



Lloyd's Register
Marine

Working together
for a safer world

Your options for emissions compliance

Guidance for shipowners and operators
on the Annex VI SOx and NOx regulations

Understanding technology



Contents

Foreword	3		
1 Introduction	4	8 Integrating NOx and SOx abatement techniques	41
2 Air pollution regulations and controls	6	8.1 Using SCR with wet scrubbing	41
2.1 MARPOL Annex VI	6	8.2 Using EGR with wet scrubbing	41
2.2 SOx emission regulations	6	9 In-service considerations	42
2.3 NOx emission regulations	8	9.1 Health and safety	42
3 Primary compliance techniques for SOx	9	9.2 Operational difficulties	42
3.1 The science of SOx	9	9.3 Compliance difficulties	43
3.2 Low-sulphur distillate oil	9	9.4 Contractual difficulties	43
3.3 Alternative low-sulphur fuels	11	Appendix A1 – Impacts of marine exhaust emissions on human health and the environment	45
4 Primary compliance techniques for NOx	13	Appendix B1 – MEPC 184(59) – Exhaust Gas Cleaning System Guidelines	47
4.1 The science of NOx	13	Appendix B2 – The NOx Technical Code	53
4.2 Gas as fuel	13	Appendix B3 – Regional, national and local air quality regulations	54
4.3 Exhaust gas recirculation	14	Appendix C – Operational considerations for using compliant fuel within ECA-SOx from 1 January, 2015	56
4.4 Advanced fuel injection	16	Appendix D – Chemical reactions	58
4.5 Fuel emulsification	16	Acronyms and abbreviations	59
4.6 High-pressure supercharging	16	References	60
5 Secondary compliance techniques for SOx	18		
5.1 Wet scrubbing	18		
5.2 Dry scrubbing	26		
5.3 Non-thermal plasma	28		
5.4 Comparing SOx scrubber technologies	29		
4.5 Fuel emulsification	16		
4.6 High-pressure supercharging	16		
6 Secondary compliance techniques for NOx	32		
6.1 Selective catalytic reduction	32		
7 Secondary compliance techniques for NOx and SOx – common challenges	36		
7.1 Flexibility	36		
7.2 The risk of non-compliance	36		
7.3 Backpressure	36		
7.4 EGTS bypass	37		
7.5 Exhaust gas velocity	38		
7.6 Integration of multiple combustion devices	38		
7.7 Maintenance, crew training and workload	38		
7.8 EGTS approvals	38		
7.9 Independent verification	40		

Foreword

This publication was first launched in 2012 as “Understanding Exhaust Gas Treatment Systems”. This updated edition builds on three more years of experience. We address operational and in-service considerations, based on our experience of working closely with clients, industry groups and regulators. We also examine a wider scope of options for SOx and NOx compliance beyond exhaust gas treatment.

Since 2012, some of the early adopters of the technology featured in our original guide, such as DFDS, have gone ahead with fleet-wide scrubber implementation programmes. Carnival Corporation has also initiated a retrofit programme for more than 70 ships. Early adopters gain valuable operational experience. A head start makes them better placed to reap the benefits of the technology when the cost of compliance increases.

At the same time, in the majority of the tanker, bulk carrier and container segments, the uptake of scrubber technology remains slow. With shorter periods inside Emission Control Areas (ECAs), lower fuel consumption (especially due to slow steaming) and typically lower asset residual values, the business case in scrubber technology is not deemed strong enough – yet.

The bunker price collapse during 2014 has been another factor. While the price difference between heavy fuel and distillates has remained relatively constant, the fuel costs inside ECAs have reduced, giving operators more time to consider their options. Recently, several suppliers have released new hybrid fuel products for ECA compliance. These are aimed at addressing the operational risks of operating on distillates, but they also present several challenges of their own.

Looking ahead, there two key years: 2016 and 2018. Ships built after 1 January, 2016, will need to comply with NOx ‘Tier III’ limits when trading to the US or Canada and we explore some of the technological compliance options. Other ECAs for NOx may be introduced in the future, but these will only affect newbuild ships.

In 2018, the IMO will publish a fuel availability study, determining whether the global 0.50% sulphur limit will enter into force in 2020 or 2025. If 2020, the implications will be widespread: a possible rapid uptake of scrubber technology (with a question mark over whether supply will meet demand) and a dramatic increase in operational costs for those who choose to operate on distillate fuels. Early adopters of LNG-as-fuel could start seeing a real return on their investment and any ‘LNG-ready’ ships may start converting to LNG, with a parallel drive towards bunkering infrastructure development.

The time for decisions is fast approaching. In 2012, the industry needed to start considering their options; today, in 2015, this time is running out. The compliance options are clear. Ship operators need to evaluate their compliance strategies based on their ships’ specific operational and risk criteria. This evaluation needs to be unbiased and separate from any vested interests. At Lloyd’s Register, we are ready to offer independent support in the journey from making a decision to implementing it.



Katharine Palmer, Environmental Manager,
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1. Introduction

Lloyd's Register has been at the forefront of understanding emissions to air from marine diesel engines since we started our Marine Exhaust Emissions Research Programme [1], which assessed the nature and magnitude of shipping's contribution to atmospheric pollution.

Exhaust emissions from marine diesel engines mainly comprise nitrogen, oxygen, carbon dioxide (CO₂) and water vapour, plus smaller quantities of nitrogen oxides, sulphur oxides, carbon monoxide, various hydrocarbons at different states of combustion and complex particulate matter (PM). It is these smaller quantities, together with CO₂, that are of most concern to human health and the environment. Adverse effects are experienced at local, regional and global levels. Appendix A1 provides further information about these impacts, which include contribution to climate change through increasing concentrations of CO₂ in the atmosphere; respiratory damage; cancers and genetic mutation; and damage to the natural and built environment.

The regulatory framework

In response to these impacts, the International Maritime Organization (IMO), through its Marine Environment Protection Committee (MEPC), introduced regulations for the prevention of air pollution under Annex VI of the MARPOL Convention.

Annex VI imposes a framework of mandatory limits on emissions of sulphur oxides (SO_x) and nitrogen oxides (NO_x) both globally and within designated sea areas, known as Emission Control Areas (ECAs). These are regions where neighbouring states have shown that emissions to air have particular impacts on human health and the environment.

In parallel with Annex VI, a number of regional, national and local regulators have introduced their own controls, leading to a patchwork of regulatory requirements.

Section 2 of this publication gives an overview of MARPOL Annex VI, and Appendix B3 includes a summary of the main regional, national and local regulations. At Lloyd's Register we monitor and influence the development of environmental regulations at MEPC as a participant in national and observer delegations.

Compliance options

As emission limits become more stringent, compliance becomes more challenging and costly. There are a number of ways to comply, each of which presents different technical and operational challenges. This guidance provides an understanding of the different compliance options and the practical challenges of implementing them on board ships.

Primary and secondary compliance techniques

Within this guidance, we divide compliance options into **primary** and **secondary** techniques.

Primary compliance techniques (covered in Sections 3 and 4) work by lowering SO_x and NO_x emissions at source. Examples include using low-sulphur fuel to reduce SO_x or manipulating the combustion process to reduce NO_x.

Secondary compliance techniques (covered in Sections 5, 6 and 7) lower SO_x and NO_x emission levels by treating the exhaust gas after combustion. In this guidance, we refer to them as exhaust gas treatment systems (EGTS). Treatment systems include 'scrubbers' for SO_x and selective catalytic reduction (SCR) for NO_x.

We have structured the guidance in this way for two reasons.

- Feedback from the industry indicates that many operators are interested in primary options because they avoid the need to fit secondary compliance technologies.
- There are common challenges associated with secondary techniques for NO_x and SO_x.

SO_x compliance options

The MARPOL regulations are clear in that the default means of SO_x compliance is to use low-sulphur fuel. This is the primary compliance option. There is a wide variety of low-sulphur fuels, including low-sulphur distillate oil, 'hybrid' fuel oil, liquefied natural gas (LNG), liquefied petroleum gas (LPG), biofuels, dimethyl ether (DME), ethane and methanol. It is also possible to de-sulphurise residual fuel. This is technically straightforward although the energy demand and cost are high if using traditional techniques. There are technologies which can de-sulphurise high-sulphur fuels as they are delivered to the ship, or even on board the ship by washing the sulphur out of the fuel as it is transferred between the storage and service tanks.

The secondary compliance option for SO_x is to use an exhaust gas treatment system, such as a scrubber, to de-sulphurise the exhaust gas and reduce SO_x emissions to a level equivalent to the required fuel sulphur content. This offers the flexibility to operate on either low-sulphur fuels or higher sulphur fuels.

The choice of SO_x compliance option depends on a number of factors, including the cost of compliant low-sulphur fuels, the capital expenditure (CAPEX) and operating expenditure (OPEX) of installing an alternative compliance method such as a scrubber, and the amount of time that the ship is expected to spend inside ECA-SO_x.

We have developed the 'ECA Calculator' to help operators understand the costs associated with different compliance options. Visit www.lr.org/eca to download your copy.

NO_x compliance options

Unlike SO_x emissions, which are a product of fuel sulphur content, NO_x emissions are created during the combustion process. How much NO_x is created depends on the fuel being used; some fuels, such as LNG and methanol, have lower NO_x emissions than traditional marine fuel oils. As with SO_x, there are primary compliance techniques which achieve the required NO_x emission levels and there are secondary compliance techniques that denitrify the flue gas. Ships built after 1 January, 2016, will need to meet the more stringent Tier III NO_x emission limits inside ECAs designated to control NO_x emissions (ECA-NO_x).

As with any emerging technology, there is a steady stream of new innovations and developments. However, this guidance covers only techniques that have demonstrated compliance with emissions regulations.

At the time of publishing this guidance, every effort has been made to ensure that it reflects the current status of emissions compliance technologies and emission regulations. We will be updating it regularly. To download the latest version visit www.lr.org/eca

2. Air pollution regulations and controls

International, regional, national and local instruments regulate emissions of SO_x, NO_x and particulate matter from ships. In response to greater concern about air quality, the extent and complexity of regulations have increased while emissions limits have become tougher. Annex VI of the MARPOL Convention applies to all ships trading internationally and has been used as the basis for many other regional, national and local regulations.

Even the lowest limits for SO_x and NO_x emissions, either already in force or planned for ships engaged in international trade, are higher than equivalent emission limits for land-based industry located in areas where there are ECAs, when considered on the basis of sulphur content of fuel consumed or an engine's NO_x emissions in g/kWh. However, when considered on the basis of unit of emission per unit of transport work delivered (e.g. SO_x per teu•km) the emissions of ships are generally lower than other forms of transportation due to shipping's significantly higher transport efficiency.

2.1 MARPOL Annex VI

With MARPOL Annex VI, the IMO has prioritised reduction of NO_x and SO_x emissions to air on the basis of their environmental and public health impacts. Shipping emits other environmentally damaging pollutants to air from machinery (such as carbon monoxide and particulate matter) but only NO_x and SO_x are subject to quantified emission limits. PM is also included within Annex VI but is not quantified. There are industrial standards for PM emissions but these have not been adopted by the marine industry.

MARPOL applies to ships engaged in international trade; it does not apply to ships which do not trade internationally. Ships which trade entirely within the waters of a single state will be subject to the state's national laws and regulations, or in some cases they will be subject to regional requirements which are outside the scope of MARPOL.

2.2 SO_x emission regulations

2.2.1 MARPOL Annex VI Regulation 14

Regulation 14 limits fuel sulphur content to restrict SO_x and PM emissions, and applies to all ships in service. The regulation specifies different limits for operating inside and outside ECAs for SO_x (ECA-SO_x) and these follow a stepped reduction over time, as shown in Figure 1.

Four ECA-SO_x – the Baltic; the North Sea (which includes the English Channel); the North American; and the US Caribbean – are currently in force. Figure 2 shows the geographical extent of these areas.

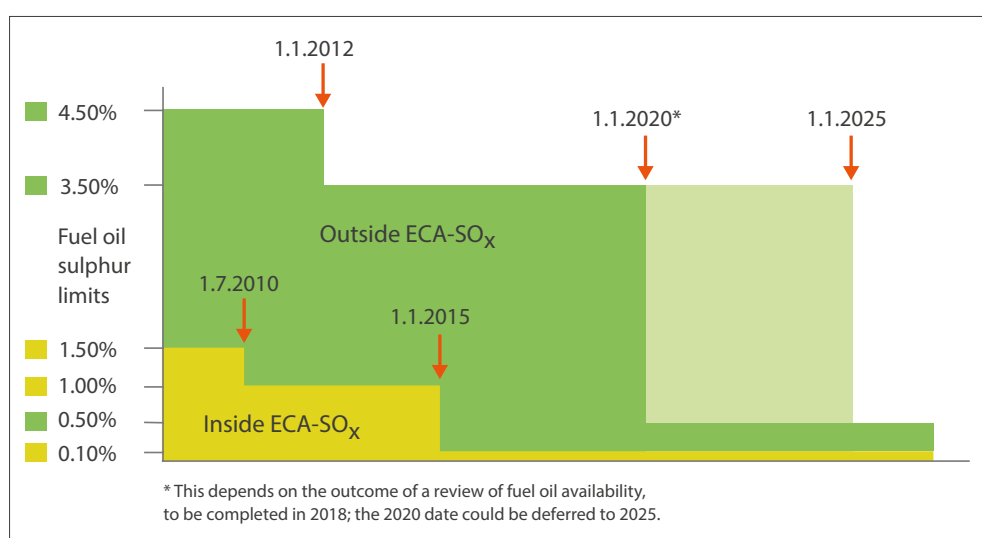


Figure 1: Marine fuel sulphur content reduction as required by Regulation 14.



Figure 2: Existing ECA-SOx

2.2.2 MARPOL Annex VI Regulation 4

Regulation 4 allows flag administrations to approve alternative means of compliance with Regulation 14 that are at least as effective in terms of emissions reduction as the prescribed sulphur limits. This means that a ship may operate on fuel with a higher sulphur content than that allowed by the regulations, providing that SO_x emissions are controlled to a level which is no higher than the levels emitted if using compliant fuel.

If an alternative means of compliance such as a scrubber is fitted then it must be approved by the flag administration and this approval must be notified to the IMO.

Approval of 'wet' scrubbers (see section 5.1, page 18) as an alternative compliance method must generally be in accordance with the IMO Exhaust Gas Cleaning Systems Guidelines (MEPC 184(59) – 2009 Guidelines for Exhaust Gas Cleaning Systems [2]). We refer to these as the 'IMO MEPC 184(59) Guidelines' throughout this guidance, and more detailed information is contained in Section 5 and Appendix B1.

The IMO MEPC 184(59) Guidelines specify two testing, survey, certification and verification schemes:

- Scheme A: initial approval and certification of performance followed by in-service continuous monitoring of operating parameters plus daily spot checks of the SO₂/CO₂ emission ratio; and
- Scheme B: continuous monitoring of SO₂/CO₂ emission ratio using an approved system with in-service daily spot checks of operating parameters.

In either case, any washwater discharged to sea must also be continuously monitored. Interestingly, it is washwater discharge which has tended to be the most problematic part of scrubber approvals.

There are no IMO guidelines for other alternative means of SO_x compliance such as fuel washing, non-thermal plasma or even dry scrubbing. Therefore, approvals are considered on a case-by-case basis by flag administrations and their recognised organisations (ROs).

2.3 NOx emission regulations

2.3.1 MARPOL Annex VI Regulation 13

Regulation 13 limits NOx emissions from marine diesel engines. The limits are divided into three 'tiers'. How these tiers apply depends on the ship's construction date (or the installation date of additional or non-identical replacement engines) and the engine's rated speed (n), as shown in Figure 3.

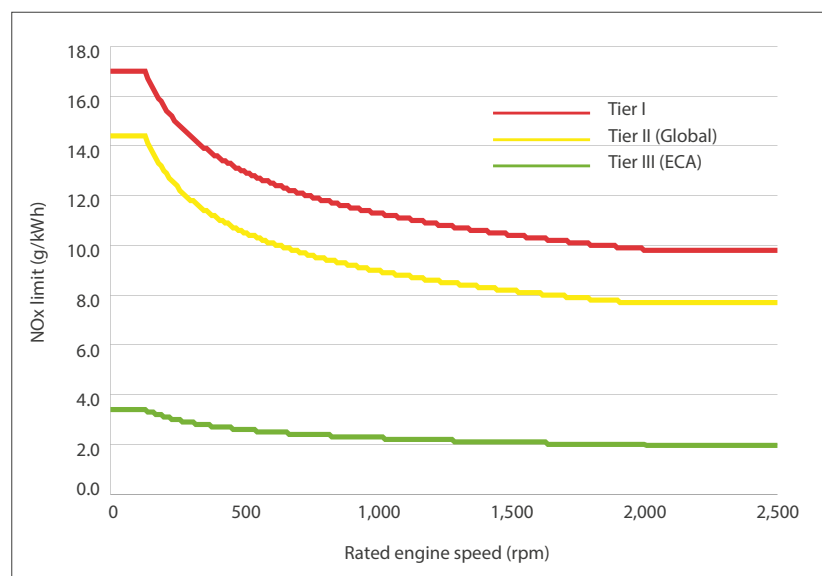


Figure 3: Regulation 13 NOx emission limit values

Tier I and Tier II limits apply to engines installed on ships built on or after 1 January, 2000, and 1 January, 2011, respectively. Tier III limits will apply to ships built on or after 1 January, 2016, if operating within the North American and US Caribbean ECA-NOx. To date these are the only two declared ECA-NOx. Within any new ECA-NOx, Tier III will apply to ships built on or after the date that the ECA is circulated for adoption. Alternatively, the IMO may specify a later date when designating the ECA.

2.3.2 The NOx Technical Code

The NOx Technical Code 2008 [3] is a mandatory IMO code which provides detailed requirements for the certification of engines with respect to NOx emissions.

3. Primary compliance techniques for SOx

MARPOL Annex VI Regulation 14 limits fuel sulphur content. Several low-sulphur fuels are available including low-sulphur distillate oil, 'hybrid' fuel oil, liquefied natural gas (LNG), liquefied petroleum gas (LPG), biofuels, dimethyl ether (DME), ethane and methanol. Residual fuel oil (RFO) can also be de-sulphurised. These are primary compliance techniques as they lower SOx emissions at source.

3.1 The science of SOx

SOx derives directly from fuel sulphur content. The sulphur is oxidised in the combustion chamber, forming principally sulphur dioxide (SO₂) and sulphur trioxide (SO₃), typically in a ratio of 15:1. The use of alkaline lubricants to protect the engine surfaces from corrosion converts a small (and relatively insignificant) proportion of the SOx to calcium sulphate. The sulphur emissions from the engine are essentially proportional to the sulphur content of the fuel.

3.2 Low-sulphur distillate oil

Due to the nature of crude oil and refinery operations, RFO meeting the 0.10% sulphur limit is not expected to be widely available. So it is anticipated that low-sulphur distillate oil (LSDO) will generally be used to comply. It is also the simplest way to comply.

LSDO will normally consist of marine diesel oil (MDO) or marine gas oil (MGO); the terms MGO and MDO have no precise definition other than that both are distillates and therefore do not require heating before injection, whereas RFO, whatever the grade, does require heating. The ISO standard 8216:2010 categorises MGO and MDO as distillate marine (DM) grades. Within this guidance, MGO refers to the ISO 8217:2012 DMA and DMZ grades while MDO corresponds to the ISO 8217:2012 DMB grade.

LSDO is traditionally considered a trouble-free fuel but it is not entirely without risk. There are some technical challenges, particularly if converting existing ships from residual fuel. Equipment and systems will need to be suitable for use with LSDO, and may need to be modified. However, these engineering modifications are minor compared to those needed for other SOx compliance options.

LR offers the optional 'DIST' descriptive note to recognise ships that apply best practice beyond minimal class rule requirements for fuel oil systems.

The availability of LSDO is an industry concern. There has been a tightening of distillate fuel supplies as a result of EU requirements for ultra-low sulphur automotive fuels and an increasing demand in emerging markets. In 2009, CONCAWE^a estimated that a USD 50 billion investment in refineries was needed to meet European automotive and industrial demand for distillates, with a further USD 17.5 billion investment needed to meet potential additional demand from shipping. Little of this investment has been in Europe and in fact Europe has been losing refining capacity. There is significant investment in upgrading refineries outside of Europe, for example in Russia. This may offset expected shortfalls. The IMO will review LSDO availability in 2018 to see whether the 2020 global sulphur limit reduction is achievable. At the time of writing, LSDO is typically 300 US dollars per tonne more expensive than 380 centistokes (cSt) RFO, and while long-term fuel cost forecasting is notoriously unreliable it is generally accepted that it will remain significantly more expensive than RFO.

Some things which you should consider if using LSDO to comply with Regulation 14 are listed here, and are based on ISO 8217:2012:

Contamination

The 0.10% sulphur limit means that low-sulphur distillates could easily become non-compliant if contaminated with higher sulphur fuels. Therefore, it is essential to strictly segregate low-sulphur and other fuels.

Viscosity

Distillates generally have a viscosity in the range 2.0-5.0 cSt at 40°C; however, it is expected in the future that these fuels will tend towards lower viscosities. The DMA and DMB grades are currently limited to a minimum viscosity of 2.0 cSt at 40°C

^a Concauwe was established in 1963 by a small group of leading oil companies to carry out research on environmental issues relevant to the oil industry. Concauwe's activities...cover areas such as fuels quality and emissions, air quality, water quality, soil contamination, waste, occupational health and safety, petroleum product stewardship and cross-country pipeline performance.

and the DMZ grade (which is otherwise identical to DMA) to 3.0 cSt at 40°C. This low viscosity means that trace heating or preheating before injection should not be applied, and is also insufficient to provide necessary hydrodynamic lubrication.

