SEVENTH FRAMEWORK PROGRAMME

TEFLES

TECHNOLOGIES AND SCENARIOS FOR LOW EMISSIONS SHIPPING

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State of the art and efficiency report

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REPORT

D2.1: State of the art and efficiency report ”	
Responsible	Ralf Jürgens
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Description	Complete assessment of existing technologies for both SOx and NOx abatement and the specific potential of those technologies with respect to particle filtration

WP 2	**After treatment and thermal energy**		
Lead beneficiary	4	Type of activity	RTD
Start Month	1	End Month	24

Objectives

- Development of advanced engine and exhaust gas cleaning devices models to be used at the computer simulation of the different scenarios
- To identify and develop the most efficient after treatment technology with respect to lowest emissions and highest energy efficiency.
- Develop a holistic energy efficiency model including adjustments of engine, EGCS and energy recovery. Define an equation that displays the coherence of engine, EGCS and heat recovery.
- Develop a NOx abatement system with the smallest possible footprint and lowest capital and operating costs. Integrate technologies on new more compact systems
- Improve cleaning efficiency and exploitation costs of the systems
- Develop energy recovery systems with new refrigeration processes and thermal storage solutions
- Design and validate a SCR system for vessels with installed power generation between 1 MW and 50 MW (both 2-stroke and 4-stroke engines).
- Develop a new type of SCR based on pellets.
- Develop new compositions of catalytic materials based on rare earth materials and zeolithes.
- Design a SCR system which operates at lower temperatures, i.e. below 200°C.
- Develop a new chemical absorption process to partially reduce CO2 emissions

Description of work and role partners

Shipping is the most important means of transportation of goods today and this will most probably be the case for the next decades as well. Approximately 90 % of global cargo is transported by vessels powered by large diesel engines which are fueled with residual fuel oils. The IMO updated Annex VI of the MARPOL convention in October 2008 in order to better regulate emissions generated by marine engines. The focus has been put on the global reduction of pollutants such as nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM). SO_x emissions can be impeded by using low sulphur fuel but the mineral oil industry claims that demands from shipping cannot be met as the capacity of refineries is limited and shipping is competing with other industries such as the heating oil industry. The MEPC 58 clearly permits the use of SO_x abatement systems operated onboard. MEPC 58 also regulates the NO_x emission of ship engines. Though Tier I and Tier II are achievable by engine modifications, Tier III, valid from 2015, can most likely only be met by applying an after treatment system.

The aim of WP2.1 is to compile a complete assessment of existing technologies for both SO_x and NO_x abatement and the specific potential of those technologies with respect to particle filtration.

List of deliverables

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Milestones

Number	Name	Lead beneficiary	Date (Month)
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Glossary of terms, formulae & abbreviations

µg/l	micro (10^{-6}) grams per litre
µmol/l	micro (10^{-6}) moles per litre
% v/v	Percentage by volume e.g. the percentage volume of exhaust gas that is CO_2
% m/m	Percentage by mass e.g. the percentage mass of fuel that is sulphur
Absorbed/absorption	(In the case of light) the process of retention without reflection or transmission on passing through a medium
Adsorbed/adsorption	To be attracted and held or bonded to a surface
Alkalinity	The capacity of solutes in an aqueous system to neutralize acid; also known as buffering capacity
Ammonia	A compound of nitrogen and hydrogen with the formul
Ammonium	An ionic compound derived from ammonia with the chemical formula NH_4^+
ATT	After treatment technology
BC	Black Carbon
BFO	Bunker Fuel Oil
BTU	The British thermal unit (symbol BTU or Btu) is a traditional unit of energy equal to about 1,055.05585 joules
Buffering capacity	The capacity of solutes in an aqueous system to neutralize acid; also known as alkalinity
C	The chemical symbol for carbon
C°	Celsius
Ca	The chemical symbol for calcium
$CaCO_3$	The chemical formula for limestone
$Ca(OH)_2$	The chemical formula for calcium hydroxide
$CaSO_4$	The chemical formula for gypsum
CARB	California Air Resource Board

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
Certified Value	The SO_2/CO_2 ratio specified by the manufacturer that the EGC unit is certified as meeting when operating on a continuous basis on the manufacturers specified maximum fuel sulphur content
CH_4	The chemical formula for methane
CN	Cloud condensation nuclei or CNs (also known as cloud seeds) are small particles (typically 0.2 µm, or 1/100 the size of a cloud droplet about which cloud droplets coalesce
CO	The chemical formula for carbon monoxide
CO_2	The chemical formula for carbon dioxide
Coagulant	A chemical compound added to water to enable suspended particles to be gathered together for filtration
COD	In environmental chemistry, the chemical oxygen demand (COD) test is commonly used to indirectly measure the amount of organic compounds in water
Colloid	A type of mixture in which one substance is dispersed evenly throughout another
DFO	Distilled Fuel Oil
DNV	Det Norske Veritas; a Classification Society
dwt	dead weight tons
EC	European Community
ECA	Emission Control Area
Economizer	mechanical device intended to reduce energy consumption, or to perform another useful function like preheating a fluid
EEDI	Environmental Efficiency Design Index
EEOI	Environmental Efficiency Operation Index
EGC	Exhaust Gas Cleaning
EGC Record Book	A record of the EGC unit in-service operating parameters, component adjustments, maintenance and service records as appropriate
EGCS	Exhaust Gas Cleaning System
EGCSA	Exhaust Gas Cleaning Systems Association - see http://www.egcsa.com/
EGR	Exhaust Gas Recirculation; a primary NOx control technique
ESI	Environmental Ship Index
ETM-A	EGC system – Technical Manual for Scheme A
ETM-B	EGC system – Technical Manual for Scheme B
EU	European Union

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
F°	Fahrenheit
FGD	Flue Gas Desulphurisation
Flocculant	A chemical compound added to water to combine suspended particles together for filtration
Fluorescence	The emission of electromagnetic radiation light by a substance that has absorbed radiation of a different wavelength
FPP	Fixed Pitch Propeller
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
g	gram
g/kWh	grams per kilowatt hour
g/l	grams per litre
g/mol	grams per mole; the molecular weight or molar mass of a substance
GESAMP	Joint Group of Experts on Scientific Aspects of Marine Environmental Protection
GHG	Green House Gases
GL	Germanischer Lloyds – a Classification SOciety
H	The chemical symbol for hydrogen
H^+	hydrogen ion
HCO_3^-	The chemical formula for bicarbonate ion
H_2CO_3	The chemical formula for carbon acid
H_2O	The chemical formula for water
H_2SO_3	The chemical formula for sulphurous acid
H_2SO_4	The chemical formula for sulphuric acid
HC	The chemical formula for hydro carbons
HFO	Heavy Fuel Oil
HSD	High Speed Diesel engine
HSO_3	The chemical formula for bisulphate

HVAC	Heating Ventilation and Air Conditioning
Hydrated lime	A common name for calcium hydroxide; $Ca(OH)_2$, also known as slaked lime
IAPP	International Air Pollution Prevention
Ion	An atom or molecule or group that has lost or gained one or more electrons and so is electrically charged (positive or negative)
Ionisation	The process of being dissociated into ions
IFO	Intermediate Fuel Oil
IMO	International Maritime Organization
ISO	International Standard Organization
km	kilo meter
kW	kilo watt
LBF	Liquid bio fuel is made from vegetable oil, which also can be used directly as unprocessed fuel
LSFO	Low sulphur Fuel Oil
m	meter
m^3/MWh	cubic meters per megawatt hour
MARPOL	International Convention for the Prevention of Marine Pollution from Ships
MDO	Marine Distillate Oil
MEPC	Marine Environment Protection Committee, e.g. MEPC 60 was the sixtieth session of this IMO group and MEPC Resolution 184(59) was adopted at the fifty-ninth session
MGO	marine gas oil
MJ	Mega Joule (10^6); joule is a unit for work or energy.
MSD	Medium-Speed Diesel engine
Mt	megaton, 1 million tonnes; 1 x 10^6 tonnes
MW	mega watt
µm	micrometer
µg	microgram
µmol	micro mol
Na^+	The chemical symbol for sodium ion
NaOH	The chemical formula for sodium hydroxide
Na_2SO_3	The chemical formula for sodium sulphite
Na_2SO_4	The chemical formula for sodium sulphate
NDIR	Non-dispersive infrared sensor; a spectroscopic device used to measure the concentration of gaseous emissions, for example NOx and CO_2 from an engine
NH_3	The chemical formula for ammonium
$(NH_4)_2SO_4$,	The chemical formula for ammonium sulphate

$(NH_4)HSO_4$	The chemical formula for ammonium bisulphate
N	The chemical symbol for nitrogen
N_2O	The chemical formula for nitrous oxide
Nitrate	An ionic compound of nitrogen and oxygen; NO_3^-
nm	nano meter
Nm^3/h	Normal cubic metres per hour; the volumetric flow rate of a gas corrected for temperature and pressure
NO	The chemical formula for nitrogen monoxide
NOx	The chemical formula l for nitrogen oxides
O	The chemical symbol for oxygen
O_3	The chemical formula l for ozone
OC	Organic Carbon
OGV	Ocean going vessel
OH^-	The chemical formula for hydroxide ion
OM	Organic Matter
OMM	Onboard Monitoring Manual
P	The chemical symbol for phosphorus
Pa	Pascal; the SI unit of pressure
PAH	Polycyclic Aromatic Hydrocarbon
pH	A measure of the acidity or basicity of a solution
Phenanthrene	A polycyclic aromatic hydrocarbon and one of the USEPA's 16 priority pollutants; $C_{14}H_{10}$
Phosphate	An ionic compound of phosphorus and oxygen
PM	particulate matter
PM_{10}	particulate matter with an average size < 10 µm
$PM_{2,5}$	particulate matter with an average size < 2,5 µm
$PM_{0,1}$	particulate matter with an average size < 0,1 µm
ppb	parts per billion
ppm	parts per million
PREN	Pitting Resistance Equivalent number; indicates the ability of a stainless steel to resist pitting corrosion
PSC	Port State Control
rpm	revolutions per minute
RFO	residual fuel oil
S	The chemical symbol for sulphur
Salinity	A measure of the concentration of all the salts and ionic compounds in water
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
SCR	Selective Catalytic Reduction

SECA	Sulphur Emission Control Area
SECC	SOx Emissions Compliance Certificate
SEPC	SOx Emissions Compliance Plan
SFOC	Specific fuel oil consumption
SSD	Slow-Speed Diesel engine
SI	Systeme International d'Unites: a complete metric system of standard units of measurement
Slaked lime	A common name for calcium hydroxide; $Ca(OH)_{2,}$ also known as hydrated lime
SO_x	The chemical formula for sulphur oxides
SO_2	The chemical formula for sulphur dioxide
SO_3	The chemical formula for sulphur trioxide
$SO_3{}^{2-}$	The chemical formula for sulphite
SO_4^{2-}	The chemical formula for sulphate
Solute	A substance that dissolves in another (the solvent), to form a solution
SOx	The generic term for sulphur oxides
Spectroscopy	The study of the way in which atoms absorb and emit light electromagnetic radiation
SWFGD	Flue Gas Desulphurization using seawater
TA	Total Alkalinity
Tg	teragram
t/MWh	tonnes per megawatt hour
UN	United Nations
Urea	The name of an organic compound containing carbon, nitrogen, oxygen and hydrogen; $(NH_2)_2CO$
US	United States
USEPA	United States Environmental Protection Agency
UV	Ultraviolet light
V_2O_5	The chemical formula for vanadium pentoxide
Vapour pressure	The pressure exerted by a vapour in equilibrium with its condensed phases in a closed vessel; a substance with a high vapour pressure at normal temperatures is often referred to as volatile
Venturi	A device with a tapered central constriction that causes an increase in fluid velocity and a corresponding decrease in fluid pressure
Viscosity	a measure of the resistance of a fluid which is being deformed by either shear stress or tensile stress
VOC	volatile organic compounds
vppm	volume parts per million

WMC	water mist catcher
wt	weight

1. Introduction

Shipping is the most important means of transportation today and most probably for the next decades as well. Approximately 90 % of the global cargo is moved by vessels powered by large diesel engines which are fueled with residual fuel oils [Jürgens 2009].The world shipping fleet consists of over 100,000 vessels larger than 100 gross tonnes [Corbett 2003], consumes up to 289 million tonnes of fuel per year [Corbett 2003; Endresen 2003; Eyring 2005] and has estimated future growth of 2 – 6 % a^{-1} [Corbett 2006; Eyring 2005b].

