A practical guide to exhaust gas cleaning systems for the maritime industry

EGCSA Handbook 2012

EGCSA
exhaust gas cleaning systems association

EGCSA HANDBOOK 2012

Exhaust Gas Cleaning Systems are a highly effective solution to the challenges of IMO MARPOL Annex VI air pollution regulations and the added complexities of regional and national emissions legislation.

It is crucial that ship owners and operators fully understand their options for compliance. To aid decision making this guide contains a wealth of information, including:

- The impact of emissions, current and future regulation and the IMO Guidelines for Exhaust Gas Cleaning Systems
- Types of Exhaust Gas Cleaning System for SOx, PM and NOx, including system configuration and installation, materials of construction and compliance instrumentation
- Scrubbing processes, dry chemical treatment and washwater handling
- Comprehensive details of commercially available systems from EGCSA members

As exhaust gas cleaning technologies and legislation evolve, it is intended to further update this publication to keep pace with developments and EGCSA encourages all with an interest in this business critical area to take full advantage of each new edition as it is released.

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Foreword

The Exhaust Gas Cleaning Systems Association will record its fifth anniversary in 2013. During this period the EGCSA members have installed a variety of commercial exhaust gas scrubbing systems. All these installations are able to meet and exceed the most stringent of current IMO MARPOL Annex VI emissions regulations.

EGCSA members have provided a real alternative to the expensive low sulphur fuels prescribed in MARPOL Annex VI. More importantly, Exhaust Gas Cleaning Systems (EGCS) are now providing real and significant cumulative savings to the global shipping industry. No other recent environmental regulation (IMO or any other) has ever enjoyed the payback, lower operating cost and lower GHG footprint than is achieved by installing Exhaus Gas Cleaning Systems.

It is a credit to the Association and its membership that this trade association has also invested in scientific research to ensure the long term viability of the technology and the continuing assessment of any possible long term environmental impact.

I commend this second edition of the EGCSA Handbook which is a rich resource for those interested in understanding the technology and its application.

MR. NICHOLAS CONFUORTO

Belco Technologies Corporation (a DuPont subsidiary)
Chairman, EGCSA

Introduction

The original EGCSA handbook was published in September 2010. Since then many of the issues highlighted in the previous foreword remain. The promotion of LNG as a fuel which will displace HFO continues. Some of the questions around the handling and management of LNG fuel are still unanswered. Nevertheless LNG is certain to be in the future marine fuel mix. Dual fuelling with HFO and LNG will certainly address the range anxiety of pure LNG fuelled vessels.

The first EGCS training course at Brunel University in June 2012 set out to debunk the myths surrounding EGCS technology. It also set the context and need for cleaner air. With marketing sound bites blocking out sound technical and commercial decision making, the course provided the tools to evaluate and where appropriate assisted in developing the business case for an exhaust cleaning system investment.

Today further uncertainties prevail, including fleet over capacity in what appears to be a significant and sustained global downturn. The merchant marine business model that rode the peak freight rates and new-building tonnage has not served many ship-operators well. A shortage of free cash generation from operations and a withdrawal of finance by banks and other funders have placed a financial challenge on capital investment. The installation of ballast water systems, energy efficiency measures and emissions abatement technologies are all calling for significant investment in the existing fleet.

The certainties that will need to be faced are the reduction in sulphur to 0.10% in ECAs in 2015, possibly increasing demand for diesel by more than 40Mt. The impact on the cost of road transport diesel in Europe is uncertain but could lead to shortages and price spikes. The new ECA emissions limit will inevitably increase some seaborne transport costs, but it will also present an opportunity for those operators who have selected winning strategies to achieve massive competitive advantage. The journey to lower emissions will continue. A delay to 2025 of the global sulphur emissions cap looks increasingly unlikely, whilst the need to more closely align ship emission regulations with heavy-duty on-shore diesel emissions regulations is becoming an inevitability.

The Exhaust Gas Cleaning System industry has begun some consolidation. New entrants continue to appear whilst some of the "magic" solutions have lost their supporters. EGCSA will continue to pursue its key roles of transparency, accountability and integrity. The Association accepts that the forthcoming transition is a major and costly change. EGCSA continues to work closely with all stakeholders to ensure compliance is achieved by the most effective means.

Nevertheless the outlook appears expensive. But compared to other environmental regulations, emissions to air regulations provide a real opportunity to reduce operating costs and gain efficiency benefits.

The updated handbook contains more in-depth detail of exhaust gas cleaning processes, configurations of system deployment and the likely evolution of future emissions regulations.

A special thank-you to Mark West for his editing of the 2012 handbook.

Finally special thanks to our advertisers who chose to participate in the handbook with a page of information on their respective businesses and services. Without advertisers support producing this handbook at a reasonable cover price would be prohibitive. Please have a look at their contributions at the back of the handbook.

MR. DONALD GREGORY

Director, EGCSA
Partner Sustainable Maritime Solutions Ltd

1. Air Pollution – Combustion

Man-made air pollution was probably in evidence at a local level affecting human health from when man was first able to light fires and use them in caves and early dwellings.

In Europe two major tragedies are believed to have led to the development of air pollution policy and legislation. In December 1930 in the Meuse Valley in Belgium 63 persons died and many more fell ill [91]. The cause of the fatalities has never been fully established but it is known that the valley was heavily industrialised. In the winter of 1952 mortality rates in London increased by thousands. The London smog, the result of thousands of coal fires and poor dispersion conditions led to high levels of soot and sulphur dioxide (SO_2). The peaks of sulphur dioxide and soot are about 2mg/m^3 (750 parts per billion) [92], [93]. Figure 1 clearly shows a link between increased SO_2 concentrations and mortality. In 1956 the UK Clean Air Act was introduced banning the use of coal in "smokeless" areas and the phasing in of smokeless fuels and gas heating.

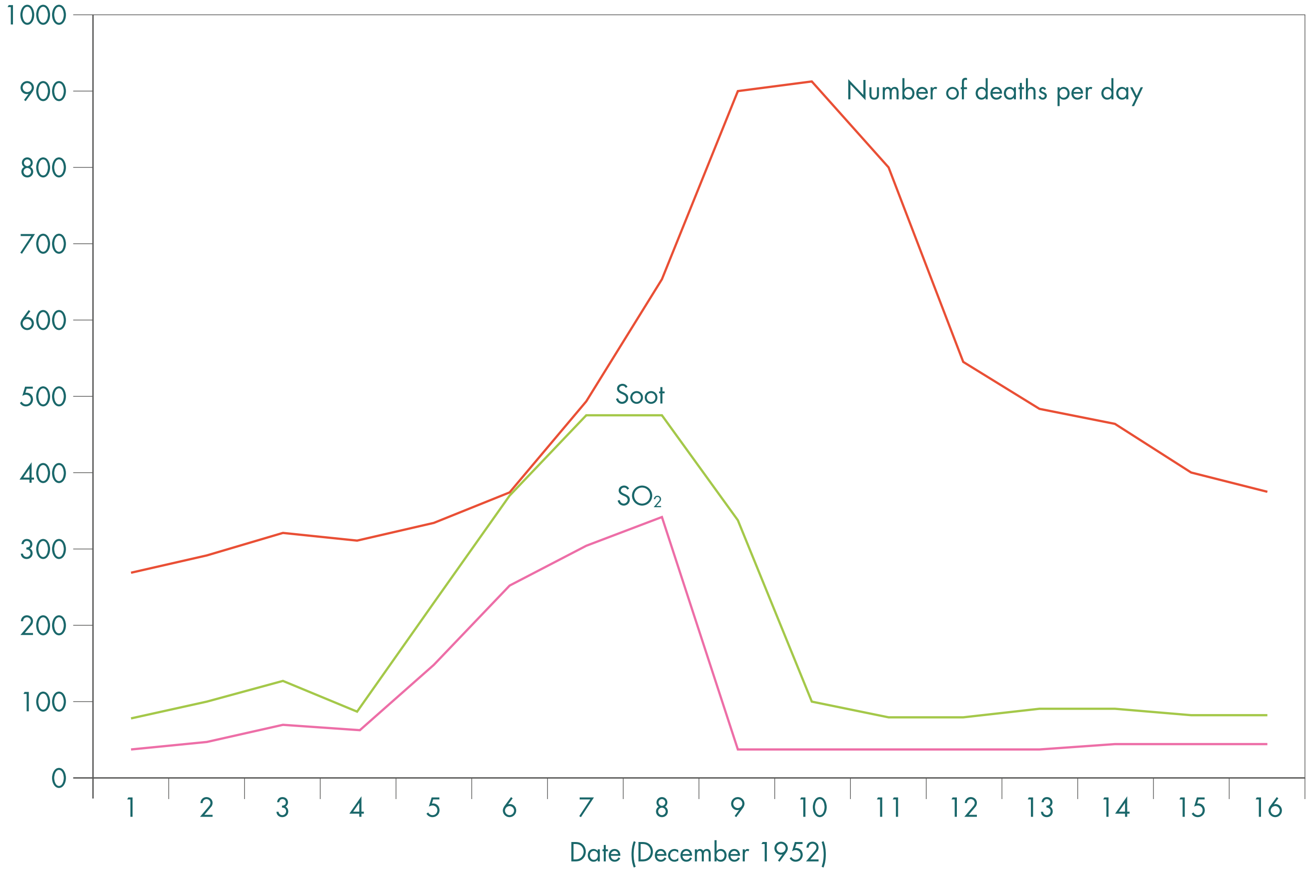


Figure 1: The link between atmospheric sulphur dioxide concentration and human mortality

Emissions of sulphur dioxide have declined steeply in the USA and Europe along with much lower levels of soot. This has been due to improved combustion technology, low-sulphur fuels and/or Exhaust Gas Cleaning Systems.

Nevertheless there remain over 3,000 known anthropogenic air pollutants. The majority are organic compounds including some organo-metals. On-road transport emits some 500 different compounds of which only about 200 have been investigated for their impacts on human health and the environment.

These pollutants can be divided into two groups [90].

1. The traditional major air pollutants (MAP) comprising, sulphur dioxide, nitrogen oxides, carbon monoxide and ozone.
2. Hazardous air pollutants (HAP) comprising chemical, physical and biological agents of different types.

Whereas MAP concentrations have been high and in most cases are declining, HAP concentrations are much lower and appear to have more localised impacts. The assessment of hazard, its measurement and its impacts are challenging to confirm. A ship is a mobile source of both MAP and HAP compounds, and may create a variety of air pollution risks dependent upon location, exhaust discharge height, population concentration and ambient air conditions.

1.1 Ship Emissions

Exhaust gases from marine diesel engines and marine boilers comprise of gaseous compounds, some of which are classified as pollutants, and some of which are classified as climate change agents and solid particles. The exhaust gas also contains vapours derived from the fuel and in the case of diesel engines also from the lubricant.

It has been estimated that 10% of sulphur dioxide emissions originating from human activities come from international shipping. This compared with some 50% of the total from combustion of sulphur containing coal by domestic, industrial and energy sector consumers on land [67]. As such primary exposure to SO_2 is most often associated with smog from the combustion of coal rather than shipping. SO_2 is heavier than air and has a suffocating odour at an atmospheric concentration of around 500 parts per billion (ppb), at which level it can be fatal. At lower levels, depending on exposure time, respiratory problems and eye irritation may be experienced. Existing coronary disease can also be aggravated. At 20 ppb or lower there should be no ill effects to a healthy person [3]. The normal atmospheric background concentration of SO_2 is generally less than 10 ppb, with the EPA reporting that the current annual concentration range is approximately 1 to 6 ppb in the USA [49].

The solid particles are referred to generically as particulate matter, (PM) of which specific components are soot and ash. Particulate matter formed during combustion is classified as primary PM and is effectively the solids in the exhaust gas at exit from the funnel into the atmosphere. Once the exhaust gas reaches the atmosphere, cooling occurs, creating condensates of some of the vapours. Other compounds undergo photochemical processes, the type and rate of which are dependent upon atmospheric conditions and other reaction compounds in the atmosphere. For fuels containing sulphur, the predominant mechanism is the reaction with ammonia in the atmosphere creating ammonium sulphate, which is a solid in the form of an aerosol. These reactions create what are known as secondary PM the concentrations of which can be many times greater than the concentrations of primary PM.

This important secondary effect impacts on both human health and the environment and is linked to increased asthma attacks, heart and lung disease and respiratory problems in susceptible population groups. Particulate matter can also accumulate onto the ground and surface of leaves, causing damage to plants and trees [3].

The 'dry' deposition of PM and gases is of particular relevance to coastal regions as it has been estimated that some 70% of ship emissions occur within 400 km of land [87], [88]. As measures are taken to reduce emissions from land based sources, the relevance of sulphur oxides pollution from shipping increases and in 2005 it was predicted that without action emissions from ships in European Union waters would exceed those from the EU member states by 2020 [89].

Further away from the emission source sulphur oxides will be converted to acids by aqueous phase reactions in the atmosphere. The acidic aerosols are eventually precipitated as acid rain, snow, sleet or fog in a process referred to as 'wet' deposition. Without man-made pollution rainwater is slightly acidic, at approximately pH 5.6, because of the formation of weak carbonic acid from dissolved CO_2 [3], [50]. Acid rain however has been measured with much lower pH levels. At a mountain site in the eastern USA, a long-term study has shown the mean summertime pH of cloud water ranges from 3.6 to 4.1, while the pH of rainwater ranges from 4.0 to 4.4. The lowest pH value recorded for cloud water is 2.6 while the lowest rainwater pH was 3.1. Chemical analysis has shown that approximately two-thirds of the acidity was due to sulphuric acid (and the remaining third was due to nitric acid derived from nitrogen oxides) [52].

Acid rain and run-off has many effects in an interconnected ecosystem and its direct impact on some species can have an indirect impact on many more. Whilst the buffering capacity of some soils and waters is able to neutralise acids, in areas where there is not sufficient natural alkalinity the effects are much greater. Acidification of lakes, watercourses and wetlands can cause leeching of heavy metals, which are toxic to aquatic life. Soils can be stripped of essential nutrients and the ability of plants and trees to take-up water impaired. Foliage can be damaged and the process of reproduction inhibited. With a reduced resistance to disease, insect attack and climate effects, deforestation and a loss of vegetation can result. Soils may be washed away leaving a landscape incapable of sustaining many species [51], [3].

Building decay can also occur. Limestone ($CaCO_3$) used in the construction of buildings and historic monuments reacts to form gypsum ($CaSO_4$), which readily flakes off under the action of the weather.

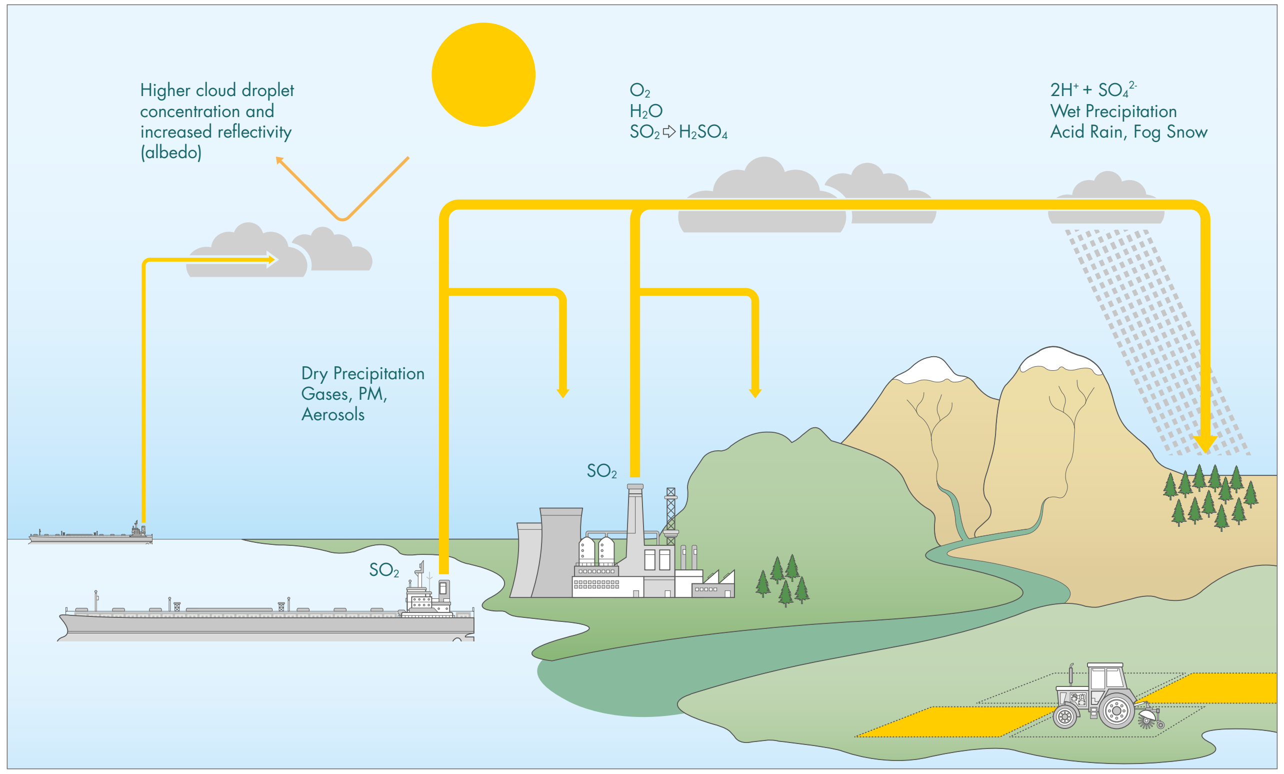


Figure 2: Sulphur oxide deposition without exhaust gas cleaning

1.1.1 MARPOL Annex VI – regulation 14

The primary objective of MARPOL Annex VI, regulation 14 is to reduce the amount of sulphur oxides emitted to the atmosphere from ships in order to reduce the mass of secondary PM created by high sulphur fuels and to reduce the impacts of acidification in areas sensitive to acid rains.

It is worth noting that the interaction of pollutants and the environment is complex. For example sulphate aerosols from ships have been linked to an increase in cloud droplet number concentration and reduction in droplet size so increasing the 'albedo' or reflectivity of low-level marine Stratus clouds. Whilst this has a potentially beneficial climate cooling effect [66], in their 2009 joint proposal to IMO, the USA and Canada stated that by designating the eastern and western seaboards of North America an Emissions Control Area, *"as many as 8,300 lives will be saved and over three million people will experience relief from acute respiratory symptoms each year". It was also stated an ECA will result in a 19 per cent reduction in excess [sulphur and nitrogen] deposition in south-western British Columbia and it will eliminate excess deposition over about 13,500 km² across Canada"*. [5], [6], [7]

It should also be noted that all fuel combustion produces harmful components. A study [97] indicated under diffusion combustion conditions, gaseous fuel produces more harmful Polycyclic Aromatic Hydrocarbon compounds (see Section 3.5.2 and Appendix 6) than might be measured in the combustion products of residual fuel oil.

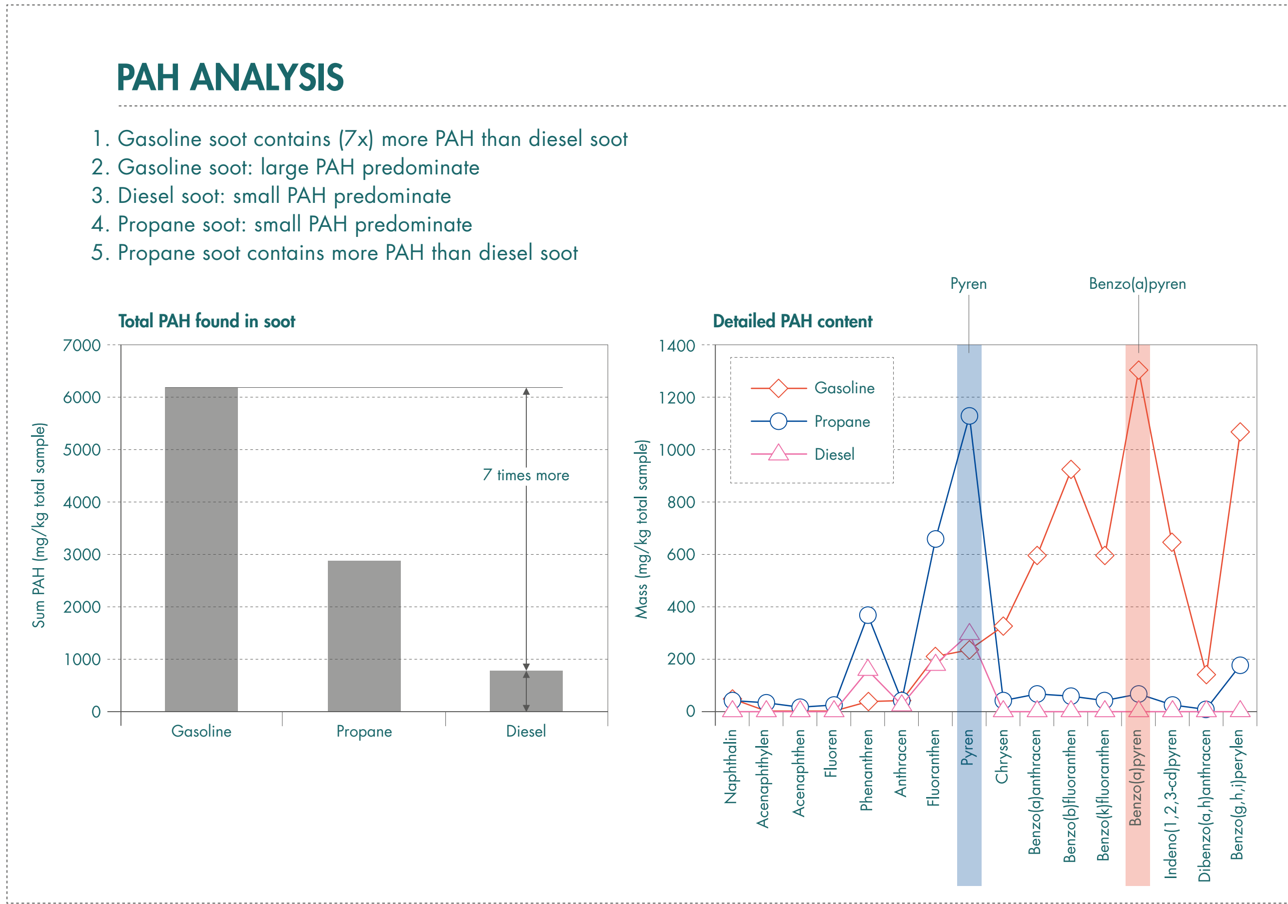


Figure 3: PAH analysis, gasoline, diesel, propane

Courtesy Dr. Lianpeng Jing, Jing Ltd [97]

1.1.2 Gaseous emissions

Table 1 summarises the gaseous emissions from marine combustion plant that are currently regarded as harmful to humans or the environment, or are a climate change agent and are regulated in land-based transport:

EMISSION	SOURCE	IMPACTS
Sulphur dioxide (SO_2) SO_2 and SO_3 are collectively known as SOx.	From sulphur contained in petroleum sourced liquid fuels. During combustion oxidises to sulphur dioxide.	SO_2 is the majority component of SOx in the exhaust and a major contributor to acidification and secondary particulate formation.
Sulphur trioxide (SO_3)	As above but in aerosol form further oxidised by catalytic reaction in combustion passages.	A highly acidic compound, very hygroscopic, causing damage to metal components.
Nitric oxide (NO) NO and NO_2 are collectively known as NOx.	Formed during combustion at high temperature and an oxygen-enriched atmosphere in a marine diesel engine chamber.	Converts to NO_2 in the atmosphere.
Nitrous Oxide (NO_2)	Formed by the oxidation of NO; a minor portion (<5%) of nitrogen oxide emissions (NOx) in the exhaust	Toxic gas. Under certain conditions causes photochemical smogs and ground level ozone.
Carbon Dioxide (CO_2)	Formed (along with water) during the complete combustion of hydrocarbon fuels	The increasing atmospheric concentration of CO_2 is the major controlling factor in global climate change
Carbon monoxide (CO)	Formed due to incomplete combustion of fuel.	May cause long-term damage to heart and nervous system.
Polycyclic aromatic hydrocarbons (PAH)	May be contained in the fuel and formed during combustion process.	Some PAHs are classified as carcinogenic.
Methane (CH_4)	Natural gas fuel. During incomplete combustion some gaseous fuel passes into the exhaust and is known as methane slip.	A climate change gas with twenty times the global warming potential of carbon dioxide over a timescale of 100 years and seventy times over 25 years.
Ammonia (NH_3)	Ammonia discharge into the exhaust may occur on marine diesel engine installations where Selective Catalytic Reduction (SCR) equipment is fitted. In marine installations ammonia, formed from urea is used as a reductant.	Toxic gas. In the atmosphere may react with sulphur dioxide to form ammonium sulphate aerosols.

Table 1: Gaseous pollutants and climate change agents

1.1.3 Primary particulates

Primary particulates consist of the components and compounds of combustion of the fuel and to a lesser extent, the lubricant on the cylinder liner wall. The combustion process in a diesel engine is known as diffusion combustion. The fuel and air are not premixed and the combustion proceeds as long as the flame front can find oxygen and the gas temperatures are high enough to retain the flame front. Whilst the aim is to maximise the energy release from the fuel and convert all of the hydrocarbons to carbon dioxide (CO_2) and water (H_2O), zones with a shortage of oxygen may result on the formation of carbon monoxide (CO). As combustion proceeds and the combustion space expands due to the displacement of the piston, the gases cool rapidly and a very small portion of the fuel may avoid oxidation or simply go through a change of composition forming a range of other organic particles.

The fuel may also contain metals, most notably vanadium and nickel but at quite low concentrations. The lubricant may contain magnesium, calcium, zinc and phosphorus which are the predominant metals used in modern additive technology.

Metals may be oxidised but usually do not form vapours. These incombustible products are known as "ash" and form a relatively minor part of the overall primary particulate emission.

Primary particulate formation is believed to follow a sequence of nucleation, where extremely small nano-particles of soot (predominantly elemental carbon) are formed by pyrolysis and polymerisation of the injected fuel droplets, followed by growth from the adherence of combustion related materials and aggregation as the soot particles collide to first form clusters of spheroids and then ultrafine chain type structures in the cylinder. Particles at any one of these stages may be present at the same time during combustion and although engine design should ensure most are fully burned, it is inevitable that some soot and ash particulate will exit the cylinder.

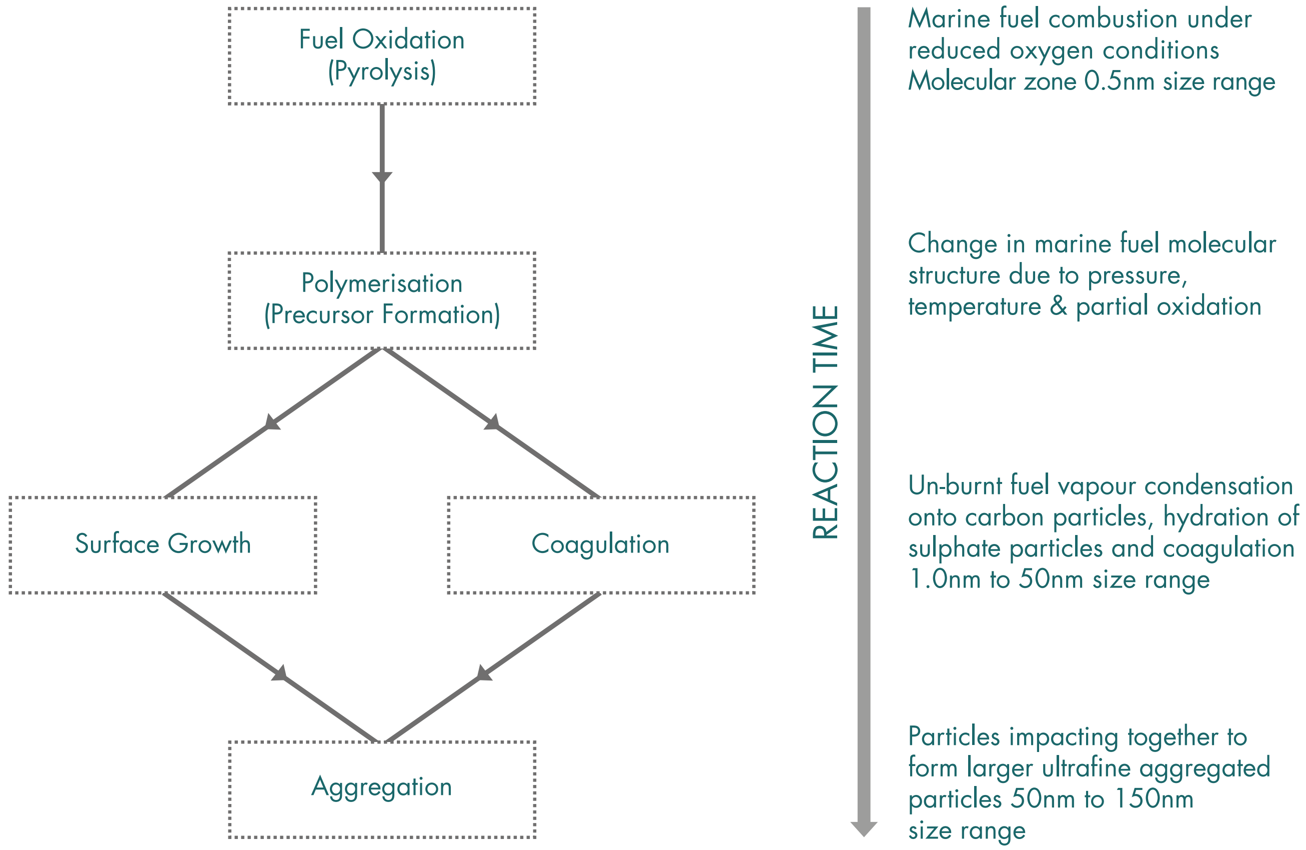


Figure 4: Particle formation – diesel engine fuel combustion

On leaving the cylinder, the exhaust cools and larger and more complex particles are formed as various incompletely burned hydrocarbons (known as the soluble organic fraction -SOF) accumulate onto the surface of the particulate by adsorption and condensation. In addition atmospheric dilution and cooling of diesel exhaust triggers the nucleation of new particles such as semi-volatile hydrocarbons and sulphuric acid.

A small proportion of the gaseous sulphur dioxide from the fuel sulphur is oxidised to SO_3, which either reacts with water to form sulphuric acid (H_2SO_4), undergoes gas phase oxidation and condensation to form sulphate particles or is oxidised as sulphate onto the particulate formed during combustion. These sulphates are hygroscopic with a high affinity for water.

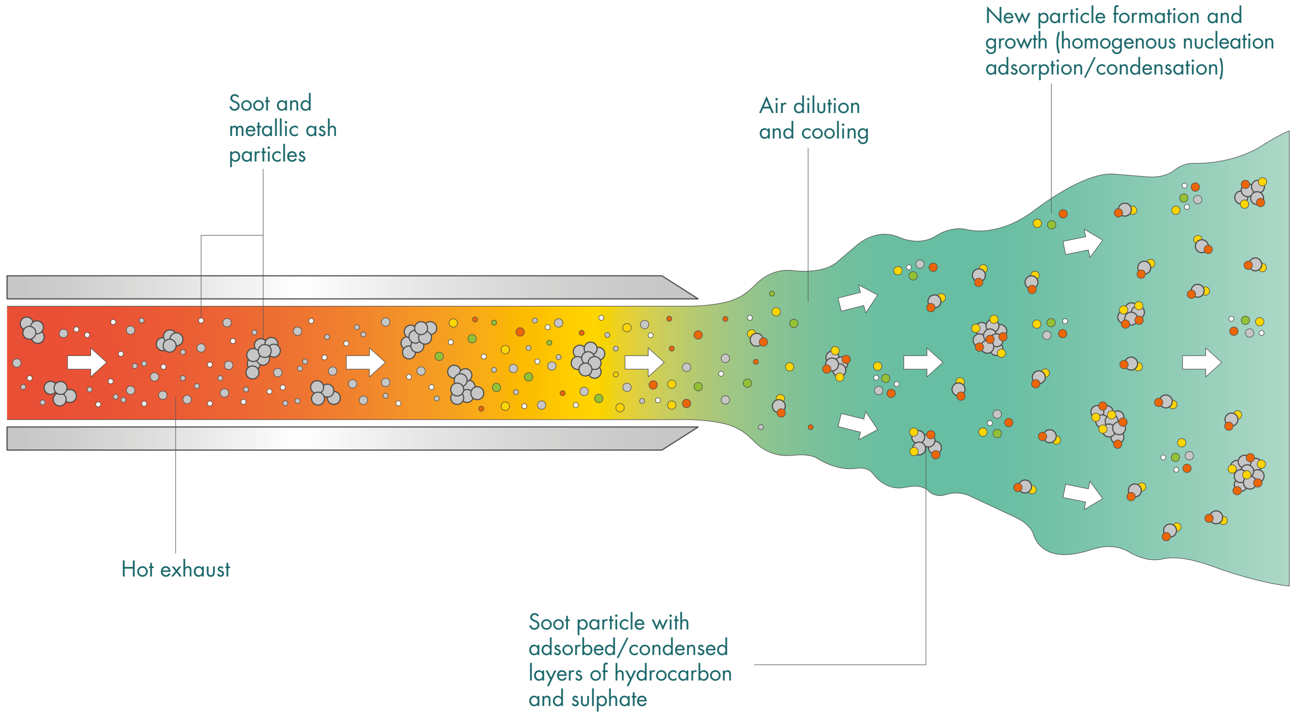


Figure 5: The effects of cooling and air dilution

Courtesy Technology Today, Spring 2006 Dr Imad A. Khalek, SwRI, The Particulars of Diesel Particle Emissions

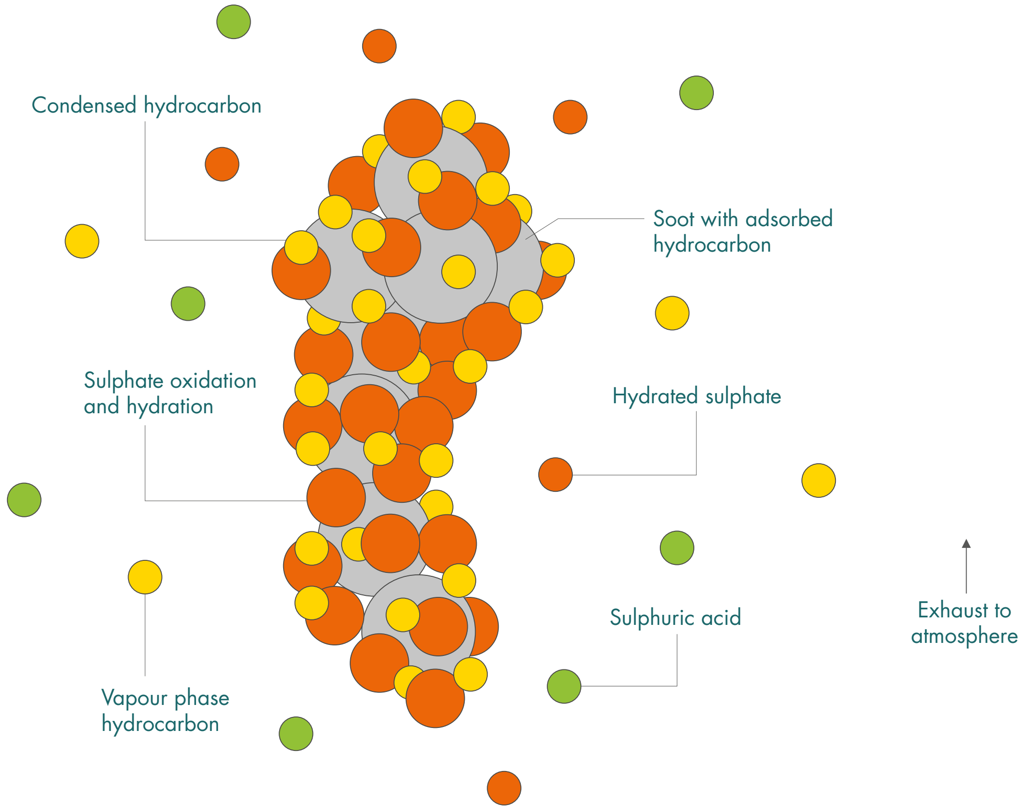


Figure 6: Diesel engine particulate
(Solid carbon spheres (10 to 80nm diameter) form to make ultrafine solid particles. Ultrafine particles agglomerate with adsorbed hydrocarbons to form larger particulate (0.5 to 1.0µm diameter). Fenger & Tjell Air Pollution 2009 [94])

The predominant size range by quantity of particulate emissions from internal combustion engines is 100nm with a bimodal distribution of particles and a second peak in the range of 2.5μm.

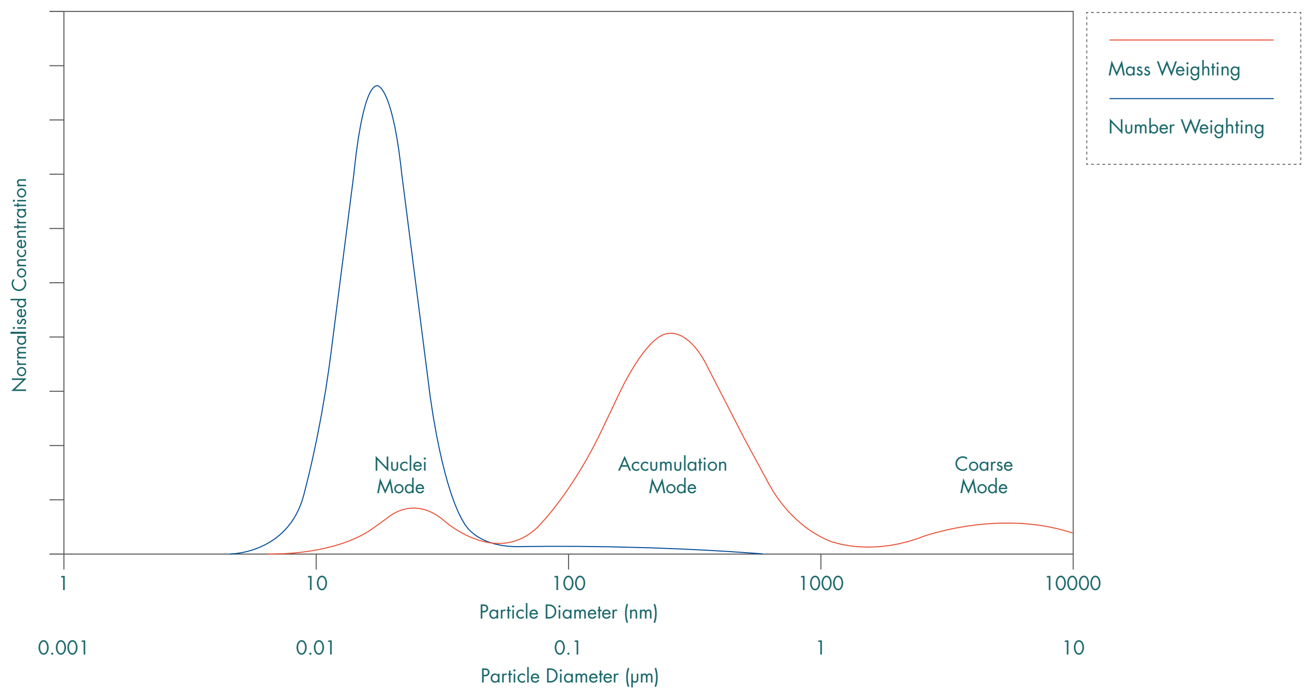


Figure 7: Graph of bimodal range of PM for diesel engines

1.1.4 Secondary particulates

In high sulphur fuel combustion, the predominant secondary particulates produced, dependent on other precursors, are sulphates (ammonium sulphate). Although of a lesser magnitude many other secondary particulates and condensates are formed once the exhaust gases cool. When considering a mobile emission source such as road transport, vehicle exhaust gas emissions are in close proximity to the human population and it is expected that the extended range of hazardous air pollutants will have a direct effect on local air quality. That is why unlike power utilities where PM is measured in the hot gas phase, road transport PM measurement is undertaken once the exhaust gases are cooled. Currently there are no standards for the measurement of marine diesel engine PM emissions. It is likely that any future measurement standard will follow the road transport PM measurement requirements as the impacts are much more likely to be the effects on local air quality. (For further information on PM measurement techniques see Section 7.1.2)

2. Regulations and Guidelines

2.1 International Maritime Organization (IMO)

IMO's 1997 protocol to amend MARPOL 73/78 added Annex VI - Regulations for the Prevention of Air Pollution from Ships. This entered into force on 19 May 2005. Regulation 14 included a 1.50% limit on the sulphur content of fuel to be used in a SOx Emission Control Area (SECA). Alternatively the use of an approved Exhaust Gas Cleaning System to reduce the total emissions from the ship to an equivalent level of 6g SOx /kW h was permitted.

On 11 August 2006 the Baltic Sea became the first fully implemented SECA. This was approximately 3 months later than the date under Annex VI as it was necessary to allow European Union member states time to transpose the requirements into national law. One year later, on 11 August 2007 the North Sea and English Channel became the second SECA under European Commission Directive 2005/33. (This was approximately 3 months earlier than under Annex VI, which set a date of 21 November 2006 for the SECA to enter into force followed by an exemption period of 12 months).

Almost immediately after Annex VI came into force in 2005, IMO began a review with the "aim of significantly strengthening the emissions limits in light of technological improvements and implementation experience". This work was completed and adopted by IMO in 2008 and the revised Annex VI with associated NOx Technical Code entered into force in July 2010.

A key revision was the change from SOx Emission Control Area to Emission Control Area (ECA), which is defined as an "area where the adoption of special mandatory measures for emissions from ships is required to prevent, reduce and control air pollution from NOx or SOx and particulate matter or all three types of emissions and their attendant adverse impact on human health and the environment".

As a result there will be a phased reduction of SOx emissions in ECAs by reduction of fuel sulphur from the current limit of 1.00%, which was introduced in July 2010 to 0.10% in January 2015.

Outside of ECAs, the global limit of 4.50% sulphur-in-fuel was reduced to 3.50% at the beginning of 2012, and will be further reduced to 0.50% in 2020 or 2025 depending on a review to be completed by 2018 to determine the availability of fuel to enable implementation of this standard.

In March 2010 the sixtieth session of the IMO Marine Environment Protection Committee (MEPC 60)[10] adopted a proposal from the USA and Canada for an ECA extending 200 nautical miles from both east and west coasts and around the islands of Hawaii [5], [6], [7]. Unlike the Baltic and North Sea, which will remain SOx Emission Control Areas for the time being, the North American ECA is for SOx, particulate matter and NOx. It will become fully implemented on 01 August 2012.

A similar proposal for an ECA around Puerto Rico and the U.S. Virgin Islands was submitted by the USA for discussion at MEPC 61 in September 2010 [58], [59], [60]. The proposal was adopted at MEPC 62 in July 2011 and will be fully implemented on 01 January 2014.

Figure 8: MARPOL Annex VI Emission Control Areas
(See Appendix 3 for geographic co-ordinates of MARPOL Annex VI ECA)

2.1.1 Compliance by Exhaust Gas Cleaning

Annex VI now uses the sulphur content of fuel as a way of defining SOx emissions and specific emissions limits (grams SOx per kilowatt hour) are no longer given. Although sub-titled 'equivalents' in order to clarify that these fuels are not mandatory, the revised regulation 4 confirms that an Administration can allow alternatives, including "any fitting, material, appliance or apparatus… if such… methods are at least as effective in terms of emissions reduction as that required by the Annex". This means that both inside and outside of ECAs approved abatement technologies can be used to reduce SOx emissions to a level that would be produced by the sulphur-in-fuel limits.

Both the desulphurisation of flue gas in industrial process and power plant and the seawater scrubbing of ships' boiler exhausts to produce inert gas for the safe carriage of oil cargoes have been successfully used for many years. However the cleaning of ships' exhausts to reduce sulphur oxides whilst monitoring emissions to both air and water is a relatively new application.

In 2004, with the impending entry into force of MARPOL Annex VI, the development of Guidelines for Exhaust Gas Cleaning Systems was raised from a low to high priority by IMO and an initial version was adopted in 2005 – IMO Resolution MEPC 130(53).

The first marine Exhaust Gas Cleaning Systems used water to remove sulphur oxides and particulate matter from exhaust streams, however the engineering technology used by different manufacturers has varied considerably and there is one supplier of a 'dry' system that uses granulated lime as a scrubbing medium. Although future updates may be expected to specifically recognise the approval and use of dry systems the Guidelines for Exhaust Gas Cleaning Systems have been performance rather than design-based from the outset and contain 2 methods of achieving compliance with regulation 14. The methods are detailed later in this book, but can be summarised as:

- 'Scheme A' – initial certification of performance followed by periodic survey with continuous monitoring of key operating parameters and daily emission checks to confirm performance in service; and
- 'Scheme B' – performance confirmation by continuous monitoring of emissions with daily checks of key operating parameters.

Under both schemes emissions of 'washwater' to sea must be monitored and importantly rather than monitoring the specific emissions rate of SO_2 in g/kW h, the ratio of parts per million-sulphur dioxide to percentage-carbon dioxide (SO_2 ppm/CO_2 %) is allowed. This offers a number of practical advantages, which will also be explained later.

As practical experience has grown, the Guidelines for Exhaust Gas Cleaning Systems have been reviewed with a particular focus on washwater emissions. This enabled an updated version to be adopted in 2008 – IMO Resolution MEPC 170(57), which contained extensive revisions to improve the structure and logic of the document and washwater emissions criteria. It was agreed that the washwater criteria "should be revised in the future as more data becomes available on the contents of the discharge and its effects, taking into account any advice given by GESAMP", The Joint Group of Experts on Scientific Aspects of Marine Environmental Protection – an advisory body to the United Nations. It was also agreed later in 2008 that 170(57) should remain valid until the revised MARPOL Annex VI entered into force in July 2010.

In 2009, a third iteration of the Guidelines for Exhaust Gas Cleaning Systems, – IMO Resolution MEPC 184(59), was adopted and this latest version replaced 170(57) in July 2010. The latest Guidelines reflect the changes to Annex VI and include the SO_2/CO_2 ratios relating to various levels of sulphur-in-fuel, as the requirement to determine a specific SOx emissions value in g/kW h is no longer required. It was once again agreed that the washwater discharge criteria should continue to be reviewed taking into account advice received from GESAMP.

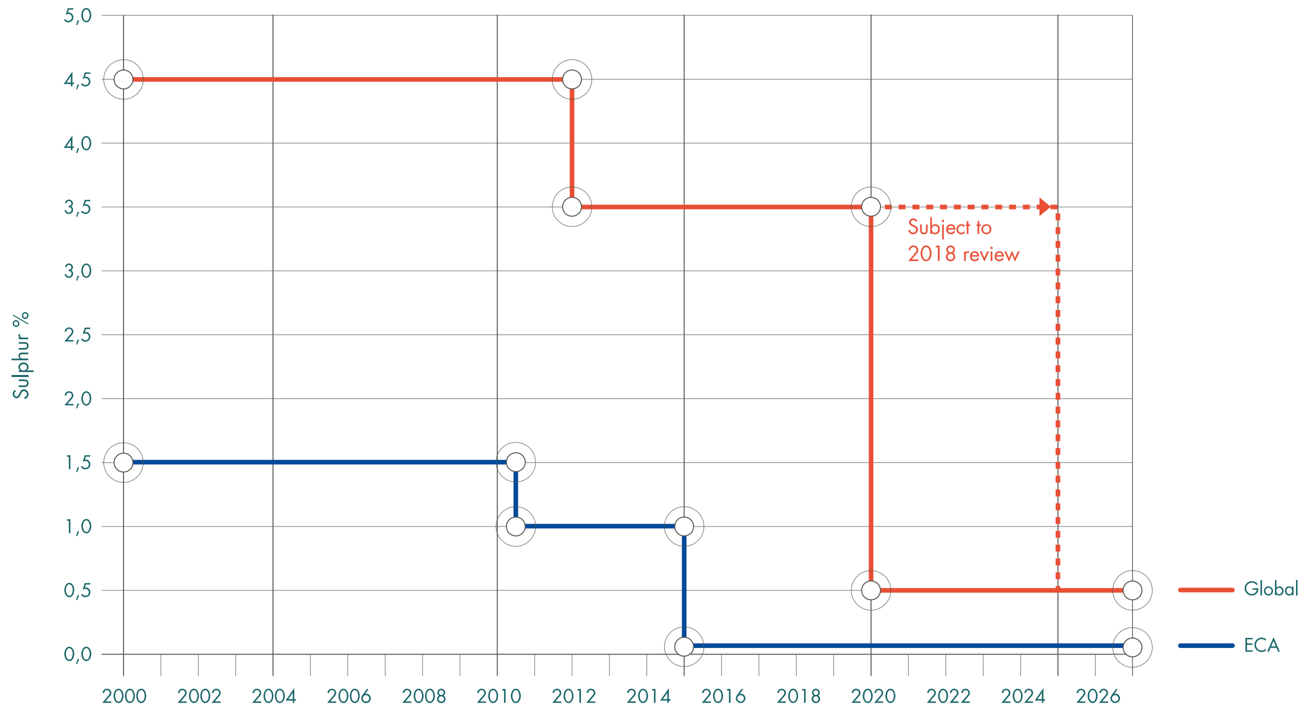


Figure 9: IMO timeline for reduction in fuel sulphur content

2.2 Regional Emissions Control

2.2.1 Europe

In addition to IMO's regulations for the North Sea and Baltic ECAs, European Council Directive 2005/33/EC (which amends Directive 1999/32/EC) requires all vessels in a European Union member state port, at berth or at anchor to use 0.10% sulphur fuel*. The Directive also requires that during 'regular' service between member state ports and in European Union waters, passenger vessels must use a fuel containing no more than 1.50% sulphur. This could mean a passenger vessel potentially having to use 3 fuels whilst in transit and a fourth for power generation if in a EU port for more than 2 hours:

- Outside of ECAs and European waters – the IMO global sulphur limit applies
- In European waters outside of ECAs 2005/33/EC limit applies – 1.50% sulphur fuel
- In ECAs the IMO limit applies – 1.00% sulphur fuel (See Info Box 2)
- In EU port for more than 2 hours 2005/33/EC limit applies – 0.10% sulphur fuel

Whilst in transit, passenger ships on regular service between EU ports could use 1.00% sulphur fuel because availability will be greater and multiple fuel changeovers can be avoided. However the potential technical complexity surrounding fuel switching and onboard storage and handling systems, in order to ensure legal compliance with all of the above requirements should be noted.

