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 wastewater handling
- Comprehensive details of commercially available systems from EGCSA members

As exhaust gas cleaning technologies and regulation 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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ADDITIONAL CORRIGENDA
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 IWO 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 Exhaust 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.

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 onshore 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.

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. NICHOLAS CONFUORTO
Belco Technologies Corporation (a DuPont subsidiary)
Chairman, EGCSA

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 these 1930 deaths remains unclear, however, the death toll was probably due to an unusual combination of low wind speeds, release of soot and gas pollution, and the phasing in of smokeless fuels and gas heating.

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 organometals. 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 SO2 is most often associated with smoke from the combustion of coal rather than shipping SO2 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 [15]. The normal atmospheric background concentration of SO2 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 [14].

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 [14].

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 [17], [18]. 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 [19].

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 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 CO2 [14], [20]. 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 to 4.1, while the pH of rainwater is slightly more alkaline at pH 6.6.
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 leaching 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. Building decay can also occur. Limestone (CaCO3) used in the construction of buildings and historic monuments reacts to form gypsum (CaSO4), which readily flakes off under the action of the weather.

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], it was also stated an ECA would 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].

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 2:** Sulphur oxide deposition without exhaust gas cleaning

**Figure 3:** PAH analysis, gasoline, diesel, propane

**PAH ANALYSIS**

1. Gasoline soot contains (7x) more PAH than diesel soot
2. Gasoline soot: large PAH predominate
3. Diesel soot: small PAH predominate
4. Propane soot: small PAH predominate
5. Propane soot contains more PAH than diesel soot

**Detailed PAH content**

<table>
<thead>
<tr>
<th></th>
<th>Gasoline</th>
<th>Propane</th>
<th>Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benz(a)pyrene</td>
<td>7x more</td>
<td>7x more</td>
<td></td>
</tr>
<tr>
<td>Pyrene</td>
<td>large PAH</td>
<td>small PAH</td>
<td>small PAH</td>
</tr>
<tr>
<td>Total PAH found in soot</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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.

<table>
<thead>
<tr>
<th>EMISSION</th>
<th>SOURCE</th>
<th>IMPACTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur dioxide (SO₂)</td>
<td>From sulphur contained in petroleum sourced liquid fuels. During combustion oxidises to sulphur dioxide.</td>
<td>SO₂ is the majority component of SOx in the exhaust and a major contributor to acidification and secondary particulate formation.</td>
</tr>
<tr>
<td>Sulphur trioxide (SO₃)</td>
<td>As above but in aerosol form further oxidised by catalytic reaction in combustion passages.</td>
<td>A highly acidic compound, very hygroscopic, causing damage to metal components.</td>
</tr>
<tr>
<td>Nitric oxide (NO)</td>
<td>Formed during combustion at high temperature and an oxygen-enriched atmosphere in a marine diesel engine chamber.</td>
<td>Converts to NO₂ in the atmosphere.</td>
</tr>
<tr>
<td>Nitrous Oxide (NO₂)</td>
<td>Formed by the oxidation of NO; a minor portion (&lt;3%) of nitrogen oxide emissions [NOₓ] in the exhaust</td>
<td>Toxic gas. Under certain conditions causes photochemical smog and ground level ozone.</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>Formed (along with water) during the complete combustion of hydrocarbon fuels</td>
<td>The increasing atmospheric concentration of CO₂ is the major controlling factor in global climate change.</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>Formed due to incomplete combustion of fuel.</td>
<td>May cause long-term damage to heart and nervous system.</td>
</tr>
<tr>
<td>Polycyclic aromatic hydrocarbons (PAH)</td>
<td>May be contained in the fuel and formed during combustion process</td>
<td>Some PAHs are classified as carcinogenic.</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>Natural gas. During incomplete combustion some gaseous fuel passes into the exhaust and is known as methane slip.</td>
<td>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.</td>
</tr>
<tr>
<td>Ammonia (NH₃)</td>
<td>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.</td>
<td>Toxic gas. In the atmosphere may react with sulphur dioxide to form ammonium sulphate aerosols.</td>
</tr>
</tbody>
</table>

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 (CO₂) and water (H₂O), zones with a shortage of oxygen may result in 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.

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 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.

![Image of particle formation - diesel engine fuel combustion](image-url)

Table 1: Gaseous pollutants and climate change agents
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. Ultratine particles agglomerate with adsorbed hydrocarbons to form larger particulate (0.5 to 1.0μm diameter). Tanger & 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)

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### 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 sixth session of the IMO Marine Environment Protection Committee (MEPC 60) 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 [31, 46, 57]. 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 [32, 33, 34]. 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 coordinates 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 all key operating parameters.

Under both schemes emissions of ‘washwater’ to sea must be monitored and importantly rather than monitoring the specific emissions rate of SOx in g/kW h, the ratio of parts per million-sulphur dioxide to percentage-carbon dioxide (SO2 ppm/CO2 %) 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 revision replaced 170(57) in July 2010. The latest Guidelines reflect the changes to Annex VI and include the SO2/CO2 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.

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 1.30% 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 – 1.30% sulphur fuel
• In ECAs the IMO limit applies – 1.00% sulphur fuel
• 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 IWO”.

*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

Figure 9: IMO timeline for reduction in fuel sulphur content
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 any waste streams discharged into enclosed ports, harbours and estuaries where it can be shown that 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.

While the EC has issued official advice confirming the latest limits to all EU territorial waters, i.e. within 12 nautical miles of the coastline.

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.

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

As of 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 “variable, 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 0.10% 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 operations must comply with the stricter limit of 0.10% 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 SECA’s but is operating a regular service to or from an EU port, from 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.

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 [55]:

“Stricter limits on the sulphur content of shipping fuels are set to improve air quality along European coastlines and reduce the estimated 30,000 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.”

Info Box 2: EC – new sulphur standard for shipping

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 [56].

Title 40 of the U.S. Code of Federal Regulations, CFR Part 1042 [57] 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. Flag Ocean Going Vessels (OGVs) 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 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 [58].

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 [59]. In its Interim Guidance on the Non-Availability of Compliant Fuel Oil for the North American Emission Control Area [60], the EPA states that:
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 onroad vehicles and in some cases less restrictive than limits on industrial combustion plants.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Current Standard for New Engines Tier II</th>
<th>2016 Standard for New Engines Tier III</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx (g/kW h)</td>
<td>14.4 to 7.7 (engine speed dependent)</td>
<td>3.4 to 2.0 (engine speed dependent)</td>
</tr>
<tr>
<td>CO (g/kW h)</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>HC (g/kW h)</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>PM</td>
<td>To be reported by OEM</td>
<td>To be reported by OEM</td>
</tr>
</tbody>
</table>

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

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).

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.
Black Carbon acts in two ways to accelerate climate change: after carbon dioxide. Black Carbon is defined by UNFCCC as having the second highest anthropogenic sourced climate change forcing impact of all greenhouse gases. 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 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. 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 covers 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.
3.2 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 SO2 (sulphur dioxide) to CO2 (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 CO2 is also derived from the combustion of hydrocarbon fuel and typically makes up about 6% of a diesel engine’s exhaust gas. The SO2/CO2 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 SO2 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 – “Path of the SO2/CO2 Ratio Method”).

Table 3 shows the SO2 (ppm)/CO2 (%) ratios that must be measured after an exhaust gas cleaning unit in order to achieve equivalence and therefore compliance with the sulphur/CO2 limits under regulation 14.

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 SO2/CO2 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 (ETMA).

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.

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)

<table>
<thead>
<tr>
<th>FUEL OIL SULPHUR CONTENT (% m/m)</th>
<th>RATIO EMISSION SO2 (ppm)/CO2 (% v/v)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.50</td>
<td>195.0</td>
</tr>
<tr>
<td>3.50</td>
<td>151.7</td>
</tr>
<tr>
<td>1.50</td>
<td>65.0</td>
</tr>
<tr>
<td>1.00</td>
<td>43.3</td>
</tr>
<tr>
<td>0.50</td>
<td>21.7</td>
</tr>
<tr>
<td>0.10</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Table 3

The Guidelines for Exhaust Gas Cleaning Systems specify the requirements for the test, approval/certification and verification of an EGC. 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.

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 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 monitored.
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.

### 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 EGCS unit is within that required without the need for actual exhaust emission measurements, (although daily spot 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 EGCS unit achieves no more than the required SO₂/CO₂ 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 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 EGCS 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. 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 airborne emissions simply being directly transferred to the seas.

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**

![Figure 11: Typical exhaust gas composition—slow speed two stroke engine using residual fuel](image-url)
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.

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.

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.

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.

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.

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 unburned 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. 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 50g/1 above that at washwater system inlet is related to a flow rate of 45s/MW h, which is typical for an open seawater Exhaust Gas Cleaning System.

Table 4: PAH discharge concentration limits

<table>
<thead>
<tr>
<th>FLOW RATE (t/MW h)</th>
<th>DISCHARGE CONCENTRATION LIMIT (kg/1 PAH&lt;sub&gt;phen&lt;/sub&gt; EQUIVALENTS)</th>
<th>MEASUREMENT TECHNOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1</td>
<td>2250</td>
<td>Ultraviolet light</td>
</tr>
<tr>
<td>2.5</td>
<td>900</td>
<td>– –</td>
</tr>
<tr>
<td>5</td>
<td>450</td>
<td>Fluorescence*</td>
</tr>
<tr>
<td>11.25</td>
<td>200</td>
<td>– –</td>
</tr>
<tr>
<td>22.5</td>
<td>100</td>
<td>– –</td>
</tr>
<tr>
<td>45</td>
<td>50</td>
<td>– –</td>
</tr>
<tr>
<td>90</td>
<td>25</td>
<td>– –</td>
</tr>
</tbody>
</table>

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 2.5s/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.

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 activity, 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.

Sediments can be disturbed during shallow water maneuvering 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 receptor 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 maneuvering.

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 (NO₂) in the presence of excess oxygen. Collectively NO and NO₂ are often referred to as NOx.

When NO₂ 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.

Photosynthesis and within limits a fixed rate 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 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, runoff from agriculture or direct input of domestic sewage), addition of nitrate may lead to enhanced biomass production.