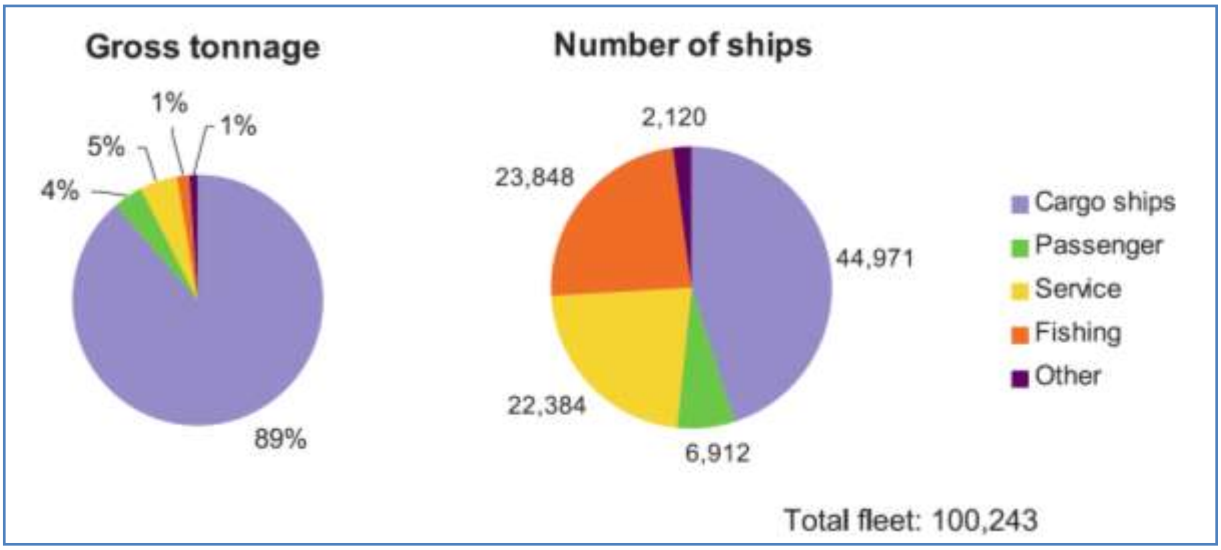


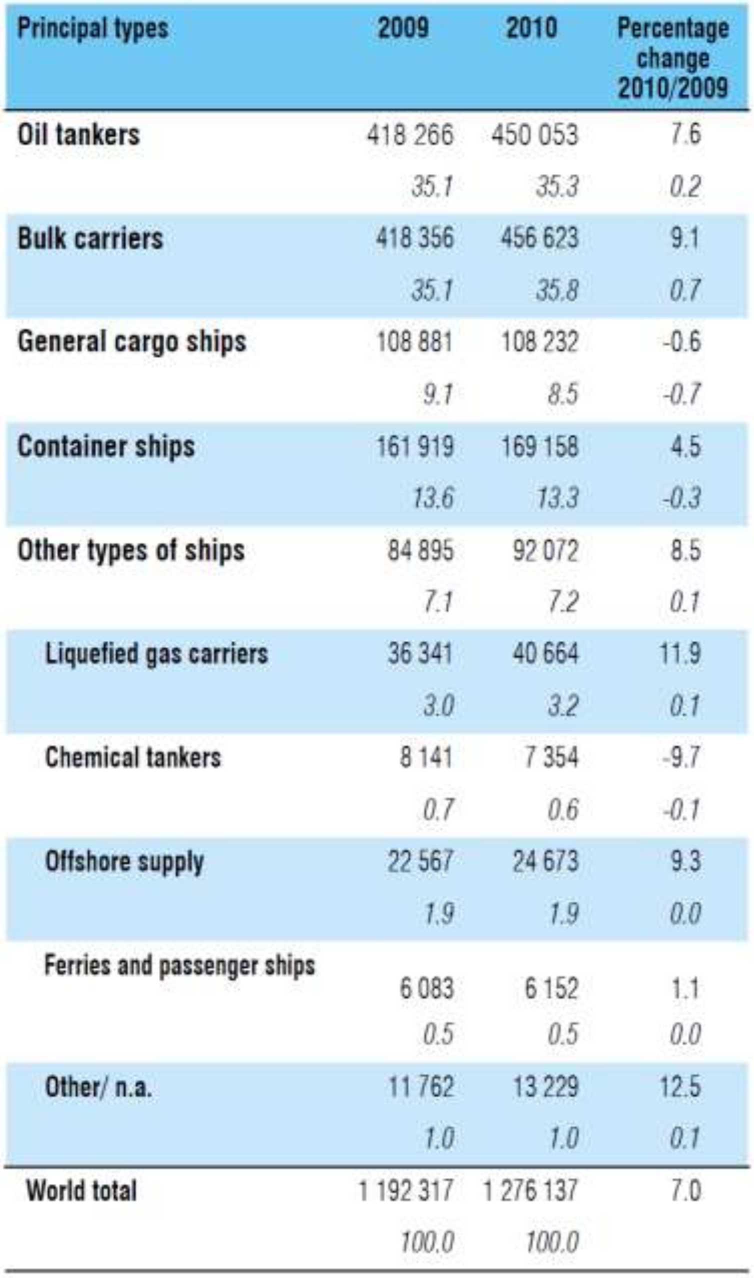
Figure 1: Composition of the world fleet [Lloyds 2007]

At the beginning of 2010, the world merchant fleet reached 1,276 million deadweight tons (dwt), an increase of 84 million dwt (7 per cent) over 2009. This growth resulted from record new deliveries of 117 million dwt, as against demolitions and other withdrawals from the market of approximately 33 million dwt. In spite of the economic crisis, new deliveries in 2009 grew by 42 per cent over 2008 as a result of ships having been ordered prior to the downturn in demand. The resulting oversupply of tonnage then led to a surge in demolitions of older tonnage by more than 300 per cent [UN 2010].

In 2009, China overtook Germany as the third-largest ship owning country, surpassed Japan as the second-biggest shipbuilding country, and replaced India as the busiest ship-recycling country. China has also emerged as an important provider of ship finance, supporting owners and shipyards in avoiding the cancellation of ship orders [UN 2010].

In January 2010, there were 102,194 commercial ships in service, with a combined tonnage of 1,276,137 thousand dwt (Table 1). Oil tankers accounted for 450 million dwt (35.3 per cent) and dry bulk carriers for 457 million dwt (35.8 per cent), representing annual increases of 7.6 and 9.1 per cent respectively. Container ships reached 169 million dwt – an increase of 4.5 per cent over 2009 – while the fleet of general cargo ships declined during 2009, reaching 108 million dwt in January 2010, corresponding to just 8.5 per cent of the fleet.

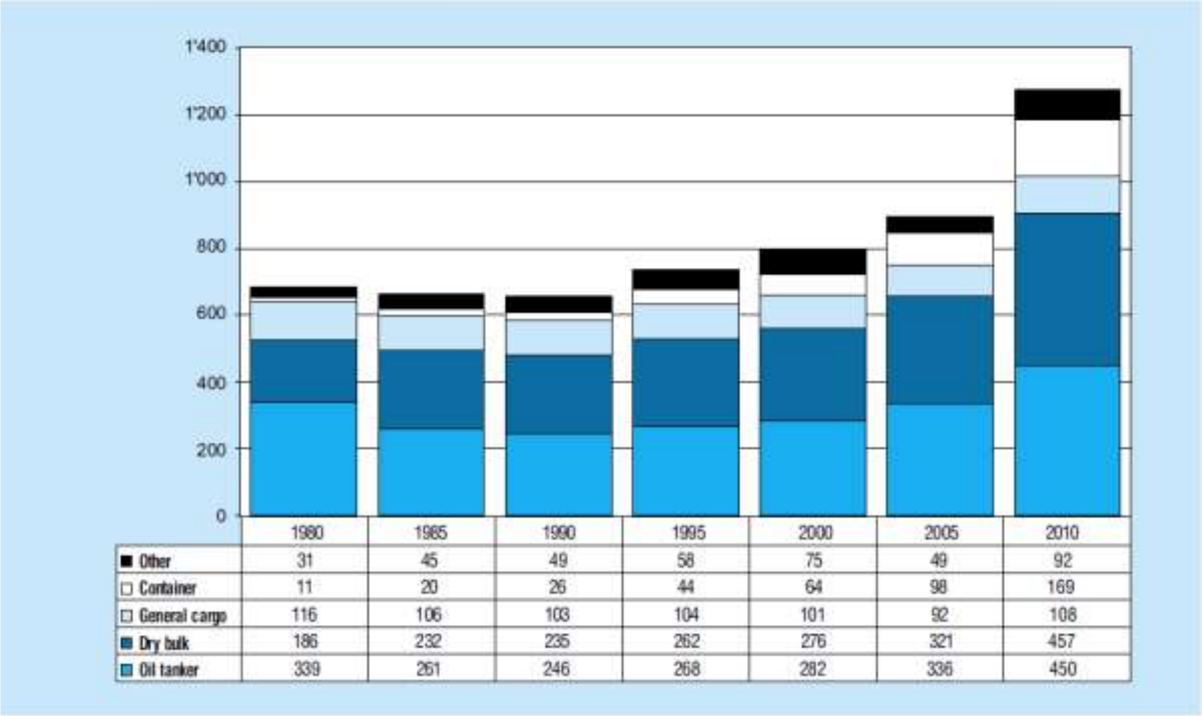
Among other vessel types, the tonnage of liquefied gas carriers continued to grow, reaching 41 million dwt. This was an increase of almost 12 per cent over 2008, in which deliveries had already reached a historic high.



Principal types	2009	2010	Percentage change 2010/2009
Oil tankers	418 266	450 053	7.6
	35.1	*35.3*	*0.2*
Bulk carriers	418 356	456 623	9.1
	35.1	*35.8*	*0.7*
General cargo ships	108 881	108 232	-0.6
	9.1	*8.5*	*-0.7*
Container ships	161 919	169 158	4.5
	13.6	*13.3*	*-0.3*
Other types of ships	84 895	92 072	8.5
	7.1	*7.2*	*0.1*
Liquefied gas carriers	36 341	40 664	11.9
	3.0	*3.2*	*0.1*
Chemical tankers	8 141	7 354	-9.7
	0.7	*0.6*	*-0.1*
Offshore supply	22 567	24 673	9.3
	1.9	*1.9*	*0.0*
Ferries and passenger ships	6 083	6 152	1.1
	0.5	*0.5*	*0.0*
Other/ n.a.	11 762	13 229	12.5
	1.0	*1.0*	*0.1*
World total	1 192 317	1 276 137	7.0
	100.0	*100.0*	

Table 1: World fleet size by principal vessel types 2009-2010 (beginning of year figures, thousands of dwt) [UN 2010]

The long-term trend in the composition of the world fleet is illustrated in figure 2. During the last decade, the container ship fleet has grown by 154 per cent and the dry and liquid bulk fleet has grown by about 50 per cent, while general cargo tonnage has remained relatively stable. Since 1980, the share of containerized tonnage has increased eightfold, against a reduction by half of the general cargo fleet; this is a reflection of the increased containerization of the trade in manufactured goods. The last five years have seen a historic surge in the total tonnage, by 42 per cent; this includes a 72 per cent increase in the containerized fleet.



	1980	1985	1990	1995	2000	2005	2010
■ Other	31	45	49	58	75	49	92
□ Container	11	20	26	44	64	98	169
□ General cargo	116	106	103	104	101	92	108
■ Dry bulk	186	232	235	262	276	321	457
■ Oil tanker	339	261	246	268	282	336	450

Figure 2: World fleet by principal vessels, selected years (beginning of year figures, thousands of dwt) [UN 2010]

The global fleet will increase by 35 % over the next five years and 60 % by 2020 [Meech 2008] which corresponds to the 7 % of growth in 2009 reported by the United Nations [UN 2010]. The world financial crises may delay this process by 2 or 3 years.

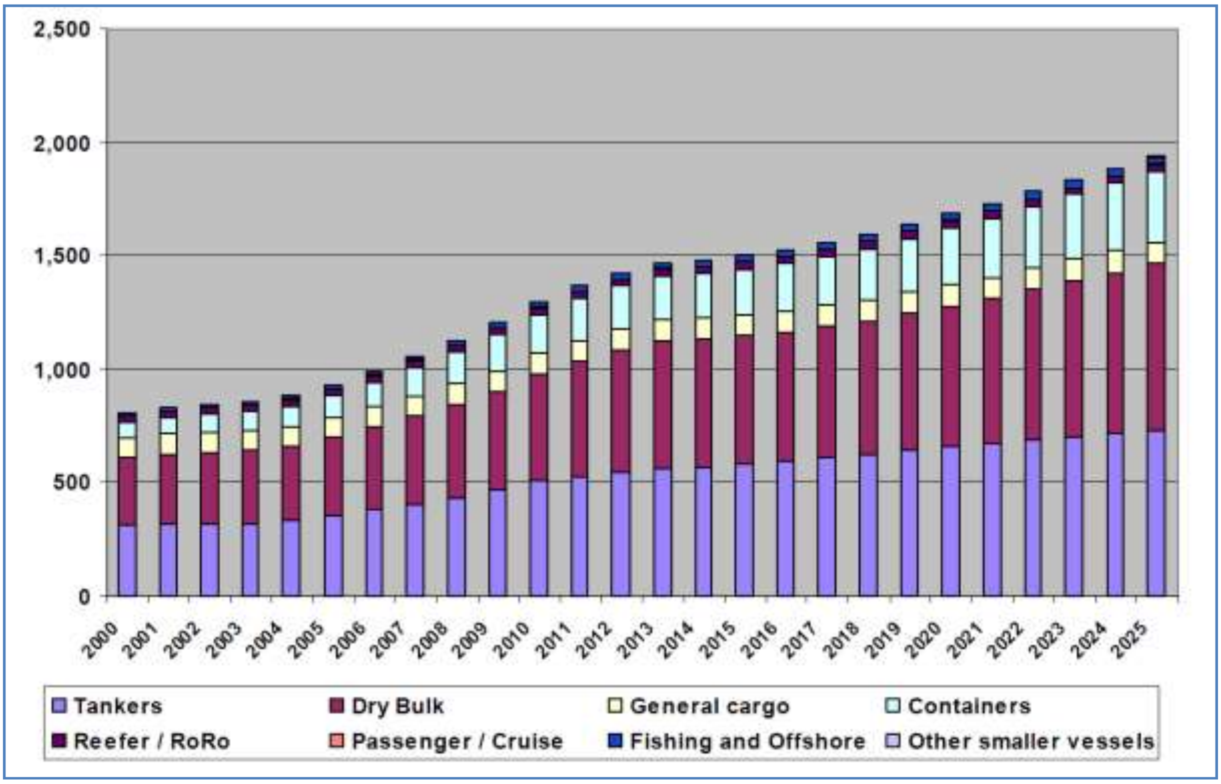


Figure 3: Prediction of growth rate of the global fleet [Meech 2008]

Oceangoing ships running large slow-speed diesel (SSD) engines generally burn low-quality residual fuels that tend to contain high amounts of sulphur and heavy metals [Lack 2009]. Smaller vessels, such as tugboats, fishing vessels and ferries operate medium-speed diesel (MSD) engines that use mostly distillate fuels within non-road equipment fuel quality standards [USEPA 2004]. International commercial shipping vessels operate across international waters with little or inconsistent regulation of fuel quality or pollution emissions; domestic fleets serve coastal shipping, resource extraction, harbor service, and vessel assist duties.