Fuel transfer and supply pumps, fuel valves and other parts of the fuel oil system should be checked to ensure they can operate with fuels at lower viscosities, as they can all be affected on diesel engines. These viscosity values are based on a reference temperature of 40°C; in actual operation, temperatures might be higher, causing the viscosity to drop further.

Cold flow

Cold flow is a property often overlooked by ships. Fuel cold flow properties are controlled by setting a limit on the pour point (the lowest temperature at which a fuel will continue to flow). However, given that wax crystals form at temperatures above the pour point, fuels that meet the limits can still be challenging when operating in colder regions. Wax particles can rapidly block filters, potentially plugging them completely. Temperatures of 22°C or more may be needed to ensure trouble-free operation. Ships operating in warmer operating zones will not generally suffer these problems but ships transiting from warm to cold zones need to be aware of them. For further advice, contact your local LR group office.

Lubricity

Distillates are more likely to have lower lubricity than residual fuel oils. Therefore, they may not provide the required boundary lubricating performance. High-pressure fuel pumps and other equipment should be checked to see if they have any minimum lubricity requirements for the fuel being used.

Fuel seepage

Converting RFO systems to LSDO may result in seepage of fuel from pipe flanges, equipment seams and other fittings (such as pressure gauges and other sensors) because of the 'searching' nature of LSDO. This may only become apparent after a period of time as accumulated material is removed by the cleaning action of the distillate.

Sludge formation

If you plan to switch between different fuels according to whether or not the ship is in an ECA-SOx, there is a risk that incompatible fuels will result in the formation of excessive quantities of sludge. This can disrupt the combustion process and the functioning of fuel oil treatment, service systems and associated equipment. Mixing of significant quantities of fuel should be avoided. During fuel change-over between residual fuel and distillate, the fuel system, including fuel pumps, will be subject to a significant change in temperature as a result of the need to heat the residual fuel to maintain viscosity at the correct levels for the engine. This temperature change will be approximately 100°C; therefore the change-over procedure is critical to prevent machinery seizure, machinery wear, micro-seizure and loss of performance. The fuel change-over procedure should be in accordance with the instructions of the engine manufacturer. Typically, unless stated otherwise by the engine manufacturer, a maximum rate of temperature change is 2°C per minute for two-stroke slow speed engines and 4°C per minute for other engines.

Ignition and combustion

RFO and LSDO have different ignition and combustion characteristics. An engine set up for RFO can experience a number of issues if operated on LSDO:

- Deposition may be caused within the cylinder and inlet/exhaust valves. This reduces the life expectancy of piston rings, liners and valves.
- Fuel valves may require increased maintenance to counter the effects of using LSDO.
- In some cases, fuel valves may need to be changed to an alternative material specification based on the manufacturer's advice.
- The reduced viscosity of distillates may result in worn high-pressure fuel pumps being unable to deliver sufficient fuel to the fuel valves to maintain engine power output. This may result in excessive fuel leakage and engine failure, and may also present difficulties in starting the engine.

Other implications include:

- On two-stroke engines, the lower sulphur content of LSDO will reduce the rate of acidic corrosion of the cylinder liner.
- The sulphur in high-sulphur fuels has a positive effect on piston ring/liner wear because controlled acid corrosion prevents polishing of the liner and helps to maintain an open graphite structure on the liner face to promote a hydrodynamic oil film between the rings and liner.

Finally, the cylinder oil base number must be suitable for the fuel in use:

- If the cylinder oil base number is too high relative to the acidity of fuel, there is a risk of hard alkaline deposition to cylinder liners, which can cause polishing and accelerated wear.
- If it is too low, the rate of acidic corrosion of the liner may be too high, resulting in accelerated wear.

Converting boiler and incinerator burners

Converting boiler and incinerator burners presents particular challenges. Specific RFO and distillate burner tips should be fitted to burners which are intended to operate on both residual fuel and distillate, and the tips must be changed over as required. Steam atomiser supply to burners will usually need to be shut off when using distillate to avoid heating the fuel in those designs where the steam supply surrounds the core fuel oil supply (concentric gun type). There are certain burner types where the steam supply is carried in a separate channel away from the fuel supply (parallel gun type), thereby avoiding the risk of fuel over heating. Transfer between fuels is likely to result in some smoke formation if no remedial action is taken to control combustion. Fuel and air systems are controlled by automatic boiler control, automatic combustion control or burner management systems, all of which may require modification. The burner manufacturer and combustion control system manufacturer should be consulted to determine the extent of any modifications required.

Procedures and training

Operational procedures and appropriate crew training are critical to the safe and reliable change-over between residual and distillate fuels. These procedures should be incorporated within the onboard Safety Management System (SMS) and operators are responsible for ensuring these procedures are in place and that crews are suitably trained.

Sea trials

Full sea trials in safe navigational waters are recommended to test machinery systems operating continuously on distillate – in particular to test manoeuvrability of the engines.

3.3 Alternative low-sulphur fuels

3.3.1 Hybrid fuels

To meet the increasing demand for 0.10% sulphur marine fuel, several suppliers have developed new low-sulphur 'hybrid' fuels that are claimed to be more cost-effective than conventional distillate fuels like MGO. They are called hybrids because they combine properties of distillate and residual marine fuels. Typically, they have lower viscosity and density, and better ignition and combustion properties, than conventional RFO.

An expanding range of hybrid fuels is being marketed to the shipping sector. They are generally categorised as heavy distillates requiring heating, but some are actually RFO-based products, often derived from existing refinery side streams, and their price will be driven by marine market conditions and competition for base stocks from other industrial sectors. This is a rapidly evolving sector with great potential. Because of the wide range of products in development and the relatively early stage of their development, this guidance doesn't cover hybrid fuels in detail, but some factors to consider include:

- compatibility with other fuels, particularly residual fuels
- fuel segregation
- pour point, viscosity and heating requirements
- low density variations that may require separator plant adjustment.

Positive characteristics of hybrid fuels include their improved combustion characteristics and low levels of metals and ash, in particular abrasive catalytic fines.

For more detailed guidance on hybrid fuels, visit www.lr.org/eca

3.3.2. Biofuels

There are also biofuels which are low in sulphur; the most common are Fatty Acid Methyl Ester (FAME) types derived from vegetable oils. Second and third generation biofuels are expected to address some of the societal concerns relating to the supply of FAME-type fuels. Biofuels are generally very similar to petroleum distillate oils. There are materials compatibility and storage issues related to the use of biofuels.

3.3.3 LNG

LNG is low in sulphur and easily combusted in engines and boilers using mature and reliable technology. Gas engines are widely used in land-based industry and have been used in LNG carriers for many years. The IMO is developing a new code for gas as fuel – the IGF Code – but until this enters into force there is uncertainty over the legal framework for operators and designers to work within. LR has published class rules for gas-fuelled ships.

Wholesale LNG prices are generally lower than RFO prices, but a lack of marine supply facilities means LNG may be more expensive than RFO once delivery costs are taken into account. In some markets, LNG prices are indexed to oil prices and can match them even before supply costs are added. Known gas reserves have steadily increased. International Energy Agency data shows they increased more than threefold between 1975 and 2010, and gas prices have become very attractive in some markets as a result of this abundance, particularly in North America. Where LNG supply infrastructure is in place, LNG is expected to become very financially attractive as a marine fuel.

Converting existing ships to alternative fuels such as LNG is possible, and there is a lot of interest in this area in the North American market. However, conversions are expensive and technically challenging. Challenges include installing the fuel tank and containment systems, gas zoning and engine conversion.

3.2.4. Other alternative fuels

Other alternative fuels include liquefied petroleum gas (LPG) and methanol. While LR currently expects the use of LPG as a marine fuel to be limited to niche markets, such as LPG carriers using cargo to provide fuel, it is expected that methanol will establish a place in the market and we are already working on several methanol projects. We have published provisional rules for methanol-fuelled ships and the IMO is working on incorporating methanol into the draft IGF Code.

Further advice on alternative fuels

Given the particular technical challenges and complexity of operating on fuels such as LNG and methanol this guide does not cover them in detail. If you are interested in alternative fuels, contact your local LR group office for advice. We have extensive experience in supporting clients in adopting alternative fuels, and can provide a wide range of services including both classification and consulting.

4. Primary compliance techniques for NOx

All current marine engines can easily achieve Tier II compliance. Tier III compliance, however, will require significant changes to the engine using either the complex primary techniques discussed in this section or by using secondary exhaust gas treatment systems.

4.1 The science of NOx

The formation of NOx is complex. NOx is the collective term for Nitrogen dioxide (NO₂) and Nitrous Oxide (NO). Nitrous Oxide is not NOx.

Nitrogen is a natural element in the atmosphere and is also found in the chemical structure of some fuels. During the fuel combustion process, NOx is formed in the cylinder in three ways:

- **thermal formation**, as a result of the reaction between atmospheric nitrogen and oxygen at high temperatures
- **fuel formation**, as a result of the reaction between nitrogen in the fuel and oxygen
- **prompt formation**, as a result of complex reactions with hydrocarbons and atmospheric nitrogen.

NOx is formed both at the initial stage of combustion in very high temperatures and later in the combustion process after a longer dwell time in the combustion chamber. Therefore, the formation of NOx requires both high temperatures and exposure time.

The major component of NOx on exit from the ship is nitric oxide, which readily oxidises in the atmosphere.

The proportion of nitric oxide attributable to thermal and fuel formation depends on the combustion conditions, which in turn are determined by the combustion unit type, configuration and operation, together with the fuel's grade and composition.

Prompt formation can exceed thermal formation under certain conditions where combustion temperatures are low, residence time is short and combustion conditions are fuel-rich.

Lowering the temperature of the combustion process reduces NOx but also reduces engine efficiency. Theoretical ideal heat engine efficiency is represented by the Carnot cycle, where heat efficiency is a function of the ratio maximum temperature to minimum temperature. Marine engines are not Carnot engines but efficiency is still related to the temperature differential across the cycle. Reducing the compression ratio by adjusting engine valve opening and closing, adding water to fuel or charge air or applying high-pressure super charging can reduce maximum combustion temperature. Lower combustion temperatures and lower combustion, atmospheric oxygen and nitrogen levels are the main approaches to reducing NOx emissions.

4.2 Gas as fuel

Fuel type is critical to engine NOx emissions performance. While the difference in NOx emissions between residual and distillate fuels is not dramatic, some of the alternative fuels listed in 3.3 can reduce NOx to a level where Tier III compliance can be achieved. Fuels such as natural gas (stored on-board as LNG or potentially compressed natural gas) can achieve Tier III NOx levels. However, this depends on the engine design; not all gas engines can achieve Tier III. Some of these design considerations include:

Thermal cycle

NOx performance is linked to the thermal cycle of the engine. A pure gas Otto or Miller cycle engine can achieve Tier III emissions levels relatively easily. A gas diesel cycle engine using oil pilot ignition for the gas cannot, despite having lower NOx emissions than conventional oil-fuelled engines.

Methane slip

Pure gas Otto and Miller cycle engines are associated with methane slip^b. Methane has much higher global warming potential than carbon dioxide; as societal concerns over greenhouse gas emissions increase, methane is expected to become a more prominent part of the marine emissions debate.

^b "Methane slip is when gas leaks unburned through the engine. Methane has a GWP100 (100-year global warming potential), which is 25x higher than CO₂. If [] methane slip isn't controlled, environmental benefits to using natural gas are reduced." Source: http://en.wikipedia.org/wiki/Marine_LNG_Engine

Dual fuel engines

Under the NOx Technical Code, dual fuel engines (engines that use liquid fuel to ignite the gas) and engines that use liquid fuel are required to be tested and certified at the highest liquid-to-gas fuel ratio. This ratio will change with the engine design.

In accordance with this, an engine can be certified as either a dual fuel or a gas engine. If certified as a gas engine, it will be Tier III compliant when operating on gas, but not when operating on liquid fuel. The operator will only be able to use liquid fuel during an emergency or failure, reducing operational flexibility.

4.2.1 LPG and methanol

These design considerations also apply to LPG and methanol. If you are interested in using these fuels, please contact your local LR group office for advice.

4.3 Exhaust gas recirculation

Exhaust gas recirculation (EGR) is a mature technology, used in automotive engines for several decades. Exhaust gas is fed back into the cylinder air intake, lowering oxygen and increasing CO₂, which has a higher specific heat capacity than air. This slows combustion and reduces temperature, lowering NOx. The EGR fan can adjust the amount of exhaust gas that is recirculated (the EGR ratio).

The main components of an EGR system are shown in Figure 4, and comprise:

- a high-pressure exhaust gas scrubber fitted before the engine turbocharger
- a cooler to further reduce the temperature of the recirculated gas
- a water mist catcher (WMC) to remove entrained water droplets
- a high-pressure blower to increase recirculated gas pressure before reintroduction to the engine scavenge air
- automated valves for isolating the system.

The main washwater components of the scrubber are typical of a closed loop SOx scrubber system (see section 5.1.2 on page 18) and comprise:

- a buffer tank with fresh water make-up
- a sodium hydroxide dosing device
- a circulating pump
- a water treatment plant with sludge collection.

4.3.1 MAN Diesel & Turbo EGR systems

MAN Diesel & Turbo has tested its own EGR systems on two-stroke engines.

A first generation MAN EGR system was trialled on board *M.V. Alexander Maersk*. Initial issues with materials [4] required material upgrades and improved sodium hydroxide dosage because of iron and sodium sulphate deposits in the main engine air coolers, and corrosion of EGR system components including the cooler casing and blower.

MAN's second generation EGR system is shown in Figure 5. This integrates the engine, scrubber, cooler, water mist catcher and blower into a single unit. It is designed to be fitted in the same way as a charge air cooler. With 40% recirculation, this EGR can potentially reduce NOx to Tier III levels on a two-stroke low-speed marine engine, and increased fuel consumption, carbon monoxide (CO) emissions and PM emissions resulting from reduced combustion efficiency are manageable with engine adjustments.

MAN also report that specific fuel consumption is improved when using EGR to reduce NOx to Tier II levels, when compared with using engine adjustments to achieve the same level of emissions, particularly at part load. While most attention has focused on using the MAN EGR system for slow-speed engines, high-speed and medium-speed engine manufacturers are also considering EGR NOx abatement technology.

4.3.2 CO and PM emissions

EGR systems can cause higher CO and PM emissions. CO emissions can be controlled by adding water to the fuel. However, adding water can reduce fuel efficiency and increase PM. Increasing turbocharger and fuel injection pressure can help to reduce the PM emissions.

There is a balance to be struck between EGR ratio and water addition to achieve an optimum balance between NOx, CO, PM and fuel efficiency.

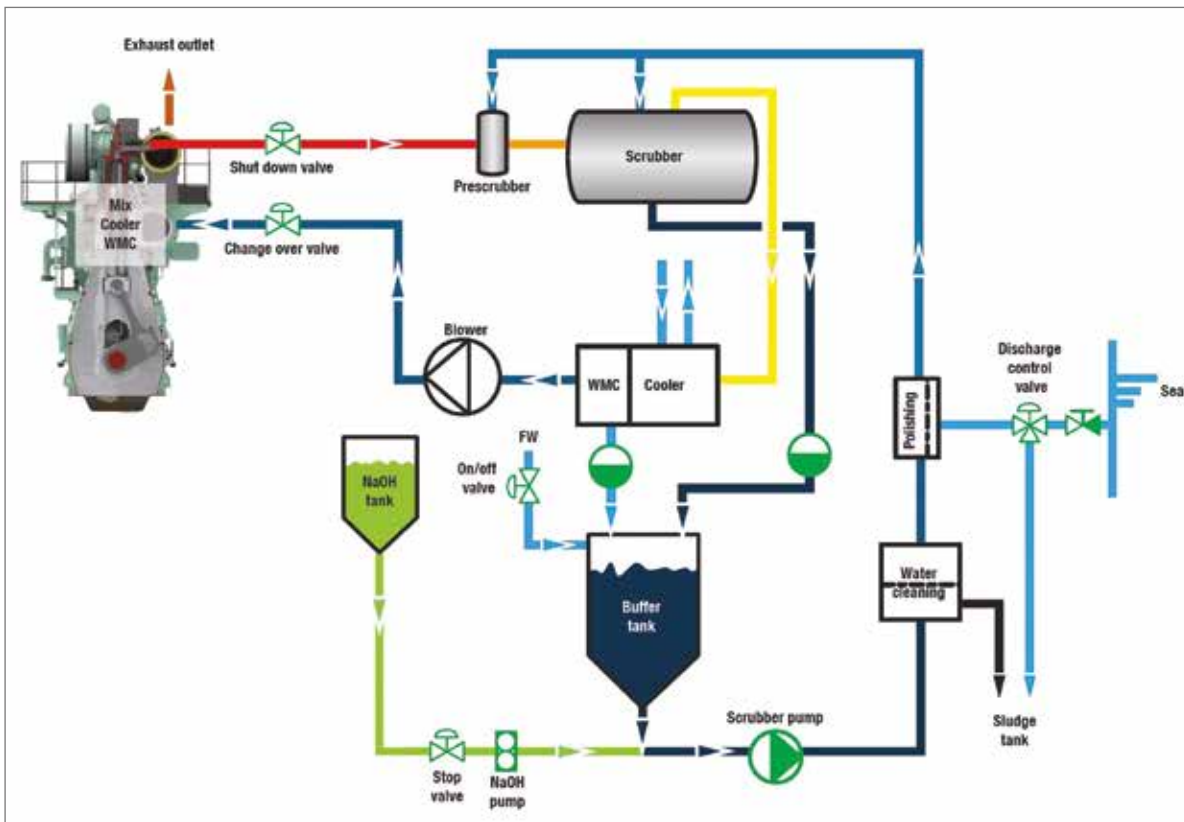


Figure 4: A two-stroke EGR system arrangement (image courtesy of MAN Diesel & Turbo)



Figure 5: Graphic of the second generation MAN EGR system. The orange sections are the EGR system components, integrated into the engine (Image courtesy of MAN Diesel & Turbo)

4.3.3 Combining EGR with other techniques

There is great potential to combine EGR with other techniques such as fuel emulsification, charge air humidification and pushing engines onto an extreme Miller cycle, in order to achieve Tier III compliance.

The reduction in NOx achieved by these techniques means that the EGR system can be downsized, leading to a lower footprint, and a large reduction in EGR ratio and required electrical load.

4.4 Advanced fuel injection

In the longer term, the most promising primary NOx compliance option is advanced fuel injection using split or pulsed injection to control placement of fuel and the combustion characteristics within the cylinder. This technology is not available for marine engines yet but indicates future possibilities; it is already widely used in automotive engines.

Advanced fuel injection allows better control of cylinder pressures and heat release rates, establishing separate heat release stages so that cylinder temperatures and NOx formation are reduced. It may be used with a simple EGR system to achieve Tier III compliance. It is also technically possible that advanced fuel injection could achieve Tier III with no EGR or secondary exhaust treatment device.

4.5 Fuel emulsification

Fuel emulsification has been recognised as an effective way of reducing NOx emissions for many years. Forming a stable and homogeneous emulsion can be challenging (particularly with distillate fuels) but it can be done. While achieving Tier III compliance using emulsification alone is proving to be challenging, it could be used with other techniques such as mild EGR or high-pressure super charging to achieve Tier III.

Given that emulsification systems affect the composition of fuel it is important to ensure that the resulting emulsified mixture is suitable for combustion machinery and that measures are in place to prevent the emulsification system exceeding the allowable fuel parameters for machinery.

4.6 High-pressure supercharging

Since combustion temperatures are related to the compression ratio of internal combustion engines, reducing this compression ratio can lower temperature and reduce NOx. This can be achieved by high-pressure supercharging using multi-stage turbochargers and by applying the Miller thermal cycle. In a Miller engine, the air inlet valves remain open for much longer than in a Diesel or Otto engine, with the result that typically only 70-80% of the upward piston stroke is compressing the charge air or pre-mixed charge air and fuel. While this is unlikely to achieve Tier III emissions compliance by itself, it can be used in conjunction with other techniques.

Although high-pressure supercharging improves emissions performance, it has high energy demand. If using turbochargers, this will significantly reduce the energy which is available for waste heat recovery systems. This is potentially quite important for ships with a high heating load. Clearly the supercharging system will be more complex and more expensive, particularly where multi-stage devices are used and these will require more complex charge air cooling arrangements. If the compression ratio is lowered too much, there may be problems with engine operability.

Primary technique	Tier III compliance when used alone	Tier III compliance when combined with other techniques
Gas as fuel	✓ (but depends on engine design – see Section 4.2, page 13)	N/A
Exhaust gas recirculation (EGR)	✓	N/A
Advanced fuel injection (AFI)	Technically possible in the future	Technically possible in the future
Fuel emulsification (FE)	Challenging	EGR or HPSC
High-pressure supercharging (HPSC)	Unlikely	EGR, AFI or FE

Table 1: Primary NOx techniques and Tier III compliance when used alone or with other techniques

5. Secondary compliance techniques for SOx

Operators can use exhaust gas treatment systems as an alternative way to comply with the SOx emissions limits, if permitted^c. Currently the market for marine exhaust gas cleaning technology is dominated by SOx scrubbers. A less mature technology option is non-thermal plasma (NTP).

There are two main types of SOx scrubber:

- wet scrubbers (section 5.1) that use water (seawater or fresh water) as the scrubbing medium; and
- dry scrubbers (section 5.2) that use a dry chemical.