2005/33/EC allows abatement technologies to be used to achieve emissions that are equivalent to the sulphur-in-fuel limits either during a trial approved by EU member states or if the equipment has been properly approved, "taking into account guidelines to be developed by the IMO".

*The following are currently exempted:
- Ships that spend less than 2 hours at berth according to published timetables
- Ships that switch off all engines and use shore-side electricity

As an alternative to using low sulphur marine fuels meeting the requirements of Articles 4a and 4b, Member States may allow ships to use an approved emission abatement technology, provided that these ships:

- Continuously achieve emission reductions which are at least equivalent to those which would be achieved through the limits on sulphur in fuel specified in this Directive,
- Are fitted with continuous emission monitoring equipment, and
- Document thoroughly that any waste streams discharged into enclosed ports, harbours and estuaries have no impact on ecosystems, based on criteria communicated by the authorities of port States to the IMO

In other words the Directive requires a performance-based approach that can be considered the same as Scheme B of the Guidelines for Exhaust Gas Cleaning Systems

Info Box 1: Article 4c of Directive 2005/33/EC

As 2005/33 and 1999/32 are no longer fully aligned with MARPOL air pollution regulations the EC is in the process of harmonising its sulphur Directive for ships with the latest revisions to Annex VI. It is proposed that the additional requirement to use 0.10% sulphur fuel in port remains in place and that passenger vessels will continue to use no more than 1.50% sulphur fuel when operating on regular services to or from any EU port whilst in member state territorial seas, exclusive economic zones and pollution control zones falling outside of ECAs. It is proposed that this be reduced to 0.10% in 2020 so restoring the link with ECA requirements.

The proposal defines an emission abatement method in line with the revised MARPOL Annex VI, but adds that the alternative method of compliance must be "verifiable, quantifiable and enforceable". Exhaust Gas Cleaning Systems must specifically comply with MEPC 184(59) although continuous monitoring of sulphur dioxide emissions remains a requirement [53].

Although the updated Directive has yet to be finalised the EC has issued official advice confirming the latest MARPOL Annex VI sulphur-in-fuel limits must be used during the interim period [54].

Q: What fuel do I need to use if I want to enter a SECA after 1 July 2010?

A: According to the revised MARPOL Annex VI, only fuel with a maximum sulphur content of 1.00% can be used.

Q: The EU Directive contains a limit value of 1.5%? Is this still applicable?

A: The 1.5% limit in EU law is still in force, but operators must comply with the stricter limit of 1.00% of the revised Annex VI. The Commission is in the process of amending EU law for the purpose aligning the limits contained in the EU Directive with those in MARPOL. Annex VI.

Q: What if a ship uses fuel exceeding 1.00% but below 1.5% sulphur whilst in 'an EU SECA'?

A: The ship is in breach of MARPOL Annex VI. It will be up to the Flag State and the Port States to apply sanctions to the ship and to ensure that the ship continues its voyage using compliant fuel.

Q: What fuels must passenger ships use when operating on regular services to or from EU ports?

A: If a passenger ship operates in one of the seas designated as SECA, it has to use fuel not exceeding 1.00% sulphur as required by MARPOL Annex VI. If a passenger ship operates outside the SECAs but is operating a regular service to or from an EU port, than the ship has to use fuel not exceeding 1.5% sulphur as required by the Directive 1999/32/EC relating to the sulphur content in liquid fuels.

Info Box 2: EC – new sulphur standard for shipping

In the final step to amendment of the Directive the European Parliament debated marine fuel sulphur limits in September 2012 and posted a statement, which included the following [98]:

"Stricter limits on the sulphur content of shipping fuels are set to improve air quality along European coastlines and reduce the estimated 50,000 premature deaths caused each year by air pollution from ships. Parliament today approved legislation agreed with member states, which requires new general limits to be in place by 2020".

"Highly polluting shipping fuels have a serious impact on the environment but this is also the most important health reform of this parliamentary mandate. With air pollution from shipping expected to outstrip land-based emissions by 2020, urgent remedial action is needed".

"The new rules will bring European legislation in line with limits agreed by the International Maritime Organization. The general sulphur limit for fuels in European seas will fall from 3.5% to 0.5% by 2020, after MEPs [Members of the European Parliament] insisted on deleting provisions that would have allowed the deadline to be postponed by five years".

"Fuel used in the Baltic Sea, North Sea and English Channel – Europe's 'sulphur emission control areas' (SECAs) – will need to meet the new international standard of 0.1% by 2015 (from 1% currently)".

"The limits can be met by using cleaner fuels or technology, such as scrubbers, that can deliver an equivalent result".

"As part of its review of air quality legislation, the legislation asks the Commission to consider extending the stricter SECA limits to all EU territorial waters, i.e. within 12 nautical miles of the coastline."

2.2.2 USA and Canada

United States federal marine air pollution legislation defines three categories of engine, subdivided by cylinder displacement and engine power or speed. Each sub division has Tiers of reducing emission limits for NOx, particulate matter, carbon monoxide and hydrocarbons and a model year from which the limits will apply [61], [62].

Title 40 of the U.S. Code of Federal Regulations, CFR Part 1043 [63] incorporates MARPOL Annex VI into U.S. Law. With the exception of a small number of old vessels operating on the Great Lakes the regulation is for all U.S. flagged Ocean Going Vessels (OGV) operating worldwide including the United States, and foreign flag vessels whilst in U.S. waters. (Part 1043 not only applies to open seas and the ECAs defined under Annex VI, but also all U.S. internal waters that are navigable including the Great Lakes). As such emissions of NOx, SOx and PM are controlled from the largest Category 3 marine engines with a per cylinder displacement of over 30 litres. Smaller category 1 and 2 auxiliary engines on vessels with Category 3 propulsion engines are also permitted to comply with Annex VI under 40 CFR Part 1042.650 [62].

The U.S. Environmental Protection Agency (EPA) and the U.S. Coast Guard (USCG) jointly enforce U.S. and international air pollution requirements for vessels operating in U.S. waters [79]. In its Interim Guidance on the Non-Availability of Compliant Fuel Oil for the North American Emission Control Area [80], the EPA states that:

- "First, and most importantly, fuel oil that complies with the 1.00% m/m (10,000 ppm) sulfur standard is expected to be available for ships that plan to operate in the North American ECA [from 01 August 2012] just as it has been available for ships operating in the North Sea and Baltic Sulfur Emission Control Areas since July 2010".
- "The United States government also expects that vessel operators are vigorously preparing for the 0.10% m/m (1,000 ppm) MARPOL Annex VI ECA fuel oil sulfur standard that will become effective January 1, 2015, and that will likely necessitate the use of distillate fuel oil. We expect that vessel operators will be prepared to operate their vessels using fuel oil that meets the 0.10% m/m (1,000 ppm) sulfur standard as soon as that standard takes effect."

Whilst it is not required to bunker distillate if 1.00% sulphur residual fuel is unavailable, ship operators must make best efforts to procure compliant fuel. If best efforts have been made and the fuel cannot be obtained the United States and the vessel's flag Administration must be formally advised no later than 96 hours before entry into the ECA. However this will not mean the ship is deemed to be in compliance with MARPOL Annex VI. The U.S. government will take into account the information provided as well as all relevant circumstances, to determine what action, if any, to take in response to the MARPOL Annex VI violation.

Compliant fuel oil, if available, must be purchased from a U.S. port-of-call prior to further transit in the North American ECA. "Furthermore the United States government may require additional documentation and substantiation of fuel oil non-availability claims from owners or operators of ships that have submitted repeated or multiple Fuel Oil Non-Availability Reports. The United States government may also consider conducting more extensive inspections or exams of such ships while in port."

Rather than using low sulphur fuel the guidance document reconfirms that approved Exhaust Gas Cleaning Systems can be used as an equivalent method of compliance.

It is an additional and separate requirement of The California Air Resources Board that distillate fuel is to be used in all main and auxiliary engines and boilers of Ocean Going Vessels within 24 nautical miles of the Californian coast unless on "continuous and expeditious navigation" [70]. If a vessel is calling at a California port facility or anchorage or entering internal waters such as an estuary, the following fuels have been required since December 2011 [64], [68]:

- Until August 2012 marine gas oil (MGO), with a maximum of 1.5 percent sulphur, or marine diesel oil (MDO), with a maximum of 0.5 percent sulphur
- From 01 August 2012 marine gas oil (MGO), with a maximum of 1.0 percent sulphur, or marine diesel oil (MDO), with a maximum of 0.5 percent sulphur
- After 01 January 2014 marine gas oil (MGO), or marine diesel oil (MDO), with a maximum of 0.1 percent sulphur

The second step coincides with the North American ECA becoming fully implemented. It partly harmonises the California fuel rule with Annex VI, although the latter does not stipulate that distillate fuel must be used in an ECA nor does it link sulphur content to the fuel grade.

In order to maximise the effectiveness of the new measures and discourage commercial shipping from using alternative routes outside of the controlled area the geographic boundaries of where the California fuel rule applies were also updated as of December 2011. The alternative routing was commercially attractive to ship operators as it reduced fuel costs but impinged on an active military sea range.

Abatement technologies including Exhaust Gas Cleaning Systems may be used in trials of up to 6 years (3 years + 3 year extension) as part of an emissions control research programme officially approved by the Californian authorities. However the fuel rule also states that if the USA adopts federal regulations that achieve emissions reductions within the regulated California waters that are equivalent to those achieved by the sulphur-in-fuel limits, then the limits will cease to apply. This appears to open the door for approved abatement technologies to be used after January 2015 under regulation 4 of the revised MARPOL Annex VI and CFR Part 1043.

The foregoing further illustrates the complex nature and fluidity of national, regional and international marine fuel rules that must be followed in order to comply with air pollution regulation. Again there are attendant technical considerations. Unless an approved emissions abatement system is fitted or the lowest sulphur content and therefore more expensive fuel oil permanently used, there is a need for properly managed fuel switching when moving between areas where different emissions limits apply. The practical and safety issues of fuel switching are subject of several advisory notices from industry bodies including the Classification Societies, ship operator associations and national coast guards. An example from the U.S. Coast Guard is given in Appendix 5.

2.3 Future Emission Limits

MARPOL Annex VI regulates the emissions of sulphur dioxide and nitrogen oxides. Indirectly secondary particulate matter is also regulated through the reductions in the formation of sulphate aerosols. The current regulation 14 limits are much less onerous when compared to limits for on-road vehicles and in some cases less restrictive than limits on industrial combustion plant.

The U.S. Environment Protection Agency (EPA) imposes stricter limits on marine diesel engines built for use on US flag vessels. The current limits shown in the Table 2 apply to the large Category 3 engines.

U.S. EPA CATEGORY 3 (LARGE MARINE ENGINES) – EMISSIONS STANDARDS		
POLLUTANT	CURRENT STANDARD FOR NEW ENGINES TIER II	2016 STANDARD FOR NEW ENGINES TIER III
NOx (g/kW h)	14.4 to 7.7 (engine speed dependent)	3.4 to 2.0 (engine speed dependent)
CO (g/kW h)	5.0	5.0
HC (g/kW h)	2.0	2.0
PM	To be reported by OEM	To be reported by OEM

Table 2: U.S. EPA Category 3 engine emission limits

Category 1 and 2 marine engines are subject to more stringent requirements. There is no reason to suppose that the more stringent will not eventually be imposed upon Category 3 marine engines.

Given the stricter limits imposed in other sectors and the continued growth of fuel consumption in the merchant marine it is inevitable that additional limits will be introduced at IMO. The Exhaust Gas Cleaning Systems Association believes that future IMO mandated emissions limits will include carbon monoxide (CO), hydrocarbons (HC), particulate matter (PM) and black carbon (BC).

2.3.1 Carbon Monoxide (CO)

Diesel engines and boilers have relatively low emissions of carbon monoxide, due to the large amounts of excess air and well-formed steady state combustion respectively. Nevertheless whenever there is a lack of oxygen in the combustion process (perhaps due to sudden change in engine load and turbocharger lag) or a relatively low temperature towards the end of the expansion stroke, carbon may only oxidise to carbon monoxide rather than complete oxidation to carbon dioxide. This effect applies to all types of fuels including natural gas and bio derived fuels.

Carbon monoxide is extremely hazardous to life in high concentrations; it is also highly flammable. Although not regarded as a climate change gas, CO indirectly increases the amount of other climate change gases (methane), by reacting with atmospheric compounds that otherwise have a controlling effect [95]. CO eventually oxidises to carbon dioxide.

Ship's systems must be designed to avoid build-up of CO in confined spaces. However at low concentrations CO remains a hazard, with long-term exposure causing heart disease and damage to the nervous system.

Control of carbon monoxide emissions as part of an Exhaust Gas Cleaning System is relatively straightforward. The most common method used in on-road vehicles is with an oxidation catalyst. Such systems may be included in future marine Exhaust Gas Cleaning Systems.

2.3.2 Hydrocarbons (HC)

Unburned fuel in exhaust gases is classified as hydrocarbons. In steady state combustion such as boilers this can occur during commencement of firing or during start-up under cold conditions. Under steady state and correctly adjusted firing conditions HC emissions from boilers should be negligible.

This is not the case for diesel engines where a number of factors conspire towards incomplete combustion. These include light load running or idling and sudden changes in engine load and turbocharger lag. Combustion is also inhibited by the cool expanding combustion gases as the piston moves down inside the cylinder and fuel can lodge in crevices such as the annular space between the piston crown land and the liner wall.

Apart from minor loss of energy, unburned hydrocarbons are a photo-chemical pollutant which may under certain atmospheric conditions create photo-chemical smogs and increase ground level ozone. In the case of natural gas as a diesel engine fuel, methane slip causes both a pollutant and is a climate change gas with a global warming potential 20 times greater than that of carbon dioxide (see Table 1).

Hydrocarbon emissions can be eliminated in exhaust gas treatment systems, with on-road vehicles using an oxidation catalyst.

2.3.3 Particulate Matter (PM)

MARPOL Annex VI, regulation 14 mentions in the title emissions of particulate matter. However the regulation does not set any limits. This is in stark contrast to most other sectors of industry and transportation. In Europe and North America only aviation PM emissions remain unregulated.

Particulate matter emissions are present for all types of fuels and thus the only means of limiting emissions is by use of Exhaust Gas Cleaning Systems. Both wet and dry scrubbers can be effective in removal of micron range PM, and are capable of achieving virtually zero emissions.

However diesel engines produce a much higher number of ultrafine particles. Studies indicate that the ultrafine PM may have significant and harmful health effects. On-road vehicles have had imposed a continuous lowering of PM limits due to these concerns.

The removal of ultrafine particles appears to be more effectively achieved at lower temperatures created by wet scrubbers, however further development work is needed before zero emissions of ultrafine PM can be achieved. Dry scrubbers may take on the on-road approach using particulate traps and periodic regeneration.

2.3.3.1 Black Carbon (BC)

Black Carbon is a form of ultrafine particulate matter, which has a very high surface area to mass ratio and acts as a very effective black body radiator. It is estimated [96] that transport diesel emits about 22% of anthropogenic Black Carbon and that some of these emissions may be contributing to the accelerated ice loss in the Arctic.

A definition of Black Carbon from international shipping has yet to be agreed by IMO. This is currently under discussion along with possible measurement techniques and control measures [99], [100], [101].

Black Carbon is defined by UNFCCC as having the second highest anthropogenic sourced climate change forcing impact after carbon dioxide.

Black carbon acts in two ways to accelerate climate change:

1. Fine particles in the atmosphere normally act as nucleation points for condensing water in the process of cloud formation. Black carbon particles act in a way that prevents cloud formation and thus allows greater radiant energy to reach the lower atmosphere and ground level.
2. Black carbon cover on ice and snow reduces the albedo effect (reflectivity) increasing the absorbance of radiant energy. The radiant energy is then transferred through to the ice and snow causing increased melt rates.

Although Black Carbon is a significant climate change agent it is short lived, (approximately days to weeks). The elimination of BC emissions from shipping would have an immediate effect in slowing the rate of climate change, possibly by several years.

Means to deal with BC are similar to exhaust cleaning techniques used for trapping and removal of other ultrafine particles.

3. Guidelines for Exhaust Gas Cleaning Systems (EGCS)

3.1 Introduction

The 2009 Guidelines for Exhaust Gas Cleaning Systems– MEPC 184(59) have been effective since 1st July 2010. The timing aligned with the entry into force of the revised MARPOL Annex VI, under which regulation 4 now permits the use of approved abatement technologies that are at least as effective in reducing emissions as the Annex's sulphur-in-fuel limits.

IMO cannot implement or enforce regulations, nor mandate that guidelines must be followed - the responsibility rests with the ship's Flag State and each national government. The bodies responsible for maritime matters related to territorial waters and ports provide what is known generically as 'port State Control' (PSC). The power of PSC is derived from national legislation and the existence of regional PSC organizations. When ratified by nations, regulations such as those within Annex VI, become law enabling their practical enforcement so that foreign ships in national ports can be inspected to verify the compliance of the ship and its equipment. Although the Guidelines for Exhaust Gas Cleaning Systems are just that – guidelines, which do not carry the same statutory weight as regulations, it would be normal for PSC to accept and apply them in the same way.

Although scrubbing technology has been successfully used on oil tankers and in shore-side industry for many years, exhaust gas cleaning to meet air pollution limits is a relatively new application for ships. IMO has recognised that as the technology continues to develop so the Guidelines for Exhaust Gas Cleaning Systems may have to evolve and has focussed in particular on the washwater discharge criteria. The current limits are intended to act as initial guidance for implementing Exhaust Gas Cleaning System designs and IMO has strongly requested that washwater samples be collected for analysis and data shared so that the criteria may be further reviewed in the future.

Figure 10: Longannet Power Station – Firth of Forth, Scotland UK

Courtesy _gee_flickr

The coal fired Battersea Power Station on the River Thames in London was one of the first commercial applications of flue gas cleaning using water. This continued from the early 1930s to the 1960's. Later the process using seawater was applied to boilers, smelters and refineries. The first in Norway was fitted to an aluminium smelting plant in 1968 followed by a number of industrial oil fuelled boilers. In 1981 a pilot plant was fitted to an oil fuelled utility boiler at the Cabras power station on the island of Guam. This was subject of a long-term bioassay test program using plankton, shellfish and other marine organisms in aquaria with water from the cleaning system's treatment plant. Using similar organisms kept in fresh seawater as a cross reference, no harmful effects were found on the marine life over a one year test period. The test was carried out by marine biologists from R.W.Beck and Associates and was monitored by the U.S. EPA. [22]

The expansion of seawater flue gas desulphurisation, or SWFGD as it is known ashore, has gathered pace. In 1988 a unit capable of handling gas flow from a source equivalent to 125 MW was fitted to a coal-fired power station – Tata's Trombay Unit 5 in Mumbai, India. In 1989 the equivalent of a 110 MW unit was fitted to the catalytic cracker at Statoil's Mongstad refinery in Norway. The equivalent of 160MW and 130MW units were also fitted to oil fuelled power stations on Tenerife in 1995 and Cyprus in 2005. [23]

Not only has the use of SWFGD increased but so too has the size of the installations. The equivalent of eight 700MW units were fitted to coal fired power stations in Malaysia from 2002 to 2008 and three units each capable of handling gas flow from a source equivalent to 600 MW were commissioned at the Longannet coal fired power station on Scotland's Firth of Forth in 2009. The latter is of particular note as alkaline estuarial waters are used for the scrubbing process and this was regarded as the "Best Available Technique" for abatement of sulphur dioxide under the terms of UK Pollution Prevention and Control Regulations [24]. Compliance with the regulations is monitored by the Scottish Environmental Protection Agency. [25], [26]

The reference list of one major supplier to land based industry shows over 90 SWFGD units either installed or pending and that these manage sulphur dioxide emissions from sources with an equivalent total power of over 32GW (32 x 10^9W). [23]

Info Box 3: Flue gas desulphurisation with water in land based applications

3.2 Overview

Similar to the requirements of the NOx Technical Code for engines, an Exhaust Gas Cleaning (EGC) unit may be used subject to parameter checks following initial certification of its emissions performance or it may be equipped with an approved emission monitoring system. However unlike the NOx Technical Code the monitoring of a specific SOx emission rate (grams per kilowatt hour) is not required. Instead monitoring the ratio of SO_2 (sulphur dioxide) to CO_2 (carbon dioxide) emissions is permitted.

Sulphur oxide emissions from an engine (or other combustion unit such as a boiler) are almost entirely derived from the sulphur content of the fuel and unlike NOx formation are not related to engine design, operation and combustion conditions. The majority of CO_2 is also derived from the combustion of hydrocarbon fuel and typically makes up about 6% of a diesel engine's exhaust gas. The SO_2/CO_2 ratio therefore gives a robust measure of SOx emissions in proportion to the sulphur content of the fuel burned, which greatly simplifies monitoring requirements without compromising accuracy. Gas concentrations (parts per million/percent) can be used rather than determining the actual mass flow rate of SO_2 and engine (or boiler) power is not required. It also removes the need to measure parameters such as engine speed and fuel flow as well as various other temperatures and pressures that are required under the NOx Technical Code. (Further technical details are given in the Guidelines for Exhaust Gas Cleaning Systems under Appendix 2 – "Proof of the SO_2/CO_2 Ratio Method").

Table 3 shows the SO_2 (ppm)/CO_2 (%) ratios that must be measured after an exhaust gas cleaning unit in order to achieve equivalence and therefore compliance with the sulphur-in-fuel limits under regulation 14.

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 3: Fuel oil sulphur limits recorded in MARPOL Annex VI regulations 14.1 and 14.4 and corresponding emissions values (For petroleum based fuel oils)

The Guidelines for Exhaust Gas Cleaning Systems specify the requirements for the test, approval/certification and verification of an EGCS. Typically a Classification Society will oversee the initial approval and ongoing survey processes on behalf of a flag State Administration and either Scheme A or Scheme B may be followed. The choice is typically made by the EGC unit manufacturer as part of their offer to the market:

- Scheme A requires initial certification of performance followed by periodic survey with continuous monitoring of key operating parameters and daily emission checks to confirm performance in service; and
- Scheme B allows performance confirmation by continuous monitoring of emissions with daily checks of key operating parameters.

Whichever scheme is employed, the condition of any water that is used for exhaust gas cleaning and then discharged to sea must be monitored and the data securely logged against time and ship's position. Those systems that require the addition of chemicals or create them for exhaust gas cleaning or conditioning of the washwater before discharge are required to undergo a specific assessment and, if necessary, implement the monitoring of additional washwater criteria.

An approved SOx Emissions Compliance Plan (SECP) is also required for ships fitted with an Exhaust Gas Cleaning System. This must demonstrate how the overall ship will comply with regulation 14 and is required to cover all fuel oil combustion units onboard i.e. all engines, boilers etc regardless of whether fitted with exhaust gas cleaning units or not.

3.3 Scheme A

Under Scheme A, an exhaust gas cleaning unit must have a SOx Emissions Compliance Certificate (SECC) prior to its use onboard. This certifies it is capable of meeting an SO_2/CO_2 emissions value specified by the manufacturer on a continuous basis with fuel oils of the manufacturer's specified maximum % sulphur content and for the range of operating parameters in the equipment's Technical Manual (ETM-A).

The emissions value should at least be suitable for ship operations under requirements of regulation 14 and is referred to as the "Certified Value".

The exhaust gas cleaning unit must be tested over a prescribed load range with one or more fuel oils to demonstrate its operational behaviour and that the emissions value can be achieved. Testing can be carried out either prior to, or after installation onboard and test data is to be submitted for approval together with the Technical Manual.

On approval the SOx Emissions Compliance Certificate is issued. (The Guidelines for Exhaust Gas Cleaning Systems also give the methods by which identical units and those of the same design but of different capacity may be certified without the need for repeat testing.)

A survey is required after installation onboard and the exhaust gas cleaning unit is also subject to periodic survey as part of the ship's International Air Pollution Prevention (IAPP) Certification. The Technical Manual must contain a verification procedure for these surveys. The basis of the procedure is that if all relevant components and operating values or settings are within those as approved, then the performance of the Exhaust Gas Cleaning System is within that required without the need for actual exhaust emission measurements. However to ensure compliance there is an additional requirement for certain system operating parameters to be continuously recorded and daily spot checks of emissions are also recommended.

An Onboard Monitoring Manual (OMM) is required to give details of the monitoring sensors and their position, care and calibration to ensure compliance. The OMM must be approved.

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 approval is granted, maintenance and service records can be recorded in the ship's planned maintenance system.

3.4 Scheme B

Under Scheme B, compliance is confirmed by continuous emissions monitoring with daily spot-checks of a number of Exhaust Gas Cleaning System operating parameters. Whereas under Scheme A, if all relevant components and operating values or settings are within those as approved, the performance of the EGC unit is within that required without the need for actual exhaust emission measurements, (although daily spots checks of the latter are recommended to ensure compliance).

Unlike Scheme A the exhaust gas cleaning unit does not need to be certified that it is capable of meeting an emissions value with fuel oils of the manufacturer's specified maximum % sulphur content. Instead a continuous emissions monitoring system has to show that the EGC unit achieves no more than the required SO_2/CO_2 emission value at any load point, including during transient operation, and thus compliance with the requirements of regulation 14.

The continuous emissions monitoring system must be approved and is subject to survey on installation. It is also subject to periodic survey as part of the ship's International Air Pollution Prevention Certification. An Onboard Monitoring Manual is required to give details of the monitoring sensors and how they are to be surveyed. It must also give their position, care and calibration to ensure compliance. The OMM must be approved.

A Scheme B Technical Manual (ETM-B) is also to be approved and the daily spot checks of various parameters that are required to verify proper operation of the Exhaust Gas Cleaning System must be logged in the system's EGC Record Book or the engine room logger system.

Emissions data must be securely logged against standard time and ship's position and be available for inspection as necessary to confirm compliance.

3.5 Washwater

Hot exhaust gases from marine diesel engines and boilers contain amongst other things oxides of sulphur, nitrogen and carbon, unburned hydrocarbons, and particulate matter, which comprises mainly carbon and ash together with oxidised and condensed material derived from the fuel oil and to a much lesser extent the combustion of lubricating oil [3]. These reach air, land and water based ecosystems when unscrubbed exhaust gases are emitted into the atmosphere. As most Exhaust Gas Cleaning Systems use water to remove sulphur oxides and particulate matter before they reach the atmosphere, the aim of the washwater criteria is to prevent the undesirable effects and components of the air borne emissions simply being directly transferred to the seas.

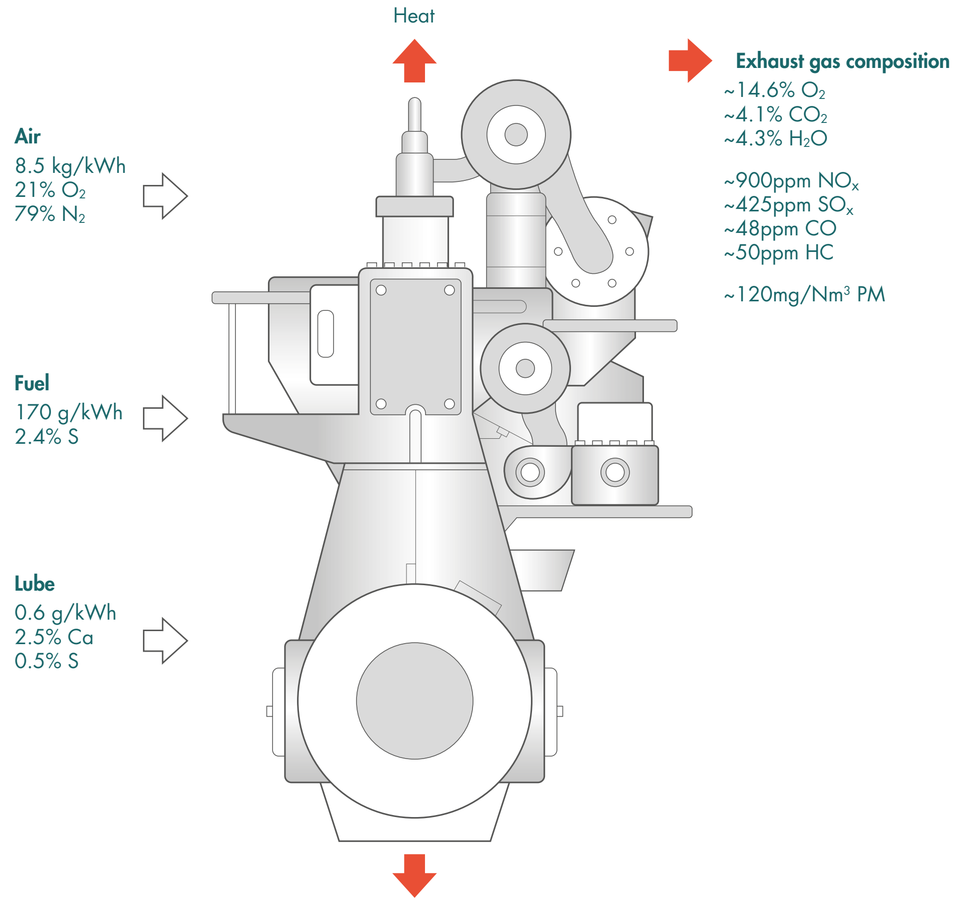


Figure 11: Typical exhaust gas composition – slow speed two stroke engine using residual fuel

The Guidelines for Exhaust Gas Cleaning Systems therefore require that the following washwater parameters are continuously monitored and the results securely logged against time and ship's position. Data has to be retained for a period of not less than 18 months from the date of recording:

- pH (with temperature compensation)
- Polycyclic Aromatic Hydrocarbon (PAH)
- Turbidity

3.5.1 pH

The Guidelines for Exhaust Gas Cleaning Systems require a limit of pH 6.5 to be applied using one of the following two methods:

1. The pH of the washwater at the ship's overboard discharge should be no less than 6.5 except during manoeuvring and transit, when a maximum difference of 2 pH units is allowed between the ship's washwater inlet and overboard discharge.

The two different pH discharge criteria for when the vessel is stationary and moving allow the adoption of a more stringent limit for stationary ships in ports when the main engine is not running, whilst still having a limit for moving ships. For vessels underway there is a highly effective mixing of the discharged washwater with fresh seawater by the turbulence from the ship's wake so that recovery of the pH to that of the surrounding water is very rapidly achieved.

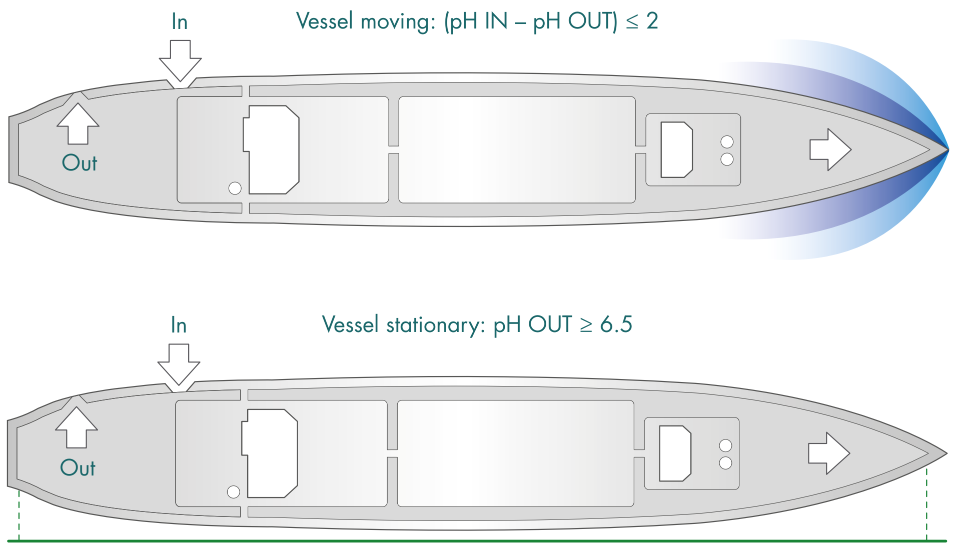


Figure 12: Measurement of position pH – Method 1

2. During commissioning of the Exhaust Gas Cleaning System, the pH of the discharged washwater plume should be measured externally from the ship (at rest in harbour). When the pH of the plume is equal to or greater than 6.5 at 4 metres from the discharge point the pH at the overboard pH monitoring point must be recorded. This then becomes the overboard pH discharge limit for the Exhaust Gas Cleaning System on the ship.

This alternative compliance method uses the CORMIX principle, which is used, by United States EPA and 4m is considered the boundary of the initial mixing zone between water discharged overboard and water surrounding the vessel.

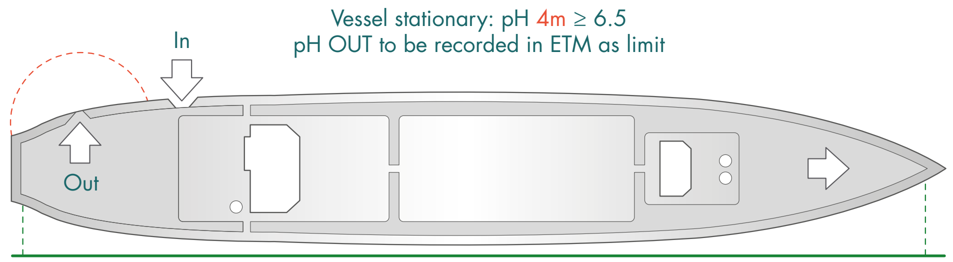


Figure 13: Measurement of position pH – Method 2

3.5.2 Polycyclic Aromatic Hydrocarbons (PAH)

Polycyclic aromatic hydrocarbons are a large group of organic compounds with two or more fused aromatic rings. PAHs occur naturally in petroleum and are also produced as by-products of fuel combustion.

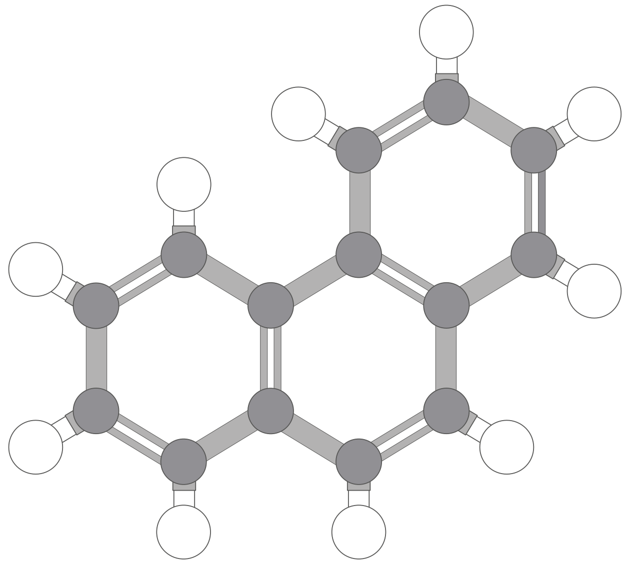


Figure 14: Phenanthrene $C_{14}H_{10}$

A source of PAHs is the incomplete combustion of fuel oils and although engines and boilers are designed to optimise the combustion of fuel, exhaust gases will always contain a proportion of incompletely combusted material. This results in gaseous hydrocarbon and particulate emissions that range from methane to very large complex molecules; a proportion of which will include polycyclic aromatic hydrocarbons [3]. Whilst low molecular weight PAHs are mainly found unbound in the gaseous phase of the exhaust stream, heavier molecular weight PAHs constitute a group of the substances that are bound onto soot created during combustion. [4]

PAHs can enter ecosystems via unscrubbed engine and boiler emissions to air however Exhaust Gas Cleaning Systems remove particulate matter and hence the heavier molecular weight and generally more toxic PAHs from the exhaust stream. Before washwater can be returned to the sea a treatment plant must remove the particulate matter. Low molecular weight PAHs may also be dissolved in the washwater so continuous online monitoring of PAH is used to ensure that the treatment is effective and marine ecosystems are not impacted. Furthermore, as PAHs are also found naturally in petroleum their monitoring ensures that un-burned oil does not enter the sea.

3.5.2.1 PAH measurement

The Guidelines for Exhaust Gas Cleaning Systems have PAH discharge limits based upon the concentration of 'phenanthrene equivalents' in the washwater. Studies to date have shown no negative influences of washwater on port environments and that phenanthrene from diesel exhaust is the most prevalent of the 16 U.S. EPA priority pollutants to be found in the washwater systems onboard [4]. The concept of equivalents is explained in the Addendum.

In order to control the total quantity of potentially unsafe and environmentally harmful PAH related material that is discharged, a limit of 50μg/l above that at washwater system inlet is related to a flow rate of 45t/MW h, which is typical for an open seawater Exhaust Gas Cleaning System.

FLOW RATE (t/MW h)	DISCHARGE CONCENTRATION LIMIT (μg/l PAH_{phe} EQUIVALENTS)	MEASUREMENT TECHNOLOGY
0 - 1	2250	Ultraviolet Light
2.5	900	– " –
5	450	Fluorescence*
11.25	200	– " –
22.5	100	– " –
45	50	– " –
90	25	– " –

Table 4: PAH discharge concentration limits

By relating the discharge limit to a flow rate different concentrations are acceptable requiring different monitoring technologies to be used. For closed systems with a very low discharge rate ultraviolet light absorption technology is appropriate. UV light at a specific wavelength is emitted and the amount of light absorbed by the PAH is used to determine the concentration in the washwater.

*At flow rates above 2.5t/MW h, the allowable concentration is lower and so the use of a more sensitive measurement technology is required. Ultraviolet light is again used but the technique makes use of the ability of selected PAHs to fluoresce or emit light at a different wavelength when exposed to a UV light source. Rather than measuring the amount of light absorbed, fluorescent devices measure the intensity of the light emitted to determine concentration. The instruments are suited to the higher flow rates from open systems as can measure to parts per billion and are less susceptible than the UV absorption types to interference from particles and bubbles.

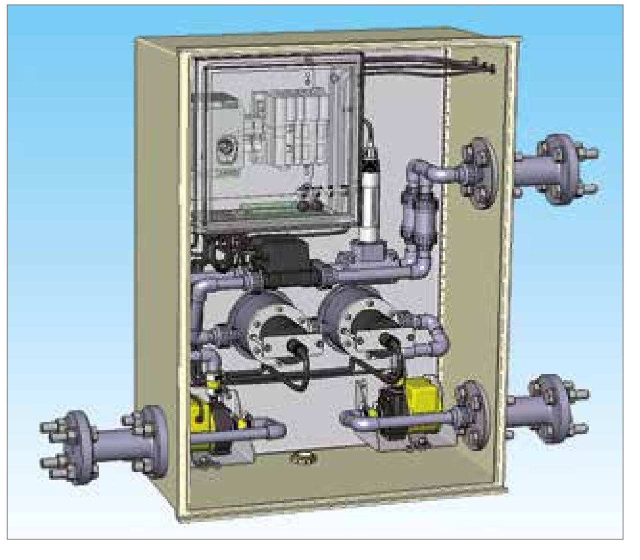


Figure 15: Washwater monitoring instrumentation cabinet (From bottom to top, left to right: sampling pumps, turbidity and PAH sensors, flow and pH sensors, control electronics)

Courtesy Chelsea Technologies Group Ltd

There are a very wide variety of sources for PAHs to enter the environment, both natural and man-made. These include industrial wastewater, road runoff, fossil fuel combustion, oil spills, forest and grass fires, volcanic particles, and natural oil seeps. There are also seasonal variations in concentration, for example increases can be seen in winter because of the heating of buildings in towns and cities. Low molecular weight PAHs with two or three rings are present normally in dissolved form in water or gaseous in the atmosphere. However the higher the molecular weight the more hydrophobic they behave and the more they are bound to particles.

The highest PAH concentrations are therefore found in sediments [4].

Sediments can be disturbed during shallow water manoeuvring of a ship and as a result may enter the washwater system. The Guidelines for Exhaust Gas Cleaning Systems therefore require the background concentration of PAH and turbidity at the washwater inlet be taken into account when monitoring the condition of the system discharge. It is also required that PAH measurement at discharge is after the washwater treatment plant but before any dilution or reactant dosage if used for correction of the washwater pH (see Figure 24, Section 4.1).

3.5.3 Turbidity

Turbidity is a measure of the degree to which the water loses its transparency due to the presence of suspended particulates. The more total suspended solids in the water, the hazier it becomes and the higher the turbidity. When combined with PAH, turbidity measurement is an effective means of continuously monitoring particulate matter removal by the washwater treatment plant.

The Guidelines for Exhaust Gas Cleaning Systems have turbidity limits for washwater, however because the measurement may be affected by the turbidity of the water entering an EGCS, a rolling 15-minute average of the difference between the water at inlet and discharge (before any dilution for pH correction) is allowed. A typical reason for the turbidity at inlet being high is sediment disturbance during shallow water manoeuvring.

3.5.4 Nitrate

In an engine combustion chamber a series of reactions occur that oxidise a small part of the nitrogen in the charge air and the majority of the nitrogen in the fuel oil so that nitric oxide (NO) is formed. In the cooler exhaust after the combustion chamber approximately 5% to 10% of the NO is then converted to nitrogen dioxide (NO_2) in the presence of excess oxygen. Collectively NO and NO_2 are often referred to as NOx.

When NO_2 is dissolved in water a series of reactions occur which finally result in the formation of nitrate. Nitrite is also formed in systems using sodium hydroxide but is then quickly converted to nitrate by nitrifying bacteria in the sea. Nitrate is an important nutrient, which if sufficient can promote the growth of organisms such as algae in a process known as eutrophication. A rapid increase or accumulation in the population of algae is known as an algal bloom, which can disrupt functioning of an aquatic system, causing a variety of problems such as toxicity and a lack of oxygen in the water needed for fish and shellfish to survive [8], [86].

Photosynthesis and within limits a fixed ratio of nitrogen, phosphorus and carbon are required for microscopic algae to be produced in marine systems. The production therefore depends not only on the actual amount of nitrogen added but also on the phosphorus. In the open oceans the availability of phosphorus is generally regarded as the limiting factor and additional nitrogen will not have any effects on growth. However in near-shore or harbour situations, where phosphorus is available (e.g. from river inputs, run-off from agriculture or direct input of domestic sewage), addition of nitrate may lead to enhanced biomass production [8].

The level of unscrubbed NOx emissions is mainly governed by the design and operation of an engine, the combustion temperature and to a lesser extent the nitrogen content of the fuel. (Although IMO give typical figures of 4% nitrogen for residual fuel and zero for distillate [18] the mechanisms for NOx production occur in differing proportions during the combustion of these fuels [3] so there is only a small reduction in NOx emissions from the use of distillate [7]). Whilst the majority nitric oxide in NOx is not readily dissolved, the approximately 5% to 10% nitrogen dioxide is soluble and therefore likely to be at least partly removed during the exhaust gas cleaning process to form nitrate in the washwater. However, when compared with the removal of SO_2, the amount of NO_2 removed by a typical wet Exhaust Gas Cleaning System is small and constant for an engine burning residual fuel and this has been confirmed by in-field testing [4].

The Guidelines for Exhaust Gas Cleaning Systems, therefore, do not currently require continuous monitoring of nitrate. There is however a limit on nitrate emissions based on removing 12% of the NOx from an exhaust stream. (This is based on an Exhaust Gas Cleaning System design with high alkalinity washwater that is capable of removing more NOx than the soluble NO_2 fraction [85] and gives some future proofing whilst mitigating the risk of eutrophication).

Compliance has to be proven by laboratory analysis of a sample drawn during initial system certification and within 3 months of each 5 yearly renewal survey. Results must be retained in the EGC Record Book and be available for inspection, for example by Port State Control, as required. The EGC Technical Manual (ETM-A or -B) must also contain details of the sampling and analysis programme and typical nitrate levels if above 80% of the limit figure.

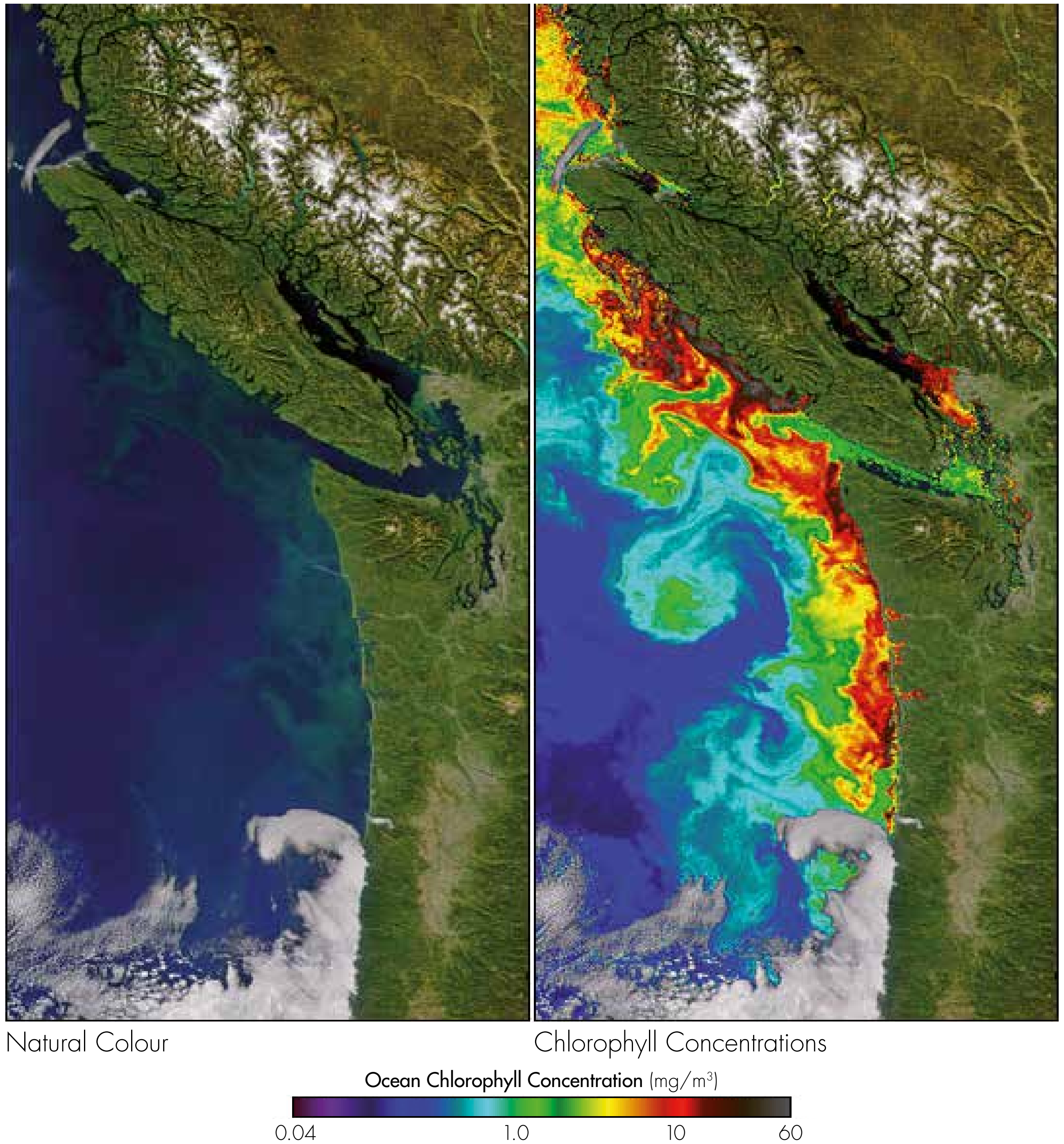
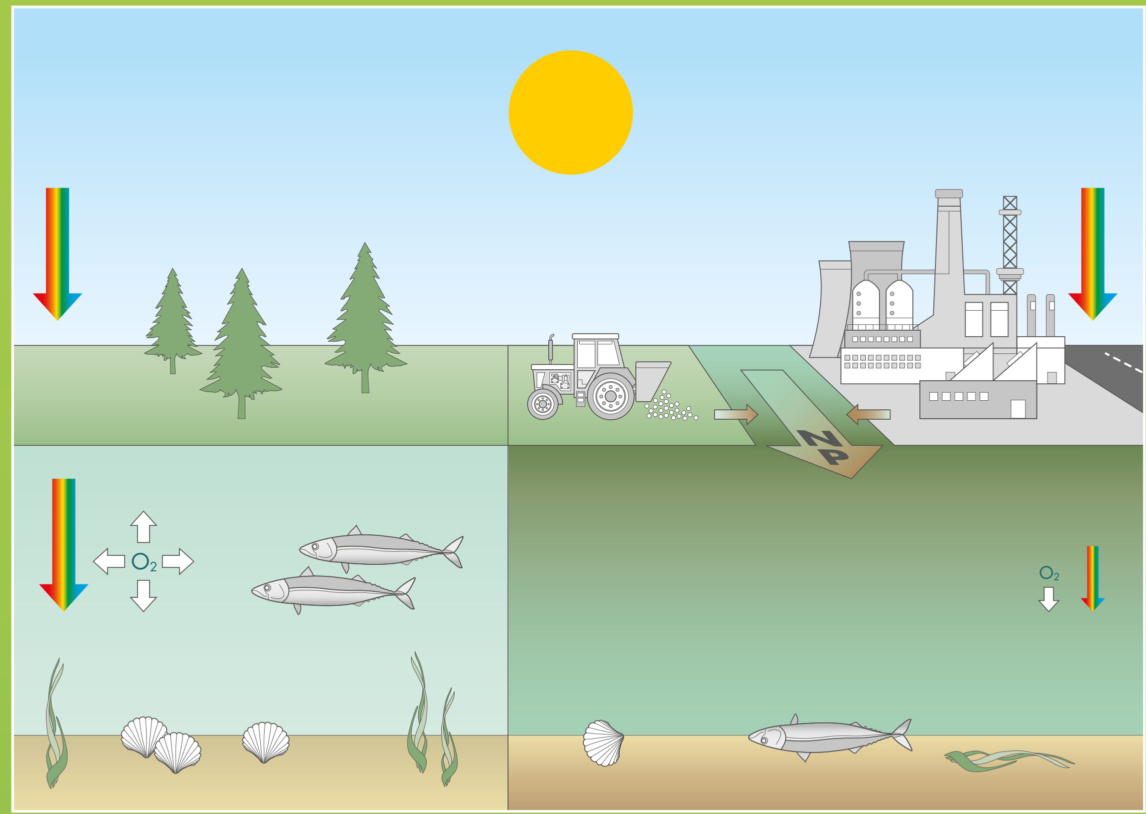


Figure 16: Algal bloom – coast of Washington and Vancouver Island, 2004

NASA images courtesy the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE



Nitrogen and phosphorus are essential nutrients that promote the growth and development of plants and animals.

