Comparison air pollutant emissions MARPOL Annex VI compliance options in 2020

CE Delft

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This report was prepared by:
Anne Kleijn

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Further information on this study can be obtained from the contact person Jasper Faber (CE Delft)

Content

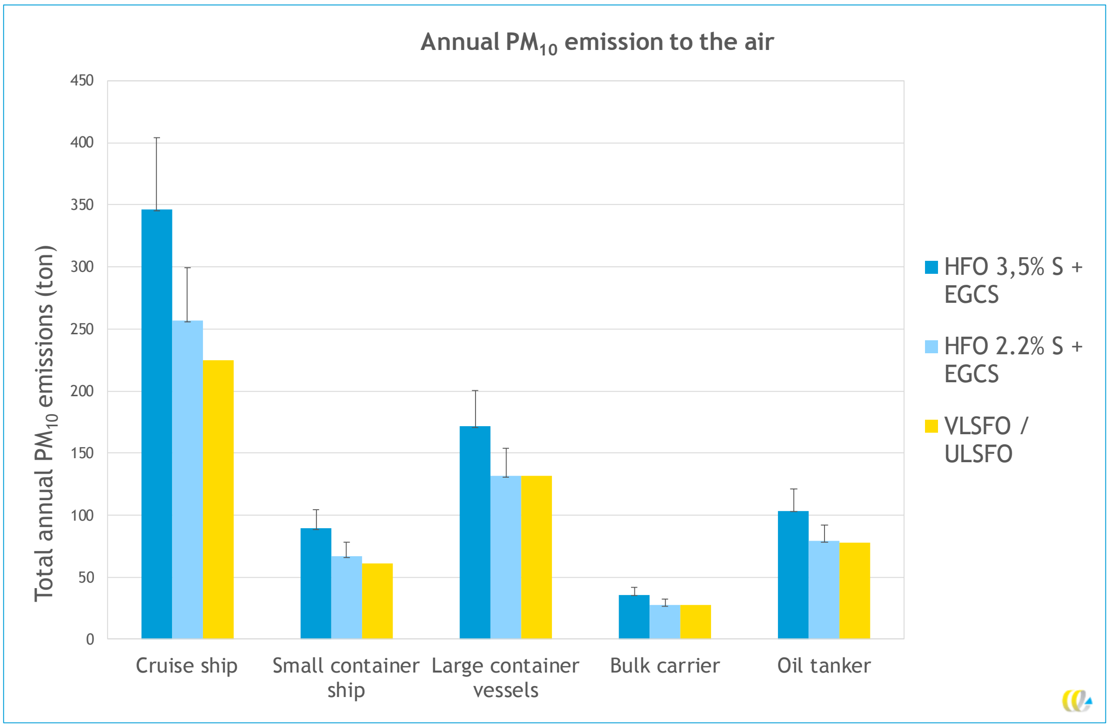
List of abbreviations

Abbreviation	Description
CO_2	Carbon dioxide
Cr	Chrome
Cu	Copper
DT	Dilution tunnel
DWT	Deadweight tonnage
ECA	Emission Control Areas
EGCS	Exhaust gas cleaning system
ELPI	Electric low pressure impactor
FPS	Fine particle sampler
GT	Gross tonnage
HFO	Heavy fuel oil
HSD	High-Speed Diesel
IMO	International Maritime Organization
LSFO	Low sulphur fuel oil
MARPOL	International Convention for the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
MDO	Marine diesel oil
MW	Megawatts
Ni	Nickel
NO	Nitric oxide
NO_x	Nitrogen oxides
NO_2	Nitrogen dioxide
N/A	Not applicable
PAH	Polycyclic aromatic hydrocarbon
pH	Potential of Hydrogen, a scale used to specify the acidity of an aqueous solution
PM	Particulate matter
PM_{10}	Particulate matter with particles of 10 micrometres and smaller
$PM_{2.5}$	Particulate matter with particles of 2.5 micrometres and smaller
Ro-Pax ferry	Roll-On-Roll-Off-Passenger ferry
S	Sulphur
SO_x	Sulphur oxides
SFOC	Specific fuel oil consumption
SMPS	Scanning mobility particle sizer
SSD	Slow-Speed Diesel
TEU	Twenty-Foot Equivalent Unit
TTW	Tank-to-wake
ULSFO	Ultra low sulphur fuel oil
V	Vanadium
VLSFO	Very low sulphur fuel oil
WTT	Well-to-tank
WTW	Well-to-wake
Zn	Zinc