Both wet and dry scrubbing technologies are established and mature and have been used in industries such as electricity generation for many years.

5.1 Wet scrubbing

Wet scrubbing is a simple, robust and effective technique; the first application was at Battersea power station in the 1930s. There are three main types of wet scrubbing:

- ‘open loop’ systems, which use seawater to treat the exhaust gas
- ‘closed loop’ systems, which use fresh water with the addition of an alkaline chemical to treat the exhaust gas; and
- ‘hybrid’ systems, which can operate in both open loop and closed loop modes.

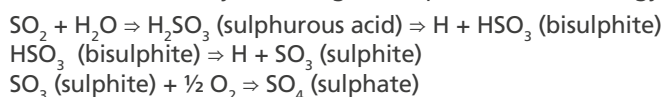
All wet scrubbers generate ‘washwater’. This is the seawater or fresh water mixed with the exhaust gases in the scrubber chamber. Requirements for treatment, monitoring and discharge of washwater are contained in the IMO MEPC.184(59) Guidelines, and are covered in detail in this section.

A fourth option is to operate in open loop mode and closed loop mode simultaneously.

5.1.1 Open loop scrubbers

Open loop scrubbers pump seawater into the scrubber and discharge the washwater back to the sea. A simple open loop scrubber is shown in Figure 6.

In an open loop system, sulphur oxides (SOx) are removed from the exhaust gas in a series of conventional chemical reactions; these vary according to the particular technology used but typical chemistry is:



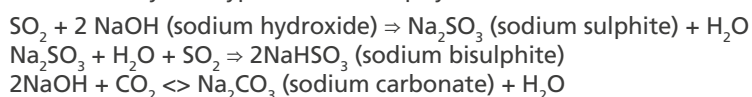
The sulphate is discharged to sea. Washwater is not recirculated. A typical washwater flow rate in an open loop system is 45m³/MWh. Open loop systems are sensitive to local washwater controls and are associated with higher parasitic loads but do not normally need alkaline additives and are simple.

5.1.2 Closed loop scrubbers

Closed loop scrubbers circulate fresh water in a closed loop, ‘bleeding off’ contaminants to keep the washwater clean. A closed loop arrangement is shown in Figure 7.

SOx and particulates are removed from the exhaust gas as the washwater dissolves them. Dissolved SOx forms sulphuric and sulphurous acids; a series of chemical conversions results in these acids being converted to sulphite and bisulphite, generating excess hydrogen ions and acidity. This acidity is neutralised by alkaline carbonates and bicarbonates in the sea water – a process known as pH buffering. Many marine systems use sodium hydroxide^d for pH buffering.

The chemistry of a typical closed loop system is:



^c See Table 4 in Appendix B3 on page 55 for information on regional and local regulation governing SOx scrubbing

^d Also known as caustic soda or lye

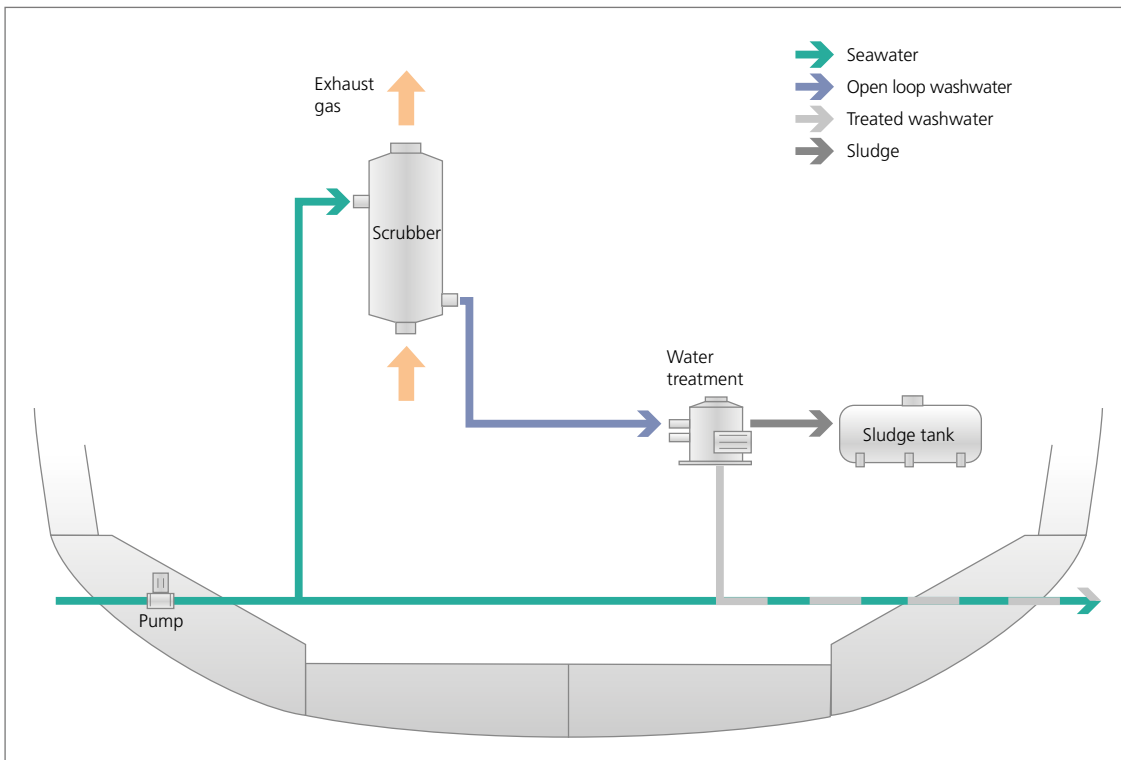


Figure 6: An open loop scrubber arrangement

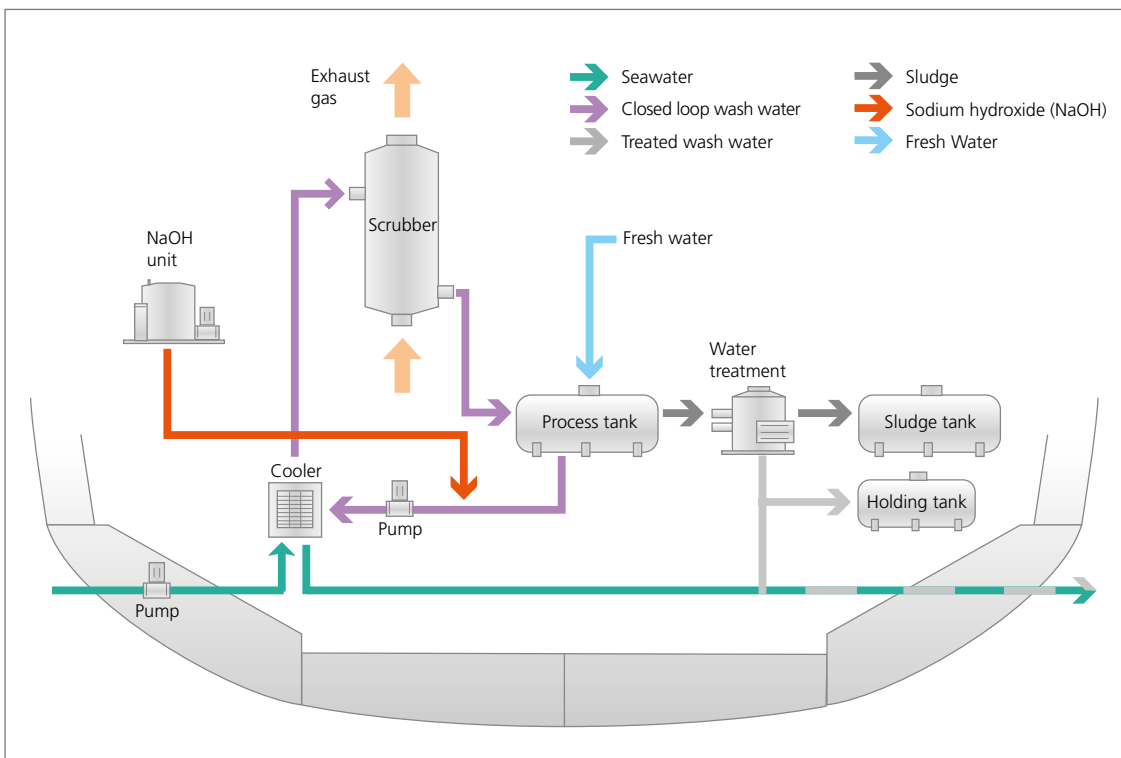


Figure 7: A closed loop scrubber arrangement

Sodium hydroxide

Closed loop systems typically consume sodium hydroxide in a 50% aqueous solution. The dosage rate is approximately 15 litres/MWh of scrubbed engine power. The choice of materials for pipework, fittings and tanks is an important consideration as sodium hydroxide is corrosive to aluminium, brass, bronze, tin, zinc (including galvanised coatings) and glass.

Sodium hydroxide is usually delivered by road tanker at a transportation temperature of around 40°C. The temperature when pumping must be above 20°C, as the viscosity rapidly rises below this temperature. However, it should not be above 50°C to prevent corrosion cracking of mild steel pipework, although stainless steel is resistant at higher temperatures.

Onboard storage temperature is therefore between 20°C and 50°C. If onboard temperature is regulated by cooling water systems, the risk of a heat transfer coil failing (leading to cross contamination of the cooling system with sodium hydroxide) should be noted. Sodium hydroxide has a pH of 14 and is hazardous. It can cause severe skin burns, respiratory damage and eye injury. Robust procedures are required for handling sodium hydroxide, including use of appropriate personal protective equipment (PPE) if there is risk of exposure. Reference should be made to material safety datasheets (MSDS).

Alternative alkaline additives such as magnesium oxide and sodium bi-carbonate may be used which are less hazardous than sodium hydroxide.

Washwater in closed loop systems

Closed loop systems discharge small quantities of treated washwater to reduce the concentration of sodium sulphate. If sodium sulphate is left uncontrolled, crystals will form and lead to progressive degradation of the washwater system. Information from scrubber manufacturers suggests that the washwater discharge rate is approximately 0.1 m³/MWh^e.

The rate of fresh water replenishment to the system not only depends on the discharge to sea but also on losses to the exhaust through evaporation and via the washwater treatment plant. The rate of evaporation is influenced by exhaust and scrubbing water temperatures, which in turn are governed by factors such as engine load and the temperature of the seawater supply to the system coolers. Some of the water vapour incorporated within the exhaust may be captured after the scrubber and reused to reduce fresh water consumption.

If a washwater holding tank is added, closed loop systems can operate in zero discharge mode for a period of time (the exact length of time depends on the size of the holding tank). This flexibility is ideally suited to operation in areas where there is sensitivity to washwater discharges, such as ports and estuaries, removing the risk that coastal states and harbour authorities may not accept the use of scrubbing despite the IMO MEPC 184(59) Guidelines allowing open loop systems.

Closed loop systems operate with lower parasitic electrical loads due to lower washwater flows.

Closed loop systems require more tankage than open loop systems. A process or buffer tank is required in the scrubbing water circulation system, a holding tank is required for zero discharge mode (size dependent on ship requirements) and loading facilities, storage tanks and dosing equipment are required for sodium hydroxide.

Operation in fresh water

The alkalinity and pH buffering of sodium hydroxide reduces water flow compared to open loop systems and removes sensitivity to seawater carbonate and bicarbonate levels. Control of pH by dosing with sodium hydroxide enables the washwater circulation rate, and therefore power consumption, to be about half that of open loop systems at approximately 20 m³/MWh and between 0.5 – 1% of the power of the engine being scrubbed. Closed loop systems can also be operated when the ship is operating in enclosed waters where the alkalinity would be too low for open loop operation.

5.1.3 Hybrid scrubbers

Hybrid scrubbers can operate in either open loop or closed loop mode. This provides the flexibility to operate in closed loop mode (including zero discharge mode) where the water alkalinity is insufficient or where there is sensitivity to, or regulation of, washwater discharge, and in open loop mode without consuming sodium hydroxide at all other times. This offers advantages in the sodium hydroxide is only used when necessary, reducing handling, storage and associated costs. And freshwater consumption is also reduced. There are also hybrid systems that can operate in open and closed loop mode simultaneously.

^e The washwater flow rates described in this guidance are estimates and are sensitive to system design; therefore, they may differ significantly. A well-designed system may offer washwater flow rates much lower than these estimates while a less efficient system may have much higher washwater flow rates.

Although hybrid scrubbing is the preferred option for many operators, mitigating the uncertainty over the acceptance of open loop systems while retaining the simplicity of open loop operation where allowed, hybrid scrubbers are more complex.

Figures 8a and 8b show the layout of a typical hybrid scrubber, in open and closed loop modes.

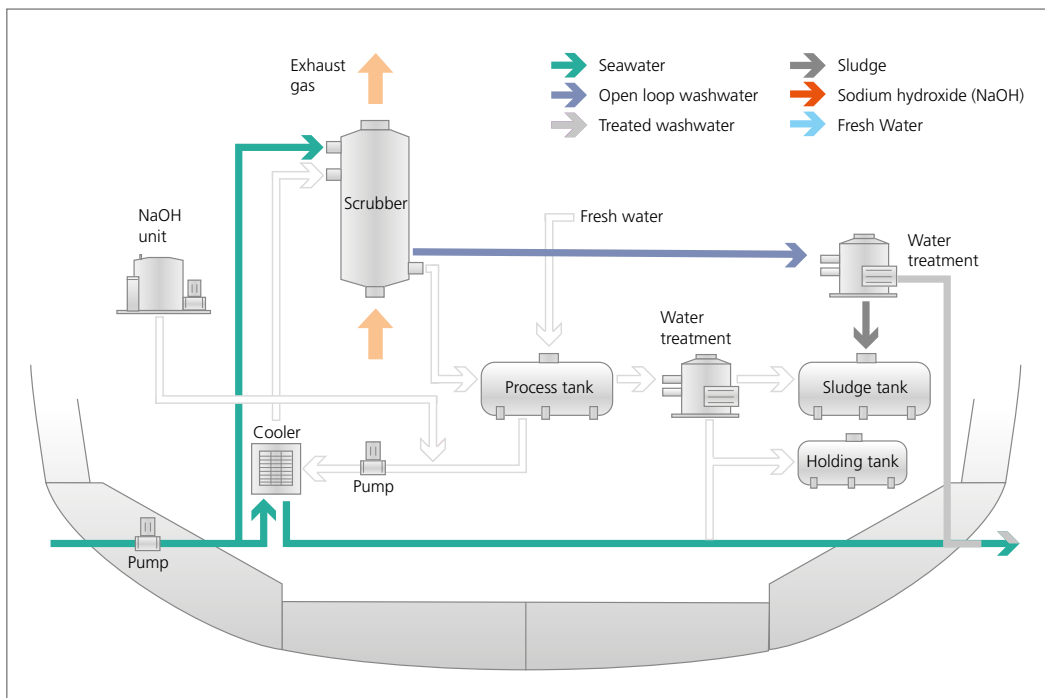


Figure 8a: A hybrid SOx scrubbing system, operating in open loop mode

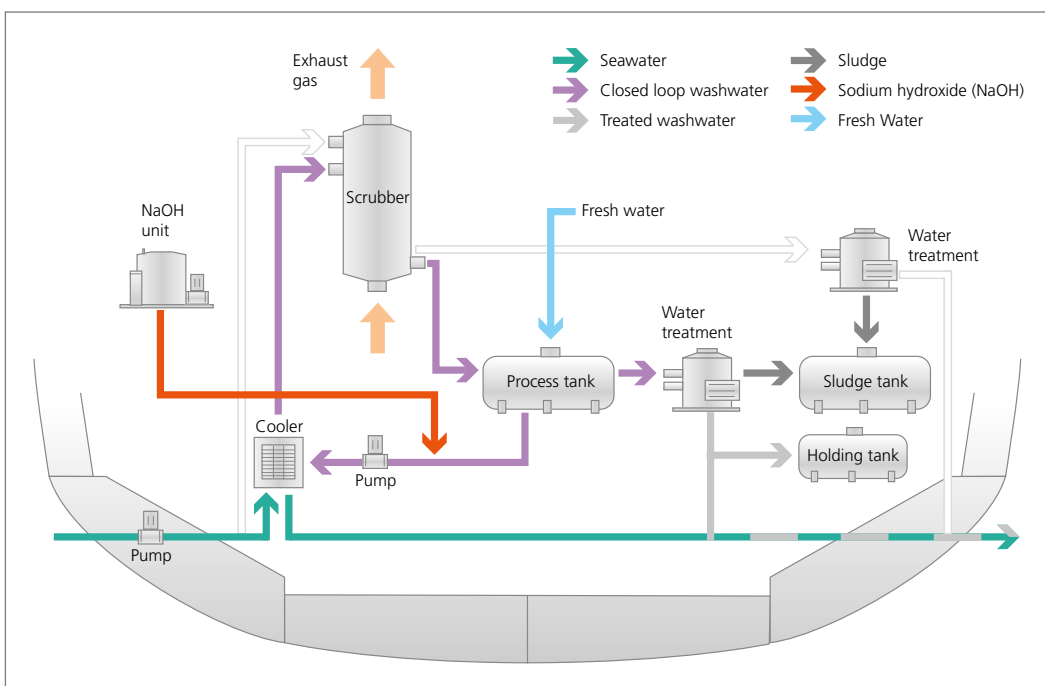


Figure 8b: A hybrid SOx scrubbing system, operating in closed loop mode

5.1.4 Common challenges of wet scrubbing

Service experience shows that wet SOx scrubbers can achieve emissions reductions of over 99%, the equivalent emissions of 0.10% sulphur fuel with all marine fuels. The technology is simple, claimed parasitic loads are relatively low (manufacturers estimate 0.5% of installed power for closed loop systems or 1.5% for open loop systems) and the return on investment time is short, potentially less than one year if operating in an ECA constantly. Retrofitting older vessels is relatively easy; some systems fit within the uptake space occupied by the engine silencer.

Wet scrubbing does present challenges, however, and these are outlined here:

Backpressure

Wet scrubbing causes higher exhaust back pressure, typically 1000 – 2000Pa. Reverse flow of water can flood the engine and boiler. Exhaust gas leaves the scrubber at approximately 60°C so waste heat recovery systems and selective catalytic reduction units (SCR) will be fitted before the scrubber in order to be effective. Waste heat recovery units already operate in acidic exhaust gas and temperature is above dew point when running. However, if an SCR is fitted, catalyst materials and geometry should be suitable for such exhaust gas or a high-pressure SCR should be used.

Stability

Scrubber towers add top weight, affecting ship stability. Additional tanks are required, consuming hull volume and increasing deadweight, increasing fairway dues and reducing overall ship efficiency. Engine room flooding can occur if a pipe fails. Wet scrubbers can generate a visible plume of water vapour at the funnel and there have also been problems with particulates being emitted from the funnel and deposited onto ships' after decks. Washwater is highly aerated after being sprayed through nozzles and mixing with exhaust gas. This can cause frothing and foaming on the sea surface if the washwater is discharged overboard.

Corrosion of materials and pipework

Washwater in wet SOx scrubbers is highly corrosive and the scrubber components that come into contact with it should be constructed of suitable corrosion-resistant materials. Glass reinforced epoxy (GRE) piping (the black piping shown in Figure 10) has been used successfully in a number of installations. GRE piping is lightweight, which makes it easier to handle during retrofits, but its reduced rigidity makes it necessary to install appropriate bracketing – in excess of that required for steel pipe. The relevant LR Rules should be followed, for example use of steel transition pieces fitted with suitable closing devices where GRE piping passes through watertight bulkheads. GRE piping close to the scrubber must also be protected from exposure to hot exhaust gases.

Experience indicates that coated steel piping may not be suitable as it can suffer rapid localised corrosion typically at welds and flanges, where there is an increased risk of breakdown of the coating. Stainless steel 316L may also be subject to rapid corrosion, particularly in open loop systems using seawater, which has a moderately high temperature after scrubbing and a low pH. In these cases, nickel alloys with a higher pitting resistance equivalence number (PREN) may be used.

Typically, it is not necessary to change the materials of the exhaust duct and systems downstream of a wet SOx scrubber if the exhaust gas temperature is kept above the dew point. If this is not the case, corrosion-resistant materials should be used.

During class approval (see section 7.8.2), the materials used in the construction of the SOx scrubber and its associated systems, including chemical storage and handling systems, will be reviewed for compliance with class Rules.

Particulate matter and soot removal

Some systems use particulate matter and soot removal devices before the scrubbing tower to simplify washwater conditioning and make polycyclic aromatic hydrocarbon (PAH) discharge compliance easier. This may negate the need for a washwater treatment system, making this an attractive option. However, these devices add complexity, and soot handling and disposal can be problematic. Disposing it as hazardous industrial waste is expensive and rigorous work safety controls are needed to protect the crew from long-term exposure to harmful substances. If a soot removal device fails, the ship will need a conventional washwater treatment system to operate in open loop mode. If a conventional washwater treatment system is fitted, it negates the advantages of having a soot removal device.

Washwater discharge to sea

One of the principal challenges associated with wet scrubbing is handling the washwater discharge. Wet scrubbers clean a wide range of pollutants out of exhaust gas, in addition to SOx, which affect washwater composition. Unless there are controls to govern washwater discharge to sea there is a possibility of pollution shift from air to water, negating the environmental benefits of exhaust gas cleaning.

In an open loop system the washwater goes into the sea. Closed loop systems require bleed off; unless the ship is provided with very large collecting tanks or the ship is in a position to discharge holding tanks to shore reception facilities frequently, this bleed off will also go into the sea.