Aside from CO_2 and H_2O vapor, the expected gas phase products of fuel combustion from shipping (ranked on a mass basis) include nitrogen oxides (NOx), sulphur dioxide (SO_2) and carbon monoxide (CO) [Williams 2008]. CO_2 is the most ubiquitous greenhouse gas and emissions from commercial shipping vessels represent app. 3.3 % of global anthropogenic emissions (excludes CO_2 from land use change) [Eyring 2005a].

NO_X is a catalyst in tropospheric ozone (O_3) formation which has both health and climate impacts [IPCC 2007] and shipping contributes app. 15 – 30 % to global fossil fuel sourced NOX emissions [Corbett 2007a].

Commercial shipping is estimated to contribute 5 – 8 % of global anthropogenic SO_2 emissions [Eyring 2005a]. Gaseous oxides of sulphur produced during combustion of fossil fuels can be oxidized to particulate sulfate (SO_4^{2-}). In addition to SO_4^{2-} formed from SO_2, particulate emissions from shipping include black carbon (BC), organic matter (OM) and ash [Petzold 2004], which include particles of fuel-bound minerals and heavy metals.

Globally, shipping is thought to contribute almost as much primary PM as road traffic (1.7 Tg a^{-1} compared to 2.1 Tg a^{-1} [Eyring 2005a]), including 1.7 % of global total BC emissions [Lack 2008a] and 7.5 % of fossil and biofuel sourced OM emissions [Ito 2005, Wang 2008]. Field observations of the chemical composition of PM emissions from shipping vessels are scarce. Hobbs et al. [Hobbs 2000] ruled out BC, SO_4 salts and ammonium nitrate as major contributors to the direct PM from ship emissions; and their results for BC are consistent with engine tests that show high-temperature, high-pressure engines (e.g., large marine engines) are efficient at converting fuel carbon to CO_2.

Results of volatility experiments from Hobbs et al. [Hobbs 2000] showed that the major components of the PM were high boiling point organics with some sulphuric acid. Kasper et al. [Kasper 2007] and Petzold et al. [Petzold 2008] both found, that after passing PM through a thermal denuder, condensation nuclei (CN) emission factors decreased from 35 to 90 % suggesting that much of the PM from marine diesel engines is in the form of externally mixed volatile particles, supporting the findings of Hobbs et al. [Hobbs 2000]. Petzold et al. [Petzold 2008] estimated that PM emissions from a marine diesel engine burning heavy fuel oil (HFO) in controlled laboratory conditions (at 25 % engine load) contained organic carbon (OC, 7 %), SO_4^{2-} (38%), SO_4-bound water (30 %), BC (7 %) and ash (7 %).

Kasper et al. [Kasper 2007] measured mass emissions from a two-stroke marine diesel engine burning both residual and distillate marine fuels; that study reported that PM emissions contained ∼ 17 % OC and ∼ 17 % elemental carbon (EC). Sax and Alexis [Sax 2007] compiled and reviewed PM mass emission factors from stack tests of marine diesels on oceangoing vessels. They summarized more than 10 unique studies and presented an averaged PM mass-based emission factor for ships burning marine distillate oil (MDO, fuel sulphur content ∼ 0.25 %) and HFO (fuel sulphur content ∼ 2.5 %). Sax and Alexis's [Say 2007] review reveals large variability in PM mass emissions, with only a weak relationship between PM emissions and fuel sulphur content for HFO-burning vessels. This variability was also demonstrated in the Lloyd's Register [Lloyds 1995] study for PM mass and by Lack et al. [Lack 2008] for BC emissions.

Hobbs et al. [Hobbs 2000], Petzold et al. [Petzold 2008], Kasper et al. [Kasper 2007], Frick and Hoppel [Frick 2000], and Durkee et al. [Durkee 2000] all investigated size distributions of PM emissions from marine diesel engines and found the majority of particles having diameters from 10 to 100 nm with very few above 250 nm. Lyyranen et al. [Lyyranen 2002] found additional modes around 2 and 10 mm which formed from heavy metals (i.e., ash) and fuel residue particles respectively. Lyyranen et al. [Lyyranen 1999] showed that although the size distributions of PM from large and small marine diesel engines were very similar, the absolute magnitude of PM mass from the smaller engines was higher by as much as a factor of two.

Emissions from commercial shipping vessels contribute significantly to perturbations in air quality, visibility and climate. The link between PM emissions and health effects was recently assessed for global shipping emissions when Corbett et al. [Corbett 2007] estimated that up to 60,000 premature deaths result annually. The primary reason for the efficacy of shipping emissions to health is because 70 % of shipping occurs within 400 km of land [Corbett 2007; Wang 2008] and major shipping ports are located in areas surrounded by large populations.

The World's marine governing bodies have introduced a number of legislative regulations to reduce future airborne emissions levels from ships. The International Marine Organisation (IMO) introduced legislation to prevent pollution under the MARPOL 73/78 regulations *"The International Convention for the Prevention of Pollution from Ships"* [IMO 1983], Annex VI, *"Prevention of Air Emissions from Ships",* specifically deals with air emissions, which was amended by MARPOL 93/97 [IMO 2004]. Its aims were offset future global limits for nitrogen oxides (NOx), sulphur oxides (SOx) and particulate matter (PM) emissions from shipping through the implementation of technology and best practises. The regulations set current and future limits on NOx, SOx and PM emissions acceptable from a ship based on the available and developing technologies and techniques to reduce emissions.

The objectives of TEFLES include identifycation and development of the most efficient after treatment technology with respect to lowest emissions and highest energy efficiency. The most efficient after treatment technology will depend on the engine and fuel type, rating etc.. However, there will be obviously no one-size-fit-all solution but differing solutions for vessel types such as feeder, bunker, tanker and ferries.

Also we will see different designs for new builds and retrofits as i.e. the integration of ATT into the design of a new build appears to be a lot easier as opposed to a retrofit.

1.1. Legal Framework

In certain geographic areas, environmental regulations require that ship operators burn low sulphur fuel to directly limit sulphur-oxide emissions. A secondary, but important consideration is that these measures are expected to indirectly reduce particulate matter emissions. As an alternative to utilizing low-sulphur fuel, MARPOL Annex VI recognizes exhaust gas cleaning systems (EGCS) provided they provide reductions in sulphur emissions at least as effective as that obtained by using low-sulphur fuel [Reynolds 2011].

The geographic scope of these requirements is a patch-work that includes International Maritime Organization (IMO) designated emissions control areas (ECAs), European Union (EU) designated port areas, and a California State designated coastal zone. Each of these programs has its own phased implementation schedule, but all reach a fuel quality limit of 0.1% sulphur on or before 1 January 2015.

ECAs currently in force include the Black Sea and Baltic Sea, and will expand to add the North American zone, extending approximately 200 nautical miles offshore, in 2012. Zones for Puerto Rico and U.S. Virgin Islands have been accepted, and submittals are being prepared for Korea, Japan, and Singapore. Eventually, the ECA scope may include all coastal areas of the world. The area outside of ECAs is subject to world-wide limits set by IMO. The current world-wide sulphur limit of 4.5 % is more generous than typical fuel quality which averages 2.7 % sulphur by weight. This limit changes, in principal, to a 3.5 % sulphur limit in 2012. This limit changes, in practice, to a world-wide sulphur limit of 0.5 % in either 2020 or 2025 depending on a fuel availability review to be conducted in the interim.

Ship's that operate on international voyages are generally subject to the agreements of the IMO, as detailed in Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL). These requirements are comprehensive including requirements for low sulphur fuel or sulphur scrubbing, particulate matter and nitrogen oxide levels, and hydrocarbon management. In addition, significant recordkeeping and certifications are required.

Flag State is a general term referring to the administration where a ship is registered. Flag States that are party to Annex VI are required to enforce the annex within the international ocean going fleet that they administer. In some cases, such as the United States, the Flag State may have additional requirements.

Port State is a general term referring to an administration that controls a port(s) where ships registered by other administrations may call. Port States that are party to Annex VI have the right to board commercial ships arriving from international voyages to determine compliance with the Annex. In general, the Port State will review documentation in accordance with the Annex, and perform a visual inspection of any installed equipment. There are numerous exemptions and exceptions from Annex VI.

Ship operators considering such exemptions and exceptions should perform a detailed analysis of the Annex, and gain acceptance from their Flag State prior to implementing a strategy. In general, exemptions include: vessels under 400 gross tons (international), diesel engines less than 130 kW output, technology research trials, emergency equipment, emergency situations, military and government vessels, emissions from sea-bed mineral exploration. There are also time phased exemptions for older ships, specifically for engines manufactured prior to 1990. Additionally, there are exclusions based on geographical considerations such as transport on the US/Canada Great Lakes where regional agreements are more appropriate [Reynolds 2011].

1.1.1 International Maritime Organization MARPOL Annex VI

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 1.5 % 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 6 g SOx/kWh was permitted [Gregory 2010].

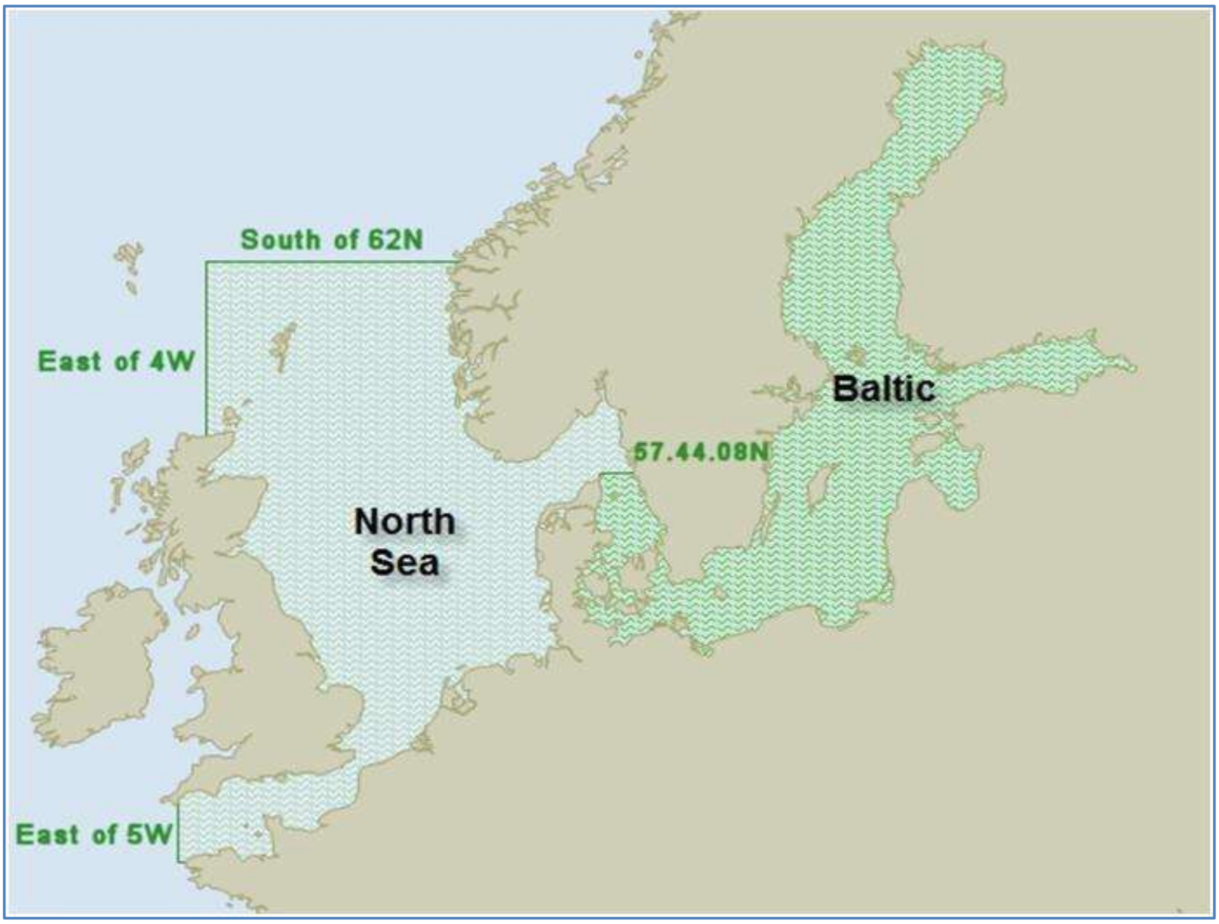


Figure 4: North Sea and Baltic Emission Control Areas

For the reduction and monitoring of green house gases (GHG) emissions the IMO developed and adoption regulations, such as *"Interim Guidelines for Voluntary Ship CO_2 Emission Indexing for Using in Trials (2005)"* [MEPC 2005a] and *"Guidelines for Voluntary use of the Ship Energy Efficiency Operational Indicator (EEOI-2010)"* [MEPC 2009a]. GHG emissions covered in these regulations include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The EU implemented similar regulations setting limits on marine emissions, such as *EU Sulphur Directive 2005/33/EC*, setting limits for SOx and PM emissions from marine traffic in EU territorial waters and the setting up of Emission Control Areas (ECA) in line with MARPOL 93/97 Annex VI [EU 2005]. The international and European legislation gave a real intent to reduce maritime pollution through reductions of SOx, NOx, PM and CO_2, as well as CO, volatile organic compounds (VOC; including methane) and N_2O. Figure 5 shows the various emission abatement policies adopted by the EU and IMO from 2004 to 2010.