In healthy aquatic systems inputs of nitrogen and phosphorus are such that the growth of algae and phytoplankton is in balance with the rate of consumption by other life forms.

A balanced level of algae and phytoplankton results in high water clarity enabling light to reach plants and a dissolved oxygen content that sustains fish and shellfish stocks.

Eutrophication occurs when levels of phosphorus, nitrogen and sediment are such that the growth of algae and phytoplankton exceed the consumption by other life forms and blooms result.

The chlorophyll in the algae and phytoplankton together with sediment cause reduced water clarity preventing light reaching submerged plants resulting in death and decay. Surface plant growth can become excessive, further choking the system. The dissolved oxygen content of the water can become severely depleted impacting fish and shellfish stocks.

Phosphorus and nitrogen can enter aquatic ecosystems from human activities. Both are constituents of agricultural fertilisers in the form of phosphates and nitrates. Phosphates are found in human and animal waste. They are components of detergents and water treatments used to soften hard water, prevent boiler scale, suspend dirt particles and reduce corrosion. Phosphorus compounds are also widely used in industry, for example in the production of metals, glass, china and certain foodstuffs. [27]

The availability of phosphorus is a limiting factor in the growth of blooms in open seas but near shore can enter the marine environment via rivers from sewage, urban and industrial run-off and agriculture. If sufficient nitrogen and carbon are also available blooms can result.

Info Box 4: Eutrophication

3.5.5 Washwater additives and treatments

Where substances are added to the washwater or created in the system for the purpose of exhaust gas cleaning or conditioning before discharge overboard, the Guidelines for Exhaust Gas Cleaning Systems contain a catchall paragraph that encompasses all the additives and techniques that may be used. Examples include the addition of chemicals, such as sodium hydroxide and electrolysis of seawater to create highly alkaline conditions. A specific assessment is required and if necessary the implementation of additional washwater discharge criteria. Approving bodies can draw on other guidelines such as those for ballast water management systems, which require an environmental risk characterisation and evaluation before approval for the treatment process can be granted.

> 10.1.6.1 An assessment of the washwater is required for those EGC technologies, which make use of chemicals, additives, preparations or create relevant chemicals in-situ. The assessment could take into account relevant guidelines such as resolution MEPC.126(53), procedure for approval of ballast water management systems that make use of active substances (G9)[19] and if necessary additional washwater discharge criteria should be established.

Info Box 5: The use of chemicals, additives, preparations or creating chemicals in-situ

3.5.6 Washwater treatment plant residue

In order to meet the PAH and turbidity limits a washwater treatment plant has to remove particulate matter with oil related material. This is a complex mixture consisting mainly of carbon, with ash containing heavy metals such as vanadium and nickel, sulphates, water, nitrates carbonates and various unburned and partially combusted components of the fuel and lubricating oil (see Figures 5 and 6, Section 1.1) [3].

The Guidelines for Exhaust Gas Cleaning Systems require that the resulting residue, which may be wet and therefore of low pH, be delivered ashore to adequate reception facilities and that it must not be discharged to the sea or incinerated onboard. The storage and disposal must also be recorded in an approved logbook or system.

4. Treatment Processes – SOx

There are several different designs of marine Exhaust Gas Cleaning System (often referred to as scrubbing systems) that remove sulphur oxides and particulate matter from ship's engine and boiler exhaust gases. However they can be broadly divided into 2 types – wet and dry.

Wet systems use either seawater, freshwater with chemical addition or both for the removal of sulphur oxides and particulate matter.

Although dry systems of various types are used in shore-side industrial and power generation plant there is currently only one manufacturer of an onboard dry system for the removal of sulphur oxides and particulate matter. This uses granular hydrated (slaked) lime.

4.1 Wet Exhaust Gas Cleaning Systems

Most wet Exhaust Gas Cleaning Systems have four basic components

- An exhaust gas cleaning unit (scrubber) that enables the exhaust stream from one or more engines or boilers to be intimately mixed with water – either seawater or freshwater (or both) for the primary purpose of removing sulphur oxides and particulate matter
  - For reasons of available space and access wet exhaust gas cleaning units tend to be high up in the ship in or around the funnel area
  - As the exhaust temperature is significantly reduced during cleaning, EGC units are positioned after any waste heat recovery systems
  - Wet EGC units are spark arrestors and can be effective silencers, so saving space by allowing the existing silencer in an exhaust system to be replaced
  - Depending on design some units can either be bypassed or run dry, although this may result in reduced noise attenuation
- A treatment plant to remove pollutants from the washwater after the exhaust gas cleaning process before discharge overboard
- Sludge handling facilities - residue removed by the washwater treatment plant must be retained onboard for disposal ashore and may not be burned in the ship's incinerator
- An instrumentation and control system

The basic layout of systems is shown in Figures 17 to 21 and the actual positions of the main system components when integrated into a ship are shown in Section 7– Figures 42 and 43, 48 and 49.

In practice a single piping and washwater treatment system can serve multiple EGC units. When integrated in this way, elements of the instrumentation and controls are also likely to be shared so that ship's staff can operate and monitor the system from a combined screen (HMI) arrangement, typically located in the engine control room.

Where a single multi-inlet EGC unit is treating more than one exhaust stream [20] there will be a means of isolating exhaust systems to prevent a flow of exhaust gas back to the engines or boilers that are not operating. Combustion units can be of different types and sizes, have different backpressure limits and operate at various loads. EGC units are therefore designed to cope with all operating scenarios so there is no impedance to the passage of exhaust gas, as this can have adverse affects on combustion unit operation and condition. An Induced Draught (ID) fan may be fitted after the EGC unit to ensure proper flow. This is particularly relevant when boiler flue gas is cleaned, as boilers are more sensitive to backpressure increases than engines and some EGC unit designs do not allow the exhausts of boilers and engines to be combined.

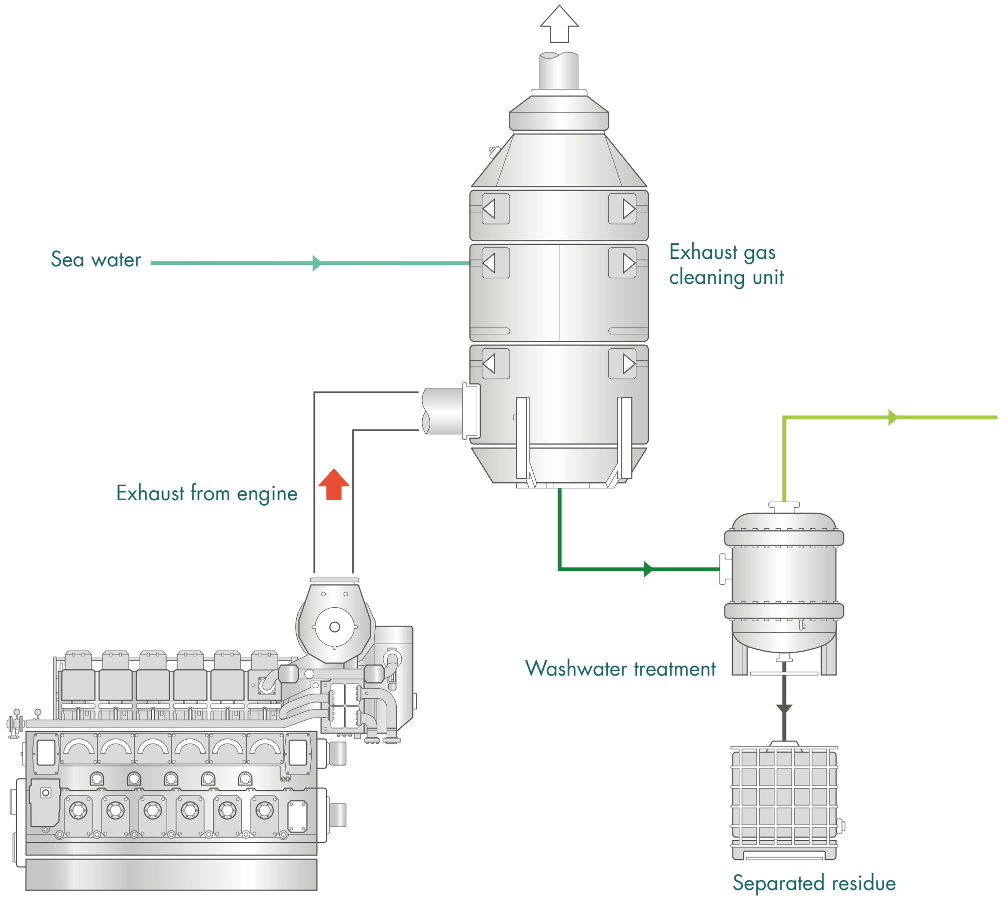


Figure 17: Exhaust Gas Cleaning System basic components
(See Figure 24 for position of instruments)

'Open loop' scrubbing is a once-through process, whereby water is taken from the sea, used for exhaust gas cleaning, then treated as appropriate and discharged back to sea. The natural chemical composition of seawater is used to neutralize the results of SOx removal.

Typically open loop operation requires approximately 45m^3 seawater per megawatt hour (MW h) [13] of combustion unit power if 2.7% sulphur fuel is consumed.

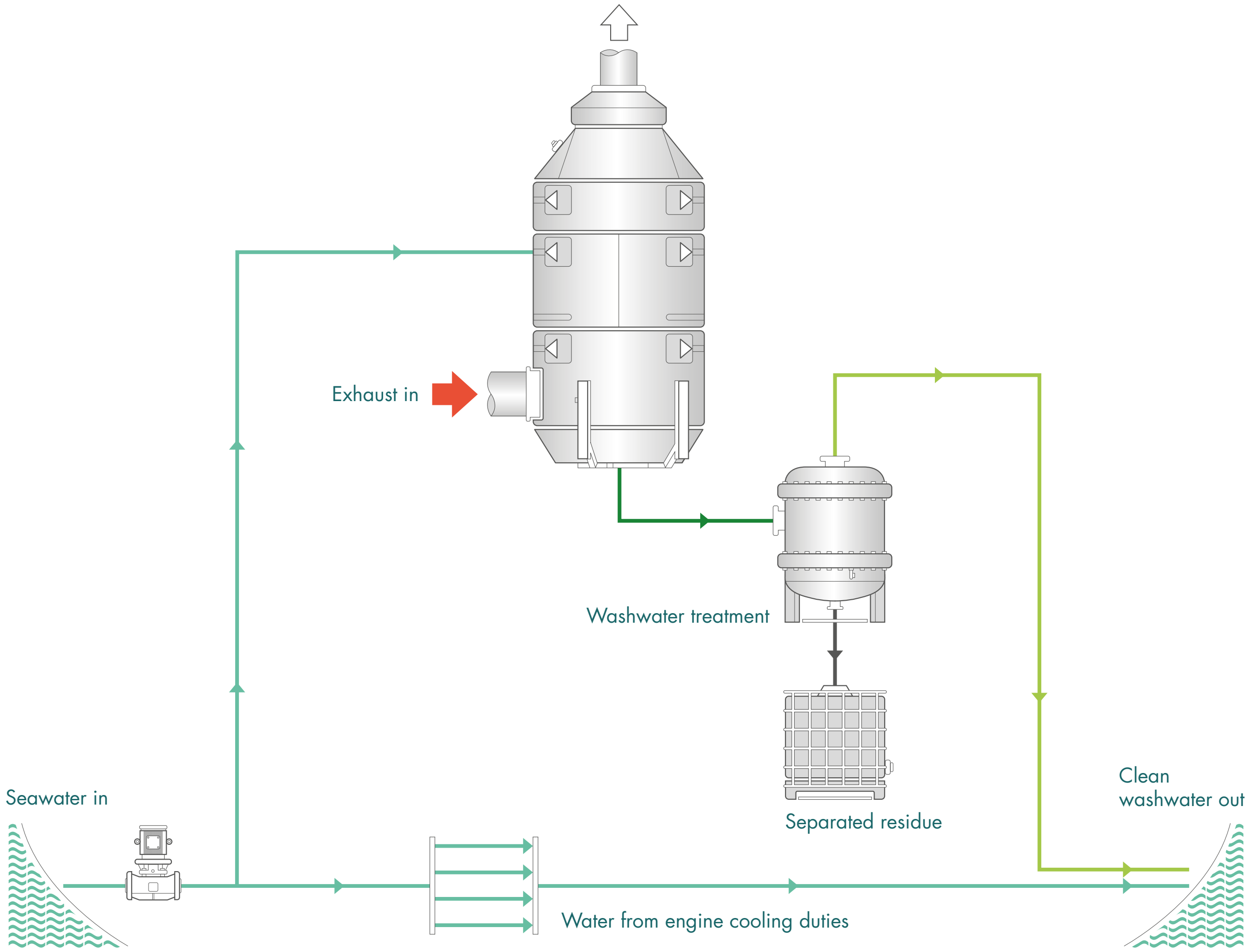


Figure 18: Open Loop Exhaust Gas Cleaning System

'Closed loop' scrubbing typically uses freshwater (although seawater is possible) treated with an alkaline chemical such as sodium hydroxide for neutralization and exhaust gas cleaning. The majority of washwater is recirculated with a process or buffer tank providing a workable system quantity and any losses (in water level and alkalinity) made up with additional water and chemical. Typically the recirculation rate in a closed system is less than 20m^3/MW h. A small quantity of the washwater is bled off to a treatment plant before discharge to sea. Typically closed loop operation requires a discharge rate of 0.1 to 0.3m^3/MW h [13] although the system shown can operate with zero discharge for limited periods if a holding tank is fitted.

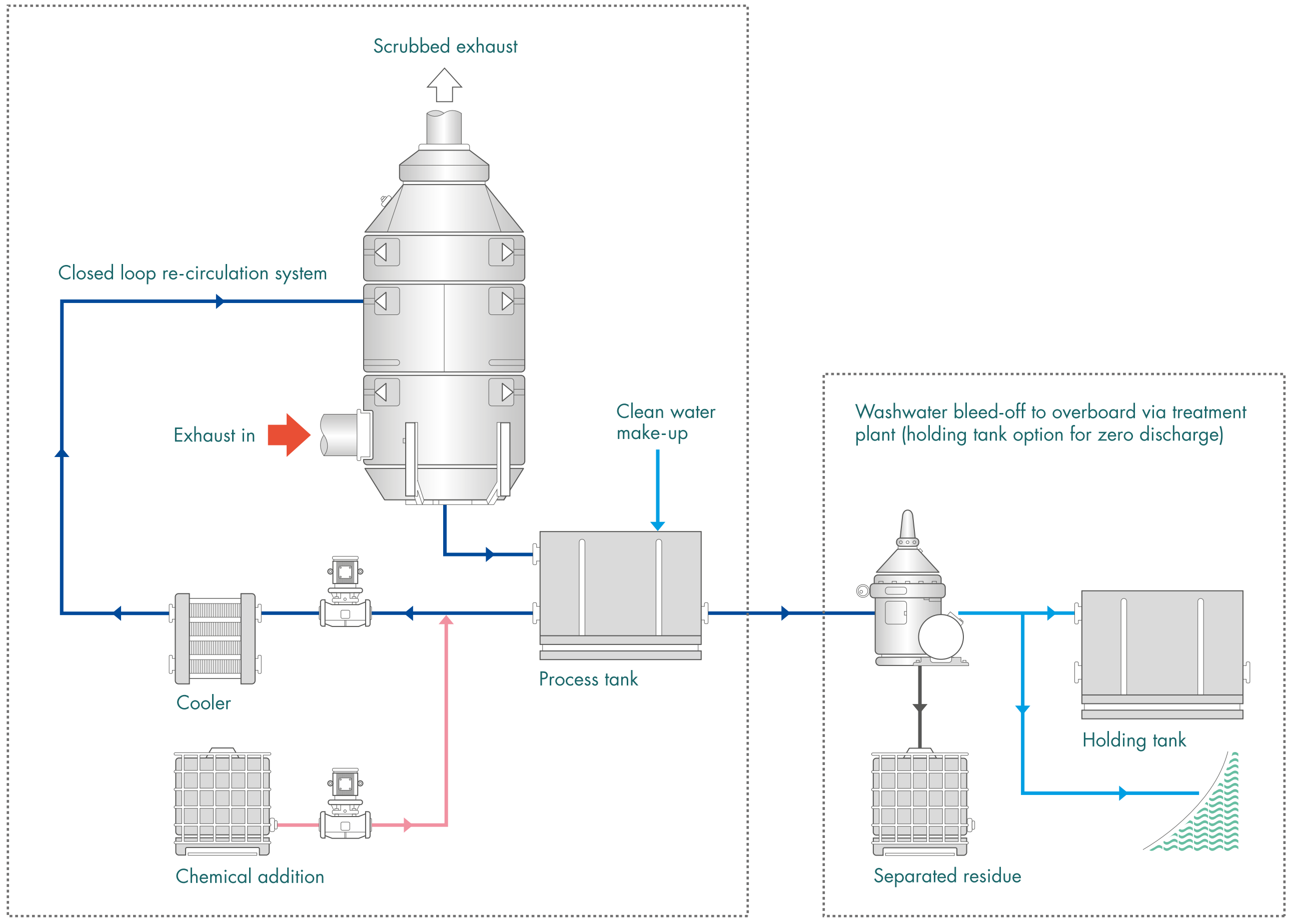


Figure 19: Closed Loop Exhaust Gas Cleaning System

'Hybrid' scrubbing systems use seawater in open loop mode and, depending on the system design, either freshwater or seawater plus chemical in closed loop mode. Seawater is typically used in open waters where the alkalinity is sufficiently high for effective scrubbing. Chemical addition is used in enclosed waters or where the alkalinity of the seawater at inlet is low. This optimises chemical usage and ensures discharges do not affect sensitive or contained areas with little water exchange.

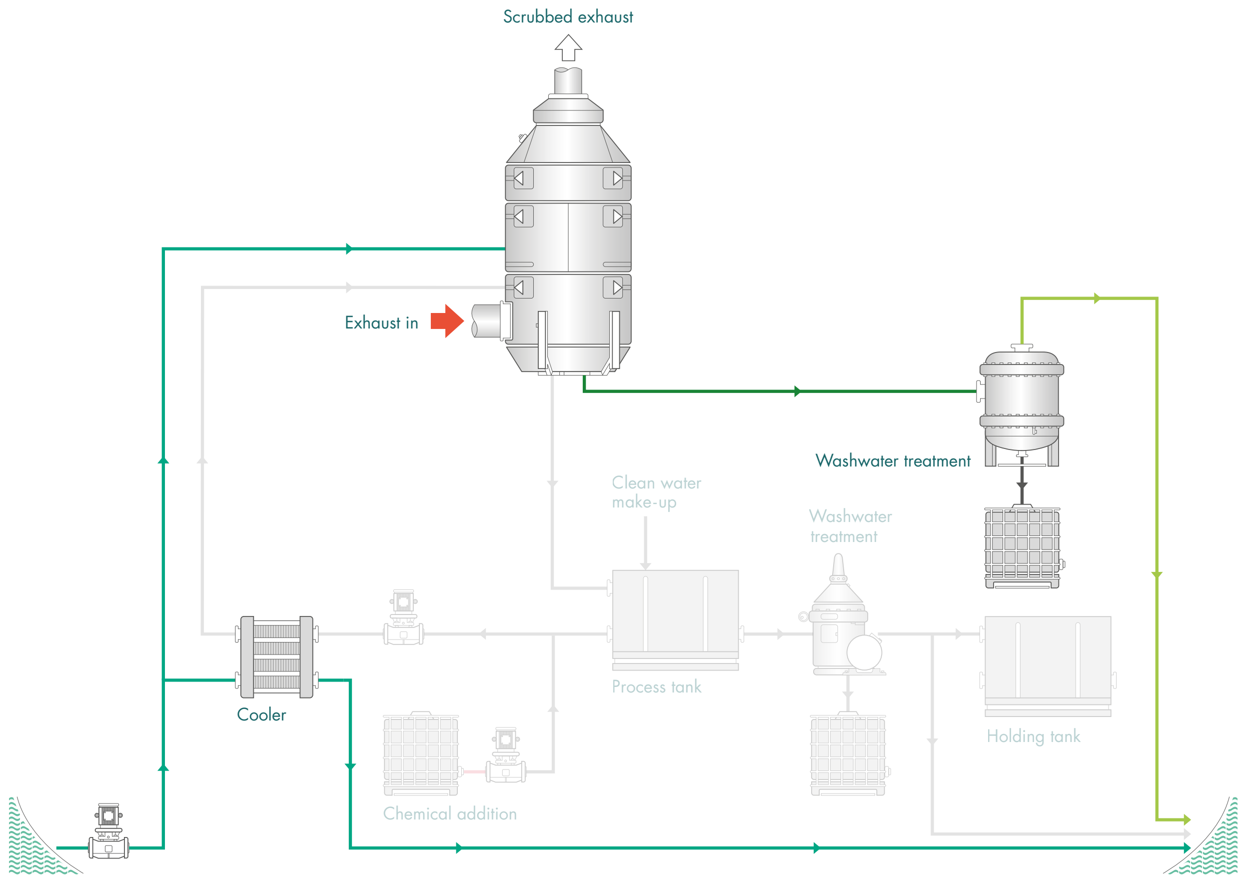


Figure 20: Hybrid Exhaust Gas Cleaning System – open loop operation

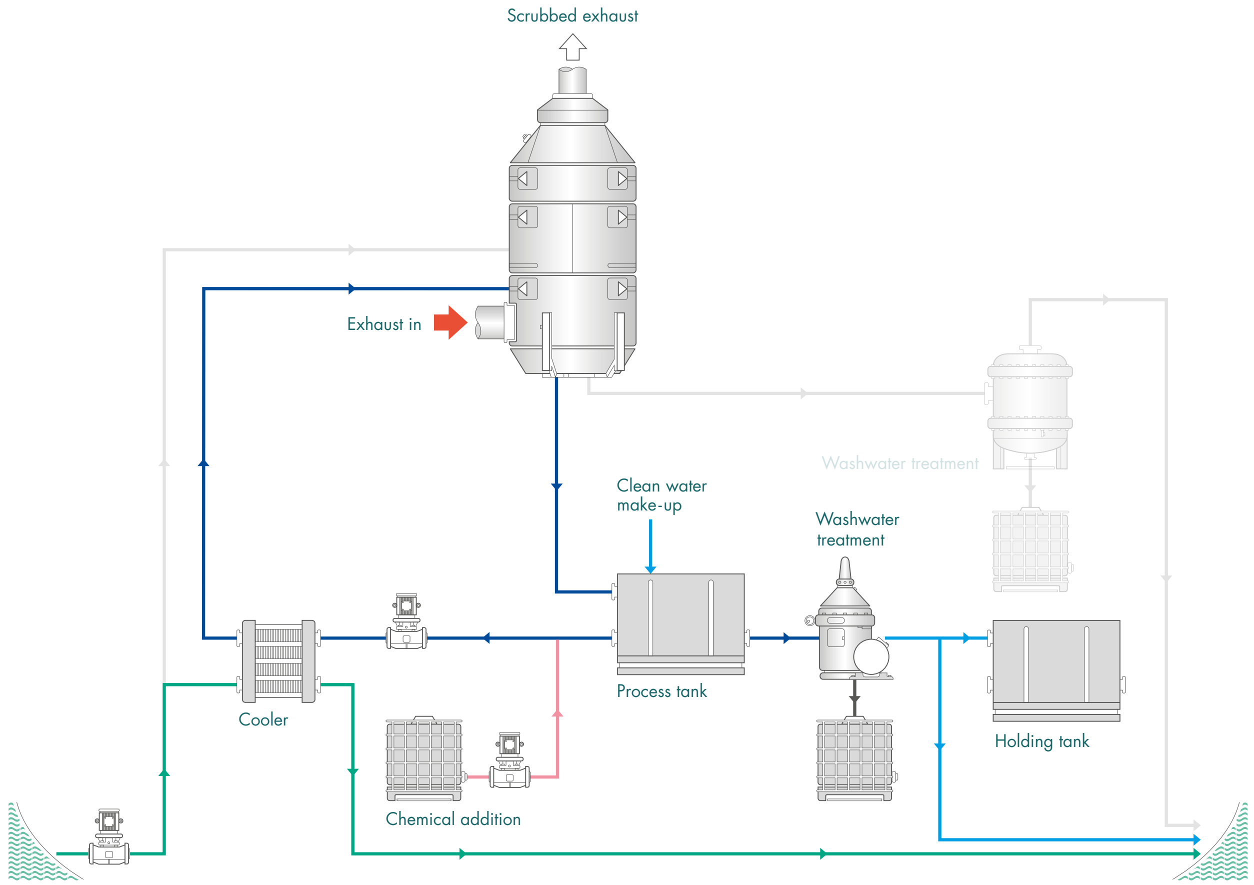


Figure 21: Hybrid Exhaust Gas Cleaning System – closed loop operation

4.1.1 Removal of sulphur oxides – seawater

Exhaust gas cleaning with water requires the exhaust gases to be intimately mixed with seawater in order to dissolve the sulphur oxides. Manufacturers use various techniques to achieve mixing without unduly obstructing the passage of exhaust gas as this could result in a 'backpressure' outside of the engine builder's limits and adversely affect engine operation and condition. Sulphur oxides in the exhaust from ships are virtually all sulphur dioxide – SO_2, a very small percentage of which is further oxidised to sulphur trioxide – SO_3. When dissolved in seawater a reaction occurs whereby the sulphur dioxide is ionised to bisulphite and sulphite, which is then readily oxidized to sulphate in seawater containing oxygen [1].

SULPHUR DIOXIDE:

- $SO_2 + H_2O \Leftrightarrow$ 'H_2SO_3' (sulphurous acid) $\Leftrightarrow$ $H^+ + HSO_3^-$ (bisulphite)
- HSO_3^- (bisulphite) $\Leftrightarrow H^+ + SO_3^{2-}$ (sulphite)
- SO_3^{2-} (sulphite) + ½ $O_2 \Rightarrow SO_4^{2-}$ (sulphate)

SULPHUR TRIOXIDE:

- $SO_3 + H_2O \Rightarrow H_2SO_4$ (sulphuric acid)
- $H_2SO_4 + H_2O \Rightarrow HSO_4^-$ (hydrogen sulphate) + H_3O^+ (hydronium*)
- HSO_4^- (hydrogen sulphate) + $H_2O \Rightarrow SO_4^{2-}$ (sulphate) + H_3O^+ (hydronium*)

*See glossary

Info Box 6: Relevant chemistry – sulphur oxides to sulphate

The ionisation to bisulphite and sulphite produces excess hydrogen (H^+) ions i.e. acidity, as does sulphuric acid formed from the small amounts of sulphuric trioxide. This will be initially neutralized by the seawater's buffering capacity or alkalinity, which is mainly imparted by its natural bicarbonate content. However once the initial buffering capacity is consumed and the pH reduces to approximately 3 the ionisation of sulphur dioxide to sulphite is negligible [1] and removal becomes limited. (Note: sulphur trioxide reacts very rapidly with water to form sulphuric acid (comprising hydrogen and sulphate ions), which in turn has a great affinity for water. This enables Exhaust Gas Cleaning Systems to be highly effective at removing and neutralizing this minor component).

The washwater flow of Exhaust Gas Cleaning Systems is optimised, so that sulphur dioxide can dissolve and an appropriate amount of buffering capacity is available to enable emissions to be reduced to the required level. Too little effective washwater flow, mixing or alkalinity and the required reduction in SO_2 is not achieved, however too much washwater is inefficient in terms of pumping power and component size and weight. A system designer will also take into account the temperature of the water available for exhaust gas cleaning as the lower the temperature the greater the SO_2 solubility.

4.1.2 Removal of sulphur oxides – freshwater with chemical addition

Exhaust gas cleaning can also be successfully achieved using freshwater with the addition of a suitably alkaline chemical. The majority of marine Exhaust Gas Cleaning Systems use sodium hydroxide, also known as caustic soda, which is typically sold as a 50% solution, eliminating the need for solids handling equipment:

- $NaOH$ (s) + $H_2O \Leftrightarrow Na^+$ (aq) + OH^- (aq) + H_2O

Info Box 7: Relevant chemistry – aqueous sodium hydroxide

As with the seawater Exhaust Gas Cleaning System the first step in an alkaline freshwater system is the absorption of SO_2 into the aqueous solution. Depending on the pH bisulphite and sulphite form, followed by oxidation to sulphate.

- $SO_2 + H_2O \Leftrightarrow$ "H_2SO_3" (sulphurous acid)
- "H_2SO_3" (sulphurous acid) $\Leftrightarrow H^+ + HSO_3^-$ (bisulphite)
- HSO_3^- (bisulphite) $\Leftrightarrow H^+ + SO_3^{2-}$ (sulphite)
- SO_3^{2-} (sulphite) + ½ $O_2 \Rightarrow SO_4^{2-}$ (sulphate)

Info Box 8: Relevant chemistry – sulphur oxides to sulphate

The overall reactions with SO_2 therefore produce a mixture of sodium bisulphite, sodium sulphite, and sodium sulphate. The exact proportions of the sulphur species depend on the pH and degree of oxidation. [28]

FOR SO_2

- $Na^+ + OH^- + SO_2 \Rightarrow NaHSO_3$ (aq sodium bisulphite)
- $2Na^+ + 2OH^- + SO_2 \Rightarrow Na_2SO_3$ (aq sodium sulphite) + H_2O
- $2Na^+$ $2OH^- + SO_2$ + ½ $O_2 \Rightarrow Na_2SO_4$ (aq sodium sulphate) + H_2O

FOR SO_3

- $SO_3 + H_2O \Rightarrow H_2SO_4$ (sulphuric acid)
- $2NaOH + H_2SO_4 \Rightarrow Na_2SO_4$ (aq sodium sulphate) + $2H_2O$

Info Box 9: Relevant chemistry – sodium hydroxide to sodium sulphate

The available alkalinity enables the washwater circulation rate in a typical Exhaust Gas Cleaning System with caustic soda addition to be approximately 20m^3/MW h. This is less than half of the typical once-through rate of 45m^3/MW h for a seawater system. This type of system therefore has advantages in terms of reduced power requirements for pumping, low or zero discharge rates and potentially less issues with corrosion of system components. However this needs to be balanced by the need to store and handle caustic soda, the need for system coolers to maintain the recirculated washwater at a suitable temperature and the potential for additional freshwater generating capacity for top up purposes.

CAUSTIC SODA – NAOH [29]

Typical commercial form is a 50% w/v* solution:

- pH 14
- Density 1.52 t/m^3
- Melting point 12°C

HANDLING

- Colourless and odourless.
- Reacts exothermically with water, producing heat.
- Non-combustible
- Harmful to eye and skin, requiring appropriate personal protective equipment to be worn and safety showers are recommended.
- Corrosive to certain metals, for example aluminium, brass, bronze, tin and zinc (galvanised coatings)
- Typically delivered by road tanker and 1000 litre IBC* container
- Product temperature greater than 20°C required for pumping (viscosity approximately 110cSt at 20°C rapidly increases at temperatures lower than 18°C) [30]
- Bulk transportation temperature often at 40°C (delivery temperature should not be above 120 to125°F (50°C) to minimize corrosion of unlined steel piping systems and equipment [31], [32]).

STORAGE

- Tank can be of normal shipbuilding steel.
- Coating not necessary, but recommended.
- Stainless steel is not required.
- Temperature between 20°C and 50°C
- Uncoated mild steel tanks should not exceed 120 to 125°F (50°C) to prevent caustic corrosion cracking [31], [32]
- Product density needs to be considered during fabrication of tanks

* See glossary

Info Box 10: Caustic soda handling and storage

4.1.3 Water quality at Exhaust Gas Cleaning System inlet

Wet Exhaust Gas Cleaning Systems are highly effective at reducing sulphur oxide emissions and removal rates of greater than 98% are possible. A key factor for sulphur acid neutralization, and therefore SOx removal, is the alkalinity of water used to 'wash' the exhaust gases, rather than its salinity. Alkalinity is available naturally in seawater, which of course is also saline, but it can also be added artificially by use of an alkaline chemical such as sodium hydroxide.

$$CO_{2(aq)} + H_2O \Leftrightarrow H_2CO_3 \text{ (Carbonic Acid)} \Leftrightarrow H^+ + HCO_3^- \text{ (Bicarbonate)} \Leftrightarrow H^+ + CO_3^{2-} \text{ (Carbonate)}$$

The process of exhaust gas cleaning with water creates an excess of hydrogen (H^+) ions i.e. acidity of the washwater.

Within an Exhaust Gas Cleaning System washwater acidity will be initially neutralized by the seawater's natural alkalinity. Carbonate ions in the seawater combine with free hydrogen ions, to form free bicarbonate ions (HCO_3^-), and decrease the hydrogen ion activity.

Similarly calcium and magnesium bicarbonates, which contribute to the majority of total seawater alkalinity combine with hydrogen ions so decreasing their activity, i.e. both bicarbonate and carbonate ions in seawater act to neutralise or buffer the washwater by consuming hydrogen ions and in so doing move the carbonate system equilibrium to the left.

Within an Exhaust Gas Cleaning System once the buffering capacity is consumed and the pH reduces to approximately 3 the ionisation process is negligible and sulphur oxide removal becomes limited. The pH is however quickly restored on mixing of the washwater with fresh seawater.

Info Box 11: Relevant chemistry – seawater neutralisation of acidic washwater

Alkalinity does not refer simply to pH, but to the ability of water to resist changes in pH. The buffering components of seawater are primarily bicarbonates and carbonates, but about 4.0% of the neutralisation is provided by borates and other ions in low concentrations [12]. Total alkalinity, is the sum of all these and for the open ocean is usually constant and high at approximately 2200 to 2300μmol/l [1]. Salinity describes the total salt content of water and for the open ocean this is approximately 3.5% by weight (the majority salt in seawater being sodium chloride).

- Alkalinity is the capacity of solutes in an aqueous system to neutralize acid. [33]
  - Bicarbonates and carbonates contribute 89.8% and 6.7% respectively to the total alkalinity of seawater [34]
- pH can be considered an abbreviation for power of the concentration of hydrogen ions. The mathematical definition is pH is equal to the negative logarithmic value of the hydrogen ion (H^+) concentration, or pH = -log [H^+]
  - pH values are calculated in powers of 10. The hydrogen ion concentration of a solution with pH 1.0 is 10 times larger than the hydrogen ion concentration in a solution with pH 2.0. The larger the hydrogen ion concentration, the smaller the pH:
  - When the pH is above 7 the solution is basic
  - When the pH is below 7 the solution is acidic [35]
- Salinity is a measure of the concentration of *all* the salts and ionic compounds in water.
  - Sodium and chlorine, which combine to form sodium chloride make up greater than 85% of the salts in seawater, the majority of the remainder are sulphate (> 7.5%), and salts of magnesium (>3.5%) calcium (>1%) and potassium (>1%).
  - Bicarbonates make-up less than 0.5% of the salts in seawater [11]
  - Salinity is practically determined from the conductivity ratio of the sampled seawater to a standard potassium chloride solution.

Info Box 12: Definitions - alkalinity, pH and salinity

It is possible for waters to a have high alkalinity and a very low salinity (<0.05%) depending mainly on the calcium concentration [2]. Alkalinity in some coastal areas, ports, rivers and estuaries can be affected by the different drainage areas of the inflowing rivers, resulting in variations in the chemistry. Rivers flowing through a limestone area with soil rich in carbonates will be high in alkalinity whereas those flowing through acid soils and over igneous bedrock will not. For example, the areas crossed by the northern rivers of the Baltic Sea have a granite geology resulting in a lower alkalinity of approximately 500 to 1300μmol/l, whereas the southern rivers flow across a region of calcite geology resulting in high carbonate concentrations with consequently higher alkalinity of approximately 1650 to 1950μmol/l. In general, the alkalinity in the Baltic Sea is also lower than open sea areas because of the minimal exchange of water through the Danish straits.

At low alkalinity levels the seawater Exhaust Gas Cleaning System can still operate, but removal will be reduced [2] where alkalinity is less than 1000μmol/l SO_2 unless more washwater is supplied. The alkalinity of the majority of open sea areas and harbours is however high and therefore suitable for exhaust gas cleaning. In fact many rivers also have a suitably high alkalinity.

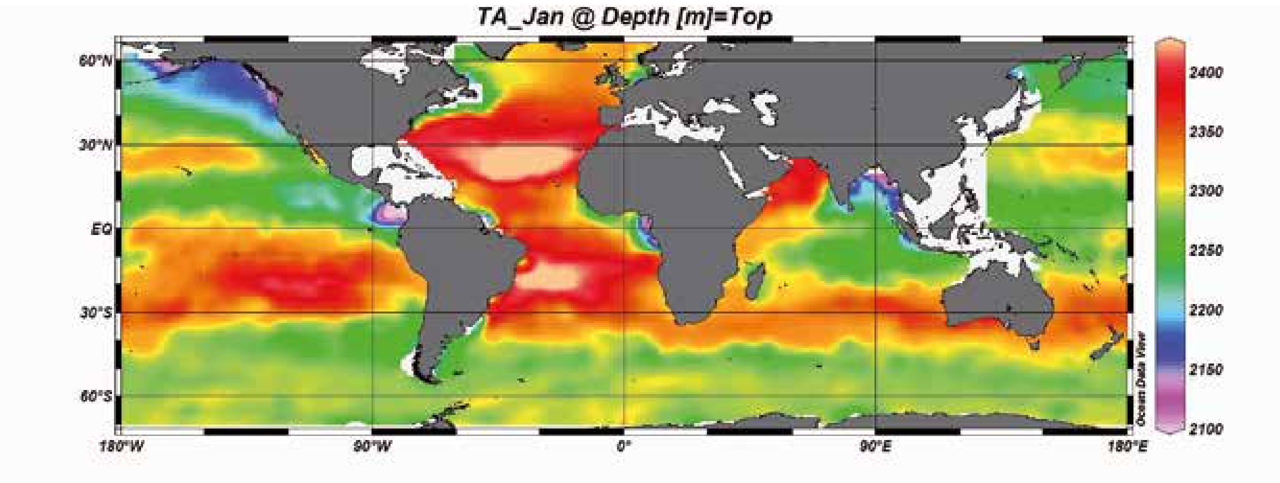
AREAS		PORTS			
ALKALINITY (μmol/l)		ALKALINITY (μmol/l)			
LOCATION	MIN.	PORT	MIN.	MAX.	RIVER
North Sea	2200	Amsterdam	2200		
Norwegian Sea	2300	Antwerpen	2200	4500	Scheldt
North Atlantic Ocean	2300	Bilbao	2200		
South Atlantic Ocean	2300	Bordeaux	2300	2400	Gironde
Mediterranean Sea	2400	Calais	2800	3100	
Black Sea	2500	Dover	1100	1300	
Gulf of Mexico	2250	El Ferrol	2280		
Caribbean Sea	2250	Hamburg	2050	2400	Elbe
Panama	1800	Hanko	1600		
Panama Canal	1000	Helsinki	1250	1500	
Gulf of Alaska	2000	Hull	1350		Humber
North Pacific Ocean	2100	Kotka	900	1000	Kymijoki
South Pacific Ocean	2200	Miami	2300		
Red Sea	2400	New Orleans	2400	3000	Mississippi
Persian Gulf	2500	Oslo	1350		
Arabian Sea	2300	Rotterdam	2200	2700	Rhine
Bay of Bengal	2300	St Petersburg	490		Neva
Indian Ocean	2200	Travemünde	1800		
Gulf of Thailand	2000				
South China Sea	2000				
Philippine Sea	2100				
Coral Sea	2150				
Tasman Sea	2300				
Gulf of California	2150				

The above tables show alkalinity levels in various areas and ports. It can be seen that the alkalinity of open sea areas is relatively constant whilst more variable in ports. In order to provide some indication of the exhaust cleaning capability of these waters, three examples are considered:

- The alkalinity of Dover is 1100 to 1300 μmol/l compared with 2800 to 3100 for Calais however Wärtsilä-Hamworthy has successfully used the Pride of Kent, a large Ro-Ro ferry operating between these ports, as a long-term trial platform for an open Exhaust Gas Cleaning System using seawater with SO_2 removal rates unaffected.
- Helsinki has a similar alkalinity to Dover; however St Petersburg on the River Neva to the east has a significantly lower alkalinity, which is likely to impact sulphur oxide removal efficiency. Under these conditions chemical addition could be used
- Ports fed by rivers such as Rotterdam, Antwerp and New Orleans have alkalinities similar to or higher than that of the open ocean

Info Box 13: Alkalinity in sea areas and ports

Alkalinity data tables courtesy Wärtsilä [29]



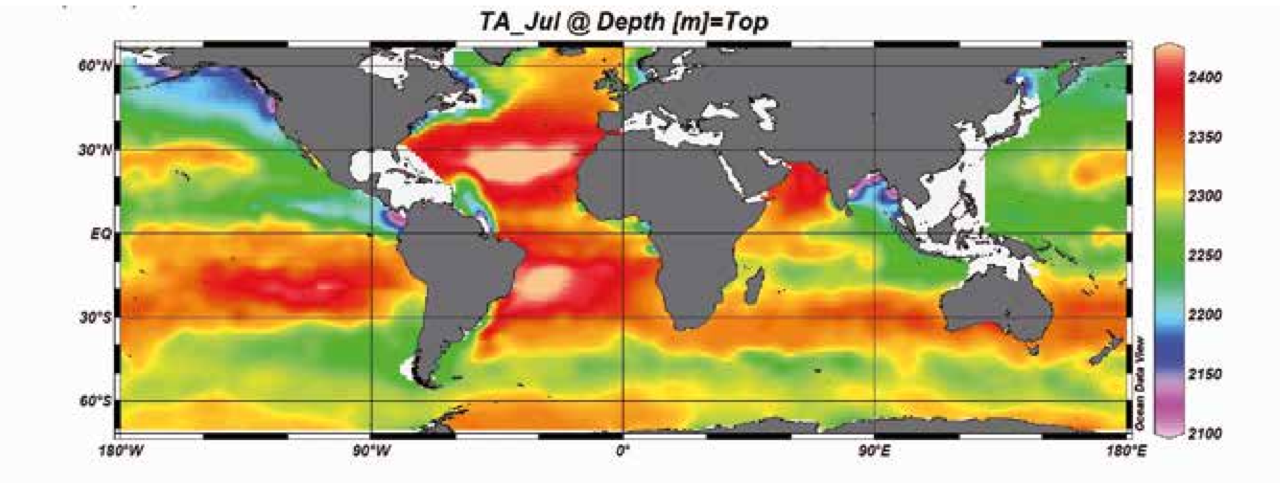


Figure 22: Surface alkalinity of open seas – January and July

Courtesy Lee et al 2006 [36]

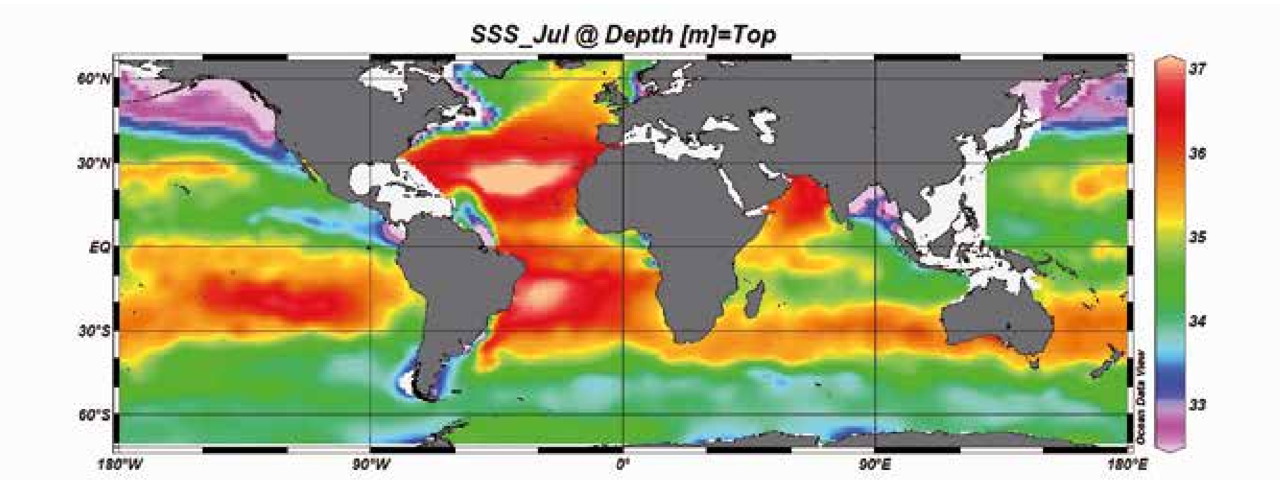


Figure 23: Surface salinity of open seas – July (Although alkalinity and salinity show a similar distribution, there is not an absolute link between the buffering capacity of water and salinity)

Courtesy Lee et al 2006 [36]

It is not possible to carry out continuous online monitoring of alkalinity with sensors, but it could be checked by chemical titration, which is not entirely practicable onboard ship. Although there is no absolute link between salinity, pH and buffering capacity, online monitoring of the Exhaust Gas Cleaning System's water supply with pH and salinity sensors is used as a robust indicator of possible issues i.e. a low salinity and/or pH would suggest entry to brackish water. Under paragraphs 4.2.2.1 and 5.6.1 of the Guidelines for Exhaust Gas Cleaning Systems the technical manual for each EGCS must provide the standard of inlet water required to ensure emissions reduction performance:

> 4.2.2.1/5.61 Each EGC unit should be supplied with an ETM-A/B provided by the manufacturer. This ETM-A/B should, as a minimum, contain the following information:
>
> (iii) Maximum and minimum washwater flow rate, inlet pressures and minimum inlet water alkalinity (ISO 9963-1-2);
>
> (vi) Salinity levels or fresh water elements necessary to provide adequate neutralizing agents;

Info Box 14: Guidelines for the Exhaust Gas Cleaning System inlet water

The technical manual is also required to give details of actions required if emissions to air are exceeded.

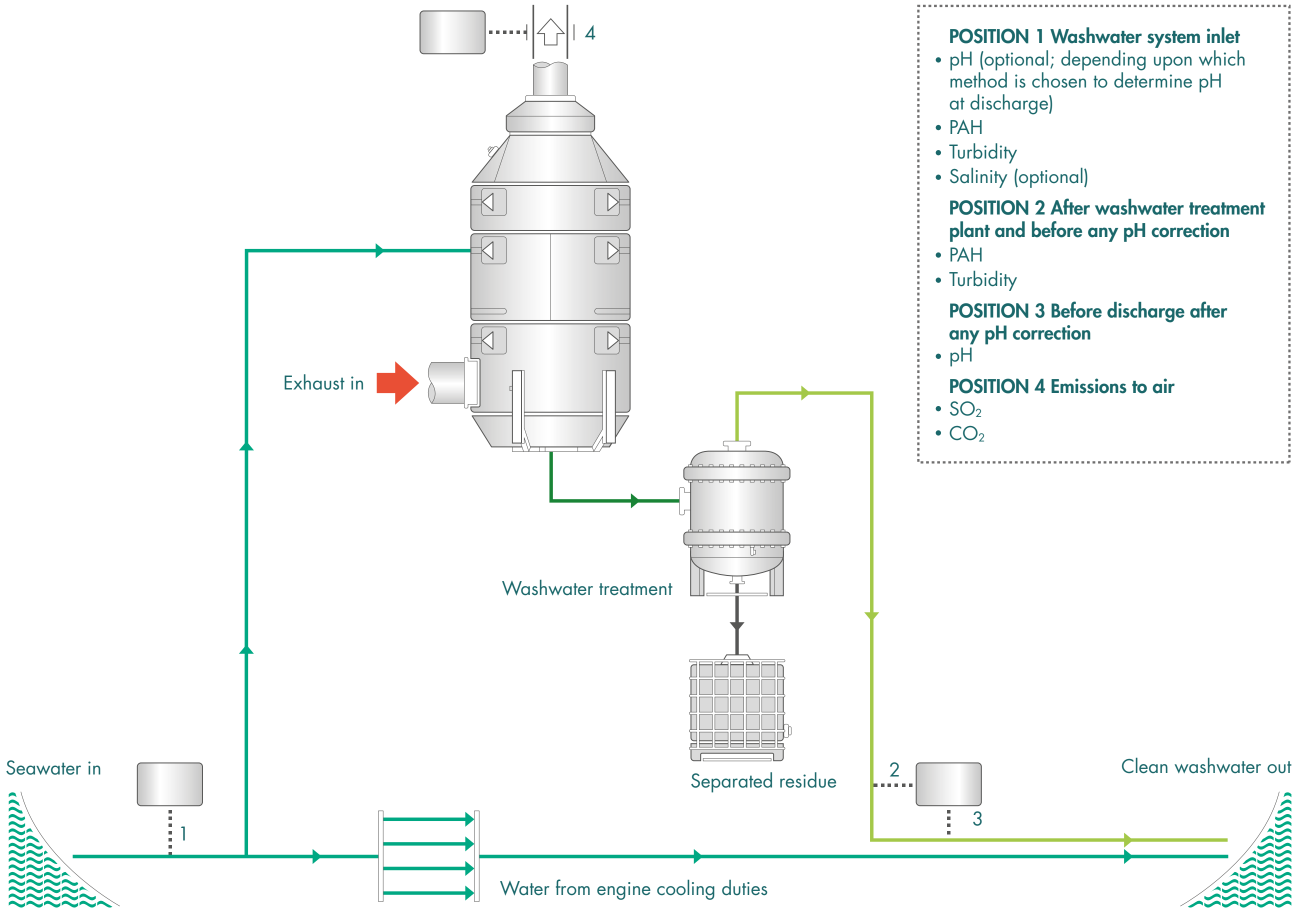


Figure 24: Position of water quality and emissions monitoring instrumentation

4.1.4 Washwater treatment

4.1.4.1 pH

The acidity of the washwater immediately after an EGC unit can be as low as pH 3. In order to meet the requirements of the Guidelines for Exhaust Gas Cleaning Systems and so avoid a negative impact on ecosystems or potential corrosion issues, the washwater can be further diluted to increase the pH level to at least 6.5. To reduce the energy consumed by pumps, seawater already used for cooling duties in the engine room can be mixed with the washwater before discharge.

4.1.4.2 Particulate matter and oil

In addition to reducing sulphur oxides Exhaust Gas Cleaning Systems are very effective at reducing emissions of particulate matter and oil based material with removal rates in excess of 80% possible.