The IMO MEPC.184(59) Guidelines place emission limits on washwater discharge, but do not contain any geographical restrictions; providing the emission limit values are satisfied, they allow for exhaust gas cleaning systems to operate while discharging washwater to sea with no further restrictions. They do not reference open or closed loop modes; the controls apply to all wet scrubbers.

In the US, the Environmental Protection Agency (EPA) has put in place Vessel General Permit (VGP) requirements for discharges incidental to the normal operation of ships. Ships with exhaust gas cleaning systems must have a VGP in order to discharge SOx scrubber washwater. These requirements are broadly equivalent to those of the IMO MEPC.184(59) Guidelines but a significant exception is that the washwater must meet a pH limit of 6.5 at the point of discharge to sea. The permit requirements apply to “waters of the United States, including the contiguous zone or ocean”.

There are further complications when using wet scrubbers within the North Sea and Baltic ECA because of the interaction between the European Water Framework^f and Sulphur Directives^g. Despite European requirements for scrubbers also being generally aligned with the IMO MEPC.184(59) requirements (with the exception that continuous emissions monitoring is mandatory) it is not yet clear if coastal states and local authorities will impose more stringent controls on washwater discharge.

However, we are seeing many references to restrictions on open loop systems. This is creating uncertainty for some operators, and a perceived risk that wet scrubbing will not be a viable solution if they are not allowed to use these systems in littoral and inshore waters. This problem is not limited to open loop systems and will also affect closed loop systems. To date, most concerns appear to relate to the acidity of washwater discharges although this is not the only emission limit for the washwater. There have also been concerns about contaminants which are not monitored, such as heavy metals, and the potential for them to accumulate in sediment on the bed of closed docks and other areas with limited water exchange.

Washwater emission parameters and monitoring

The IMO MEPC.184(59) Guidelines require three washwater parameters to be continuously monitored if discharged to sea:

Acidity (pH)

pH must be limited to 6.5 at the ship's side at rest, with a maximum difference of 2 pH units when the ship is manoeuvring or in transit; **or**

the pH is to meet a limit of 6.5 measured four metres from the ship's side. This must be continuously monitored and the monitoring data recorded and retained.

Turbidity

The washwater treatment system should minimise suspended particulate matter, including heavy metals and ash, and the maximum turbidity in washwater is limited to 25 FNU (formazin nephelometric units) or 25 NTU (nephelometric turbidity units) or equivalent units, above the inlet water turbidity, and is to be continuously monitored.

However, during periods of high inlet turbidity, the precision of the measurement device and the time lapse between inlet measurement and outlet measurement make using a difference limit unreliable. Therefore, all turbidity difference readings should be a rolling average over a 15-minute period to a maximum of 25 FNU. For the purposes of this criteria the turbidity in the wash water should be measured downstream of the water treatment equipment but upstream of washwater dilution (or other reactant dosing) before discharge. For a 15 minute period in any 12 hour period, the continuous turbidity discharge limit may be exceeded by 20%.

Polycyclic aromatic hydrocarbons (PAH)

The maximum PAH concentration in the washwater must not be greater than 50 µg/L PAHphe (phenanthrene equivalence) above the inlet water PAH concentration and is to be continuously monitored. The PAH concentration in the washwater should be measured downstream of the water treatment equipment, but upstream of any washwater dilution or other

^f Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy

^g Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 amending Directive 1999/32/EC as regards the sulphur content of marine fuels

reactant dosing unit, if used, before discharge. The 50 µg/L limit is normalised for a washwater flow rate through the EGC unit of 45 t/MWh where the MW refers to the MCR or 80% of the power rating of the fuel oil combustion unit. This limit would have to be adjusted upward for lower washwater flow rates per MWh, and vice-versa, according to a table provided in section 10.1.3.3 of the IMO MEPC.184(59) guidelines. For a 15 minute period in any 12 hour period, the continuous PAH_{phe} concentration limit may exceed the limit described above by up to 100%.

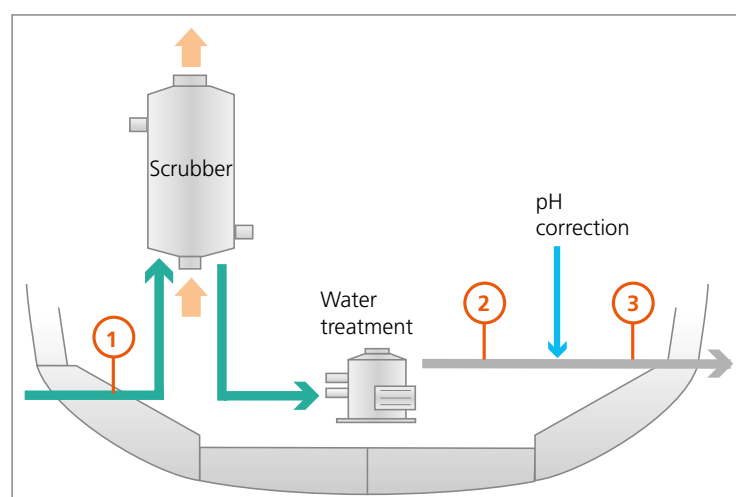


Figure 9: washwater instrumentation

Figure 9 shows the position of instruments that can be fitted to an open loop system for the monitoring of water quality at the system inlet and the point of overboard discharge. The washwater instrumentation shown is:

Point 1 washwater system inlet

- pH
- PAH
- turbidity
- salinity (optional)

Point 2 (after washwater treatment plant and before any pH correction)

- PAH
- turbidity

Point 3 (before discharge after any pH correction)

- pH.

The position, care, calibration and survey requirements for washwater monitoring instruments must be contained within an approved Onboard Monitoring Manual (OMM). Further information is included in Appendix B1. Short periods of instrument downtime are allowed for maintenance and cleaning but only when the ship is not in ports, harbours or estuaries. This may have commercial implications if there are tasks that have to be undertaken at sea requiring attendance by the manufacturer or specialists.

There are also some requirements for washwater discharge which are not subject to continuous monitoring. The washwater treatment system should prevent the discharge of nitrates beyond that associated with a 12% removal of NO_x from the exhaust, or beyond 60 mg/l normalized for washwater discharge rate of 45 tons/MWh, whichever is greater. This does not have to be continuously monitored and is verified by periodic extractive sampling. An assessment of the washwater is required for technologies which make use of chemicals, additives, preparations or create relevant chemicals in situ. The assessment could take into account relevant guidelines such as IMO Resolution MEPC.126(53) – Procedure for Approval of Ballast Water Management Systems That Make Use of Active Substances (G9)^h and if necessary additional washwater discharge criteria should be established.

^h This resolution has been superseded but remains as a reference in the IMO MEPC.184(59) Guidelines

There appears to be some confusion in the industry regarding washwater and waste residue sludge produced by scrubbers. Washwater refers to water that, while contaminated with various substances, is allowed to be discharged to sea subject to the controls given in the IMO MEPC.184(59) Guidelines. Waste residue sludge results from conditioning the washwater to remove contaminants and comply with the MEPC.184(59) washwater discharge limits. This sludge is a pollutant and cannot be discharged to sea. It must be transferred to an appropriate waste reception facility for processing and disposal in an environmentally responsible way.

The composition of washwater and sludge will vary because of variations in the materials entrained within the fuel. Wet scrubbing will dissolve SO_x. In addition, gaseous volatile organic compounds will condense into the washwater and solids and incombustibles will be washed out of the exhaust gas into the washwater.

Environmental impacts of washwater

The environmental impact of washwater discharge has been studied in a number of technical papers. These have primarily focused on the effects of washwater acidity, reflecting concerns about ocean acidification. Various papers have found the effects of washwater discharge on ocean acidification to be negligible. A study by University College London found that acidic jets discharged into an alkaline environment, as per washwater discharges from exhaust gas cleaning systems, can be safely absorbed by the sea with a negligible effect on acidification.

On the other hand, a study led by Chalmers University found that shipping is a major contributor to ocean acidification. However, this study focused on precipitation following gaseous emissions of SO_x and NO_x; given that exhaust gas cleaning will remove the overwhelming majority of SO_x from exhaust gas, this will greatly reduce acidic precipitation. This is an important consideration; while LR does not advocate or support pollution shift, existing SO_x emissions result in acidic precipitation and also the carbon reductions associated with scrubbing will have a significant positive impact on acidic precipitation.

Washwater treatment

The technology and techniques used for washwater treatment are influenced by the overboard discharge rate. The low discharge rate of closed loop systems (0.1 m³/MWh) enables use of centrifugal separators (similar to those used for fuel and lubricating oil) or multi-stage oily water separators. Wärtsilä's washwater treatment plant (shown in Figure 10) is an example of the latter.



Figure 10: Washwater treatment system with GRE piping (image courtesy of Hamworthy-Krystallon)

For open loop systems with a higher discharge rate (≈ 45 m³/MWh), cyclonic separation is appropriate. This technique is widely used in onshore and offshore industry and may also be encountered in ships' ballast water treatment systems. The heavy fractions are moved outward and downward to the outlet (underflow) at the bottom of the device. The light fractions move toward the central axis and upward to the outlet (overflow) at the top of the device. A hydrocyclone is a

tapered device that converts velocity of a liquid into a rotary motion. It does this by means of a tangential inlet or inlets near its top. This causes the entire contents to spin, creating centrifugal force in the liquid.

Hydrocyclones can either consist of a single vessel or a 'nest' of hydrocyclone 'liners' within a vessel (see Figure 11). The latter, which may be either horizontally or vertically orientated, is arranged with a plate (similar to a tube plate in a cooler) at each end. The overflow plate holds the overflow end of each liner in place while the underflow plate holds the underflow ends.

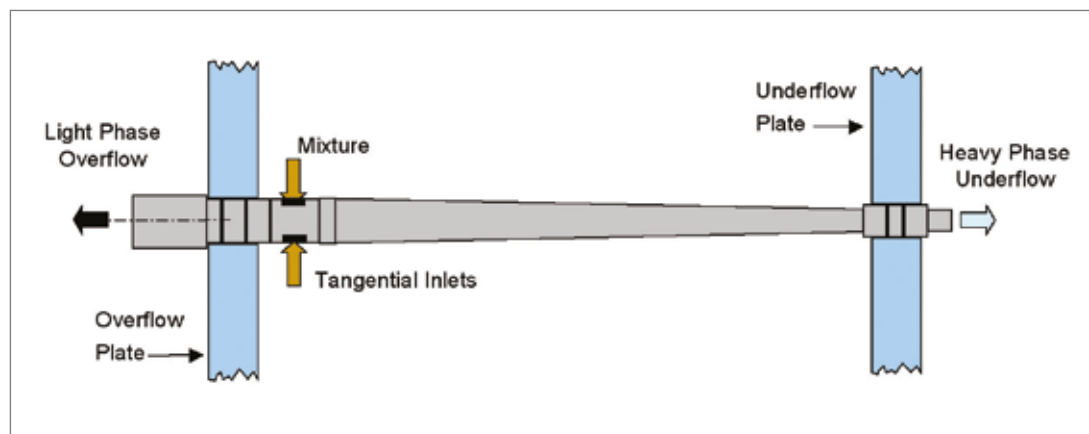


Figure 11: A hydrocyclone liner

Depending on design, hydrocyclones can separate solids from liquid, or liquids of differing densities. Combinations can therefore be used to separate both particulate matter and hydrocarbons from washwater. The velocity of the washwater is either imparted by a pump or by the height of the scrubber above the washwater plant in the engine room, if sufficient.

In US submissions to the IMO supporting the introduction of the North American ECA [5], test data showed PM10 emissions being dependent on fuel sulphur levels, with emission rates of 0.23 g/kWh with distillate fuel (0.24% sulphur content) and 1.35 g/kWh with residual fuel (2.46% sulphur content) – which compared closely with the findings of LR's Marine Exhaust Emissions Research Programme. If a scrubber removes 70% of the particulate matter, then approximately 500kg of sludge may be expected for every 100 tonnes (t) of residual fuel consumed by a diesel engine. This is dependent on removal rate at the scrubber and the efficiency of the washwater treatment, both in removing PM and not including excess water. Wet SOx scrubber manufacturers typically recommend a sludge tank of around 0.5m³/MW of scrubbed engine power.

Residue removed from SOx scrubber washwater must be stored on board, landed ashore and disposed of appropriately; it is not permitted to incinerate it or discharge it to sea.

5.2 Dry scrubbing

Dry scrubbers use a dry reactant – calcium hydroxideⁱ – to remove SOx from exhaust gas. The calcium hydroxide reacts with SOx and oxygen or water to give calcium sulphate and water. Dry scrubbing is widely used in land-based industry. A difference between marine and land-based systems is that marine systems use granulated calcium hydroxide rather than a powdered form. Injecting powdered calcium hydroxide into baghouse filters offers responsive control to changes in SOx levels but is very bulky. In contrast, granulated calcium hydroxide systems have no controllability, operating with a pre-set cleaning efficiency which is typically set at 85% maximum continuous rating (MCR) at the highest sulphur content of the fuel being used. The only marine dry scrubber supplier has sadly gone out of business but they demonstrated an efficiency of 99% SOx removal with 4.5%mm sulphur fuel.

There is no risk of flooding or reverse flow with dry systems; the reaction is exothermic and installation is upstream of SCR and waste heat recovery units. The SCR operates with clean gas and waste heat recovery systems can use cheaper, less corrosion resistant materials. Parasitic load is insignificant and retrofitting is possible.

ⁱ Also known as slaked lime

Size and weight are key considerations for dry scrubbers. A 20MW dry unit weighs 211 tonnes, compared to an equivalent wet scrubber, which weighs around 10 tonnes. Dry scrubbers also have a bigger footprint compared to wet scrubbers. Large storage tanks are required for the granulated calcium hydroxide, and equal amounts of spent calcium sulphate granulate are produced. Couple Systems advised that 16Kg/MWh of granulate was produced when operating with high sulphur residual fuel. An 18MW engine would consume 288Kg/hour of granulate with a density of 800Kg/m³, equating to 8.6m³ per day for both new and spent granulate. The cost-effectiveness of a dry scrubber relates strongly to how much time a ship spends in an ECA. Currently there is very limited availability of dry scrubbers compared to the proliferation of wet scrubber designs and suppliers.

Figure 12 shows a typical dry SO_x scrubber. It has the following main components:

A scrubber unit, in this case known as an ‘absorber’, which brings the exhaust gas from one or more combustion units into contact with calcium hydroxide granules. Unlike the majority of wet scrubbers, the exhaust gas entry is perpendicular to the vertical downward flow of the scrubbing medium. No heat is removed from the exhaust gas during scrubbing (in fact the reaction is exothermic and releases heat) so dry scrubbers can be positioned before waste heat recovery and SCR equipment.

A granule supply silo and screw conveyor for discharge, positioned at the top and bottom of the absorber respectively. A pneumatic conveyor system enables granules to be transported from and returned to onboard storage facilities. The use of flexible pipework facilitates the storage of granules at various locations on board.

A scrubber control and emission monitoring system. Removal of the used granules and any exhaust-related particulate matter is an automated process and may either be continuous or intermittent to ensure the correct flow of fresh granules under gravity down through the absorber.

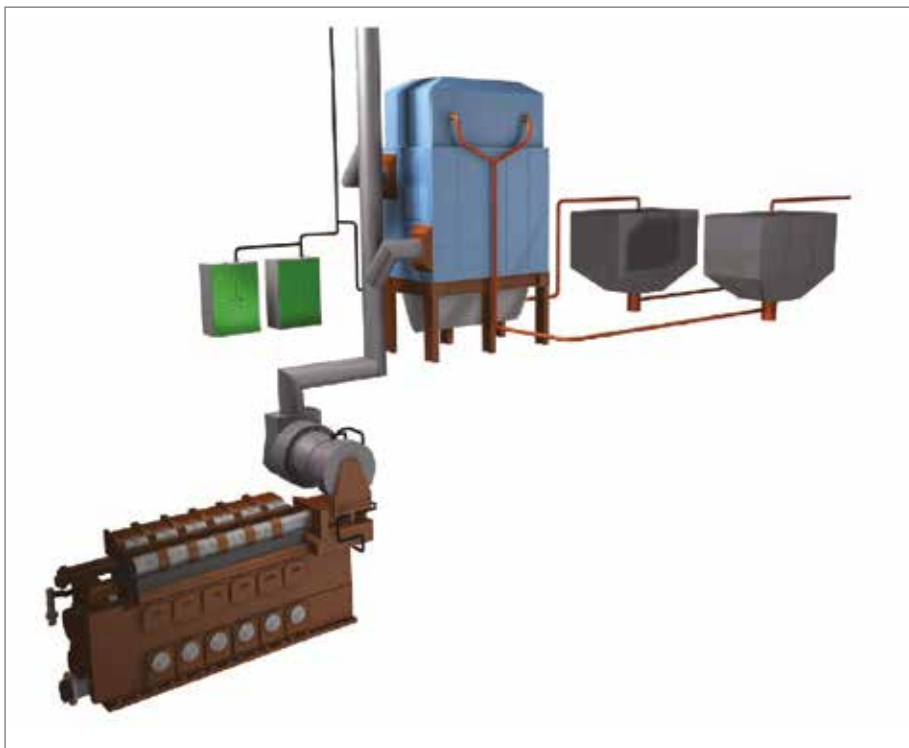


Figure 12: Couple Systems dry SO_x scrubber for marine use (image courtesy of Couple Systems)

Dry scrubbers typically operate at exhaust temperatures between 240°C and 450°C. Calcium hydroxide granules are between two and eight millimetres in diameter (see Figure 13) with a very high surface area to maximise contact with the exhaust gas. Within the absorber, the calcium hydroxide granules (Ca(OH)₂) react with sulphur oxides to form gypsum (CaSO₄•2H₂O). Details of the chemical reactions can be found in Appendix D1.3. Trials on a 3.6MW engine using up to 1.80% sulphur content fuel are reported to have shown a 99% and 80% reduction in SO₂ and particulate matter emissions respectively. It should be noted that the PM reduction was tested according to DIN51402 whereby particulate is captured on a filter of silica fibre material.

The filter is then assessed either visually or by photometer, which compares the intensity of reflected light with that from the original light source, enabling a smoke number to be derived by a standard conversion procedure.



Figure 13: Calcium hydroxide granules (image courtesy of Couple Systems)

To reduce SOx emissions to those equivalent to fuel with a 0.10% sulphur content, a typical marine engine using residual fuel with a 2.70% sulphur content would consume calcium hydroxide granules at a rate of 40 kg/MWh and, based on a density of 800kg/m³, the volume of granulate required would be approximately 0.05 m³/MWh (i.e., a 20MW engine would require approximately 19 tonnes of granulate per day with a volume of 24m³). Electrical power consumption is lower than for wet systems at approximately 0.15 – 0.20% of the power of the engine being scrubbed.

Unlike wet scrubbers, dry scrubbers have no requirement for washwater treatment systems and their associated pipework, tankage, instrumentation and controls. This simplifies installation and operation, and makes dry scrubbers ideally suited to areas where there is increased sensitivity regarding discharges to sea. However, as with closed loop operation of a wet system, there is a need for storage and handling of consumables. Used granules must also be stored before disposal ashore. The scrubber manufacturer may be able to co-ordinate the logistics of supplying, removing and disposing of granulate.

Calcium hydroxide is classed as harmful to eyes and skin and the inhalation of dust should be avoided. Although calcium hydroxide has hazardous properties, it is considerably less hazardous than 50% aqueous sodium hydroxide solutions typically used in wet scrubbing systems. It should be kept dry and away from contact with acids. It is also important that used granules remain dry, and fully contained storage and handling systems are therefore an advantage. If a ship's own storage is used, advice should be taken as to appropriate alkali-resistant coatings.

While dry scrubbing does not reduce NOx emissions by itself, it is ideally suited for use in conjunction with selective catalytic reduction (SCR) systems (see section 6.1, page 32) which require hot exhaust gas to attain an operating temperature of above 300°C.

5.3 Non-thermal plasma

Unlike wet and dry scrubbing, which achieve de-sulphurisation through a series of conventional chemical reactions, non-thermal plasma (NTP) works by breaking the molecular bond between sulphur and oxygen, achieved through molecular excitation. NTP has the potential to treat multiple pollutants and is not restricted to SOx abatement. It can be applied in a variety of ways including systems reliant on high voltage electrical apparatus or ionising beam lasers. NTP systems may incorporate wet or dry elements to convert and condition the free elements created by the dissociation of pollutants. These may include wet scrubbing, baghouse filters and electro-static precipitators.

There has been limited interest in applying NTP to shipping. Unlike wet and dry scrubbing, which are fundamentally simple, NTP needs to achieve the molecular excitation, which can involve expensive apparatus. The proprietary nature of such apparatus makes in-service support difficult if the supplier ends product support. If used with wet or dry techniques for conditioning the free elements created by breaking the molecular bonds of pollutants, the energy demand, complexity and space demands may be similar to that of a wet or dry scrubber.

5.4. Comparing SOx scrubber technologies

Operation in fresh water

Alkalinity or the buffering capacity of seawater is a key parameter for the effective operation of wet open loop SOx scrubbers (including hybrid SOx scrubbers when operating in open loop mode). When exhaust gas is mixed with seawater inside the scrubber, sulphur oxides are dissolved, increasing the acidity and lowering the pH of the washwater. Alkalinity is a measure of the ability to resist changes in pH; in seawater, alkalinity is naturally provided by bicarbonates, carbonates, borates and anions of other 'salts' in more minor quantities. It is not the sodium chloride content of seawater that facilitates scrubbing. Hence, salinity (a measure of all salts present) only indirectly indicates that sufficient alkalinity is present. Some natural fresh water can be highly alkaline and suitable for scrubbing, although efficiency may be reduced. The water in the Great Lakes and areas within the Baltic Sea does not have sufficient alkalinity to support the operation of wet, open loop SOx scrubbers. Closed loop wet SOx scrubbers (including hybrid SOx scrubbers operating in closed loop mode) and dry SOx do not use sea water as their scrubbing medium and are therefore unaffected by the properties of the sea water in which they operate.