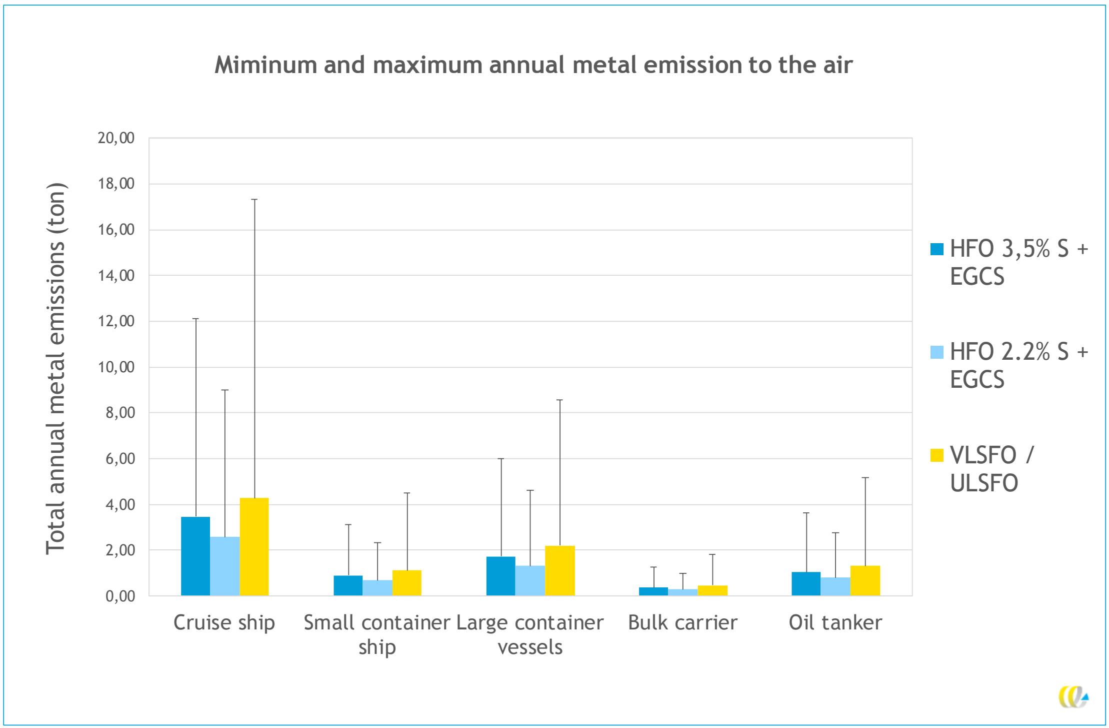
Summary

Emissions of ships impact human health and ecosystems, especially fine particle emissions (PM), metal emissions and emissions of polycyclic aromatic hydrocarbons (PAH). This report analyses how these emissions depend on the option chosen to comply with the MARPOL Annex VI sulphur limit. In general, ships can either choose to use fuels with a low sulphur content or to use an Exhaust Gas Cleaning System (EGCS) to remove sulphur oxides from the exhaust. Compliant fuels can either be low-sulphur fuel oils or distillates; the latter are more expensive and therefore less attractive.

PM emissions comprise of sulphate and other substances. In general, high sulphur fuels result in higher emissions and even though EGCSs remove a share of the PM from the exhaust, PM emissions of ships using high sulphur fuels in combination with an EGCS are higher than PM emissions of ships using low-sulphur fuels.



Low-sulphur fuel oils like VLSFO and ULSFO probably contain similar amounts of metals as high-sulphur fuel oils. Because an EGCS removes a share of the metals from the exhaust, metal emissions of ships sailing on compliant fuels are higher than ships with an EGCS, although the uncertainty range is considerable.



Very little is known about the relation between PAH emissions and fuels. As a result, this report has not been able to draw a conclusion of the impact of the compliance option on PAH emissions.

1 Introduction

1.1 Background of the study

Since its adoption in 1997, MARPOL Annex VI has included a 4.50% m/m limit to the sulphur content of marine fuel. In October 2008, MEPC 58 agreed to reduce the maximum sulphur content to 3.5% m/m from 2012 and to 0.5% m/m from 2020 onwards (in emission control areas, stricter limits apply) by prohibiting the use of any fuel oil that exceeds this limit. The 2020 implementation state has been reaffirmed in 2016 after a fuel oil availability assessment concluded the refinery sector has sufficient capacity to meet the demand of the shipping sector for compliant fuels.

Apart from using compliant fuels, MARPOL Annex VI allows ships to comply by using alternative compliance options, as long as those options are at least as effective in terms of emission reductions as the sulphur content limits. In the case of sulphur, alternative compliance options comprise the use of exhaust gas cleaning systems that remove sulphur oxides from the exhaust (commonly called EGCSs).

The number of ships with EGCSs installed or on order was about 1,000 in May 2018 (EGCSA, 2018) and is around 4,600 in January 2021 (Clarksons, 2021). At the same time, discussions continue about the environmental impacts of the use of EGCSs. Both Japan and Panama have submitted studies to MEPC 74 on the environmental impacts of EGCSs, which reach different conclusions.

The Japanese research study concludes that risks of discharge water from scrubbers to the marine environment and marine aquatic organism are in the acceptable range or negligible from both short-term and long-term perspectives (MEPC, 2019). The Panamanian literature study concludes that there is cause for concern about the impacts of EGCSs on marine life and that PM emissions of ships with an EGCS may be higher than emissions of ships using low-sulphur fuels.

Other studies have analysed the environmental impacts of EGCSs on water quality in ports and coastal waters (CE Delft, 2019) or the impact of difference MARPOL Annex VI Compliance options on air and water emissions, based on a case study (IVL, 2019).

From the different submissions and other studies, it is clear that there is uncertainty about the environmental impacts of the use of EGCSs, both about which environmental impacts are relevant, how large the impacts are and about how they should be judged.

In order to provide factual input to the debate, this report analyses the environmental impact of the EGCSs and compare the results with the environmental impact of using compliant fuels. The focus of this report is on Particulate Matter (PM), metal and Polycyclic Aromatic Hydrocarbon (PAH) emissions. Carbon dioxide (CO_2) emissions are discussed in a previously done study called ‘Comparison of CO_2 emissions of MARPOL Annex VI compliance options 2020’.

1.2 Objective of the study

The objective of the study is to compare the PM, metal and PAH emissions of two ways to comply with the MARPOL Annex VI sulphur regulation: using EGCSs in combination with high-sulphur fuels or using low-sulphur fuels.

In contrast to CE Delft (2020), this report analyses tank-to-wake (TTW) emissions. The reason for this is that PM, metal and PAH emissions emitted during the extraction and production of the fuels vary according to the environmental permits of the refineries and because literature is not always public available.

1.3 Scope of the study

In this study, the following basic principles are applied:

- As mentioned in Section 1.2, the focus of this study is on the tank-to-wake PM, metal and PAH emissions of using low-sulphur fuels and using EGCSs in combination with high-sulphur fuels. The environmental and health impact of these emissions are subsequently discussed.
- The comparative analysis of using low-sulphur fuel and using an EGCS is carried out for five reference ships:
  - a 100,000 GT cruise ship;
  - a 4,000 TEU container ship;
  - a 18,000 TEU container ship;
  - a 80,000 dwt bulk carrier;
  - a 200,000 dwt oil tanker.

  These five ships provide a good reflection of the main ship types that currently have installed scrubbers of which have a large demand for scrubbers. More detailed information of these five reference ships can be found in Section 3.3.
- In this study, we assume that all ships comply with MARPOL Annex VI. In other words, the impact of non-compliance on emissions is not assessed.
- The study will be confined to ships using petroleum-based fuels. In principle, LNG, methanol and other low-sulphur fuels can also be used to comply with MARPOL Annex VI. However, in practice LNG is only an option for new ships since the costs of retrofitting existing ships are prohibitive. Methanol and other alternative fuels are only used by a very small number of ships so these are currently not really viable options.