Whilst particulate matter from unscrubbed exhausts already enters ecosystems via the atmosphere it is not obviously desirable to shortcut this process and simply move the pollutants directly into the sea. An effective washwater treatment plant is therefore required that is capable of removing both particles and oil. The choice of technology depends on the overboard discharge rate.

A number of suppliers of open loop systems use separation by hydrocyclone - a static device that applies centrifugal force to a liquid mixture in order to promote the separation of heavy and light components.

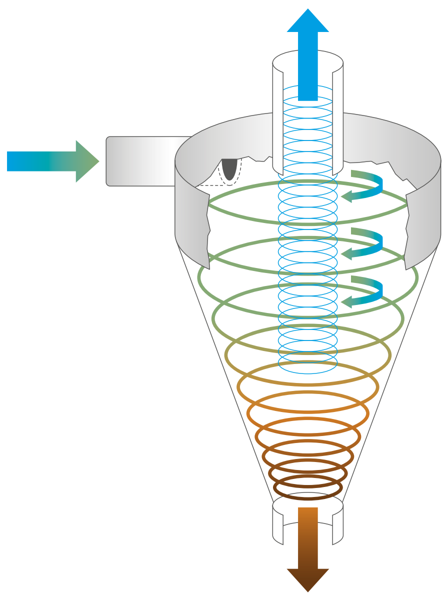


Figure 25: Hydrocyclone schematic

The hydrocyclone is a vessel designed to convert incoming liquid velocity into a rotary motion. In an open loop Exhaust Gas Cleaning System the velocity is imparted by means of a pump in the washwater system or the height of the EGC unit above the washwater treatment plant. Rotary motion is created by means of a tangential inlet or inlets to the hydrocyclone. This causes the entire contents to spin, creating centrifugal force in the liquid. The heavy fractions are moved outward towards the wall of the hydrocyclone and in Figure 25 downward to the outlet at the bottom. The light fractions move toward the central axis of the hydrocyclone and in Figure 25 upward to the outlet at the top.

Hydrocyclones can be constructed either as larger individual separator vessels or as smaller elements grouped within a single vessel, which may be vertically or horizontally orientated. The latter configuration is similar to a tube cooler but with the washwater inlet at the centre and an outlet at each end. An overflow plate holds the overflow ends of the multiple hydrocyclone 'liners' or 'multi-clones' and an underflow plate holds the underflow ends. As such hydrocyclones can be readily sized for the larger flow of open systems and depending on design can provide solid/liquid or liquid/liquid separation. Combinations can therefore be used to separate both particulate matter and oil from the washwater in a treatment plant.

Smaller centrifugal separators similar to those used for fuel and lubricating oils can be used for the lower discharge rates of closed loop systems. An alternative technology is the multi-stage separation plant using air, chemical addition and filtration.

Firstly by using dissolved air, the oil contained within the washwater is floated to the surface, where it is skimmed off.

Secondly coagulation and flocculation are used to remove suspended solids and break any emulsion in the washwater. The washwater contains suspended solids (colloids) that are stabilized by negative electric charges, causing them to repel each other. Since this prevents the formation and settling out of larger masses or flocs, a sequence of chemical and physical procedures is used to enable separation. Coagulants are used to neutralize the charges of the suspended solids, so that they can agglomerate and the flocculant binds them together into larger masses. Once flocculated, dissolved air flotation is again used to promote the separation and subsequent removal of the particles from the washwater.

Before discharge the washwater may be subjected to active carbon filtration, which is effective at removal of organic compounds from water by adsorption [17].

Figure 26: Open loop system washwater treatment plant (Hydrocyclones (white) in background)

Courtesy Wärtsilä-Hamworthy

4.1.5 Effects on seawater composition

4.1.5.1 Sulphate

As seen in Section 4.1.1 when SO_2 dissolved in seawater a reaction occurs whereby the sulphur dioxide is ionised to bisulphite and sulphite, which is then readily oxidized to sulphate. Sulphate is a naturally occurring constituent of seawater. It is soluble and has a long 'residence time', as it is unaffected by the natural pH, temperatures and pressures found in the oceans. It is therefore said to be 'conservative' in that regardless of the total salinity it occurs mixed throughout the oceans in the same ratio to the other conservative constituents such as sodium [15]. The large amount of sulphate in seawater is derived from volcanic activities and degassing at the seafloor. Further, sulphate reaches the oceans via river flows, but the concentration in open seawater remains constant at around 2.65 g/l [8].

Studies [1] and in field testing [4] confirm that the sulphate increase from exhaust gas cleaning will be insignificant when compared with the quantity already in the oceans.

An analogy that has been used is if all the sulphur in the world's oceans were to be removed, it would form a layer around the earth about 1.7m thick. All the sulphur in all the known oil reserves would add only another 10 micron to this layer [16].

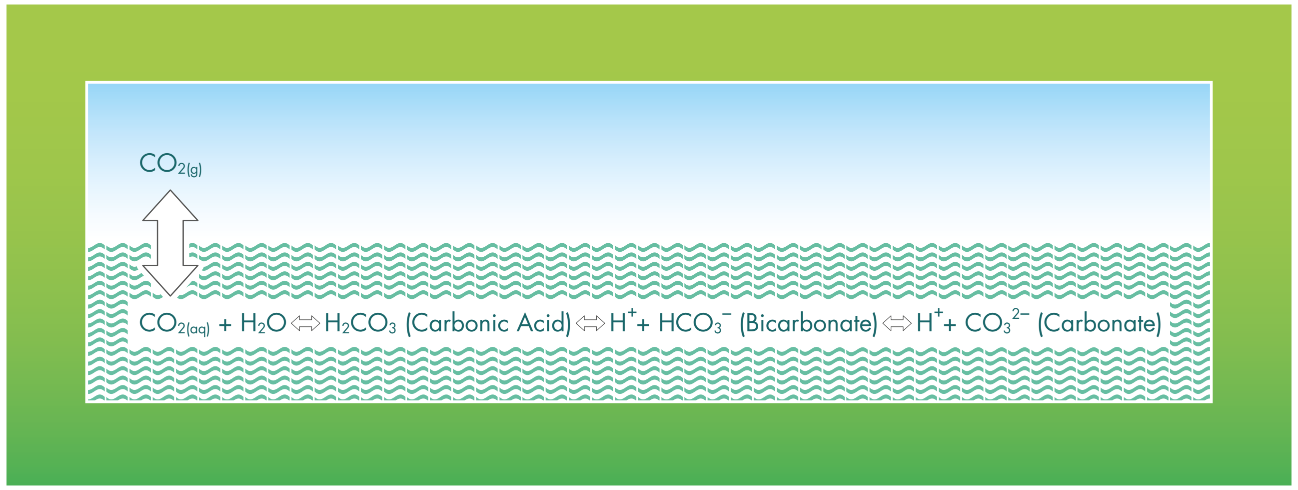
4.1.5.2 Oxygen

The process of oxidising sulphite to sulphate increases the Chemical Oxygen Demand (COD) on water used for exhaust gas cleaning, which could potentially have an adverse impact on aquatic systems when discharged. Using worse case scenarios Karle and Turner [1] evaluated the dilution of washwater required to return oxygen levels to within 1% of those of the ambient water. Using different waters from full seawater to full freshwater and intermediate alkalinities/salinities, it was found that, other than for full open ocean water above 15°C, no further dilution was required if the pH of the water had already been corrected to within 0.2 of ambient.

As it known from various in-field tests and modelling of discharge plumes that the pH and oxygen of discharged water very rapidly returns to that of the surrounding water, especially when the vessels is underway, the Guidelines for Exhaust Gas Cleaning Systems do not require dissolved oxygen to be monitored [13].

4.1.5.3 Acidification

The increase in atmospheric carbon dioxide concentrations from pre-industrial levels of 280ppm to the present 380ppm is calculated to have decreased the average pH of ocean surface waters from 8.18 to 8.07. If the increase continues at the same rate, average pH of ocean surface waters will approach 7.70 over the next 100 years [1].



Info Box 15: Relevant chemistry – the ocean carbonate system

There have been various estimates for the quantity of SO_2 emitted by shipping. Using Corbett & Fischbeck's (1997) [14] estimate of 8.48Mt, Karle and Turner [1] calculated that if 80% of the sulphur dioxide were to be removed by onboard Exhaust Gas Cleaning Systems, 6.78Mt of SO_2 would be discharged into the oceans each year. However also commented that almost all of the sulphur dioxide transferred to the ocean through the cleaning process would have eventually ended up in the ocean from the emission of unscrubbed exhaust gases.

Distributed evenly over the uppermost 100m of the ocean, this would lower the pH in oceanic surface water by 0.02 units in 100 years, but the effect would be minor when compared to ocean acidification resulting from increased carbon dioxide concentrations in the atmosphere.

Whilst this would apply for open seas, in enclosed waters with a low level of water exchange there is a potential for acidification in shorter time scales, depending upon factors such as alkalinity and shipping traffic [1], [4]. Closed loop and hybrid Exhaust Gas Cleaning Systems with chemical addition and a low washwater discharge rate have been designed for prolonged operation in waters such as the Baltic where these conditions are encountered.

Importantly exhaust gas cleaning can prevent the entry of a large amount of sulphur dioxide into the atmosphere, thereby significantly reducing the threat to both the environment and human health from primary exposure and the secondary effects of particulate matter and acidic precipitation.

4.1.6 Materials of construction

4.1.6.1 Exhaust gas cleaning system

Warm acidic seawater at pH 3 can rapidly corrode the ferrous and non-ferrous metals normally used for ships equipment. To ensure a long service life the materials used for construction of exhaust gas cleaning units and downstream components such as pumps, coolers, interconnecting pipework and valves include chromium-nickel based alloys (stainless steels) with a high pitting resistance equivalent number (PREN), titanium and non-metallics such as glass-reinforced epoxy (GRE) and suitable plastics. The latter when used for piping systems require class-approved solutions for bulkhead transition and the lower levels of rigidity require close attention to component bracketing to withstand the vibration found onboard ship. The lighter weight and ease of assembly of non-metallic materials does however facilitate retrofit and the service life can substantially outlast metals.

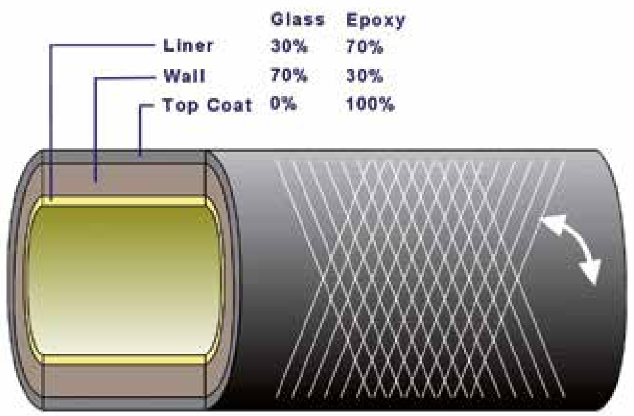


Figure 27: Glass reinforced epoxy pipe construction

Courtesy NOV Fiber Glass Systems

Courtesy M West

Pitting and crevice corrosion can be a problem in stainless steels requiring the correct grades to be selected for Exhaust Gas Cleaning System components.

Stainless steels depend on the presence of an adherent self-healing oxide film to prevent local corrosion. Pitting results from a breakdown of the barrier, which exposes the bare metal at point sites. This may be caused by mechanical damage and stress, chemical breakdown of the surface film, oxygen depletion underneath debris, and inclusions or inconsistencies in the metal matrix. Corrosion can be very rapid in the presence of acidic chlorides, which contribute to film breakdown and prevent film repair.

Stainless steel contains at least 11% chromium to enable the formation of the protective oxide barrier. Nickel, molybdenum and nitrogen are also included in various amounts to improve corrosion resistance. Pitting Resistance Equivalent Number is a theoretical method of determining the corrosion resistance of a particular grade and is based on laboratory tests using solutions containing chlorides. The most commonly used formula for PREN is:

$$PREN = (\%Cr) + 3.3(\%Mo) + 16(\%N)^*$$

Stainless steel grades such as 304 and 316L are commonly found onboard ship, but have PREN of around 20 and 25 respectively, which are too low for Exhaust Gas Cleaning Systems. Typically 'Super-Duplex' and 'Super-Austenitic' steels with PREN of over 40 are used to ensure corrosion resistance and longevity.

*A factor of 30 (rather than 16) may be used for nitrogen in some formulae, however as the actual nitrogen levels are quite low in most stainless steels this does not have a significant effect.

Info Box 16: Stainless steel corrosion resistance (PREN)

4.1.6.2 Exhaust duct

A significant amount of water is produced by the combustion of hydrocarbon fuel oils and a typical exhaust gas stream from a slow speed 2-stroke diesel engine can contain over 5% water.

Throughout their length exhaust pipes on unscrubbed engines must be maintained at a minimum temperature of around 180°C, as this is above the dew point for sulphuric acid [3]. Condensation onto metal surfaces and corrosion is therefore prevented, which allows the use of mild steel for construction.

Temperature is also a key parameter in determining the mass of water that can be contained in a given quantity of exhaust gas i.e. the higher the temperature, the greater the mass of water that can be held before saturation is reached.

Between the engine and an EGC unit the exhaust temperature can be approximately 300°C, but after passage through an EGC unit the temperature is reduced very significantly – perhaps by 85% and water together with any sulphur-based acids in the gas phase are condensed out through contact with the relatively cold washwater. This means the mass of water in a given quantity of exhaust gas can actually be less at exit from an EGC unit than that at entry i.e. water is not necessarily added to the exhaust gas by the cleaning process.

Needless to say this depends upon the washwater temperature and whilst the actual mass may be reduced, the exhaust gas will be fully saturated on immediate exit from the EGC unit. In order to prevent liquid carry-over with the exhaust gas, a demister at the EGC unit exit can be used to remove any entrained liquid droplets. In addition a re-heater [16], [21] may be used to raise the temperature of the exhaust gas so that it is no longer fully saturated with water. Alternatively a reduction in washwater temperature in closed loop systems will reduce the rate of water evaporation in the EGC unit so reducing the level of saturation. Depending on the temperature of seawater to the washwater coolers the dew point of the exhaust can be reduced to below the temperature of the outside air. These measures prevent water vapour in the gas phase condensing onto cooler exhaust pipe surfaces and creating a visible exhaust plume in cold ambient conditions. The exhaust ducting may also be designed in such a way that the exhaust stream slowed in the EGC unit is accelerated away from the ship. On exit from the funnel into the atmosphere the volume of exhaust gas is immediately diluted, which reduces saturation levels to again prevent water vapour from condensing.

Without the formation of water vapour any small amounts of gaseous SO_2 that remain unscrubbed (typically < 2%) cannot be dissolved and the risk of subsequent acidification is mitigated. This means that an effective design can preclude the need for the exhaust duct above the EGC unit to be fabricated from higher than normal grade steels, although this may still be recommended where the condensation of water vapour cannot be fully mitigated or where demisters are not fitted in order to reduce pressure drop.

Figure 28: Exhaust deplume
(The connection into the side of the deplume diffuser is the supply of warmed or heated air from the engine casing to raise scrubbed exhaust gas temperature above saturation to eliminate a visible plume. A demister will be fitted below the deplume, at the top of the exhaust gas cleaning unit. An ID fan can be just seen at the next level above the deplume)

Courtesy Wärtsilä-Hamworthy

4.2 Dry Exhaust Gas Cleaning Systems

The dry Exhaust Gas Cleaning System uses a packed bed of granulated hydrated lime (calcium hydroxide – $Ca(OH)_2$) rather than water as the scrubbing medium with calcium sulphate ($CaSO_4$) as the reaction product. It is typically installed after the turbocharger, operates at temperatures of between 240°C and 450°C and is an effective silencer. As the reaction is exothermic (heat is released) there is no loss of exhaust gas temperature during the cleaning process and the exhaust gas cleaning unit can be installed before a ship's waste heat boiler or economiser. Operation at lower temperatures is possible, but requires a higher consumption of granulate.

The cleaning process removes both sulphur oxides and particulate matter, with the internal design of the exhaust gas cleaning unit such that the exhaust gas is constrained to flow horizontally through the packed bed, so optimising the chemical reaction.

SULPHUR DIOXIDE:

- $SO_2 + Ca(OH)_2 \Rightarrow CaSO_3$ (calcium sulphite) + H_2O
- $2CaSO_3 + O_2 \Rightarrow 2CaSO_4$ (calcium sulphate)
- $CaSO_4 + 2H_2O \Rightarrow CaSO_4 \cdot 2H_2O$ (calcium sulphate dihydrate – gypsum)

SULPHUR TRIOXIDE:

- $SO_3 + Ca(OH)_2 + H_2O \Rightarrow CaSO_4 \cdot 2H_2O$ (calcium sulphate dihydrate – gypsum)

Info Box 17: Relevant chemistry – Dry Exhaust Gas Cleaning System

Fresh granulate is stored in a supply silo at the top of the exhaust gas cleaning unit and a controlled extraction of the reacted granulate and any particulate matter at the bottom ensures the correct feed under gravity. Extraction may be continuous or intermittent. Automation is provided from a control cabinet with an integrated exhaust emissions monitoring system to ensure compliance with regulations.

A pneumatic conveyor system is the standard method of filling the supply silo and removing the spent granulate to storage.

The design of the conveying pipelines is flexible which enables storage tanks and containers to be located in various locations onboard.

The exhaust gas residence time within the exhaust gas cleaning unit enables a high level of sulphur oxide removal with up to 98% being quoted for similar shore-side installations [39] and 99% has been achieved during trials onboard ship [57]. A reduction in particulate matter of 80% has also been measured.

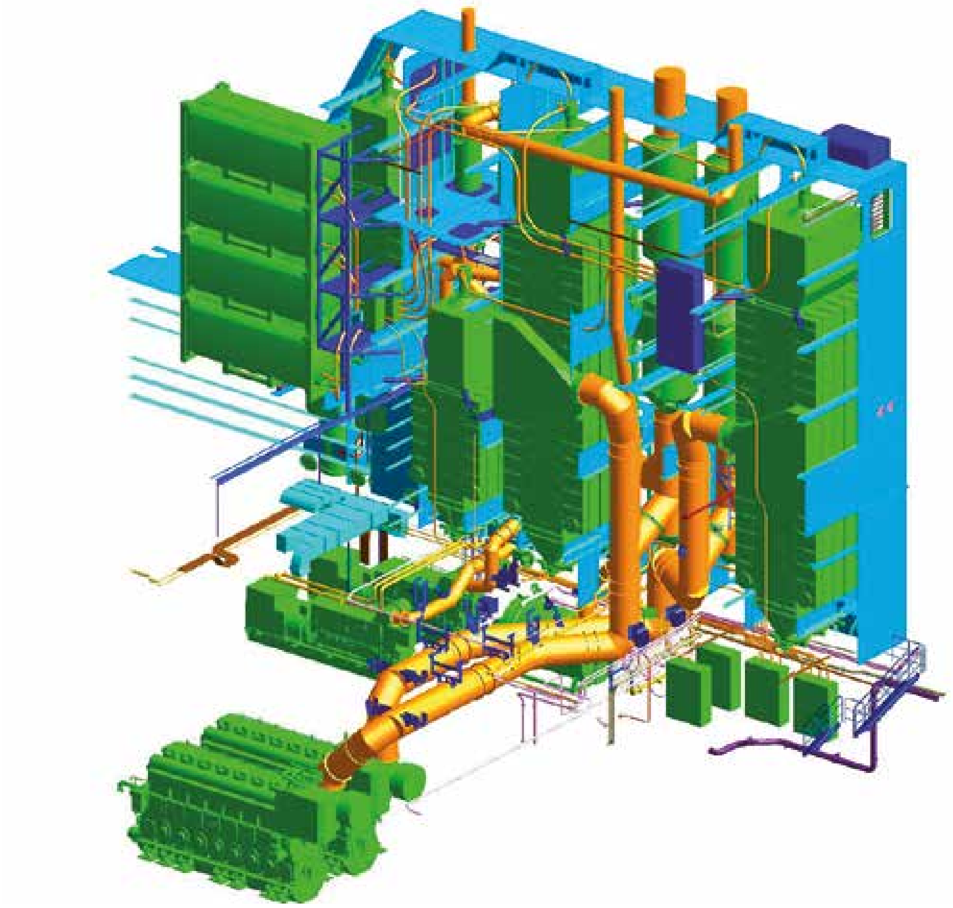


Figure 29: Arrangement of dry exhaust gas cleaning for multiple engines
(Exhaust gas cleaning units for the 2 main engines are forward (right) and middle of the funnel casing. Smaller exhaust gas cleaning units for the 2 auxiliary engines are middle and aft (partly obscured). Granulate storage containers can be seen aft, in the top foreground. Total engine power 22MW.)

Courtesy of Couple Systems GmbH

The flow schematic in Figure 30 shows a dry Exhaust Gas Cleaning System combined with Selective Catalytic Reduction (SCR) for the removal of NOx. Dampers enable control of exhaust flow in case it is required to bypass the complete system.

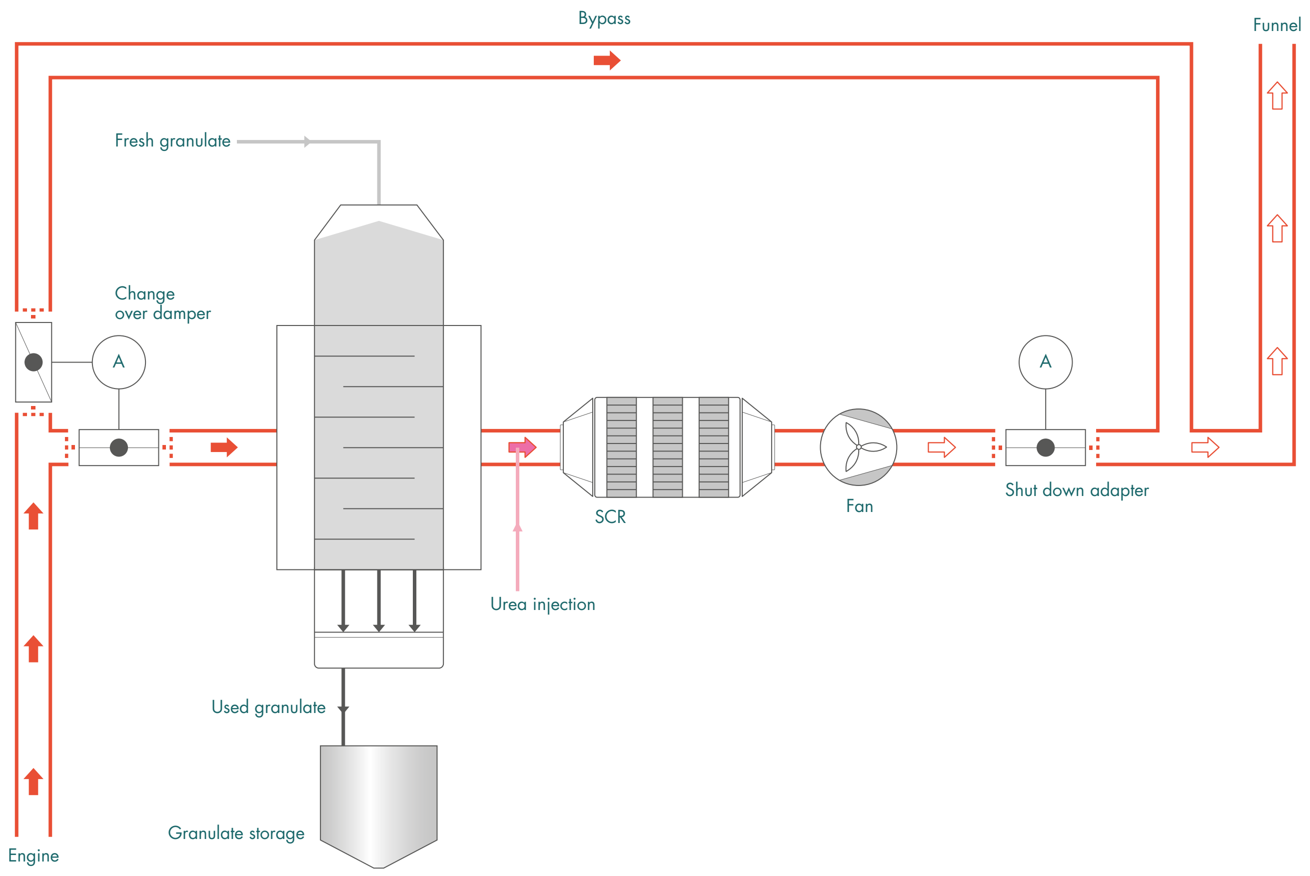


Figure 30: Flow schematic – dry Exhaust Gas Cleaning System combined with SCR
(Note: the exhaust fan is an option dependent on exhaust backpressure created by the system and may not be required)

Courtesy of Couple Systems GmbH

Dry exhaust gas cleaning facilitates downstream fitting of a Selective Catalytic Reduction system. SCR reduces polluting NOx emissions to nitrogen and water and is further explained in Section 6, however in marine systems the catalysts for the reaction typically require exhaust gas temperatures of over 300°C to function at an optimum. As there is no loss of exhaust gas temperature during the dry cleaning process reheating of the exhaust stream before entry into the SCR reactor is not required.

Exhaust gas entering a SCR reactor with a high level of SO_2 also risks deposition of ammonium sulphates, derived from the urea used in the SCR process. Catalyst elements are highly porous to give a large contact area and the pores can be physically blocked by ammonium bisulphate and combustion related particulate matter. Depending on system design and catalyst materials chemical 'poisoning' by compounds derived from fuel and lubricating oil combustion can also occur. Both mechanisms impair performance and shorten catalyst life. Removing the majority of sulphur oxides and particulate matter therefore has the potential to allow fitting of smaller SCR catalysts, with a significantly longer life expectancy.

4.2.1 Supply and disposal of consumables

Hydrated lime is a readily available commodity. Both lime production and power generation plants (for disposal) are located worldwide within a radius of 200km of all major ports.

There is currently one supplier of dry Exhaust Gas Cleaning Systems to the marine market and the vendor will ensure the supply of fresh granulate as required. It is proposed that granulate be supplied via strategic logistics centres by road tanker, in big bags or by use of 20 or 40 foot special containers, which can be handled in the same way as standard containers. The special containers will be divided into compartments to allow the same box to be used for the storage of both fresh and used granulate, and each is to be fitted with a self-contained pneumatic conveyor system.

The residue has a commercial value to other industries, which enables its free collection and disposal after use onboard. The options for disposal include:

- Power generation industry: used granulate is only partially spent during the onboard exhaust gas cleaning process, which enables the residue to be reused for high temperature desulphurisation of land-based power plant emissions by direct injection into the boiler furnace or exhaust duct. The reaction product is gypsum, which is used to produce plasterboards for the construction industry.
- Agro-technology: mixed with other components used granulate can be used for soil remediation in areas that have been subject to surface mining
- Steel plants: used granulate can be used for the process of binding slag from blast furnaces, which is converted into gravel for road construction
- Cement plants: with a high content of gypsum used granulate can be used as a retarding agent in cement for construction work

5. Exhaust Gas Cleaning Technologies

The exhaust gas treatment processes featured in this Handbook focus on the removal of pollutants, with the exception of Selective Catalytic Reduction which converts NOx to nitrogen and water and Exhaust Gas Recirculation, which is a primary control technique; restricting the formation of nitric oxide and thus NOx at source in the cylinder, (although the system does require an exhaust gas cleaning unit).

The following sections review the common Exhaust Gas Cleaning technologies used in industrial plant and power production to reduce and eliminate harmful emissions, gaseous vapours and particulate matter.

SOx and PM removal technologies that lend themselves to marinisation are detailed and methods of NOx control are covered in Section 6. The limiting factors for shipboard installations include weight, block footprint or size, consumable needs and effect of diesel engine exhaust gases, which are to typically much more "oily" than combustion gases from boilers. It has been reported that combustion of residual fuel in boilers can also produce an "oily" exhaust, probably due to un-combusted vapours of high molecular weight hydrocarbon compounds.

5.1 Removal methods

Gaseous Pollutants: Gaseous pollutants from marine diesel engine exhausts include SO_2, SO_3, CO, NO, NO_2. These can be removed by adsorption onto a suitable substrate, absorption into liquid (usually water) or by conversion to other compounds (for example by SCR).

Primary Particulates: These can be removed by filtration, gravity separation, centrifugal separation, separation by electronic charge, or trapping in a liquid medium (normally water).

Secondary Particulates: These are actually formed as part of atmospheric chemistry processes beyond the envelope of the ship. However technology and fuel selection can reduce the production of secondary particulate matter at source.

Whilst all designers of Exhaust Gas Cleaning Systems will use a variant of the following gas cleaning techniques, it has already been shown in Section 4 that a system fitted on board ship is a fully functional 'emissions compliance' solution comprising of many more components than simply the gas cleaning function.

TECHNOLOGY	BRIEF DESCRIPTION	SUITABILITY
Gravity Settlers	Gravity settling requires very low gas velocity and significant volume to enable gravity to settle out particles. It is not suitable for removal of gaseous components. Not suitable for marine exhaust cleaning applications.	✗
Wet Scrubbers – Absorption	Wet marine scrubbers typically use either seawater or freshwater with an alkali consumable additive (normally caustic soda). There are a number of designs for mixing the gas and particulate with the scrubbing water. Marine wet scrubbers use water to absorb certain pollutant gases such as sulphur dioxide and are also able to trap particles. The absorbed gases are converted into benign compounds. The particles are removed prior to the discharge of the process water. Wet scrubbers have been used for inert gas preparation on board tanker ships for about 50 years and are suitable for marine exhaust gas cleaning applications.	✓
Cyclones	Cyclones use centrifugal force to remove particles. The centrifugal force can be more powerful than gravity. If used with water as a wet scrubber, a cyclone scrubber can remove both particles and gaseous components. Suitable for marine exhaust cleaning applications.	✓
Dry Scrubbers – Adsorption	Dry scrubber systems used on board ship use a surface active material to adsorb and sequester pollutant gases (SO_2). The consumable is normally a specially prepared hydrated lime granulate.	✓
Bag Filters	This type of filter is extensively used where there are high levels of dust. Not suitable for marine exhaust cleaning applications where exhausts conditions exceed the limit of bag materials (200°C) and are very oily, causing the filter material to quickly block.	✗
Membrane Filters	A similar principle to the bag filter. The membrane material may be engineered to specific pores sizes to target specific pollutants. However temperature limitations only allow its use post wet scrubbing as a possible final gas polishing stage.	✓
Electrostatic Precipitators	Electrostatic precipitators use special plates to charge the particles in the exhaust stream. The charged particles are then separated from the gas stream by use of electric field, which is more powerful than both gravity and centrifugal forces. It has been reported by a power utility that electrostatic precipitators are not effective when using residual fuels due to tar deposits on the charging and collection plates. May be adapted to be suitable for marine exhaust cleaning applications.	✓
Thermal Oxidation	Thermal oxidation is a type of incineration process. It is used for oxidising pollutant gases such as 'carry-over' combustible products of chemical processing. It is not applicable for marine exhaust cleaning applications.	✗
Non-Thermal Plasma	Non-thermal plasma has been tested by the UK Navy for removal of NOx using a hydrocarbon reductant. In theory it has advantages over SCR. At present the main obstacle to adoption of this technology has been the high energy consumption. (See also Section 7.1.3).	✓
Exhaust Catalysts	Exhaust catalysts are used in on-road vehicles (oxycats, SCR) to both oxidise hydrocarbons and carbon monoxide and reduce NOx to nitrogen and water in the exhaust gas. Have been adapted for marine exhaust cleaning applications.	✓
Biological Methods	This system uses bacteria or other organisms to filter and react with pollutants. Such systems require significant space and management of the organic filtration system and are at present unsuitable for marine exhaust gas cleaning systems.	✗

Table 5: Exhaust gas cleaning techniques

Of the listed methods the following are currently in use for exhaust gas cleaning on-board ship.

1. Wet scrubbing with absorption
2. Dry scrubbing with adsorption
3. Exhaust Catalysts

5.1.1 Wet scrubbers

The principle of wet scrubbing is:

1. Formation of water droplets in a size range of around 100μm to 1000μm.
2. A method of forcing contact between water droplets and gas (including particulate).
3. Removal of water droplets and drying of the cooled, clean exhaust gas.

At a pH of around 8.0 sulphur dioxide and sulphur trioxide readily dissolve (absorption) into water. Other gases including carbon dioxide and oxides of nitrogen have very limited solubility and pass through the wet scrubbing section. Particulate in the range of 0.1μm to 100μm can also be readily removed from the gas stream.

There are believed to be three processes of particle removal:

1. Direct impact of the particle with the water droplet.
2. By interception when the particle is not fully displaced around the water droplet.
3. By diffusion through random molecular (Brownian) motion.

The diagram below indicates how gas, which is very low density will stream around the droplets of water in a wet scrubber. Larger particles, which have more inertia and are thus resistant to changing direction eventually impact onto the water droplets. This trapping mechanism is most effective when there is a large relative velocity between the particle and water droplets (which increases the inertial effects).

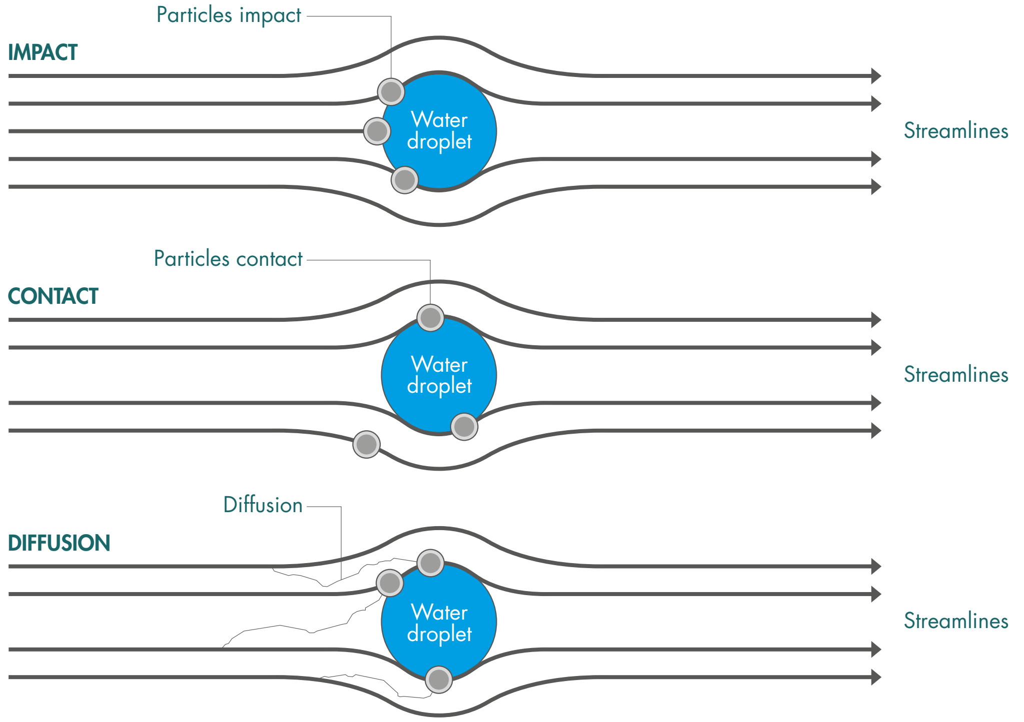


Figure 31: Particle trapping process

Courtesy Fenger & Tjell, Air Pollution 2009 [94]

Smaller particles may still be trapped, as they will tend to be carried on the edge of the streamlines adjacent to the water droplets. Particles that are less than 1μm with much lower density will closely follow the streamlines and are most likely to be trapped by diffusion caused by random molecular movement.

Ultrafine particles (100nm range) have a very low mass and act virtually as the gas. To improve trapping coalescing techniques may be required, in which water vapour is used as the coalescing agent forming on the ultrafine particles and causing them to come together to form larger wetted particles.

The range of water droplets is critical to efficient trapping. Water droplets less that 100μm will tend to be carried with the gas and have less opportunity for direct impact with the gas and particles. Droplets larger than 1000μm will reduce droplet concentration (for a fixed water flow) reducing the frequency of impact opportunities.

There are a number of methods of creating water droplets and a number of methods of creating effective gas and water mixing.

Figure 32: Wet scrubber packed bed material
(The packed bed provides a large wetted surface area to induce intimate contact between the exhaust gas and washwater. The choice of packing depends on a number of factors including the operating temperature, scrubbing media and surface area required for optimum scrubbing performance).

Courtesy The Pall Ring Company; www.pallrings.co.uk

In most wet scrubbers nozzles of an appropriate shape and pressure drop are used to break-up the water flow and create a range of suitably sized droplets. Some nozzles are arranged with compressed air or ultrasonic energy as a source for creating a range of droplet sizes. Other designs use gas turbulence to break the water jet, through shear between gas and water. Examples of designs intended to cause shear are a bubble plate and a venturi. Gas and water can be arranged with co-current flow, counter-current flow or cross flow. Another method uses cyclonic action to create shear between the water and the gas.

As well as balancing droplet size ranges to create high efficiency scrubbing, gas velocity must be varied to suit trapping different particle size ranges. High velocity of gas relative to the water droplets improves impact trapping. The trapping of finer particles and particles requiring coalescing methods requires lower velocities and less turbulence.

Once scrubbing is completed any remaining water droplets must be removed from the gas stream. This requires a lower velocity gas flow and a mechanism to coalesce and create larger water droplets of any remaining water. The larger droplets can then be removed by gravity, cyclonic separation or by use of special meshes that act as coalescing points and to some extent centrifugal separation due to the tortuous gas path.

The classical designs of wet scrubbers (key design feature that brings the water and gas together for both absorption and trapping processes include:

1. Bubble Plate
2. Cyclonic
3. Packed Bed
4. Spray Tower
5. Venturi
6. Wet Bath

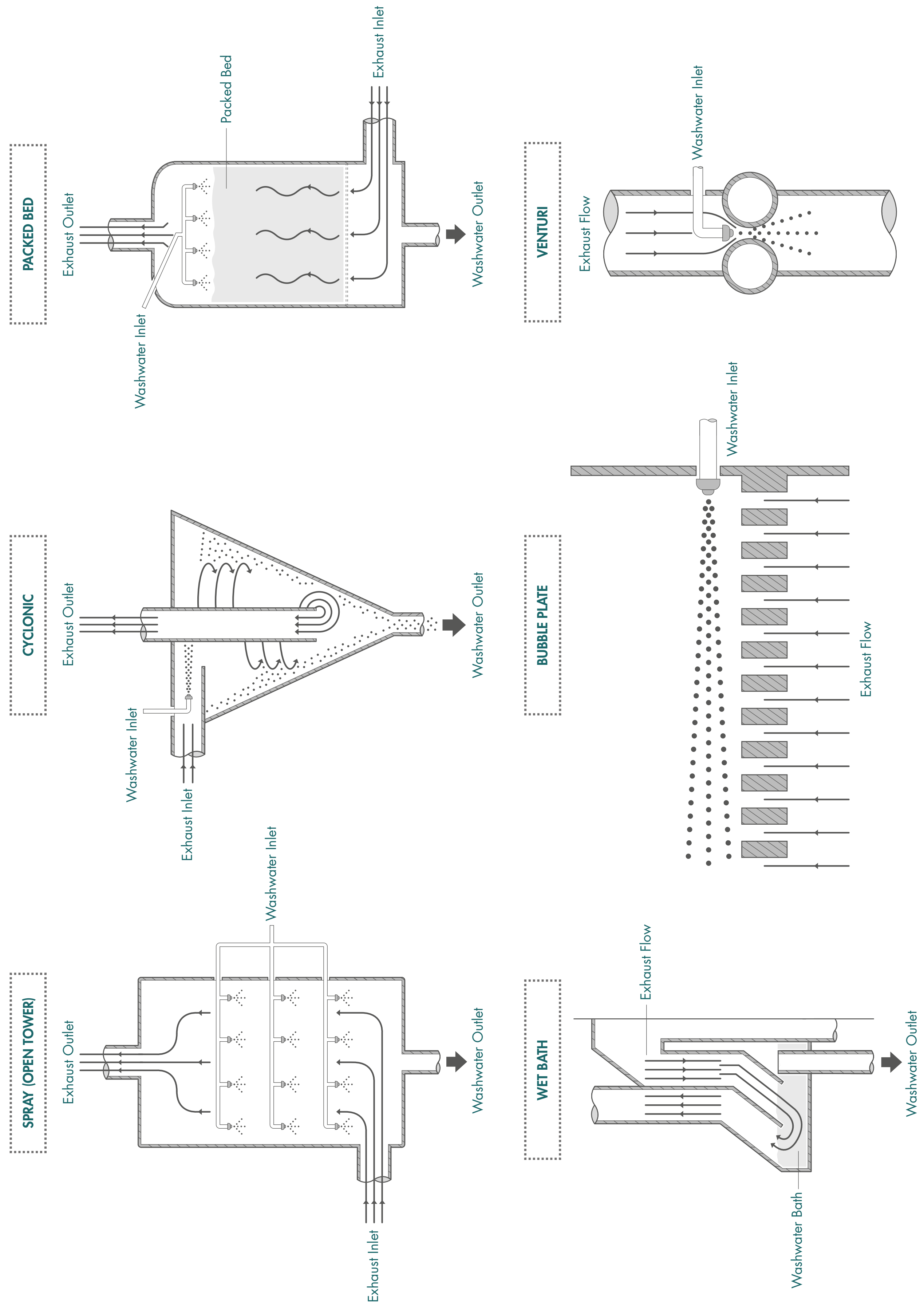


Figure 33: Wet scrubber types

In virtually all wet scrubber designs for hot exhaust gases the first stage consists of a quench section. This stage reduces the hot gas temperature to around 60°C. The quench, which is typically constructed as a throat and an expander section, is effective in removing about 60% of the sulphur dioxide and a portion of the particulate. Particulate removal through impaction is aided by the large differential in exhaust gas and water droplet velocities at the throat inlet.

In order to achieve adiabatic cooling about 20% of total washwater flow is used in this section. Hot exhaust gases passing through the quench are adiabatically cooled to the saturation temperature by expansion and the transfer of heat to washwater sprayed into the exhaust stream, so whilst the exhaust temperature is significantly lowered, the heat content of the process flow remains the same.

Sufficient washwater must be added to aid cooling of the exhaust without undue levels of evaporation, which would adversely affect scrubber sizing, collection efficiency and in the case of seawater create salt aerosols with the potential for deposits. If flow is low and the gases in the quench and downstream scrubber remain hot, some liquid droplets may evaporate before they have a chance to contact pollutants in the exhaust stream, and others may evaporate after contact, causing captured particles to become re-entrained. Once the exhaust gas is cooled the volume of gas is reduced significantly. This is very helpful in order to maintain reasonable dimensions of the wet scrubber and reduce gas velocities below that in the exhaust ducts.

Following the quench section the design of wet scrubbers diverges according to designer's existing designs and empirical experiences.

As a minimum a wet scrubber will have at least one further stage of gas scrubbing in which the remaining sulphur dioxide is brought into contact with the water and absorbed. The overall efficiency of the gas scrubbing and removal of sulphur dioxide is a function of the effectiveness of the gas contact with water (diffusion process), water temperature and the extent of saturation of the water with sulphur dioxide. Effective designs will normally have achieved 95% to 98% removal of sulphur dioxide prior to the demister. The demister is usually wetted with the remaining water flow. The gas velocity through this section is low and thus the demister acts not only to trap free water droplets carried with gas flow, it also acts as the final "polishing" stage to absorb the remaining sulphur dioxide.

Both closed loop (scrubbers using an added alkali treatment) and open loop wet scrubbers (seawater and any river water of sufficient alkalinity) use the same principles of trapping and absorption. Both systems must deal with hot gases that need to be cooled. Sulphur dioxide and particles need to be absorbed and trapped respectively and the cooled cleaned gas must be free of aerosols of water prior to exit.

Figure 34: Dual inlet exhaust gas cleaning unit (for 2 combustion units)
(Note inlet quench arrangement on the left)

Courtesy Alfa Laval

Two further design considerations are the buoyancy and velocity of the gas exiting to atmosphere and the relative humidity of the gas stream.

The former may be of concern if the design conditions are not sufficient to disperse the gas into the atmosphere and away from the vessel and other zones in which human activity is located. There are various options dependent upon flow and backpressure considerations. These include:

- A constricted gas exit to increase velocity. This may not be practical if there are backpressure limitations on the exhaust system.
- Use of re-heat of the cooled gas to increase buoyancy. This is also useful in removing the risk of a condensation plume but may require additional energy if waste heat recovery is impractical.
- Use of an induced draft fan to increase exit velocity. This option increases energy consumption but is very useful in overcoming backpressure limitations.

The typical cooled and cleaned gas has a relative humidity of close to 100%. Under certain atmospheric conditions exiting gas will be cooled by the surrounding air and condense some of the water content forming a white plume of moist air. Although this has no significant adverse effects, industrial plant emissions legislation prohibits moisture plumes. It is not clear what the impact is likely to be for merchant shipping. Most designers make arrangements to avoid plume formation.

5.1.2 Dry scrubbers

Dry scrubbers use the mechanism of adsorption to remove pollutant gases.

There are two methods of adsorption. Physical adsorption occurs where the gas molecules stick to the adsorbent surface due to van der Waals' forces. This process is reversible and molecules trapped on the adsorbent surface can be released by use of heat or by varying the gas concentration.

Marine dry scrubbers utilise a chemical adsorption process known as chemisorption. In this process a chemical reaction takes place to trap the sulphur dioxide by converting it into a stable compound. Marine dry scrubbers utilise calcium hydroxide (hydrated lime) to adsorb and sequester sulphur dioxide.

The effectiveness of a dry scrubber is in the characteristics of the adsorbent, and in particular in the specific surface area. The adsorbent, calcium hydroxide is supplied as granulate with a size range of 2mm to 8mm and a very high surface area to mass ratio. The high surface area coupled with the use of only about 50% of the active chemisorption potential provides for a sulphur dioxide reduction efficiency of 99%.

Figure 35: Calcium hydroxide granulate

Courtesy of Couple Systems GmbH

As the exhaust gas temperature is not reduced during dry scrubbing, the gas volume remains the same throughout the process. In order to achieve effective removal of primary particulate matter the scrubber volume must be sufficiently sized to reduce the gas flow rate to a suitably low level. This enables impact and filter trapping processes to occur, removing primary particulate.

Although removing the majority of sulphur oxides from the exhaust will largely prevent the eventual formation of sulphates the constant high temperature operation may reduce the effectiveness of removal of other condensable secondary particulate. It is understood further development is underway to introduce further scrubbing sections, which may address secondary PM.

6 Treatment Processes – NOx

6.1 Selective Catalytic Reduction (SCR)

Regulation 13 of MARPOL Annex VI sets out a schedule for the reduction of nitrogen oxide (NOx) emissions from marine diesel engines. Subject to an imminent review of enabling technologies the third step or Tier III of these reductions (emissions to be no more than 2 to 3.4 g/kW h, depending on engine speed) is to be introduced from 1 January 2016. It will apply to engines installed on newly built ships and will likely require the use of exhaust after-treatment to achieve the required standard when operating in an emission control area where NOx is controlled (see Appendix 4).

Selective catalytic reduction (SCR) converts NOx into nitrogen (N_2), and water (H_2O), by means of a reducing agent adsorbed onto a catalyst. This is typically ammonia, formed by the decomposition of urea [71], $(NH_2)_2CO$ injected into the exhaust gas stream.

The effectiveness of SCR is reduced with exhaust temperature and during engine operation at partial load. Typically, SCR systems are applied to four-stroke medium and high speed engines, which have exhaust temperatures above 300°C at normal load. Slow speed crosshead engines have lower exhaust temperatures because of their higher efficiency and to date the very small number that have been equipped with SCR have had the reactor placed upstream of the turbocharger to expose the catalyst to the highest temperature exhaust. In an alternative design the reactor has been placed after the turbocharger and a burner used to increase the exhaust temperature to the required level [76].

For marine applications urea is used because of the hazards associated with handling ammonia, which is classed as toxic, corrosive and harmful to the environment. It is supplied in solution or can be mixed onboard using bagged granules and freshwater.

The injected urea solution must be mixed thoroughly with the hot exhaust gas in a specifically designed duct before entering the reactor housing containing the catalyst. Whilst in the duct the urea combines with water from the exhaust stream and the injected solution, then decomposes to form ammonia (NH_3) and some carbon dioxide. On contact with the surface of the catalyst the NOx components, nitric oxide (NO) and nitrogen dioxide (NO_2) react with the ammonia and oxygen from the exhaust to form nitrogen and water.