Operation without discharge to sea

The high washwater discharge rate ($\approx 45\text{m}^3/\text{MWh}$) of open loop systems (and hybrid systems in open loop mode) means that when operating they have to discharge washwater into the sea continuously. The much lower discharge rate ($0.1\text{m}^3/\text{MWh}$) of closed loop systems (and hybrid systems operating in closed loop mode) means that it is possible to retain washwater to be discharged on board for a limited period of time (i.e., operate in zero discharge mode). Dry SOx scrubbers have no discharges to sea. Given the uncertainty surrounding the acceptability of discharging washwater to sea, this is a critical consideration.

Weight

The filled dry SOx scrubber unit for a 20 MW engine is heavier (≈ 200 tonnes) than comparable exhaust capacity wet scrubbers (30-55 tonnes). However, the overall weight of wet and dry systems may be similar once the washwater systems, such as the processing tank, holding tank and chemical storage, are taken into account. As most of the weight of the dry scrubber system is installed relatively high up in the ship, the impact of the system on the vertical centre of gravity (VCG) of the ship is likely to be greater than for wet SOx scrubbers, where many of the components may be lower down. When installing a SOx scrubber on an existing ship, the resulting change in lightship weight and/or VCG may necessitate the revision of the ship's stability manuals.

Power consumption

The washwater flow rate in an open loop SOx scrubber is higher ($\approx 45\text{m}^3/\text{MWh}$) than a closed loop SOx scrubber ($\approx 20\text{m}^3/\text{MWh}$) because the buffering capacity of seawater is less than the buffering capacity of fresh water dosed with sodium hydroxide. Consequently, open loop SOx scrubbers require larger pumps and have higher power requirements. The power requirement of dry SOx scrubber systems is mainly associated with a screw conveyor that moves the calcium hydroxide granules through the scrubber unit (known as an absorber). The power required is therefore significantly less than for wet SOx scrubbers.

The energy consumption associated with SOx scrubbers does not adversely impact a ship's attained Energy Efficiency Design Index (EEDI) value as, for almost all conventional cargo ships, the auxiliary power consumption will be calculated as a fixed proportion of the installed main engine power, and is unrelated to the actual auxiliary power consumption. However, if the installation of the system reduces cargo carrying capacity then the EEDI will be affected.

The energy consumption will affect any operational energy efficiency key performance indicators (KPIs) that include actual energy consumption of auxiliary systems, such as the Energy Efficiency Operational Indicator (EEOI).

Compatibility with waste heat recovery units and SCR systems

All wet SOx scrubbers significantly cool the exhaust gas. Therefore, they are not suitable for installation before a waste heat recovery unit. For the same reason, it would not be possible to install a wet SOx scrubber before an SCR system unless a reheater was fitted after the wet scrubber to raise the exhaust gas temperature back up to around 300°C – the temperature required for SCR systems to work effectively. Dry SOx scrubbers do not cool the exhaust gas so they are suitable for installation before both waste heat recovery units and SCR systems.

Particulate matter (PM) removal

SOx scrubbers can be an effective means of reducing PM (see section A1.5 in Appendix A1), both indirectly by removal of SOx and by direct mechanical cleaning when particles come into direct contact with either washwater or chemical granules. SOx scrubber manufacturers typically claim between 70% and 90% removal rates.

The sulphates, which make a significant contribution to PM, are formed post-combustion in the exhaust plume. Oxidation of SO₂, followed by further oxidation and condensation processes, contributes to the growth of complex particles after the cylinder [6] and the majority of sulphates form in reactions after release from the stack [7].

The IMO Exhaust Gas Cleaning System Guidelines require monitoring of the SO₂ to CO₂ ratio in the exhaust gas but do not require PM monitoring as this is not necessary to demonstrate equivalence with fuel sulphur content limit. The in-service measurement of particulate matter can be challenging; methods involving weighing deposits on filters are difficult to measure continuously on board.

Ship operators should note that the 'wet' method for collecting PM on filters contained in ISO 8178^j includes sulphates and any incompletely burned hydrocarbons, whereas the 'hot/dry' technique contained in ISO 9096^k does not. Significantly different results will therefore be obtained from the same engine operating under the same conditions consuming the same fuel, with ISO 8178 tests reporting a greater mass of particulate. Scrubber manufacturers have used differing methodologies during their trials, which make it difficult to compare like-for-like the PM reduction performance of various scrubbers.

Visible smoke

Smoke is a collection of airborne solid and liquid particulates and gases, together with entrained air. Visible smoke from combustion devices on ships is largely comprised of black carbon, heavy metals from the ash content, and water vapour. Some countries impose 'smoke' control measures on shipping in their coastal waters. For example, within three miles of the Alaska coastline, visible emissions, excluding condensed water vapour, must not reduce visibility through the exhaust of a marine vessel by more than 20 percent. Short defined periods of increased emissions are, however, permitted in port, at anchor or when manoeuvring [8]. A visible plume may also be undesirable for commercial reasons.

All SOx scrubbers reduce the black carbon and ash from the exhaust but wet SOx scrubbers may increase the water vapour content in the exhaust stream, resulting in a highly visible white plume unless the exhaust is kept well above the dew point (see Figure 14). This plume is not smoke but there is a risk that local authorities may assume it to be smoke. Wet SOx scrubber manufacturers can provide de-plume devices but operators should be aware that these may not be part of the standard system and may be offered as optional extras.

Attenuation of engine noise

SOx scrubbers are commonly installed in the place of the silencer when converting existing ships. Equipment manufacturers have differing views on the attenuation that their equipment might provide. For wet SOx scrubbers this attenuation may change depending on whether or not the SOx scrubber is in operation, although some designs attenuate noise effectively in both conditions. For some operators, particularly cruise ship and ropax operators, the option of combining a SOx scrubber with the engine silencer, and incorporating a scrubber within the footprint allocated to a silencer in the uptake area, is critical.



Figure 14: a vapour plume produced by an operating wet scrubber

^j The international standard for reciprocating internal combustion engines – exhaust emission measurement

^k The international standard for stationary source emissions – manual determination of mass concentration of particulate matter

	Wet scrubber, open loop	Wet scrubber, closed loop	Wet scrubber, hybrid	Dry scrubber
Main system components	<ul style="list-style-type: none"> – Scrubber – Washwater piping – Washwater pumps – Washwater treatment equipment – Sludge handling equipment 	<ul style="list-style-type: none"> – Scrubber – Washwater piping – Washwater pumps – Washwater processing tank – Washwater holding tank – Sodium hydroxide storage tank – Washwater treatment equipment – Sludge handling equipment 	<ul style="list-style-type: none"> – Scrubber – Washwater piping – Washwater pumps – Washwater processing tank – Washwater holding tank – Sodium hydroxide storage tank – Washwater treatment equipment – Sludge handling equipment 	<ul style="list-style-type: none"> – Absorber – Fresh granulate hopper – Used granulate hopper – Granulate transport system – Additional granulate – storage (new and used granules)
Operation in fresh water	✗	✓	✓ (only when operating in closed loop mode)	✓
Operation without discharge to sea	✗	For a limited time depending on the size of the washwater holding tank	For a limited time depending on the size of the washwater holding tank	✓
Weight Based on typical values for a 20MW SO _x scrubber	30-55t (Excluding washwater system and treatment equipment)	30-55t (Excluding washwater system, treatment equipment, washwater processing tank and washwater holding tank)	30-55t (Excluding washwater system, treatment equipment, washwater processing tank and washwater)	≈200t (Including granules stored adjacent to the absorber but excluding additional granulate storage)
Power consumption (% of max. scrubbed engine power)	1-2%	0.5-1%	0.5-2% (depending on whether it is operating in open or closed loop mode)	0.15-0.20%
Scrubbing chemical consumable	✗	Sodium hydroxide solution (≈6 l/MWh·%S)	Sodium hydroxide solution (only when operating in closed loop mode) (≈6 l/MWh·%S)	Calcium hydroxide granules (≈10 kg/MWh·%S)
Compatibility with waste heat recovery system	Yes, provided the scrubber is installed after the waste heat recovery system	Yes, provided the scrubber is installed after the waste heat recovery system	Yes, provided the scrubber is installed after the waste heat recovery system	Yes. Can be placed before or after the waste heat recovery system
Compatibility with SCR system	No, unless a reheater is fitted after the wet scrubber to raise the exhaust gas temperature	No, unless a reheater is fitted after the wet scrubber to raise the exhaust gas temperature	No, unless a reheater is fitted after the wet scrubber to raise the exhaust gas temperature	✓
Compatibility with EGR system	✓	✓	✓	✓
Particulate matter removal	✓	✓	✓	✓

Table 2: Comparison of SO_x scrubber technologies

6. Secondary compliance techniques for NO_x

The mechanisms which form NO_x and the primary techniques to reduce NO_x have been covered in section 4. Some of these primary techniques, such as using alternative fuels, have significant additional engineering requirements for safe storage, handling and use of fuels, while others can reduce engine efficiency. Secondary techniques are therefore potentially very attractive in avoiding engine efficiency penalties and the complexities of designing and installing an alternative fuels package.

6.1 Selective catalytic reduction

Selective catalytic reduction (SCR) is a relatively mature technology, widely used for NO_x control in land-based industry and land-based transportation. SCR can reduce NO_x emissions by 80-90% to below 2g/kWh. SCR systems are currently fitted to four-stroke medium-speed engines on a number of ships in service, which are able to gain commercial advantage¹ from reduced NO_x emissions.

The SCR system converts nitrogen oxides into nitrogen and water, by means of a reducing agent injected into the engine exhaust stream before a catalyst. Urea is the reductant typically used for marine applications. It decomposes to form ammonia in a mixing duct before adsorption onto the catalyst that facilitates the reduction process. Details of the chemical reactions can be found in Appendix D2.1.

An SCR system comprises the following main components:

- a pumping unit for transfer of urea solution from storage
- a urea dosing unit
- a mixing duct with urea injection point
- a reactor housing containing replaceable catalyst blocks
- a control system
- a soot/ash cleaning system.

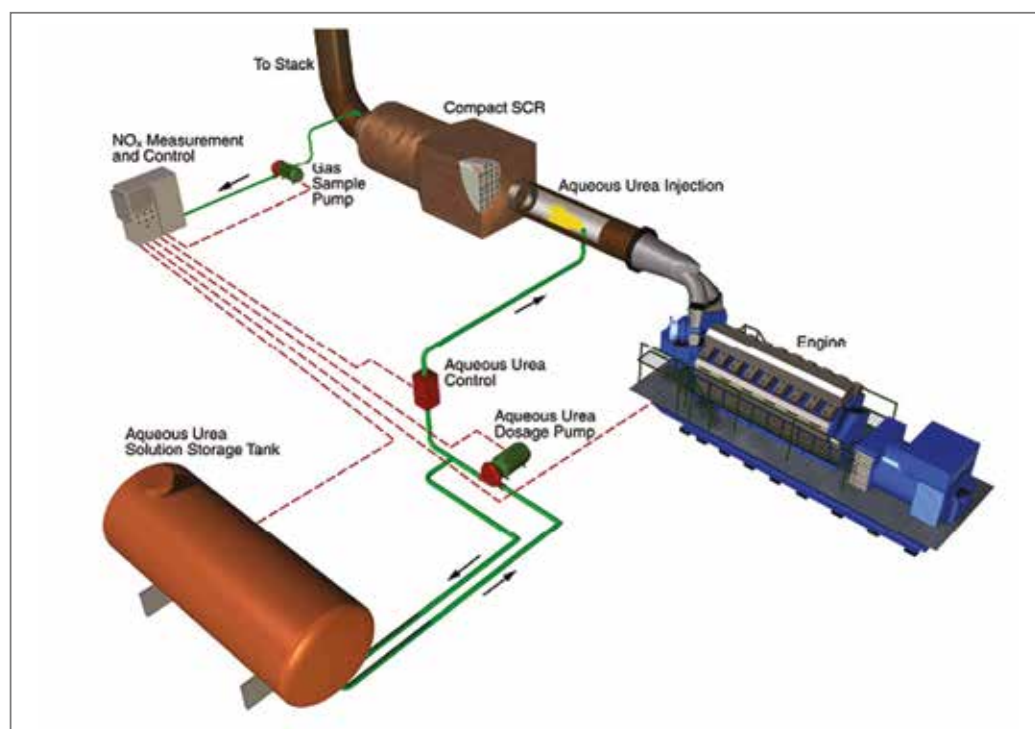


Figure 15: A marine SCR arrangement – four-stroke medium-speed engine (image courtesy of Wärtsilä)

¹ These advantages include: differentiated port or fairway dues in Sweden; the NO_x tax and NO_x fund in Norwegian territorial waters; voluntary incentive schemes run by ports (for example, the Port of Long Beach and Port of Singapore); and voluntary ship rating schemes (for example, the Environmental Ship Index and the Green Award)

SCR systems also offer ship-operators a potential fuel saving benefit when operating outside an ECA-NOx, as it is possible to use the SCR to meet Tier II NOx limits. This would allow the engine settings to be adjusted for optimum efficiency (Tier II engines are typically 4 – 4.5% less efficient than Tier I engines), resulting in reduced fuel consumption and lower CO₂ emissions. For this the SCR control system would require control set points for operation inside and outside of ECA-NOx. It may be possible to apply this CO₂ saving when calculating a ship's EEDI.

7.1.1 SCR systems fitted to four-stroke medium speed engines

The exhaust temperature dictates the position of the reactor containing the catalyst. To date, virtually all marine SCR systems have been installed on four-stroke engines, as there is a sufficiently high exhaust temperature to allow efficient catalyst operation after the turbocharger. In this arrangement the reactor is fitted before any waste heat recovery system. When the SCR is not required, reactors may be run dry without the need for a bypass.

Effective catalytic reduction typically requires an exhaust temperature of over 300oC, but below 500oC to prevent thermal damage to the catalyst. It is possible to run at lower temperatures but the sulphur content of the fuel needs to be reduced to prevent deposits, which can plug the catalyst. The warming up period after engine start is typically 30 – 90 minutes (unless pre-warming equipment is fitted). This assumes that the engine loading is high enough to heat the SCR to its operating temperature. Extended operation at low loads will result in longer start up times and may result in the SCR not reaching its operating temperature. It is not yet clear how authorities will view ships that are non-compliant during the warming up period.

The reactor and mixing duct are installed as integral parts of the engine exhaust system; it is crucial that urea mixes completely with the exhaust gas before entering the SCR reactor.

The catalyst has a finite life and part of the maintenance regime for the SCR should be periodic analysis of catalyst activity. Empirical evidence from oil fired power plant SCR indicate that the two principal elements causing accelerated catalyst deactivation are potassium and sodium.

The mechanism for deposit formation involves an undesirable parallel reaction (to the NOx conversion) at the catalyst whereby sulphur dioxide in the exhaust is oxidised to sulphur trioxide (SO₃), which can then react with ammonia to form ammonium sulphate and bisulphate. Deposits reduce the effective area and shorten the lifespan of the catalyst, with fuel-related hydrocarbon and particulate matter adding to the fouling. As conditions deteriorate, NOx reduction is impaired and more un-reacted ammonia will slip past the catalyst. Figure 16 shows clean, partially fouled, and heavily fouled catalyst elements.

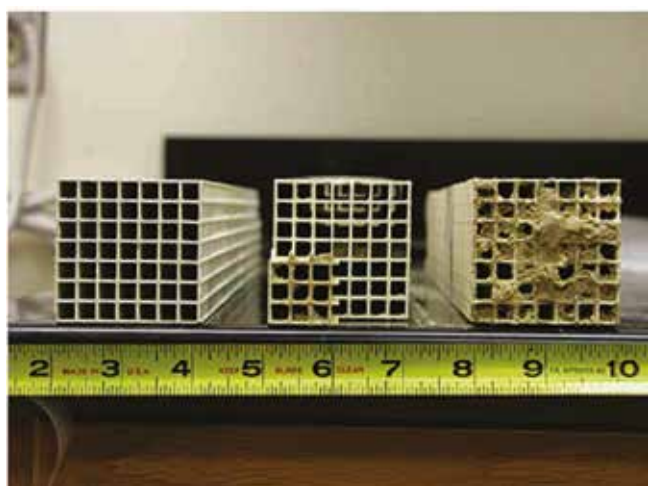


Figure 16: Clean, partially fouled and heavily fouled catalyst elements

Manufacturers endeavour to minimise the oxidation of sulphur dioxide with their reduction catalyst materials and by specifying that only fuels with a sulphur content of less than 1.00% should be used. This not only prevents the formation of ammonium sulphates, but also sulphuric acid. Systems capable of operating with higher sulphur content are possible but higher exhaust temperatures are required. As an alternative to low-sulphur fuel, a SOx scrubber fitted before the reactor may be used. When installed after a wet SOx scrubber the exhaust gas would require reheating from around 50oC to at least 300oC. No reheat would be required for a dry scrubber.

An additional undesirable parallel reaction will take place if calcium is present, resulting in calcium sulphate deposits.

An oxidation catalyst may be included in the reactor after the reduction catalyst. Its purpose is to oxidise carbon monoxide (CO) and unburned hydrocarbons (HC) to water and carbon dioxide or act as a 'slip catalyst', oxidising un-reacted ammonia to nitrogen and water. An oxidation catalyst may also be fitted before the reactor to convert NO to NO₂, increasing the rate of NOx reduction and allowing a reduced reactor size and lower operating temperature.

Sulphur in the fuel is a concern, however, and must be limited for systems using oxidation catalysts, as oxidised SO₂ compounds form, deactivating and damaging the catalyst.

6.1.2 SCR systems fitted to two-stroke low-speed engines

To date, a very small number of two-stroke low-speed engines have been equipped with SCR systems [9,10]. For low-speed engines, the reactor is typically placed upstream of the turbocharger to provide the catalyst with a sufficiently high exhaust temperature. Figure 17 shows a two-stroke engine fitted with an SCR system. This type of installation is more challenging than for four-stroke engines because of space constraints and a need to bypass the reactor during various engine operating modes. The reactor in this configuration is relatively smaller than a downstream unit because the exhaust gas density is higher.



Figure 17: SCR arrangement
– two-stroke low speed engine
(image courtesy of MAN Diesel & Turbo)

The catalyst has a significant heat capacity which means that for two-stroke engines the reactor must be bypassed at start-up and when rapidly accelerating to ensure sufficient energy reaches the turbocharger. Bypass may also be required when decelerating to prevent excess heat energy at the turbocharger. Despite the position of the reactor, the exhaust temperature may also be too low for efficient catalyst operation and for preventing ammonium sulphate deposits when the engine is operating at low loads on residual fuel.

As an alternative the reactor can be placed after the turbocharger on a two-stroke low speed engine if a burner is fitted to increase the exhaust temperature to the required level [11].

6.1.3 Urea and catalyst

Typically, a 40% urea solution is injected as a fine spray into the mixing duct before the catalyst by means of compressed air. Effective dispersion of the urea in the exhaust stream is critical to efficient SCR performance; this may be achieved by suitable injection nozzles, atomising air, high-pressure injection (typically 25 Bar), duct design, or a combination of all four. The urea converts to ammonia before entering the reactor.

Regular cleaning of filters in the urea handling system and the injection nozzles is an important part of the system maintenance requirements. Urea is classed as non-hazardous and can be stored in existing tanks if epoxy-coated. It is used because of the difficulty with the storage and direct handling of ammonia, which is both toxic and corrosive. Using poor

quality urea does degrade the performance of the SCR. A standard for Maritime Grade Urea Solution based on work by the European Chemical Industry Council (CEFIC) is available from the International Association for Catalytic Control of Ship Emissions to Air (www.IACCSEA.com).

The rate of urea injection must be sufficient to reduce NOx emissions to the required level but not so great that un-reacted ammonia exits the ship. 15 litres/MWh is typical for a 40% solution. Control is based on the load and speed of the engine with active feedback provided on some systems by NOx and ammonia emissions monitoring. At engine start-up urea injection is initiated once the catalyst reaches operating temperature, which is key for effective NOx reduction performance, deposit prevention and to avoid ammonia slip.

Catalysts have considerable heat capacity so the time taken to reach the injection trigger temperature is dependent on a number of factors including the minimum catalyst operating temperature recommended for the fuel type, the period of cool down since the engine was last operated, the size of the catalyst and the engine load pattern at start-up. Injection can begin up to 30 minutes after a fully cold start, whereas it may begin within 10–15 minutes if the catalyst is still warm from running in the previous 6–10 hours.

There will be similar considerations when entering an ECA-NOx if the reactor has been bypassed, as the catalyst will need to be brought online and reach the required temperature before injection can commence. While these figures are indicative for both pre and post turbocharger catalysts, those fitted before turbochargers on two-stroke engines are relatively more compact and therefore should heat up more quickly.

In marine SCR systems the catalyst is typically made up of porous titanium dioxide (TiO₂) ceramic material in layers of replaceable honeycomb blocks. The high surface area construction acts as a carrier for the catalyst's active compounds such as vanadium pentoxide (V₂O₅) and tungsten trioxide (WO₃). The reactor and blocks can be orientated so the exhaust gas passes either vertically or horizontally, with the former favoured for higher particulate/dust applications. Regular cleaning by compressed air soot blowers or sonic horn is used to reduce fouling of the gas passages and catalyst surfaces. It should be noted that urea injection and soot blowing will likely require the installation of additional air compressor capacity sized for all SCR systems on board.