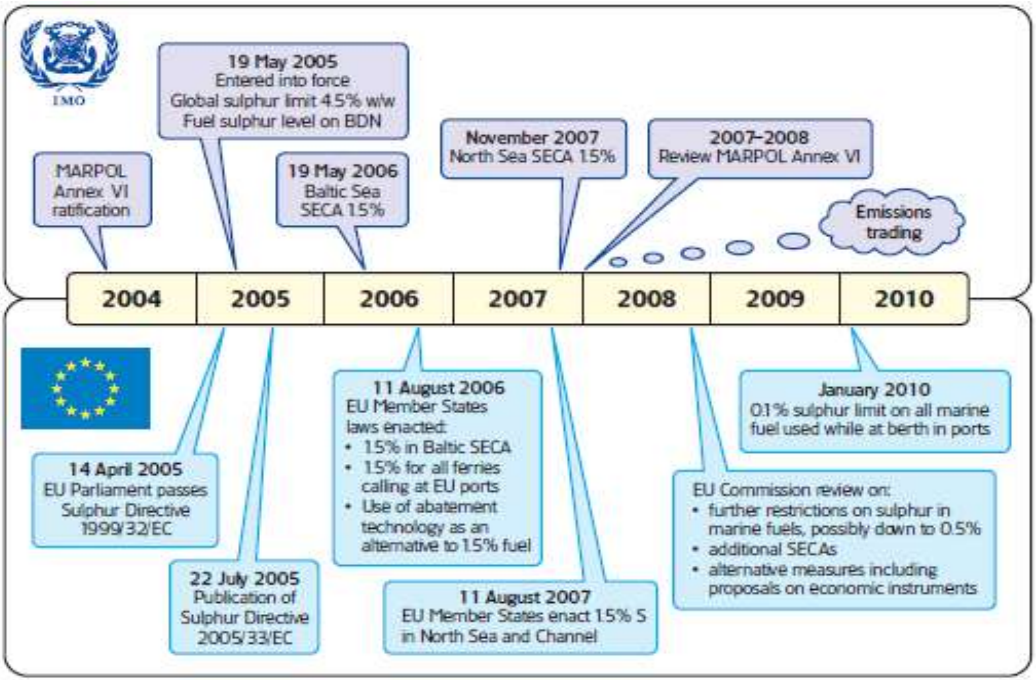


Figure 5: EU and IMO legislative timeline [IPIECA 2009]

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 is 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 (PM) 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 ECA's by reduction of fuel sulphur first to 1.0 % in July 2010 and then 0.1 % in January 2015.

Outside of ECA's, the current global limit of 4.5% sulphur-in-fuel will be reduced to 3.5 % in 2012, then 0.5 % in 2020 or 2025 depending on a review in 2018 to determine the availability of fuel to enable implementation of this standard.

Annex VI now uses the sulphur content of fuel as a way of defining SOx emissions and specific emissions limits (g SOx/kW h) 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 ECA's 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 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 130(53).

Marine Exhaust Gas Cleaning Systems have generally 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 now at least one supplier of a 'dry' system that uses granulated lime as a scrubbing medium. The Guidelines for Exhaust Gas Cleaning Systems have therefore 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 parameter and emission checks to confirm performance in service; and
- "Scheme B" - performance confirmation by continuous monitoring of emissions with parameter checks.

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

As practical experience has grown, the Guidelines for Exhaust Gas Cleaning Systems have been reviewed with a particular focus on "washwater" emissions. This enabled an updated version to be adopted in 2008 - IMO Resolution 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 184(59), was adopted and this latest version replaced 170(57) in July 2010. The new Guidelines reflect the changes to Annex VI and include the SO_2/CO_2 ratios relating to various levels of sulphur-in-fuel, as the requirement to determine a specific SOx emissions value in g/kW h is no longer required. It was once again agreed that the washwater discharge criteria should continue to be reviewed taking into account advice received from GESAMP.

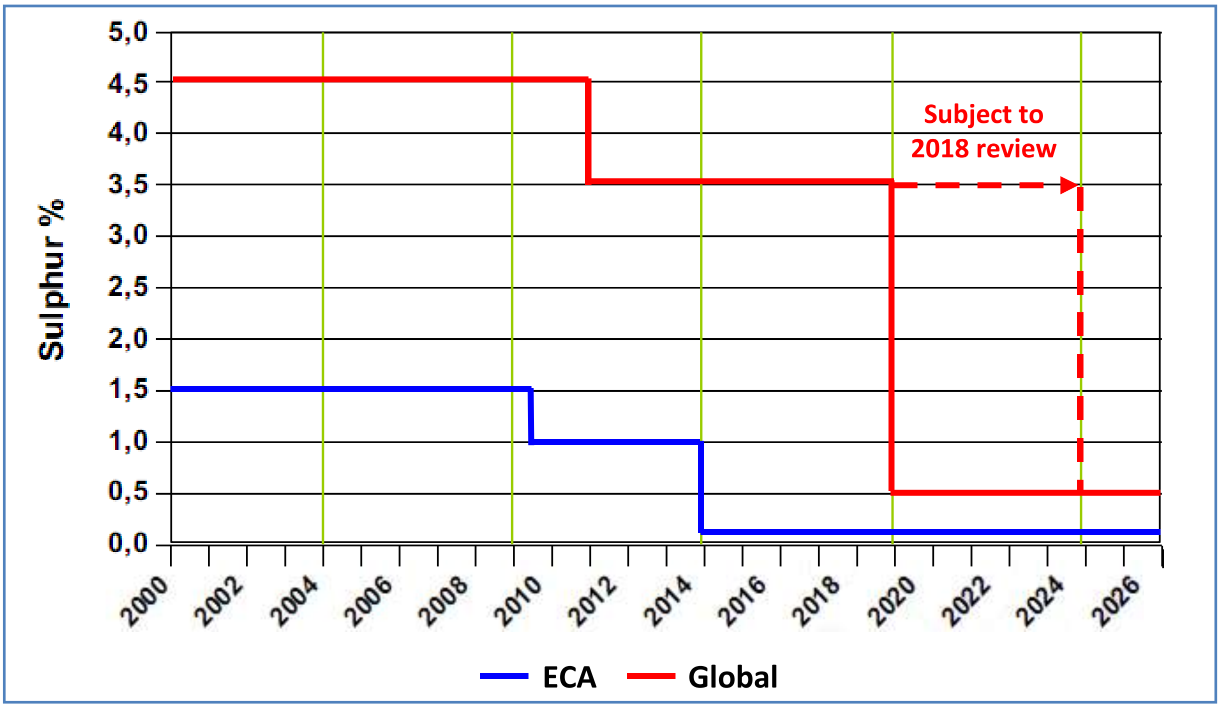


Figure 6: IMO timeline for reduction in fuel sulphur content

1.1.2 EU Directive 2005/33

In addition to IMO's regulations for the North Sea and Baltic ECA's, European Council Directive 2005/33 (which amends EC Directive 1999/32) requires all vessels in a European Union member state port, at berth or at anchor to use 0.1 % sulphur fuel. The Directive also requires that during “regular” service between member state ports and in European Union waters, passenger vessels must use a 1.5 % sulphur fuel. 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 EC 2005/33 applies - 1.5 % sulphur fuel
- In ECAs the IMO limit applies – 1.0 % sulphur fuel
- In EU port for more than 2 hours EC 2005/33 applies – 0.1 % sulphur fuel

Whilst in transit, passenger ships on regular service between EU ports could use 1.0 % 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 [Gregory 2010].

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

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

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

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

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

Recently it has been reported that the EC is in the process of amending European Union law to harmonise sulphur regulations for ships with the latest amendments to MARPOL Annex VI. The aim is to complete the proposed amendments by end 2010, which will then need to be adopted by the European Council and Parliament before being published sometime in 2011 [Bunkerworld 2010].

In the meantime the EC has issued official advice confirming the stricter IMO sulphur-in-fuel limits must be used during this interim period [EU 2011].

1.1.3 USA and Canada

Federal regulation in the United States applies to all vessels flagged or registered in the United States. In addition, the U.S. has the authority and has stated that it will enforce IMO Annex VI on all U.S. and foreign vessels operating in U.S. waters, as per the Act to Prevent Pollution from Ships. U.S. regulation of air emissions is dictated by the U.S. Environmental Protection Agency. As such, rather than regulating by the international standard of engine speed, diesel powered compression engines are broken into three categories designated by the engine cylinder volume [Reynolds 2011].

Category 3 vessels, those with an engine of cylinder displacements above 30 liters, are required to meet equivalent standards to MARPOL Annex VI. In addition, the U.S. is finalizing standards for Category 3 engine to control hydrocarbons (HC) and carbon monoxide (CO), as well as monitoring of particulate matter (PM) emissions. Control of Emissions From New Marine Compression-Ignition Engines at or Above 30 Liters per Cylinder (40 CFR Parts 80, 85, 86, et al.) took effect in June 2010. This rule is equivalent to the IMO Annex VI that governs ocean going vessels (OGV). Like Annex VI, it includes fuel standards targeting sulphur emissions and a phased in schedule for NOx reductions. EPA
has indicated two important clarifications to the rules governing OGVs:

- Category 1 and 2 engines on Category 3 vessels can be certified as meeting Annex VI instead of gaining EPA certification.
- OGVs that are Category 1 or 2 vessels and operate offshore extensively, can comply with Annex VI as an alternate to meeting EPA designated tier requirements.

Category 1 and 2 vessels, those with cylinder displacements below 30 liters that are not OGVs are required to meet the more stringent EPA 2008 Final Rule.

In March 2010 the sixtieth session of the IMO Marine Environmental Protection Committee (MEPC 60)[MEPC 2010a] adopted a proposal from the USA and Canada for ECAs extending 200 nautical miles from both east and west coasts and around the islands of Hawaii [MEPC 2009b, MEPC 2009c, EPA 2009]. The ECAs, which are for SOx, particulate matter and NOx will become fully implemented on or after August 2012. A similar proposal for an ECA around Puerto Rico and the US Virgin Islands was submitted by the USA for discussion at MEPC 61 in September 2010 [MEPC 2010b, EPA 2010b, MEPC 2010c]. It appears likely that the ECA will now be adopted at MEPC 62 in July 2011 with full implementation by 2014. It is a requirement of The California Air Resources Board that distillate fuel is to be used in all main and auxiliary engines and boilers within 24 nautical miles of the Californian coast unless the vessel is on “continuous and expeditious navigation”. If a vessel is calling at a

California port facility or anchorage or entering an internal water such as an estuary the following fuels must be used:

- Until January 2012 marine gas oil (MGO), with a maximum of 1.5 % sulphur, or marine diesel oil (MDO), with a maximum of 0.5 % sulphur
- After January 2012 marine gas oil (MGO, or marine diesel oil (MDO), with a maximum of 0.1 % sulphur

Abatement technologies including Exhaust Gas Cleaning Systems may be used in trials as part of an emissions control research programme officially approved by the Californian authorities. However the regulations also state that if the USA adopts and enforces requirements that will achieve emissions reductions within the regulated California waters that are equivalent to those achieved by the sulphur-in-fuel limits, then the limits will cease to apply. This appears to open the door for approved abatement technologies to be used after August 2012 under regulation 4 of the revised MARPOL Annex VI.

Figure 7: North American Emission Control Area *(Courtesy US EPA)*

Figure 8 displays the global emission restricted areas.