1.4 Outline of the report

The potential environmental and health impacts of PM, metal and PAH emissions are discussed in Chapter 6. The methodology applied in this study is discussed in detail in Chapter 2. The PM emissions of the two MARPOL Annex VI compliance options are presented in Chapter 4, the metal emissions in Chapter 5 and the PAH emissions in Chapter 6. Finally, the conclusions of the study can be found in Chapter 7.

2 Potential environmental and health impacts of the emissions from the different compliance options

The potential environmental and health impacts of the PM, metal and PAH emissions are discussed in Section 6.1. Specific impact and consequences of the choice of the different compliance options are discussed in Section 6.2. This study only considers the impact of the emissions to the air. The effect of EGCS wash water to the surface water can be found in CE Delft (2019).

2.1 Potential environmental and health impact of emissions

All emitted emissions are initially released to the air when using compliant fuels. Open loop EGCS discharge water directly to the surface water. In this way EGCS reduces atmospheric pollution by redirecting (some of) the pollutants to the seawater by extracting them from the exhaust gases. This process raises the question whether the redirected pollutants will have positive or negative consequences for the environment.

Emission release into the atmosphere generates a variety of risks to human health. It has primarily impact on the respiratory organs and the cardiovascular system. Additional consequences are the formation of ground-level ozone and enhanced eutrophication and acidification of water and soil. The potential environmental and health impact of important exhaust gas emissions are described hereafter.

2.1.1 Particulate Matter

Particulate matter consists of a mixture of soot, sulphate, metals and other organic and inorganic fragments. The prime component is sulphate which is formed by oxidation. The quantity and the size of PM depends on the type of fuel and its sulphur content and on the engine type. Open loop EGCS will reduce the emissions of particles into the atmosphere, but will also change their physical and chemical properties. EGCSs influence the micro- and nano-structural characteristics of the particles as well as their size distribution (Turner, et al., 2017).

The size of the particles is directly linked to the potential for health problems. Smal particles create the greatest problems since they can go deep into the lungs and some may even reach the bloodstream. Exposure to PM can affect both lungs and heart and can cause a variety of problems, including:
- premature death of people with heart and lung disease;
- irregular heartbeat;
- heart attacks;
- asthma;
- decreased lung function;
- increased respiratory symptoms, such as irritation of the airways, coughing and difficult breathing (EPA, 2020).

Research has indicated that ship emissions may be responsible for about 8% of the total PM-attributed mortality. Most deaths occurring near coastlines in Europe, East Asia and South Asia (Wen, et al., 2018).

Particulate matter can have the following effect on the environment:
- reduced visibility by fine particles ($PM_{2.5}$);
- acidification of coastal waters, ports and waterways;
- changing of the nutrient balance in coastal waters and waterways;
- depleting the nutrients in soil;
- damaging of forests and farm crops;
- affecting the diversity of ecosystems;
- contribution to acid rain;
- damaging of buildings by acid rain.

(EPA, 2020)

2.1.2 Metal

A part of the PM emissions consists of metal particles or particles containing metal. Common metal types in PM emission from fossil fuels are chrome (Cr), copper (Cu), nickel (Ni), zinc (Zn) and vanadium (V). Metals occur in small quantities in the air, water and soil. In the air, metals can exist as particles and as vapour. These metals can be breathed in by humans which can cause adverse health effects. Although each metal type has its own effect and although a small daily intake of certain metals is required to maintain a healthy life, too much metal ingestion is toxic and carcinogenic.

2.1.3 Polycyclic aromatic hydrocarbon

Polycyclic aromatic hydrocarbons (PAH) are associated with small-sized particulate matter and are the organic pollutants with the greatest concern. Many PAHs are carcinogenic, mutagenic and toxic. Due to their biological and chemical stability and their potential for accumulation, they are persistent in the environment and can accumulate in organisms (Turner, et al., 2017; German Federal Environment Agency, 2012).

3 Methodology

3.1 Introduction

In this chapter we present the methodology applied in this study to assess the PM, metal and PAH emissions of applying low-sulphur fuels and using EGCSs. In Section 3.2 we first briefly describe the general approach of the study. The reference scenarios applied in the assessments are discussed in Section 3.3.

3.2 General approach

The methodology of the present study is based on CE Delft (2020), which compares well-to-wake GHG emissions (expressed in CO_2-equivalent, i.e. CO_2-eq.) for five reference ships when using low-sulphur fuel oil high sulphur fuel oil in combination with EGCSs. So, in the present study:
- the low-sulphur fuel pathway requires desulphurisation of fuels in the refinery;
- the EGCS pathway uses the same fuel as the reference scenarios.

In contrast with CE Delft (2020), the present study does not take a well-to-wake approach. In other words, the PM, metal, and PAH emissions associated with desulphurising fuels in the refinery are not calculated. The reason is that these emissions depend on the environmental permit of specific refineries as well as the processes employed by refineries and we are not aware of literature on these issues.

3.3 Reference scenarios

In this section, we briefly discuss the main issues with respect to the reference scenario. This includes among others the reference ships, the type of fuel used by the ships and the extent to which these ships sail in emission control areas.

3.3.1 Reference ships

The calculations carried out in this study are performed for five different types of reference ships. These ships are selected because they are known to have installed EGCSs. The key characteristics such as engine power and total fuel consumption was based on the average power/fuel consumption of similar ships in 2012, according to the 3rd IMO GHG study (2014). These ships and their main characteristics are presented in more detail in Table 1 and their sources/assumptions mentioned hereafter.