SCR catalyst material is susceptible to fouling, plugging and poisoning:

Fouling is a general deposition of material and is obvious when carrying out a visual inspection. The fouling masks the catalyst, preventing contact between the catalyst surface and the reactants. Fouling can be addressed by soot blowing and should not affect the life of the catalyst.

Plugging does not refer to plugging of the catalyst honeycomb (see figure 17) but rather the plugging of the catalyst pores. The catalyst is a very porous material, and to work effectively these pores must be open as they give the catalyst a very large contact area with the reactants. Plugging may not be seen during a visual inspection, as it can occur without there being a heavy deposition on the catalyst.

Poisoning refers to chemical attack of the active element of the catalyst. The activity of the catalyst will decay with age but it can be deactivated by attack from phosphorous or alkaline/heavy metals.

Catalyst lifespan depends on a number of factors that result in physical plugging of the catalyst pores, including combustion conditions, engine operating (load) regime, exhaust temperature and fuel sulphur level. In addition 'poisoning' can occur when fuel- and lubricating oil-related compounds in the exhaust are adsorbed onto the catalyst resulting in progressive chemical deactivation. These compounds are formed from alkali metals (sodium, potassium), alkaline earth metals (calcium, magnesium), phosphorus or zinc. Manufacturers may have strict limits on concentrations in the exhaust gas and as such it is important to follow recommendations regarding fuel and lubricating oils. Excessive lubricating oil consumption should be avoided, and certain biofuels, for example, could have a high level of alkali metals/alkaline earth metals.

Typical lifespan figures for catalyst blocks are between two and five years with replacement undertaken by the SCR vendors or authorised contractors. In California spent catalyst elements require specialist disposal because of the vanadium content. Generally, however, the material is not considered to be hazardous; metals are recycled and waste is removed to landfill.

The ongoing monitoring of catalyst condition is important, not only to ensure NOx reduction is maintained but also to make sure that the injected urea is fully utilised to avoid ammonia slip. Emissions monitoring can also be utilised; increased urea feed to obtain the required NOx reduction indicates a loss of catalyst efficiency, as does an increase in un-reacted ammonia at the catalyst outlet.

7. Secondary compliance techniques for NOx and SOx – common challenges

A number of common challenges apply to both secondary compliance techniques for SOx and NOx. We cover these here.

7.1 Flexibility

One of the benefits of exhaust gas treatment systems (EGTS) is that they offer operational flexibility. A SOx scrubber allows an operator to choose between meeting emission limits by using low-sulphur fuels or by using the SOx scrubber to clean the SOx from the exhaust gas. NOx treatment systems will offer ships constructed after 1 January, 2016, the flexibility to operate inside ECA-NOx (see section 2.3). They allow the engine to run at peak thermal efficiency because the resulting high NOx emissions are reduced after combustion.

7.2 The risk of non-compliance

If you are using an EGTS to comply with emissions regulations, you should consider the likelihood and consequences of it failing. The likelihood of failure will depend on the reliability of the system components and the redundancy included in the system's design. Building in redundancy reduces the likelihood that the system as a whole will fail.

For example, designing a wet SOx scrubber with three pumps each capable of meeting 50% of the washwater pump demand or with two pumps each capable of meeting 100% of the washwater pump demand would allow the scrubber to continue to operate in the event of a single pump failure. Other areas where redundancy can be built in include the exhaust gas and washwater monitoring systems. It is worth noting that the integration of multiple exhaust streams into a single scrubber does exacerbate the consequences of the system failing.

The consequences of an EGTS failure will depend on whether your ship can use an alternative means to comply with the requirements. For example, in the event of a main engine SOx scrubber failing, you may be able to bypass the scrubber and use compliant fuel. You will need to make sure that enough compliant fuel is stored on board. If no compliant fuel is available, the ship will no longer be able to comply.

How flag and port states will respond in the event that a ship cannot comply is not yet apparent, but one possible outcome would be to require the ship to sail to the nearest port until either the EGTS has been fixed or an alternative method of compliance is available. The commercial consequences of the resulting delay will depend on the ship's trading pattern. Understanding the likelihood and consequences of a failure of an EGTS will allow you to make informed decisions about the amount of redundancy to be designed into the system.

7.3 Backpressure

Engine manufacturers include a permitted range of exhaust backpressures within the technical specifications of their engines – operating outside this range may lead to accelerated wear, greatly reduced maintenance intervals, reduced power and increased fuel consumption. In addition, an engine's NOx Technical File may also specify a range of permissible backpressures – operating outside this range will invalidate the engine's NOx approval.

EGTS intrinsically increase backpressure and system designers need to understand the impact of this on the engine. If the EGTS will increase backpressure to a level outside allowable operating limits, it may be reduced by adding an induced draft fan (ID fan) into the exhaust duct (see Figure 18). Although fitting an ID fan to control backpressure is technically straightforward this clearly increases the electrical load of the EGTS and increases the footprint of the EGTS in the uptake space. For some ships these two factors will make use of an ID fan unattractive.

The main concern with excessive backpressure is that it will result in reduced engine power output. If this happens, it will be obvious and can be rectified during the EGTS installation and commissioning period. Perhaps a more serious problem is a slight increase in backpressure above the allowable limits, as there is unlikely to be an obvious change in engine performance and the problem may remain hidden.



Figure 18: ID fans in exhaust ducts (image courtesy of Hamworthy-Krystallon)

Build up of deposits within the EGTS components (for example soot clogging of demisters or deposits on SCR catalysts) will increase backpressure while the ship is in operation. Monitoring the pressure differential across the EGTS will indicate if cleaning is required. Some of these deposits can present a significant health and safety risk to people entering the EGTS to carry out maintenance and cleaning activities.

7.4 EGTS bypass

A bypass provides an alternative path for the exhaust gas so that it avoids the EGTS. When the bypass is 'closed' exhaust gas will pass through the EGTS and when it is 'open' the exhaust gas will exit the ship without passing through the EGTS. Some wet SO_x scrubbers are designed to 'run dry' whereas others may be damaged if hot exhaust gas is passed through them while they are not operating. For systems not designed to run dry, the bypass damper can be interlocked with the EGTS controls to provide a failsafe protection.

Opening the bypass when the EGTS is not operating will prevent a build-up of soot and unburned hydrocarbons within the system. When the bypass is open it might also be possible to undertake maintenance of the EGTS while the associated engine (or engines) is running (although care should be taken as the bypass damper is not a secure way of isolating the EGTS chamber).

The risk of using a bypass is that leakage past the bypass valve may cause the ship's emissions to exceed the limits. Because of the corrosive properties of SO_x-laden exhaust gas, and the particular conditions associated with bypass arrangements, it is critical to ensure that materials are reliable and durable. There is also a risk in service that unless bypass valves are exercised regularly they will stick and not operate when needed.

LR does not require EGTS bypass valves to be fitted unless the EGTS is not suitable for operating in a hot and dry condition.

7.5 Exhaust gas velocity

The introduction of EGTS may slow the exhaust gas and any cooling will slow it down further. Consequently, to ensure the exhaust gas clears the ship, the exhaust duct outlet may have to be redesigned to increase the velocity of the gas as it exits the funnel. While relevant to all ships, this is particularly important for cruise ships and ferries. Care must be taken to ensure that the resulting increase in backpressure is acceptable (see section 5.1.4).

7.6 Integration of multiple combustion devices

It is possible to combine the exhausts from a number of different combustion devices into a single EGTS. This may be necessary due to space restrictions, or simply to reduce the cost of the installation. Combining exhausts is uncommon within the marine industry where typically each engine has its own independent intake and exhaust. Concerns arising from combining exhausts include:

- backflow of exhaust gas into the exhaust duct of combustion devices that are not operating
- increased backpressure when two or more combustion devices are combined that have different exhaust gas flow characteristics; and
- designing the EGTS to operate effectively over a wide range of exhaust gas flow rates.

Dampers might be required for each exhaust to preclude the back flow of exhaust gas into the exhaust of combustion devices that are not operating. Monitoring is required to confirm that the backpressure on each device remains within allowable limits.

If you plan to integrate diesel engine exhaust arrangements with boiler exhaust arrangements, controlling backpressure is especially critical. This is due to the very different sensitivities of engines and boilers to exhaust backpressure.

7.7 Maintenance, crew training and workload

It is important to understand the impact of EGTS maintenance on system availability. For instance, annual inspection and cleaning of an SCR chamber will result in the SCR system not being available for a period of time, which may impact the availability of the ship to operate in an ECA-NOx. You will either need to schedule cleaning while the ship is operating in locations where the SCR system is not required, or you might need to take the ship out of service.

Hazardous chemicals are used in a number of EGTS and adequate controls should be put in place to protect ships' staff. There is also a possibility of further hazardous chemicals and compounds (such as ammonium bi-sulphate in SCR systems) being generated. These will require robust procedures and crew training, as well as adequate signage and personal protective equipment (PPE).

Crew training should cover the normal operation of the EGTS, including bunkering of any chemicals (consumables), calibration of sensors and routine maintenance, as well as the procedures to be followed in case of system failure and deviation from normal operation. You should be aware that not all crew members will be familiar with basic chemical handling requirements and that all crew members should be provided with training specific to the chemicals, substances and effluents associated with the EGTS to be installed on board.

The additional workload associated with system operation and maintenance should be assessed. If it is significant, measures may need to be implemented to prevent crew fatigue.

7.8 EGTS approvals

As with most shipboard equipment installed to meet a regulatory requirement, EGTS require both statutory certification (issued by, or on behalf of, a flag administration) to show that the equipment meets the required performance criteria, and classification society approval (class approval) to show that the equipment does not present an unacceptable risk to the ship and the essential equipment required for the ship's continued operation.

There are a number of different statutory and class approvals associated with exhaust gas treatment systems and their ship-specific installation. In addition to these formal approvals, equipment manufacturers and operators may also wish to undertake independent verification of the performance of either a given equipment design (Type Approval) or the performance of a ship-specific installation (verification of performance).

7.8.1 Statutory approvals

Table 3 shows the statutory approval requirements for EGTS. These are described in more detail in Appendices B1 and B2. Scheme A statutory approval of SOx scrubbers is sometimes referred to as 'type approval'. Note: this is different to Lloyd's Register Type Approval, described in section 7.9.1, which involves independent verification of performance against standards specified by the equipment manufacturer.

For statutory approval, the equipment manufacturer should provide equipment with all of the approved documentation required to demonstrate compliance.

Statutory – flag state ship-specific approval (May be delivered by the ship's class society acting as a recognised organisation if authorised by the flag state)	
SOx scrubber	<p>IMO MEPC 184(59) – 2009 Guidelines for Exhaust Gas Cleaning Systems^m.</p> <p>Scheme A: Technical and Operating Manuals including SECP Initial shop or onboard test of scrubber Daily monitoring of SO₂/CO₂ Continuous monitoring of key operating parameters Continuous monitoring of washwater</p> <p>Scheme B: Technical & Operating Manuals including SECP No shop or onboard test of scrubber Continuous onboard monitoring of SO₂/CO₂ Daily monitoring of key operating parameters Continuous monitoring of washwater</p> <p>Deliverable: Approved documentation (including Scheme A Certificate if applicable) and post-installation Initial Survey</p>
NOx-reducing device	<p>Engine specific – certified entity is 'engine + device'</p> <p>Reviewed against NOx Technical Code 2008</p> <p>Technical File (including Onboard NOx Verification Procedure) Engine group / family certification Pre-certification Survey</p> <p>Deliverable: 'engine + device' certificate supported by approved documentation and post-installation Initial Survey</p>

Table 3: Statutory approval requirements for EGTS

7.8.2 LR Class approval

EGTS to be installed on board LR classed ships must comply with the applicable LR Rules. Specific Rules for EGTS are included within Part 5, Chapter 24 of the LR Rules for Ships and Volume 2, Part 12 of the LR Rules for Naval Ships. These rules are intended to ensure that EGTS are comprehensively and consistently approved, and provide stakeholders with information on Lloyd's Register's requirements.

^m These Guidelines apply to wet systems

The approval includes the EGTS design, installation on board and any chemical handling arrangements. The approval is a combination of a document review and onboard survey. It focuses on the system's impact on ship safety and covers ship-specific piping installations, electrical and control installations, and structural modifications.

LR Class approval is intended to protect the reliability of essential systems and to ensure that the EGTS is safe to operate. LR Class approval does not consider environmental performance or operational aspects. In particular, system redundancy and EGTS durability are outside of class approval; you will need to consider your own requirements for redundancy, durability and longevity. We provide consulting services to help define EGTS system requirements and provide additional assurance beyond class rules compliance.

7.9 Independent verification

7.9.1 Lloyd's Register Type Approval

LR's Type Approval service provides equipment manufacturers with independent confirmation of the performance of their products. It applies to series production of equipment whose critical components remain unchanged; typically, products are surveyed on a sample basis (as opposed to surveying every unit). The scope of the approval is specified by the equipment manufacturer and agreed by LR. For EGTS the scope of the Type Approval might include one or more of the following:

- compliance with statutory requirements (performance standard)
- class approval (to confirm that the unit complies with applicable LR class rules)
- compliance with specified maintainability and durability standards.

To apply for Type Approval the equipment manufacturer submits documents and plans and, depending on the scope of the approval, performance tests may also be required. As Type Approval does not follow a defined scope it is important to note what the equipment-specific Type Approval documents state; Type Approval is not a panacea. Note: aspects such as EGTS functionality, reliability and durability are not included within any of the statutory approvals or class approval of EGTS.

7.9.2 Verification of performance

LR can also provide independent verification of EGTS in-service performance. This service is delivered by exhaust emissions specialists experienced in exhaust gas measurement, analysis and legislative interpretation, who are familiar with working on board ships.

8. Integrating NOx and SOx reduction techniques

All of the NOx and SOx techniques discussed in this guidance can work together. If you plan to install both SOx and NOx reduction techniques on board, they will need to be integrated carefully to ensure they operate reliably and effectively. Figure 19 summaries how well different NOx and SOx techniques work together.

		NOx Tier II						
		SCR	EGR	Emulsification	Advanced fuel injection	Extreme Milton cycle + charge air humidification + water in fuel	Tier II dual fuel engine	Pure gas engine
SOx	Wet scrubber	With conditions	Proven	Approval needed	Possible future	Possible future	Not applicable	Not applicable
	Dry scrubber	Proven	Proven	Approval needed	Possible future	Possible future	Not applicable	Not applicable
	Onboard fuel sulphur removal	With conditions	With conditions	Approval needed	Possible future	Possible future	Not applicable	Not applicable
	Distillate/hybrid fuels (e.g. LDSO)	Proven	Proven	Approval needed	Possible future	Possible future	Not applicable	Not applicable

With conditions
Proven
Approval needed
Possible future
Not applicable

Figure 19: How well SOx and NOx emission control techniques work together

8.1 Using SCR with wet scrubbing

The most problematic scenario is operating SCR with a wet scrubber. Because an SCR system needs high operating temperatures, it needs to be installed before a wet scrubber. This means the SCR will have to be suitable for operating in exhaust gas which has high levels of SOx and other substances produced by burning high-sulphur fuels. Operating an SCR system satisfactorily depends on the manufacturer applying suitable catalyst materials, substrate and geometry and on the operator staying within the manufacturer's operating parameters.

There have been proposals to place SCRs after wet scrubbers and to reheat the exhaust gas to bring it to the required temperature for the SCR. While this is technically straightforward, it would consume a lot of energy, increasing fuel consumption and carbon emissions.

8.2 Using EGR with wet scrubbing

If burning RFO, a closed loop wet scrubber is needed to clean and cool the re-circulated gas. The cleaning action prevents the acidic and corrosive gas from causing accelerated engine wear. The cooling action prevents excessive cylinder temperatures.

Adding the wet scrubber increases the EGR system's complexity and energy demand, and also introduces the need for sodium hydroxide. However, an EGR scrubber is more compact than a similar capacity scrubber after the turbocharger as the exhaust gas density is higher. If EGR is applied to engines restricted to LDSO or other clean fuels, it may be possible to eliminate the scrubber, making the system less complex.

Unlike selective catalytic reduction, fuel sulphur content and low load operation are not constraining factors for EGR systems. However, although EGR scrubbers have been found to remove up to 80% of SOx in the recirculated gas, this does not mean they will achieve compliance with ECA-SOx requirements. A further scrubber could be needed in the exhaust system after the turbocharger when using high-sulphur fuel.

9. In-service considerations

SOx and NOx compliance technologies do not only present technical challenges during installation and commissioning. Owners and operators considering these technologies also need to be aware of in-service implications, such as the increased complexity of machinery or the hazardous chemicals and waste products that some technologies introduce. In addition, some technologies have difficulties achieving or maintaining compliance during practical application at sea.

None of these challenges are insurmountable, but in-service risks need to be understood before they can be mitigated. In fact, the majority of these risks can be managed contractually between the owner/operator and the equipment supplier.

9.1 Health and safety

9.1.1 Flooding and piping

The technologies considered in this guidance present significant safety risks. Wet scrubbing is associated with warm, acidic, aerated washwater. A pipe failure may cause engine room flooding. Some early installations suffered severe corrosion and failed in service, requiring several revisions to materials specifications. Corrosion-resistant pipe materials should be used. Coated or protected non-corrosion-resistant piping should be avoided. Damaged coated pipes corrode more rapidly than uncoated pipes as a result of localised galvanic cells. Polymeric coatings have to accommodate the expansion, contraction and bending/twisting movement of pipes. Careful attention should be given to internal weld seams which can initiate accelerated corrosion if not ground flush and free of intrusions.

Reverse flooding of the exhaust duct can result in major damage to engines. Passive risk controls are more reliable than active ones but providing an overflow arrangement on some ship types (for example, ropax) may not be practical. If level switches are used they must be manufactured from high grade materials and robust enough for use in the most hostile environments; some manufacturers specify simple level switches without considering their dependability or the environment they will operate in.

9.2.2. Chemicals

The most serious safety risk associated with wet scrubbing is the introduction of hazardous chemicals such as sodium hydroxide to regulate pH. Suitable materials specification is essential; if stainless steel is given as the material for sodium hydroxide systems then this must include the grade of stainless steel. A particular safety challenge facing passenger ships is loading sodium hydroxide at the same time that passengers are embarking or disembarking. We recommend carrying out a dedicated risk assessment if sodium hydroxide is to be used, including consideration of emergency procedures and crew training. There are alternatives to sodium hydroxide including benign substances such as magnesium oxide. There are compelling safety arguments for using these alternatives if they will work effectively. Risk elimination is preferable to risk mitigation. The same principles apply to using aqueous ammonia as a chemical reductant for SCR. Urea is a relatively benign substance to bunker and store on board and is an effective alternative reductant.

9.3.3. Waste products

Waste products and effluents produced by emissions abatement processes are safety and environmental hazards. Maintenance activities may expose staff to these residues. In the case of certain installation projects, these risks have not been considered until a late stage. Robust work controls, equipment and staff training are essential and need to be incorporated into the safety management system by the operator.

9.2 Operational difficulties

Crews are not generally familiar with chemical process plant; many operators have specified fully automated processes to reduce the risk of plant being operated incorrectly. This can result in crews not gaining the familiarity and competence to respond effectively to deviations from normal operation. Installation design should facilitate safe maintenance, access on some installations has not been ideal.

The parasitic electrical load of some wet scrubbing systems is significantly higher than the 0.5 – 1.5% figures offered by most manufacturers; such systems tend to be associated with tall small diameter scrubber towers. This is not universally applicable, and some manufacturers have installed tall small diameter systems without this load penalty indicating a link with the level of technical capability and expertise of the designer.

Integration with platform management and engine control systems can be problematic with some vendors struggling to deliver fully automated systems. Incorporating requirements for warm up and cooling down periods, load change requests and emissions abatement system failure and emergency instructions into the vessels platform management system has proven to be very challenging.

For multi-streaming installations the exhaust back pressure must be within the allowable limits for machinery under all operating conditions. This requires consideration of combinations such as running an engine at full load in parallel with one idling. Exhaust system modelling to verify this can be difficult to obtain.

Back pressure may be an obvious blockage but is more likely to be a less severe increase. An increase just above the allowable back pressure curves of engines may be hidden, causing reduced engine power output and efficiency. In one extreme example an engine could not operate above 50% of rated output due to excessive back pressure caused by poor system design. Some installations have restricted space in the uptakes and limited electrical, making installation of an induced draught fan difficult. Exhaust bypass arrangements are sometimes fitted to avoid thermal shock however these take up space in the uptakes, tend to corrode and if they leak risk emissions going out of compliance.

Standard offerings often include no redundancy. Classification societies are not substitutes for contractual specification; if operators want a degree of redundancy then they have to specify it. In the case of SO_x, the operator is required to hold a SO_x Emissions Compliance Plan (SECP) which needs to demonstrate the measures to be implemented if the emissions abatement system fails. The operator is responsible for the application of the SECP. Compliance is a statutory, not a classification matter. We advise specifying some degree of redundancy to reduce compliance risks but the operator has responsibility for specifying such redundancy.

9.3 Compliance difficulties

The difficulties which worry operators most are those concerned with environmental compliance. All of the technologies considered in this paper are effective however practical application at sea has been problematic.