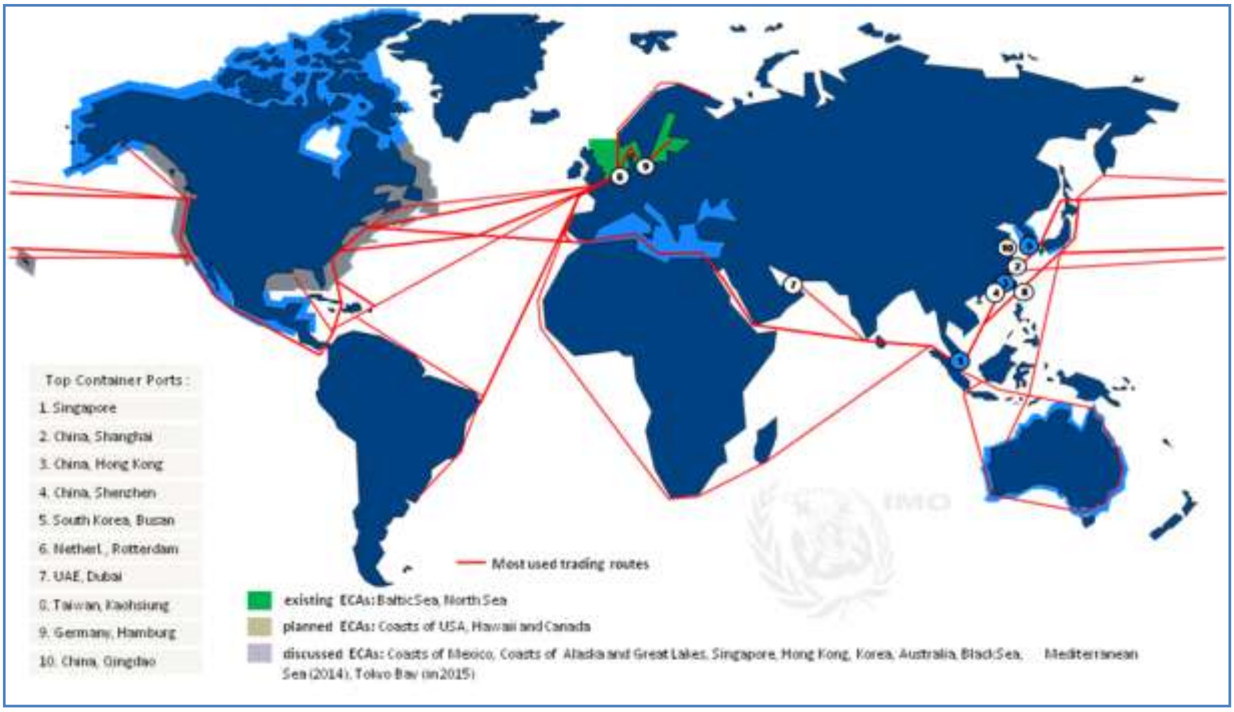


Figure 8: Emission restricted areas by IMO – ECAs in 07/2009, Source: MAN

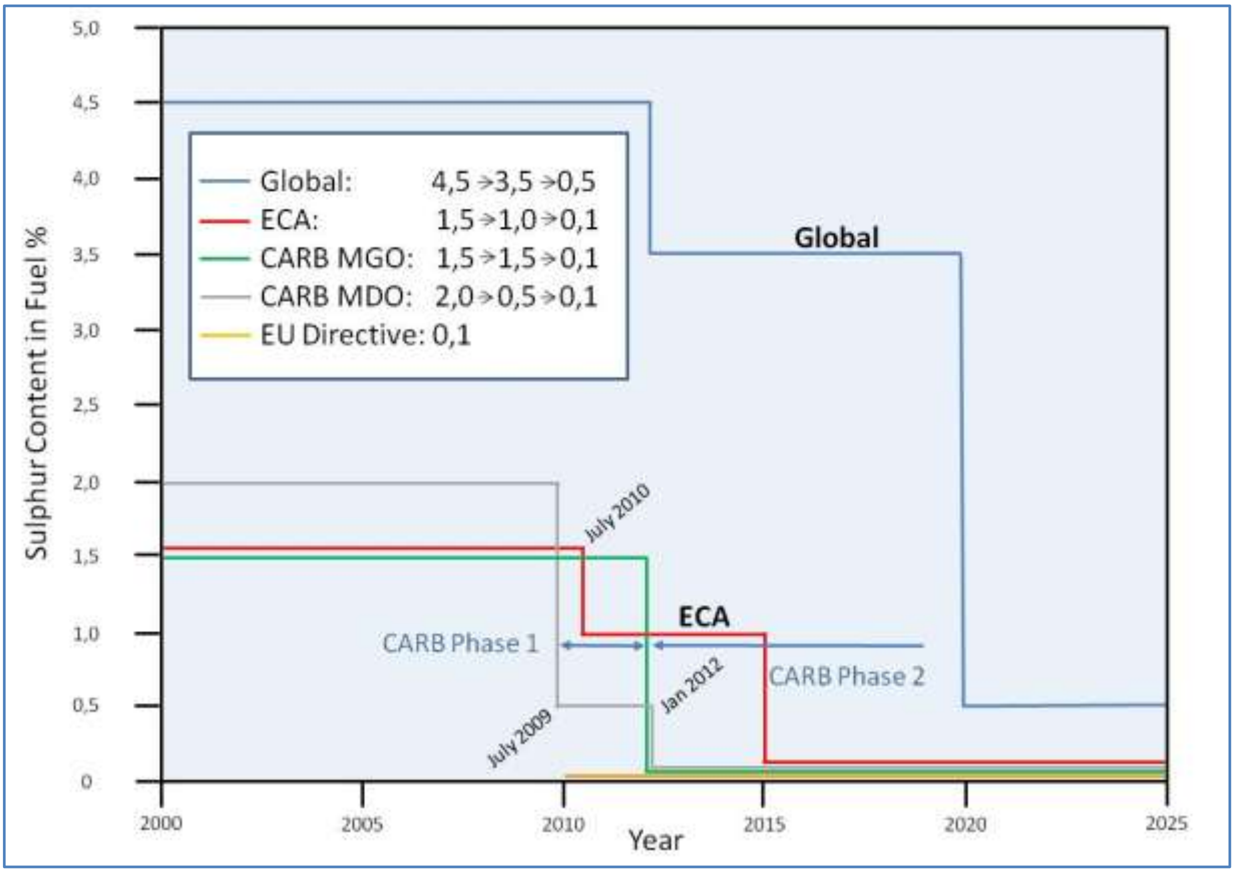


Figure 9: Global timeline for reduction in fuel sulphur content

2. Fuel Consumption in the Shipping Industry

In 2007 the global shipping industry has burned app. 369 Mill. Tons of fuel whereof 286 Mill tons were Heavy Fuel Oils (HFO) which represents app. 50 % of the world's HFO production and app. 83 Mill tons. of marine distillates (Lauer 2009].

Meech has estimated the total world bunker demand in 2007 close to 350 million tons [Meech 2008]. Inland/domestic, offshore and in harbor consumption increases this in total by some 32 Mill tons.

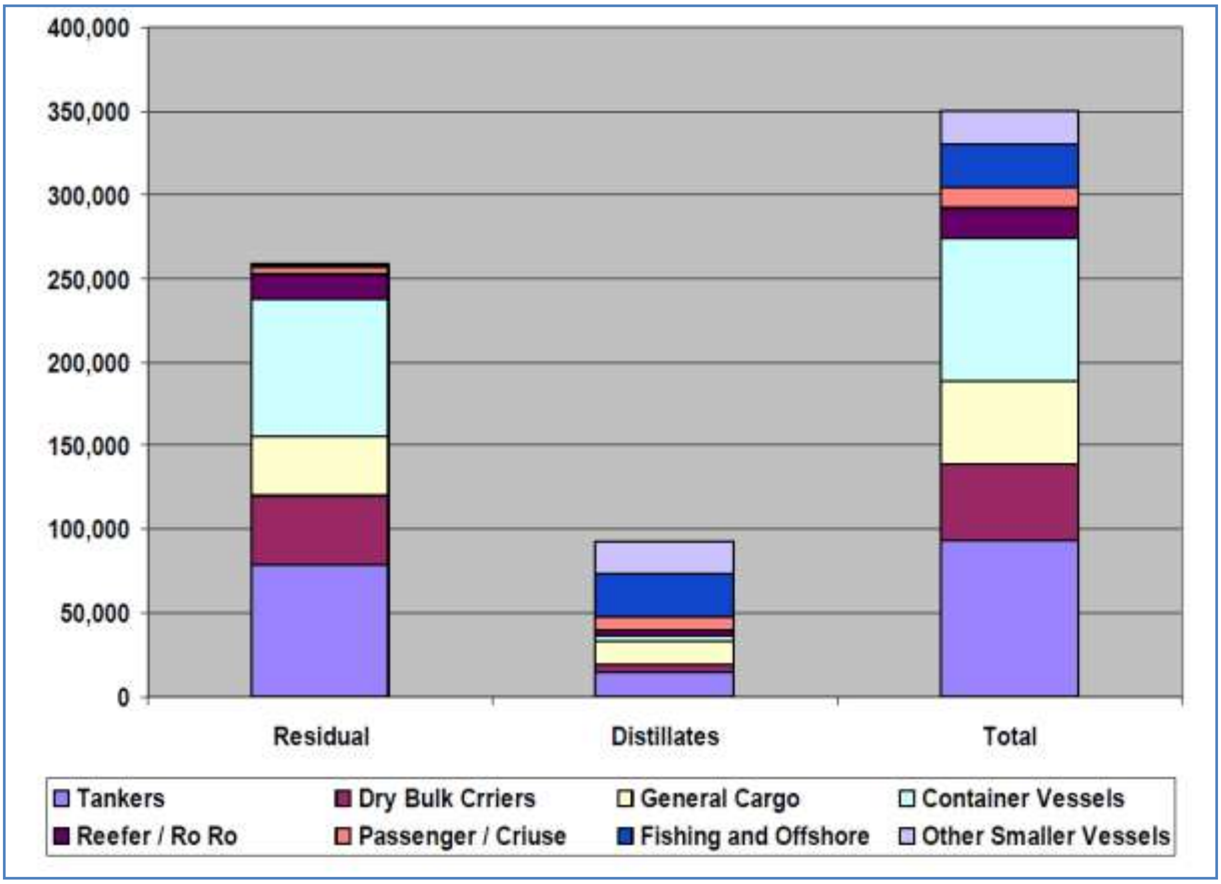


Figure 10: Global bunker demand in 2007

Marine fuels are classified as distillates and fuel oil. Fuel oil refers to residual fuel oil manufactured at the bottom end of an oil refining process; that is, the residue remaining after atmospheric distillation to 340 – 370 °C [Feng 2010; Jones 2006]. Fuel oil also calls heavy fuel oil (HFO) or Bunker fuel. HFO is the heaviest grade, and has the highest viscosity of marine fuels. It contains significant amounts of sulphur; the average sulphur content of HFO worldwide being 2.7 wt % [Endresen 2003]. Bunker fuel is the residuum from crude oil after lighter fuels have been removed: naphthagasoline, No. 1 fuel oil (No. 1 fuel oil is a light petroleum distillate, straight-run kerosene, consisting primarily of hydrocarbons in the range C9-C16), and No. 2 fuel oil (No. 2 fuel oil is characterized by hydrocarbon chain lengths in the C11-C20 range). The most commonly used bunker fuel is called No. 6 fuel oil, which is a heavy residual fuel normally a mixture of atmospheric and vacuum distillation residues cut back to adjust for viscosity with kerosene or gas oil cutter stock. Bunker fuel is more complex in composition and in impurities than distillate fuels. Limited literature data are available on the composition of bunker fuel oil. Bunker fuel oils are identified by viscosity, and sometimes, they are blended with distillates to attain the required viscosity, which are called intermediate fuel oils (IFO), of which IFO180 and IFO380 are the most commonly used.

Marine distillate fuel can be divided into two types: marine gas oil (MGO) and marine diesel oil (MDO). MGO is a light distillate fuel containing light aromatic hydrocarbons and no residual components, while MDO is a heavier distillate and may contain residual fuel oil. MDO is a blended distillate. In addition to the viscosity, a range of other characteristics, e.g. density, flash point, and pour point, are different for distillate fuels and HFO. Furthermore, distillate fuels contain lower levels of sulphur, water, metals, ashes and carbon residues. The characteristics of different marine fuels are shown in Table 2.

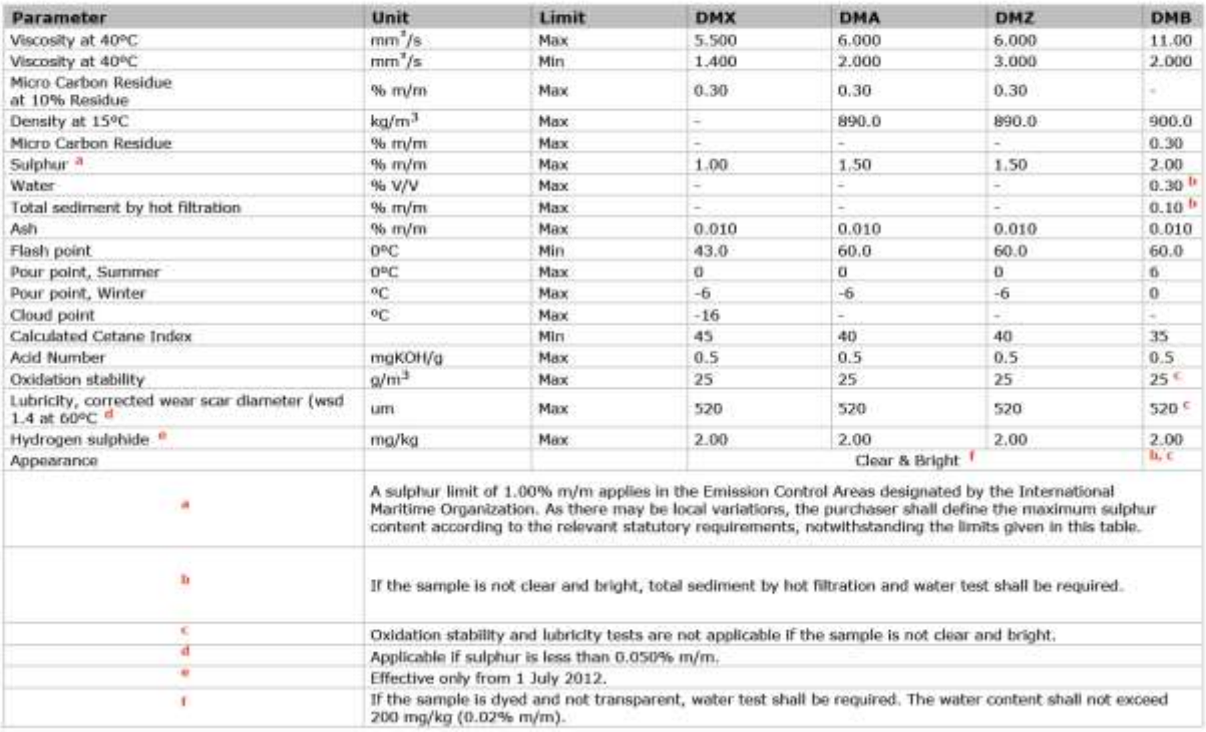
Fuel type	Characteristics
Marine gas oil, MGO	Light distillate fuel, low viscosity, low impurities
Marine diesel oil, MDO	Heavier distillate, may contain some residual components
Intermediate fuel oil, IFO	Heavy fuel oil that might contain distillate fuels
Heavy fuel oil, HFO	Residual fuel with the highest viscosity and highest levels of impurities

Table 2: Characteristics of marine fuels

The specifications of marine fuels are regulated by the International Standard Organization (ISO), usually in cooperation with the marine and petroleum industry to meet the supply worldwide for heavy shipping. There are 19 categories of residual fuels available internationally, among which, four categories or grades are most frequently supplied and used by ships.