Table 1 - Overview reference ships and their technical and design characteristics

Characteristics	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
Ship size					
Gross tonnage, TEU or DWT:	100,000 GT	4,000 TEU	18,000 TEU	80,000 DWT	200,000 DWT
Type and number of engines/boilers					
Type of power generation (1)	Diesel - Electric propulsion	Diesel (mechanical) propulsion	Diesel (mechanical) propulsion	Diesel (mechanical) propulsion	Diesel (mechanical) propulsion
Main engine type (2)	N/A	Medium speed 4 stroke engine	Slow speed 2 stroke engine	Slow speed 2 stroke engine	Slow speed 2 stroke engine
No. of main engines	N/A	1	2(2)	1	1
No. of auxiliary engines	6	3(3)	6(3)	3	3
No. of boilers(4)	2	1	2	2	2
Installed power and engine load					
Average installed power (MW) (5)	76.1	34.6	60.2	9.7	27.2
Average installed main engine power (MW) (7)	N/A	24.7	43.0	8.2	21.4
Average installed auxiliary engine power (MW) (7)	N/A	9.9	17.2	1.5	5.7
Average main engine load (%MCR)(8)	N/A	33	56	54	47
Average aux engine load (%MCR) (5)	N/A	60	60	60	50
Average required power (MW)	55.5	14.1	34.4	5.4	12.9
Average required total engine load (%)	73	41	57	55	48
Fuel consumption					
Average annual main engine fuel consumption (tonnes) (8)	47,200	13,900	25,300	5,400	15,300
Average annual auxiliary engine fuel consumption (tonnes) (8)	25,500	3,900	6,100	1,100	3,600
Average annual boiler fuel consumption (tonnes) (8)	500	600	1,100	300	1,100
Average total annual fuel consumptions (tonnes) (8)	73,200	18,400	32,500	6,800	20,000
SFOC (g/kWh) of main engine at average load (9)	210.8	202.6	179.4	180.1	183.2

Characteristics	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
SFOC (g/kWh) of auxiliary engine at average load (9)	226.3	229.0	229.0	229.0	233.7
Scrubbers and pumps (Packed bed technology)					
Number of scrubber(s) (10)	2	1	2	1	1
Number of pump(s) (10)	4	2	3	2	2
Scrubbers and pumps (Inline technology)					
Number of scrubber(s) (10)	5	2	2	1	2
Number of pump(s) (10)	5	2	3	1	2

Sources: IMO (2014) and CE Delft.

(1) Assumption made by CE Delft based on generic propulsion trend based on the ship size.

(2) Assumption made by CE Delft based on technical expertise and for bulk carrier, propulsion trends from (The Motorship, 2014) is used for the assumption.

(3) Assumption made by CE Delft based on bulk carrier configuration due to lack of data.

(4) Assumption made by CE Delft based on operational profile/technical expertise.

(5) Data derived from 4th IMO GHG Study 2018.

(6) Data derived from Clarkson. Container ships selected which are built between 2015 and 2020 and which has corresponding ship size as the reference container ships.

(7) Data derived from the main engine to auxiliary engine power ratio which is given in the IMO 3rd GHG study 2014.

(8) Data derived from IMO 3rd GHG study 2014 (IMO, 2014) and a range has been provided that takes into consideration all the operation modes (at berth, manoeuvring, anchorage and at sea).

(9) SFOC has been calculated based using the Eq.(3) of IMO 3rd GHG study.

(10) Average data provided by Alfa Laval, Wärtsilä and Yara Marine.

3.3.2 Reference maritime fuels

Prior to the introduction of the global sulphur cap of 0.50% m/m, the mean sulphur content of heavy fuel oil was: 2.6% m/m, with over 80% samples between 2.0 to 3.5% (MEPC, 2018).

The reference fuels of ships equipped with EGCSs are the same as in CE Delft (2020):
- a fuel with a sulphur content of 2.2% m/m;
- a fuel with a sulphur content of 3.5% m/m.

An exemption is made for the PAH emissions, whereby calculations are done with a fuel with a sulphur content of 2.77% m/m, due to the available data.

The used reference fuels of ships without EGCSs installed are ULSFO and VLSFO since most ships without EGCSs currently operate on these types of fuels. This is due to the price difference in relation to distillate fuels (BunkerEx, 2020).

3.3.3 Emission Control Areas

Emission Control Areas (ECAs), or sulphur Emission Control Areas (SECAs), are sea areas in which stricter requirements with respect to air pollutant emissions are imposed on ships. Areas covered by such requirements are, for example, the Baltic Sea, the North Sea, the North American ECA (including most of the US and Canadian coast) and the US Caribbean

ECA. In the MARPOL regulations, a distinction is made between the sulphur limits inside and outside SECAs/ECAs. The current SECA/ECA limit is 0.10% m/m sulphur in the fuel. The global limit was up to and including 2019 equal to 3.50% m/m, but is reduced to 0.50% m/m since the 1st of January 2020.

The reference ships considered in this study sail both within and outside SECAs/ECAs. To take this into account in estimating the PM, metal, and PAH emissions of both compliance options, we have made a distinction in our calculations between the fuel consumed inside and outside these areas. Heavy fuel oil with a sulphur content equal to 3.5% m/m and heavy fuel oil with a sulphur content equal to 2.2% are considered to be representative for the maritime fuel market.

The average annual fuel consumption within and outside SECAs/ECAs is shown for the various reference ships in Table 2.

Table 2 - Annual fuel consumption (%) within and outside SECAs/ECAs

	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
Annual fuel consumption within SECAs/ECAs (%)	15	10	5	5	5
Annual fuel consumption outside SECAs/ECAs (%)	85	90	95	95	95

4 PM emissions of compliance options

4.1 Introduction

PM stands for particulate matter and is a term for a mixture of a large variety of extremely small particles of organic and inorganic origin. PM can contain carbon, metals, ash, soot, acids such as sulphates and nitrates and carbonates. PM emissions exists in many different sizes and shapes and is dependent on the engine type, the engine load and the fuel type. In this chapter PM_{10} emissions are calculated. PM_{10} includes all particles of 10 micrometres and smaller. $PM_{2.5}$ includes all particles of 2.5 micrometres and smaller. According to the 4th IMO GHG Study 2020, 92% of the mass of PM_{10} is $PM_{2.5}$ (IMO, 2020).

The sulphur content of the fuel has a large influence on PM emissions: the lower the sulphur content in the fuel, the lower the PM emissions (Green Ship, 2020).

This chapter compares the PM emissions of the five reference ships, which are mentioned in Section 3.3.1, with and without Exhaust Gas Cleaning Systems (EGCSs). The two scenarios which are modelled are:
- Ships that use high-sulphur HFO in combination with EGCS(s). The results are provided in Section 4.2.
- Ships that use compliant fuels. The results are provided in Section 4.3.

Finally, the conclusion is reflected in Section 4.4.

4.2 PM emissions when using an EGCS

The PM emissions released to the air during the operation of the ship are the PM emissions contained in the exhaust fumes. These are the PM emissions released immediately after the engine(s) minus the PM emission caught by the EGCS(s).