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 NOx give typical figures of 4% nitrogen for residual fuel and zero for distillate the mechanisms for NOx production occur in differing proportions during the combustion of these fuels so there is only a small reduction in NOx emissions from the use of distillate. 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 SO₂, the amount of NOx 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.
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 NO2 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

Natural Colour
Chlorophyll Concentrations

Ocean Chlorophyll Concentration (mg/m$^3$)

0.04 1.0 10 10 60

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

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.

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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.

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).

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.

4.1 Wet Exhaust Gas Cleaning Systems

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.

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, 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.

‘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 4.5 m³ seawater per megawatt hour (MW h) of combustion unit power if 2.7% sulphur fuel is consumed.
‘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 20m³/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 0.3m³/MW h [13] although the system shown can operate with zero discharge for limited periods if a holding tank is fitted.

‘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 optimizes chemical usage and ensures discharges do not affect sensitive or contained areas with little water exchange.

Figure 19: Closed Loop Exhaust Gas Cleaning System

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 – SO₂, a very small percentage of which is further oxidised to sulphur trioxide – SO₃. 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].

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 neutralising 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 SO₂ is not achieved, however too much washwater is inefficient 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.

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.

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 SO₂ into the aqueous solution. Depending on the pH bisulphite and sulphite form, followed by oxidation to sulphate.

Info Box 8: Relevant chemistry – sulphur oxides to sulphate

The overall reactions with SO₂ 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. [14]
neutralization, and therefore SOx removal, is the alkalinity of greater than 98% are possible. A key factor for sulphur acid at reducing sulphur oxide emissions and removal rates of Wet Exhaust Gas Cleaning Systems are highly effective

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.

Alkalinity does not relate 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% of the neutralisation is provided by borates and other ions in low concentrations [14]. Total alkalinity, is the sum of all these and for the open ocean is usually constant and high at approximately 2200 to 2300μmol/l [2]. 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).

CAUSTIC SODA – NAOH [29]
Typical commercial form is a 50% w/v solution:
- pH 14
- Density 1.52 t/m³
- 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 1.105cSt at 20°C rapidly increases at temperatures lower than 18°C). [29]
- Bulk transportation temperature often at 40°C (delivery temperature should not be above 120 to 125°C [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.
- Temperature between 20°C and 50°C
- Uncoated mild steel tanks should not exceed 120 to 125°C [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

CO₂(aq) + H₂O  → H₂CO₃ (Carbonic Acid)  → H⁺ + HCO₃⁻ (bicarbonate)  → H⁺ + CO₃²⁻ (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 (HCO₃⁻), 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 is in so doing move the carbonate system equilibrium to the left.

Within an Exhaust Gas Cleaning System once the buffering capacity is consumed 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

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. All 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 1500 to 1930μmol/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/ICO₃ 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.

When the pH is above 7 the solution is basic
When the pH is below 7 the solution is acidic

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 seawaters [31].
Salinity is practically determined from the conductivity ratio of the sampled seawater to a standard potassium chloride solution.

*[See glossary]
### Info Box 13: Alkalinity in sea areas and ports

Alkalinity data tables courtesy Wärtsilä

<table>
<thead>
<tr>
<th>AREAS</th>
<th>PORTS</th>
<th>ALKALINITY (μmol/l)</th>
<th>RIVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Sea</td>
<td>Amsterdam</td>
<td>2200</td>
<td>Scheldt</td>
</tr>
<tr>
<td>Norwegian Sea</td>
<td>Antwerp</td>
<td>2200</td>
<td>4500</td>
</tr>
<tr>
<td>North Atlantic Ocean</td>
<td>Bilbao</td>
<td>2200</td>
<td></td>
</tr>
<tr>
<td>South Atlantic Ocean</td>
<td>Bordeaux</td>
<td>2300</td>
<td>2400</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>Cadiz</td>
<td>2400</td>
<td>3100</td>
</tr>
<tr>
<td>Black Sea</td>
<td>Dover</td>
<td>1100</td>
<td>1300</td>
</tr>
<tr>
<td>Gulf of Mexico</td>
<td>El Ferrol</td>
<td>2250</td>
<td>2380</td>
</tr>
<tr>
<td>Caribbean Sea</td>
<td>Hamburg</td>
<td>2250</td>
<td>2400</td>
</tr>
<tr>
<td>Panama</td>
<td>Hanko</td>
<td>1800</td>
<td>1600</td>
</tr>
<tr>
<td>Panama Canal</td>
<td>Helasinki</td>
<td>1000</td>
<td>1250</td>
</tr>
<tr>
<td>Gulf of Alaska</td>
<td>Hull</td>
<td>2600</td>
<td>3500</td>
</tr>
<tr>
<td>North Pacific Ocean</td>
<td>Kila</td>
<td>2100</td>
<td>500</td>
</tr>
<tr>
<td>South Pacific Ocean</td>
<td>Miami</td>
<td>2200</td>
<td>2300</td>
</tr>
<tr>
<td>Red Sea</td>
<td>New Orleans</td>
<td>2400</td>
<td>3000</td>
</tr>
<tr>
<td>Persian Gulf</td>
<td>Oslo</td>
<td>2250</td>
<td>2700</td>
</tr>
<tr>
<td>Arabian Sea</td>
<td>Rotterdam</td>
<td>2300</td>
<td>490</td>
</tr>
<tr>
<td>Bay of Bengal</td>
<td>St Petersburg</td>
<td>2300</td>
<td></td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>Travesonda</td>
<td>2200</td>
<td>1800</td>
</tr>
<tr>
<td>Gulf of Thailand</td>
<td>2000</td>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>South China Sea</td>
<td>2000</td>
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<td></td>
</tr>
<tr>
<td>Philippine Sea</td>
<td>2100</td>
<td>2100</td>
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</tr>
<tr>
<td>Coral Sea</td>
<td>2150</td>
<td>2150</td>
<td></td>
</tr>
<tr>
<td>Red Sea</td>
<td>2300</td>
<td>2300</td>
<td></td>
</tr>
<tr>
<td>Gulf of California</td>
<td>2150</td>
<td>2150</td>
<td></td>
</tr>
</tbody>
</table>

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 longterm trial platform for an open Exhaust Gas Cleaning System using seawater with SO2 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 alkalinitie similar to or higher than that of the open ocean.
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.

4.2.2.1/5.6.1 Each EGCS 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.

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 24: Position of water quality and emissions monitoring instrumentation

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 2.5 downward to the outlet at the bottom. The light fractions move toward the central axis of the hydrocyclone and in Figure 2.5 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 used 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 wastewater. 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 large masses or floccs, 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 wastewater may be subjected to active carbon filtration, which is effective at removal of organic compounds from water by adsorption [17].

4.1.5 Effects on seawater composition

4.1.5.1 Sulphate

As seen in Section 4.1.1 when SO2 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 [18]. 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 [19].

Studies [20] and in-field testing [21] 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 [20].

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 worst case scenarios Karle and Turner [11] evaluated the dilution of wastewater 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 alkalinites/salinites, it was found that, other than for full open ocean water above 1.5°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 [12].

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 [22].
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 components such as pumps, coolers, interconnecting pipework for construction of exhaust gas cleaning units and downstream equipment. To ensure a long service life the materials used the ferrous and non-ferrous metals normally used for ships

Figure 27: Glass reinforced epoxy pipe construction

Courtesy NOV Fiber Glass Systems

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. 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.

4.1.6.2 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. 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 carryover with the exhaust 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:

$$PREN = (\%Cr) + 3.3(\%Mo) + 16(\%N) \times 0.3$$

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)
gas, a demister at the EGC unit exit can be used to remove any entrained liquid droplets. In addition a reheater \([16], [21]\) 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.

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 turbochargers, operates at temperatures 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.

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

- **SULPHUR DIOXIDE:**
  - \(\text{SO}_2 + \text{Ca(OH)}_2 \rightarrow \text{CaSO}_3 + \text{H}_2\text{O}\)
  - \(2\text{CaSO}_3 + \text{O}_2 \rightarrow 2\text{CaSO}_4\)

- **SULPHUR TRIOXIDE:**
  - \(\text{SO}_3 + \text{Ca(OH)}_2 + \text{H}_2\text{O} \rightarrow \text{CaSO}_4 + 2\text{H}_2\text{O}\)

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 28: Exhaust deplume](image)

*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*

![Figure 29: Arrangement of dry exhaust gas cleaning for multiple engines](image)

*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

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 200 km 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 maximisation of detail methods and detailed 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 SOx, CO, NO, NOx. 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.

### Table 5: Exhaust gas cleaning techniques

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>BRIEF DESCRIPTION</th>
<th>SUITABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity Settlers</td>
<td>Gravity settling requires very low gas velocity and significant volume to enable gravity to settle out particles. Not suitable for marine exhaust cleaning applications.</td>
<td>×</td>
</tr>
<tr>
<td>Wet Scrubbers – Absorption</td>
<td>Wet marine scrubbers typically use either seawater or freshwater with an alkaline 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 pollutants such as sulphur dioxide and are also able to trap particles.</td>
<td>✓</td>
</tr>
<tr>
<td>Cyclones</td>
<td>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.</td>
<td>✓</td>
</tr>
<tr>
<td>Dry Scrubbers – Adsorption</td>
<td>Dry scrubber systems used on board ship use a surface active material to adsorb and sequestrate pollutant gases (SOx). The consumable is normally a specially prepared hydrated lime granulate.</td>
<td>✓</td>
</tr>
<tr>
<td>Bag Filters</td>
<td>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.</td>
<td>×</td>
</tr>
<tr>
<td>Membrane Filters</td>
<td>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.</td>
<td>✓</td>
</tr>
<tr>
<td>Electrostatic Precipitators</td>
<td>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.</td>
<td>✓</td>
</tr>
<tr>
<td>Thermal Oxidation</td>
<td>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.</td>
<td>×</td>
</tr>
<tr>
<td>Non-Thermal Plasma</td>
<td>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).</td>
<td>✓</td>
</tr>
<tr>
<td>Exhaust Catalysts</td>
<td>Exhaust catalysts are used in onroad vehicles (oxy-cat, 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.</td>
<td>✓</td>
</tr>
<tr>
<td>Biological Methods</td>
<td>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.</td>
<td>×</td>
</tr>
</tbody>
</table>
Of the listed methods the following are currently in use for exhaust gas cleaning onboard 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).

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).