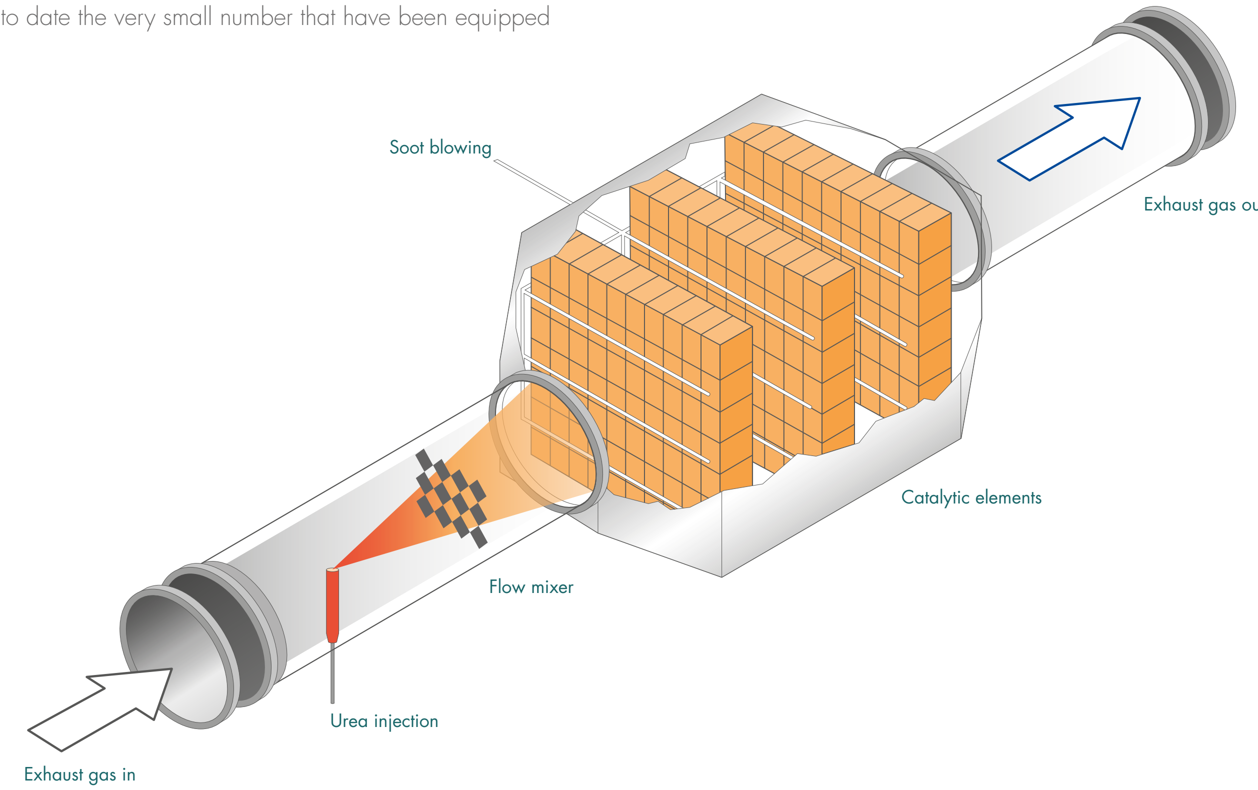


Figure 36: Selective Catalytic Reduction unit

Courtesy Wärtsilä

UREA DECOMPOSITION IN THE MIXING DUCT:

1. $(NH_2)_2\,CO$ (urea) ⇨ NH_3 (ammonia) + HNCO
2. HNCO + H_2O ⇨ NH_3 + CO_2

NOX REDUCTION AT THE CATALYST

1. $4NO + 4NH_3 + O_2$ ⇨ $4N_2 + 6H_2O$
2. $2NO + 2NO_2 + 4NH_3$ ⇨ $4N_2 + 6H_2O$
3. $6NO_2 + 8NH_3$ ⇨ $7N_2 + 12H_2O$

Info Box 18: Relevant chemistry – Selective Catalytic Reduction

SCR efficiency is such that NOx emissions can be reduced by 80 to 90% i.e. <2g/kW h can be achieved and the quantity of CO_2 produced from the urea is negligible when compared with that produced by the fuel oil combustion.

In 4 stroke engine installations the reactor housing is fitted in the exhaust after the turbocharger and before any waste heat recovery system. Depending on the application it may be vertically or horizontally orientated. Compact designs can include an integrated silencer as a space saving measure for smaller vessels. Typically the maximum allowable exhaust temperature is 500°C to prevent thermal damage of the catalyst and when required catalysts can generally be 'run dry', for example outside of an area where NOx is controlled.

TYPICAL LIFESPAN FOR CATALYST BLOCKS IS BETWEEN TWO AND FIVE YEARS:

- Specialist companies or vendors undertake catalyst removal
- Protective clothing including respirators are worn during disassembly
- Catalyst elements are kept dry and protected from crushing during transportation
- Disposal is either as waste or by recycling; no special permits are usually required
- Waste elements are normally removed to landfill or used in road construction as foundation material
- Metals in the spent catalyst may also be recycled
- In California spent catalysts are regarded as hazardous waste (because of the vanadium content) and must be handled by a specialised plant

Info Box 19: Spent SCR catalyst disposal

The catalyst elements within the reactor housing are typically composed of replaceable porous blocks arranged in layers. The blocks have multiple gas paths, providing an optimal area for contact with the exhaust whilst not imposing an unacceptable obstruction to flow. The blocks may be manufactured from various ceramic materials such as titanium dioxide (TiO_2) coated with an active component such as vanadium pentoxide (V_2O_5), together with tungsten trioxide (WO_3) to optimise performance.

The selection of materials and construction of catalysts is a careful balance. Subject to manufacturers limits it is based on the ability to cope with thermal conditions at the chosen position and the pollutants in the exhaust, so that the conversion performance is maximised and the production of additional undesirable pollutants is minimised.

6.1.1 SCR control

It is important to tightly manage the rate of urea injection in order to restrict the release of un-reacted ammonia to atmosphere, which is referred to as 'ammonia slip'. Catalyst temperature is used to control when injection begins after an engine is started. The delay period may be over 30 minutes but this depends on the position and size (heat capacity) of the catalyst, the length of time the catalyst has been cooling and the initial engine load. When operating, a characteristic curve of NOx emissions across the engine load range can be used to regulate the injection equipment with enhanced feedback provided by continuous monitoring of the NOx emissions after the reactor. A 'slip' catalyst may also be fitted after the reduction catalyst to reduce the release of ammonia to atmosphere.

Catalyst temperature is a key parameter for optimum system performance, and operation at the design level is vital to prevent both ammonia slip and a reaction with sulphur trioxide (SO_3) in the exhaust stream [69]. Typically, a minimum of 300°C to 360°C is required. At lower temperatures the formation of ammonium sulphate, $(NH_4)_2SO_4$; a dry powdery compound, can result. Ammonium bisulphate, $(NH_4)HSO_4$ is also formed at higher levels of SO_3 (hence fuel sulphur). This is an adhesive and corrosive compound that reduces the effective area of the catalyst and is deposited in downstream components of the exhaust system impeding gas flow and the transfer of heat. Higher NOx emissions ensue and conditions overall can deteriorate with more ammonia slip and further fouling from the adherence of combustion derived particulate matter.

In an SCR catalyst unwanted reactions can take place when sulphur dioxide in the exhaust is oxidized to sulphur trioxide.

- $2SO_2 + O_2 \Rightarrow 2SO_3$.

Two reactions can then follow

- $2NH_3$ (ammonia) + SO_3 (sulphur trioxide) + H_2O $\Rightarrow$ $(NH_4)2SO_4$ (ammonium sulphate)
- $NH_3 + SO_3 + H_2O \Rightarrow NH_4HSO_4$ (ammonium bisulphate)

The balance of the 2 species depends upon the exhaust temperature and concentration of ammonia from injected urea and sulphur trioxide from fuel sulphur.

Info Box 20: Undesirable reactions in an SCR catalyst

Although a number of suppliers advise that a higher sulphur content is acceptable, particularly at higher exhaust temperatures, fuel oil with a low sulphur content (typically 1% maximum [77]) or an upstream SOx Exhaust Gas Cleaning System*, which does not impact exhaust temperature is generally specified to maximise the effective life of catalysts. By requiring a low sulphur content, deposits of ammonium sulphate and bisulphate that mask the surface and plug the pores of the catalyst are controlled, so ensuring contact with the exhaust gas is properly maintained. Depending on the materials of construction compounds can also be adsorbed onto and chemically react with active parts of catalysts further degrading performance. These 'poisons' include alkalis (sodium, potassium and calcium compounds) phosphorus and certain heavy metals. This requires adherence to manufacturers recommendations in terms of the fuel oil type, composition and ash content (for example biofuels can have a high level of alkali metals). Recommended lubricating oil specifications for engines also have to be followed.

As deposits of soot, ash, and ammonium sulphates adversely affect the activity of the catalyst and cause an increase in pressure drop, a system using pressurised air or low frequency infrasound from an acoustic horn can be installed for regular cleaning of loose fouling from the catalyst surfaces.

*The Exhaust Gas Cleaning System could be either dry or wet with reheating of the exhaust gas after the cleaning process.

6.1.2 Oxidation catalysts

The majority nitrogen oxide in NOx is NO, which is reduced to nitrogen and water by reaction 1 in Info Box 18. However because this reaction is slower than reaction 2, an oxidation catalyst may be fitted before the reduction catalyst. This converts some NO to NO_2 and allows manufacturers to use a smaller reactor and/or operate at lower temperatures [37].

Oxidation catalysts can also effectively convert other pollutants into simpler, less toxic compounds, such as carbon dioxide and water. These pollutants include carbon monoxide (CO), hydrocarbons, the soluble organic fraction of particulates (derived from unburned or partially combusted fuel oil and engine lubricant), and several hydrocarbon derivatives, including polycyclic aromatic hydrocarbons (PAHs) [38].

The sulphur content of the fuel must however be considered for systems using oxidation catalysts. Whilst in a typical diesel engine exhaust a very small percentage of SO_2 is oxidised to SO_3, this can be significantly increased, particularly at higher engine loads and exhaust temperatures [37]. A proportion of the SO_3 formed will react with some of the water vapour present to form damaging sulphuric acid. There will also be an increased potential for degrading deposits of particulate matter including sulphates of ammonia and metals [9] derived from the combusted fuel.

6.2 Exhaust Gas Recirculation (EGR)

During the process of combustion in an engine a series of complex reactions occur which cause some of the nitrogen in the charge air and most of any nitrogen in the fuel to oxidise and form nitric oxide (NO).

The majority of this NO is formed thermally by reactions between the nitrogen and oxygen in the charge air at a rate that is mainly dependent on the temperature within the combustion zone. Thermal NO formation is significant at 1200° C and rises exponentially above 1500° C. The amount of oxygen available i.e. excess air within the combustion zone and the time the combustion gas is exposed to a sufficiently high temperature are also important secondary factors [3].

On leaving the combustion chamber some of the nitric oxide is oxidised to nitrogen dioxide (NO_2) and together these 2 gases form NOx in the ratio of approximately 90% to 95% NO, 5% to 10% NO_2 [3].

Primary methods of NOx control focus on the process of NO formation and reductions down to Tier II levels can be achieved through the improved design and operational adjustment of engines. Factors influencing NO formation include the pressure, timing and rate of fuel injection, fuel nozzle configuration, exhaust valve timing, the temperature and pressure of scavenge air, and compression ratio. Further reductions can be achieved by wet techniques such as fuel-water emulsions and by injection of water into the charge air or directly into the cylinders. Such measures lower combustion zone temperatures and oxygen levels. NO formation is suppressed but not to a sufficiently low level for Tier III compliance. Exhaust Gas Recirculation (EGR) is however another 'at-engine' method of NOx control, which can meet Tier III requirements. It is a well-known technology in on-road applications that has been now applied to large two-stroke marine diesel engines and is being explored for medium speed engines. It is a technique that lowers the oxygen content and increases the heat capacity of the 'charge fluid' – the mixture of fresh air and recirculated exhaust in the combustion chamber. This lowers the peak combustion temperature thereby suppressing the primary formation of NO.

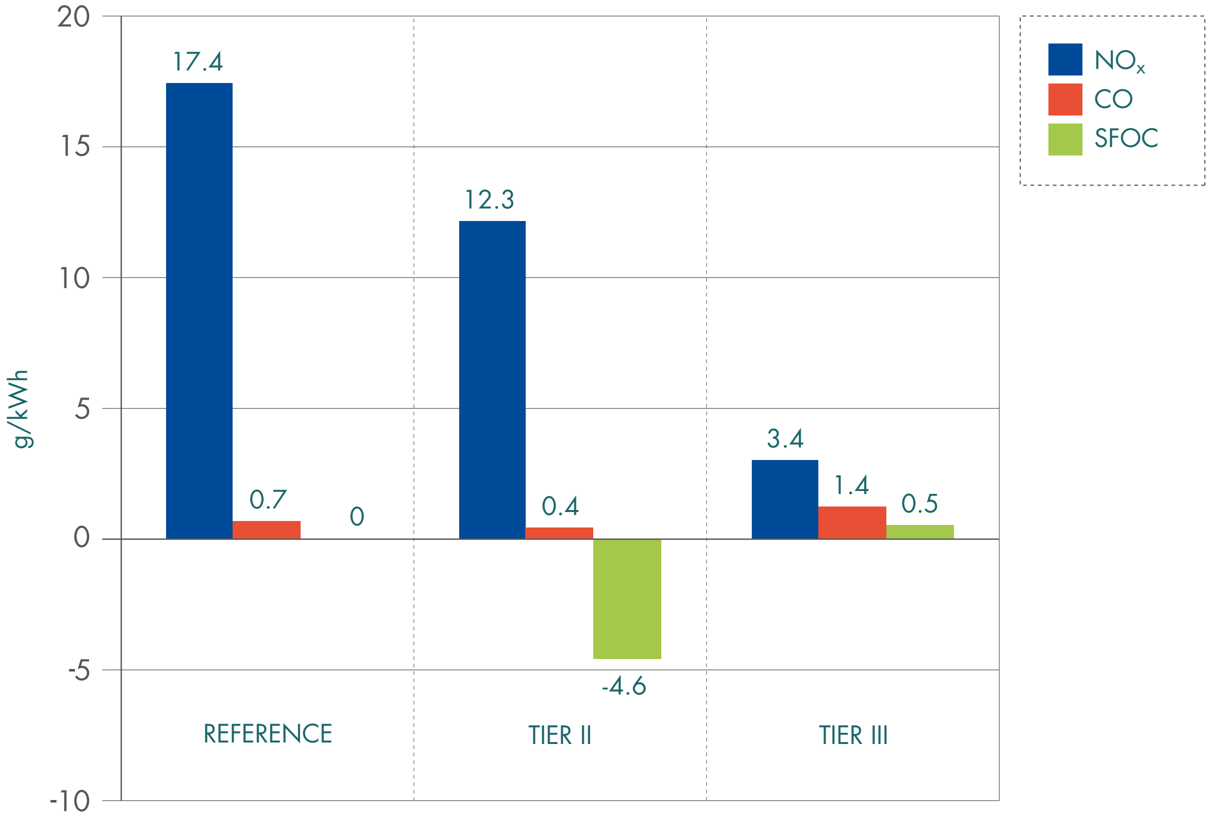


Figure 37: Results of EGR tests on 2-stroke test engine adjusted to achieve Tier II & Tier III compliance.
(Power for the EGR blower is not included in Specific Fuel Oil Consumption values. Other emission values (PM, HC) remain basically unchanged)

Courtesy MAN Diesel & Turbo

NOx reduction rates of more than 85% have been achieved but with an increase in specific fuel consumption and carbon monoxide (CO) levels. It has however been found that adjustment of the engine set-up can compensate for a large part of this penalty, which appears to make IMO's Tier III NOx limit practically achievable. Operation at low engine loads, which can be a problem for other NOx reduction technologies such as SCR, also does not seem to pose a problem for EGR.

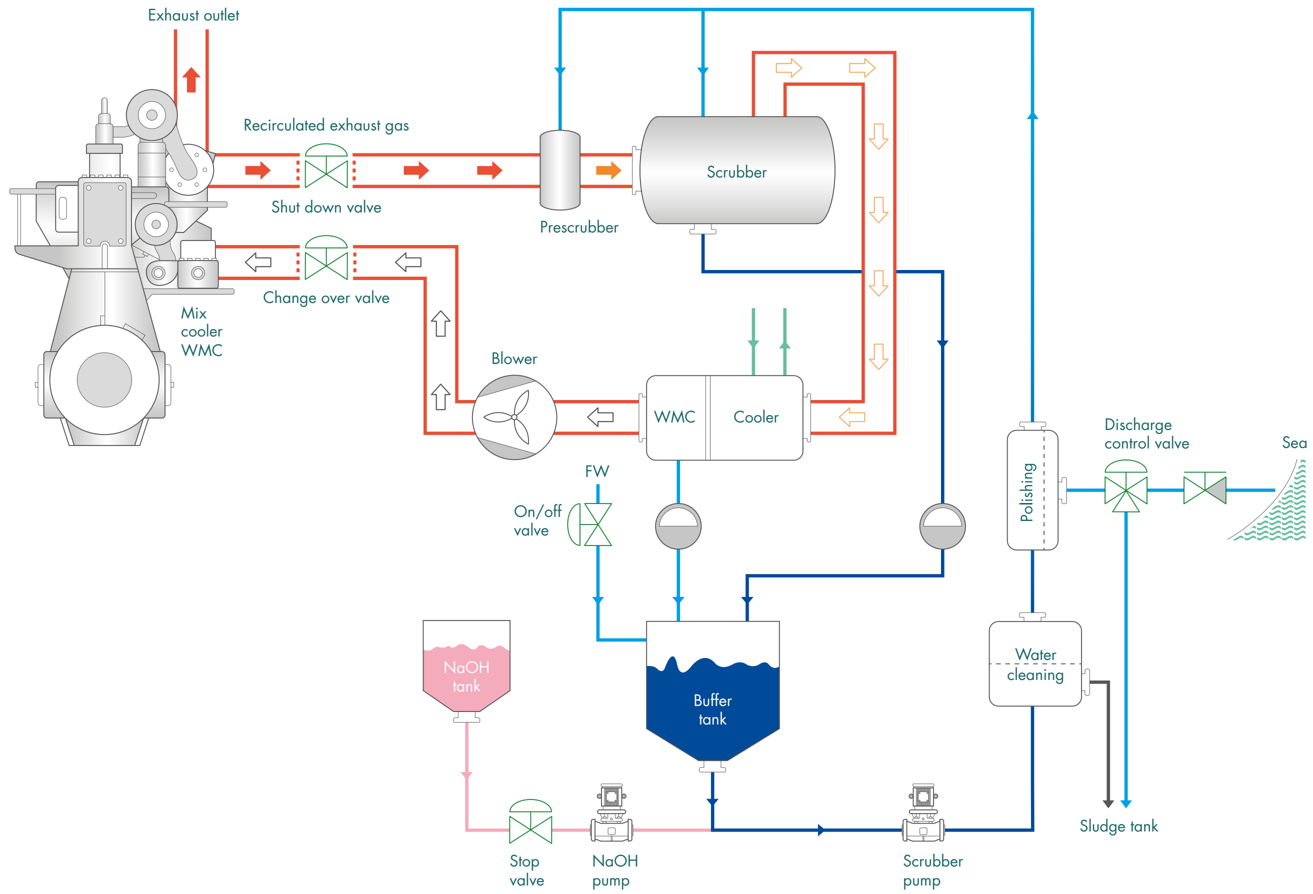


Figure 38: EGR system
(Colour of exhaust gas indicates reducing temperature, SOx and PM in direction of flow)

Courtesy MAN Diesel & Turbo

The EGR system includes, an exhaust gas wet scrubber integrated onto the engine, a cooler and 'water mist catcher' (WMC), a single-step, high-pressure blower, a washwater treatment system and a control unit for controlling the washwater treatment system and EGR blower speed. In excess of 40% of the exhaust gas can be recirculated.

The scrubber removes sulphur oxides and particulate matter from the recirculated exhaust gas to prevent fouling and corrosion of engine components and the EGR system. Freshwater, circulated in a closed loop system is used as the scrubbing medium. Acidity resulting from the sulphur oxides is neutralised using caustic soda in the washwater treatment plant, which also separates solid residues into tanks for onshore disposal.

The cooling effect of the scrubber reduces the exhaust gas temperature to a maximum of 100°C. This is further reduced to the required scavenge air temperature by the downstream cooler. The demister removes droplets of condensed and entrained water from the scrubbed exhaust. The fan then increases the pressure of the recirculated gas by 0.4 to 0.7bar, before it is introduced to the scavenge air.

The scrubber operates at higher pressures and temperatures than downstream Exhaust Gas Cleaning Systems, as the cleaning is performed on the inlet side of the exhaust gas turbine where pressures are up to 4bar absolute and temperatures are 400°C at full load. This enables the scrubber to be smaller than downstream exhaust gas cleaning units at approximately 3m long and 2m in diameter for a 10MW engine.

Between 40% and 80% of SO_2 is removed by the scrubber and particulate matter reduction efficiency is believed to be very high. However standard methods of PM measurement are not suited to the high-pressure exhaust conditions at the scrubber and so a new technique for testing is being developed.

The scrubber means that NOx reduction by Exhaust Gas Recirculation is not constrained by fuel sulphur content in the same way as SCR. Furthermore EGR can be combined with an additional downstream Exhaust Gas Cleaning System (either wet or dry) to reduce SOx emissions to the level required in an ECA.

The initial field trial of an EGR system on the 10MW main engine of container vessel Alexander Maersk focused on the effect on engine components of 20% exhaust gas recirculation, and greater than 50% NOx reduction was achieved with no adverse effects on cylinder conditions. Upgrades were also made to control and safety systems and the materials used for the scrubber and coolers [72], [73], [74].

Building on the experience gained during the initial service trial a second generation EGR system is to be fitted to a larger 27MW container ship main engine. The new design combines the scrubber unit, cooler, water mist catcher and blower into a single unit, which is to be fitted in the same way as a charge air cooler. The compact arrangement results in only minor changes to the engine outline, and as such it is reported that major ship design changes are not required when installing this type of engine with EGR [75].

Figure 39: EGR system high-pressure scrubber unit

Courtesy MAN Diesel & Turbo

Figure 40: Second generation EGR system (orange)

Courtesy MAN Diesel & Turbo

7. EGC Systems and Vendors

In order to gain an overview of the Exhaust Gas Cleaning System offers available to the market, each of the EGSCA members was asked to complete a questionnaire with sections relating to:

- Cleaning performance
- Mechanical details
- Experience, testing and approvals
- Installation and after care
- Commercial information

The information, which is compiled into a table in Appendix 1 and discussed below, should be treated simply as an overview. Although systems are commercially available and have been sold, the market for this particular application is still relatively new. Not all information has been provided for a variety of reasons; in some case the question is not applicable to the particular system, in others it may be considered confidential. It is not intended to make recommendations and importantly each vendor should be contacted to confirm specific details.

Figure 41: Alfa Laval's trial EGC unit during installation

Courtesy Alfa Laval

7.1 Performance Overview

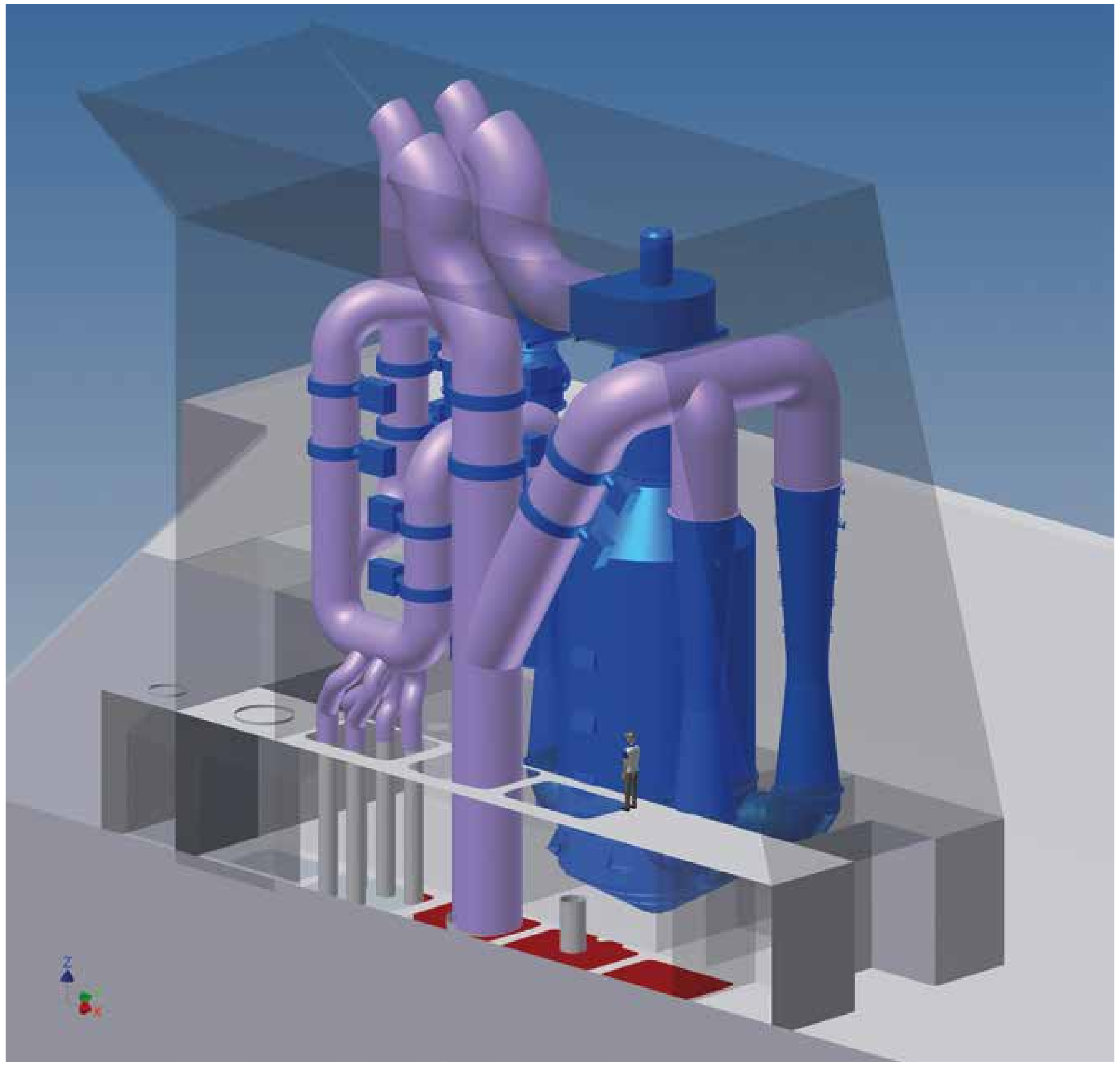


Figure 42: Multi-stream exhaust gas cleaning unit
(2 inlet quench sections can be seen at the
right and an ID fan at the top of the exhaust gas cleaning unit)

Courtesy Wärtsilä-Hamworthy

Of the six vendors that have provided information for this publication, three supply hybrid systems that can be switched between an open loop using seawater to a closed loop using freshwater treated with a 50% sodium hydroxide solution (Alfa Laval, BELCO® and Clean Marine). The hybrid system from Wärtsilä-Hamworthy uses the same caustic soda treatment but recirculates seawater rather than freshwater. There are three suppliers of a solely freshwater and chemical closed loop system (Alfa Laval, Wärtsilä-Hamworthy and BELCO®), again chemical treatment is with 50% caustic soda solution.

Four vendors, Alfa Laval, BELCO®, Marine Exhaust Solutions (MES) and Wärtsilä-Hamworthy supply a seawater only, open loop system, whilst the exhaust gas cleaning unit from Couple Systems differs from the others in that it uses dry granular calcium hydroxide as a scrubbing medium and no water at all.

All vendors offer a solution for multiple engines per exhaust gas cleaning unit.

7.1.1 SOx

The maximum percentage of sulphur in the fuel that can be consumed by an engine so that the emissions after exhaust gas cleaning are equivalent to 0.10%S varies between 3% and no upper limit for the standard systems offered by the vendors. However in practical terms the latter is governed by available space for the exhaust gas cleaning unit and where applicable, water flow rate and chemical consumption. This equates to a removal efficiency of 96.6% to greater than 98%.

7.1.2 Particulate matter

The removal of particulate matter varies between 60% and 90%. All six vendors have advised this has been measured, with the ISO 8217 method used by three.

There are many methods of measuring PM emissions including:

- ISO 8178 (part 1): Reciprocating internal combustion engines – Exhaust emission measurement [41]
- DIN 51402: Testing of flue gases of oil burning systems; visual and photometric determination of the smoke number [42]
- EPA Method 5/AQMD Method 5.2: Determination of Particulate Matter emissions from stationary sources [43]

Care therefore needs to be taken with assessment of measurements and like-for-like comparisons. Not only does the test method need to be considered but also the fuel used during the test. As part of the North American ECA proposal U.S. EPA presented data [7] showing PM_{10} emission rates as dependent upon fuel sulphur levels, with base PM_{10} emission rates of 0.23g/kW h with distillate fuel (0.24% sulphur) and 1.35g/kW h with residual fuel (2.46% sulphur). The ISO and EPA test methods shown above have been referred to as wet and dry (or hot filter) techniques [40], [3]. The latter is primarily used in land based installations in the USA and requires the filter to be maintained at a higher temperature so semi-volatile hydrocarbons and sulphates remain in the vapour phase and are not collected during the test. The EPA method therefore considers solid particles dispersed in the exhaust stream whilst ISO 8178 also takes into account the condensable hydrocarbons, sulphates and associated water, hence the higher the sulphur the higher the particulate matter content by the ISO method.

In a submission to the IMO Sub-Committee on Bulk Liquids and Gases regarding MARPOL Annex VI in 2007, the USA indicated that there would be a move to EPA Method 202 for stationary source compression ignition engines of 30 litres per cylinder or greater. Planned changes to the Method would make the final measurement methodology very comparable to ISO 8178-1.

- PM_{10} is particulate matter with an aerodynamic diameter nominally less than 10μm
- PM_{10} comprises coarse particles (PM_{10} to $PM_{2.5}$), fine particles ($PM_{2.5}$ to $PM_{0.1}$) and ultrafine particles ($PM_{0.1}$)
- $PM_{2.5}$ is particulate matter with an aerodynamic diameter nominally less than 2.5μm.
- $PM_{2.5}$ fine particles include the ultra-fine particles ($PM_{0.1}$)
- $PM_{0.1}$ is particulate matter with an aerodynamic diameter of up to 0.1μm (100nm)

Info Box 21: Particulate matter definitions

Quantifying particulate matter content by the dilution method can be complex and time consuming, requiring equipment that is not readily suited to shipboard use and engine steady state running. As an alternative the DIN smoke spot method for example can seem a considerably more usable in-service technique that meets a national standard. There are also several other proprietary smoke appearance, opacity or smoke density and smoke spot tests, however whilst an engine with high particulate emissions may well have high smoke levels, this is not always the case and an absence of smoke does not necessarily indicate the overall rate of particulate emissions is low [3].

- Under ISO 8178 particulate matter mass is determined by sampling either part or all of an exhaust stream and weighing material collected on a specified filter medium after diluting the exhaust gases with clean, filtered air. The temperature of the diluted gas has to be greater than 42°C and less than or equal to 52°C, as measured at a point immediately upstream of the primary filter [41]
- The purpose of dilution is to reproduce the effects that occur when the exhaust gas from a diesel engine is emitted to atmosphere. The rapid mixing and cooling stops the growth of particulate matter and causes hydrocarbons, sulphates and associated water to condense.
- Smoke spot number is the measurement unit for the degree of filter blackening as defined by DIN 51402 Part 1. The soot content of flue gas is determined by capturing particulate matter on a filter of silica fibre material. The smoke spot is then assessed either visually or by photometer, which compares the intensity of reflected light with that from the original light source enabling the smoke number to be derived by a standard conversion procedure. Photometric measurement is carried out either directly in the stack or by extractive sampling [42]
- Under EPA Method 5 particulate matter mass is determined by sampling part of an exhaust stream and weighing material collected on a on a glass fibre filter maintained at a temperature of 120 ± 14°C (unless otherwise approved). The particulate matter includes any material that condenses at or above the filtration temperature, after the removal of un-combined water [43]
- EPA Method 5 (which is similar to ISO 9096 [45]) has historically been the method of choice for measurement of stationary particulate matter sources in the United States, since the majority consist of coal fired boilers. In these applications, the particulate matter control measures (e.g. electrostatic precipitators [44]) are in a position of elevated temperature, where sulphuric acid condensation has to be prevented and therefore hydrocarbons and sulphates are kept in the vapour phase [40].
- ISO 8178 states that particulates defined under the standard are substantially different in composition and weight from particulates or dust sampled directly from the undiluted exhaust gas using a hot filter method (e.g. ISO 9096). It is also stated in ISO 8178 that particulates measurement as described in the relevant part of the standard is conclusively proven to be effective for fuel sulphur levels up to 0.8% [41]. This is because at higher sulphur levels there is a possibility of sulphate loss due to condensation within the test apparatus before the filter [3].

Info Box 22: A brief comparison of PM measurement methods

As with sulphur oxide removal exhaust gas cleaning unit design is important with regards the efficiency of particulate matter reduction. One vendor – Alfa Laval has tested two different pre-cleaning methods for their exhaust gas cleaning unit – a simple jet nozzle and a more advanced adjustable venturi section. Using the jet quench, washwater is atomised by a nozzle in a straight downward flow with almost no pressure drop on the exhaust gas side. By this method up to 55% of particulate matter was removed. With the venturi, as exhaust gas enters the constricted throat section, its velocity increases greatly. This shears washwater from the venturi walls, atomising the liquid into tiny droplets for the particles to impact on. An increased pressure drop results in increased turbulence because of a higher gas velocity and therefore higher removal efficiencies. The adjustable throat enabled the pressure drop to be varied from 100 to 400mm water gauge during tests, and at 400mm water gauge up to 78% of particulate matter was removed [46].

From this it can be appreciated that the process of removing pollutants has a significant affect on the conditions of pressure and velocity within an exhaust stream, particularly as the volume of gas is much reduced and its density increased by the cooling effect of the washwater. The design of an exhaust gas cleaning unit that can achieve the desired levels of reduction is therefore a careful balance, requiring exhaust backpressure conditions to be maintained within engine builders limits, so that engine efficiency and performance also remain unimpaired.

7.1.3 NOx

The wet and dry Exhaust Gas Cleaning Systems for control of SOx emissions have little effect on NO. This is reflected by all six vendors who advise their standard systems remove between zero and less than 10% NOx by measurement onboard, although four vendors, list SCR as an alternative means of NOx control. BELCO® positions the SCR reactor upstream i.e. before the exhaust gas cleaning unit [21]. This obviates issues associated with low temperature that arise by placing the catalyst after a wet exhaust gas cleaning unit. However as the catalyst is exposed to unscrubbed exhaust, it is necessary to comply with manufacturer's recommendations regarding the maximum allowable fuel sulphur content relevant to the exhaust temperature. As dry exhaust gas cleaning systems do not have a cooling effect Couple Systems positions the catalyst downstream. Wärtsilä offers SCR as well as other engine related NOx control techniques [47]. (MAN Diesel & Turbo also offers similar technologies and is actively testing Exhaust Gas Recirculation as explained in Section 6.2) With Selective Catalytic Reduction 80% to over 90% NOx can be removed.

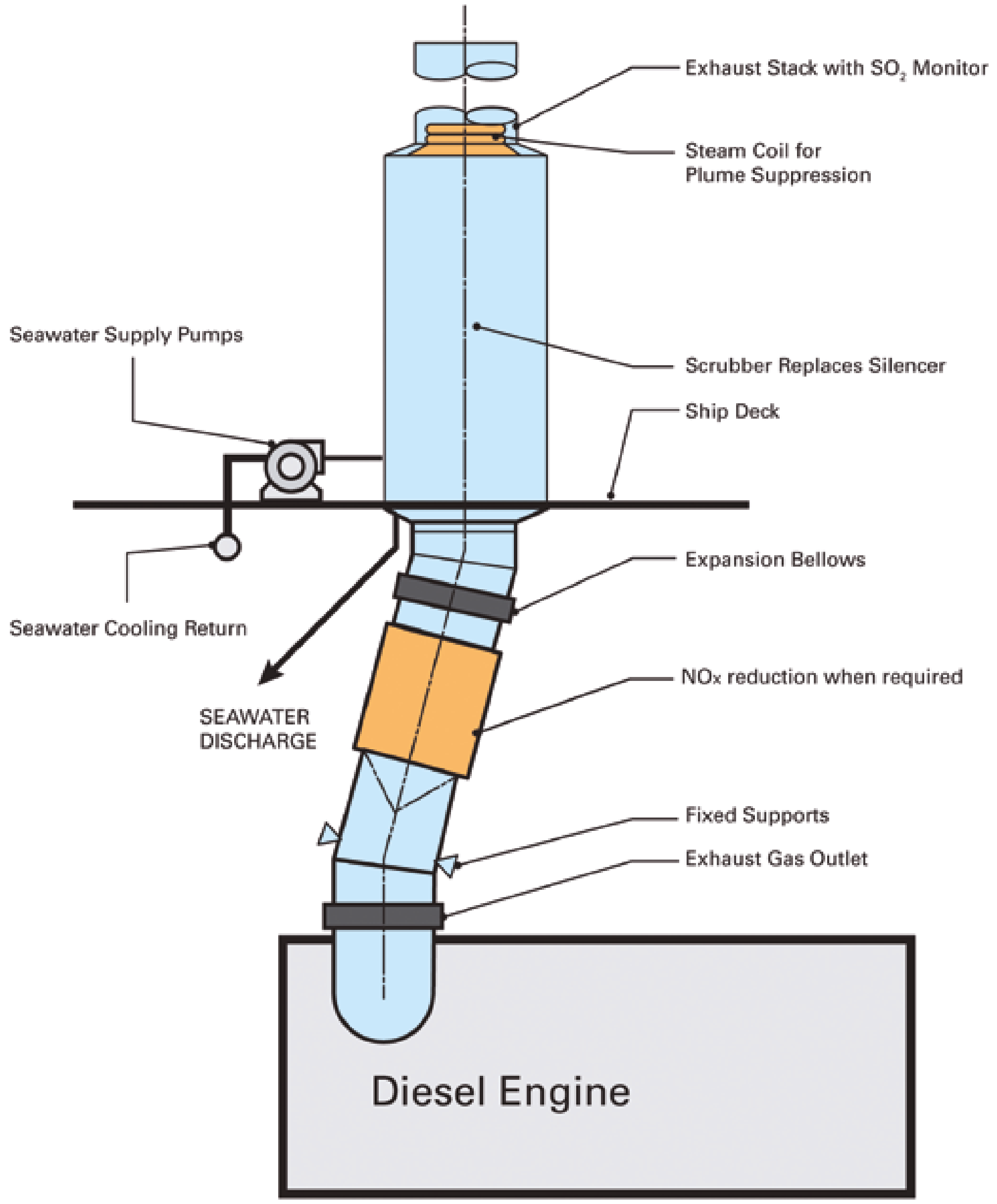


Figure 43: SCR reactor before exhaust gas cleaning unit

Courtesy BELCO®

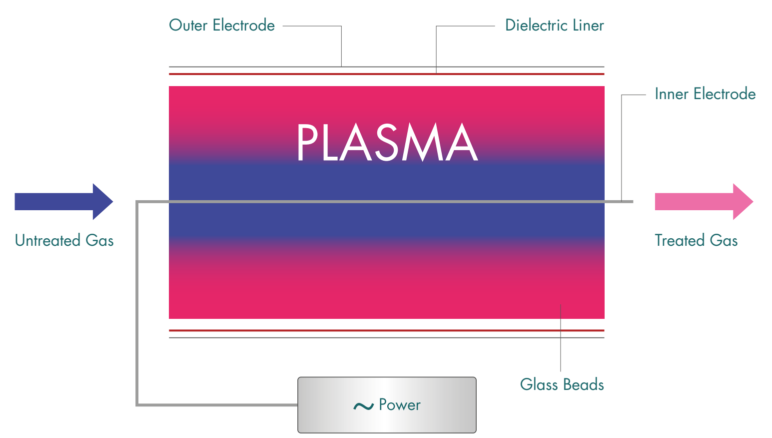
As part of a 2-step scrubbing process, an alternative oxidation technology from BELCO® converts nitric oxide and nitrogen dioxide to nitrogen sesquioxide (N_2O_3) and nitrogen pentoxide (N_2O_5). These higher nitrogen oxides are highly water-soluble and are efficiently removed with wet scrubbers, enabling a NOx reduction efficiency in excess of 90%. The technique uses 'non-thermal plasma' to produce ozone from industrial grade oxygen, which is injected into the flue gas stream where it reacts with NO and NO_2. Continuous emissions monitoring is used to accurately match the oxygen/ozone flow rates to the concentration of NOx in the exhaust stream [55], [56].

Non-thermal plasma is created in a reactor using an effect similar to that of static electricity when the electrical potential between two points exceeds the insulating effect and there is an electrical discharge across the gap. The reactor consists of two electrodes – one electrode is in the form of a metal pipe, and the other electrode is a metal wire that runs down the middle of the pipe. They are separated by a void space filled with glass beads and lined with a dielectric material (i.e. one that does not readily conduct electricity but can sustain an electrostatic field). This type of reactor is called Dielectric-Barrier Discharge (DBD).

The gas to be treated flows through the pipe and when the voltage through the beads exceeds their insulating effect, millions of extremely rapid micro-discharges occur. This causes atoms to be separated from their molecules to become highly reactive 'free radicals' that quickly re-combine with other atoms and/or molecules to form new compounds.

The effect will only occur if an alternating current or pulse power source is used. The individual discharges cannot be seen with the human eye, but the overall effect produces a silent glow at a low temperature (hence non-thermal).

Using this technique an O_2 oxygen molecule can be split into two highly reactive O^* free radicals that will combine with normal O_2 molecules to form ozone, O_3.



Info Box 23: What is non-thermal plasma?

7.1.4 CO_2

Carbon dioxide is not removed by the standard Exhaust Gas Cleaning Systems of all six vendors. However two of the wet systems (from BELCO® and Clean Marine) can be arranged to remove this greenhouse gas; Clean Marine has undertaken laboratory tests confirming a reduction of up to 15% is possible. The dry system from Couple Systems, which uses calcium hydroxide can also remove up to 15% CO_2.

Maintaining wet systems at a pH of 10 or above increases chemical consumption to more than twice the typical rate as CO_2 reacts with the caustic soda to create $NaCO_3$ (sodium carbonate). In most cases CO_2 absorption is not desired since the $NaCO_3$ that results has a limited solubility. This, together with particulate matter in the washwater can cause longer term plugging issues within the exhaust gas cleaning unit.

- $CO_2 + 2\ NaOH \Rightarrow Na_2CO_3 + H_2O$

Info Box 24: Relevant chemistry – sodium hydroxide and carbon dioxide reaction

7.1.5 Instrumentation – gaseous emissions

One vendor, Couple Systems has provided details of the analyser used to confirm the reduction in CO_2 and NOx emissions. Measurement was by non-dispersive infrared (NDIR) detector – a well-established technology, which uses the absorbance of infrared light to determine gas concentration.

The Guidelines for Exhaust Gas Cleaning System require that "emission testing should follow the requirements of the NOx Technical Code 2008, chapter 5, and associated Appendices" unless stated otherwise.

The NOx Technical Code contains detailed "specifications for analysers to be used in the determination of gaseous components of marine diesel engine emissions". This includes criteria for accuracy, response drift over a period of time and the interference effects of certain gases and water vapour on analyser performance. As Exhaust Gas Cleaning Systems can readily reduce emissions to the equivalent of 0.10% sulphur fuel, it is key that analysers are able to accurately determine the equivalent SO_2/CO_2 ratio of 4.3 (see Table 3, Section 3.2). Figure 11, Section 3.5 shows that there can be less than 5% CO_2 in the exhaust of a slow speed diesel engine, meaning that the analyser must meet the performance criteria when measuring an SO_2 concentration of less than 20ppm.

The Guidelines currently require that CO_2 should be measured on a dry basis using an analyser operating on the non-dispersive infrared (NDIR) principle. SO_2 should be measured on a dry or wet basis using analysers operating on the non-dispersive infrared (NDIR) or non-dispersive ultra-violet (NDUV) principles and with additional equipment such as dryers as necessary. Other systems or analyser principles may be accepted, subject to approval, provided they yield equivalent or better results.

The NOx Technical Code 2008 requires that "the nitrogen oxides analyser shall be of the chemiluminescent detector (CLD) or heated chemiluminescent detector (HCLD) type with a NO_2/NO converter".

CLD sensors use the luminescence of NO_2 in an excited electronic state (i.e. the emission of electromagnetic radiation without heat) to determine the concentration of NOx in a gas sample

1. Gas is passed through a converter, which converts any NO_2 in the sample to NO
2. NO produced from the conversion together with NO already in the sample is combined with ozone to produce NO_2 in an excited state.
3. The luminescence of the NO_2 in an excited state is used to determine the NOx concentration ($NO+NO_2$)
4. In order to determine the concentrations of the individual species
   a. Gas not passed through the converter will result in only the NO in the sample being combined with ozone and producing NO_2 in an excited state. The luminescence can then be used to determine only the NO concentration.
   b. By subtracting the NO concentration from the NOx concentration the NO_2 concentration can be determined

Info Box 25: The basic principle of chemiluminescent detectors

Figure 44: Heated sample line and probe for extractive analyser

Courtesy of Couple Systems GmbH

Figure 45: In-situ analyser probe

Courtesy Azurtane

Again, subject to approval, other systems or analysers may be accepted if they yield equivalent results to the prescribed technology. In establishing equivalency it has to be demonstrated using recognized national or international standards that the proposed alternative will yield equivalent results when used to measure diesel engine exhaust emission concentrations. For reasons of cost and practicality a single analyser capable of measuring multiple gases is often preferred. Whilst there are many analyser technologies, other light absorption techniques that may be encountered in marine Continuous Emissions Monitoring Systems (CEMS) for SOx, CO_2 and NOx include Fourier transform infrared spectroscopy, or FTIR and quantum cascade lasers or QCL.

At a high level it can be considered that Continuous Emissions Monitoring Systems have components for sample acquisition and conditioning, analysis of the required gases, facilities for calibration, and data capture, storage and reporting.

In addition to the various analyser technologies there are broadly two methods of sample acquisition – in-situ, where the analyser is mounted directly onto the exhaust pipe or extractive, where exhaust gas is transported via heated sample lines through the analyser located at a convenient remote position.

Depending on the analysis technique in-situ systems may measure emissions at a point in the exhaust flow or the average concentration across the entire exhaust duct. There is typically one multi-gas analyser per exhaust, which must be robust for the local conditions. The system response time is only dependent on the analyser response time and it is not subject to the time lags or potential changes in sample composition that can be experienced by an extractive system when gas is transported to a remote location. In general the system also has fewer components and the sample only needs filtering to remove particulate matter as the gas is at exhaust temperature and interfering water vapour will not condense at the analyser.

By having a central analyser (typically with a back-up) extractive systems can be used in a time-share configuration, whereby a valve arrangement allows sampling of each exhaust pipe in turn. However care has to be taken that the sample is fully representative and there is no cross contamination or losses during transportation through what can be long heated sampling lines. Whilst the analyser can be located in a more hospitable position, the sample must be conditioned not only to remove particulate matter, but also to avoid the uncontrolled condensation of water.

In cold-dry conditioning systems water is purposely condensed before the analyser by means of a chiller, which reduces the gas temperature, or the sample is passed through a permeable membrane filter, which uses dry air to selectively remove water vapour. As SO_2 and NO_2 are water-soluble it is important that the drying process does not remove any of the gases that are to be measured. Hot-wet systems maintain the sample at a temperature above the dew point during both transport and analysis by means of heat tracing, whereas dilution systems mix clean dry compressed instrument air with the sampled gas to reduce the saturation level.

The Guidelines require the data recording and processing device to be robust and tamper-proof with read-only capability. Emissions logged against time and ship's position must be retained onboard for a minimum of 18 months and as records may be required for inspection by port State Control, for example, there must be facilities to download data for specified time periods in a readily useable format.

The approved Onboard Monitoring Manual is required to have details of calibration procedures (see also Section 3.4). Both in-situ and extractive systems will likely use certified bottles of span gases for calibration and verification purposes in line with manufacturer's recommendations. Calibration may be an automated process (particularly if demanded at very regular intervals by local regulation) or undertaken manually for example every 6 or 12 months when servicing the analyser system. Automated checking and correction of zero may also use certified bottles of gas, but often clean, dry instrument air is utilised. To correct for short-term drift the analyser may be automatically zeroed every 24 hours, or more frequently if necessary.

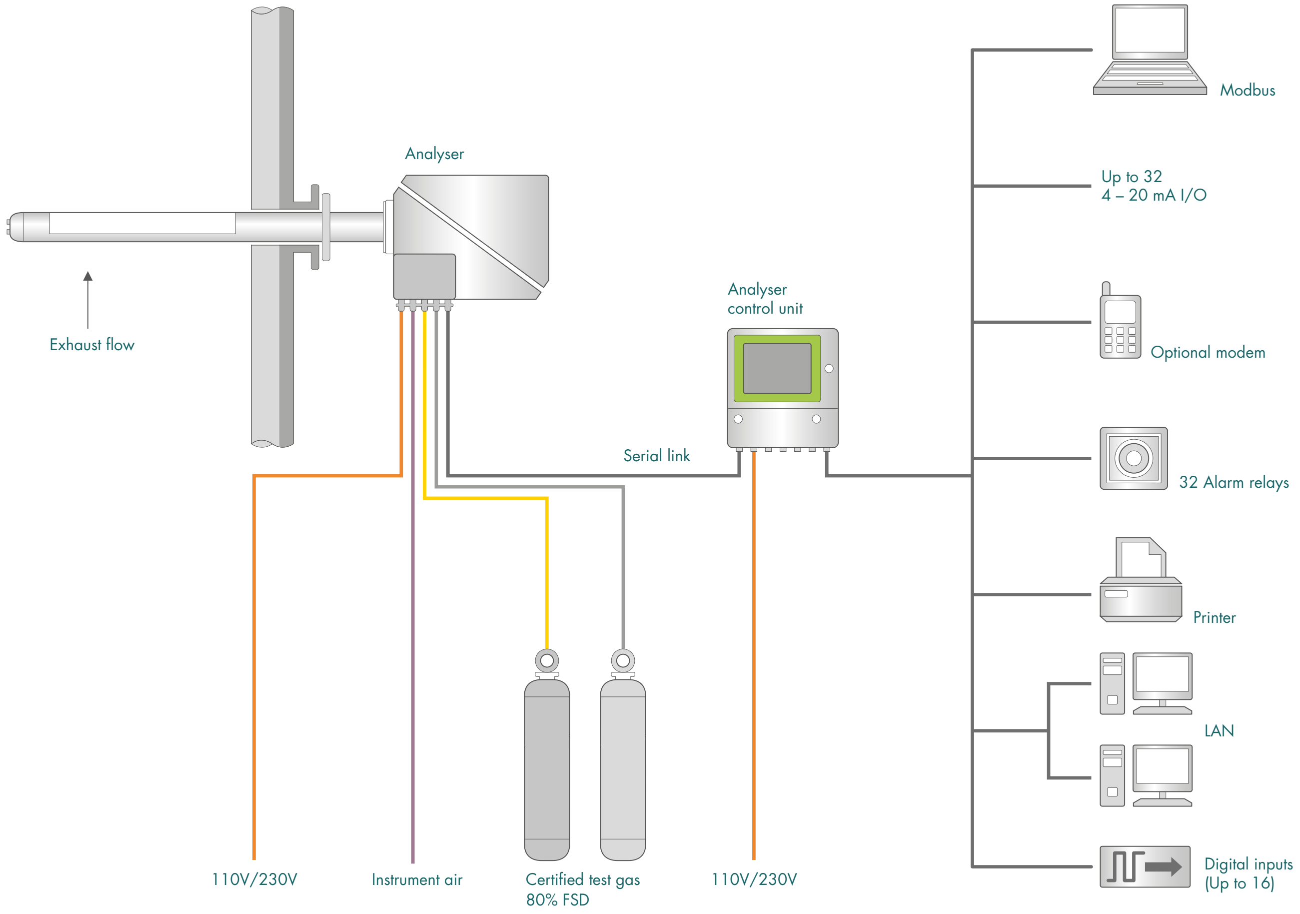


Figure 46: In-situ CEMS arrangement

Courtesy Parker Procal

The Guidelines for Exhaust Gas Cleaning Systems give various SO_2/CO_2 ratios that must be measured after an exhaust gas cleaning unit in order to achieve equivalence and therefore compliance with the sulphur-in-fuel limits under regulation 14 (see Table 3, Section 3.2). It has also been discussed in Section 3.2 how the ratio is a robust measure of SOx emissions in proportion to the sulphur content of the fuel burned because all sulphur oxides and virtually all CO_2 are derived from the combustion of fuel that is hydrocarbon based and contains sulphur.