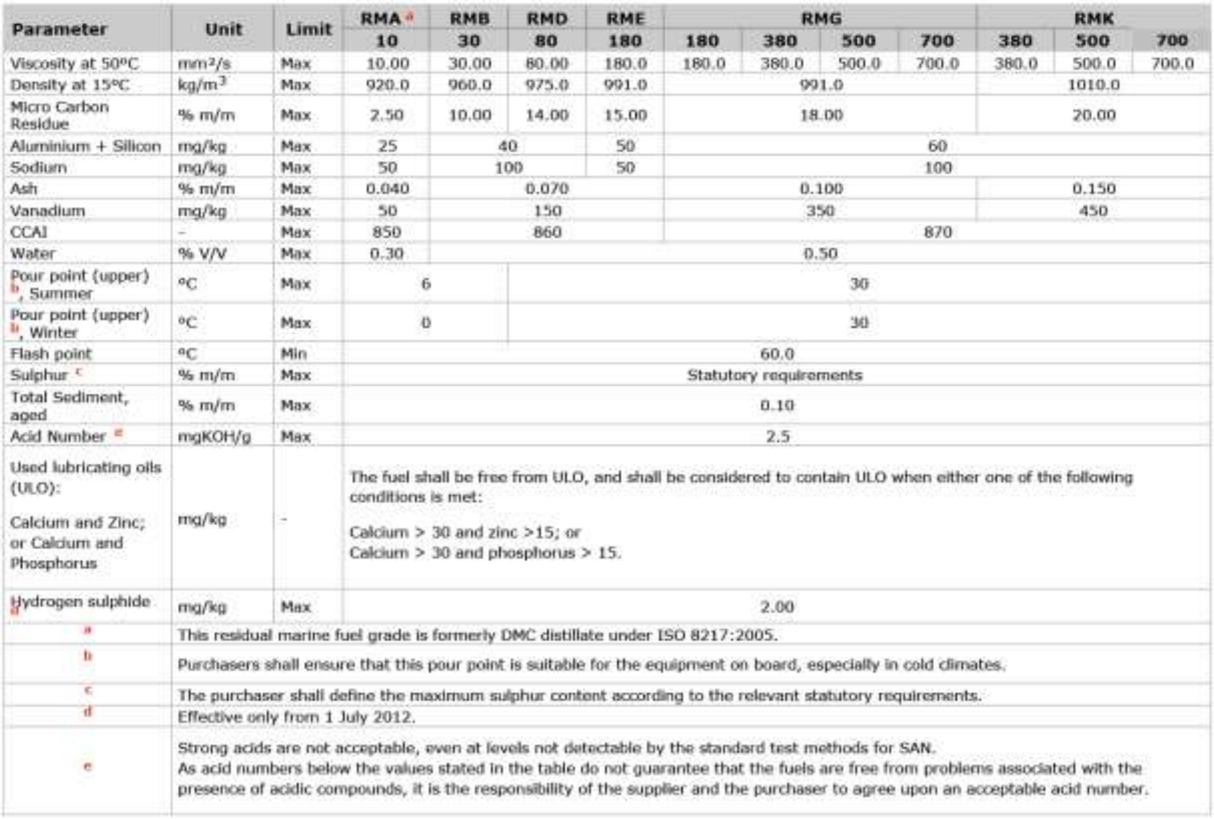
The industrial names for the four most commonly used grades are IFO-180 (Intermediate Fuel Oil), IFO-380, MDO (Marine Diesel Oil) and MGO (Marine Gas Oil), which correspond to the ISO grades RME 25, RMG 35, DMB and DMA, respectively [DNV 2010]. Industrial nomenclature is based on the fuel viscosity at 50 °C. IFO 180 indicates that the viscosity of the fuel is 180 cSt at 50 °C [Feng 2009], and IFO 380 fuel has a viscosity of 380 cSt at 50 °C. MDO is a blend of gas oil and heavy oil. MGO is clear and not blended with heavy fuel.

IFO-180 (or RME 25) contains about 6 to 7 % gas oil, while IFO-380 (or RMG 35) has about 3 % gas oil. Because of the higher gas oil content, the price of IFO-180 is higher than the heavier IFO-380 grade. MDO or DMB is a blend of heavy fuel and gas oil, and they are cheaper than pure MGO or DMA. Requirements are different for both the grades. In addition to gas oil content difference, requirements for 4 out of 11 parameters are different for the two grades. In the table, the maximum viscosity, carbon residue, ash content, and vanadium are different. The ISO specifications for bunker fuels are listed in Table 3 and Table 4, respectively.



Parameter	Unit	Limit	DMX	DMA	DMZ	DMB
Viscosity at 40ºC	mm^2/s	Max	5.500	6.000	6.000	11.00
Viscosity at 40ºC	mm^2/s	Min	1.400	2.000	3.000	2.000
Micro Carbon Residue at 10% Residue	% m/m	Max	0.30	0.30	0.30	-
Density at 15ºC	kg/m^3	Max	-	890.0	890.0	900.0
Micro Carbon Residue	% m/m	Max	-	-	-	0.30
Sulphur [a]	% m/m	Max	1.00	1.50	1.50	2.00
Water	% V/V	Max	-	-	-	0.30 [b]
Total sediment by hot filtration	% m/m	Max	-	-	-	0.10 [b]
Ash	% m/m	Max	0.010	0.010	0.010	0.010
Flash point	0ºC	Min	43.0	60.0	60.0	60.0
Pour point, Summer	0ºC	Max	0	0	0	6
Pour point, Winter	ºC	Max	-6	-6	-6	0
Cloud point	ºC	Max	-16	-	-	-
Calculated Cetane Index		Min	45	40	40	35
Acid Number	mgKOH/g	Max	0.5	0.5	0.5	0.5
Oxidation stability	g/m^3	Max	25	25	25	25 [c]
Lubricity, corrected wear scar diameter (wsd 1.4 at 60ºC [d]	um	Max	520	520	520	520 [c]
Hydrogen sulphide [e]	mg/kg	Max	2.00	2.00	2.00	2.00
Appearance			Clear & Bright [f]			[b, c]
a	A sulphur limit of 1.00% m/m applies in the Emission Control Areas designated by the International Maritime Organization. As there may be local variations, the purchaser shall define the maximum sulphur content according to the relevant statutory requirements, notwithstanding the limits given in this table.					
b	If the sample is not clear and bright, total sediment by hot filtration and water test shall be required.					
c	Oxidation stability and lubricity tests are not applicable if the sample is not clear and bright.					
d	Applicable if sulphur is less than 0.050% m/m.					
e	Effective only from 1 July 2012.					
f	If the sample is dyed and not transparent, water test shall be required. The water content shall not exceed 200 mg/kg (0.02% m/m).					

Table 3: Marine distillate fuels [DNV 2010]



Parameter	Unit	Limit	RMA [a]	RMB	RMD	RME	RMG				RMK		
			10	30	80	180	180	380	500	700	380	500	700
Viscosity at 50°C	mm²/s	Max	10.00	30.00	80.00	180.0	180.0	380.0	500.0	700.0	380.0	500.0	700.0
Density at 15°C	kg/m³	Max	920.0	960.0	975.0	991.0	991.0				1010.0		
Micro Carbon Residue	% m/m	Max	2.50	10.00	14.00	15.00	18.00				20.00		
Aluminium + Silicon	mg/kg	Max	25	40		50	60						
Sodium	mg/kg	Max	50	100		50	100						
Ash	% m/m	Max	0.040	0.070			0.100				0.150		
Vanadium	mg/kg	Max	50	150			350				450		
CCAI	-	Max	850	860			870						
Water	% V/V	Max	0.30	0.50									
Pour point (upper) [b], Summer	°C	Max	6		30								
Pour point (upper) [b], Winter	°C	Max	0		30								
Flash point	°C	Min	60.0										
Sulphur [c]	% m/m	Max	Statutory requirements										
Total Sediment, aged	% m/m	Max	0.10										
Acid Number [e]	mgKOH/g	Max	2.5										
Used lubricating oils (ULO): Calcium and Zinc; or Calcium and Phosphorus	mg/kg	-	The fuel shall be free from ULO, and shall be considered to contain ULO when either one of the following conditions is met: Calcium > 30 and zinc >15; or Calcium > 30 and phosphorus > 15.										
Hydrogen sulphide [d]	mg/kg	Max	2.00										
a	This residual marine fuel grade is formerly DMC distillate under ISO 8217:2005.												
b	Purchasers shall ensure that this pour point is suitable for the equipment on board, especially in cold climates.												
c	The purchaser shall define the maximum sulphur content according to the relevant statutory requirements.												
d	Effective only from 1 July 2012.												
e	Strong acids are not acceptable, even at levels not detectable by the standard test methods for SAN. As acid numbers below the values stated in the table do not guarantee that the fuels are free from problems associated with the presence of acidic compounds, it is the responsibility of the supplier and the purchaser to agree upon an acceptable acid number.												

Table 4: Marine residual fuels [DNV 2010]

Several decades ago, heavy fuel oil was used to run boilers for power generation, and to propel tankers and other large vessels. It once accounted for as much as 30 % of the oil burned in stationary uses, and 20 % of all United States oil use. By 1997, those shares had fallen to 7 % and 4 %, respectively. Since then, residual fuel oil consumption in the U.S. has been dropping.

Currently, a slowdown in global shipping, combined with increased shipping efficiency, could minimize fuel oil consumption by the industry. Most of the demand increase of the marine fuel for shipping and for power comes from Asia, which keeps prices steady in the region, especially during tight summer months in the Middle East and East Asia. In these areas, rising fuel cost might affect cargo shipping cost and global trade. To keep up with the demand, the majority of new upgrading units will be in Asia [Feng 2010].

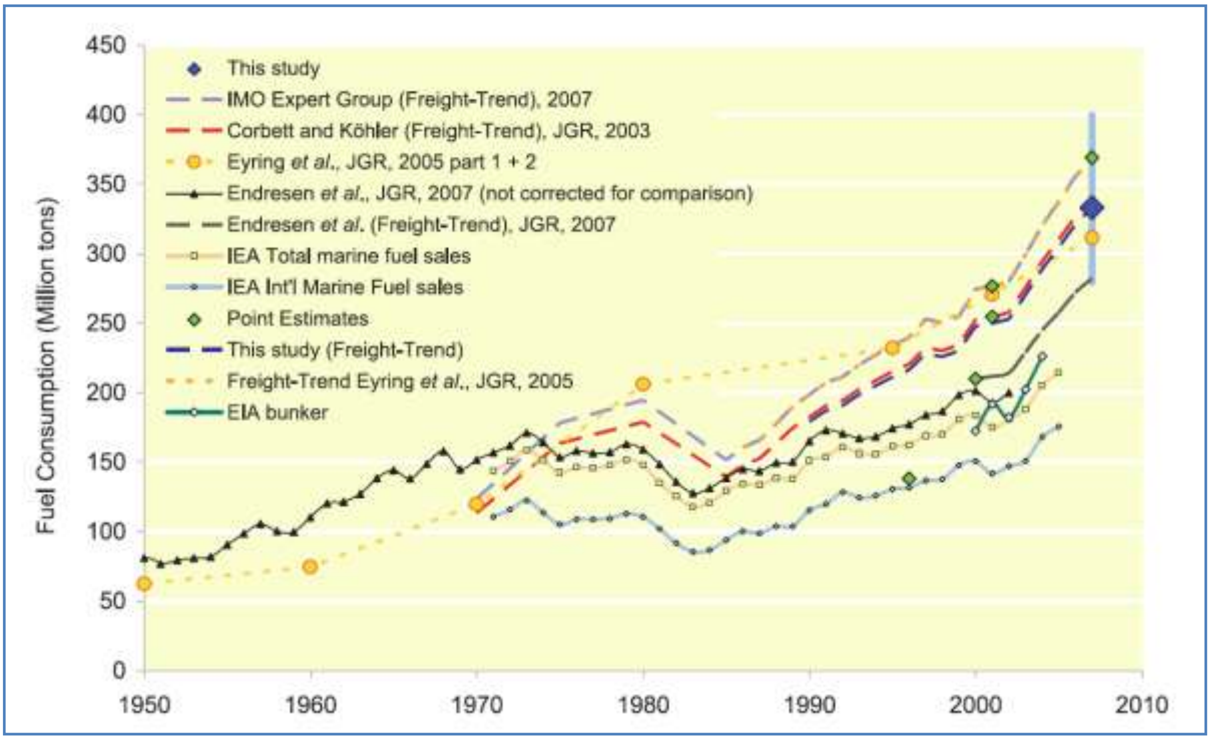


Figure 11: World fleet fuel consumption (except military vessels) from different activitybased estimates and statistics. Symbols indicate the original estimates for individual years and the solid lines show the original estimates of trend. Dashed lines show the backcast and forecast, calculated from the time evolution of freight tonne-miles with the point estimates. The blue square shows the activity-based estimate from this study and the blue range bar indicates the high and low bound estimates [IMO 2009b]

However, it is important to notice that depending on the type of the vessel the fuel costs can account for more than 50 % of the operating costs as displayed in figure 12.