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 than 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 31: Particle trapping process
Courtesy Fenger & Tjell, Air Pollution 2009 [9]

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 concurrent flow, countercurrent 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 passing through the quench are adiabatically cooled to the washwater flow is used in this section. Hot exhaust gases through impaction is aided by the large differential in dioxide and a portion of the particulate. Particulate removal section, is effective in removing about 60% of the sulphur which is typically constructed as a throat and an expander 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 watered 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.

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 watered 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.

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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 areas 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 reheat 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 absorb 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%.

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 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 (N2) and water (H2O), by means of a reducing agent adsorbed onto a catalyst. This is typically ammonia, formed by the decomposition of urea (NH2)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 [79].

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 steam and the injected solution, then decomposes to form ammonia (NH3) and some carbon dioxide. On contact with the surface of the catalyst the NOx components, nitric oxide (NO) and nitrogen dioxide (NO2) react with the ammonia and oxygen from the exhaust to form nitrogen and water.

\[
\text{NH}_2\text{CO} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{CO}_2
\]

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Catalytic elements are typically ammonia, formed by the decomposition of urea (NH2)2CO injected into the exhaust gas stream.

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\[
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Catalytic elements

\[\text{Urea decomposition in the mixing duct:}\]
\[1. \quad (\text{NH}_2\text{CO}) \rightarrow \text{NH}_3 + \text{CO}_2\]
\[2. \quad \text{NH}_2\text{CO} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{CO}_2\]

\[\text{NOx reduction at the catalyst:}\]
\[1. \quad 4\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}\]
\[2. \quad 2\text{NO} + 2\text{NO}_2 + 4\text{NH}_3 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}\]
\[3. \quad 6\text{NO}_2 + 8\text{NH}_3 \rightarrow 7\text{N}_2 + 12\text{H}_2\text{O}\]

6.1.1 SCR control

It is important to tightly manage the rate of urea injection in order to restrict the release of unreacted ammonia to atmosphere, which is referred to as ‘ammonia slip’. Catalytic 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.

Catalytic elements

\[\text{Spent SCR catalyst disposal}\]

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 (TiO2) coated with an active component such as vanadium pentoxide (V2O5) 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.

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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 (SO₃) in the exhaust stream. Typically, a minimum of 300°C to 360°C is required. At lower temperatures the formation of ammonium sulphate, (NH₄)₂SO₄, a dry powdery compound, can result. Ammonium bisulphate, (NH₄)HSO₄, is also formed at higher levels of SO₃ (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 adherences 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.

- 2SO₂ + O₂ → 2SO₃

Two reactions can then follow:

- 2NH₃ (ammonia) + SO₃ (sulphur trioxide) + H₂O → NH₄HSO₄ (ammonium bisulphate)
- NH₃ + SO₂ + H₂O → NH₄HSO₄

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

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) 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 biodiesel 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 NO₂ and allows manufacturers to use a smaller reactor and/or operate at lower temperatures.

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 unburnt or partially combusted fuel oil and engine lubricant, and several hydrocarbon derivatives, including polycyclic aromatic hydrocarbons (PAHs). 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 SO₂ is oxidised to SO₃, this can be significantly increased, particularly at higher engine loads and exhaust temperatures. A proportion of the SO₃ 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 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.

On leaving the combustion chamber some of the nitric oxide is oxidised to nitrogen dioxide (NO₂) and together these 2 gases form NOx in the ratio of approximately 90% to 93% NO, 5% to 10% NO₂.

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 scavenging 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.
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 setup 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.

The EGR system includes an exhaust gas wet scrubber integrated onto the engine, a cooler and ‘water mist catcher’ (WMC), a single-stage, 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 0.7 bar, before it is introduced to the scavenging air.

The EGR system 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 4 bar 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 SO2 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].

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 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.
7.1 Performance Overview

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.

![Image of multi-stream exhaust gas cleaning unit](source: Wärtsilä-Hamworthy)

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)

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
- DIN 51402: Testing of flue gases of oil burning systems; visual and photometric determination of the smoke number
- EPA Method 5/AQMD Method 5.2: Determination of Particulate Matter emissions from stationary sources

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 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. 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.

**Info Box 21: Particulate matter definitions**

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

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.
to 78% of particulate matter was removed [46].

Towards the pressure drop to be varied from 100 to 400mm water higher removal efficiencies. The adjustable throat enabled turbulence because of a higher gas velocity and therefore to impact on. An increased pressure drop results in increased walls, atomising the liquid into tiny droplets for the particles increases greatly. This shears washwater from the venturi as exhaust gas enters the constricted throat section, its velocity to 55% of particulate matter was removed. With the venturi, pressure drop on the exhaust gas side. By this method up by a nozzle in a straight downward flow with almost no venturi section. Using the jet quench, washwater is atomised different pre-cleaning methods for their exhaust gas cleaning unit – a simple jet nozzle and a more advanced adjustable 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 [45].

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 spot content of five 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 ± 1.4°C (unless otherwise approved). The particulate matter includes any material that condenses at or above the filtration temperature, after the removal of uncombined water [43].

EPA Method 5 (which is similar to ISO 9096 [44]) has historically been the method of choice for measurement of stationary particulate matter sources in the United States. Since the majority consist of cool fired boilers. In these applications, the particulate matter control measures (e.g. electrostatic precipitators [45]) 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 [44].

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 particulate measurements as described in the relevant part of the standard is conclusively proven to be effective for fuel sulphur levels up to 0.8% [46]. This is because at higher sulphur levels there is a possibility of sulphates loss due to condensation within the test apparatus before the filter [41].

From this it can be appreciated that the process of removing pollutants has a significant effect 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, 1st SCR as an alternative means of NOx control. BEECOM positions the SCR reactor upstream i.e. before the exhaust gas cleaning unit [47].

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. Wartsila offers SCR as well as other engine related NOx control techniques [48]. 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 BEECOM®

Info Box 22: A brief comparison of PM measurement methods
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 recombine 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 O2 oxygen molecule can be split into two highly reactive O+ free radicals that will combine with normal O2 molecules to form ozone, O3, and nitrogen sesquioxide (N2O3) and nitrogen dioxide to nitrogen pentoxide (N2O5). 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 NO2. Continuous emissions monitoring is used to accurately match the oxygen/ozone flow rates to the concentration of NOx in the exhaust stream [15], [16].

Maintaining wet systems at a pH of 10 or above increases chemical consumption to more than twice the typical rate as CO2 reacts with the caustic soda to create Na2CO3. In most cases CO2 absorption is not desired since the Na2CO3 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.

Another system from Couple Systems uses a sodium hydroxide solution, which is pumped at a rate of 4% of the fuel mass on a dry basis. The solution absorbs CO2 to form sodium carbonate, Na2CO3. In some cases, calcium hydroxide can also remove up to 15% CO2. Calcium hydroxide has a limited solubility, and its use in the washwater can cause longer term plugging issues within the exhaust gas cleaning unit.

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% CO2.
CLD sensors use the luminescence of NO₂ 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 NO₂ in the sample to NO.
2. NO produced from the conversion together with NO already in the sample is combined with ozone to produce NO₂ in an excited state. The luminescence can then be used to determine only the NO₂ concentration.
3. The luminescence of the NO₂ in an excited state is used to determine the NOx concentration (NO+NO₂).

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 NO₂ in an excited state. The luminescence can then be used to determine only the NO concentration.
   b. By subtracting the NO concentration from the NO₂ concentration, the NOx 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

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 SO₂ and NO₂ 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 readily 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 usable 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.
The Guidelines for Exhaust Gas Cleaning Systems give various SO₂/CO₂ ratios that must be measured after an exhaust gas cleaning unit in order to achieve equivalence and therefore compliance with the sulphur/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 CO₂ are derived from the combustion of fuel that is hydrogenated based and contains sulphur.

Some Exhaust Gas Cleaning Systems however use the natural buffering capacity of seawater to neutralise the acids produced from scrubbing SO₂, which moves the carbonate system equilibrium towards CO₂ release (see Info Boxes 11 and 15, Section 4.1). This could at first be considered to compromise the validity of the SO₂/CO₂ 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 CO₂ 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 CO₂ produced by neutralizing the acidity produced by 1 tonne of residual fuel* is minimal, particularly when compared with the CO₂ 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 CO₂. The Guidelines also take account of this and state that in justified cases where the CO₂ concentration is reduced by the exhaust gas cleaning unit, the CO₂ 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 CO₂ emissions and the SO₂/CO₂ 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 50m³ per hour per megawatt of engine power for an open loop seawater system. It is about 20 to 25m³ per hour per megawatt for a closed loop system with chemical addition. Some systems design for energy consumption to be optimised by automatically adjusting washwater flow rate according to the engine power and the sulphur content of the fuel (7). 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 SO₂ absorption into the...
wastewater and thus pH degradation depends on parameters such as the wastewater temperature, which in turn is affected by the temperature of seawater used for washwater cooling. The rate of water consumption and therefore makeup 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 concentration (e.g. 40%), so although the consumption rates of pure NaOH may be similar, they would appear quite different for more dilute solutions.

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 retrofit, 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 build units can be readily accommodated at the planning stage. A wet system 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.

Wastewater 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 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 comparable with Wärtsilä Hamworthy, which advises a typical consumption of 0.1 m³/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 makeup and bleed off to sea.

Minor consumables include coagulants and flocculants used for treatment of washwater prior to discharge overboard and bags for handling desalinated 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 wastewater 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 dryer exhaust gas cleaning unit.

Water may be condensed from the exhaust gas in the exhaust gas cleaning unit or lost through 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 1.1 m³/h freshwater will be consumed; a figure comparable with Wärtsilä/Hamworthy, which advises a typical consumption of 0.1 m³/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 makeup and bleed off to sea.

Vendor suggest various sizes for residue collection tanks with an average of approximately 0.5 to 1 m³ 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 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 desalinated, 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 40 m³ depending on engine power. The capacity for holding wastewater 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 11.5 m³ 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. Closed Systems suggest 14 m³ per megawatt of engine power as an indicative figure based on continuous combustion of a 2.7% sulphur residual fuel over a year period.

Waste water treatment residue collection

Figure 47: Washwater treatment residue collection

Courtesy Wärtsilä Hamworthy
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 shoreside 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 Ficaria Seaways and has been in continuous supply for the interconnection of ports 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 piping, 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 retrofit 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 that 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 begin on 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 long-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.

7.4 Installation and after-care

Apart from the core system components 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.

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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 of 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. 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.