Some Exhaust Gas Cleaning Systems however use the natural buffering capacity of seawater to neutralise the acids produced from scrubbing SO_2, which moves the carbonate system equilibrium towards CO_2 release (see Info Boxes 11 and 15, Section 4.1). This could at first be considered to compromise the validity of the SO_2/CO_2 ratio method but a typical air: fuel ratio for a marine diesel engine is typically between 50 to 35 depending on load i.e. the mass of combustion air is 50 to 35 times greater than the mass of fuel to be combusted and CO_2, formed from the fuel and air will typically make-up 6% of the exhaust [3]. It can be shown by calculation [12] and has been demonstrated by in-field testing that the CO_2 produced by neutralizing the acidity produced by 1 tonne of residual fuel* is minimal, particularly when compared with the CO_2 produced in combusting that tonne of fuel. The validity of the method therefore remains unaffected.

*For example with a typical sulphur content of ~2.7%

For Exhaust Gas Cleaning Systems using freshwater Info Box 24 explains how some chemicals have the potential to remove CO_2. The Guidelines also take account of this and state that in justified cases where the CO_2 concentration is reduced by the exhaust gas cleaning unit, the CO_2 concentration can be measured at the EGC unit inlet, provided that the correctness of such a methodology can be clearly demonstrated.

Info Box 26: The effect of exhaust gas cleaning on CO_2 emissions and the SO_2/CO_2 ratio method

7.2 Mechanical Details

7.2.1 Consumption and flow

Consumables including power and chemicals contribute the majority of running costs of an Exhaust Gas Cleaning System. The proportion is dependent upon configuration and design. Wet systems in open loop mode typically consume electrical power at a rate of 1 to 3% of the engine power (i.e. 10 to 30kW h per 1MW h). Consumption is lower for closed loop operation at around 0.5 to 1% of engine power, as washwater circulation rates are lower and the pump lift to the exhaust gas cleaning unit can be less, although there is a need to power pumps to supply coolers. The dry system, with no water circulation has the lowest power requirement of approximately 0.2% of engine power.

Higher power consumption can be expected where an SCR system is fitted after a wet exhaust gas cleaning unit, as there is a need to reheat the exhaust for effective catalyst operation.

The rate of washwater flow through an exhaust gas cleaning unit is typically around 45 to 50m^3 per hour per megawatt of engine power for an open loop seawater system. It is about 20 to 25m^3 per hour per megawatt for a closed loop system with chemical addition. Some system designs enable energy consumption to be optimised by automatically adjusting washwater flow rate according to the engine power and the sulphur content of the fuel [78].

Reduced power consumption needs to be balanced against the consumption (and storage and handling) of caustic soda for a wet closed loop system and new and used hydrated lime for the dry system. Hydrated lime is typically consumed at a rate of 16 kg per hour per megawatt of engine power and caustic soda at a rate of between 6 and 16.5 litres per hour per megawatt of engine power in freshwater systems when a 2.7% sulphur residual fuel is used (18 litres /MW h for a 3.5% sulphur fuel).

Caustic soda consumption is influenced by both external and system factors.

It is primarily driven by the specific quantity of SOx that has to be removed as a result of the fuel sulphur content and engine load i.e. fuel consumption. The rate of SO_2 absorption into the washwater and thus pH degradation depends on parameters such as the washwater temperature, which in turn is affected by the temperature of seawater used for washwater cooling. The rate of water consumption and therefore make-up has a diluting effect, which also reduces pH.

It should be noted that although all vendors of closed loop and hybrid systems advise that treatment with 50% caustic soda is required, others may recommend a different concentration (e.g. 40%), so although the consumption rates in terms of pure NaOH may be similar, they would appear quite different for more dilute solutions.

In closed loop and hybrid systems freshwater consumption is mainly driven by any losses to atmosphere with the scrubbed exhaust and a need to control the dissolved solids (particularly sulphate salts) in circulation. Without control SO_2 removal can be impaired and deposits have the potential to cause blockages and scaling so washwater is bled to sea via the treatment plant. Replenishment with clean water enables scrubbing efficiency to be maintained and keeps the concentration of solids below the level at which precipitation can occur.

There may be small freshwater losses with residue separated by the washwater treatment plant although system designers endeavour to minimise this for reasons of economy. Apart from needing to replace the loss with freshwater, larger than necessary tankage is required to store the wet residue and the costs of handling and shore-side disposal are increased.

Water may be condensed from the exhaust gas in the exhaust gas cleaning unit or lost though evaporation. The loss or gain is dependent on the washwater temperature and therefore the temperature of seawater used for washwater cooling. BELCO® advises that for a closed loop system serving a 10MW engine with a seawater temperature of 25°C at the cooler inlet and 40°C at the cooler outlet approximately 1.1m^3/h freshwater will be consumed; a figure comparable with Wärtsilä-Hamworthy, which advises a typical consumption of 0.1m^3/MW h. BELCO® also advises that zero consumption is possible in colder seas, where more water is condensed from the incoming exhaust stream, however locations where such low seawater temperatures are available are limited and are not typically used as a design condition. Whatever the losses or gains with the exhaust, the system water volume must be managed and maintained within appropriate working levels, by means of the clean make-up and bleed-off to sea.

Minor consumables include coagulants and flocculants used for treatment of washwater prior to discharge overboard and bags for handling dewatered and dried residue separated by the treatment plant. Availability and consumption of compressed air also needs to be considered and on some vessels there may be a need to fit an additional air compressor and receiver. The air may be required for instrumentation and emissions monitoring purposes and therefore must be clean and oil free. It is used in some washwater treatment plant to aid separation of oil and particulate floc. Low-pressure air is also required for the transportation of fresh and spent hydrated lime to and from a dry exhaust gas cleaning unit.

7.2.2 Size and position

All vendors can supply Exhaust Gas Cleaning Systems for the largest sizes of marine engine, as their upper limit is either unlimited or up to 80MW. Clean Marine's system allows multiple smaller 25MW units to be operated in parallel to give no upper limit to the overall engine power that can be handled. The smallest exhaust gas cleaning units for use on ship vary between 150kW and 2MW, although BELCO® advise that sizes suitable for all engines are available.

For retrofits the availability of space to fit the exhaust gas cleaning unit may be a limiting factor, although depending on design they can be fitted inside an existing or extended funnel or outside. For new builds units can be readily accommodated at the planning stage. A wet system unit will be fitted above any exhaust boiler or economiser and may be suitable to replace the exhaust silencer. Naval architects will not only consider the dimensions but also the filled weight of both the unit and complete system in terms of the effect on ship stability.

Washwater treatment plant for wet systems will need to be accommodated although most vendors suggest that its position is flexible and does not need to be in the engine room. Depending on system design, the proximity to existing pump sets and sea chests or the length and routing of pipework to alternative, more remote locations may need to be considered. Space may be less available on vessels with medium speed propulsion engines such as cruise and ferry when compared with cargo ships powered by slow speed engines.

Tanks will be required for all onboard Exhaust Gas Cleaning Systems. In the case of a seawater open loop system, this may be limited to a small collection tank for residue separated from the washwater by the treatment plant. The Wärtsilä-Hamworthy system includes a de-aeration tank to allow entrapped air and gas to separate from the washwater after the scrubber. This encourages sub-micron particles to be released from the air/gas and to become 'wetted', so facilitating particle capture in the water treatment process and preventing the appearance of bubbles and a visible sheen on the surface at the overboard discharge.

Figure 47: Washwater treatment residue collection

Courtesy Wärtsilä-Hamworthy

Vendors suggest various sizes for residue collection tanks with an average of approximately 0.5 to 1m^3 per MW of engine power. The Guidelines for Exhaust Gas Cleaning Systems do not allow residue to be incinerated onboard but it can be landed ashore with other oil-sludge waste, so the actual size will largely depend on the period of time the ship needs residue to be stored onboard. Alfa Laval advises a collection rate of 0.2 litres per megawatt of engine power per hour. An area for processing and storage will also be required if the residue is to be dewatered, dried and bagged before disposal.

A residue collection tank will be similarly required for closed loop systems. There will also be a process tank for the circulating washwater and a holding tank or tanks in the event zero discharge is required (see Figure 19, Section 4.1) together with caustic soda storage.

The capacity of the process tank is a matter of system design. Alfa Laval require a volume of between 10 and 40m^3 depending on engine power. The capacity for holding washwater for zero discharge and caustic soda storage is based on the vessel's itinerary and need for autonomy. However caustic soda storage figures of between 5 and 11.5m^3 per megawatt of engine power can be considered as indicative of the capacity that may be required.

Minor areas of storage will also be required for any flocculants and coagulants used in the washwater treatment plant.

Storage of fresh and spent hydrated lime is required for the dry Exhaust Gas Cleaning System. Couple Systems suggest 14m^3 per megawatt of engine power as an indicative figure based on continuous combustion of a 2.7% sulphur residual fuel over a one-month period.

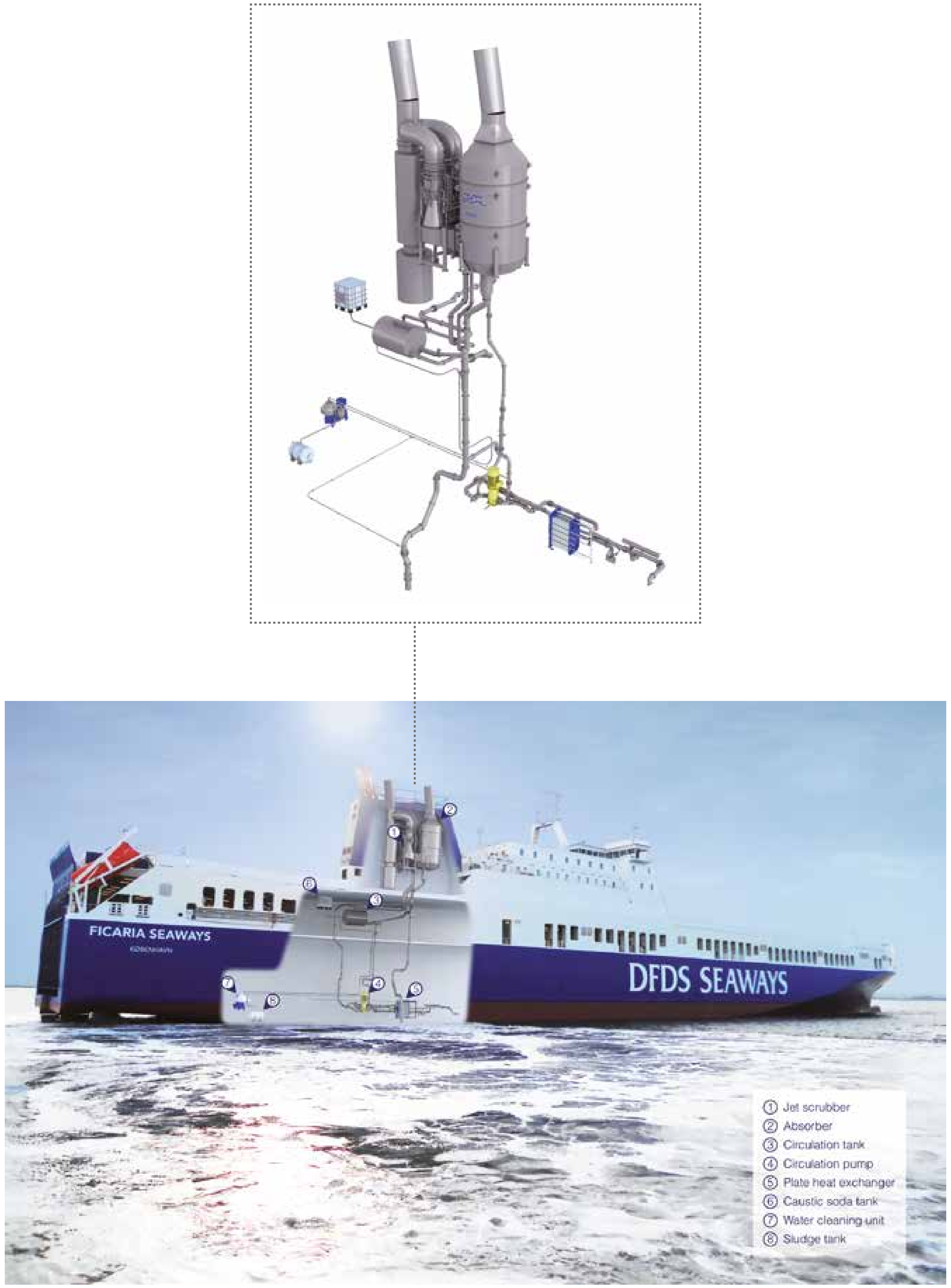


Figure 48: Exhaust Gas Cleaning System arrangement – RO-RO (Hybrid scrubbing system - 21MW slow speed main engine)

Courtesy Alfa Laval

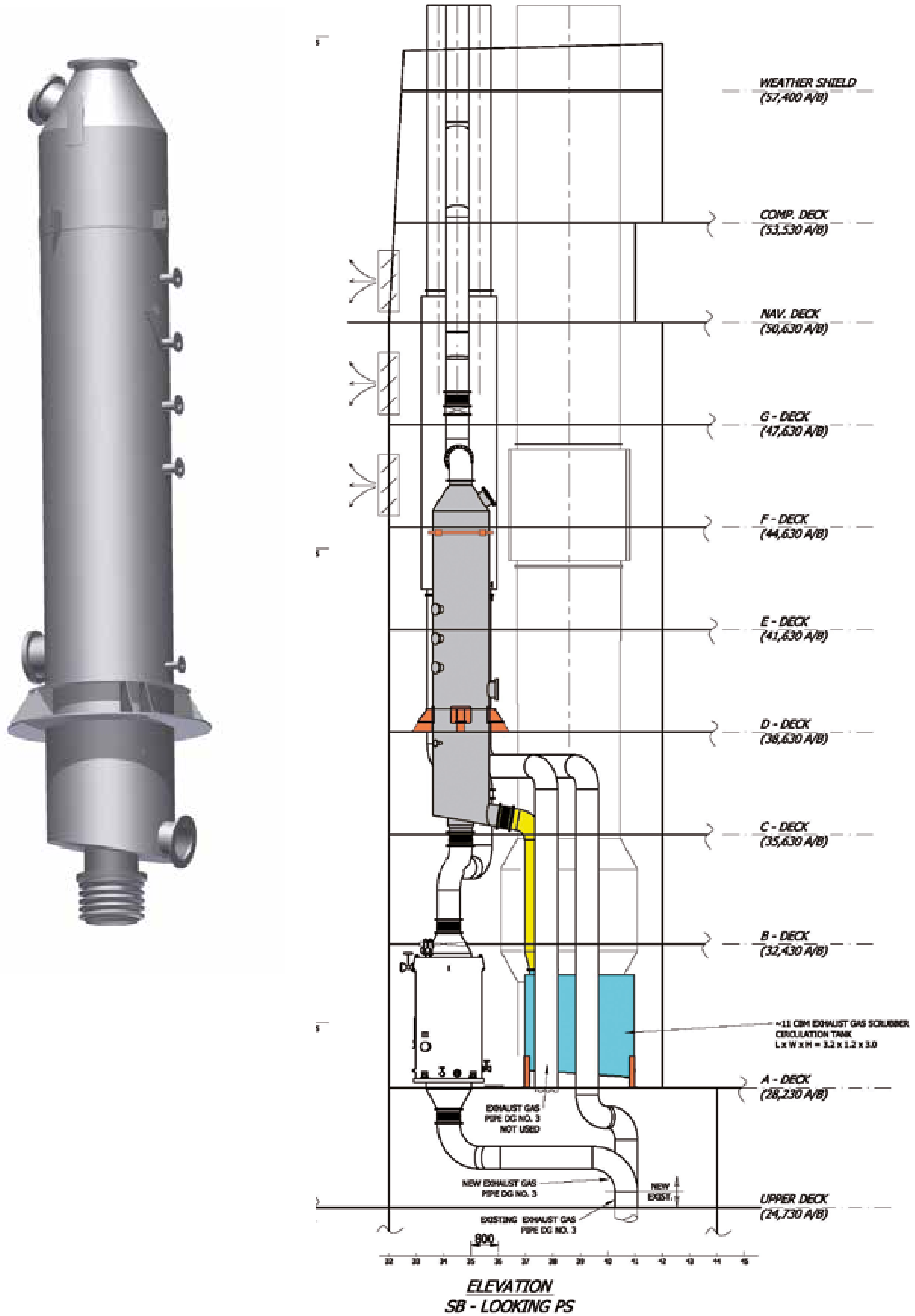


Figure 49: Exhaust gas cleaning unit arrangement – container vessel (Hybrid scrubbing system - 3.5MW auxiliary engine. Note position of circulation (process) tank is above the vessel's upper deck)

Courtesy BELCO®

7.3 Experience, Testing and Approvals

Three vendors, BELCO® (part of the DuPont group), Couple Systems and Wärtsilä-Hamworthy are experienced with exhaust gas cleaning solutions for land based applications. BELCO® is a leading supplier to the oil refining industry with systems for a wide variety of applications, using differing fuels with a sulphur content of up to 6.50%, and producing a flue gas flow of up to the equivalent of a 150MW combustion unit. Couple Systems has two large dry systems at the test bed facilities of marine engine manufacturers, including a combined Exhaust Gas Cleaning and SCR system for engines up to 24MW. Wärtsilä supplies the power generation market with systems for residual fuel burning engines of up to 80MW. BELCO® and Couple Systems specifically advise their marine design is based on solutions used in land based industry.

Alfa Laval and Wärtsilä-Hamworthy are experienced in the supply of inert gas scrubbing systems to the marine industry.

Four vendors, Alfa Laval, Clean Marine, Couple Systems and Wärtsilä-Hamworthy have run trial marine units in shore-side test facilities. Wärtsilä-Hamworthy has a dedicated test and training centre.

Five vendors have fitted Exhaust Gas Cleaning Systems to ships for tests. The now combined Wärtsilä-Hamworthy organization has conducted trials of greater than 50,000 running hours on ships including the RO-RO ferry Pride of Kent, tanker Suula [81], cruise ship Zaandam and a multi-inlet unit for three auxiliary engines on container ship APL England, (range of engine powers tested 610kW to 10MW). The hybrid exhaust gas cleaning system from Alfa Laval is currently the largest onboard a ship. It is installed on the RO-RO ferry Ficaria Seaways and has been in continuous operation for more than 7000 hours as of October 2012. BELCO® will test two systems including one fitted to a 3.5MW engine during 2012[82], [83]. Unlike the others, which are installed in the funnel area, Couple Systems' exhaust gas cleaning unit on general cargo vessel Timbus (3.6MW engine power) is fitted immediately forward of the accommodation block rather at the funnel. 4000 running hours have been completed.

Trial fuel sulphur content has varied between 1.78% and 4.07%. Engine powers have been between 150kW (MES) and 21MW (Alfa Laval), although orders have been placed with Alfa Laval and Wärtsilä-Hamworthy for two hybrid systems, each of which will scrub multiple exhausts from engines with a combined power of 28MW [78], [84].

Other than the Clean Marine trial on M.V. Baru, trials to date have been of an exhaust gas cleaning unit fitted to a single engine or a multi-inlet unit fitted to auxiliary engines. However on M.V. Baru the exhaust from the main engine, up to two auxiliary engines and occasionally the boiler is commonly collected at the top of the funnel and drawn through the cyclonic EGC unit by a downstream fan. The typical total power of engines during exhaust gas cleaning has been approximately 6MW.

Figure 50: Clean Marine EGCS Development
(Photo montage shows the evolution of the Clean Marine Exhaust Gas Cleaning System. From left to right: Initial testing of a 1MW unit with MAN in Holeby, 2006 to 2008. Full scale retrofit (back pack) installation of a 10MW system onboard M.V. Baru, 2009. The 0.6MW commercial demonstrator installed at MARINTEK, Sintef in Norway 2011.)

Courtesy Clean Marine

Independent performance reports on emissions to air have been compiled on systems from Alfa Laval, (published) Couple Systems (available on request) and Wärtsilä-Hamworthy (published) [81]. BELCO® has similar reports for its industrial but not marine systems. Independent reports on washwater discharges have been published on systems from Alfa Laval and Wärtsilä-Hamworthy.

Three vendors have Scheme B approval for various sizes of Exhaust Gas Cleaning System – Alfa Laval (21MW; LR), Couple Systems (3.6MW, GL) and Wärtsilä-Hamworthy (610kW, 1MW, 2MW and 8MW; DNV, GL and RINA). Only Wärtsilä-Hamworthy has a Scheme A approval for its closed loop freshwater and caustic soda system (610kW; BV, DNV, GL).

7.4 Installation and after-care

Apart from the core system components of exhaust gas cleaning unit, washwater treatment plant and instrumentation and controls, the scope of supply to allow the interconnection of parts and installation on the ship varies from vendor to vendor. As such each project will need to be agreed on a case-by-case basis. Some vendors can supply all components, others the core, with items such as pipework, valves, ducting, supporting steel work, cabling and switchboard connections needing to be provided by the ship operator. Although system tanks may often be self-contained, these too may need to be supplied by the ship operator if they need to be integrated into the fabric of the ship and existing tankage cannot be used.

Similarly the labour that can be supplied by vendors varies from a complete turnkey solution to project management and design services. This will also depend on whether the installation is a retrofit or for a new building, as in the case of the latter the shipyard will typically supply all labour, cranes, staging etc. Again the scope will need to be agreed on a project-by-project basis.

In the case of retrofits dry-docking is not likely to be required unless existing sea chests and hull penetrations for overboard discharge connections cannot be used. Although the exhaust gas cleaning units will need to be fitted with the vessel out of service, with planning it is possible that a significant amount of preparation work in terms of piping and electrical systems can be carried out whilst the vessel is trading.

Generally the vendors and ship operator will need to work together on matters involving Class. It seems likely the vendor will take the lead on certification of the Exhaust Gas Cleaning System and associated documentation, with the ship operator taking the lead on items involving the vessels structure. System commissioning will again need all parties to work together.

Photographs and the timeline for installation of a Clean Marine hybrid system for main and auxiliary engines and a boiler totalling 10MW in power are shown in Appendix 7.

Once in service the maintenance and calibration of emissions monitoring instruments for both air and water will be an important area of after-care to ensure the vessel continues to comply with regulations. Filter cleaning or changes may also be needed and items requiring service in the longer-term will include pumps and fans. In some cases specific components within the exhaust gas cleaning unit may need to be changed or cleaned although designs are such that a long service life should generally be expected.

Figure 51: Installation of a Couple Systems dry exhaust gas cleaning unit

Courtesy Couple Systems GmbH

7.5 Commercial Information

All vendors have Exhaust Gas Cleaning Systems commercially available and the rate of orders is increasing. As such the following information should be treated as an illustration of increased market growth and not necessarily a complete picture of all commercial activity to date.

In addition to the two large multi-inlet hybrid systems to be supplied by Alfa Laval and Wärtsilä-Hamworthy, (see Section 7.3), Wärtsilä-Hamworthy has received orders for open loop systems for four newbuildings in Korea. Each ship has four auxiliary engines and a boiler, each of which will have individual exhaust gas cleaning units. The installation on one vessel is now complete. A further eight vessels operating on the Great Lakes are to be supplied with closed loop systems for all engines and two VLGCs (very large gas carriers) are to be fitted with open loop systems, each with a single exhaust gas cleaning unit for the main engine and multi-inlet units for the three auxiliary engines. Clean Marine has most recently supplied the multi-exhaust hybrid system shown in Appendix 7 for main and auxiliary engines and a boiler totalling 10MW in power. Couple Systems is also planned to supply a vessel with a dry system for all engines totalling 22MW in power (see Figure 29).

All vendors will target both retrofits and newbuildings. Whilst four vendors advise that all vessel types and engine powers are to be targeted, Clean Marine will focus on vessels with power plant in the 5 to 25MW range. MES specifically lists large yachts, workboats and military vessels and Couple Systems engine powers up to 36MW.

Warranties vary from 12 to 24 months after commissioning and typically cover system components and emissions abatement performance. Couple Systems also guarantee the availability of calcium hydroxide and free-cost disposal of spent granules.

Most teams dedicated to exhaust gas cleaning are quite small (20 persons or less) although BELCO® has 60 and Wärtsilä-Hamworthy 55. Most teams are however part of wider companies or groups that range in size from 65 to 30,000 people.

Exhaust Gas Cleaning Systems for ships are a relatively new application and it is not easy to produce commercial data. Installations can vary considerably depending on the ship design, whether a retrofit or new build, configuration of combustion units, type of exhaust gas cleaning system and performance requirements. Some estimated figures are however available for capital costs.

Couple Systems has estimated the cost of installing a dry system for a 1MW engine to be USD500k and USD4 million for a 20MW engine. MES estimate USD1 million for an open loop system for a 1MW engine and USD3 million for a 20MW engine. Wärtsilä-Hamworthy advise that pay back should be achieved in less than one year depending upon fuel price i.e. the differentials between low sulphur residual fuel or distillate (depending on the location of the vessel) and higher sulphur residual fuel.

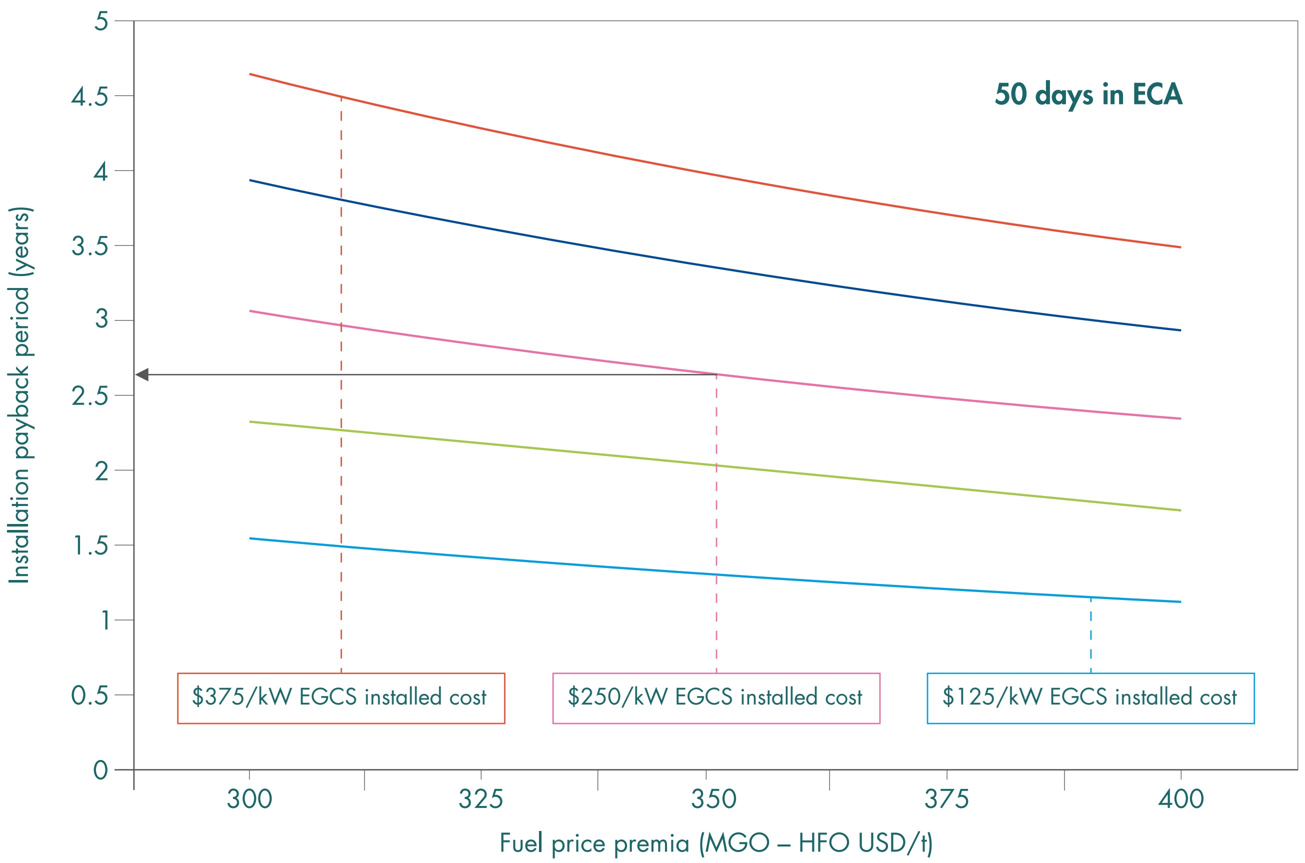
An installed turnkey price of 100 to 300 Euros per kW of scrubbed engine power (operating costs not included) can be used as an indicative range. (This approximates to 125 to 375 USD per kW).

Couple Systems estimate the all-in annual operating cost to be USD43.5k for a 1MW engine system and USD477k for a 20MW engine system when using 2.7% sulphur fuel for 300days. This can be compared with the estimates from Wärtsilä-Hamworthy of USD3 to 5 per MW h for a closed loop system and MES of 3% of the capital installed cost of an open loop system to give a range of figures.

Currently residual fuel with a sulphur content of less than 1.00% must be used in ECAs, however from 01 January 2015 fuel with a sulphur content of less than 0.10% will be required unless emissions abatement is used. Traditionally residual fuel oil has been approximately 66% of the price of Marine Gas Oil and today's price differential is between USD250 and USD300 per tonne. In order to meet the increased demand from oil industry analysts predict that this must rise to at least USD350 per tonne to recover the costs of adding production capacity.

Figure 52 is a simple illustration of the potential periods for payback of capital for an Exhaust Gas Cleaning System depending on fuel consumed in ECA, price premium (distillate fuel over residual fuel), and installed cost of equipment.

The installed cost (USD per kW of engine power) includes both the EGCS equipment and work and materials required for installation onboard. It does not include vessel off-hire costs or the cost of capital. A specific fuel oil consumption of 180g/kWh and EGCS utilization rates of 250 and 50 days per year are assumed.



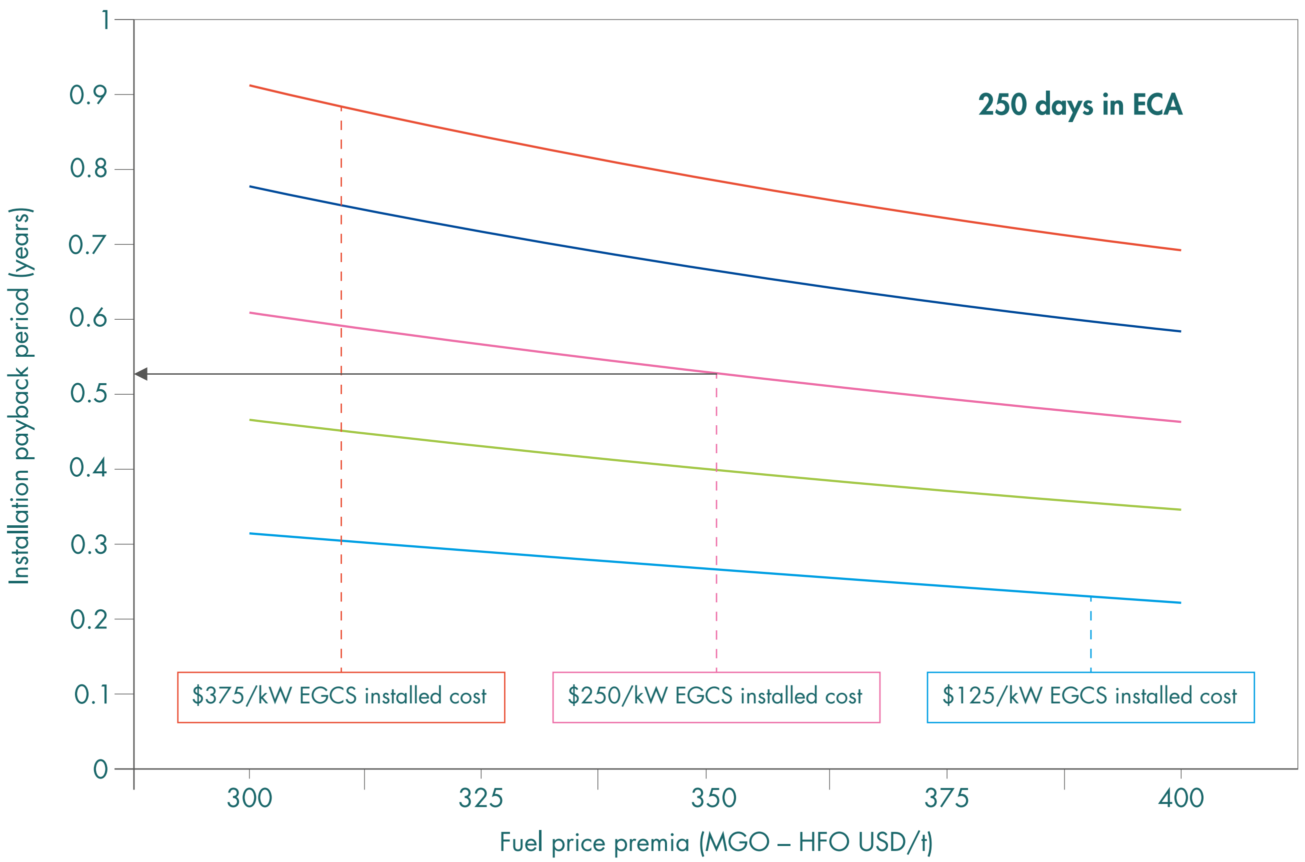


Figure 52: Illustration of payback for an Exhaust Gas Cleaning System (Equipment and initial installation)

Ships vary considerably and vessel operators are encouraged to work closely with EGCS vendors and undertake their own financial analysis to properly understand the return on investment.

Analysis will include a costed technical feasibility study, which will take into account the age, size and type of vessel and its engines. Exhaust Gas Cleaning Systems can be readily incorporated into newbuildings at the design stage. Whilst retrofitting can offer more challenges, it has been proven that the position of the exhaust gas cleaning unit can be flexible with multi-inlet units increasing the options. Often much of the work to install supporting systems can be readily undertaken with the vessel in service and drydocking may not be necessary. There must be sufficient space either existing or made available for the main components of the chosen system type, with an appropriate level of equipment redundancy. This needs to be balanced against additional tanks and handling systems for low sulphur fuel and relevant lubricants. The affect of the filled EGCS unit(s) and supporting systems on trim and stability will need to be checked as will availability of sufficient electrical power and if required, compressed air and steam. The supply chain for consumables, facilities for sludge disposal and any support network for third party servicing, particularly of compliance monitoring equipment will also need to be confirmed. Again this needs to be balanced against the availability of low sulphur fuel alternatives if this method of compliance is considered.

Key drivers in the financial calculation are the installed cost of the system, the quantity of fuel consumed whilst in an ECA and the low sulphur fuel price premium. An independent guide by the U.S. Department of Transportation [65] makes an in-depth analysis of 3 scenarios for a containership and tanker. This not only takes into account the key drivers but also other factors including the costs of capital, inflation, power to operate the system, maintenance, consumables, the reduced energy available from residual fuel oil when compared with distillate, heating of residual fuel, which is not required for distillate, documentation, manpower and training.

The Guide concludes that: "cost savings are so significant that some ship operators may find installing an EGCS a competitive necessity".

APPENDIX 1 Information and Data Summary – EGC Systems and Vendors

The information in this table should be treated as an overview. Although systems are commercially available and have been sold, the market for this particular application is still relatively new. Not all information has been provided for a variety of reasons; in some cases the question is not applicable to the particular system, in others it may be considered confidential. It is not intended to make recommendations and importantly each vendor should be contacted to confirm specific details.

PERFORMANCE OVERVIEW		ALFA LAVAL	BELCO® (DUPONT)	CLEAN MARINE	COUPLE SYSTEMS	MARINE EXHAUST SOLUTIONS	WÄRTSILÄ/HAMWORTHY
EGC System description		System name: PureSOx A hybrid system that can operate on either sea or freshwater and chemical with optional low or zero discharge rate. Also available as either seawater scrubbing only or freshwater & chemical scrubbing only.	Hybrid design that can be switched between open loop (seawater) and closed loop (freshwater & chemical) as needed with optional low or zero discharge rate Open loop – seawater Closed loop – freshwater & chemical	Switchable seawater open loop / freshwater and chemical closed loop system with optional low or zero discharge rate.	Dry chemical system with optional SCR	Seawater open loop system	Open loop – seawater Closed loop – freshwater and chemical Hybrid – seawater, seawater and chemical
Exhausts per EGC unit		One EGC unit can handle exhaust from multiple sources or from a single source as may be required	One EGC unit can handle exhaust from multiple sources or from a single source as may be required	One EGC unit can handle exhaust from several sources simultaneously. EGC units in parallel can handle unlimited amounts.	Main engine plus 3 auxiliary engines possible	Multiple engines in a flexible configuration based on owner's requirements	Mainstream unit – one exhaust Integrated unit – all exhausts
Maximum % fuel sulphur to achieve equivalent of 0.1%	Standard Offer	3%	No upper limit (cleaning unit size, water flow rate and chemical consumption dependent on sulphur content and engine size)	3.5%	5%	3.5%	3.5%
	Possible	Up to 4.5%	Experience on land with SO_2 levels greater than the equivalent of 10% sulphur-in-fuel	No upper limit (water flow rate and chemical consumption dependent)		>4.5%	>4.5%
% Particulate removal	By EGCS	Up to 80% (depending engine exhaust gas quality)	>90% if required (unit design varies based on particulate removal requirement and particle size distribution)	Up to 85% PM mass reduction measured	80%	90% of visible PM (50% by mass) based on MDO fuel tests	Typically 60% to 85%
	Estimated or measured (test method)	Measured (ISO 8178)	Measured >94% removal on land	By dilution tunnel and ISO standard	Measured ISO 8178	Measured	Measured
% NOx removal	By EGCS	0.2%	less than 10%	0 -10%		2-5%	5-10%[5]
	By SCR (or other technology) used in combination with EGCS		>90% (when EGCS combined with LoTOx[12] or SCR)	Tier III level in combination with SCR or EGR.	90% by SCR		See note 5
	Estimated or measured		Measured >95% removal on land		Measured (NDIR)	Measured	Measured
%CO_2 removal	By EGCS	<0.1%	Standard offer 0%, higher is possible but not recommended	Up to 15% (depending on NaOH dosage)	Up to 15%	0%	0%
	Estimated or measured		Not measured	Laboratory test – MAN Holeby	Measured (NDIR)		Measured

Flow and Consumption Data

		ALFA LAVAL	BELCO® (DUPONT)	CLEAN MARINE	COUPLE SYSTEMS	MARINE EXHAUST SOLUTIONS	WÄRTSILÄ/HAMWORTHY
Scrubbing medium		Seawater or freshwater and caustic soda (NaOH)	Open loop with seawater and closed loop with freshwater and caustic soda (NaOH)	Seawater, freshwater and caustic soda (NaOH)	Calcium Hydroxide $(Ca(OH)_2$ sorption granules)	Seawater	Seawater Freshwater Caustic soda (closed loop)
Washwater flow rate	$m^3/h/MW$ engine power	50 (seawater)	Dependent on flue gas volume and SO_2 content. Information provided to potential clients on a case by case basis	20 to 40[3]	None	50	45 (open loop) 25 (closed loop)
Freshwater consumption	$m^3/h/MW$ engine power	Depending on ships operating profile and seawater temperature	Dependent on flue gas volume and SO_2 content. Information provided to potential clients on a case by case basis	None	None	None	~0.1 $m^3/h/MW$ (dependent on operating parameters)
Liquid chemical consumption – exhaust gas cleaning[14]	l/h/MW engine power	13 –16.5[1] (20-25 kg/h/MW)	Buffer only used in closed loop mode. Consumption directly proportional to SO_2 in flue gas. Typical ratio is 1.25 kg caustic soda per 1 kg SO_2	6 to 12 caustic soda[1, 3, 17,18]	None	None	18 caustic soda[1, 9]
Dry chemical consumption – exhaust gas cleaning	kg/h/MW engine power	None	None	None	16[11]	None	None
Other consumption	Washwater treatment	None	None	None	Not applicable	Flocculant (amount to be verified)	Minor amount coagulant & flocculent for bleed off treatment depending on system configuration
	Residue handling		None		None	None	None
	Other	Compressed service air	None	Compressed air	Compressed air – dependant on conveying distance from granulate storage to EGCS. For 10 m horizontal & 20 m vertical pneumatic conveying 250 m^3/h at 50 mbar	None	Compressed air (minor quantities)
EGC System Power Requirements	kW/MW engine power	10 to 12	Dependent SO_2 content and engine size. Information provided to potential clients on a case by case basis	18 to 23	1.5 to 2	20 to 30	3 – 6 (closed loop) 10 – 20 (open loop)

Physical Data

		ALFA LAVAL	BELCO® (DUPONT)	CLEAN MARINE	COUPLE SYSTEMS	MARINE EXHAUST SOLUTIONS	WÄRTSILÄ/HAMWORTHY
Maximum size of engine that can have EGC unit fitted	MW engine power	1 – 80MW	Unlimited	Unlimited, but above 25MW more than one EGC unit required	unlimited	Scalable to fit all sizes	Any
Sizes of EGC units offered	MW engine power	1 – 80MW	Sizes suitable for all engines	From 25MW (180,000 Nm^3/h) to 2 MW (14,000 Nm^3/h)	Range available on request	150kW to 70MW	From 400kW up
Footprint & height of EGC unit (m^2 & m)	Smallest EGC unit in range	D=0.8m for 0.5MW D=4.6m for 21MW D=7.5m for 60MW	Installation specific – slightly larger than the exhaust silencer	2MW:~4m^2 x (5 to 8)m	1MW – 8.8m^2 x 6.3m	25% of traditional silencer	Installation specific. E.g.: 1MW: 1m^2 x 5m
	Largest in range		Have experience up to an equivalent of 200 MW engines/boilers (land based)	20MW: ~32m^2 x (10 to 15)m	20MW – 47.7m^2 x 13.3m		20MW: <20m^2 x 7m
Weight in service i.e. filled (t)	Smallest EGC unit in range	0.5 MW = 3 t	Unit is designed to be lightweight and does not retain a liquid fill level	~10 t (not including NaOH storage)	1MW – 14 t	Installation specific	Installation specific. E.g.: 1MW: 2 t
	Largest in range	60MW = 70 t		~30 t (not including NaOH storage)	20MW – 211 t		20MW: 55 t

		ALFA LAVAL	BELCO® (DUPONT)	CLEAN MARINE	COUPLE SYSTEMS	MARINE EXHAUST SOLUTIONS	WÄRTSILÄ/HAMWORTHY
Typical position of EGC unit		Inside funnel or inside extended funnel area	Where space is available	Inside and outside funnel	Normally directly after the engine turbocharger or between turbocharger and exhaust gas boiler.	In place of traditional silencer/spark arrester	Retrofit: Inside existing or extended funnel Newbuildings: inside funnel
Footprint of washwater treatment plant (m^2)	Smallest EGC unit in range	$4m^2$ (for 21MW unit)	Installation specific	~$1.5m^2$ x 2m	Not applicable	Installation specific	Installation and closed/open loop specific. E.g.: 12MW closed loop: $4.5m^2$
	Largest in range			~$4m^2$ x 3m	Not applicable		
Typical position of washwater treatment plant		Fresh water cleaning unit can be positioned at any free location	Where space is available. Typically on lower decks	Optional – on open deck or inside	Not applicable	Exhaust casing, engine room or outside	Anywhere that is suitable in terms of available space and practicability
Tankage required (m^3/MW engine power)[6]	Washwater treatment plant residue	Dependent on installation and client's storage requirements. Typical sludge production rate ~0.2 litre / MW h (Freshwater mode)	Flexible & installation specific – based on amount of ash in flue gas and client requirement for storage duration	~$1m^3$ sludge/MW	Not applicable	~ 0.5 m^3 sludge/MW	70 – 300kg sludge/MW
	Chemical addition – Exhaust Gas Cleaning System	Dependent on vessel, routing and opportunity to bunker – ~$11.5m^3$ NaOH/MW (16 litres/MW/hour can be used for 2.7 % sulphur fuel to determine required autonomy)	Flexible & installation specific – based on amount of SO_2 in flue gas and client requirement for closed loop operation duration	~5 – $6m^3$ NaOH/MW	$14m^3$ $Ca(OH)_2$ /MW (11.2 t $Ca(OH)_2$ /MW)	None	Open loop: nothing Closed loop: ~$11.5m^3$ NaOH/MW (16 litres/MW/hour can be used for 2.7% sulphur fuel to determine required autonomy)
	Other	Circulation tank for fresh water operation. 0 – 10MW: $10m^3$, >10MW – 20MW: $20m^3$ >20MW: $40m^3$	None		None		Open loop: Optional de-aeration tank. Closed loop: bleed-off and effluent tanks for zero discharge. Size dependent on ship's operational needs

Testing

		ALFA LAVAL	BELCO® (DUPONT)	CLEAN MARINE	COUPLE SYSTEMS	MARINE EXHAUST SOLUTIONS	WÄRTSILÄ/HAMWORTHY
Tested in commercial land based applications or test facilities ?		Yes	Yes – marine design based on 200 land based units. Initial on board operation are on 3.5 MW and 2.2 MW engines	Yes	a) Marine design based on industrial land based units b) 2 trial marine units at Technical University Hamburg c) 2 engine manufacturer test beds	No	Yes – total installed power 465MW
Sizes		1MW	from 1 MW to 150 MW equivalent	1MW	250,000 Am^3/h[7] or ~ 124,000 Nm^3/h		Up to 80MW
When fitted		2008 (200 hours testing)	Since mid 1970s	2006 (testing between 2006 and 2008)	a) Operational over last 20 years		Since mid 1990's
Where		MAN Diesel test facility	Mainly oil refineries also on oil fired engines, power boilers, oily waste incinerators & various industrial applications	MAN Holeby	a) Ceramic industry, biomass incineration		Power generation – global Test installations – Norway
Combustion material		Residual Fuel	Crude oil, oil waste, solid waste, coal, pet coke		Heavy fuel oil (ceramic industry)		MGO, MDO, HFO
Maximum % sulphur		2.4%	6.5%		5%		Up to 5%
Tested on ship?		Yes – Ficaria Seaways Second ship (Spliethoff) to start testing Q4 2012	Some applications in 1970's for reduction of black smoke. Ship installation of current design will be tested in 4Q2012	Yes – one	Yes – one	Yes – two	Yes

		ALFA LAVAL	BELCO® (DUPONT)	CLEAN MARINE	COUPLE SYSTEMS	MARINE EXHAUST SOLUTIONS	WÄRTSILÄ/HAMWORTHY
Sizes	MW engine power	21 MW 28 MW (Q4 2012)	3.5MW and 2.2MW	10MW	3.6MW	1.2 kW, 5600 kW	610kW – 10MW
Where		Ro-Ro ferry, North Sea	Europe and North America	Panamax Tanker, Far East-Australia	General Cargo vessel, North Sea, Baltic	Ferry	Ferry, Cruise, Tanker, Container
Time in operation		>7000 hours	More than 500 operating years with land based applications.	Fitted July 2009. Operated for ~200hours	Fitted November 2009, 4000 running hours & still operating	8000 hours	>50,000 hours
Maximum % sulphur		2.7%	Experience on land with SO_2 levels greater than the equivalent of 11% sulphur-in-fuel	4.07%	1.78%	2.7%	3.4%
Independent emissions to air report published?		Yes	Yes for land based applications but not for ship installations	No	Independently verified by Germanischer Lloyd, report available from vendor on request		Yes – June 2010
Independent emissions to water report published?		Yes	No	No	Not applicable	Independently verified, not published	Yes – November 2011

Approvals

		ALFA LAVAL	BELCO® (DUPONT)	CLEAN MARINE	COUPLE SYSTEMS	MARINE EXHAUST SOLUTIONS	WÄRTSILÄ/HAMWORTHY
EGC units Scheme A certified?		No	No	No	No	No	Yes
Sizes	MW engine power						610kW
By who, when							DNV & GL, August 2009
EGC units Scheme B certified?		Yes	Pending	No	Yes	No	Yes
Sizes	MW engine power	21 MW			3.6MW		610kW, 1MW, 2MW, 8MW
By who, when		Approval acc. to MEPC.170(57) by Lloyd's Register March 29, 2012			Germanischer Lloyd 27 April 2010		DNV, GL, RINA

Supply, Installation and After Care

		ALFA LAVAL	BELCO® (DUPONT)	CLEAN MARINE	COUPLE SYSTEMS	MARINE EXHAUST SOLUTIONS	WÄRTSILÄ/HAMWORTHY
Scope of components to be supplied by EGCS vendor for installation		All except piping and cabling	All components can be supplied as required	All except below	All except below	All except supports and brackets, cabling and switchboard connections	To be agreed on a project by project basis, dependent on vessel and EGCS configuration
Scope of components to be supplied by ship owner/operator for installation		Piping and cabling Fresh water generator NaOH tank	Scope will be discussed with shipowner/operator to optimise costs/timing	Tankage, piping, supports and brackets, cabling and switchboard connections	Support structures and bracketing, all exhaust ducting and connections, insulation and cladding, exhaust dampers and bypass (raw and clean gas side, as required), exhaust fan (installation dependent), bulkhead transitions, dry oil-free compressed air supply, cabling and all switchboard connections. Outer housing for EGCS if retrofitted on deck	Sea chest, equipment mounts and supports, switchboard connections	To be agreed on a project by project basis, dependent on vessel and EGCS configuration

		ALFA LAVAL	BELCO® (DUPONT)	CLEAN MARINE	COUPLE SYSTEMS	MARINE EXHAUST SOLUTIONS	WÄRTSILÄ/HAMWORTHY
Scope of labour to be supplied by EGCS vendor for installation and commissioning		All as required	Advisory role liasing with shipowner/operator and installer. Training and aftermarket services provided as required	Project management and supervision. Design and drafting, documentation and certification	Project management, naval architecture services	Design, installation drawings, class approval support, project management, system installation and integration	Turnkey solution for retrofits. Basic design, equipment and commissioning supervision for newbuilds. All as required
Scope of labour to be supplied by ship owner/operator for installation		Installation labour costs for ship operator's account. Ship owner will typically contract the installer. Vendor will supply a supervisor	Shipowner/operator to hire contractor or shipyard for on ship installation of EGCS	Superintendent engineer, labour for mechanical and electrical system installation	Sign-off of plans and calculations provided by vendor. Freight of system components from vendor. Labour, services and staging for mechanical and electrical installation. Storage and handling of sorption granules & used product	Vessel drawings and yard schedule	To be agreed on a project by project basis, dependent on ship owner/operator, vessel and EGCS configuration
After care requirements		Instrument calibration, visual inspection, pump maintenance as per manufacturer's recommendations	None other than replacement spray nozzles for EGC unit – nozzles are designed for long term operation	Exchange of exhaust gas monitoring head every six months. Replacement of turbidity and pH sensors. Cleaning and calibration of PAH monitoring equipment. Long term overhaul of pumps, fans and filters	Instrument calibration and six monthly check of mechanical and electronic components	Instrument calibration, visual inspection, pump maintenance as per manufacturer's recommendations	Maintenance of pumps instrumentation etc. Regular inspections offered

Commercial

		ALFA LAVAL	BELCO® (DUPONT)	CLEAN MARINE	COUPLE SYSTEMS	MARINE EXHAUST SOLUTIONS	WÄRTSILÄ/HAMWORTHY
EGC system commercially available?		Yes	Yes	Yes	Yes	Yes	Yes
Production capacity (EGC units)	First year	As required	As required		200	As required	As required
	After first year	As required	As required			As required	As required
Target market	New-build, retrofit	Both	Both, new-builds and retrofits	Both, new build first	Both	Both	Both
	Vessel type/market sector	All commercial vessels	All	All	All	Commercial, Yacht/Workboat, Naval	All
	Engine size range	Up to 80MW	Any size	5 to 25MW	1 to 36MW (currently 20MW)	to 70 MW	All, including boilers
Supplier staff numbers	EGC team	>20 and growing	60 dedicated staff plus other DuPont staff on an as needed basis	14	18	17 and growing	55
	Entire company or group	15,000	DuPont 30,000 – 40,000		167	65	19,000
Estimated capital expenditure retrofit cost (USD)	Smallest EGC unit in range	Vessel and operating profile specific	Will provide pricing to individual clients on an as requested basis	USD3-4 million for 10MW EGCS including installation cost	1MW – USD0.5M	1 MW – USD900K	Pay back less than one year dependent upon fuel price and ECA operation ratio
	Largest in range				20MW – USD4M	20MW – USD3M	
Estimated annual operating cost (USD)[8]	Smallest EGC unit in range	Depends on EGCS configuration and the vessels operating profile	Will provide to individual clients as part of each proposal	20-40USD/t fuel consumed by scrubbed combustion units, depending on NaOH and fuel price, fuel sulphur level and scrubber operating mode	1MW – USD43,500 [13]	3% of capital costs	3 – 5 USD/MW h[10]
	Largest in range	Depends on EGCS configuration and the vessels operating profile			20MW - USD477,200 [13]		
Guarantee		12 months	Full process guarantees and 12 month mechanical warranty provided with each purchase	12 months	Guarantee 24 months after commissioning/36 months after delivery includes availability of calcium hydroxide at predetermined ports and free-cost disposal of residues	12 months – extended warranty offered	SOx reduction guaranteed. Equipment guarantee 12 months

Units – See also Glossary of terms, formulae & abbreviations

~	Approximately
<	Less than
>	Greater than
g/kW h	Grams per kilowatt per hour
l/h	Litres per hour
l/h/MW	Litres per hour per megawatt of engine power
kg	Kilogram
kg/h/MW	Kilograms per hour per megawatt of engine power
kW	Kilowatt (10^3 watts)
m	Metre
m^2	Square metre
m^3	Cubic metre
m^3/h/MW	Cubic metres per hour per megawatt engine power
MW	Megawatt (10^6 watts)
Nm^3/h	Normal cubic metres per hour
SCFM	Standard cubic feet per minute
t	Tonne (1000 kilograms)
USD	United States Dollar

Supporting Notes

1	50% NaOH solution
2	40% NaOH solution
3	Lower washwater flow requires larger addition of NaOH and vice versa
4	30% urea solution
5	Wartsila also offer a separate Selective Catalytic Reduction system which reduces NOx by 80 – 90%
6	Based on continuous combustion of 2.7% sulphur residual fuel over a one month period
7	For comparison a 6 cylinder 10MW slow speed engine delivers a maximum exhaust gas flow rate of around 60,000 Nm^3/h
8	Based on combustion of 2.7% sulphur residual fuel for 300 days
9	Based on a 3.5% sulphur residual fuel
10	Includes power consumption, NaOH, flocculant, maintenance and supervision
11	Based on 2.7% sulphur residual fuel at a specific fuel consumption of 200g/kWh
12	See section 7.1.3 for description
13	Includes power consumption, $Ca(OH)_2$, maintenance and labour
14	Based on a 2.7% sulphur residual fuel

APPENDIX 2 Resolution MEPC.184(59)
2009 Guidelines for Exhaust Gas Cleaning Systems

ANNEX 9

RESOLUTION MEPC.184(59)
Adopted on 17 July 2009

2009 GUIDELINES FOR EXHAUST GAS CLEANING SYSTEMS

THE MARINE ENVIRONMENT PROTECTION COMMITTEE,

RECALLING Article 38(a) of the Convention on the International Maritime Organization concerning the functions of the Marine Environment Protection Committee conferred upon it by international conventions for the prevention and control of marine pollution,

RECALLING ALSO that MARPOL Annex VI entered into force on 19 May 2005,

RECALLING FURTHER resolution MEPC.170(57) by which the Committee adopted the Guidelines for exhaust gas cleaning system,

NOTING that the revised MARPOL Annex VI was adopted by resolution MEPC.176(58) which is expected to enter into force on 1 July 2010,

NOTING ALSO that regulation 4 of the revised MARPOL Annex VI allows the use of an alternative compliance methods at least as effective in terms of emission reductions as that required by the revised MARPOL Annex VI, including any of the standards set forth in regulation 14, taking into account guidelines developed by the Organization,

RECOGNIZING the need to revise the Guidelines for exhaust gas cleaning systems, in accordance with provisions of the revised MARPOL Annex VI,

HAVING CONSIDERED the 2009 Guidelines for exhaust gas cleaning systems prepared by the Sub-Committee on Bulk Liquids and Gases at its thirteenth session,

1. ADOPTS the 2009 Guidelines for exhaust gas cleaning systems, as set out in the Annex to this resolution;

2. INVITES Governments to apply the 2009 Guidelines from 1 July 2010;

3. URGES Administrations to provide for collection of data under Appendix III; and

4. REVOKES the Guidelines adopted by resolution MEPC.170(57) as from 1 July 2010.

ANNEX

2009 GUIDELINES FOR EXHAUST GAS CLEANING SYSTEMS

1 INTRODUCTION

1.1 Regulation 14 of Annex VI to MARPOL 73/78 requires ships to use fuel oil with a sulphur content not exceeding that stipulated in regulation 14.1 or 14.4. Regulation 4 allows, with the approval of the Administration, the use of an alternative compliance method at least as effective in terms of emission reductions as that required by the Annex, including the standards set forth in regulation 14. The Administration of a party should take into account any relevant guidelines developed by the Organization pertaining to alternatives provided for in regulation 4.