The PM emissions released during the combustion of the HFO by the engine(s), also called tank-to-wake (TTW) emissions, mainly depends on the fuel type and slightly depends on the engine type. The energy-based emission factors for PM_{10} are based on below formula which is provided in the fourth IMO GHG study 2020 (IMO, 2020):

HFO energy-based emission factor PM_{10} (g PM_{10}/kWh) = 1.35 + SFOC * 7 * 0.02247*(S-0.0246)

Where:
SFOC = Specific fuel oil consumption (g/kWh)
S = Sulphur content (% m/m)

This has led to a range of emission factors (kg PM_{10}/ton fuel) for both main and auxiliary engines of the five reference ships, which is shown in Table 3.

Table 3 - Range of emission factors (kg PM_{10}/ton fuel) for the main en auxiliary engines of the five reference ships

	Main engine(s)	Auxiliary engines
HFO 3.5% S	8.04–9.16	7.41–7.60
HFO 2.2% S	6.00–7.12	5.37–5.56

By means of the energy–based mass emission factors for the different engines (as provided in Table 3), the specific fuel oil consumption (SFOC) and the annual fuel consumption of the main engines, auxiliary engines and boilers (as provided in Table 1), the total annual amount of PM_{10} emissions are calculated for all five reference ships in the event that the EGCSs are not in use.

Winnes et al. (2020) is used as reference for the PM emission reduction calculation when using HFO in combination with EGCSs to be compliant with the sulphur regulations from MARPOL Annex VI. The report is based on emission measurements of a 4-stroke marine engine using low sulphur fuel (LSFO) and heavy fuel oil (HFO) at different steady state engine loads. An open loop EGCS is installed on board.

Results from the report relevant to consider for this study:
- Sampling and dilution procedures bring uncertainties to the particle measurements:
  - related to the representativeness of the extracted partial flow exhaust sample;
  - related to the dilution process affecting both condensation and nucleation of semi-volatile species and hence the measured PM mass and number.
- The EGCS removes between 32% (at 76% engine load) and 42% (at 48-49% engine load) of the PM emissions from the exhaust at the HFO test upstream and downstream of the EGCS. However, the reduction of PM emissions is not evenly distributed over the engine load variation.

Winnes et al. (2020) only focusses on emission measurements on a 4-stroke marine engine. Danish Technological Institute et al. (2012) provides data regarding emission measurements on a 2-stroke marine engine using high sulphur content fuel (2.3% m/m S) in combination with an EGCS. Two different type of instruments were applied for these measurements, namely a scanning mobility particle sizer (SMPS) and an electrical low-pressure impactor (ELPI). These different methods measure the particle number using different physical principles which results in different equivalence diameters. The ELPI method shows that the PM emission reduction by an EGCS on a 2-stroke engine is in the same reduction range as on the 4-stroke engines in Winnes et al. (2020). The SMPS method provide completely different results, however, this method is known to provide less accurate results of the particle size (Gulijk, et al., 2003).

Based on these studies we have decided to:
- Calculate the PM_{10} emissions to the air based on a PM removal of 30 and 40% when using HFO in combination with EGCS(s):
  - due to the above described particle measurement uncertainties;
  - due to the fact that the reduction of PM emissions is not evenly distributed over the engine load variation;
  - no distinction is made between open loop packed bed and inline EGCSs due to lack of relevant data;
  - no distinction is made between 4-stroke engines and 2-stroke engines.

The PM_{10} emissions to the air for the five reference ships by using HFO in combination with EGCSs with a PM reduction efficiency of 30-40% are provided in Table 4.

Table 4 - PM_{10} emissions to the air for the five reference ships by using HFO in combination with EGCSs with a PM reduction efficiency of 30-40%

Annual PM_{10} emissions to the air (ton/year)	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
HFO 3.5% S	404-346	104-90	200-172	42-36	121-104
HFO 2.2% S	299-256	78-67	154-132	32-28	92-79

Some studies, i.e. Danish Ministry of the Environment (2012) and Fridell & Salo (2014), have shown reduction efficiencies up to 75-80%. These results were based on tests of an EGCS with a venturi quenching pretreatment. It was possible to adjust the venturi and thus the exhaust gas velocity which increases the PM capture, however at the expense of increased backpressure. EGCSs of today are designed to give as little possible increase in the engine backpressure. Too high backpressure increases fuel consumption. For this reason, we have not used these high PM reduction efficiency values.

4.3 PM emissions when using compliant fuel

The PM emissions released during the combustion of the VLSFO and ULSFO by the engine(s), also called tank-to-wake (TTW) emissions, mainly depends on the fuel type and slightly depends on the engine type. The energy-based emission factors for PM_{10} are based on below formulas which are provided in the fourth IMO GHG study (2020). We have assumed that VLSFO and ULSFO resemble HFO with a lower sulphur content.

HFO energy-based emission factor PM_{10} (g PM_{10}/kWh) = 1.35 + SFOC * 7 * 0.02247 * (S-0.0246)
MDO/MGO energy-based emission factor PM_{10} (g PM_{10}/kWh) = 0.23 + SFOC * 7 * 0.02247 * (S-0.0024)

Where:
SFOC = Specific fuel oil consumption (g/kWh)
S = Sulphur Content (% m/m)

This has led to a range of emission factors (kg PM_{10}/ton fuel) for both main and auxiliary engines of the five reference ships, which is shown in Table 5.

Table 5 - Range of emission factors (kg PM_{10}/ton fuel) for the main and auxiliary engines of the five reference ships

	Main engine(s)	Auxiliary engines
VLSFO (0.5% S)	3.32-4.44	2.69-2.88
ULSFO (0.1% S)	2.69-3.81	2.06-2.25
MDO (0.1% S)	0.86-1.05	0.75-0.79

By means of the energy-based emission factors for the different engine types (as provided in Table 5), the specific fuel oil consumption (SFOC) and the annual fuel consumption of the main engines, auxiliary engines and boilers (as provided in Table 1), the total annual amount of PM_{10} emissions are calculated for all 5 reference ships. The results are shown in Table 6.