<table>
<thead>
<tr>
<th>PERFORMANCE OVERVIEW</th>
<th>ALFA LAVAL</th>
<th>BELCO® (DU Pont)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGC System description</td>
<td>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 &amp; chemical scrubbing only.</td>
<td>Hybrid design that can be switched between open loop (seawater) and closed loop (freshwater &amp; chemical) as needed with optional low or zero discharge rate. Open loop – seawater; Closed loop – freshwater &amp; chemical.</td>
</tr>
<tr>
<td>Exhausts per EGC unit</td>
<td>One EGC unit can handle exhaust from multiple sources or from a single source as may be required.</td>
<td>One EGC unit can handle exhaust from multiple sources or from a single source as may be required.</td>
</tr>
<tr>
<td>Maximum % fuel sulphur to achieve equivalent of 0.1%</td>
<td>Standard Offer: 3%</td>
<td>No upper limit (cleaning unit size, water flow rate and chemical consumption dependent on sulphur content and engine size).</td>
</tr>
<tr>
<td>Possible</td>
<td>Up to 4.5%</td>
<td>Experience on land with SOx levels greater than the equivalent of 10% sulphur in fuel.</td>
</tr>
<tr>
<td>% Particulate removal</td>
<td>By EGC5</td>
<td>Up to 80% (depending on engine exhaust gas quality).</td>
</tr>
<tr>
<td></td>
<td>Measured (ISO 8178)</td>
<td>Measured &gt;94% removal on land.</td>
</tr>
<tr>
<td>% NOx removal</td>
<td>By EGC5</td>
<td>0.2% less than 1%.</td>
</tr>
<tr>
<td></td>
<td>By SCR (or other technology) used in combination with EGC5</td>
<td>&lt;0.05% (when EGC5 combined with LCTC or SCR.</td>
</tr>
<tr>
<td></td>
<td>Estimated or measured</td>
<td>Measured &gt;95% removal on land.</td>
</tr>
<tr>
<td>% CO2 removal</td>
<td>By EGC5</td>
<td>&lt;0.1% Standard offer: 0%; higher is possible but not recommended.</td>
</tr>
<tr>
<td></td>
<td>Estimated or measured</td>
<td>Not measured.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CLEAN MARINE</th>
<th>COUPLE SYSTEMS</th>
<th>MARINE EXHAUST SOLUTIONS</th>
<th>WARTSILA/HAMWORTHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switchable seawater open loop / freshwater and chemical closed loop system with optional low or zero discharge rate.</td>
<td>Dry chemical system with optional SCR</td>
<td>Seawater open loop system</td>
<td>Open loop – seawater; Closed loop – freshwater and chemical.</td>
</tr>
<tr>
<td>One EGC unit can handle exhaust from several sources simultaneously. EGC units in parallel can handle unlimited amounts.</td>
<td>More engine plus 3 auxiliary engines possible</td>
<td>Multiple engines in a flexible configuration based on owner’s requirements</td>
<td>Mainstream unit – one exhaust; Integrated unit – all exhausts.</td>
</tr>
<tr>
<td>3.5% 3.5%</td>
<td>3.5%</td>
<td>3.5%</td>
<td>3.5%</td>
</tr>
<tr>
<td>3% 3% 3% 3%</td>
<td>5%</td>
<td>3.5%</td>
<td>5%</td>
</tr>
<tr>
<td>0% 0% 0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>0% 0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Tier II level in combination with SCR or EGR.</td>
<td>&gt;90% by SCR</td>
<td>See note 5</td>
<td>Measured</td>
</tr>
<tr>
<td>Measured (NDIR)</td>
<td>Measured</td>
<td>Measured</td>
<td></td>
</tr>
<tr>
<td>10% 10% 10% 10%</td>
<td>3-10%</td>
<td>3-10%</td>
<td>3-10%</td>
</tr>
<tr>
<td>Laboratory test – MAN Holley</td>
<td>Measured (NDIR)</td>
<td>Measured</td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>Measured</td>
<td>Measured</td>
<td>Measured</td>
</tr>
</tbody>
</table>
## Flow and Consumption Data

<table>
<thead>
<tr>
<th></th>
<th>ALFA LAVAL</th>
<th>BELCO® (DUPONT)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scrubbing medium</strong></td>
<td>Seawater or freshwater and caustic soda (NaOH)</td>
<td>Open loop with seawater and closed loop with freshwater and caustic soda (NaOH)</td>
</tr>
<tr>
<td><strong>Washwater flow rate</strong></td>
<td>m³/h/MW engine power</td>
<td>50 (seawater)</td>
</tr>
<tr>
<td><strong>Freshwater consumption</strong></td>
<td>m³/h/MW engine power</td>
<td>Depending on ships operating profile and seawater temperature</td>
</tr>
<tr>
<td><strong>Liquid chemical consumption – exhaust gas cleaning</strong></td>
<td>l/h/MW engine power</td>
<td>13 – 16.5! (20 – 25 kg/l/MW)</td>
</tr>
<tr>
<td><strong>Dry chemical consumption – exhaust gas cleaning</strong></td>
<td>kg/h/MW engine power</td>
<td>None</td>
</tr>
<tr>
<td><strong>Other consumption</strong></td>
<td>Washwater treatment</td>
<td>None</td>
</tr>
<tr>
<td><strong>Residue handling</strong></td>
<td>Compressed service air</td>
<td>None</td>
</tr>
<tr>
<td><strong>EGC System Power Requirements</strong></td>
<td>kW/MW engine power</td>
<td>10 to 12</td>
</tr>
</tbody>
</table>

## Physical Data

<table>
<thead>
<tr>
<th></th>
<th>ALFA LAVAL</th>
<th>BELCO® (DUPONT)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum size of engine that can have EGC unit fitted</strong></td>
<td>MW engine power</td>
<td>1 – 80MW</td>
</tr>
<tr>
<td><strong>Sizes of EGC units offered</strong></td>
<td>MW engine power</td>
<td>1 – 80MW</td>
</tr>
<tr>
<td><strong>Footprint &amp; height of EGC unit (m² &amp; m)</strong></td>
<td>Smallest EGC unit in range</td>
<td>D=0.8m for 0.5MW D=6m for 21MW D=7.5m for 60MW</td>
</tr>
<tr>
<td></td>
<td>Largest in range</td>
<td>Installation specific – slight larger than the exhaust silencer</td>
</tr>
<tr>
<td><strong>Weight in service i.e. filled (t)</strong></td>
<td>Smallest EGC unit in range</td>
<td>0.5 MW = 3 t</td>
</tr>
<tr>
<td></td>
<td>Largest in range</td>
<td>60MW = 70 t</td>
</tr>
</tbody>
</table>

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**CLEAN MARINE**

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Scrubbing medium</strong></td>
<td>Seawater, freshwater and caustic soda (NaOH)</td>
<td>Calcium Hydroxide (Ca(OH)₂)</td>
<td>Seawater Freshwater Caustic soda (closed loop)</td>
</tr>
<tr>
<td><strong>Washwater flow rate</strong></td>
<td>m³/h/MW engine power</td>
<td>None</td>
<td>50</td>
</tr>
<tr>
<td><strong>Freshwater consumption</strong></td>
<td>m³/h/MW engine power</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Liquid chemical consumption – exhaust gas cleaning</strong></td>
<td>l/h/MW engine power</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Dry chemical consumption – exhaust gas cleaning</strong></td>
<td>kg/h/MW engine power</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Other consumption</strong></td>
<td>Washwater treatment</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Compressed service air</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>EGC System Power Requirements</strong></td>
<td>kW/MW engine power</td>
<td>18 to 23</td>
<td>1.5 to 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 – 6 (closed loop) 10 – 20 (open loop)</td>
<td></td>
</tr>
</tbody>
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<tr>
<td><strong>Footprint &amp; height of EGC unit (m² &amp; m)</strong></td>
<td>Smallest EGC unit in range</td>
<td>1MW: 1m² x 5m 2MW: ~4m² x (5 to 8)m</td>
<td>25% of traditional silencer</td>
</tr>
<tr>
<td></td>
<td>Largest in range</td>
<td>1MW: 1m² x 5m 2MW: ~4m² x (5 to 8)m</td>
<td>20MW: &lt;20m² x 7m</td>
</tr>
<tr>
<td><strong>Weight in service i.e. filled (t)</strong></td>
<td>Smallest EGC unit in range</td>
<td>1MW: 2 t</td>
<td>1MW: 14 t</td>
</tr>
<tr>
<td></td>
<td>Largest in range</td>
<td>1MW: 14 t</td>
<td>1MW: 2 t</td>
</tr>
</tbody>
</table>

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</tr>
<tr>
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<td>1MW: 14 t</td>
</tr>
<tr>
<td></td>
<td>Largest in range</td>
<td>1MW: 14 t</td>
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<td>1MW: 14 t</td>
</tr>
<tr>
<td></td>
<td>Largest in range</td>
<td>1MW: 14 t</td>
<td>1MW: 2 t</td>
</tr>
</tbody>
</table>
**Typical position of EGC unit**
- Inside funnel or inside extended funnel area
- Where space is available

**Footprint of washwater treatment plant (m²)**
- Smallest EGC unit in range: 4m² (for 1 MW unit)
- Installation specific

**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

**Tankage required (m³/MW engine power)**
- Washwater treatment plant residue
  - Dependent on installation and client’s storage requirements.
- Typical sludge production rate: ~0.2 litre / MW h (Freshwater mode)

**Chemical addition – Exhaust Gas Cleaning System**
- Dependent on vessel, routing and opportunity to bunker – ~11.5m³ NaOH/MW (10 litres/MW/hour can be used for 2.7 % sulphur test to determine required autonomy)

**Other**
- Circulation tank for fresh water operation
  - Open loop: 0 – 10MW: 10m³,
  - >10MW – 20MW: 20m³
  - >20MW: 40m³

**Testing**

<table>
<thead>
<tr>
<th>ALFA LAVAL</th>
<th>BELCO® (DUPONT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested in commercial land based applications or test facilities?</td>
<td>Yes</td>
</tr>
<tr>
<td>Sizes</td>
<td>1MW</td>
</tr>
<tr>
<td>When tested</td>
<td>2008 (200 hours testing)</td>
</tr>
<tr>
<td>Where</td>
<td>MAN Diesel test facility</td>
</tr>
<tr>
<td>Combustion material</td>
<td>Residual fuel</td>
</tr>
<tr>
<td>Maximum % sulphur</td>
<td>2.4%</td>
</tr>
<tr>
<td>Tested on ship?</td>
<td>Yes – Ficaria Seaways</td>
</tr>
</tbody>
</table>