1.2 Similar to a NO_x emission reduction system, an EGC unit may be approved subject to periodic parameter and emission checks or the system may be equipped with a continuous emission monitoring system. These Guidelines have been developed with the intention of being objective and performance oriented. Furthermore, use of the SO_2 (ppm)/CO_2 (%) ratio method will simplify the monitoring of SO_x emission and facilitate approval of an EGC unit. See Appendix II for the rationale explaining the use of SO_2 (ppm)/CO_2 (%) as the basis for system monitoring.

1.3 Compliance should be demonstrated on the basis of the SO_2(ppm)/CO_2(% v/v) ratio values.

Table 1
Fuel oil sulphur limits recorded in regulations 14.1 and 14.4 and corresponding emissions values

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

Note: The use of the Ratio Emissions limits is only applicable when using petroleum based Distillate or Residual Fuel Oils. See Appendix II for application of the ratio method.

1.4 These Guidelines are recommendatory in nature; however, Administrations are invited to base their implementation on these Guidelines.

2 GENERAL

2.1 Purpose

2.1.1 The purpose of these Guidelines is to specify the requirements for the testing, survey certification and verification of exhaust gas cleaning (EGC) systems under regulation 4 to ensure that they provide effective equivalence to requirements of regulations 14.1 and 14.4 of Annex VI of MARPOL 73/78.

2.1.2 The Guidelines permit two schemes; Scheme A (Unit Certification with Parameter and Emission Checks, and Scheme B (Continuous Emission Monitoring with Parameter Checks).

2.1.3 For ships which are to use an exhaust gas cleaning system in part or in total in order to comply with regulations 14.1 and/or 14.4 of MARPOL Annex VI there should be an approved SO_x Emissions Compliance Plan (SECP).

2.2 Application

2.2.1 These Guidelines apply to any EGC unit as fitted to fuel oil combustion machinery, excluding shipboard incinerators, installed on board a ship.

2.3 Definitions and Required Documents

Fuel oil combustion unit	Any engine, boiler, gas turbine, or other fuel oil fired equipment, excluding shipboard incinerators
EGC	Exhaust gas cleaning
SO_x	Sulphur oxides
SO_2	Sulphur dioxide
CO_2	Carbon dioxide
UTC	Universal Time Co-ordinated
Certified Value	The SO_2/CO_2 ratio specified by the manufacturer that the EGC unit is certified as meeting when operating on a continuous basis on the manufacturers specified maximum fuel sulphur content
In situ	Sampling directly within an exhaust gas stream
MCR	Maximum Continuous Rating
Load Range	Maximum rated power of diesel engine or maximum steaming rate of the boiler
SECP	SO_x Emissions Compliance Plan
SECC	SO_x Emissions Compliance Certificate
ETM-A	EGC system – Technical Manual for Scheme A
ETM-B	EGC system – Technical Manual for Scheme B
OMM	Onboard Monitoring Manual
EGC Record Book	A record of the EGC unit in-service operating parameters, component adjustments, maintenance and service records as appropriate

Document	Scheme A	Scheme B
SECP	X	X
SECC	X	
ETM Scheme A	X	
ETM Scheme B		X
OMM	X	X
EGC Record Book or Electronic Logging System	X	X

3 SAFETY NOTE

3.1 Due attention is to be given to the safety implications related to the handling and proximity of exhaust gases, the measurement equipment and the storage and use of pressurized containers of pure and calibration gases. Sampling positions and permanent access platforms should be such that this monitoring may be performed safely. In locating discharge outlet of washwater used in the EGC unit, due consideration should be given to the location of the ship's seawater inlet. In all operating conditions the pH should be maintained at a level that avoids damage to the vessel's anti-fouling system, the propeller, rudder and other components that may be vulnerable to acidic discharges, potentially causing accelerated corrosion of critical metal components.

4 SCHEME A – EGC SYSTEM APPROVAL, SURVEY AND CERTIFICATION USING PARAMETER AND EMISSION CHECKS

4.1 Approval of EGC systems

4.1.1 General

Options under Scheme A of these Guidelines provide for:

a) Unit approval;
b) Serially manufactured units;
c) Production range approval.

4.1.2 Unit approval

4.1.2.1 An EGC unit should be certified as capable of meeting the limit value, (the Certified Value), specified by the manufacturer (e.g., the emission level the unit is capable of achieving on a continuous basis) with fuel oils of the manufacturer's specified maximum % m/m sulphur content and for the range of operating parameters, as listed in 4.2.2.1(b), for which they are to be approved. The Certified Value should at least be suitable for ship operations under requirements given by MARPOL Annex VI regulations 14.1 and/or 14.4.

4.1.2.2 Where testing is not to be undertaken with fuel oils of the manufacturer's specified maximum % m/m sulphur content, the use of two test fuels with a lower % m/m sulphur content is permitted. The two fuels selected should have a difference in % m/m sulphur content sufficient to demonstrate the operational behaviour of the EGC unit and to demonstrate that the Certified Value can be met if the EGC unit were to be operated with a fuel of the manufacturer's specified maximum % m/m sulphur content. In such cases a minimum of two tests, in accordance with section 4.3 as appropriate, should be performed. These need not be sequential and could be undertaken on two different, but identical, EGC units.

4.1.2.3 The maximum and, if applicable, minimum exhaust gas mass flow rate of the unit should be stated. The effect of variation of the other parameters defined in 4.2.2.1(b) should be justified by the equipment manufacturer. The effect of variations in these factors should be assessed by testing or otherwise as appropriate. No variation in these factors, or combination of variations in these factors, should be such that the emission value of the EGC unit would be in excess of the Certified Value.

4.1.2.4 Data obtained in accordance with this section should be submitted to the Administration for approval together with the ETM-A.

4.1.3 Serially manufactured units

In the case of nominally similar EGC units of the same mass flow ratings as that certified under 4.1.2, and to avoid the testing of each EGC unit, the equipment manufacturer may submit, for acceptance by the Administration, a conformity of production arrangement. The certification of each EGC unit under this arrangement should be subject to such surveys that the Administration may consider necessary as to assure that each EGC unit has an emission value of not more than the Certified Value when operated in accordance with the parameters defined in 4.2.2.1(b).

4.1.4 Product range approval

4.1.4.1 In the case of an EGC unit of the same design, but of different maximum exhaust gas mass flow capacities, the Administration may accept, in lieu of tests on an EGC unit of all capacities in accordance with section 4.1.2, tests of EGC systems of three different capacities provided that the three tests are performed at intervals including the highest, lowest and one intermediate capacity rating within the range.

4.1.4.2 Where there are significant differences in the design of EGC units of different capacities, this procedure should not be applied unless it can be shown, to the satisfaction of the Administration, that in practice those differences do not materially alter the performance between the various EGC unit types.

4.1.4.3 For EGC units of different capacities, the sensitivity to variations in the type of combustion machinery to which they are fitted should be detailed together with sensitivity to the variations in the parameters listed in 4.2.2.1(b). This should be on the basis of testing, or other data as appropriate.

4.1.4.4 The effect of changes of EGC unit capacity on washwater characteristics should be detailed.

4.1.4.5 All supporting data obtained in accordance with this section, together with the ETM-A for each capacity unit, should be submitted to the Administration for approval.

4.2 Survey and certification

4.2.1 Procedures for the certification of an EGC unit

4.2.1.1 In order to meet the requirements of 4.1 either prior to, or after installation on board, each EGC unit should be certified as meeting the Certified Value specified by the manufacturer (e.g., the emission level the unit is capable of achieving on a continuous basis) under the operating conditions and restrictions as given by the EGC Technical Manual (ETM-A) as approved by the Administration.

4.2.1.2 Determination of the Certified Value should be in accordance with the provisions of these Guidelines.

4.2.1.3 Each EGC unit meeting the requirements of 4.2.1.1 should be issued with a SECC by the Administration. The form of the SECC is given in Appendix I.

4.2.1.4 Application for an SECC should be made by the EGC system manufacturer, shipowner or other party.

4.2.1.5 Any subsequent EGC units of the same design and rating as that certified under 4.2.1.1 may be issued with an SECC by the Administration without the need for testing in accordance with 4.2.1.1 subject to section 4.1.3 of these Guidelines.

4.2.1.6 EGC units of the same design, but with ratings different from that certified under 4.2.1.1 may be accepted by the Administration subject to section 4.1.4 of these Guidelines.

4.2.1.7 EGC units which treat only part of the exhaust gas flow of the uptake in which they are fitted should be subject to special consideration by the Administration to ensure that under all defined operating conditions that the overall emission value of the exhaust gas down stream of the system is no more than the Certified Value.

4.2.2 EGC System Technical Manual "Scheme A" (ETM-A).

4.2.2.1 Each EGC unit should be supplied with an ETM-A provided by the manufacturer. This ETM-A should, as a minimum, contain the following information:

(a) the identification of the unit (manufacturer, model/type, serial number and other details as necessary) including a description of the unit and any required ancillary systems;

(b) the operating limits, or range of operating values, for which the unit is certified. These should, as a minimum, include:

  (i) maximum and, if applicable, minimum mass flow rate of exhaust gas;

  (ii) the power, type and other relevant parameters of the fuel oil combustion unit for which the EGC unit is to be fitted. In the cases of boilers, the maximum air/fuel ratio at 100% load should also be given. In the cases of diesel engines whether the engine is of 2 or 4-stroke cycle;

  (iii) maximum and minimum washwater flow rate, inlet pressures and minimum inlet water alkalinity (ISO 9963-1-2);

  (iv) exhaust gas inlet temperature ranges and maximum and minimum exhaust gas outlet temperature with the EGC unit in operation;

  (v) exhaust gas differential pressure range and the maximum exhaust gas inlet pressure with the fuel oil combustion unit operating at MCR or 80% of power rating whichever is appropriate;

  (vi) salinity levels or fresh water elements necessary to provide adequate neutralizing agents; and

  (vii) other factors concerning the design and operation of the EGC unit relevant to achieving a maximum emission value no higher than the Certified Value;

(c) any requirements or restrictions applicable to the EGC unit or associated equipment necessary to enable the unit to achieve a maximum emission value no higher than the Certified Value;

(d) maintenance, service or adjustment requirements in order that the EGC unit can continue to achieve a maximum emission value no higher than the Certified Value. The maintenance, servicing and adjustments should be recorded in the EGC Record Book;

(e) corrective actions in case of exceedances of the applicable maximum allowable SO_2/CO_2 ratio, or wash water discharge criteria;

(f) a verification procedure to be used at surveys to ensure that its performance is maintained and that the unit is used as required (see section 4.4);

(g) through range performance variation in washwater characteristics;

(h) design requirements of the washwater system; and

(i) the SECC.

4.2.2.2 The ETM-A should be approved by the Administration.

4.2.2.3 The ETM-A should be retained on board the ship onto which the EGC unit is fitted. The ETM-A should be available for surveys as required.

4.2.2.4 Amendments to the ETM-A which reflect EGC unit changes that affect performance with respect to emissions to air and/or water should be approved by the Administration. Where additions, deletions or amendments to the ETM-A are separate to the ETM-A as initially approved, they should be retained with the ETM-A and should be considered as part of the ETM-A.

4.2.3 In service surveys

4.2.3.1 The EGC unit should be subject to survey on installation and at Initial, Annual/Intermediate and Renewals Surveys by the Administration.

4.2.3.2 In accordance with MARPOL Annex VI regulation 10, EGC units may also be subject to inspection by port State control.

4.2.3.3 Prior to use each EGC unit should be issued with an SECC by the Administration.

4.2.3.4 Following the installation survey as required by 4.2.3.1, section 2.6 of the Supplement to the ship's International Air Pollution Certificate should be duly completed.

4.3 Emission limits

4.3.1 Each EGC unit should be capable of reducing emissions to equal to or less than the Certified Value at any load point when operated in accordance with the criteria as given within 4.2.2.1(b), as specified in paragraphs 4.3.2 to 4.3.5 of these Guidelines, and as excepted in paragraph 4.3.7.

4.3.2 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.3.1 at all loads between 25-100% of the load range of the engines to which they are fitted.

4.3.3 EGC units fitted to auxiliary diesel engines should meet the requirements of 4.3.1 at all loads between 10-100% of the load range of the engines to which they are fitted.

4.3.4 EGC units fitted to diesel engines which supply power for both main propulsion and auxiliary purposes should meet the requirements of 4.3.3.

4.3.5 EGC units fitted to boilers should meet the requirements of 4.3.1 at all loads between 10-100% of the load range (steaming rates) or, if the turn down ratio is smaller, over the actual load range of the boilers to which they are fitted.

4.3.6 In order to demonstrate performance, emission measurements should be undertaken, with the agreement of the Administration, at a minimum of four load points. One load point should be at 95-100% of the maximum exhaust gas mass flow rate for which the unit is to be certified. One load point should be within ± 5% of the minimum exhaust gas mass flow rate for which the unit is to be certified. The other two load points should be equally spaced between the maximum and minimum exhaust gas mass flow rates. Where there are discontinuities in the operation of the system the number of load points should be increased, with the agreement of the Administration, so that it is demonstrated that the required performance over the stated exhaust gas mass flow rate range is retained. Additional intermediate load points should be tested if there is evidence of an emission peak below the maximum exhaust gas mass flow rate and above, if applicable, the minimum exhaust gas flow rate. These additional tests should be sufficient number as to establish the emission peak value.

4.3.7 For loads below those specified in 4.3.2 to 4.3.5, the EGC unit should continue in operation. In those cases where the fuel oil combustion equipment may be required to operate under idling conditions, the SO_2 emission concentration (ppm) at standardized O_2 concentration (15.0% diesel engines, 3.0% boilers) should not exceed 50 ppm.

4.4 Onboard procedures for demonstrating compliance

4.4.1 For each EGC unit, the ETM-A should contain a verification procedure for use at surveys as required. This procedure should not require specialized equipment or an in-depth knowledge of the system. Where particular devices are required they should be provided and maintained as part of the system. The EGC unit should be designed in such a way as to facilitate inspection as required. The basis of this verification procedure is that if all relevant components and operating values or settings are within those as approved, then the performance of the EGC system is within that required without the need for actual exhaust emission measurements. It is also necessary to ensure that the EGC unit is fitted to a fuel oil combustion unit for which it is rated – this forms part of the SECP. A Technical File related to an EIAPP certificate, if available, or an Exhaust Gas Declaration issued by the engine maker or designer or another competent party or a Flue Gas Declaration issued by the boiler maker or designer or another competent party serves this purpose to the satisfaction of the Administration.

4.4.2 Included in the verification procedure should be all components and operating values or settings which may affect the operation of the EGC unit and its ability to meet the Certified Value.

4.4.3 The verification procedure should be submitted by the EGC system manufacturer and approved by the Administration.

4.4.4 The verification procedure should cover both a documentation check and a physical check of the EGC unit.

4.4.5 The Surveyor should verify that each EGC unit is installed in accordance with the ETM-A and has an SECC as required.

4.4.6 At the discretion of the Administration, the Surveyor should have the option of checking one or all of the identified components, operating values or settings. Where there is more than one EGC unit, the Administration may, at its discretion, abbreviate or reduce the extent of the survey on board, however, the entire survey should be completed for at least one of each type of EGC unit on board provided that it is expected that the other EGC units perform in the same manner.

4.4.7 The EGC unit should include means to automatically record when the system is in use. This should automatically record, at least at the frequency specified in paragraph 5.4.2, as a minimum, washwater pressure and flow rate at the EGC unit's inlet connection, exhaust gas pressure before and pressure drop across the EGC unit, fuel oil combustion equipment load, and exhaust gas temperature before and after the EGC unit. The data recording system should comply with the requirements of sections 7 and 8. In case of a unit consuming chemicals at a known rate as documented in ETM-A, records of such consumption in the EGC Record Book also serves this purpose.

4.4.8 Under Scheme A, if a continuous exhaust gas monitoring system is not fitted, it is recommended that a daily spot check of the exhaust gas quality in terms of SO_2 (ppm)/CO_2 (%) ratio, is used to verify compliance in conjunction with parameter checks stipulated in 4.4.7. If a continuous exhaust gas monitoring system is fitted, only daily spot checks of the parameters listed in paragraph 4.4.7 would be needed to verify proper operation of the EGC unit.

4.4.9 If the EGC system manufacturer is unable to provide assurance that the EGC unit will meet the Certified Value or below between surveys, by means of the verification procedure stipulated in 4.4.1, or if this requires specialist equipment or in-depth knowledge, it is recommended that continuous exhaust gas monitoring of each EGC unit be used, Scheme B, to assure compliance with regulations 14.1 and/or 14.4.

4.4.10 An EGC Record Book should be maintained by the shipowner recording maintenance and service of the unit including like-for-like replacement. The form of this record should be submitted by the EGC system manufacturer and approved by the Administration. This EGC Record Book should be available at surveys as required and may be read in conjunction with engine-room log-books and other data as necessary to confirm the correction operation of the EGC unit. Alternatively, this information should be recorded in the vessel's planned maintenance record system as approved by the Administration.

5 SCHEME B – EGC SYSTEM APPROVAL, SURVEY AND CERTIFICATION USING CONTINUOUS MONITORING OF SO_x EMISSIONS

5.1 General

This Scheme should be used to demonstrate that the emissions from a fuel oil combustion unit fitted with an EGC will, with that system in operation, result in the required emission value (e.g., as stated in the SECP) or below at any load point, including during transient operation and thus compliance with the requirements of regulations 14.1 and/or 14.4 of MARPOL Annex VI.

5.2 Approval

Compliance demonstrated in service by continuous exhaust gas monitoring. Monitoring system should be approved by the Administration and the results of that monitoring available to the Administration as necessary to demonstrate compliance as required.

5.3 Survey and certification

5.3.1 The monitoring system of the EGC system should be subject to survey on installation and at Initial, Annual/Intermediate and Renewals Surveys by the Administration.

5.3.2 In accordance with regulation 10 of MARPOL Annex VI monitoring systems of EGC units may also be subject to inspection by port State control.

5.3.3 In those instances where an EGC system is installed, section 2.6 of the Supplement to the ship's International Air Pollution Prevention Certificate should be duly completed.

5.4 Calculation of emission rate

5.4.1 Exhaust gas composition in terms of SO_2 (ppm)/CO_2 (%) should be measured at an appropriate position after the EGC unit and that measurement should be in accordance with the requirements of section 6 as applicable.

5.4.2 SO_2 (ppm) and CO_2 (%) to be continuously monitored and recorded onto a data recording and processing device at a rate which should not be less than 0.0035 Hz.

5.4.3 If more than one analyser is to be used to determine the SO_2/CO_2 ratio, these should be tuned to have similar sampling and measurement times and the data outputs aligned so that the SO_2/CO_2 ratio is fully representative of the exhaust gas composition.

5.5 Onboard procedures for demonstrating compliance with emission limit

5.5.1 The data recording system should comply with the requirements of sections 7 and 8.

5.5.2 Daily spot checks of the parameters listed in paragraph 4.4.7 are needed to verify proper operation of the EGC unit and should be recorded in the EGC Record Book or in the engine-room logger system.

5.6 EGC System Technical Manual "Scheme B" (ETM-B)

5.6.1 Each EGC unit should be supplied with an ETM-B provided by the Manufacturer. This ETM-B should, as a minimum, contain the following information:

(a) the identification of the unit (manufacturer, model/type, serial number and other details as necessary) including a description of the unit and any required ancillary systems;

(b) the operating limits, or range of operating values, for which the unit is certified. These should, as a minimum, include:

(i) maximum and, if applicable, minimum mass flow rate of exhaust gas;

(ii) the power, type and other relevant parameters of the fuel oil combustion unit for which the EGC unit is to be fitted. In the cases of boilers, the maximum air/fuel ratio at 100% load should also be given. In the cases of diesel engines whether the engine is of 2 or 4-stroke cycle;

(iii) maximum and minimum washwater flow rate, inlet pressures and minimum inlet water alkalinity (ISO 9963-1-2);

(iv) exhaust gas inlet temperature ranges and maximum and minimum exhaust gas outlet temperature with the EGC unit in operation;

(v) exhaust gas differential pressure range and the maximum exhaust gas inlet pressure with the fuel oil combustion unit operating at MCR or 80% of power rating whichever is appropriate;

(vi) salinity levels or fresh water elements necessary to provide adequate neutralizing agents; and

(vii) other parameters as necessary concerning the operation of the EGC unit;

(c) any requirements or restrictions applicable to the EGC unit or associated equipment;

(d) corrective actions in case of exceedances of the applicable maximum allowable SO_2/CO_2 ratio, or washwater discharge criteria;

(e) through range performance variation in washwater characteristics;

(f) design requirements of the washwater system.

5.6.2 The ETM-B should be approved by the Administration.

5.6.3 The ETM-B should be retained on board the ship onto which the EGC unit is fitted. The ETM-B should be available for surveys as required.

5.6.4 Amendments to the ETM-B which reflect EGC unit changes that affect performance with respect to emissions to air and/or water should be approved by the Administration. Where additions, deletions or amendments to the ETM-B are separate to the ETM-B as initially approved, they should be retained with the ETM-B and should be considered as part of the ETM-B.

6 EMISSION TESTING

6.1 Emission testing should follow the requirements of the NO_x Technical Code 2008, chapter 5, and associated Appendices, except as provided for in these Guidelines.

6.2 CO_2 should be measured on a dry basis using an analyser operating on non-dispersive infra-red (NDIR) principle. SO_2 should be measured on a dry or wet basis using analysers operating on non-dispersive infra-red (NDIR) or non-dispersive ultra-violet (NDUV) principles and with additional equipment such as dryers as necessary. Other systems or analyser principles may be accepted, subject to the approval of the Administration, provided they yield equivalent or better results to those of the equipment referenced above.

6.3 Analyser performance should be in accordance with the requirements of Appendix III sections 1.6 to 1.10 of the NO_x Technical Code 2008.

6.4 An exhaust gas sample for SO_2 should be obtained from a representative sampling point downstream of the EGC unit.

6.5 SO_2 and CO_2 should be monitored using either *in situ* or extractive sample systems.

6.6 Extractive exhaust gas samples for SO_2 determination should be maintained at a sufficient temperature to avoid condensed water in the sampling system and hence loss of SO_2.

6.7 If an extractive exhaust gas sample for determination needs to be dried prior to analysis it should be done in a manner that does not result in loss of SO_2 in the sample as analysed.

6.8 Where SO_2 is measured by an *in situ* system, the water content in the exhaust gas stream at that point is also to be determined in order to correct the reading to a dry basis value.

6.9 In justified cases where the CO_2 concentration is reduced by the EGC unit, the CO_2 concentration can be measured at the EGC unit inlet, provided that the correctness of such a methodology can be clearly demonstrated.

7 DATA RECORDING AND PROCESSING DEVICE

7.1 The recording and processing device should be of robust, tamper-proof design with read-only capability.

7.2 The recording and processing device should record the data required by sections 4.4.7, 5.4.2, and 10.3 against UTC and ships position by a Global Navigational Satellite System (GNSS).

7.3 The recording and processing device should be capable of preparing reports over specified time periods.

7.4 Data should be retained for a period of not less than 18 months from the date of recording. If the unit is changed over that period, the shipowner should ensure that the required data is retained on board and available as required.

7.5 The device should be capable of downloading a copy of the recorded data and reports in a readily useable format. Such copy of the data and reports should be available to the Administration or port State authority as requested.

8 ONBOARD MONITORING MANUAL (OMM)

8.1 An OMM should be prepared to cover each EGC unit installed in conjunction with fuel oil combustion equipment, which should be identified, for which compliance is to be demonstrated.

8.2 The OMM should, as a minimum, include:

(a) the sensors to be used in evaluating EGC system performance and washwater monitoring, their service, maintenance and calibration requirements;

(b) the positions from which exhaust emission measurements and washwater monitoring are to be taken together with details of any necessary ancillary services such as sample transfer lines and sample treatment units and any related service or maintenance requirements;

(c) the analysers to be used, their service, maintenance, and calibration requirements;

(d) analyser zero and span check procedures; and

(e) other information or data relevant to the correct functioning of the monitoring systems or its use in demonstrating compliance.

8.3 The OMM should specify how the monitoring is to be surveyed.

8.4 The OMM should be approved by the Administration.

9 SHIP COMPLIANCE

9.1 SO_x Emissions Compliance Plan (SECP)

9.1.1 For all ships which are to use an EGC unit, in part or in total, in order to comply with the requirements of regulations 14.1 and 14.4 of MARPOL Annex VI there should be an SECP for the ship, approved by the Administration.

9.1.2 The SECP should list each item of fuel oil combustion equipment which is to meet the requirements for operating in accordance with the requirements of regulations 14.1 and/or 14.4.

9.1.3 Under Scheme A, the SECP should present how continuous monitoring data will demonstrate that the parameters in paragraph 4.4.7 are maintained within the manufacturer's recommended specifications. Under Scheme B, this would be demonstrated using daily recordings of key parameters.

9.1.4 Under Scheme B, the SECP should present how continuous exhaust gas emissions monitoring will demonstrate that the ship total SO_2 (ppm)/CO_2 (%) ratio is comparable to the requirements of regulation 14.1 and/or 14.4 or below as prescribed in paragraph 1.3. Under Scheme A, this would be demonstrated using daily exhaust gas emission recordings.

9.1.5 There may be some equipment such as small engines and boilers to which the fitting of EGC units would not be practical, particularly where such equipment is located in a position remote from the main machinery spaces. All such fuel oil combustion units should be listed in the SECP. For these fuel oil combustion units which are not to be fitted with EGC units, compliance may be achieved by means of regulations 14.1 and/or 14.4 of MARPOL Annex VI.

9.2 Demonstration of Compliance

9.2.1 Scheme A

9.2.1.1 The SECP should refer to, not reproduce, the ETM-A, EGC Record Book or Engine-Room logger system and OMM as specified under Scheme A. It should be noted that as an alternative, the maintenance records may be recorded in the ship's Planned Maintenance Record System, as allowed by the Administration.

9.2.1.2 For all fuel oil combustion equipment listed under 9.1.2, details should be provided demonstrating that the rating and restrictions for the EGC unit as approved, 4.2.2.1(b), are complied with.

9.2.1.3 Required parameters should be monitored and recorded as required under 4.4.7 when the EGC is in operation in order to demonstrate compliance.

9.2.2 Scheme B

9.2.2.1 The SECP should refer to, not reproduce, the ETM-B, EGC Record Book or Engine-Room logger system and OMM as specified under Scheme B.

10 WASHWATER

10.1 Washwater discharge criteria[1]

10.1.1 When the EGC system is operated in ports, harbours, or estuaries, the washwater monitoring and recording should be continuous. The values monitored and recorded should include pH, PAH, turbidity and temperature. In other areas the continuous monitoring and recording equipment should also be in operation, whenever the EGC system is in operation, except for short periods of maintenance and cleaning of the equipment. The discharge water should comply with the following limits:

10.1.2 pH criteria

10.1.2.1 The washwater pH should comply with one of the following requirements which should be recorded in the ETM-A or ETM-B as applicable:

(i) 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.

(ii) During commissioning of the 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.

10.1.3 PAHs (Polycyclic Aromatic Hydrocarbons)

10.1.3.1 The washwater PAH should comply with the following requirements. The appropriate limit should be specified in the ETM-A or ETM-B.

[1] The washwater discharge criteria should be revised in the future as more data becomes available on the contents of the discharge and its effects, taking into account any advice given by GESAMP.

10.1.3.2 The maximum continuous PAH concentration in the washwater should not be greater than 50 μg/L PAH_{phe} (phenanthrene equivalence) above the inlet water PAH concentration. For the purposes of this criteria, the PAH concentration in the washwater should be measured downstream of the water treatment equipment, but upstream of any washwater dilution or other reactant dosing unit, if used, prior to discharge.

10.1.3.3 The 50 μg/L limit described above is normalized 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 the table below.

Flow Rate (t/MWh)	Discharge Concentration Limit (μg/L PAH_{phe} equivalents)	Measurement Technology
0 - 1	2250	Ultraviolet Light
2.5	900	– ” –
5	450	Fluorescence*
11.25	200	– ” –
22.5	100	– ” –
45	50	– ” –
90	25	– ” –

10.1.3.4 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%. This would allow for an abnormal start up of the EGC unit.

10.1.4 Turbidity/Suspended Particle Matter

10.1.4.1 The washwater turbidity should comply with the following requirements. The limit should be recorded in the ETM-A or ETM-B.

10.1.4.2 The washwater treatment system should be designed to minimize suspended particulate matter, including heavy metals and ash.

10.1.4.3 The maximum continuous turbidity in washwater should not be greater than 25 FNU (formazin nephlometric units) or 25 NTU (nephlometric turbidity units) or equivalent units, above the inlet water turbidity. However, during periods of high inlet turbidity, the precision of the measurement device and the time lapse between inlet measurement and outlet measurement are such that the use of a difference limit is 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 washwater should be measured downstream of the water treatment equipment but upstream of washwater dilution (or other reactant dosing) prior to discharge.

10.1.4.4 For a 15-minute period in any 12-hour period, the continuous turbidity discharge limit may be exceeded by 20%.

10.1.5 Nitrates

10.1.5.1 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.

10.1.5.2 At each renewal survey nitrate discharge data is to be available in respect of sample overboard discharge drawn from each EGC system with the previous three months prior to the survey. However, the Administration may require an additional sample to be drawn and analysed at their discretion. The nitrate discharge data and analysis certificate is to be retained on board the ship as part of the EGC Record Book and be available for inspection as required by Port State Control or other parties. Requirements in respect of sampling, storage, handling and analysis should be detailed in the ETM-A or ETM-B as applicable. To assure comparable nitrate discharge rate assessment, the sampling procedures should take into account paragraph 10.1.5.1, which specifies the need for washwater flow normalization. The test method for the analysis of nitrates should be according to standard seawater analysis as described in Grasshoff *et al.*

10.1.5.3 All systems should be tested for nitrates in the discharge water. If typical nitrate amounts are above 80% of the upper limit, it should be recorded in the ETM-A or ETM-B.

10.1.6 Washwater additives and other substances

10.1.6.1 An assessment of the washwater is required for those EGC technologies which make use of chemicals, additives, preparations or create relevant chemicals *in situ*. The assessment could take into account relevant guidelines such as resolution MEPC.126(53), procedure for approval of ballast water management systems that make use of active substances (G9) and if necessary additional washwater discharge criteria should be established.

10.2 Washwater monitoring

10.2.1 pH, oil content (as measured by PAH levels), and turbidity should be continuously monitored and recorded as recommended in section 7 of these Guidelines. The monitoring equipment should also meet the performance criteria described below:

pH

10.2.2 The pH electrode and pH meter should have a resolution of 0.1 pH units and temperature compensation. The electrode should comply with the requirements defined in BS 2586 or of equivalent or better performance and the meter should meet or exceed BS EN ISO 60746-2:2003.

PAH

10.2.3 The PAH monitoring equipment should be capable to monitor PAH in water in a range to at least twice the discharge concentration limit given in the table above. The equipment should be demonstrated to operate correctly and not deviate more than 5% in washwater with turbidity within the working range of the application.

10.2.4 For those applications discharging at lower flow rates and higher PAH concentrations, ultraviolet light monitoring technology or equivalent, should be used due to its reliable operating range.

* For any Flow Rate > 2.5 t/MWh Fluorescence technology should be used.

Turbidity

10.2.5 The turbidity monitoring equipment should meet requirements defined in ISO 7027:1999 or USEPA 180.1.

Temperature recording

10.3 Washwater monitoring data recording

10.3.1 The data recording system should comply with the requirements of sections 7 and 8 and should continuously record pH, PAH and Turbidity as specified in the washwater criteria.

10.4 Washwater residue

10.4.1 Residues generated by the EGC unit should be delivered ashore to adequate reception facilities. Such residues should not be discharged to the sea or incinerated on board.

10.4.2 Each ship fitted with an EGC unit should record the storage and disposal of washwater residues in an EGC log, including the date, time and location of such storage and disposal. The EGC log may form a part of an existing log-book or electronic recording system as approved by the Administration.

APPENDIX I

FORM OF SO_x EMISSION COMPLIANCE CERTIFICATE

Badge or Cipher

NAME OF ADMINISTRATION

SO_x EMISSION COMPLIANCE CERTIFICATE

CERTIFICATE OF UNIT APPROVAL FOR EXHAUST GAS CLEANING SYSTEMS

Issued under the provisions of the Protocol of 1997, as amended by resolution MEPC.176(58) in 2008, to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 related thereto under the authority of the Government of:

....

(full designation of the country)

by...

(full designation of the competent person or organization authorized under the provisions of the Convention)

This is to certify that the exhaust gas cleaning (EGC) unit listed below has been surveyed in accordance with the requirements of the specifications contained under Scheme A in the Guidelines for exhaust gas cleaning systems – adopted by resolution MEPC.***(**).

This Certificate is valid only for the EGC unit referred to below:

Unit manufacturer	Model/ type	Serial number	EGC System Unit and Technical Manual approval number

A copy of this Certificate, together with the EGC System Technical Manual, shall be carried on board the ship fitted with this EGC System unit at all times.

This Certificate is valid for the life of the EGC System unit subject to surveys in accordance with section 4.2 of the Guidelines and regulation 5 of the revised MARPOL Annex VI, installed in ships under the authority of this Government.

Issued at ....

(place of issue of certificate)

dd/mm/yyyy

....

(date of issue) (*signature of duly authorized official issuing the certificate)*

(Seal or Stamp of the authority, as appropriate)

APPENDIX II

PROOF OF THE SO_2/CO_2 RATIO METHOD

1 The SO_2/CO_2 ratio method enables direct monitoring of exhaust gas emissions to verify compliance with emissions limits set out in Table 1 in section 1.3 of these Guidelines. In the case of EGC systems that absorb CO_2 during the exhaust gas cleaning process it is necessary to measure the CO_2 prior to the cleaning process and use the CO_2 concentration before cleaning with the SO_2 concentration after cleaning. For conventional low alkali cleaning systems virtually no CO_2 is absorbed during exhaust gas cleaning and therefore monitoring of both gases can be undertaken after the cleaning process.

2 Correspondence between the SO_2/CO_2 ratio can be determined by simple inspection of the respective carbon contents per unit mass of distillate and residual fuel. For this group of hydrocarbon fuels the carbon content as a percentage of mass remains closely similar, whereas the hydrogen content differs. Thus it can be concluded that for a given carbon consumption by combustion there will be a consumption of sulphur in proportion to the sulphur content of the fuel, or in other words a constant ratio between carbon and sulphur adjusted for the molecular weight of oxygen from combustion.

3 The first development of the SO_2/CO_2 ratio considered its use to verify compliance with emissions from 1.5% S fuel. The limit of 65 ([1]ppm/%) SO_2/CO_2 for 1.5% sulphur in fuel can be demonstrated by first calculating the mass ratio of fuel sulphur to fuel carbon, which is tabulated in Table 1 in this appendix for various fuels and fuel sulphur contents; including 1.5% sulphur for both distillate and residual fuels. These ratios were used to solve for the corresponding SO_2 and CO_2 concentrations in exhaust, which are tabulated in Table 2 of this Appendix. Molecular weights (MW) were taken into account to convert mass fractions to mole fractions. For the 1.5% sulphur fuels in Table 2, the amount of CO_2 is set first at 8% and then changed to 0.5% to show that there is no effect due to changes in excess air. As expected, the absolute SO_2 concentration changes, but the SO_2/CO_2 ratio does not. This indicates that the SO_2/CO_2 ratio is independent of fuel-to-air ratios. Therefore, SO_2/CO_2 ratio can be used robustly at any point of operation, including operation where no brake power is produced.

Note that the SO_2/CO_2 ratio varies slightly from distillate to residual fuel. This occurs because of the very different atomic hydrogen-to-carbon ratios (H:C) of the two fuels. Figure 1 illustrates the extent of the SO_2/CO_2 ratios' sensitivity to H:C over a broad range of H:C and fuel sulphur concentrations. From Figure 1, it can be concluded that for fuel sulphur levels less than 3.00% S, the difference in S/C ratios for distillate and residual fuel is less than 5.0%.

In the case of using non-petroleum fuel oils, the appropriate SO_2/CO_2 ratio applicable to the values given in regulations 14.1 and/or 14.4 will be subject to approval by the Administration.

Table 1: Fuel properties for marine distillate and residual fuel*

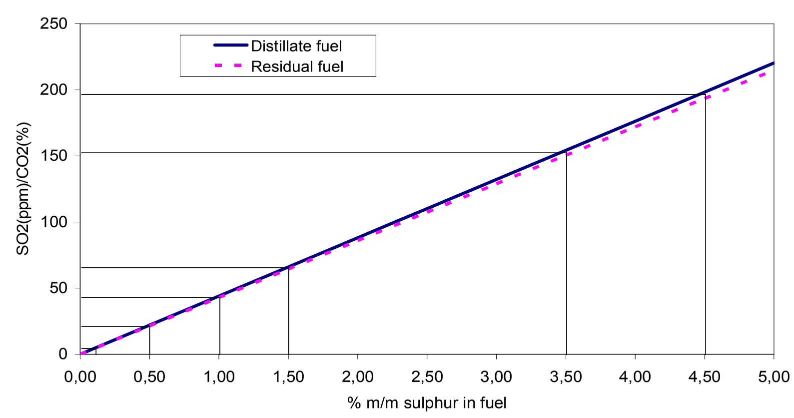
	Carbon	Hydrogen	Sulphur	Other	C	H	S	Fuel S/C	Exh SO_2/CO_2
Fuel Type	%(m/m)	%(m/m)	%(m/m)	%(m/m)	mol/kg	mol/kg	mol/kg	mol/mol	ppm/%(v/v)
Distillate	86.20	13.60	0.17	0.03	71.8333	136	0.0531	0.00074	7.39559
Residual	86.10	10.90	2.70	0.30	71.7500	109	0.8438	0.01176	117.5958
Distillate	85.05	13.42	1.50	0.03	70.8750	134.2	0.4688	0.006614	66.1376
Residual	87.17	11.03	1.50	0.30	72.6417	110.3	0.4688	0.006453	64.5291

* Based on properties in the IMO NO_x Monitoring Guidelines, resolution MEPC.103(49).

Table 2: Emissions calculations corresponding to 1.5 % fuel sulphur

	CO_2	SO_2	Exh SO_2/CO_2	Exh S/C
	%	[1]ppm	[1]ppm/%	m/m
Distillate 0.17% S	8	59.1	7.4	0.00197
Residual 2.70% S	8	939.7	117.5	0.03136
Distillate 1.5% S	8	528.5	**66.1**	**0.01764**
Residual 1.5% S	8	515.7	**64.5**	**0.01721**
Distillate 1.5% S	0.5	33.0	**66.1**	**0.01764**
Residual 1.5% S	0.5	32.2	**64.5**	**0.01721**

SO_2/CO_2 ratio vs % sulphur in fuel



4 Correspondence between 65 ([1]ppm/%) SO_2/CO_2 and 6.0 g/kWh is demonstrated by showing that their S/C ratios are similar. This requires the additional assumption of a brake-specified fuel consumption value of 200 g/kWh. This is an appropriate average for marine diesel engines. The calculation is as follows:

Note 1: The S/C mass ratios calculated above, based on 6.0 g/kWh and 200 g/kWh BSFC, are both within 0.10% of the S/C mass ratios in the emissions table (Table 2). Therefore, 65[1] (ppm/%) SO_2/CO_2 corresponds well to 6.0 g/kWh.

Note 2: The value of 6.0 g/kWh, hence the 200g/kWh brake-specified fuel consumption is taken from MARPOL Annex VI as adopted by the 1997 MARPOL Conference.

$$S/C_{fuel} = \frac{\text{brake-specific } SO_2 * \left(MW_S / MW_{SO2} \right)}{BSFC * \left(\%\text{ carbon in fuel} / 100 \right)}$$

brake-specific SO_2 = 6.0 g/kW-hr

MW_S = 32.065 g/mol

MW_{SO2} = 64.064 g/mol

BSFC = 200 g/kW-hr

% carbon in 1.5% S fuel (from Table 1) = 85.05% (distillate) & 87.17% residual

$$\underline{S/C_{residual\ fuel}} = \frac{6.0 * \left(32.065/64.064\right)}{200 * \left(87.17\%/100\right)}$$

$$\underline{S/C_{residual\ fuel}} = 0.01723$$

$$\underline{S/C_{distillate\ fuel}} = \frac{6.0 * \left(32.065/64.064\right)}{200 * \left(85.05\%/100\right)}$$

$$\underline{S/C_{distillate\ fuel}} = 0.01765$$

5 Thus, the working formulas are as follows:

For complete combustion = $\dfrac{SO_2\ (ppm^*)}{CO_2\ (\%^*)} \le 65$

For incomplete combustion = $\dfrac{SO_2\ (ppm^*)}{CO_2(\%^*) + (CO\ (ppm^*)/10000) + (THC\ (ppm^*)/10000)} \le 65$

* Note: gas concentrations must be sampled or converted to the same residual water content (e.g., fully wet, fully dry).

6 The following is the basis of using the ([2]ppm/%) SO_2/CO_2 as the limit for determining compliance with regulation 14.1 or 14.4:

(a) This limit can be used to determine compliance from fuel oil burners that do not produce mechanical power.

(b) This limit can be used to determine compliance at any power output, including idle.

(c) This limit only requires two gas concentration measurements at one sampling location.

(d) There is no need to measure any engine parameters such as engine speed, engine torque, engine exhaust flow, or engine fuel flow.

(e) If both gas concentration measurements are made at the same residual water content in the sample (e.g., fully wet, fully dry), no dry-to-wet conversion factors are required in the calculation.

(f) This limit completely decouples the thermal efficiency of the fuel oil combustion unit from the EGC unit.

(g) No fuel properties need to be known.

(h) Because only two measurements are made at a single location, transient engine or EGCS unit effects can be minimized by aligning signals from just these two analysers. (Note that the most appropriate points to align are the points where each analyser responds to a step change in emissions at the sample probe by 50% of the steady-state value.)

(i) This limit is independent of the amount of exhaust gas dilution. Dilution may occur due to evaporation of water in an EGC unit, and as part of an exhaust sampler's preconditioning system.

[2] ppm means "parts per million". It is assumed that ppm is measured by gas analysers on a molar basis, assuming ideal gas behaviour. The technically correct units are actually micro-moles of substance per mole of total amount (µmol/mol), but ppm is used in order to be consistent with units in the NO_x Technical Code.

APPENDIX III

WASHWATER DATA COLLECTION

Background

The washwater discharge criteria are intended to act as initial guidance for implementing EGC system designs. The criteria should be revised in the future as more data becomes available on the contents of the discharge and its effects, taking into account any advice given by GESAMP.

Administrations should therefore provide for collection of relevant data. To this end, shipowners in conjunction with the EGC manufacturer are requested to sample and analyse samples of:

- inlet water (for background);
- water after the scrubber (but before any treatment system); and
- discharge water.

This sampling could be made during approval testing or shortly after commissioning and at about twelve-month intervals for a period of two years of operation (minimum of three samples). Sampling guidance and analysis should be undertaken by laboratories using EPA or ISO test procedures for the following parameters:

- pH
- PAH and oil (detailed GC-MS analysis)
- Nitrate
- Nitrite
- Cd
- Cu
- Ni
- Pb
- Zn
- As
- Cr
- V

The extent of laboratory testing may be varied or enhanced in the light of developing knowledge.