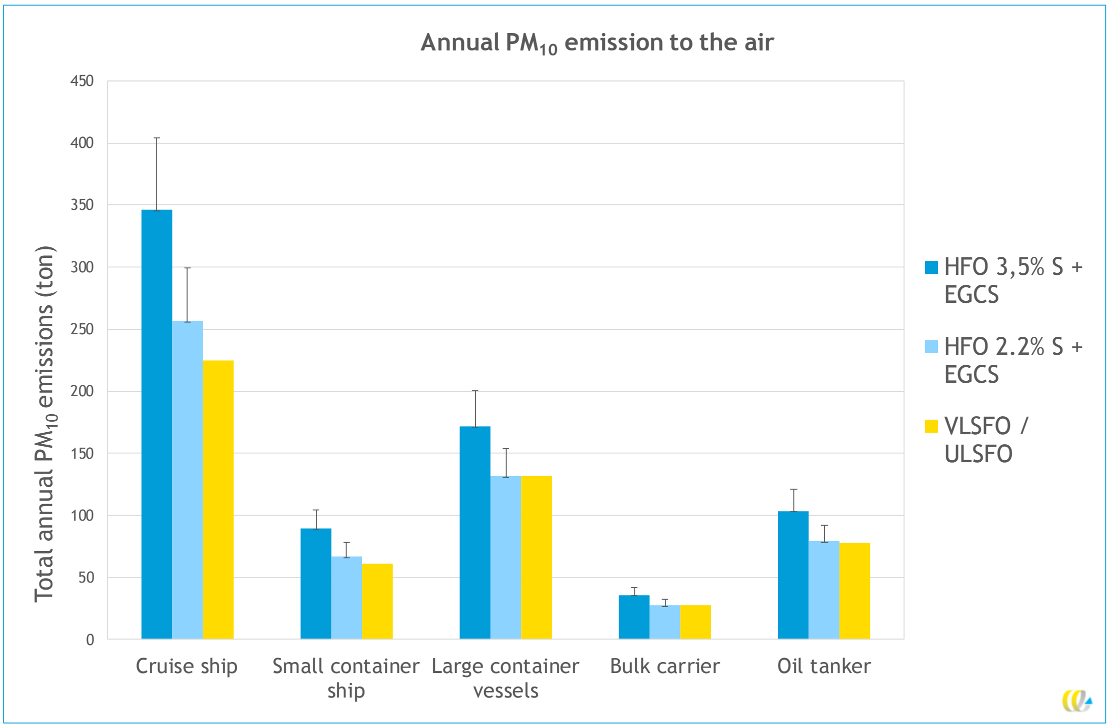
Table 6 - Annual PM_{10} emissions to the air for the five reference ships by using MDO and VLSFO/ULSFO as compliant fuels

Annual PM_{10} emissions to the air (ton/year)	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
MDO (0.1% S)	61	16	32	7	19
VLSFO/ULSFO (0.1% S in ECA and 0.5% S outside ECA	225	61	131	28	78

4.4 Conclusions

Section 4.2 provides the PM_{10} emissions to the air for the five reference ships when they are operating on high sulphur HFO in combination with EGCS(s). Section 4.3 provides the PM_{10} emissions to the air for the five reference ships when they are operating on a combination of ULSFO and VLSFO. The scenarios to comply with MARPOL Annex VI are compared in Figure 1. The blue columns show the PM emissions to the air when the EGCS(s) have a PM reduction efficiency of 40%. The error bar above these two columns shows the additional emissions to the air in case the EGCS(s) have a PM reduction efficiency of 30%.

Figure 1 - Annual PM_{10} emission comparison for the two scenarios. The EGCS has in this case a PM reduction efficiency of 30%



Depending on the PM reduction efficiency of the EGCS(s), the PM emissions when using VLSFO/ULSFO are equal or slightly lower compared to the use of HFO 2.2% S in combination with EGCS(s). The more sulphur there is in HFO when using EGCS(s), the larger the differences become between the two scenarios to comply with MARPOL Annex VI.

Note that PM emissions of distillate fuels (MGO) are much lower than of heavy fuels (IMO, 2020), however, because of the price difference between distillate fuels and low-sulphur heavy fuel oils the latter are often preferred.

5 Metal emissions of compliance options

5.1 Introduction

A part of the PM emissions consists of metal particles. Common metal types in PM emission from fossil fuels are chrome (Cr), copper (Cu), nickel (Ni), zinc (Zn) and vanadium (V). It is known that metal concentrations in fuels vary and are related to the crude oil origin and refinery process of the fuel. The metals V and NI and to a lesser extent Cu are typical tracers for residual fuels (Teuchies, et al., 2020).

This chapter compares the metal emissions of the five reference ships, which are mentioned in Section 3.3.1, with and without Exhaust Gas Cleaning Systems (EGCSs).
The two scenarios which are modelled are:
- Ships that use high-sulphur HFO in combination with EGCS(s). The results are provided in Section 5.2.
- Ships that use compliant fuels. The results are provided in Section 5.3.

Finally, the conclusion is reflected in Section 5.4.

5.2 Metal emissions when using an EGCS

The metal emissions released during the combustion of the HFO by the engine(s), also called tank-to-wake (TTW) emissions, depends on the PM emissions which depends on the fuel type and slightly depends on the engine type.

The study Zhou, et al. (2019) shows that 1-3% of the PM emissions on a 4-stroke engine consists of metals. This applies to both a high sulphur fuel oil containing 3.09% S and a low sulphur fuel oil containing 0.1% S regardless of the engine load. The report also shows that 1-3% of the PM emissions consists of metals on a 2-stroke engine regardless of the engine load when operating on a HFO with 0.5% S.

Based on this study we have decided to:
- Conclude that 1-3% of the PM emissions from the operation on heavy fuel oils with a high sulphur content consist of metal emissions.
- Calculate the metal emissions to the air based on 1-3% of the PM emissions calculated in Section 4.2. This only applies to heavy fuels oils with a high sulphur content, in this case HFO 2.2% S and HFO 3.5% S.
- It is unknown whether an EGCS filters the metal emissions from the exhaust gases in the same proportion as PM emissions. We therefore assume the same EGCS reduction efficiency of 30-40% as used in Section 4.2 for the PM emissions.
- No distinction is made between different engine loads of the main engine and the auxiliary engines.
- No distinction is made between open loop packed bed and inline EGCSs due to lack of relevant data.