Changes in the price of fuel affect the relative cost structure. If it rises, fuel and vessel running costs increase and the relative share of fuel costs as a component of day-to-day costs also goes up. The speeds of vessels also affect consumption, which has an impact on fuel costs: consumption at lower speeds is less, and fuel costs are also lower as a result. But vessels on scheduled routes cannot normally reduce their speed without it affecting the viability of the entire transport chain.

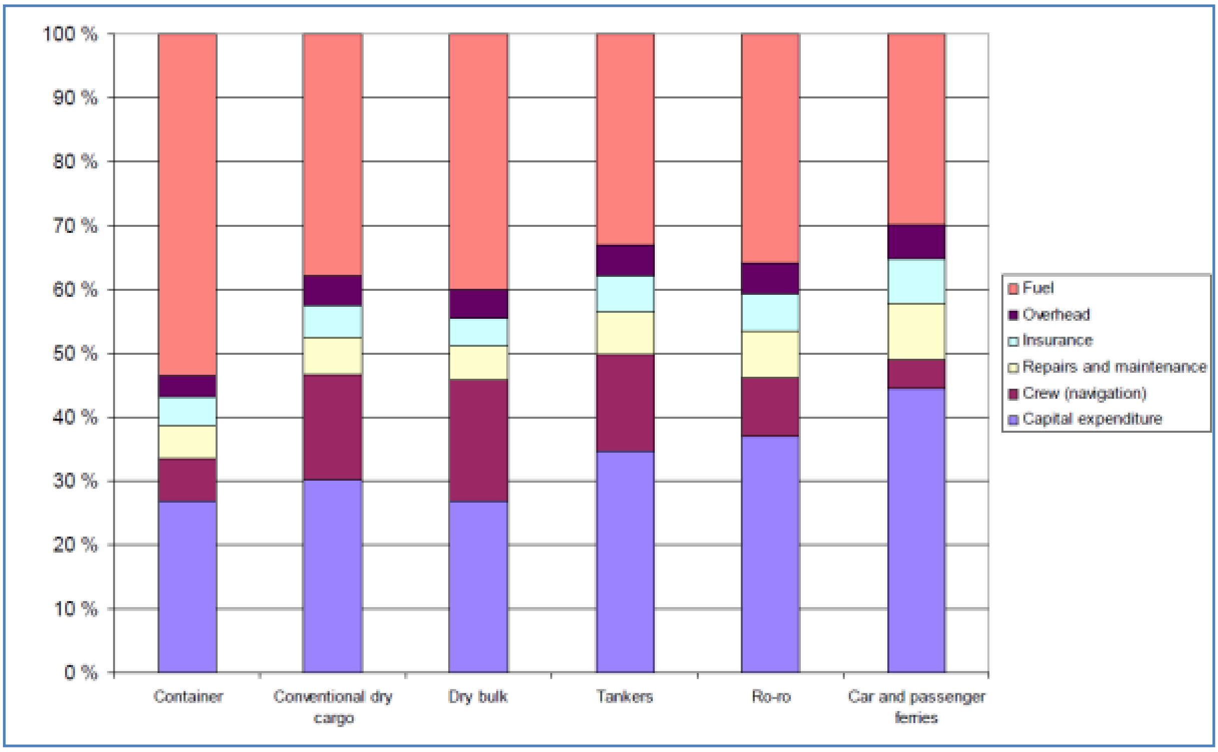


Figure 12: Distribution of costs by vessel type on average for vessels operating between Finland and other countries [Karvonen 2006]

2.1. Availability of Low Sulphur Fuel

The new limiting values valid for the fuel sulphur content as well as the introduction of new Emission Controlled Ares will tremendously change the demand of HFO, LSFO, and MDO and will become a major challenge for the fuel oil industry.

The production costs for Low Sulphur Fuel are extremely high if a desulphurization plant is operated on site of the refinery compared to the blending costs if regular crude oils and sweet oils are mixed [Jürgens 2009].

The desulphurization process consumes high amounts of energy in the form of temperature, steam and pressure as well as huge quantities of Hydrogen (H_2) which also requires enormous amounts of energy during its production process. Figure 13 shows a simplified process flow diagram for a diesel hydrotreater.

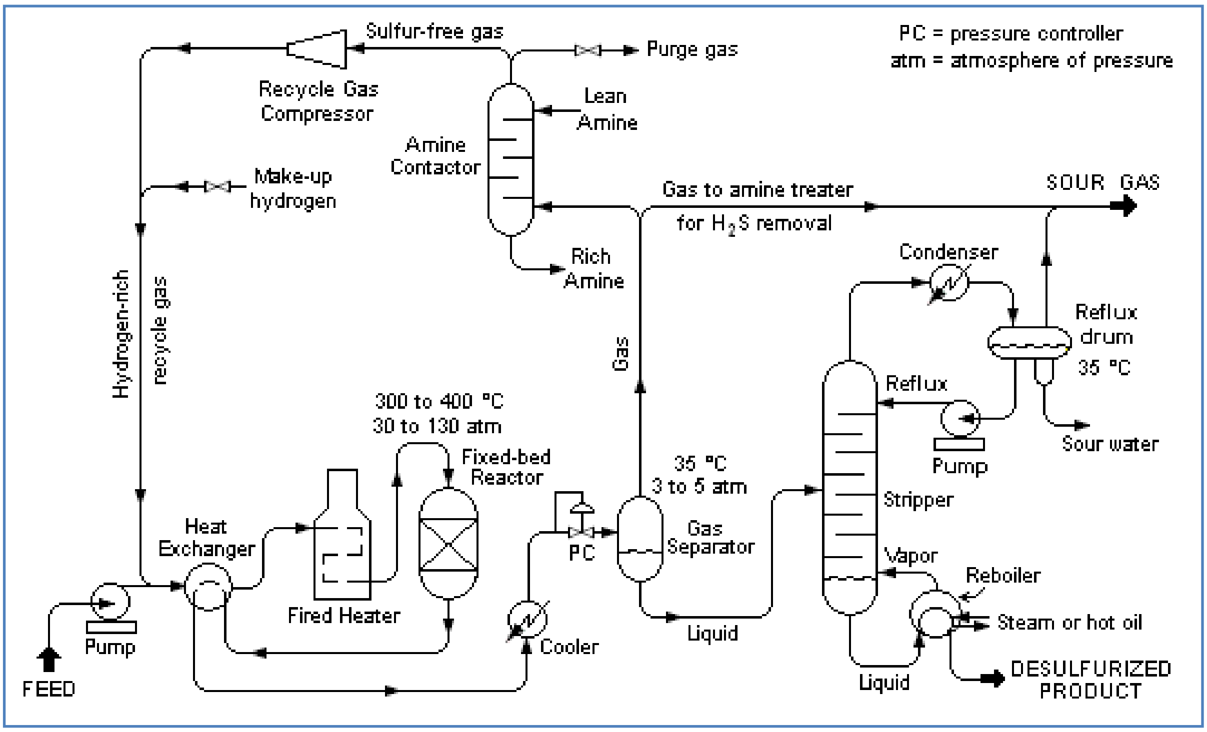


Figure 13: Process flow diagram for a diesel hydrotreater

From a fuel supply point of view, a lower SECA sulphur level will imply tighter constraints on the volume of low sulphur bunker fuel that can be made available. In particular in the case of a 0.5 % sulphur limit, low sulphur distillate fuel will need to be added in larger quantities to the fuel to meet the sulphur specification.

There are two possible solutions to meet the sulphur emission standard:

1. mandated use of distillate fuels with maximum sulphur content of 1 % in 2012 and 0.5 % in 2015,
2. blending of heavy fuel oil with distillate fuels to obtain equivalent emissions.

In this case, a large extent of distillate fuel will likely need to be blended to make sufficient low sulphur available. In switching to distillate fuels, there would no longer be a marine outlet for heavy fuel oil streams in the refining process. Unless other markets (e.g. power industry) take up these streams, they would have to be converted to other products through conversion of heavy fuel oil to lighter fractions or through use of a desulphurization process to lower the sulphur content of the fuel oil. Both Solutions 1 and 2 would require significant additional fuel processing in refineries, creating considerable amounts of incremental CO_2, seriously impacting national strategies for reducing greenhouse gas emissions and requiring large capital investments. Each option raises concerns about supplies since each refiner will decide individually whether to make the costly investment for producing low-sulphur marine fuels [Feng 2010].

One possible way of lowering the sulfur content in heavy fuel oil is by hydrodesulphurization of heavy fuel oil. High sulfur concentrations in heavy fuel oils could introduce more problems encountered in the refinery such as equipment corrosion, plugging and catalyst poisoning.

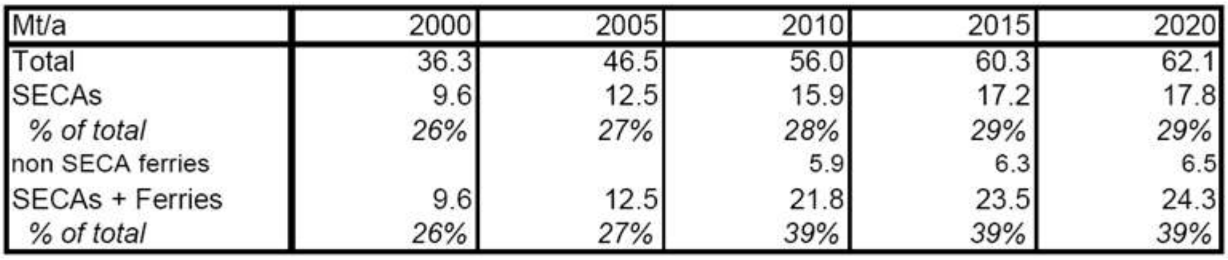
Hydrodesulphurization process is sensitive to contaminants such as heavy metals in the feedstock, and may require prior demetallization. The technology is available and widely used, and can be improved in terms of effectiveness and economy.

Direct sulfur removal from crude oil by some hydrodesulphurization methods can remove up to 90 % of the sulfur with an associated fuel loss of ~8 %. An indirect method is available, in which the light oils produced from atmospheric distillation of crude oil are redistilled under vacuum, hydrotreated to remove the sulfur, and then blended with the heavy oil to produce a lighter, lower-sulfur fuel oil. This method can achieve a sulfur reduction of about 40 % with an associated fuel loss of about 5 % [EC 2011].

Studies on impact on EU refining industry have confirmed that bunker fuel specification changes are a challenge to the refining industry. Investment requirements will probably exceed previous product specification requirements. A preliminary estimation shows that the investments foreseen and already needed are as follows [EC 2011]:

- $ 13.2 billion additional in 2015
- $ 16.7 billion in 2020
- Increase CO_2: 6.9 Mt (2015) or 5 %
- Increase unit operation cost 1-4 % ($ 0.04 0.13/barrel)
- Price increase 0.1 %: $ 250 - $ 300/ton

However, the demand for marine fuel oil has constantly increased over the last years and will continue rising. It is estimated that the consumption of marine fuel oils in Europe goes up from 37 Mill. Mt/a in 2000 to 63 Mill. Mt/a in 2020 [Concawe 2009].