When submitting sample data to the Administration, information should also be included on washwater discharge flow rates, dilution of discharge, if applicable, and engine power should be included as well as specifications of the fuel used from the bunker delivery note as a minimum.

It is recommended that the ship that has provided this information to the satisfaction of the Administration should be granted a waiver for compliance of the existing installation(s) to possible future stricter washwater discharge standards. The Administration should forward information submitted on this issue to the Organization for dissemination by the appropriate mechanisms.

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APPENDIX 3 Emission Control Area Geographic Definitions

A3.1 MARPOL Annex VI Regulation 14 – Sulphur Oxides (SOx) and Particulate Matter* – Emission Control Areas Geographic Definitions

Full details of regulation 14 are contained in 'Revised MARPOL Annex VI [18] – Regulations for the prevention of air pollution from ships and NOx Technical Code 2008 – 2009 Edition'. This publication is available from IMO (www.imo.org) both in hard copy and electronically.

A3.1.1 Baltic Sea

The Baltic Sea ECA is defined in regulation 1.11.2 of MARPOL Annex I:

- The Baltic Sea proper with the Gulf of Bothnia, Gulf of Finland and the entrance to the Baltic Sea bounded by the parallel of the Skaw in the Skagerrak at 57°44.8′ N

A3.1.2 North Sea

The North Sea ECA is defined in regulation 5(a)(f) of MARPOL Annex V:

- The North Sea proper including seas therein with the boundary between:

i. The North Sea southwards of latitude 62° N and eastwards of longitude 4° W;

ii. The Skagerrak, the southern limit of which is determined east of the Skaw by latitude 57°44.8′ N; and

iii. The English Channel and its approaches eastwards of longitude 5° W and northwards of latitude 48°30′ N

A3.1.3 North America

The North American ECA is described by the coordinates provided in Appendix VII to MARPOL Annex VI and comprises:

- The sea area located off the Pacific coasts of the United States and Canada,
- Sea areas located off the Atlantic coasts of the United States, Canada, and France (Saint-Pierre-et-Miquelon) and the Gulf of Mexico coast of the United States
- The sea area located off the coasts of the Hawaiian Islands of Hawai'i, Maui, Oahu, Moloka'i, Ni'ihau, Kaua'i, Lāna'i, and Kaho'olawe

These areas are defined by geodesic lines, which connect an extensive list of coordinates given in IMO Resolution MEPC 190(60). This is contained in Annex 11 of the final report of MEPC 60 [10]. The coordinates, that are also included as a new appendix VII of MARPOL Annex VI, have not been repeated here, as they total some 6 pages.

A3.1.4 U.S. Caribbean

The United States Caribbean ECA is described by the coordinates provided in Appendix VII to MARPOL Annex VI and comprises:

- The sea area located off the Atlantic and Caribbean coasts of the Commonwealth of Puerto Rico and the United States Virgin Islands.

Again these areas are defined by geodesic lines, which connect an extensive list of coordinates. These are not repeated here but can be found in IMO document MEPC 62/6/2

A3.1.5 New areas

Regulation 14 contains a catchall paragraph that SOx emission controls will apply to any other ECA, including any port area, designated by IMO in accordance with the criteria and procedures in Appendix III to MARPOL Annex VI.

A3.1.6 NOx Emission Control Areas

*Note: Tier III NOx emission standards will also apply to engines installed on ships constructed on or after 1 January 2016, which are operating in ECAs designated as NOx emission control areas – see Appendix 4.

APPENDIX 4 NOx Emission Limits and Schedule for Reduction

A4.1 MARPOL Annex VI Regulation 13– Nitrogen Oxides (NOx)

The following is an abridged extract from MARPOL Annex VI, Chapter III Requirements for control of emissions from ships– Regulation 13 Nitrogen Oxides (NOx). The NOx emission limits and timetable for reduction are shown below, however it should be noted these are subject to certain exceptions and exemptions. In general the standards apply to diesel engines that are installed on ships that have a power output of more than 130 kW, however for full details reference should be made to ' Revised MARPOL Annex VI [18] – Regulations for the prevention of air pollution from ships and NOx Technical Code 2008 – 2009 Edition'. This publication is available from IMO (www.imo.org) both in hard copy and electronically.

A4.1.1 Tier I

...the operation of a marine diesel engine which is installed on a ship constructed on or after 1 January 2000 and prior to 1 January 2011 is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of NO_2) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute):

1. 17.0 g/kW h when n is less than 130 rpm;
2. $45.n^{(-0.2)}$g/kW h when n is 130 or more but less than 2,000 rpm;
3. 9.8 g/kW h when n is 2,000 rpm or more.

Tier I also applies to engines of greater than 5000kW and ≥ 90litres/cylinder that are installed on ships constructed between 1 January 1990 and 1 January 2000 where an approved method of NOx control is available. Tier 1 also applies to engines that are installed on ships build before 1 January 2000 and that have had a major conversion after this date.

A4.1.2 Tier II

... the operation of a marine diesel engine which is installed on a ship constructed on or after 1 January 2011 is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of NO_2) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute):

1. 14.4 g/kW h when n is less than 130 rpm;
2. $44.n^{(-0.23)}$g/kW h when n is 130 or more but less than 2,000 rpm;
3. 7.7 g/kW h when n is 2,000 rpm or more.

A4.1.3 Tier III

... the operation of a marine diesel engine which is installed on a ship constructed on or after 1 January 2016 is prohibited except when the emission of nitrogen oxides (calculated as the total weighted emission of NO_2) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute):

1. 3.4 g/kW h when n is less than 130 rpm;
2. $9.n^{(-0.2)}$g/kW h when n is 130 or more but less than 2,000 rpm; and
3. 2.0 g/kW h when n is 2,000 rpm or more;

Tier III will only apply in ECAs where proposals for additional limits on NOx have been accepted i.e. the North American and US Caribbean ECAs. To date there have been no submissions to IMO for further controls in the Baltic and North Sea.

Outside of NOx ECAs Tier II limits will continue to apply.

The implementation date for Tier III is subject of an IMO review commencing 2012 and ending 2013, which will the consider the status of technological developments that will enable the standard to be met.

APPENDIX 5 USCG Marine Safety Alert

A5.1 Fuel Switching Safety

The following text is an extract from Marine Safety Alert 11 – 01, issued by U.S. Coast Guard District Eleven, July 11, 2011. The full text and any subsequent updates should be obtained from California's Air Resources Board and/or the U.S. Coast Guard.

- http://www.arb.ca.gov/ports/marinevess/ogv.htm
- http://www.uscg.mil/

"The purpose of this Marine Safety Alert is to increase awareness and reiterate general guidance on fuel systems and fuel switching safety in an effort to prevent propulsion losses. After a noted decrease, there has been a recent increase in the number of reported loss of propulsion incidents on deep draft vessels within the Eleventh Coast Guard District. Coast Guard studies and review of marine casualties indicate that lack of maintenance and testing of certain systems, including fuel oil systems, is one of the leading causes of propulsion failures. Advanced planning and careful fuel system management are critical to safely switching fuels. This is especially important if fuel switching is not routine practice. Proper procedures, training, and maintenance are essential for vessels to safely switch between heavy/ intermediate fuel oils and marine distillates. Additionally, vessel operators need to have a good understanding of their system requirements and limitations, and determine if any modifications may be necessary to safely switch between intended fuels.

Managing Risk

Extensive analysis of propulsion losses has revealed certain trends among vessels operating on marine distillates. In order to manage risk and improve safety, vessel owners and operators should:

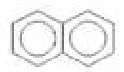
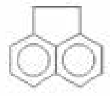
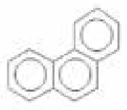
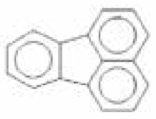
- Consult engine and boiler manufacturers for fuel switching guidance;
- Consult manufacturers to determine if system modifications or additional safeguards are necessary for intended fuels;
- Develop detailed fuel switching procedures;
- Establish a fuel system inspection and maintenance schedule;
- Ensure system pressure and temperature alarms, flow indicators, filter differential pressure transmitters, etc., are all operational;
- Ensure system seals, gaskets, flanges, fittings, brackets and supports are maintained and in serviceable condition;
- Ensure a detailed system diagram is available;
- Conduct initial and periodic crew training;
- Exercise tight control when possible over the quality of the fuel oils received;
- Complete fuel switching well offshore prior to entering restricted waters or traffic lanes; and
- Test main propulsion machinery, ahead and astern, while on marine distillates.

Additionally, the following guidance may assist vessel owners and operators in preventing propulsion losses when operating on marine distillates:

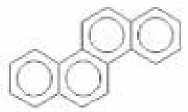
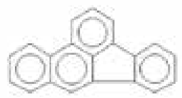
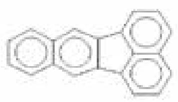
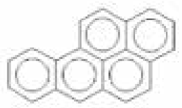
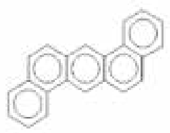
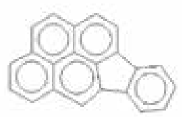
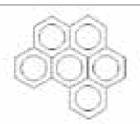
- Monitor for accelerated wear of engine/fuel system components and evaluate maintenance period intervals;
- Ensure fuel viscosity does not drop below engine manufacturer's specifications;
- Ensure proper heat management of fuel systems to maintain minimum viscosity values;
- Make appropriate fuel rack adjustments to account for potential fuel pressure differentials between residual fuel oils and marine distillates;
- Determine speed limitations for stopping the engine ahead and ordering an astern bell to ensure timely engine response; and
- Ensure start air supply is sufficient and fully charged prior to manoeuvring.

This safety alert is provided for informational purposes only and does not relieve any domestic or international safety, operational or material requirement."

APPENDIX 6 U.S. EPA 16 Priority Pollutants

U.S. EPA 16 PRIORITY POLLUTANTS	NAME AND SYNONYMS	FORMULA	CAS RN*	MOLECULAR WEIGHT [g/mol]	BOILING POINT [°C] [i]	MELTING POINT [°C] [i]	VAPOUR PRESSURE [Pa] [ii]	WATER SOLUBILITY [mg/l] [iii]
	Naphthalene	$C_{10}H_8$	91-20-3	128.17	217.0	80.2	10.9[iv]	31
	Acenaphthylene cyclopenta[d,e]naphthalene acenaphthalene	$C_{12}H_8$	208-96-8	152.19	280.2	89.6 - 93.4	9.0×10^{-1}	16
	Acenaphthene 1,2-dihydroacenaphthylene 1,8-dihydroacenapthalene 1,8-ethylenenapthalene	$C_{12}H_{10}$	83-32-9	154.21	279.2	94	3.0×10^{-1}	3.8
	Fluorene ortho-biphenylene methane diphenylenemethane 2,2-methylene biphenyl 2.3-benzidene	$C_{13}H_{10}$	86-73-7	166.22	294.2 - 298.2	115	9.0×10^{-2}	1.9
	Anthracene anthracin green oil	$C_{14}H_{10}$	120-12-7	178.23	340	217	1.0×10^{-3}	0.045
	Phenanthrene phenantrin	$C_{14}H_{10}$	85-01-8	178.23	328.15 - 340.15	99	2.0×10^{-2}	1.1
	Fluoranthene 1.2 – [1,8-Naphthylene] – benzene 1.2 – benzacenaphthene 1.2 – [1.8- naphthalenediyl]benzene benzo[j,k]fluorene	$C_{16}H_{10}$	206-44-0	202.25	375[ii]	108 - 113	1.2×10^{-3}	0.26

With some exceptions:
Increasing molecular weight = Decreasing water solubility = Decreasing volatility. Naphthalene is the most volatile Benzo(a)pyrene is the most toxic [v]

U.S. EPA 16 PRIORITY POLLUTANTS	NAME AND SYNONYMS	FORMULA	CAS RN*	MOLECULAR WEIGHT [g/mol]	BOILING POINT [°C] [i]	MELTING POINT [°C] [i]	VAPOUR PRESSURE [Pa] [ii]	WATER SOLUBILITY [mg/l] [iii]
	Pyrene benzo[d,e,f]phenanthrene beta-pyrene	$C_{16}H_{10}$	129-00-0	202.25	393[ii]	151	$6.0x10^{-4}$	0.13
	Benzo[*a*]anthracene BA;benz[a]anthracene 1,2-benzanthracene benzo[b]phenanthrene 2,3-phenanthrene 2,3-benzophenanthrene tetraphene	$C_{18}H_{12}$	56-55-3	228.29	437.8	159	$2.8x10^{-5}$	0.011
	Chrysene 1.2-benzophenanthrene benzo[a]-phenanthrene 1,2benzphenanthrene benz[a]phenanthrene 1,2,5,6-dibenzonaphthalene	$C_{18}H_{12}$	218-01-9	228.29	448.2	254.35 - 258.4	$5.7x10^{-7}$	0.006
	Benzo[*b*]fluoranthene 3,4-Benz[e]acephenanthrylene 2,3-benzfluoranthene 3,4-benzfluoranthene 2,3benzofluoranthene 3,4-benzofluoranthene benzo[e]fluoranthene	$C_{20}H_{12}$	205-99-2	252.31	481[ii]	168.3[ii]	$6.7x10^{-5}$	0.0015
	Benzo[*k*]fluoranthene 8.9-benzfluoranthene 8.9-benzofluoranthene 11.12benzofluoranthene 2,3,1.8-binaphthylene dibenzo[b,j,k]fluorine	$C_{20}H_{12}$	207-08-9	252.31	480	217	$5.2x10^{-8}$	0.0008
	Benzo[*a*]pyrene benzo[d,e,f]chrysene 3-4 benzopyrene 3,4-benzpyrene benz[a]pyrene;BP	$C_{20}H_{12}$	50-32-8	252.31	495.2	177	$7.0x10^{-7}$	0.0038
	Dibenz[*a,h*]anthracene DB[a,h]A DBA 1,2:5,6 dibenz[a]anthracene	$C_{22}H_{14}$	53-70-3	278.35	524.2	260.15 - 271.2	$3.7x10^{-10}$ [iv]	0.0006
	Indeno (1,2,3,c,d) pyrene indenopyrene IP;orthophenylenepyrene 1,10-ortho-phenylene]pyrene 1,10-[1,2-phenylene]pyrene 2,3-ortho-phenylenepyrene	$C_{22}H_{12}$	193-39-5	276.33	536[ii]	162 -164.7	$1.3x10^{-8}$	0.00019
	Benzo[*ghi*]perylene 1,12-benzoperylene	$C_{22}H_{12}$	191-24-2	276.33	542[iv]	280 - 281.2	$6x10^{-8}$ [iv]	0.00026

*Chemical Abstracts Service Registry Number – unique identifier for chemical compounds

i. NIST Chemistry Web Book, http://webbook.nist.gov/chemistry

ii. Ambient Air Pollution by Polycyclic Aromatic Hydrocarbons (PAH) Position Paper Annexes, July 27th 2001, Prepared by the European Commission Working Group On Polycyclic Aromatic Hydrocarbons

iii. Staffan Lundstedt; 2003, Analysis of PAHs and their transformation products in contaminated soil and remedial processes -

iv. http://umu.diva-portal.org/smash/record.jsf?pid=diva2:143820

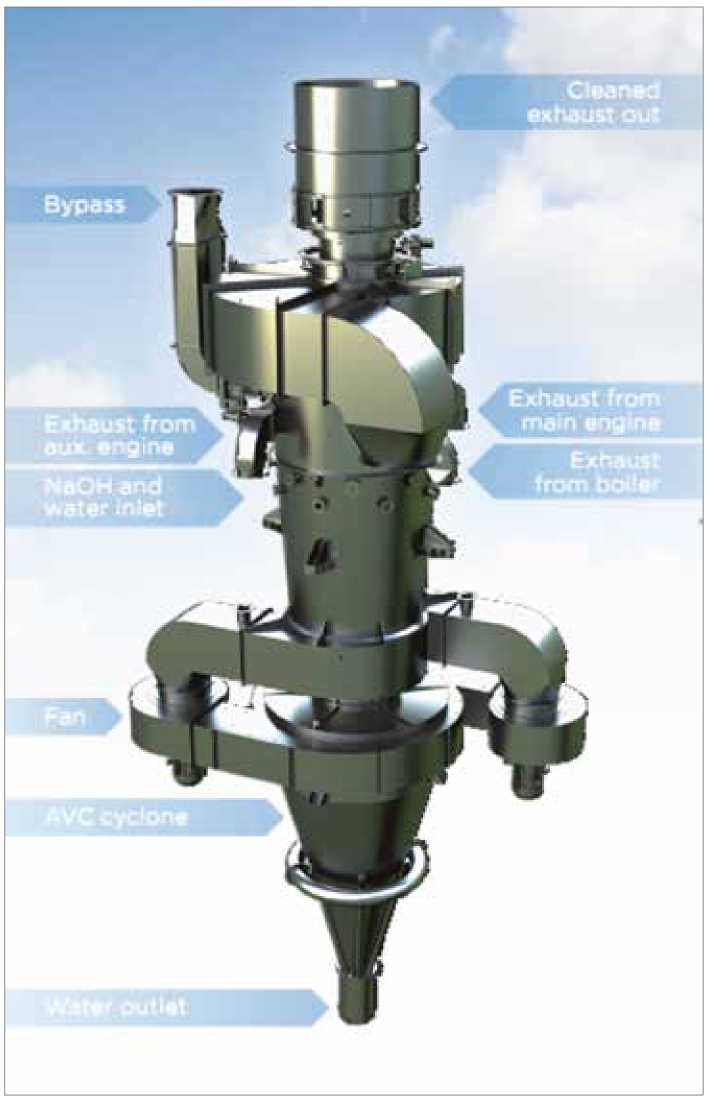
v. http://chrom.tutms.tut.ac.jp/JINNO/DATABASE/00alphabet.html

vi. http://msds.chem.ox.ac.uk/BE/benzo%28a%29pyrene.html

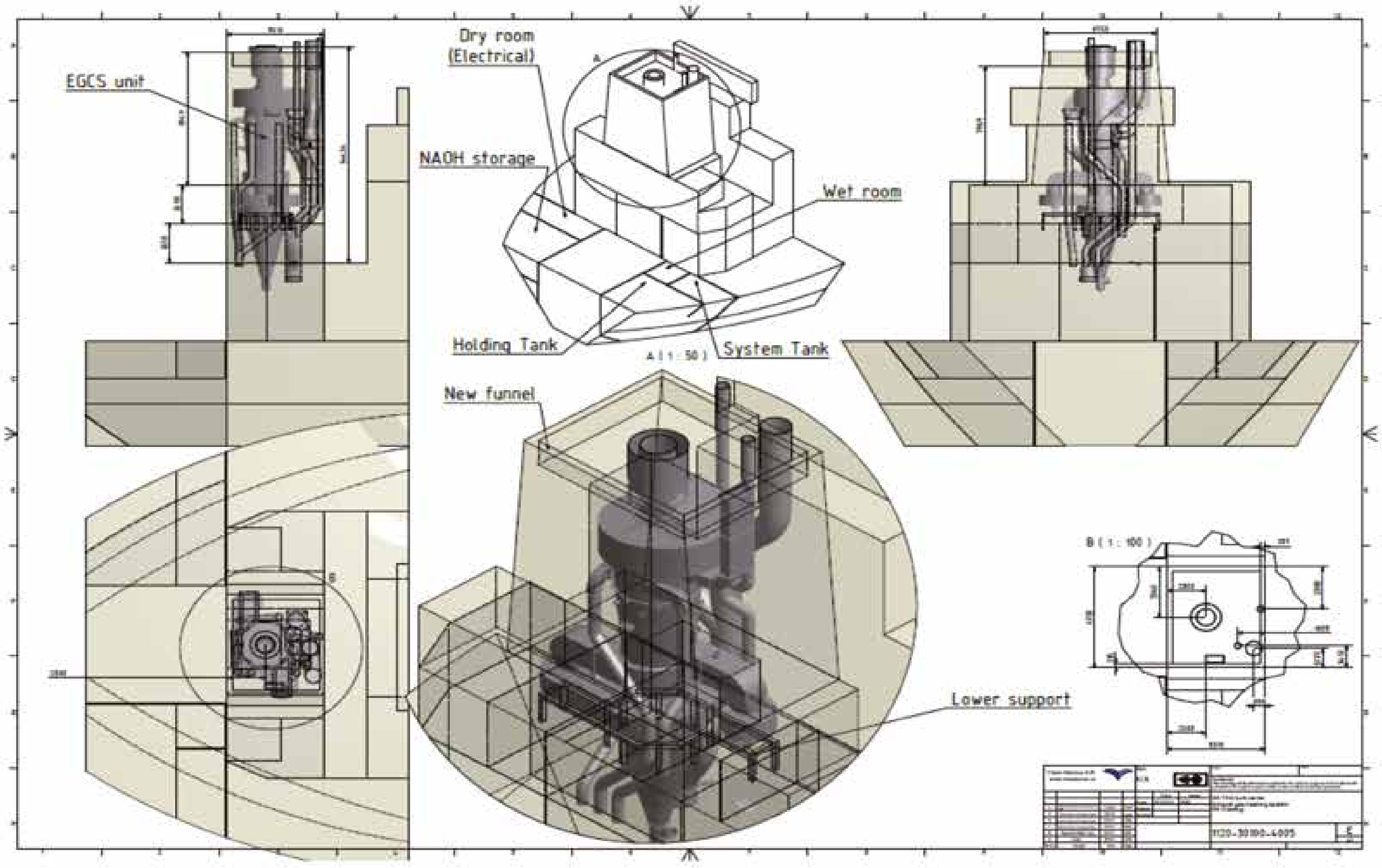
APPENDIX 7 Installation of a Multi-Stream, Hybrid EGCS - M.V. Balder

- Self-discharging Bulk Carrier, 48,184 DWT
- Main Engine: MAN B&W Diesel A/S 6S50MC-C
- Auxiliary Engines: Daihatsu Diesel Mfg. Co., Ltd. 8DK-20 x 3
- Boiler: Aalborg Industries A/S GCS-21ST

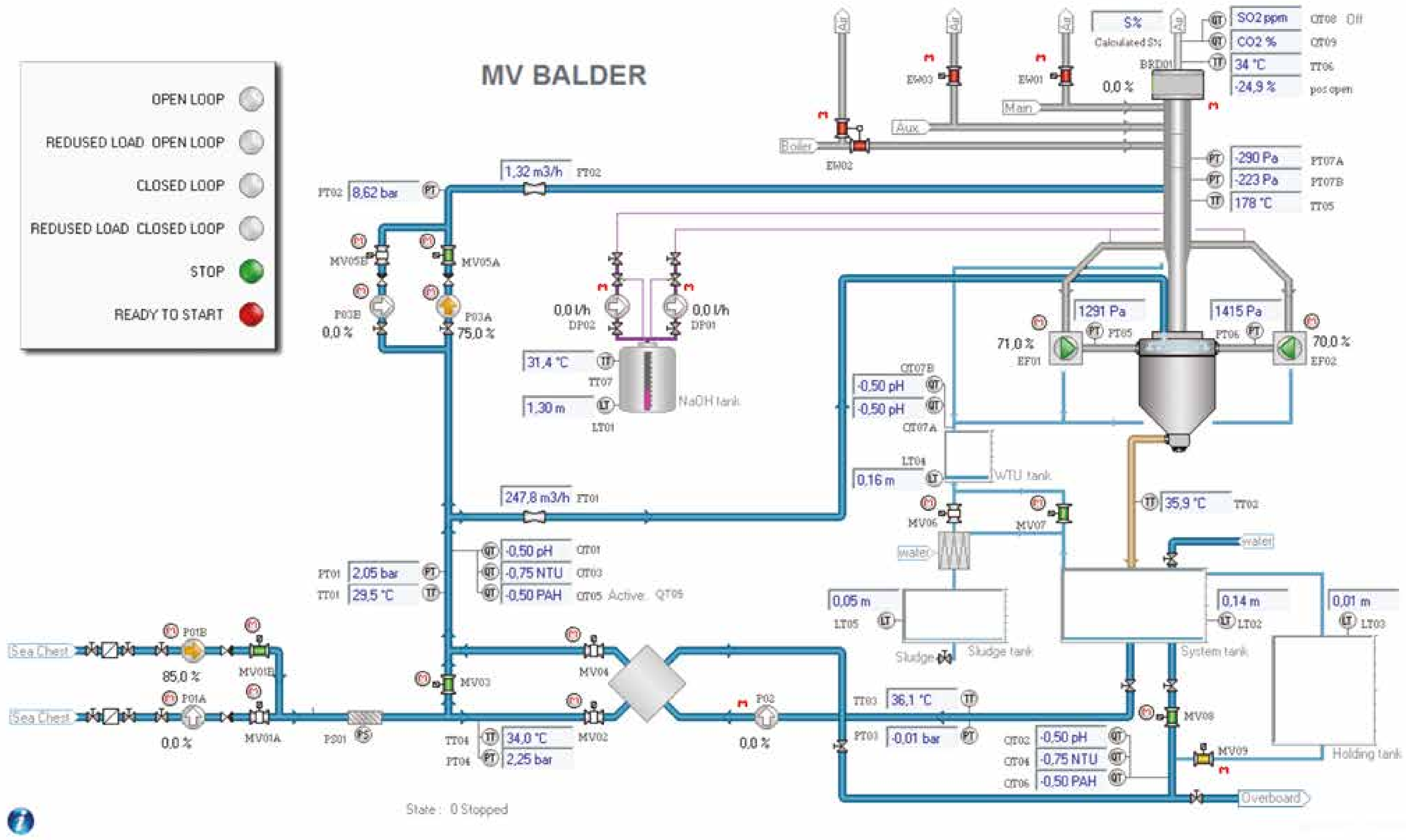
Clean Marine Mk III EGCS



Installation May/June 2012 (EGCS for total combustion unit power of 10MW)



M.V. Balder EGCS process diagram



EGCS components ready for shipment

Removal old funnel, cleaning out upper engine room casing, erection and installation of Advance Vortex Chamber (AVC), installation of fans

New fan housing and lower part of funnel, installation of outer pipe, installation of inner pipe, installation of upper part and bypass lines

Installation of funnel top

Water inlet and water supply pumps, preinjection pumps, circulation pump, overboard connection, NaOH dosage pump, NaOH filling manifold

Switchboards and frequency drives, gas monitoring – probe, dryer, monitor

Various exhaust – actuators for bypass, insulation work new piping,
top of funnel (outlet EGCS)

M.V. Balder leaving Croatia after EGCS installation inside new funnel

Delivery and commissioning timeline

TASKS / PHASES	DELIVERABLES	WEEKS
Concept study	Layout – conceptual Equipment specification – preliminary Installation requirements – general Budget	4
Contract 1	Letter of intent	1
Detailed study	Layout verification – ship inspection Installation specification Equipment specification – BOM and P&ID Yard quotes Equipment quotes	4 – 6
Contract 2	Purchase and installation	1
Preplanning	Equipment ordering and logistics Plan drafting and approval Installation scope – prefabrication	12 – 14
Installation	Equipment ready installed and approved Final documentation	4 – 6
Commissioning	Successful tests during voyage	1
	SUM TIME	27 – 33

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GLOSSARY OF TERMS, FORMULAE & ABBREVIATIONS

μg/l	Micro (10^{-6}) grams per litre
μm	Micro (10^{-6}) meter
μmol/l	Micro (10^{-6}) moles per litre
% m/m	Percentage by mass e.g. the percentage mass of fuel that is sulphur
% v/v	Percentage by volume e.g. the percentage volume of exhaust gas that is CO_2
% w/v	Weight/volume percentage e.g. a 50% w/v concentration is 50g of solute in 100ml of final aqueous solution
ABS	American Bureau of Shipping; a Classification Society – see http://www.eagle.org/
Absorbed/absorption	(In the case of light) the process of retention without reflection or transmission on passing through a medium
Adiabatic	A thermodynamic process in which there is no heat transfer into or out of the system.
Adsorbed/adsorption	To be attracted and held or bonded to a surface
Albedo	The fraction of solar energy (short-wave radiation) reflected from the Earth back into space
Algae	A diverse group of plant like organisms ranging from microscopic single cells to large seaweeds
Alkalinity	The capacity of solutes in an aqueous system to neutralize acid; also known as buffering capacity
Am^3/h	Actual cubic metres per hour; the volumetric flow rate at the stated process temperature and pressure
Ammonia	A compound of nitrogen and hydrogen with the formula NH_3
Ammonium	An ionic compound derived from ammonia with the chemical formula NH^{4+}
AQMD	South Coast Air Quality Management District (California) – see http://www.aqmd.gov/
ARB	Air Resources Board – see CARB
AVC	Advanced Vortex Chamber – acronym used to describe part of the Clean Marine cyclonic exhaust gas cleaning unit
bar	A unit of pressure approximately equal to the atmospheric pressure on Earth at sea level; 100 kilopascals
bar absolute	The sum of gauge pressure and atmospheric (barometric) pressure in bar
BAT	Best Available Technique or Technology
Biofuel	Gaseous or liquid fuels derived from biological sources including materials produced by plants, animals or micro-organisms
Biomass	The total mass of living matter in a given unit area
Bioassay	Determination of the strength or biological activity of a substance
BOM	Bill of Materials – a numbered list of parts and components needed to build a product
Borates	An ionic compound of boron and oxygen
Buffering capacity	The capacity of solutes in an aqueous system to neutralize acid; also known as alkalinity
BV	Bureau Veritas; a Classification Society – see http://www.bureauveritas.com
C	The chemical symbol for carbon
Ca	The chemical symbol for calcium
$Ca(OH)_2$	The chemical formula for calcium hydroxide
Calcite	A term for calcium carbonate, a constituent of sedimentary rock such as limestone
CARB	California Air Resources Board – see http://www.arb.ca.gov/
CAS RN	Chemical Abstracts Service Registry Number; unique identifiers for chemical compounds
Catalyst	A substance that initiates or accelerates a chemical reaction without itself being consumed in the process
Caustic soda	The common name for sodium hydroxide; NaOH
CEMS	Continuous Emissions Monitoring System
Certified Value	The SO_2/CO_2 ratio specified by the manufacturer that the EGC unit is certified as meeting when operating on a continuous basis on the manufacturers specified maximum fuel sulphur content
CO	The chemical formula for carbon monoxide
CO_2	The chemical formula for carbon dioxide
Coagulant	A chemical compound added to water to enable suspended particles to be gathered together for filtration
COD	Chemical Oxygen Demand; a measure of the oxygen required to oxidize all compounds, both organic and inorganic, in water.
Colloid	A type of mixture in which one substance is dispersed evenly throughout another
Compression ratio	For the purposes of this publication the ratio of compression pressure to scavenge air pressure in a 2-stroke slow speed engine cylinder
CORMIX	A U.S. EPA-supported mixing zone model and decision support system for environmental impact assessment of continuous point source discharges – see http://www.cormix.info/
DIN	Deutsches Institut für Normung e.V; the German Institute for Standardization – see http://din.de
DNV	Det Norske Veritas; a Classification Society – see http://www.dnv.com/
DWE	Direct Water Injection; a NOx control technique - water is injected into the engine cylinder to lower local combustion temperatures
EC	European Commission; the EC proposes EU legislation and checks it is properly applied across the EU – see http://ec.europa.eu/index_en.htm
ECA	Emission Control Area
EGC	Exhaust Gas Cleaning
EGC Record Book	A record of the EGC unit in-service operating parameters, component adjustments, maintenance and service records as appropriate
EGCS	Exhaust Gas Cleaning System
EGCSA	Exhaust Gas Cleaning Systems Association – see http://www.egcsa.com/
EGR	Exhaust gas recirculation; a NOx control technique
EMAS	Eco-Management and Audit Scheme, a voluntary European Union initiative designed to improve companies' environmental performance
EPA	(U.S.) Environmental Protection Agency – see http://www.epa.gov/
EPA-PAHs	Those Polycyclic Aromatic Hydrocarbons defined by the U.S. EPA as priority pollutants
ETM-A	EGC system – Technical Manual for Scheme A
ETM-B	EGC system – Technical Manual for Scheme B
EU	European Union; an economic and political union of 27 member states – see http://europa.eu/index_en.htm
Eutrophication	A process by which an excess of nutrients (e.g. nitrogen and phosphorus) cause excessive growth of plants and algae (blooms) resulting in reduced visibility of the water and decreased oxygen supply
Exothermic	A process that releases energy most usually in the form of heat
FGD	Flue Gas Desulphurisation
Flocculant	A chemical compound added to water to combine suspended particles together for filtration
Fluorescence	The emission of electromagnetic radiation/light by a substance that has absorbed radiation of a different wavelength

Free radical	An atom that has at least one unpaired electron in an orbital and is therefore highly reactive (unlike an ion there is no overall electrical charge as protons & electrons are equal in number)
Fuel oil combustion unit	Any engine, boiler, gas turbine, or other fuel oil fired equipment, excluding shipboard incinerators
FTIR	Fourier transform infrared spectroscopy; a technique used to measure the concentration of gaseous emissions
FWE	Fuel Water Emulsion, a NOx control technique, which lowers local combustion temperatures
g/kW h	Grams per kilowatt hour
g/l	Grams per litre
g/mol	Grams per mole; the molecular weight or molar mass of a substance
Geodesic	The shortest line between two points on a mathematically defined surface
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection – see http://www.gesamp.org
GL	Germanischer Lloyd; a Classification Society – see http://www.gl-group.com/
GW	Gigawatt; 1×10^9 watts
H	The chemical symbol for hydrogen
HAM	Humid Air Motor; a NOx control technique for 4 stroke engines – water is sprayed into the engine's charge air to reduce oxygen content and increase heat capacity.
HC	Hydrocarbon emissions (in a gaseous state at 190°C), primarily derived from the incomplete combustion of fuel
HCO_3^-	The chemical formula for bicarbonate
HFO	Heavy fuel oil; a generic term for residual fuel. Typically HFO has a high sulphur content and is not suitable for use in an ECA (also see LSFO).
HMI	Human Machine Interface; typically PC based interactive graphics representing a process system - enables monitoring and control.
H_2SO_4	The chemical formula for sulphuric acid
Hydrated lime	A common name for calcium hydroxide; $Ca(OH)_2$, also known as slaked lime
Hydronium (H_3O^+)	Hydronium; – a water molecule with an extra hydrogen ion. Acids are compounds that yield hydrogen ions (H^+) or hydronium ions (H_3O^+) when dissolved in water.
IAPP	International Air Pollution Prevention certificate
IBC	Intermediate Bulk Container; container for transport and storage of fluids and bulk materials – often seen as a1000 litre plastic cube in a metal cage.
IMarEST	The Institute of Marine Engineering, Science & Technology – see http://www.imarest.org/
IMO	International Maritime Organization – see http://www.imo.org/
Ion	An atom or molecule or group that has lost or gained one or more electrons and so is electrically charged (positive or negative)
Ionisation	The process of being dissociated into ions
ISO	International Organization for Standardization – see http://www.iso.org/
LR	Lloyd's Register; a Classification Society - see http://www.lr.org/
LSFO	Low Sulphur Fuel Oil; typically a residual fuel with a sulphur content suitable for use in an ECA until 2015
Luminescence	The emission of electromagnetic radiation, including visible light after an atom, ion or molecule becomes elevated to an excited electronic state; sometimes referred to as cold light. Chemiluminesence is exhibited as a result of chemical reaction without heat

Lye	The common name (U.S.) for sodium hydroxide; NaOH – see also caustic soda.
MARPOL	The International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78)
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee; e.g. MEPC 60 was the sixtieth session of this IMO group and MEPC Resolution 184(59) was adopted at the fifty-ninth session
m^3/MW h	Cubic meters per megawatt hour
mg/l	Milligrams per litre
MGO	Marine Gas Oil
micron	1×10^{-6}m; one thousandth of a millimetre/one millionth of a meter
MSDS	Material Safety Datasheet
Mt	1 million tonnes; 1×10^6 tonnes
N	The chemical symbol for nitrogen
Na	The chemical symbol for sodium
NaOH	Sodium hydroxide, also commonly known as caustic soda
NDIR	Non-dispersive infrared sensor; a spectroscopic device used to measure the concentration of gaseous emissions, for example NOx and CO_2 from an engine
NDUV	Non-dispersive ultraviolet sensor; a spectroscopic device used to measure the concentration of gaseous emissions, for example SO_2 from an engine
nm	Nano (10^{-9}) meter
Nm^3/h	Normal cubic metres per hour; the volumetric flow rate of a gas normalised to a standard temperature and pressure
Nitrate	An ionic compound of nitrogen and oxygen; NO_3^-
NO	The chemical formula for nitric oxide
NO_2	The chemical formula for nitrogen dioxide
NOx	The generic term for nitrogen oxides
Non-thermal plasma	Plasma that occurs at room temperature when molecules are exposed to a strong electrical field (rather than extremely high temperature)
O	The chemical symbol for oxygen
O_3	Ozone
OMM	Onboard Monitoring Manual
P	The chemical symbol for phosphorus
Pa	Pascal; the SI unit of pressure
PAH	Polycyclic Aromatic Hydrocarbon
P&ID	Piping and instrumentation drawing – shows components and flow of a process system
pH	A measure of the acidity or basicity of a solution
Phenanthrene	A polycyclic aromatic hydrocarbon and one of the U.S. EPA 16 priority pollutants; $C_{14}H_{10}$
Phosphate	An ionic compound of phosphorus and oxygen
Photosynthesis	A process that converts carbon dioxide into organic (carbon based) compounds, especially sugars, using the energy from sunlight
Phytoplankton	Microscopic organisms in the upper layers of the ocean that form the basis of the marine food chain
Plasma	A distinct phase of matter, separate from solids, liquids, and gases; a collection of charged particles (free radicals) resulting from exposure to extremely high temperatures
PM	Particulate Matter
ppm	Parts per million
PREN	Pitting Resistance Equivalent number; indicates the ability of a stainless steel to resist pitting corrosion
PSC	Port State Control
QCL	Quantum Cascade Laser; a technology used to measure the concentration of gaseous emissions
RINA	RINA; a Classification Society (created by Registro Italiano Navale) – see http://www.rina.org/
rpm	Revolutions per minute

S	The chemical symbol for sulphur
Salinity	A measure of the concentration of all the salts and ionic compounds in water
SAM	Scavenge Air Moistening; a NOX control technique for 2-stroke engines – water is sprayed into the engine's scavenge air to reduce oxygen content and increase heat capacity.
Scavenge air	The charge of air used to purge cylinders of exhaust gas and provide air for combustion in a diesel engine; normally used in relation to 2-stroke slow speed crosshead engines
SCFM	Standard cubic feet per minute; the volumetric flow rate of a gas corrected to "standardised" conditions of temperature, pressure and relative humidity.
SCR	Selective Catalytic Reduction
SECA	SOx Emission Control Area (now superseded by ECA)
SECC	SOx Emissions Compliance Certificate
SECP	SOx Emissions Compliance Plan
SI	Systeme International d'Unites: a complete metric system of standard units of measurement
Slaked lime	A common name for calcium hydroxide; $Ca(OH)_2$, also known as hydrated lime
SO_2	The chemical formula for sulphur dioxide
SO_3	The chemical formula for sulphur trioxide
SO_4^{2-}	The chemical formula for sulphate
Solute	A substance that dissolves in another (the solvent), to form a solution.
SOx	The generic term for sulphur oxides
Spectroscopy	The study of the way in which atoms absorb and emit light/electromagnetic radiation
SSS	Sea Surface Salinity
SWFGD	Flue Gas Desulphurisation using seawater
TA	Total Alkalinity
t/MW h	Tonnes per megawatt hour
UNFCCC	United Nations Framework Convention on Climate Change – see http://unfccc.int/
Urea	The name of an organic compound containing carbon, nitrogen, oxygen and hydrogen; $(NH_2)_2CO$
U.S. EPA	United States Environmental Protection Agency – see http://www.epa.gov/
UV	Ultraviolet light
V_2O_5	The chemical formula for vanadium pentoxide
Vapour pressure	The pressure exerted by a vapour in equilibrium with its condensed phases in a closed vessel; a substance with a high vapour pressure at normal temperatures is often referred to as volatile
Venturi	A device with a tapered central constriction that causes an increase in fluid velocity and a corresponding decrease in fluid pressure
WIF	Water-in-fuel; a NOx control technique, which lowers local combustion temperatures

ADDENDA/CORRIGENDA

3.5.2.1 PAH measurement

Addendum - phenanthrene equivalents

The Guidelines for Exhaust Gas Cleaning Systems require that the PAH concentration in washwater be reported in units of phenanthrene equivalents (PAH_{phe}).

This unit is used because

- Studies have shown phenanthrene from diesel exhaust to be the most prevalent PAH dissolved in scrubber washwater
- Phenanthrene is derived from petrogenic (petroleum) rather than pyrogenic (combustion related) sources and it is indicative of incompletely burned hydrocarbons in the exhaust gases
- Phenanthrene, along with other lighter PAHs, is dissolved into the washwater during scrubbing, whereas heavier (pyrogenic) PAHs become bound onto particulate matter. (Pollutants in the washwater are removed by the washwater treatment plant and the effectiveness of particle removal is measured by turbidity meter)
- Unlike laboratory analysis online instruments cannot readily differentiate between the individual PAH species, because their fluorescent signatures overlap when exposed to UV light
- Usefully, as well as being the most prevalent PAH dissolved in washwater the phenanthrene molecule gives the highest fluorescence signal of all the PAH species and online instruments can be readily tuned for its excitation and detection by calibration using a standard phenanthrene solution. (Verification of the instrument's tuning can also be confirmed with an equivalent solid calibration cell.)
- The total fluorescence emitted from all detectable PAHs in the washwater is therefore measured at the phenanthrene calibration point to express the concentration of the PAHs in PAH_{phe} units
- Phenanthrene is one of the U.S. EPA 16 priority pollutants and so this is a practical technique that gives a robust online measure of polycyclic aromatic hydrocarbons in washwater in order to prevent harmful discharges to sea

Figure: Fluorometer for PAH detection in water

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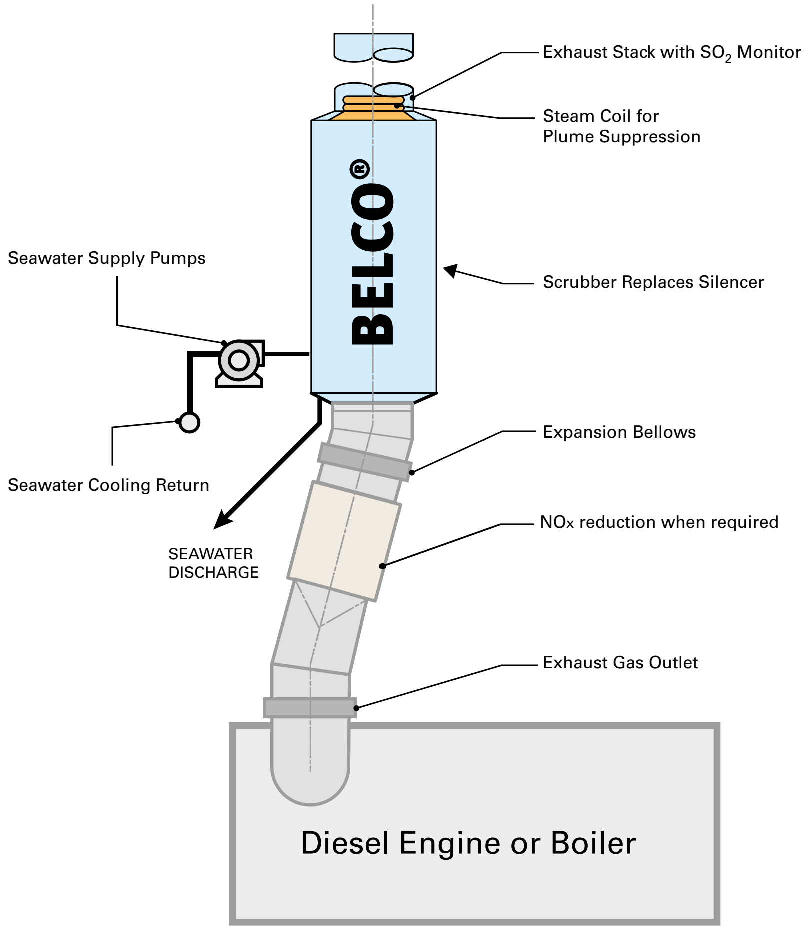

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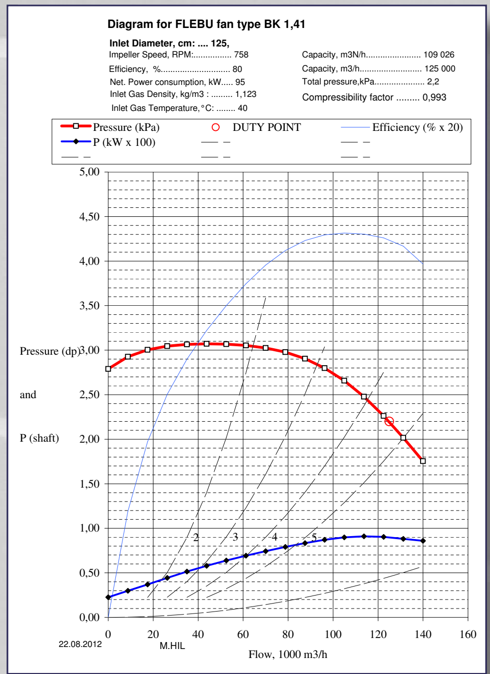

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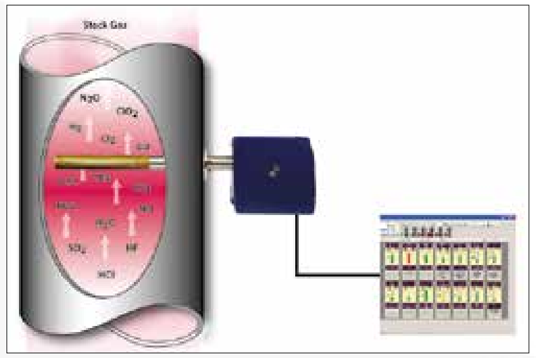

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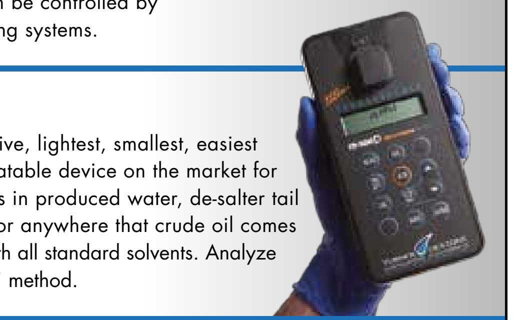

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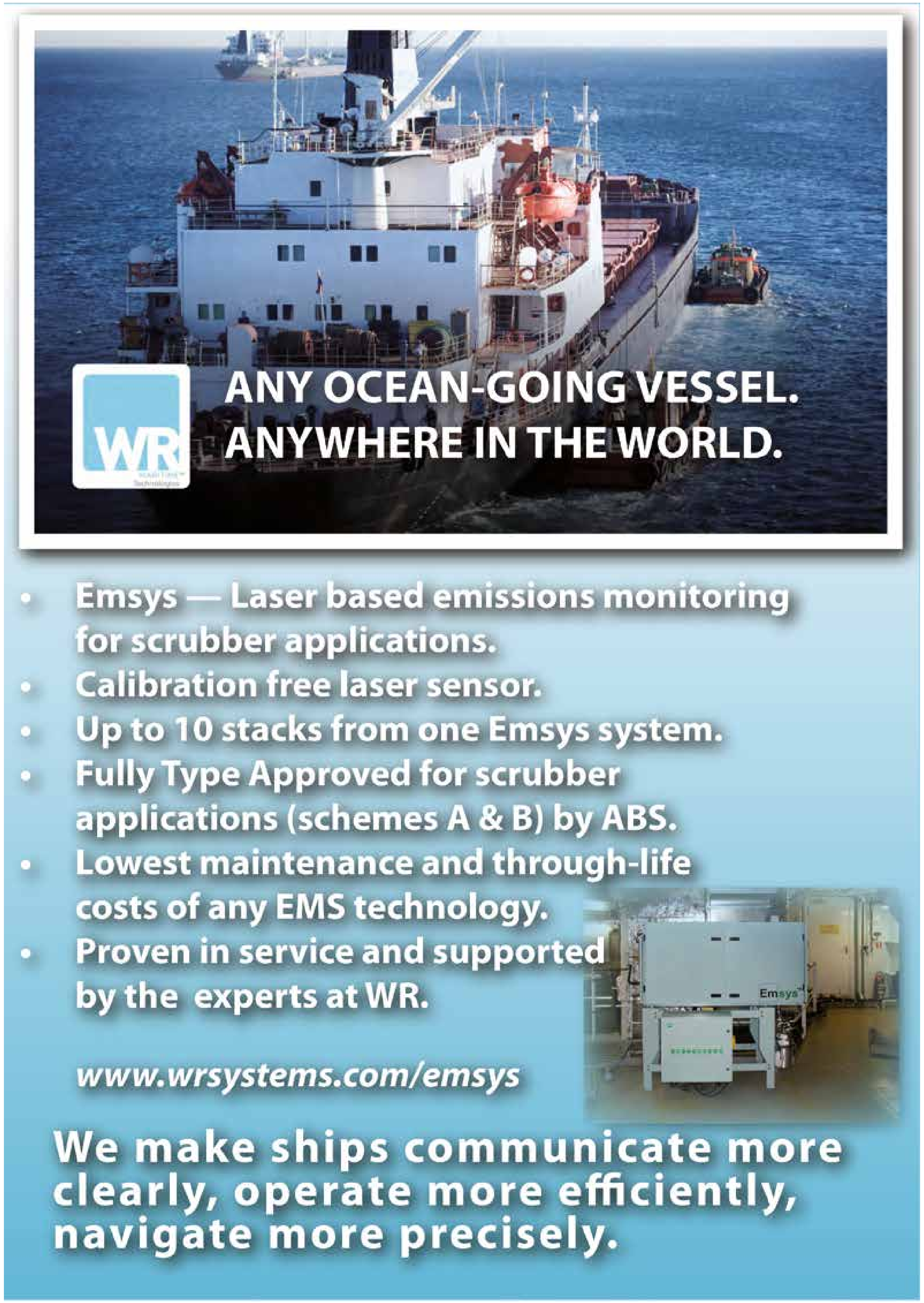
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