The metal emissions to the air for the five reference ships by using HFO in combination with EGCSs with a metal reduction efficiency of 30% are provided in Table 7. The metal emissions to the air for the five reference ships by using HFO in combination with EGCSs with a metal reduction efficiency of 40% are provided in Table 8.

Table 7 - Metal emissions to the air for the five reference ships by using HFO in combination with EGCSs with a metal reduction efficiency of 30% (1-3% of PM constitutes metals)

Metal emissions to the air (ton/year)	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
HFO 3.5% S	4.0-12.1	1.0-3.1	2.0-6.0	0.4-1.3	1.2-3.6
HFO 2.2% S	3.0-9.0	0.8-2.3	1.5-4.6	0.3-1.0	0.9-2.8

Table 8 - Metal emission to the air for the five reference ships by using HFO in combination with EGCSs with a metal reduction efficiency of 40% (1-3% of PM constitutes metals)

Metal emissions to the air (ton/year)	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
HFO 3.5% S	3.5-10.4	0.9-2.7	1.7-5.2	0.4-1.1	1.0-3.1
HFO 2.2% S	2.6-7.7	0.7-2.0	1.3-4.0	0.3-0.8	0.8-2.4

5.3 Metal emissions when using compliant fuel

The metal emissions released during the combustion of VLSFO and ULSFO by the engine(s), also called tank-to-wake (TTW) emissions, depends on the PM emissions which depends on the fuel type and slightly depends on the engine type.

Zhou, et al. (2019) show that the emissions of metals of ULSFO and HFO are similar when expressed in mg/kWh.

Ali & Abbas (2006) explains that VLSFO and ULSFO contain relatively high concentrations of metals as the desulphurisation of high sulphur HFO does chemically not have an effect on the present metals. This is due to the fact that during refining the metals tend to accumulate in the fuel oil fraction.

Based on these two studies we have assumed that VLSFO and ULSFO contain equal amounts of metals as HFO.

The metal emissions to the air for the five reference ships by using a combination of VLSFO and ULSFO as compliant fuels are provided in Table 9.

Table 9 - Metal emissions to the air for the five reference ships by using compliant fuels (1-3% of PM constitutes metals)

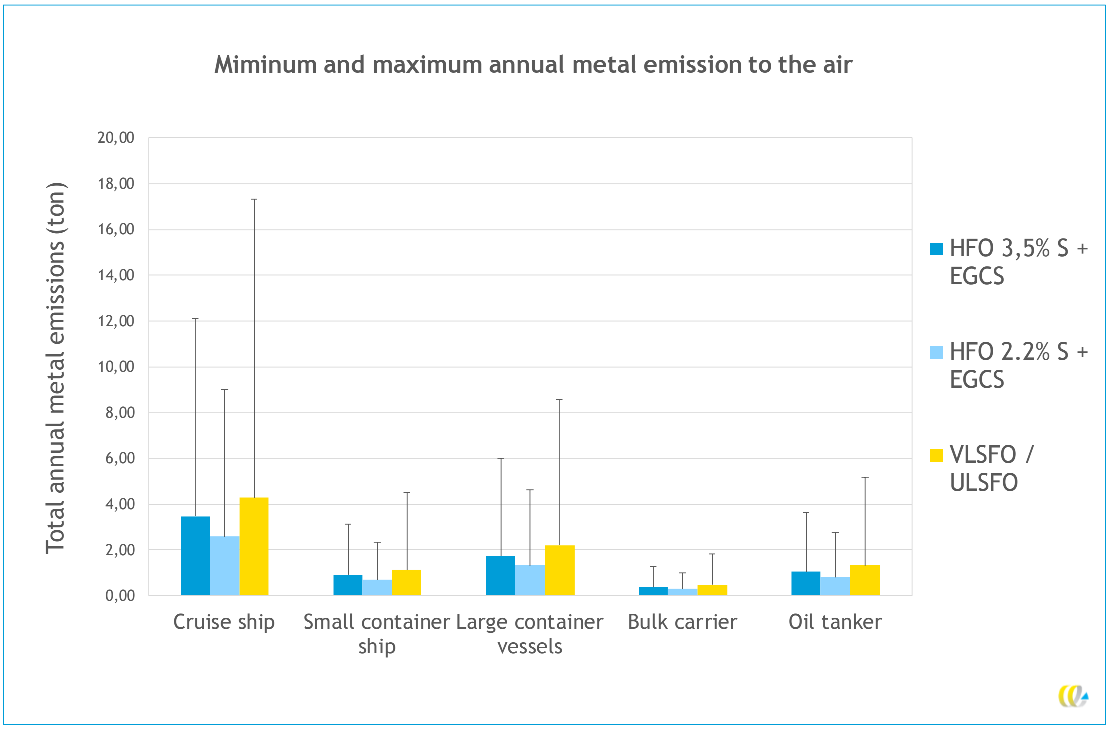
Annual metal emissions to the air (ton/year)	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
VLSFO/ULSFO (0.1% S in ECA and 0.5% S outside ECA	4.3-17.3	1.1-4.5	2.2-8.6	0.5-1.8	1.3-5.2

Distillate fuels like MDO and MGO are not included in this comparison due to lack of available data. However, we expect that the concentration of metals in MDO is lower than HFO, ULSFO and VLSFO because metals accumulate in the fuel oil fraction of a refinery and consequently, distillates contain fewer metals.

5.4 Conclusions

Section 5.2 provides the annual metal emissions to the air for the five reference ships when they are operating on high sulphur HFO in combination with EGCS(s). Section 5.3 provides the annual metal emissions to the air for the five reference ships when they are operating on a combination of ULSFO and VLSFO. The scenarios to comply with MARPOL Annex VI are compared in Figure 2. The coloured bars represent the minimum annual metal emissions to the air per scenario and the error bars represent the maximum annual metal emissions to the air. Minimum and maximum annual metal emissions are based on the EGCS reduction efficiency and the percentages of metals in PM emissions.

Figure 2 – Minimum and maximum metal emission comparison for the two scenarios. The EGCS has a metal reduction efficiency of 30-40%



With regard to metal emissions, it is more favourable to use high sulphur HFO in combination with EGCSs instead of VLSFO/ULSFO. This is due to the fact that desulphurisation of high sulphur HFO chemically does not have the same removing effect on metals, with the result that VLSFO and ULSFO contain relatively high concentrations of metals compared to the use of high sulphur HFO in combination with EGCSs which filters 30-40% of the metal emissions from the exhaust gasses.