**CLEAN MARINE COUPLE SYSTEMS MARINE EXHAUST SOLUTIONS WARTSILA/HAMWORTHY**

| Inside and outside funnel | Normally directly after the engine turbocharger or between turbocharger and exhaust gas boiler. | In place of traditional silencer/spark arrester |
| ~1.5m x 2m | Not applicable | Installation specific |
| ~4m² x 3m | Not applicable | Installation and closed/open loop specific. E.g. : 1.2MW closed loop: 4.5m² |
| Optional – on open deck or inside | Not applicable | Exhaust casing, engine room or outside |
| ~1m³ sludge/MW | Not applicable | Anywhere that is suitable in terms of available space and practicability |
| ~3 – 6m³ NaOH/MW | 1.6m³ Ca(OH)₂/MW | None |
| None | None | Open loop: nothing |
| None | None | Closed loop: bleed-off and effluent tanks for zero discharge |
| Up to 80MW | Up to 800MW | Size dependent on ship’s operational needs |
| MAN Holeby | MAN Diesel test facility | Test installations – Norway |
| Heavy fuel oil (marine industry) | Ceramic industry, biomass incineration | Power generation – global |
| 5% | 5% | Test installations – Norway |
| Yes – one | Yes – one | Yes – two |

**CLEAN MARINE COUPLE SYSTEMS MARINE EXHAUST SOLUTIONS WARTSILA/HAMWORTHY**

| Tested in commercial land based applications or test facilities? | Yes | Yes – total installed power 465MW |
| Sizes | 1MW | 250,000 Am³/hr (1) or – 124,000Nm³/hr |
| When tested | 2006 (testing between 2006 and 2008) | Up to 800MW |
| Where | MAN Diesel test facility | Since mid 1990’s |
| Combustion material | Residual fuel | MAN Holeby |
| Maximum % sulphur | 2.4% | Ceramic industry, biomass incineration |
| Tested on ship? | Yes – Ficaria Seaways | Heavy fuel oil (marine industry) |
| Yes – one | Yes – one | MDO, MDO, HFO |
| Yes – two | Yes – two | MDO, MDO, HFO |

*Notes: (1) Assumes 100% load, (2) Includes in burner (3) Includes in burner (4) 4Q2012 (5) Installation specific (6) Footprint of washwater treatment plant (m²) (7) Flexibility & installation specific – installation and closed/open loop specific. E.g. : 1.2MW closed loop: 4.5m² (8) Sizes 1MW from 1 MW to 1.5 MW equivalent |

---

**Testing**

<table>
<thead>
<tr>
<th>ALFA LAVAL</th>
<th>BELCO® (DUPONT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tested in commercial land based applications or test facilities?</td>
<td>Yes</td>
</tr>
<tr>
<td>Sizes</td>
<td>1MW</td>
</tr>
<tr>
<td>When tested</td>
<td>2008 (200 hours testing)</td>
</tr>
<tr>
<td>Where</td>
<td>MAN Diesel test facility</td>
</tr>
<tr>
<td>Combustion material</td>
<td>Residual fuel</td>
</tr>
<tr>
<td>Maximum % sulphur</td>
<td>2.4%</td>
</tr>
<tr>
<td>Tested on ship?</td>
<td>Yes – Ficaria Seaways</td>
</tr>
</tbody>
</table>

**CLEAN MARINE COUPLE SYSTEMS MARINE EXHAUST SOLUTIONS WARTSILA/HAMWORTHY**

| Inside and outside funnel | Normally directly after the engine turbocharger or between turbocharger and exhaust gas boiler. | In place of traditional silencer/spark arrester |
| ~1.5m x 2m | Not applicable | Installation specific |
| ~4m² x 3m | Not applicable | Installation and closed/open loop specific. E.g. : 1.2MW closed loop: 4.5m² |
| Optional – on open deck or inside | Not applicable | Exhaust casing, engine room or outside |
| ~1m³ sludge/MW | Not applicable | Anywhere that is suitable in terms of available space and practicability |
| ~3 – 6m³ NaOH/MW | 1.6m³ Ca(OH)₂/MW | None |
| None | None | Open loop: nothing |
| None | None | Closed loop: bleed-off and effluent tanks for zero discharge |
| Up to 80MW | Up to 800MW | Size dependent on ship’s operational needs |
| MAN Holeby | MAN Diesel test facility | Test installations – Norway |
| Heavy fuel oil (marine industry) | Ceramic industry, biomass incineration | Power generation – global |
| 5% | 5% | Test installations – Norway |
| Yes – one | Yes – one | Yes – two |

**CLEAN MARINE COUPLE SYSTEMS MARINE EXHAUST SOLUTIONS WARTSILA/HAMWORTHY**

| Tested in commercial land based applications or test facilities? | Yes | Yes – total installed power 465MW |
| Sizes | 1MW | 250,000 Am³/hr (1) or – 124,000Nm³/hr |
| When tested | 2006 (testing between 2006 and 2008) | Up to 800MW |
| Where | MAN Diesel test facility | Since mid 1990’s |
| Combustion material | Residual fuel | MAN Holeby |
| Maximum % sulphur | 2.4% | Ceramic industry, biomass incineration |
| Tested on ship? | Yes – Ficaria Seaways | Yes – one |

---

**Notes: (1) Assumes 100% load, (2) Includes in burner (3) Includes in burner (4) 4Q2012 (5) Installation specific (6) Footprint of washwater treatment plant (m²) (7) Flexibility & installation specific – installation and closed/open loop specific. E.g. : 1.2MW closed loop: 4.5m² (8) Sizes 1MW from 1 MW to 1.5 MW equivalent**
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<th></th>
<th>ALFA LAVAL</th>
<th>BELCO® (DUPONT)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sizes</strong></td>
<td>MW engine power</td>
<td>21 MW, 28 MW (Q4 2012)</td>
</tr>
<tr>
<td><strong>Where</strong></td>
<td></td>
<td>Rolfo ferry, North Sea</td>
</tr>
<tr>
<td><strong>Time in operation</strong></td>
<td></td>
<td>~7000 hours</td>
</tr>
<tr>
<td><strong>Maximum % sulphur</strong></td>
<td></td>
<td>2.7%</td>
</tr>
<tr>
<td><strong>Independent emissions to air</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Independent emissions to water</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>EGC units Scheme A certified?</strong></td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Sizes</strong></td>
<td>MW engine power</td>
<td>21 MW</td>
</tr>
<tr>
<td><strong>By who, when</strong></td>
<td></td>
<td>DNV &amp; GL, August 2009</td>
</tr>
<tr>
<td><strong>EGC units Scheme B certified?</strong></td>
<td>Yes</td>
<td>Pending</td>
</tr>
<tr>
<td><strong>Sizes</strong></td>
<td>MW engine power</td>
<td>21 MW</td>
</tr>
<tr>
<td><strong>By who, when</strong></td>
<td></td>
<td>Germanischer Lloyd 27 April 2010</td>
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**Approvals**

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**Supply, Installation and After Care**

<table>
<thead>
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<th></th>
<th>ALFA LAVAL</th>
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<tr>
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**CLEAN MARINE**

<table>
<thead>
<tr>
<th></th>
<th>COUPLE SYSTEMS</th>
<th>MARINE EXHAUST SOLUTIONS</th>
<th>WARTSILA/HAMWORTHY</th>
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<tbody>
<tr>
<td><strong>Sizes</strong></td>
<td>10 MW, 1.2 MW, 5600 kW</td>
<td>610kW – 10 MW</td>
<td>Panama, Tanker, Far East</td>
</tr>
<tr>
<td><strong>Time in operation</strong></td>
<td>~200 hours</td>
<td>~8000 hours</td>
<td>Fitted July 2009: Operated for</td>
</tr>
<tr>
<td><strong>Maximum % sulphur</strong></td>
<td>4.07%</td>
<td>2.7%</td>
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</tr>
<tr>
<td><strong>Independent emissions to air</strong></td>
<td>No</td>
<td>Independently verified by Germanischer Lloyd, report available from vendor on request</td>
<td>Independently verified, not published</td>
</tr>
<tr>
<td><strong>Independent emissions to water</strong></td>
<td>No</td>
<td>Yes</td>
<td>Yes – November 2011</td>
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</tbody>
</table>
**Commercial**

<table>
<thead>
<tr>
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<th><strong>ALFA LAVAL</strong></th>
<th><strong>BELCO® (DUPONT)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EGC system commercially available?</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Production capacity (EGC units)</strong></td>
<td>As required</td>
<td>As required</td>
</tr>
<tr>
<td></td>
<td>As required</td>
<td>As required</td>
</tr>
<tr>
<td><strong>Target market</strong></td>
<td>All commercial vessels</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>All</td>
<td>All, including boilers</td>
</tr>
<tr>
<td><strong>Engine size range</strong></td>
<td>Up to 100MW</td>
<td>Any size</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Supplier staff numbers</strong></td>
<td>&gt;20 and growing</td>
<td>DuPont 30,000 - 40,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Estimated capital expenditure (USD)</strong></td>
<td>USD 3-4 million for 100MW EGC including installation cost</td>
<td>Pay back less than one year dependent upon fuel price and ECA operation ratio</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Estimated annual operating cost (USD)</strong></td>
<td>USD 43,500 (13)</td>
<td>3 – 5 USD/MW h (10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Guarantee</strong></td>
<td>12 months</td>
<td>12 months</td>
</tr>
</tbody>
</table>

---

**EGC system commercially available?**

- Yes
- Yes

**Production capacity (EGC units)**

- First year: As required
- After first year: As required

**Target market**

- Newbuild, retrofit: Both
- Vessel type: All commercial vessels

**Engine size range**

- Up to 100MW

**Supplier staff numbers**

- EGC team: >20 and growing
- Entire company or group: 15,000

**Estimated capital expenditure (USD)**

- Smallest EGC unit in range: USD 3-4 million for 100MW EGC including installation cost
- Largest in range: USD 477,200 (13)

**Estimated annual operating cost (USD)**

- Smallest EGC unit in range: USD 43,500 (13)
- Largest in range: USD 477,200 (13)

