
  • effective and timely methods of communicating hazards.

The listed measures can not guarantee complete safety during the transportation of dangerous goods. First of all, they only record evidence. Therefore, it is necessary to insure cargo. Insurance is usually the most effective of all the selected methods of influencing risks. Due to insurance, it is possible to fully or partially compensate the losses incurred in the event of an accident. As a result, high or unacceptable risk ultimately becomes acceptable or minimal.

3. Discussion

The transportation of dangerous goods is a significant share of the total world cargo turnover in modern international trade. At the same time, it is necessary to take into account the specific properties of goods themselves. These properties include flammability, explosiveness, toxicity, etc. Most often, accidents on the water are provoked precisely because of the specific properties of dangerous goods. The accidents considered in the paper clearly demonstrate this fact. The presented examples show how dangerous goods can be harmful to both the environment and human health. It is necessary to note that not only shipping companies, but also states and international organizations are interested in reducing the potential negative impact in the case of emergencies. Therefore, in order to reduce the risks of the possibility of man-made disasters, the need for strict documentary regulation of the procedure for handling them was determined. The safety requirements set out in regulatory documents (conventions and agreements) reflect the basic rules for the provision of safety of ships transporting dangerous goods and their crews. They also contribute to the improvement of the reliability and efficiency of cargo deliveries.

Thus, in order to provide the safety of people, ships and the environment during the transportation of dangerous goods, shipping companies and crews of ships should observe the following rules:
  • Compulsory compliance with all conventions and agreements;
  • Transportation of dangerous goods only in specially equipped packages and containers;
  • Use of special designations: markings, signs indicating the hazard class of the substance, etc.;
  • Obligatory verification of the prepared set of documents which allow the transportation of dangerous goods.

The listed rules help to reduce the risks of emergencies during the transportation of dangerous goods by water transport.

4. Conclusion

The main purpose of this paper is to consider the current state of the issue of safe transportation of dangerous goods by water transport. The existing normative documents (conventions and agreements) are quite well developed. The rules presented in them indicate the importance of the provision of maritime and river safety. There is a constant need to use approaches, models and tools to identify, analyze and assess the risks of potential accidents, as well as the need to control them. Governments and international organizations express great interest in the implementation of processes for the automation of the management of these risks when making decisions to prevent accidents.

The analysis indicates that effective management of the safety of transportation of dangerous goods by water transport is impossible without the use of modern means and monitoring systems. This indicates the need to create a software package that will allow organizing management support in the system in order to provide the safety of water transportation of dangerous goods. The complex will also reduce socio-economic losses during the operation of transport system on the water. The reduction of sulfur oxide emissions into the atmosphere should also be monitored through the use of a software and hardware complex. In order to simplify the preparation of permits, a database of vessels that fully comply with all the IMO 2020 requirements should be used.
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