6 PAH emissions of compliance options

6.1 Introduction

A part of the PM emissions consists of polycyclic aromatic hydrocarbons (PAH). PAHs often occur as variable mixtures. A well-known PAH group is PAH-16. This is a group of 16 PAHs included in the priority pollutant list under the US Clean Water Act (Lawrence, 2015; EPA, ongoing).

The PAH content of fuels depends mainly on the production process of the fuel in the refinery and on the sulphur content and to a lesser extent on the crude origin (Concawe, 2005; German Federal Environment Agency, 2012). In addition, PAHs may form in the cylinder during the combustion process.

This chapter compares the PAH emissions of the five reference ships, which are mentioned in Section 3.3.1, with and without Exhaust Gas Cleaning Systems (EGCSs). The two scenarios which are modelled are:
- Ships that use high-sulphur HFO in combination with EGCS(s). The results are provided in Section 6.2.
- Ships that use compliant fuels. The results are provided in Section 6.3.

Finally, the conclusion is reflected in Section 6.3.

6.2 PAH emissions when using an EGCS

There is uncertainty about the actual amount of PAH emissions during the operation. Winnes, et al. (2020) and Zhou, et al. (2019) provide different emission values. It is unknown whether this is due to the type of fuel, the amount of sulphur content in the fuel, the engine type, the lube oil, etcetera. A systematic measurement campaign on a range of ships carried out in the 1990s also showed a large variation in PAH emissions (LLoyds Register of Shipping, 1995) which could not be attributed to the fuel used: PAH emissions of ships sailing on distillates were sometimes higher than ships sailing on heavy fuel oil and sometimes lower. On average, the emissions of ships sailing on gas oil were higher but due to the small sample and the large variation in the results no conclusions can be drawn from this. The report attributed some of the variation to the volatilisation and condensation reactions in the exhaust gas and the dynamic nature of PAHs.

Winnes, et al. (2020) is the only study which provide EGCS PAH emission reduction efficiencies. The PAH-16 emissions calculated in this chapter are therefore based on this study. The study provides data regarding PAH-16 emissions on a 4-stroke engine when:
- Using HFO containing 2.77% S in combination with an EGCS. Measurements are taken upstream and downstream of the EGCS at different engine loads.
- Using LSFO containing 0.1% S. Measurements are taken at different engine loads.

Based on this study we have decided to:
- Calculate PAH-16 emissions of the five reference ships based on HFO containing 2.77% S in combination with EGCS(s).
- Due to lack of reliable data on PAH emissions from 2-stroke engines, calculations are executed with the use of data from 4-stroke engines.
- The PAH reduction efficiency of the EGCS varies between 25 and 50% dependent on the engine load. Calculations are therefore based on a EGCS PAH reduction efficiency of 25-50%.
- No distinction is made between open loop packed bed and inline EGCSs due to lack of relevant data.

Table 10 shows the average PAH emissions upstream EGCS when operating a 4-stroke engine on HFO 2.77% S. This value is calculated based on the PAH emissions at several engine loads (Winnes, et al., 2020).

Table 10 - Average PAH emissions upstream EGCS when operating a 4-stroke engine on HFO 2.77% S

	PAH-16 (mg/kWh)
Average emissions HFO 2.77% S	1.6

The PAH-16 emissions to the air for the five reference ships by using HFO 2.77% S in combination with EGCSs are provided in Table 11. The EGCSs have a PAH reduction efficiency of 25-50%.

Table 11 - PAH emissions to the air for the five reference ships by using HFO 2.77% S in combination with EGCSs with a reduction efficiency of 25-50%

HFO 2.77% S	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
PAH-16 emissions to the air (kg/year)	407-271	106-71	207-138	43-29	124-83

6.3 PAH emissions when using compliant fuel

The second part of the PAH emission comparison is the use of compliant fuel. Because of the available information in the used source, we have chosen for a reference LSFO containing 0.1 % m/m S. This fuel will be used both inside and outside ECAs.

Winnes, et al. (2020) provides data regarding PAH-16 emissions on a 4-stroke engine when using LSFO containing 0.1% S.

The same conditions and assumptions as discussed in Section 6.2, except the specific ones for EGCSs, apply to PAH emissions when using compliant fuels.

Table 12 shows the average PAH emissions when operating a 4-stroke engine on LSFO 0.1% S. These values are calculated based on the PAH emissions at several engine loads (Winnes, et al., 2020).

Table 12 - Average PAH emissions when operating a 4-stroke engine on LSFO 0.1% S

	PAH-16 (mg/kWh)
Average emissions LSFO 0.1% S	0.59

The PAH-16 emissions to the air for the five reference ships by using LSFO 0.1% S as compliant fuel are provided in Table 13.

Table 13 - PAH emissions to the air for the five reference ships by using LSFO 0.1% S as compliant fuel

LSFO 0.1% S	Cruise ship	Small container ship	Large container ship	Bulk carrier	Oil tanker
PAH-16 emissions to the air (kg/year)	200	52	102	21	61

6.4 Conclusions

Very little is known about how PAH emissions depend on the type of fuel used. There is just one report of PAH measurements in combination with low-sulphur fuels, but because of the large variation in PAH emissions shown in other reports, no firm conclusions can be drawn from this study.

EGCSs remove a share of the PAHs from the exhaust, but it cannot be concluded whether PAH emissions of ships sailing on HFO in combination with an EGCS are higher or lower than emissions of ships sailing on VLSFO or MGO.

7 Conclusion

This study analyses how PM, metal and PAH emissions depend on the compliance option chosen for the IMO sulphur regulation. These emissions were chosen because of their impacts on human health and ecosystems.

The main conclusions of the study are:
- The PM emissions to the air of ships using high sulphur HFO in combination with EGCS(s) are ***higher*** than when ships use compliant fuels (VLSFO or ULSFO).
- The metal emissions to the air of ships using high sulphur HFO in combination with EGCS(s) are ***lower*** than when ships use compliant fuels (VLSFO and ULSFO) but probably higher than when ships use MGO.
- Too little is known about the composition of LSFO to draw a conclusion regarding the PAH emissions when comparing the chosen MARPOL Annex VI compliance options.

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