**Guarantee**

- 12 months
- 12 months extended warranty offered

---

**Project management and supervision. Design and drafting, documentation and verification.**

- Design, installation drawings, class approval support, project management, system installation and integration
- Vessel drawings and yard schedule
- To be agreed on a project by project basis, dependent on ship owner/operator, vessel and ECGS configuration

**Superintendent engineer, labour for mechanical and electrical system installation.**

- Instrument calibration and six monthly check of mechanical and electronic components
- Maintenance of pumps instrumentation etc. Regular inspections offered

**Exchange of exhaust gas monitoring head every six months. Replacement of filter media and pH sensors. Cleaning and calibration of PM10 monitoring equipment. Long term overhaul of pumps, fans and blowers.**

**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

**Guarantee**

- 12 months – extended warranty offered
- Equipment guarantee 12 months

---

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**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

**Guarantee**

- 12 months – extended warranty offered
- Equipment guarantee 12 months
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 – 92%.
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 Nm3/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

### Supporting Notes

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Approximately</td>
</tr>
<tr>
<td>2</td>
<td>Less than</td>
</tr>
<tr>
<td>3</td>
<td>Greater than</td>
</tr>
<tr>
<td>g/kW h</td>
<td>Grams per kilowatt per hour</td>
</tr>
<tr>
<td>l/h</td>
<td>Litres per hour</td>
</tr>
<tr>
<td>l/h/MW</td>
<td>Litres per hour per megawatt of engine power</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>kg/h/MW</td>
<td>Kilograms per hour per megawatt of engine power</td>
</tr>
<tr>
<td>kW</td>
<td>Kilowatt (10^3 watts)</td>
</tr>
<tr>
<td>m</td>
<td>Metre</td>
</tr>
<tr>
<td>m²</td>
<td>Square metre</td>
</tr>
<tr>
<td>m³</td>
<td>Cubic metre</td>
</tr>
<tr>
<td>m³/h/MW</td>
<td>Cubic metres per hour per megawatt of engine power</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt (10^6 watts)</td>
</tr>
<tr>
<td>Nm³/h</td>
<td>Normal cubic metres per hour</td>
</tr>
<tr>
<td>SCFM</td>
<td>Standard cubic feet per minute</td>
</tr>
<tr>
<td>t</td>
<td>Tonnes (1000 kilograms)</td>
</tr>
<tr>
<td>USD</td>
<td>United States Dollar</td>
</tr>
</tbody>
</table>

### Units – See also Glossary of terms, formulae & abbreviations

- 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
- m²: Square metre
- m³: Cubic metre
- m³/h/MW: Cubic metres per hour per megawatt of engine power
- MW: Megawatt (10^6 watts)
- Nm³/h: Normal cubic metres per hour
- SCFM: Standard cubic feet per minute
- t: Tonnes (1000 kilograms)
- USD: United States Dollar
2009 Guidelines for Exhaust Gas Cleaning Systems

ANNEX 9

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 NOx 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 SO2 (ppm)/CO2 (%) ratio method will simplify the monitoring of SO2 emission and facilitate approval of an EGC unit. See Appendix B for the rationale explaining the use of SO2(ppm)/CO2(%) as the basis for system monitoring.

1.3 Compliance should be demonstrated on the basis of the SO2(ppm)/CO2(%) ratio method, which is expected to enter into force on 1 July 2010.

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 and certification of exhaust gas cleaning (EGC) systems under regulation 4 so as to ensure that they provide effective equivalence to requirements of regulations 14.1 and 14.4 of Annex VI of MARPOL 73/78.

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.

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 wash water 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 of 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 certified. The Certified Value should at least be suitable for ship's operations under requirements given by MARPOL Annex VI regulations 14.1 and 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 is 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 fuel, 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 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.
4.2.1.5 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 the Guidelines. This should be subject to section 4.1.4 of these Guidelines.

4.2.2 EGC units subject to section 4.1.4 of these Guidelines may be accepted by the Administration subject to the following requirements: (a) the identification of the unit (manufacturer, model/type, serial number and other capacities in accordance with section 4.1.2; tests of EGC systems of three different capacities should be carried out in order to demonstrate that the performance of the EGC unit is consistent with the performance of the EGC unit); (b) the data on the SECC.

4.2.3 Emission limits

4.2.3.1 EGC units should be subject to survey on installation and at intervals of not more than 2 years thereafter. This should be subject to section 2.6 of the Supplement to the EGC Technical Manual (ETM-A). A Technical Manual should be issued by the Administration in the case of new designs, or in the case of changes to existing designs, or in the case of changes to existing installations.

4.2.3.2 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 load points should be sufficient to establish the emission peak value.

4.2.3.3 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 to establish the emission peak value.

4.2.3.4 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 to establish the emission peak value.

4.2.4 Onboard procedures for demonstrating compliance

4.2.4.1 For each EGC unit, the EGC unit should be subject to survey on installation and at intervals of not more than 2 years thereafter. This should be subject to section 2.6 of the Supplement to the EGC Technical Manual (ETM-A). A Technical Manual should be issued by the Administration in the case of new designs, or in the case of changes to existing designs, or in the case of changes to existing installations.

4.2.4.2 The ETM-A should be based on the results of the surveys mentioned in section 4.1.3. The ETM-A should be considered as part of the EGC unit.

4.2.4.3 Amendments to the ETM-A which reflect EGC unit changes that affect performance may be made, after consultation with the Administration, and should be made in accordance with section 4.1.4. The ETM-A should be considered as part of the EGC unit.

4.2.5 Emission limits

4.2.5.1 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 to establish the emission peak value.

4.2.5.2 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 to establish the emission peak value.

4.2.5.3 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 to establish the emission peak value.

4.2.6 Emission limits

4.2.6.1 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 to establish the emission peak value.

4.2.6.2 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 to establish the emission peak value.

4.2.6.3 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 to establish the emission peak value.

4.2.7 Emission limits

4.2.7.1 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 to establish the emission peak value.

4.2.7.2 EGC units fitted to main propulsion diesel engines should meet the requirements of 4.1.1 at all loads between 10-100% of the rated load of the engine to which they are fitted. These 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 to establish the emission peak value.
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 Survey by the Administration.

5.4 Calculation of emission rate
5.4.1 Exhaust gas composition in terms of SO\textsubscript{2} (ppm)/CO\textsubscript{2} (%) should be measured at an equivalent point of operation of the EGC unit.

5.4.2 If more than one analyser is to be used to determine the SO\textsubscript{2}/CO\textsubscript{2} ratio, these should be tuned to have similar sampling and measurement times and the data outputs aligned so that the SO\textsubscript{2}/CO\textsubscript{2} ratio is fully representative of the exhaust gas composition.

5.6 Onboard procedure for demonstrating compliance with emission limit
5.6.1 Each EGC unit should be provided 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 equipment;

(b) the operating limits, or range of operating values, for which the unit is certified.

These should be, 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 minimum exhaust gas inlet temperature and the expected exhaust gas composition 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\textsubscript{2}/CO\textsubscript{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 amendments to the ETM-B are separate to the EGC unit 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 NOx Technical Code 2008, chapter 5, and associated Appendices, except as provided for in these Guidelines.

6.2 CO\textsubscript{2} should be measured on a dry basis using an analyser operating on non-dispersive infra-red (NDIR) principle. SO\textsubscript{2} should be measured on a dry or wet basis using analysers operating on non-dispersive infra-red (NDIR) or non-dispersive ultraviolet (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 NOx Technical Code 2008.

6.4 An exhaust gas sample for SO\textsubscript{2} should be obtained from a representative sampling point downstream of the EGC unit.

6.5 SO\textsubscript{2} and CO\textsubscript{2} should be monitored using either in situ or extractive sample systems.

6.6 Extractive exhaust gas samples for SO\textsubscript{2} determination should be taken at a temperature not higher than 85°C and be frozen or otherwise treated (e.g., by dry or wet scrubbing) immediately after sampling, to avoid water in the sample and hence loss of SO\textsubscript{2}.

6.7 Where SO\textsubscript{2} is measured by an in situ system, the water content in the exhaust gas stream at that point should also be determined in order to correct the reading to a dry basis.

6.8 Where SO\textsubscript{2} is measured by a scrubber, the water content in the exhaust gas stream at that point should also be determined in order to correct the reading to a dry basis.

6.9 In confirmed cases where the CO\textsubscript{2} concentration is reduced by the EGC unit, the CO\textsubscript{2} concentration can be measured at the EGC unit outlet, 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 ship's 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 usable 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, at a minimum, include:

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

9.2.1 Scheme A

9.2.1.1 The SEPS should be submitted for review to the Authority, the EACD, and the CEC to demonstrate that the system meets the requirements of the SEPS and is in compliance with the requirements of regulations 14.1 and 14.4 of MARPOL Annex VI. The SEPS should be submitted for SEPS review according to the requirements of Article 4.14.1 and 14.4. The SEPS should be submitted for SEPS review according to the requirements of Article 4.14.1 and 14.4.

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 to be followed. The details should include the following:

(b) the positions from which exhaust emission measurements and washwater monitoring are to be taken together with details of any necessary ancillary services, including pH, PAH, turbidity and temperature. In other cases, where continuous monitoring and recording is not possible, the positions from which exhaust emission measurements and washwater monitoring are to be taken shall be specified in the SEPS.

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 and recording equipment.

9.2.2 Scheme B

9.2.2.1 The SEPS should be submitted for review to the Authority, the EACD, and the CEC to demonstrate that the system meets the requirements of the SEPS and is in compliance with the requirements of regulations 14.1 and 14.4 of MARPOL Annex VI. The SEPS should be submitted for SEPS review according to the requirements of Article 4.14.1 and 14.4. The SEPS should be submitted for SEPS review according to the requirements of Article 4.14.1 and 14.4.

9.2.2.2 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 to be followed. The details should include the following:

(b) the positions from which exhaust emission measurements and washwater monitoring are to be taken together with details of any necessary ancillary services, including pH, PAH, turbidity and temperature. In other cases, where continuous monitoring and recording is not possible, the positions from which exhaust emission measurements and washwater monitoring are to be taken shall be specified in the SEPS.

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 and recording equipment.