Measuring wash water discharge to sea has been more difficult than anticipated. MEPC184(59) 10.1.2.1(ii) allows for pH to be measured 4m from the ships side, meeting a pH limit of 6.5 (20). Verifying this has been carried out by divers or taking measurements from a small boat. The measurement can only be done with the ship stopped, preventing effective verification of wash water discharge for main engine cleaning systems. Fluid modelling could be used; allowing verification at all system loads. There have been some calls for a relaxation of the pH emission limit and allowing dilution of wash water in the sea with no restrictions however LR believes such a relaxation would result in many states refusing permission to use open loop systems within their waters.

If exhaust back pressure is listed on the engine international air pollution prevention certificate (IAPPC) then a change in back pressure could invalidate the engine NO_x certification. To date this has been potential rather than actual problem but it needs to be recognised so as to avoid possible enforcement action after the ship enters service.

Meeting the discharge to air emission limits at stable loads has not challenged manufacturers, but can be difficult at transient and start up conditions. MARPOL Annex VI uses absolute emission limit values rather than time weighted average emission limit values. Engines can change load very quickly resulting in a lag between load change and emissions abatement response. This can be countered by operating equipment at higher emissions reduction loads than is necessary, operating wash water pumps at maximum flow rate or over injecting reductant into an SCR. This increases energy demand and chemical reductant consumption, resulting in higher carbon emissions, costs and in the case of SCR high ammonia slip which is itself a pollutant. Using more fuel and emitting pollutants to compensate for the transient response of emissions abatement systems when this could be better managed by a more appropriate emissions limit regime does not benefit the environment.

9.4 Contractual difficulties

When there is a problem with any of the factors listed in 9.1 – 9.3 the owner or operator generally holds either the manufacturer or the shipyard to account. If there are clearly defined contractual performance and delivery requirements then this is reasonable. Where the contract is vague, not clearly defined or excludes the matters subject to dispute then it becomes difficult for all parties. Many of the disputes we have found are largely due to the absence of a defined systems integrator. Buying equipment ex-works may be cheaper initially but can result in cost escalation during the project.

To help avoid and resolve disputes, we recommend that the following items are made explicit in any contract:

1. all applicable technical standards and classification rules
2. the minimum acceptable time for the system to achieve compliant stable performance

3. the maximum zero discharge to sea operating time
4. parasitic loads, particularly at high turn down ratios
5. commissioning protocols and acceptance criteria
6. standards for safe work
7. materials in detail; statements such as high grade steel are not adequate
8. exhaust gas back pressure calculations
9. emissions monitoring equipment meeting the requirements of MARPOL Annex VI and the NOx Technical Code; generic statements that instruments will be type approved or class approved are not acceptable
10. modifications to the exhaust system
11. stability calculations
12. washwater piping material specification and installation, including calculations to verify flow rates and pressures/losses/head, washwater pumps, supply and installation
13. structural modifications to incorporate additional tanks
14. tank coatings suitable for the tank contents, supported by an assessment of fluid properties
15. sea chest modifications including consideration of wash water alkalinity
16. access arrangements to allow operation and maintenance activities to be carried out safely without an ongoing need for temporary access to be provided
17. electrical load calculations, additional switchboard(s) and breakers or extending existing switchboards and buses
18. penetrations and glands to be compliant with class and statutory rules
19. automatic system operability and acceptable dependence on manual operation
20. integration of the emissions abatement controls into the platform management system and engine control system, alarm/shut down functionality
21. loading, storage and conditioning requirements for chemicals
22. washwater conditioning, including cleaning and filtration equipment meeting the over board requirements of MARPOL Annex VI
23. modelling to confirm the system sizing
24. structural modifications and subsequent re-instatement including load calculations and statutory and classification approvals for such re-instatement
25. training and documentation deliverables
26. minimum spare parts requirements

Most importantly there should be a defined system integrator.

Appendix A1

Impacts of marine exhaust emissions on human health and the environment

A1.1 Carbon dioxide (CO₂) and water vapour

CO₂ and water vapour will be formed in all combustion processes in which complete or near complete combustion of a hydrocarbon fuel takes place. As such, the production of CO₂ and water vapour is a function of the quantity of fuel burnt. Climate change resulting from increased concentrations of CO₂ in the atmosphere is a well documented global concern. The input of water vapour (also a principal greenhouse gas) to the atmosphere is currently of little concern since the global average concentration is not changing and it has a relatively short lifespan.

A1.2 Sulphur oxides (SO_x)

Sulphur oxides derive directly from the sulphur content of the fuels used. The sulphur in the combustion chamber is oxidised, principally forming sulphur dioxide (SO₂) with a minor proportion of sulphur trioxide (SO₃).

Relatively close to the source and in the absence of rain, fog and snow, the 'dry precipitation' of gaseous SO₂ and acidic sulphate containing particulate matter is detrimental to human health and the environment, causing respiratory problems and damaging vegetation.

At sometimes considerable distances from the source the 'wet precipitation' of acid rain, fog or snow can have a directly negative impact on plant life and indirect effects on wider ecosystems. Damage to minerals used in the construction of buildings and other architecture can also occur.

A1.3 Nitrogen oxides (NO_x)

The formation of nitrogen oxides occurs as a result of oxidation of molecular nitrogen in the combustion air or, to a lesser extent, in the fuel. Adverse effects due to NO_x are diverse. Nitrogen dioxide (NO₂) causes respiratory problems and damage to vegetation, as well as contributing significantly to acid deposition. In addition, NO_x and non-methane hydrocarbons (nMHCs) are involved in a series of photochemical reactions leading to increased tropospheric ozone, which in turn may adversely affect human health, crop yield and natural vegetation.

A1.4 Hydrocarbons

The gaseous hydrocarbon fraction of exhaust gas will predominantly consist of unburned or partially combusted fuel and lubricating oils. Individual components may be present in either vapour or particulate phases. The diverse nature of hydrocarbon fraction components makes it difficult to both quantify the emissions and identify specific health and environmental problems. Polycyclic aromatic hydrocarbons (PAHs) are of particular note in this respect and are present in particulate emissions from all types of combustion sources.

As regards wider environmental effects, the non-methane hydrocarbons (nMHCs) are of concern on account of their involvement in photochemical reactions leading to the formation of tropospheric ozone (see nitrogen oxides above). Additionally, any significant methane emissions will be of concern because of both stratospheric ozone depletion and (as methane is a principal greenhouse gas) global climate change.

A1.5 Particulate matter (PM)

The particulates fraction of exhaust emissions represents a complex mixture of sulphate with associated water, non- or partially combusted hydrocarbon components, black carbon and heavy metals as represented by the ash fraction. Some flakes or deposits from the exhaust system may also be present. With the exception of the latter the majority of diesel particulates are likely to be less than 1µm in diameter and readily transportable by air currents. Potentially detrimental effects may thus be encountered outside the immediate vicinity of the exhaust gas stack.

Although study of marine diesel particulate exhaust composition is limited, extrapolation of results from other diesel applications would suggest that general respiratory problems as well as more serious toxic, mutagenic and carcinogenic effects might be encountered.

Black carbon is detrimental to human health (fine particles can penetrate deep into the lungs causing increased respiratory and heart problems) and is now recognised as being of concern in terms of global warming. When deposited on to snow and ice, particularly in Arctic regions, light surfaces are darkened, albedo (reflectivity) is reduced and there is an increase in heat energy absorbed. Similarly, airborne black carbon particles absorb heat from sunlight, so warming the atmosphere.

In 2011, IMO MEPC 62 agreed a work plan to consider the impact on the Arctic of black carbon emissions from international shipping by:

- developing a definition of Black Carbon
- identifying the most appropriate measurement method for international shipping; and
- investigating appropriate control measures.

Final agreement on the definition has yet to be made.

Appendix B1

MEPC 184(59) – Exhaust Gas Cleaning System Guidelines

MEPC 184(59) – 2009 Guidelines for Exhaust Gas Cleaning Systems specifies the requirements for the test, certification and in-service verification of SOx scrubbing systems.

MARPOL Annex VI requires that SOx emissions limits be met by controlling the sulphur content of the fuel being combusted. SOx scrubbers are approved as equivalent to the use of controlled fuels by the ship's flag administration or by a classification society acting as a recognised organisation on the flag administration's behalf. In principle, this approval of equivalency, supported by approved onboard documentation and records, should be accepted by port states as demonstrating compliance with MARPOL Annex VI. However, if the ship changes flag there is no guarantee that the receiving administration will accept the original approval and they may decide to request additional evidence on the performance of the system before issuing their approval.

The Guidelines apply to any SOx scrubber fitted to fuel oil combustion machinery (excluding incinerators) as an alternative method of compliance with Annex VI, Regulation 14. There are two schemes available:

Scheme A, under which the SOx scrubber is subject to initial certification of SOx reduction performance followed by continuous monitoring of operating parameters and a daily spot check of emissions performance;

or

Scheme B, in which there is no requirement for initial certification, but continuous emissions monitoring using an approved system and a daily spot check of operating parameters are required.

Currently the EC only accepts continuous emissions monitoring and the US Coastguard also appears to be predisposed to continuous emissions monitoring. Therefore, for those ships that either currently trade into EU or US waters, or may do so in the future, Scheme B approval would appear to be the sensible option.

The majority of sulphur oxide in an exhaust system is SO₂, which is almost entirely derived from the fuel's sulphur content. Unlike NOx its formation is not related to engine design, operation or combustion conditions. The majority of CO₂ in the exhaust of a diesel engine is also derived from the fuel. The ratio of SO₂ to CO₂ therefore gives a measure of SOx emissions in proportion to the sulphur content of the fuel consumed. This is very helpful as it allows for a significant reduction in the complexity of the monitoring system, as there is no need to integrate other engine operating parameters, such as speed and fuel consumption. It also readily allows the monitoring of other types of combustion units such as boilers, which do not directly produce a kW load.

The Guidelines therefore enable compliance with Regulation 14 to be demonstrated on the basis of the SO₂/CO₂ ratio values listed in Table 4 below. (This is only applicable to the combustion of petroleum-based distillate and residual fuel oils.)

Fuel oil sulphur content (% m/m)	Ratio emission SO ₂ (ppm)/CO ₂ (% v/v)
4.50	195.0
3.50	151.7
1.50	65.0
1.00	43.3
0.50	21.7
0.10	4.3

Table 4: The fuel oil sulphur limits recorded in MARPOL Annex VI Regulations 14.1 and 14.4 and corresponding emissions values

Each ship fitted with a scrubbing system will require a SOx Emissions Compliance Plan (SECP). The plan, prepared by the ship operator, must demonstrate how the ship in its entirety will comply with Regulation 14 and must be approved by the administration. It is required to cover all fuel oil combustion units on the ship, whether fitted with scrubbers or not.

Table 5 summarises the documents required for Scheme A and Scheme B. These will be provided by the equipment manufacturer.

Document	Scheme A	Scheme B
SOx Emissions Compliance Plan (SECP)	X	X
SOx Emissions Compliance Certificate (SECC)	X	
EGC system – Technical Manual for Scheme A (ETM-A)	X	
EGC system – Technical Manual for Scheme B (ETM-B)		X
Onboard Monitoring Manual (OMM)	X	X
EGC Record Book or Electronic Logging System	X	X

Table 5: Scrubber document requirements

B1.1 Scheme A compliance

Scheme A for SOx scrubbers is similar to EIAPP certification and the Parameter Check Method for NOx. The basis of the procedure is that the performance of the scrubber is certified before going into service. Then, if all relevant components and operating parameters are within those in the approved EGC system – Technical Manual (ETM-A), the emissions reduction performance of the scrubber is within that required without the need for continuous exhaust emission measurements on the ship.

Under Scheme A, each scrubber must have a SOx Emissions Compliance Certificate (SECC). This certifies it is capable of meeting an SO₂/CO₂ emissions value on a continuous basis at the specified exhaust gas flow rate and the maximum fuel oil sulphur content (typically 3.50% or higher), for the range of system operating parameters in the Technical Manual. The SO₂/CO₂ emissions value, the exhaust gas flow rate and the maximum fuel oil sulphur content are specified by the manufacturer.

The 'certified value' must be suitable for a ship's operating pattern, with the SO₂/CO₂ emissions being at least the equivalent of the applicable fuel sulphur limit under Regulation 14. (Generally the certified value for most scrubbers should be expected to be the equivalent of using 0.10% sulphur fuel.)

Certification testing can be carried out either on the test bed or after installation on board. Test data together with the Technical Manual is submitted by the manufacturer for approval. The scrubber must be tested over the defined range of exhaust gas flow rates with one or more fuel oils to demonstrate its operational performance and that the certified value can be achieved. On approval, the SOx Emissions Compliance Certificate is issued. (The Guidelines also give the methods by which identical, serially produced units and those of the same design, but of different capacity, from a production range may be certified without the need for repeat testing.)

A scrubber unit must be fitted to an engine or boiler for which it is rated. A survey is required after installation on board and the scrubber system is also subject to periodic survey. The Technical Manual must contain a verification procedure for the surveys and details of the combustion unit to which it is fitted. To ensure compliance in service there is a requirement for certain system operating parameters to be continuously recorded and daily spot checks of emissions are also recommended. It should be noted that if the scrubber system manufacturer cannot guarantee that the certified value or better will be met between surveys, or if the surveys require specialist equipment or knowledge, then it may be preferable to demonstrate compliance through continuous emissions monitoring (i.e., Scheme B rather than Scheme A).

Parameters that must be continuously recorded include scrubbing water pressure and flow rate at the scrubber unit inlet, exhaust gas pressure before and pressure drop across the scrubber unit, fuel oil combustion equipment load, and exhaust gas temperature before and after the scrubber. A record of chemical consumption must also be maintained. Limits and applicable ranges of these operating values must be contained within the Technical Manual. The parameters are intended to ensure water flow and chemical addition are at an optimum for scrubbing, that the back pressure imparted by the scrubber on the exhaust does not adversely impact engine operation, that the scrubber is not for some reason becoming blocked and that exhaust is not bypassing the scrubbing process. The Technical Manual must contain details of action to be taken in the event of the applicable SO₂/CO₂ ratio being exceeded.



Figure 20: Continuous emissions monitoring systems (Image courtesy of Hamworthy-Krystallon)

An approved Onboard Monitoring Manual (OMM) is required to give details of the monitoring sensors and their position, and the care and calibration needed to demonstrate compliance. Continuously recorded data, including standard time and ship's position, must be securely stored for at least 18 months and be available for inspection as necessary to confirm compliance.

Component adjustments, maintenance and service records, together with chemical consumption, if applicable, must be recorded in the system's EGC Record Book, which also must be approved. Alternatively, if approved, maintenance and service records can be recorded in the ship's planned maintenance system.

B1.2 Scheme B compliance

Under Scheme B, a continuous emissions monitoring system (see Figure 20) is required to show that the SO_2/CO_2 ratio of the scrubbed exhaust is less than or equal to the required SO_2/CO_2 ratio at any load point, including during transient operation, and thus compliant with Regulation 14.

The scrubber system is in effect treated as a 'black box' and unlike Scheme A there is no need for SO_x reduction performance to be certified before the scrubber is used in service. The continuous emissions monitoring system must, however, be approved and is subject to an initial survey at installation and periodic surveys thereafter.

As with Scheme A, Scheme B requires an approved Onboard Monitoring Manual (OMM) containing details of the monitoring sensors and their position, and the care and calibration needed to demonstrate compliance. Continuously recorded data, including standard time and ship's position, must be securely stored for at least 18 months and be available for inspection as necessary to confirm compliance.

An EGC System – Technical Manual (ETM-B) is also to be approved. Like Scheme A this must contain details of the combustion unit to which the scrubber is fitted, applicable operating values and limits, and action to be taken in the event of the relevant SO_2/CO_2 ratio being exceeded. Daily spot checks of various parameters required to verify proper operation of the scrubber must be logged in the system's EGC Record Book or the engine room logger system.

B1.3 Washwater and treatment residue

Regardless of the Scheme used, the condition of any washwater discharged to sea must be continuously monitored and data for the following parameters must be securely logged against time and ship's position.

- pH (a measure of acidity),
- PAH (a measure of the harmful components of oil); and
- turbidity (a measure of particulate matter).

A test for nitrate content is also required at each renewal survey.

Systems that require the addition of chemicals for the purpose of scrubbing or conditioning of washwater before discharge are required to undergo a specific assessment and, if necessary, additional washwater criteria should be established.

Residue from washwater treatment may not be incinerated and must be landed ashore. In some cases this sludge is landed in dedicated portable storage tanks (IBC). In others, the water is extracted from the sludge and it is carried ashore in bags for disposal, and in other cases the washwater sludge is piped into the sludge tank and disposed ashore with the sludge from the fuel oil purifiers.

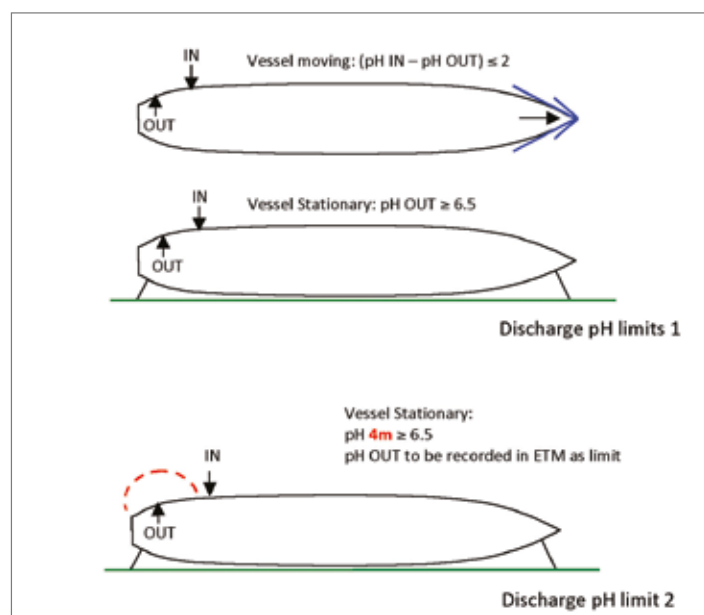


Figure 21: Washwater discharge pH limits (image courtesy of EGCSA)

B1.4 Washwater discharges – pH

Low pH water can have a detrimental impact on ecosystems and organisms such as shellfish, and can cause corrosion issues on the ship. The washwater immediately after scrubbing can have a pH of 4 or less. However, the Guidelines require the pH to comply with one of the following standards (also see Figure 21):

1. "The discharge washwater should have a pH of no less than 6.5 measured at the ship's overboard discharge with the exception that during manoeuvring and transit, the maximum difference between inlet and outlet of 2 pH units is allowed measured at the ship's inlet and overboard discharge"; or
2. "During commissioning of the [scrubber] unit(s) after installation, the discharged washwater plume should be measured externally from the ship (at rest in harbour) and the discharge pH at the ship's overboard pH monitoring point will be recorded when the plume at 4 metres from the discharge point equals or is above pH 6.5. The discharged pH to achieve a minimum pH units of 6.5 will become the overboard pH discharge limit recorded in the ETM-A or ETM-B."

The wording of this requirement makes its application very difficult and there are efforts at IMO to allow calculation and modelling to verify the pH 4 metres from the ship's side in place of physical measurement.

While it is generally recognised that no environmental harm will arise from short-term exposure of organisms to seawater down to pH 6.5 [12], the rationale for the two limits in the first option is that discharged washwater will readily mix in a ship's wake, very quickly correcting the lower pH. However, this is not possible with a stationary ship so a tighter limit is applied.

In order to comply with the pH 6.5 limit, particularly at the ship's side in port, seawater can be used to dilute the washwater. A specific pump can be used for this purpose. However, it may also be possible to reduce energy consumption by using seawater that has already been used for cooling purposes in other engine room systems.

B1.5 Washwater discharges – particulate matter and oil

Because particulate matter and potentially harmful components of oil could be discharged to sea within the washwater, the IMO Exhaust Gas Cleaning Systems Guidelines require turbidity and the concentration of polycyclic aromatic hydrocarbons (PAH) to be continuously monitored. Instruments have to be fitted after the washwater treatment plant but before any addition of fresh seawater or other treatment for pH correction.

PAHs are produced from a wide range of activities that involve the combustion of fossil fuels and hence may be present in the seawater taken up by the ship. The IMO Guidelines take this into account and allow PAH and turbidity readings at system inlet to be deducted from discharge figures.

The IMO Guidelines have limits for just one PAH – phenanthrene – which is prevalent in diesel exhaust and an indicator for the possible presence of others. In order to control the quantity of PAH at discharge, limits on concentration above the system inlet level are given at various washwater flow rates, with a higher concentration being allowable at low discharge rates and vice versa. The Guidelines also prescribe the measurement technologies that should be employed to ensure that instruments with an appropriate sensitivity are used.

Instruments either detect:

- the amount of ultra violet light absorbed by PAHs at high concentrations and low washwater flow rates; or
- the intensity of the light emitted by PAHs (fluorescence) at low concentrations and high washwater rates.

Turbidity is a measure of the loss of transparency of a liquid because of the particulates suspended within it. Although this can be used to monitor the removal of exhaust-related material by the washwater treatment plant, sediment entrained in the seawater at scrubber system inlet can impact the validity of readings particularly whilst the ship is manoeuvring. The Guidelines therefore have turbidity limits based on a rolling 15-minute average of the difference between turbidity at inlet and discharge.

B1.6 Washwater discharges – nitrates

NO_x is comprised mainly of nitric oxide (NO) formed during combustion, with a small amount of nitrogen dioxide (NO₂) formed by oxidation of NO in the exhaust. The solubility of NO is poor, whereas NO₂ reacts with water to form nitric acid (HNO₃) together with a reduction back to NO. This means conventional wet scrubbing will remove a small amount of NO_x from exhaust gas (generally less than 5%). The little that is removed is converted to nitrate, and also nitrite in SO_x scrubbers that use sodium hydroxide (NaOH).