10.1 Demarcation of Continuity

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 comply with the following limits:

- Emissions Compliance Plan (ECP)
- SO₂:
  - Continuous limit: 0.1 grams per hour
  - Short-term limit: 0.3 grams per hour

- NOₓ:
  - Continuous limit: 0.2 grams per hour
  - Short-term limit: 0.6 grams per hour

10.1.2 The washwater pH should be maintained at a value between 6.5 and 7.5 for all fuel oil combustion units. The limit may be exceeded by up to 20% for the purposes of this criteria.

10.1.3 The maximum continuous PAH concentration in the washwater should not be greater than 0.01 milligrams per liter. The maximum continuous PAH concentration in the washwater should not be greater than 0.01 milligrams per liter. The limit may be exceeded by up to 100% for the purposes of this criteria.

10.1.4.1 The washwater turbidity should comply with the following requirements:

- Continuous limit: 20 formazin nephlometric units
- Short-term limit: 40 formazin nephlometric units

10.1.4.2 The washwater treatment system should be designed to minimize suspended particulate matter. For systems using seawater, the turbidity limit should be 100 formazin nephlometric units. For systems using seawater, the turbidity limit should be 100 formazin nephlometric units.

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 NOₓ from the exhaust, or beyond the limits specified in the SEPS. The washwater treatment system should prevent the discharge of nitrates beyond that associated with a 12% removal of NOₓ from the exhaust, or beyond the limits specified in the SEPS.

10.1.5.2 At each renewal survey nitrate discharge data is to be available in respect of sample collection and analysis. 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.

10.1.6 Additional washwater discharge criteria should be established.

11.2 Washwater monitoring

11.2.1 The measurement technology should be capable of measuring washwater discharge concentrations. For systems using seawater, the measurement technology should be capable of measuring washwater discharge concentrations. For systems using seawater, the measurement technology should be capable of measuring washwater discharge concentrations.

11.2.2 The measurement technology should be capable of measuring washwater discharge concentrations. For systems using seawater, the measurement technology should be capable of measuring washwater discharge concentrations. For systems using seawater, the measurement technology should be capable of measuring washwater discharge concentrations.

11.2.3 Fluorescence technology should be used due to its reliable operating performance and ease of use. Fluorescence technology should be used due to its reliable operating performance and ease of use.

11.2.4 The measurement technology should be capable of measuring washwater discharge concentrations. For systems using seawater, the measurement technology should be capable of measuring washwater discharge concentrations. For systems using seawater, the measurement technology should be capable of measuring washwater discharge concentrations.

11.2.5 Minimum additional washwater discharge criteria should be established.
FORM OF SO\textsubscript{2} EMISSION COMPLIANCE CERTIFICATE

NAME OF ADMINISTRATION

SO\textsubscript{2} 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)

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.\textsuperscript{***(**).}

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

<table>
<thead>
<tr>
<th>Unit manufacturer</th>
<th>Model/ type</th>
<th>Serial number</th>
<th>EGC System Unit and Technical Manual approval number</th>
</tr>
</thead>
</table>

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.

APPENDIX II

PROOF OF THE SO\textsubscript{2}/CO\textsubscript{2} RATIO METHOD

1 The SO\textsubscript{2}/CO\textsubscript{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\textsubscript{2} during the exhaust gas cleaning process it is necessary to measure the CO\textsubscript{2} prior to the cleaning process and use the CO\textsubscript{2} concentration before cleaning with the SO\textsubscript{2} concentration after cleaning. For conventional low alkali cleaning systems virtually no CO\textsubscript{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\textsubscript{2}/CO\textsubscript{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 hydrocarbons 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\textsubscript{2}/CO\textsubscript{2} ratio considered its use to verify compliance with emissions from 1.5\% S fuel. The limit of 65 (1ppm/\%) SO\textsubscript{2}/CO\textsubscript{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\textsubscript{2} and CO\textsubscript{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\textsubscript{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\textsubscript{2} concentration changes, but the SO\textsubscript{2}/CO\textsubscript{2} ratio does not. This indicates that the SO\textsubscript{2}/CO\textsubscript{2} ratio is independent of fuel-to-air ratios. Therefore, SO\textsubscript{2}/CO\textsubscript{2} ratio can be used robustly at any point of operation, including operation where no brake power is produced.

Note that the SO\textsubscript{2}/CO\textsubscript{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\textsubscript{2}/CO\textsubscript{2} ratio’s 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 SO\textsubscript{2}/CO\textsubscript{2} ratios for distillate and residual fuel is less than 5.0\%.

In the case of using non-petroleum fuel oils, the appropriate SO\textsubscript{2}/CO\textsubscript{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

<table>
<thead>
<tr>
<th>Carbon</th>
<th>Hydrogen</th>
<th>Sulphur</th>
<th>Other</th>
<th>C</th>
<th>H</th>
<th>S</th>
<th>Fuel S/C</th>
<th>Exh</th>
<th>SO2/CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ppm</td>
<td>%m/m</td>
<td>ppm</td>
<td>m/m</td>
<td>m/m</td>
<td>m/mol</td>
<td>m/kg</td>
<td>m/mol</td>
<td>ppm/%</td>
</tr>
<tr>
<td>Distillate</td>
<td>64.20</td>
<td>13.60</td>
<td>0.17</td>
<td>0.03</td>
<td>71.8333</td>
<td>136</td>
<td>0.00511</td>
<td>0.00074</td>
<td>2.29599</td>
</tr>
<tr>
<td>Residual</td>
<td>87.17</td>
<td>11.03</td>
<td>1.50</td>
<td>0.30</td>
<td>72.6417</td>
<td>110.3</td>
<td>0.00488</td>
<td>0.00056</td>
<td>6.61738</td>
</tr>
</tbody>
</table>

Note: The properties presented are based on a number of assumptions, including:

- Brake-specific fuel consumption (BSFC) of 6.0 g/kWh for both fuels.
- Fuel sulphur content of 1.5% in both fuels.
- Fuel properties are calculated using the following formula:

\[ \text{Exh} = \frac{100}{\text{Fuel S/C}} \]

Correspondence between 65 (ppm%) SO2/CO2 and 6.0 g/kWh is demonstrated by showing that their S/C ratios are similar. This requires the additional assumption of a brake-specific 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 (ppm%) SO2/CO2 corresponds well to 6.0 g/kWh.

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

Table 2: Emissions calculations corresponding to 1.5 % fuel sulphur

<table>
<thead>
<tr>
<th>SO2/CO2 ratio vs % sulphur in fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>% sulphur in fuel</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Distillate 0.17% S</td>
</tr>
<tr>
<td>Distillate 2.70% S</td>
</tr>
<tr>
<td>Distillate 1.5% S</td>
</tr>
<tr>
<td>Distillate 1.5% S</td>
</tr>
<tr>
<td>Residual 0.5% S</td>
</tr>
<tr>
<td>Residual 1.5% S</td>
</tr>
</tbody>
</table>

6. The following is the basis of using the (ppm%) SO2/CO2 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 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 EGC units 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.

4 Correlation between 65 (ppm%) SO2/CO2 and 6.0 g/kWh is demonstrated by showing that their S/C ratios are similar. This requires the additional assumption of a brake-specific 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 (ppm%) SO2/CO2 corresponds well to 6.0 g/kWh.

Note 2: The value of 6.0 g/kWh, hence the 200 g/kWh brake-specified fuel consumption is taken from MARPOL Annex VI as adopted by the 1997 MARPOL Conference.
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;
  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, Molokai, Ni‘ihau, Kau‘a‘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/a/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.
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” – 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 2011 is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of NOx) 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. 9.9 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 I also applies to engines of greater than 5000kW and ≥ 90 liters/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 I also applies to engines that are installed on ships built 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 NOx) 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. 44.4 n(-0.2) g/kW h when n is 130 or more but less than 2,000 rpm; and
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 NOx) 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. 9.9 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.

Limits and Schedule for Reduction

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:

• 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

<table>
<thead>
<tr>
<th>U.S. EPA 16 PRIORITY POLUTANTS</th>
<th>NAME AND SYNONYMS</th>
<th>FORMULA</th>
<th>CAS RN*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphthalene</td>
<td>C_{10}H_{8}</td>
<td>91-20-3</td>
<td></td>
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<tr>
<td>Acenaphthylene</td>
<td>C_{12}H_{8}</td>
<td>208-96-8</td>
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<tr>
<td>Acenaphthene</td>
<td>C_{12}H_{10}</td>
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<td>Fluorene</td>
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<td>Anthracene</td>
<td>C_{14}H_{10}</td>
<td>120-12-7</td>
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<tr>
<td>Phenanthrene</td>
<td>C_{16}H_{10}</td>
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## Molecular Weight (g/mol) | Boiling Point [°C] | Melting Point [°C] | Vapour Pressure [Pa] | Water Solubility [mg/l] |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<tr>
<td>152.19</td>
<td>280.2</td>
<td>89.6 - 93.4</td>
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<td>154.21</td>
<td>279.2</td>
<td>94</td>
<td>3.0x10^{-1}</td>
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<td>166.22</td>
<td>294.2 - 298.2</td>
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<td>178.23</td>
<td>328.15 - 340.15</td>
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<tr>
<td>202.25</td>
<td>375&lt;sup&gt;[i]&lt;/sup&gt;</td>
<td>108 - 113</td>
<td>1.2x10^{-1}</td>
<td>0.26</td>
</tr>
</tbody>
</table>

With some exceptions:
- Increasing molecular weight = Decreasing water solubility = Decreasing volatility. Naphthalene is the most volatile.
- Benzo(a)pyrene is the most toxic.<sup>[v]</sup>
<table>
<thead>
<tr>
<th>U.S. EPA 16 PRIORITY POLLUTANTS</th>
<th>NAME AND SYNONYMS</th>
<th>FORMULA</th>
<th>CAS RN*</th>
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<tbody>
<tr>
<td>Pyrene</td>
<td>benzo[de]anthanthrene, beta-pyrene</td>
<td>C_{16}H_{10}</td>
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<td>Benzo[a]anthracene</td>
<td>Benzo[a]phenanthrene, 1,2-benzanthracene, benzo[a]pyrene, 2,3-benzanthracene, 2,3-benzophenanthrene</td>
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<tr>
<td>Chrysene</td>
<td>1,2-benzanthracene, benzo[a]pyrene, 1,2-benzophenanthrene, 1,2,3,4-tetraphenanthrene</td>
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<td>Benzo[b]fluoranthene</td>
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<td>Benzo[k]fluoranthene</td>
<td>8,9-benzofluoranthene, 8,9-benzofluoranthene, 11,12-benzofluoranthene, 2,3,1,8-binaphthylene, dibenzo[b,j,k]fluoranthene</td>
<td>C_{20}H_{12}</td>
<td>207-08-9</td>
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<tr>
<td>Benzo[a]pyrene</td>
<td>benzo[de]pyrene, 3,4-benzpyrene, 3,4-benzpyrene, benzo[a]pyrene</td>
<td>C_{20}H_{12}</td>
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<tr>
<td>Dibenzo[a,h]anthracene</td>
<td>DB[a,h]A, DBA</td>
<td>C_{22}H_{14}</td>
<td>53-70-3</td>
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<td>Indeno (1,2,3,c,d) pyrene</td>
<td>Indeno[1,2,3-cd]pyrene, indeno[1,2,3-cd]pyrene, indeno[1,2,3-cd]pyrene, indeno[1,2,3-cd]pyrene, indeno[1,2,3-cd]pyrene, indeno[1,2,3-cd]pyrene</td>
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<table>
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<tr>
<th>MOLECULAR WEIGHT [g/mol]</th>
<th>BOILING POINT [°C]</th>
<th>MELTING POINT [°C]</th>
<th>VAPOUR PRESSURE [Pa]</th>
<th>WATER SOLUBILITY [mg/l]</th>
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<tr>
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<td>393.1°F</td>
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<td>228.29</td>
<td>448.2°F</td>
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<td>168.3°F</td>
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<tr>
<td>252.31</td>
<td>480°F</td>
<td>217</td>
<td>5.2x10^{-5}</td>
<td>0.0008</td>
</tr>
<tr>
<td>252.31</td>
<td>495.2°F</td>
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<td>278.35</td>
<td>524.2°F</td>
<td>260.15 - 271.2°F</td>
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<tr>
<td>276.33</td>
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<td>162 - 164.7°F</td>
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<td>276.33</td>
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<td>280 - 281.2°F</td>
<td>6x10^{-11}</td>
<td>0.00026</td>
</tr>
</tbody>
</table>

*Chemical Abstracts Service Registry Number – unique identifier for chemical compounds
iii. Staffan Lundstedt, 2003, Analysis of PAHs and their transformation products in contaminated soil and remedial processes
v. http://chrom.tms.ts.ac.uk/PAH/DATABASE/00alphabet.html
vi. http://msds.chem.ox.ac.uk/BE/benzo%28a%29pyrene.html
vii. http://www.chem.ox.ac.uk/BE/benzo%28a%29pyrene.txt
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. 8DK20 x 3
- Boiler: Aalborg Industries A/S GCS21ST

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
carriage 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, dries, monitor

Various exhausts – actuator for bypass, insulation work new piping, top of funnel (oilet ECS)
### M.V. Balder leaving Croatia after EGCS installation inside new funnel

### Delivery and commissioning timeline

<table>
<thead>
<tr>
<th>TASKS / PHASES</th>
<th>WEEKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept study</td>
<td>4</td>
</tr>
<tr>
<td>Detailed study</td>
<td>1</td>
</tr>
<tr>
<td>Preplanning</td>
<td>4 – 6</td>
</tr>
<tr>
<td>Installation</td>
<td>12 – 14</td>
</tr>
<tr>
<td>Commissioning</td>
<td>4 – 6</td>
</tr>
<tr>
<td>SUM TIME</td>
<td>27 – 33</td>
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<table>
<thead>
<tr>
<th>DELIVERABLES</th>
<th>DELIVERABLES</th>
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<tr>
<td>Letter of intent</td>
<td>Letter of intent</td>
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<tr>
<td>Equipment specification – preliminary</td>
<td>Equipment specification – BOM and P&amp;ID</td>
</tr>
<tr>
<td>Installation requirements – general</td>
<td>Yard quotes</td>
</tr>
<tr>
<td>Equipment specifications – prefabrication</td>
<td>Equipment ready installed and approved</td>
</tr>
<tr>
<td>Final documentation</td>
<td>Successful tests during voyage</td>
</tr>
</tbody>
</table>

**Tasks / Phases**

1. **Concept study**
   - Letter of intent
   - Equipment specification – preliminary
   - Installation requirements – general
   - Budget

2. **Detailed study**
   - Letter of intent
   - Equipment specification – BOM and P&ID
   - Yard quotes
   - Equipment quotes

3. **Preplanning**
   - Purchase and installation
   - Equipment ordering and logistics
   - Plan drafting and approval
   - Installation scope – prefabrication

4. **Installation**
   - Equipment ready installed and approved
   - Final documentation

5. **Commissioning**
   - Successful tests during voyage

**Weeks**

- **Contract 1**
  - Letter of intent
  - Equipment specification – preliminary
  - Installation requirements – general
  - Budget
  - Week 1

- **Contract 2**
  - Purchase and installation
  - Equipment ordering and logistics
  - Plan drafting and approval
  - Installation scope – prefabrication
  - Week 12 – 14

- **Installation**
  - Equipment ready installed and approved
  - Final documentation
  - Week 4 – 6

- **SUM TIME**
  - Successful tests during voyage
  - Week 27 – 33
GLOSSARY OF TERMS, FORMULAE & ABBREVIATIONS

ppm 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
% w/v Percentage by volume e.g. the percentage volume of exhaust gas that is CO₂
% w/w Weight/volume percentage e.g. a 50% w/w 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 reflection 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
Adorsed/adsorption To be attracted and held or bonded to a surface
Albedo The fraction of solar energy (shortwave 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 solutions in an aqueous system to neutralize acid; also known as alkalinity
Am³/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 NH₃
Ammonium An ionic compound derived from ammonia with the chemical formula NH₄⁺
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
BAC Best Available Technique or Technology
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 SO₂/CO₂ 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
CO₂ 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 scavange 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.comix.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’s 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 The 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 with or without the presence of a different wavelength

http://ec.europa.eu/index_en.htm
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 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.glis-group.com/

GW
Gigawatt; 1x10⁹ watts

H
The chemical symbol for hydrogen

HAMI
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.

HCO₃⁻
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).

H₂SO₄
Hydrated lime

Hydronium (H₃O⁺)

Hydronium; – a water molecule having a hydrogen ion. Acids are compounds that yield hydrogen ions (H⁺) or hydronium ions (H₃O⁺) when dissolved in water.

International Air Pollution Prevention certificate

Intermediate Bulk Container; container for transport and storage of fluids and bulk materials—often seen as a 1000 litre plastic cube in a metal cage.

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 becoming 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. Chemiluminescence 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)

Marine Diesel Oil

Marine Environment Protection Committee; e.g. MEPC 60 was the sixtieth session of this IMO group and MEPC Resolution 186(59) was adopted at the fiftieth session

m³/MW h
Cubic meters per megawatt hour

Milligrams per litre

MGO
Marine Gas Oil

MSDS
Material Safety Datasheet

MTS
Material Safety Data Sheet

N
The chemical symbol for nitrogen

Na
Sodium hydroxide, also commonly known as caustic soda

NaOH
An ionic compound of nitrogen and oxygen

NDIR
Non-dispersive infrared sensor; a spectroscopic device used to measure the concentration of gaseous emissions, for example NOx and CO₂ from an engine

NDUV
Non-dispersive ultraviolet sensor; a spectroscopic device used to measure the concentration of gaseous emissions, for example NOx and CO₂ from an engine

nN
Nanos (10⁻⁹) meter

Nm³/h
Normal cubic metres per hour

NO
An ionic compound of nitrogen and oxygen

NO₂
The chemical formula for nitrogen dioxide

NO₃⁻

NOx
The generic term for nitrogen oxides

Non-thermal plasma
Plasma that occurs at room temperature where molecules are exposed to a strong electric field (rather than extremely high temperatures)

O
The chemical symbol for oxygen

O₂
Ozone

OMM
Onboard Monitoring Manual

P
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, C₁₄H₁₀

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

PM
Particulate Matter

PPM
Parts per million

Pitting Resistance Equivalent number; a measure of the susceptibility of a stainless steel to resist pitting corrosion

Port State Control
Quantum Cascade Laser; a technology used to measure the concentration of gaseous emissions

PSC
Port State Control

QCL
Quantum Cascade Laser

RINA
A Classification Society (created by Registro Italiano Navale) – see http://www.rina.org/
The chemical symbol for sulphur

Salinity
A measure of the concentration of all the salts and ionic compounds in water

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

SO2
The chemical formula for sulphur dioxide

SO3
The chemical formula for sulphur trioxide

SO42–
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
Tonnnes 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, (NH2)2CO

U.S. EPA
United States Environmental Protection Agency—see http://www.epa.gov/

UV
Ultraviolet light

V2O5
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\textsubscript{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\textsubscript{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
Is your ship or fleet prepared for January 1, 2015? Time to look at your options. PureSOx from Alfa Laval reduces harmful emissions by scrubbing sulphur from the exhaust gas from vessels operating on HFO. PureSOx is a hybrid system that runs in either seawater or freshwater mode.

**Cost-saving**
- Low-cost solution compared to running on low sulphur MGO

**Flexible**
- Exhaust from multiple engines cleaned with one scrubber
- PureSOx functions in all known conditions

**Easy to operate**
- Automatic switching between sea and freshwater mode
- No need for chemical additives in seawater mode

**Based on experience**
- Largest system currently in operation (21 MW)

For more information, please contact Rene Diks on +31 24 35 23 180 or rene.diks@alfalaval.com

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BS 848:Part 1:1980, class B

Flow, 1000 m³/h
Pressure (dp)
Pressure (kPa)

DUTY POINT
Efficiency (% x 20)
P (kW x 100)

Inlet Diameter, cm: 125,
Inlet Gas Density, kg/m³: 1,123
Impeller Speed, RPM: 758

Efficiency, %: 80
Net. Power consumption, kW: 95

Inlet Gas Temperature, °C: 40
Compressibility factor: 0,993

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* The GL exhaust laboratory is accredited according to ISO 17025.

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Applications

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- MEPC 184 (59) Scheme
- B Scrubber Exhaust Gas Analysis System (SO₂ / CO₂)
- Ship Efficiency

Approvals

- ABS Type Approval
- Annex VI Reg 13 NOx Tech Code
- IMO Res. MEPC 103 (49)
- IACS Unified Requirement E10 & IEC 60945 (parts)

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