Nitrates are important nutrients that promote the growth of organisms, but excess levels of nitrates, phosphates and sediment can lead to eutrophication in aquatic ecosystems, resulting in excessive growth of some organisms such as algae. Algal blooms can be toxic, reduce water clarity and starve water of the oxygen needed for fish, shellfish and plants to survive below the surface.

In near-shore waters, phosphates are available from industrial, agricultural and domestic activities; typical sources include detergents, sewage and run-off from fertilised land. The introduction of nitrates in large quantities is therefore undesirable.

Because the quantity of NO_x removed by conventional wet scrubbers is small, the Guidelines do not require continuous monitoring of overboard nitrate emissions. However, to mitigate the risk of eutrophication there is a nitrate limit based on scrubbing 12% of the NO_x from an exhaust stream (significantly more than is usually achieved). It is required that laboratory analysis of a washwater sample is undertaken in the three months leading up to each five yearly renewal survey and that the results are retained in the Exhaust Gas Cleaning Record Book, so they are available for flag and port state inspections. The Scrubber Technical Manual (ETM-A or ETM-B) must contain details of the sampling and analysis programme and typical nitrate levels if above 80% of the limit figure.

B1.7 Washwater discharges – other effects on seawater

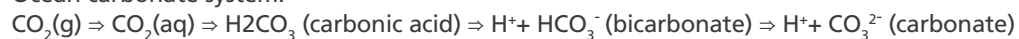
There are a number of other effects not specifically mentioned in the Guidelines. When dissolved in water sulphur oxides undergo a process of ionisation and oxidation to form sulphate. The reaction is buffered by the alkalinity of the scrubbing water, which is naturally imparted by seawater in open loop systems and by the addition of sodium hydroxide in closed loop systems. There is a common misconception that the transfer of sulphur to the ocean in the form of sulphate is in itself detrimental to ecosystems. In fact, sulphate is a major and stable constituent of seawater, a significant source being natural volcanic activity and seafloor degassing. It is relatively easy to estimate the total sulphur content of global oceans for comparison with the total sulphur content of all known oil reserves, to show how minor the contribution of the latter is.

While scrubbing prevents damaging sulphur oxides and particulate matter entering the atmosphere, the process involves two other reactions that should be considered.

Firstly, the formation of sulphate requires oxygen and so increases chemical oxygen demand (COD). This is indirectly addressed by the IMO Exhaust Gas Cleaning Systems Guidelines as it has been independently shown that oxygen levels will rapidly recover to within 1% of the receiving waters if pH limits are met. An exception to this occurs in warmer open seas, where up to 50% extra dilution is required for oxygen levels to normalise [12]. This dilution is readily available particularly as the ship will almost certainly be underway, causing the discharge to be mixed with fresh seawater in the ship's wake.

The other consideration is the impact that discharges of low pH washwater may have on receiving waters. The reaction below shows the ocean carbonate system and illustrates the interaction of carbon dioxide with seawater. Atmospheric CO_2 dissolves in the sea to form carbonic acid. Carbonic acid then dissociates by losing hydrogen ions to form bicarbonate. The increase in hydrogen ion concentration lowers the pH of the water, thereby increasing acidity. Available carbonate from shells and skeletons of marine organisms that are either dissolved in the seawater or deposited in sediments then combine with the hydrogen ions to resist further changes in pH. Using bicarbonate and carbonate to buffer washwater moves the reaction to the left and so causes increased acidity. Independent study has however shown that this is an order of magnitude smaller than that caused by CO_2 emissions from fossil fuel consumption [12].

Ocean carbonate system:



Appendix B2 – The NOx Technical Code

The NOx emissions of Tier I and Tier II (see section 2.3) engines do not require exhaust gas treatment systems, as NOx is controlled using primary, in-engine controls to constrain the combustion temperature and hence the formation of NOx. Certification of Tier I and Tier II engines is issued following successful test bed measurements of the relevant load points for the test cycle that is applicable for the function and configuration of the engine. There are three methods for confirming that the engine's in-service NOx emissions remain within the applicable limits.

By far the most common is the parameter check method. A pre-certified engine is surveyed when installed and then periodically thereafter. The principle of this approach is that if all relevant components and operating parameters are within those included and approved in the engine's Technical File, then the NOx emissions will not exceed the approved values. The simplified measurement method is similar to pre-certification testing, but with some simplification. However, it does require the engine to be run over the whole of the applicable duty cycle at each survey or port state inspection.

Under the direct measurement and monitoring method an approved emissions monitoring system is used to measure NOx while the engine is in service. Using these measurements, as well as other engine operating parameters and typically CO₂ concentration to determine exhaust flow rate, the specific g/kWh NOx emissions are calculated at the relevant engine test cycle load and speed points. Data have to be compiled within 30 days of survey in order to be considered current. Under guidelines that were adopted at MEPC 63 the SCR system is recognised as being a component of the engine; therefore pre-certification of the combined arrangement (engine + SCR) would typically be on a test bed before installation on board. This is referred to as Scheme A.

If it is not possible to test an engine and SCR together, either on a test bed or on board because of the size or construction of the arrangement, an alternative Scheme (Scheme B) allows for the engine and SCR to be tested separately subject to the agreement of the Administration. The NOx emissions from the engine are tested as usual in accordance with the appropriate test cycle. The NOx reduction performance of the SCR can be based on modelling tools using data from either a full size or scaled down version. The overall NOx emission value (g/kWh) is calculated by combining the engine emissions and SCR emission reduction rate at each load/speed point in the test cycle. Data is then entered into the engine's Technical File and the parent engine EIAPPⁿ certificate. A final and simpler confirmation test is carried out on board whereby the emissions concentration (parts per million (ppm)) is measured at the inlet and outlet of the SCR chamber and compared with the Technical File entries.

With this approach there are concerns as to the reliability and robustness of the modelling of the SCR's performance and the associated scale model testing which would be used to calculate the estimated NOx emission value entered on the Supplement to the EIAPP Certificate. These concerns arise particularly because the confirmation test is only to be undertaken on the parent engine after installation on board and hence may not fully reflect all the influencing factors which in practice could affect the performance of individual SCR units. Given these concerns, shipowners, who will be responsible for the ongoing in-service demonstration of compliance, may, irrespective of the engine's NOx certification status, be looking to see that a confirmation test is satisfactorily completed on each and every SCR-fitted engine, even identical engines, as part of the ship trials before acceptance.

Amendments to the NOx Technical Code 2008 enabling the Scheme B pre-certification procedure were adopted at MEPC 63. However, detailed procedures demonstrating ongoing compliance based on emission monitoring are expected to be further developed.

ⁿ Engine International Air Pollution Prevention

Appendix B3 – Regional, national and local air quality regulations

Table 4 shows the major regional, national and local regulations that currently apply to international shipping, none of which control NO_x emissions. Further information is provided in the sections below.

B3.1 European Union

European Council Directive 1999/32/EC as amended by 2012/33/EU relates to the sulphur content of marine fuels. In addition to incorporating the Baltic ECA-SO_x and North Sea ECA-SO_x (which includes the English Channel) into national law, European Union member states are directed to ensure all ships, regardless of flag, use fuel containing no more than 0.10% sulphur 'at berth', which is defined as including ships at anchor within port. Any fuel changeover operation must occur as soon as possible after arrival at berth, and as late as possible before departure, and be logged. The Directive also requires that during 'regular' service between member state ports and in EU waters, passenger ships must use fuel containing no more than 1.50% sulphur, unless in ECA-SO_x in which case the lower ECA-SO_x limit applies. Further information can be found in the LR FAQs on the EC Directive requirements [13].

Article 4c explicitly requires member states to accept the use of emissions abatement as an alternative to combusting compliant fuel "by ships of all flags in their ports, territorial seas, exclusive economic zones and pollution control zones, as an alternative to using marine fuels that meet the requirements of Articles 4a and 4b". Emissions abatement systems must continuously achieve emission reductions that are at least as low as those achieved by the Directive's sulphur-in-fuel limits. Article 4d provides guidance on approval and certification, calling for this to take into account guidelines developed by IMO but also to consider "effects on the environment, including achievable emission reductions, and impacts on ecosystems in enclosed ports, harbours and estuaries". Emissions abatement systems have to be fitted with continuous emissions monitoring equipment, this is a significant variation from MEPC.184(59). Whilst the Directive does not mandate Scheme B, a scrubber approved to Scheme A of the MEPC.184(59) guidelines must additionally incorporate continuous emissions to air measurement to comply with the Directive. One noteworthy point is that if the fuel used has a sulphur content higher than 3.5% then only closed loop scrubbers may be used. Article 4e of the Directive also makes provision for trials of new emissions abatement technologies. A trials permit may be issued for a period of eighteen months and all affected port states are to be notified six months in writing before trials commence.

Exhaust gas scrubbing systems are also included within Directive 2008/67/EC amending Council Directive 96/98/EC on marine equipment (the Marine Equipment Directive, MED), this provides the acceptance criteria for scrubbers onboard European flagged ships as being the IMO MEPC.184(59) guidelines.

B3.2 North America

Under United States federal marine air pollution regulation, the Environmental Protection Agency (EPA) defines three categories of engine, subdivided by cylinder displacement and engine power or speed. Each sub division has Tiers of reducing emission limits for NO_x, particulate matter, carbon monoxide and hydrocarbons and a model year from which the limits will apply to domestically operated engines [14].

Title 40 of the US Code of Federal Regulations, CFR Part 1043 [15] incorporates MARPOL Annex VI into US Law. The regulation applies to all US flagged ocean-going ships operating worldwide including the United States and foreign flag ships while in US waters. As such, emissions of SO_x, PM and NO_x are controlled from the largest category 3 marine engines with a per cylinder displacement of over 30 litres and approved exhaust gas cleaning systems are allowed as an alternative. Smaller category 1 and 2 auxiliary engines on ships with category 3 propulsion engines are also permitted to comply with MARPOL Annex VI under 40 CFR Part 1042.650 and Part 80 [16,17].

B3.3 California

In addition to US federal emission controls based on Annex VI, California has its own Regulation on Fuel Understanding exhaust gas treatment systems Sulphur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline [18]. The fuel rule was updated by the Air Resources Board (ARB) following the adoption of the North American ECA-SO_x and applies to all main and auxiliary engines and auxiliary boilers (but not emergency engines) unless a ship is on passage through regulated waters or if compliance would put the ship and people on board in danger due to extraordinary circumstances. If ships are to berth or anchor within California Waters or enter an inland waterway or estuary the requirements in Table 5 apply.

California only permits the use of exhaust control technologies, including SO_x scrubbers, in trials as part of a research programme officially approved by the Californian authorities. Before the end of the trial the ship must be brought back into full compliance with fuel rule requirements.

The regulation also includes provision for its own termination, which states the fuel requirements will cease to apply if the USA adopts and enforces controls that yield equivalent emissions reductions. California, however, specifies the use of distillate fuels, with an implementation timeline that differs in part to the federal legislation enacting Annex VI.

	SOx	SOx scrubbers permitted?	NOx	Comments
Europe Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 amending Directive 1999/32/EC	“Sulphur Content of Marine Fuels” Includes specific low-sulphur fuel rules for ships in port and passenger ships on regular service in the EU	✓ (with continuous emissions monitoring)	No regulation	
USA Title 40 of the US Code of Federal Regulations, CFR Part 1043	Control of SOx and PM from ships subject to MARPOL Annex VI	✓	No regulation	The requirements are under review. There are indications that in future the US may not accept exhaust gas treatment systems unless they are fitted with continuous monitoring of exhaust emissions.
California (Title 13 California Code of Regulations, CCR section 2299.2)	Fuel sulphur and other operational requirements within California waters and 24 nautical miles off the California coast	✗	No regulation	Specific low-sulphur fuel rules for ships visiting California

Table 6: Key regional, national, and local regulations

Fuel requirement	Effective date	Fuel grade requirement and sulphur limit
Phase 1	1 July, 2009	Marine gas oil (DMA/DMZ) at or below 1.5% sulphur; or Marine diesel oil (DMB) at or below 0.5% sulphur
	1 August, 2012	Marine gas oil (DMA/DMZ) at or below 1.0% sulphur; or Marine diesel oil (DMB) at or below 0.5% sulphur
Phase 2	1 January, 2014	Marine gas oil (DMA/DMZ) or marine diesel oil (DMB) at or below 0.1% sulphur

Table 7: California fuel regulation requirements

Appendix C – Operational considerations for using compliant fuel within ECA-SOx from 1 January, 2015

Fuel system stage	Major concerns	Probable solutions
<p>Bunker requisition/ Bunkering operation</p>	<ul style="list-style-type: none"> • Availability of compliant fuel in increased volumes required • Any limitation on rate of bunker loading due to manifold size/pipework used for loading distillate fuel • Separate bunker lines of combined heavy fuel oil (HFO)/marine gas oil (MGO) • Risk of cross contamination with high-sulphur fuel oil (HSFO) if using • Same bunkering lines for HSFO and 0.10% sulphur fuel oil (0.1SFO) <p>(Note for the most part 0.1SFO will be a distillate MGO DMA grade and HSFO will be residual fuel oil (RFO) with > 0.10% sulphur)</p>	<ul style="list-style-type: none"> • Evaluate increased 0.1SFO quantities required and tank capacity. • Plan additional bunkering time (if any) to load 0.1SFO in ship schedule • Load the 0.1SFO through segregated bunker pipelines • Order compliant fuel well in advance of enforcement date of 1st of January 2015 to allow fuel tanks and systems to flush through • Perform a fuel system/ management assessment review for individual or group of vessels to identify and address operational and technical challenges at each component point in the system
<p>Fuel storage / transfer</p>	<ul style="list-style-type: none"> • Low tolerance margin 0.1SFO contamination with RFO causing fuel to become non-compliant on board • Tank cleaning challenges of existing HSFO tanks to increase 0.1SFO tank capacity • Crew competence/awareness in managing fuel change-over • Incompatibility between HSFO and 0.1SFO causing filter blockages • Overheating of MGO from Leaking steam heating valves and high temperatures adjacent RFO tanks • Fuel quality issues during long storage such as with FAME (fatty acid methyl ester), oxidation stability, microbial contamination. 	<ul style="list-style-type: none"> • For extended ECA operation, dedicate segregated storage tanks for 0.1SFO sulphur fuel with separate service/settling tanks to HSFO – • Use segregated transfer lines and pumps for 0.1SFO distillate operation. Confirm compatibility rating between fuels before the change over. After each bunkering check compatibility across all fuels • Plan tank cleaning well in advance of 01/01/15 for ship = '2015 Ready' • Isolate steam lines to MGO tanks and check steam valves are sealing • Verify fuel change over plan and assess crew competence/awareness • Avoid long storage periods of distillate fuels, regularly drain water from tanks to reduce microbial activity. • Consult CIMAC Guidelines on managing fuels with FAME – (request for FAME scan on MGO bunker if required)
<p>Settling / service tanks</p>	<ul style="list-style-type: none"> • Leaking steam heating valves will elevate tank temperature • High fuel temperature in settling/service tanks because of close proximity with RFO settling/service tank • Note that some adjacent tank heating with regards to storage tanks where maximum temperatures are not exceeding 45°C may be advantageous for high cold flow property fuels – seek guidance on this from Lloyd's Register FOBAS on a case by case basis 	<ul style="list-style-type: none"> • If an existing LSFO settling tank is being used for 0.1 SFO then ensure steam heating is isolated (if an MGO) Conduct inspection of trace heating valves and lagging condition.
<p>Purifiers / filters</p>	<ul style="list-style-type: none"> • Filter blockage may occur especially at the time of fuel change-over or during circulation for tank cleaning due to solvency nature of the MGO • Excessive sludge generation at filters/purifiers could result in fuel supply restriction 	<ul style="list-style-type: none"> • Crew awareness and training – to be specifically attentive during change-over • Keep the backup filters clean and ready for quick change over (have sufficient spare replaceable filters where applicable) • Attention to purifier settings based on tested density and viscosity – recommended de-sludge cycles.

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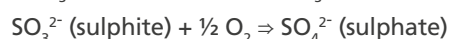
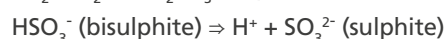
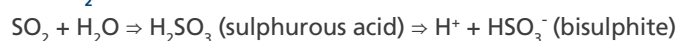
1 Carry out crew assessment and training / awareness programmes as required.
2 Advise ship's class of any planned fuel system / machinery modification which may require plan approval.

Appendix D – Chemical reactions

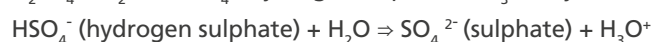
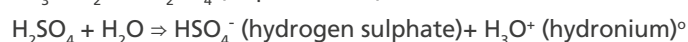
D1.1 Wet open loop SO_x scrubber (including hybrid system operating in open loop mode)

SO_x scrubbing media is seawater. Sulphur dioxide (SO₂) is dissolved and ionised to bisulphite and sulphite, which is then readily oxidised to sulphate in seawater containing oxygen. Similarly sulphuric acid (formed from SO₃) and hydrogen sulphate dissociate completely to sulphate.

For SO₂:



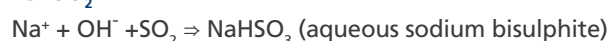
For SO₃:



D1.2 Wet closed loop SO_x scrubber (including hybrid system operating in closed loop mode)

SO_x scrubbing media is fresh water dosed with sodium hydroxide (NaOH). Sulphur oxides are dissolved and react to form sodium bisulphite, sulphite and sulphate. The proportion of each is dependent on the pH and available oxygen.

For SO₂:



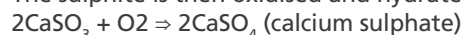
For SO₃:



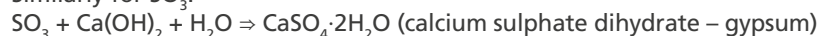
D1.3 Dry SO_x scrubber

In a dry SO_x scrubber using calcium hydroxide (Ca(OH)₂) the reaction with sulphur dioxide forms calcium sulphite: $\text{SO}_2 + \text{Ca(OH)}_2 \Rightarrow \text{CaSO}_3 \text{ (calcium sulphite)} + \text{H}_2\text{O}$

The sulphite is then oxidised and hydrated in the exhaust stream to form calcium sulphate dihydrate, or gypsum:

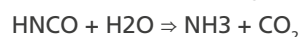
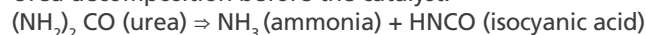


Similarly for SO₃:



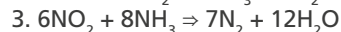
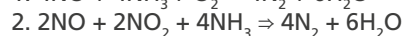
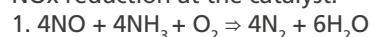
D2.1 Selective Catalytic Reduction

Urea decomposition before the catalyst:



(Note: the resulting quantity of CO₂ is minor when compared with that resulting from fuel combustion)

NO_x reduction at the catalyst:



Equation 1 shows the main SCR reaction as nitric oxide dominates in the exhaust. The reaction shown at equation 2 occurs at the fastest rate up to an NO₂:NO ratio of 1:1. However, at higher ratios the excess NO₂ reacts slowly as per equation 3.

o Hydronium is a water molecule with an extra hydrogen ion attached to it (H₂O + H⁺ ⇒ H₃O⁺). An acid is any compound that yields hydrogen ions (H⁺) or hydronium ions (H₃O⁺) when dissolved in water.

Acronyms and abbreviations

DME	Dimethyl ether – a synthetic fuel formed from natural gas or biofuel
ECA-NO_x	Emission control area for nitrogen oxides under MARPOL Annex VI
ECA-SO_x	Emission control area for sulphur oxides under MARPOL Annex VI
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EPA	Environmental Protection Agency
EGR	Exhaust gas recirculation – engine technology to reduce NO _x formation by reintroducing cleaned exhaust gas into the charge/scavenging air
EGC/EGCS	Exhaust gas cleaning/Exhaust gas cleaning system – the terms used by MEPC to refer to SO _x scrubbers
EGCSA	Exhaust Gas Cleaning Systems Association www.egcsa.com
EGTS	Exhaust gas treatment system – the term used in this guidance to refer to either treatment systems for SO _x or NO _x
ETM-A	EGCS – Technical Manual for Scheme A – the manual containing all the relevant components and operating parameter for an EGCS to meet MARPOL Annex VI SO _x limits under the Scheme A approval process
ETM-B	EGCS – Technical Manual for Scheme B
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection www.gesamp.org
GRE	Glass reinforced epoxy – a corrosionresistant material that can be used for the construction of SO _x scrubber washwater pipes, process tanks and holding tanks
HAM	Humid air motor
IBC	Intermediate bulk container
IMO	International Maritime Organization
LDSO	Low-sulphur distillate oil
LNG	Liquefied natural gas
MEPC	Marine Environment Protection Committee
MSDS	Material Safety Data Sheet
OMM	Onboard Monitoring Manual – the approved manual that details the monitoring sensors used to demonstrate compliance with MARPOL Annex VI SO _x limits
PAH	Polycyclic aromatic hydrocarbon
PM	Particulate matter
PPE	Personal protective equipment
RFO	Residual fuel oil
SAM	Scavenging air moistening
SECC	SO _x Emissions Compliance Certificate – certifies that a scrubber will reduce SO _x emissions to the required level when fuel oil of a specified maximum sulphur content is consumed
SECP	SO _x Emissions Compliance Plan – the Plan describing how the overall ship will meet MARPOL Annex VI SO _x limits
SCR	Selective catalytic reduction
VCG	Vertical centre of gravity
VGP	Vessel General Permit

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