Mt/a	2000	2005	2010	2015	2020
Total	36.3	46.5	56.0	60.3	62.1
SECAs	9.6	12.5	15.9	17.2	17.8
% of total	*26%*	*27%*	*28%*	*29%*	*29%*
non SECA ferries			5.9	6.3	6.5
SECAs + Ferries	9.6	12.5	21.8	23.5	24.3
% of total	*26%*	*27%*	*39%*	*39%*	*39%*

Table 5: Trends in EU marine fuel demand [Concawe 2009]

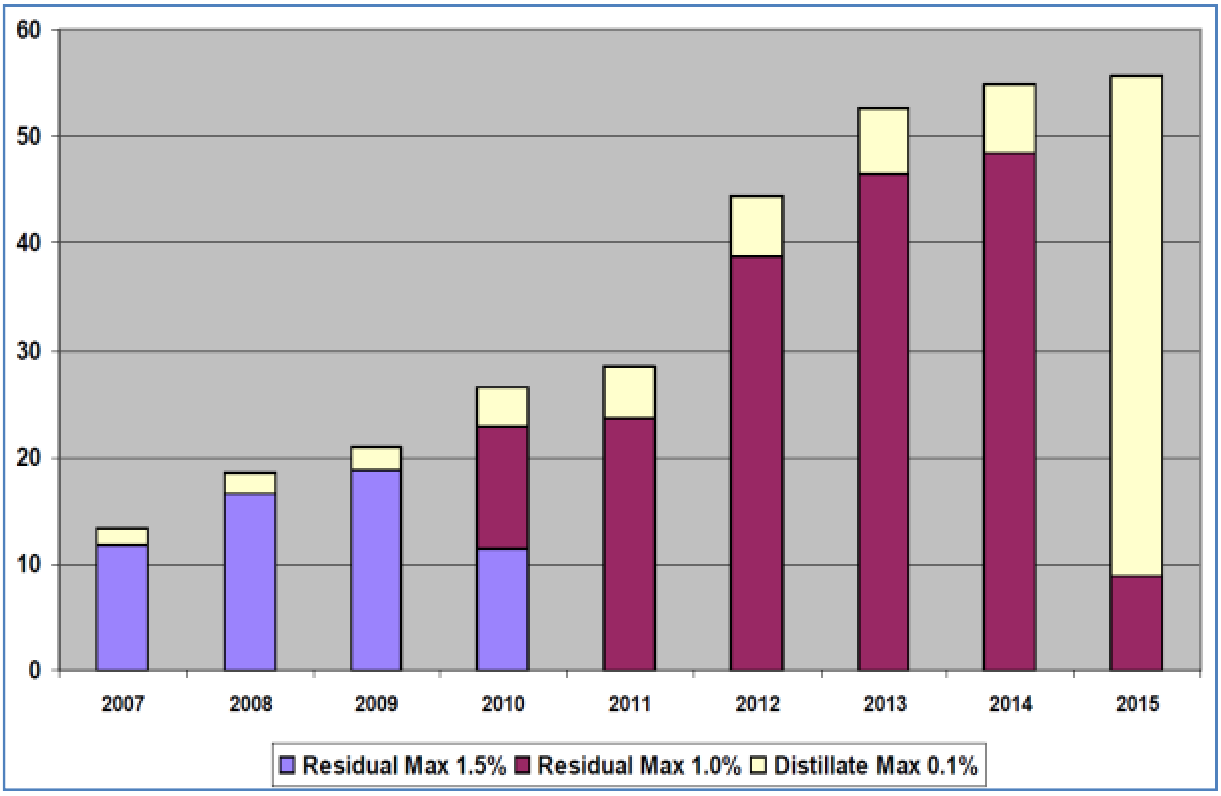


Figure 14: The consumption of lower sulphur fuels in the SOx ECA [Meech 2008]

A large part of the difference between HFO (Heavy Fuel Oil) and MDO (Marine Diesel Oil) is related to sulphur which together with water forms particulates. The removal of sulphur from residual fuel oil prior to usage is technically feasible, but the economics of residue desulphurization are not very attractive. Uncertainty of price and the often negative refinery margin limit are obstacles to investments. Distillate is an alternative fuel which can be supplied with a low or zero sulphur content. Whilst HFO is the untreated component of crude oil remaining after vacuum distillation, distillate undergoes several refinery processes all of which utilize refinery energy to produce the finished product. Thus it is important to consider both the specific energy of the respective fuels and the energy required to process the products [Notteboom 2010].

2.2. Alternative Fuels

The implication of the stricter emission limits will firstly increase the demand of low sulfur distillates fuel and hence higher fuel price. Ships operating in the ECAs need to employ NOx exhaust cleaning devices, which adds to capital and operation cost. Both increased fuel price and added operation costs due to exhaust cleaning will favor alternative fuels use [Feng 2010].

2.2.1. Liquid Bio Fuel (LBF)

Vegetable oils have potential as alternative fuels for HFO used in the low-speed diesel engines of large ships [Espadafor 2009], which will not generate SOx emissions due its lack of sulphur. The substitution of marine diesel with biodiesel produced from sunflower oil and olive oil was studied in literature [Kalligeros 2003]. The emissions for particulate matter, carbon monoxide, hydrocarbons decreased, and nitrogen oxide emissions slightly increased.

The addition of biodiesel in the traditional marine diesel fuel improves the emissions of PM, which comprise a serious disadvantage of the diesel engine, especially in polluted areas like the Asia Pacific area and Mediterranean Sea.

The majority of global biodiesel production is based in the European Union which produces 5,7 million tonnes in 2007 (70 – 80 % of world production). Biodiesel has been produced in industrial scale in EU-countries since early 1990's and the last 10 years a rapid growth in production capacities is observed. As an example the production growth from 2006 - 2007 was 17 %.The availability should not be a problem in EU, but there is still a limited production capacity in the U.S. An annual increase of bio fuel production has been observed. It may be used as ship fuel, and some demonstration projects have been reported.

The environmental effects of burning LBF in an internal combustion engine are first of all related to a significant reduction of GHG as CO_2. The CO_2 benefits commonly attributed to biodiesel are the result of the renewability of the biodiesel itself, not the comparative exhaust CO_2 emissions. The effect on the harmful exhaust emissions to air by burning LBF is shown in Figure 15.

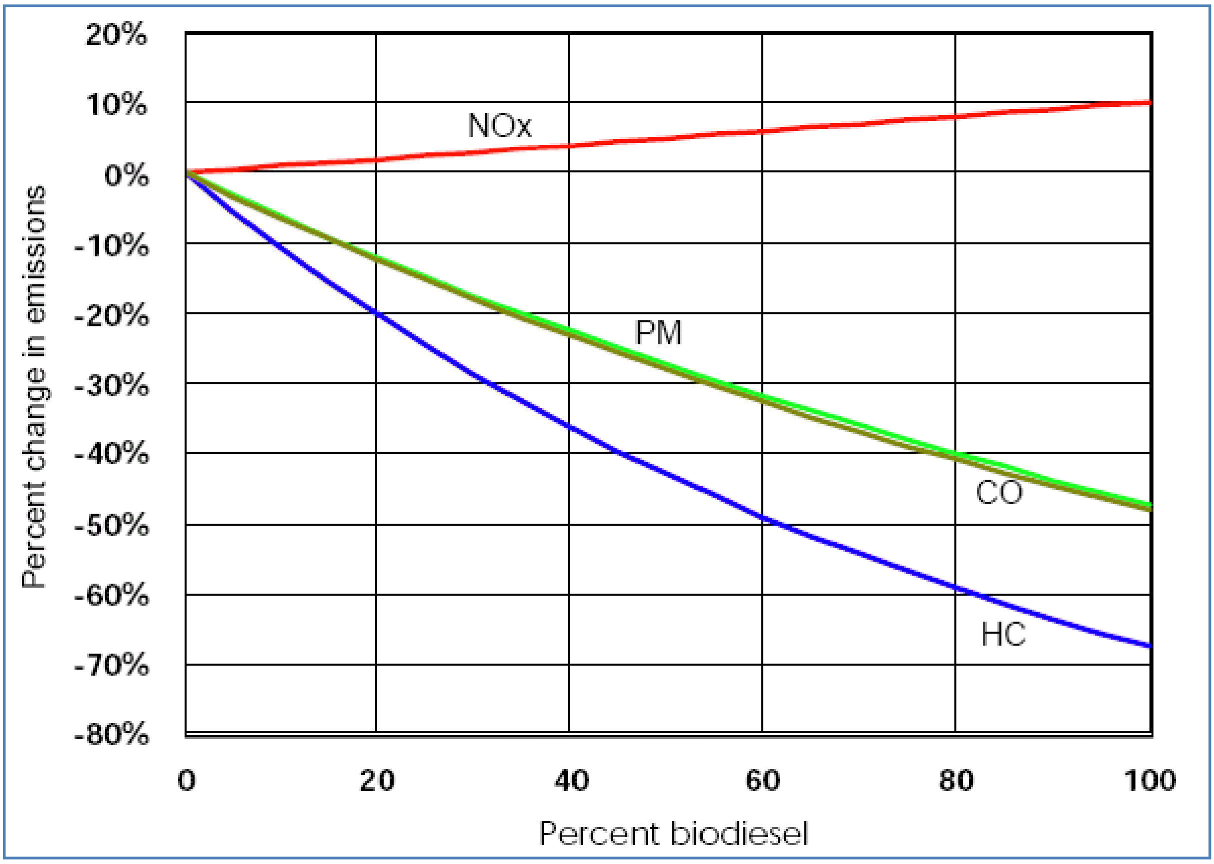


Figure 15: Average emission impacts of biodiesel for heavy-duty highway engines [EPA 2002]

Using biodiesel or biodiesel blends in ship engines, similar effects as for heavy duty highway engines may be expected with respect to emissions, i.e. a small increase in NOx and reduction of HC, CO and PM. After measuring emissions from a Wärtsilä 32 diesel engine when running on heavy fuel oil and LBF, in this case palm oil, the results lead suggests the following conclusions:

- NOX emissions are slightly higher with LBF. This result correlates with a slightly lower fuel consumption measurement with LBF. The reason for this is possibly the rate of heat release, which is faster with LBF operation due to the presence of oxygen acting as a combustion catalyst. If very low NOX emission levels are required, selective catalyst reduction (SCR) technology for NOX abatement is available.
- CO emissions are in the low range with both fuels. Although an increase was recorded when using LBF, in practice it has no influence since the measured values are in both cases very low. One reason for the increase may be some cold regions in the combustion chamber causing a disturbance of the combustion process.
- THC (total hydrocarbons) emissions are significantly lower with LBF operation. The reason for this is likely to be the different composition of hydrocarbons

present in HFO and LBF. HFO contains more light fractions, which evaporate more easily, thus influencing the THC emissions.

- Palm oil is, for all intents and purposes, a sulphur-free product since the fuel analyses indicated that it contained less than 10 mg/kg of sulphur. The difference, therefore, to an average quality heavy fuel with a sulphur content of ~ 2.7 % m/m is tremendous, and this difference is clearly indicated in the SOX emission levels.
- Particulate matter (PM) emissions are mainly influenced by the presence of sulphur and ash constituents in the fuel. Since palm oil is almost sulphur-free and contains only small amounts of ash constituents, such as iron, phosphorus, calcium, potassium, aluminum, magnesium and sodium, it is clear that measured particulate emissions are also much lower than with HFO operation.

Based on information collected by Opdal et al [Opdal 2007] some major engine manufacturers as MAN B&W, Wärtsilä, Caterpillar and Rolls Royce all claim that bio fuels may be suitable for their ship engines, but so far they have limited experience.

However, some experience exits from operation of cogeneration plant with bio fuels, and an increasing interested from the stationary market is observed. From a technical point of view, only minor modification of the engines components is required to run on bio fuel compared to conventional fuel. Wärtsilä experience is that, it can be concluded that liquid bio fuel (LBF) operation does not, to any large extent, have an effect on the condition of:

- the combustion chamber
- the exhaust system
- the power system including pistons,
- cylinder liners, bearings, etc.
- the turbocharger and charge air system.

The reason for these excellent results is that the fuel is relatively clean and has low ash content.

On the other hand, according to Wärtsilä, the changes to the external system have been radical. It is of the utmost importance to be able to control the fuel temperature all the way from the storage tank to the separator, the day tank, the booster unit, the engine, and back to the booster unit's mixing tank.

Such changes will be required for all engines types, and this will add some extra costs to the engine and fuel system.

There are also some disadvantages for biodiesel blending with marine fuels. Since biodiesel contains high oxygenates, the stability of the blended fuels could be a problem. Supply logistics are also challenging, because many current major marine oil suppliers have a streamlined supply of HFO need to install facilities to supply biodiesel.

2.2.2. Ethanol

Ethanol is used as fuel blends in gasoline in the US and some European countries. Two main production countries, Brazil and USA, have approximately 90 % of the world's production of ethanol, and the production volumes of ethanol have increased the last years. It has not been used as ship fuel, so ethanol is not considered to be a feasible alternative for marine bunker today.

Global fuel ethanol production grew 27.8 % to 26 million tonnes of oil equivalent (920 thousand barrels daily on a volumetric basis) in 2007. Supply growth accelerated for the third year in a row due to increases in the US and Brazil. US production grew by 33 % to 12 Mt as the market responded to increased mandates and oil prices. Brazilian production rose 27 % to 11.3 Mt as rising oil prices made relatively inexpensive ethanol production from sugar cane even more commercially attractive. Chinese ethanol production growth decelerated after the government imposed a moratorium on the construction of new plants, due to concerns over the impact on food production. European production rose by 7 %; performance was mixed among countries with new capacity leading output growth in some countries, but rising feedstock costs or higher imports reducing output elsewhere.

Ethanol as fuel is today used as blends in gasoline in various ratios. No ship engines have so far been developed to run on ethanol as fuel. However, Scania has developed a heavy duty bus engine which operates on 95 % ethanol + 5 % ignition improver, indicating that in a future scenario ethanol may also be made available as s ship fuel assuming that competitive prices and production volumes can be achieved [Stenersen 2008].

2.2.3. Liquefied Natural Gas (LNG)

Liquefied natural gas or LNG is natural gas (predominantly methane, CH_4) that has been converted temporarily to liquid form for ease of storage or transport.

Liquefied natural gas takes up about 1/600th the volume of natural gas in the gaseous state. It is odorless, colorless, non-toxic and non-corrosive. Hazards include flammability, freezing and asphyxia. The liquefaction process involves removal of certain components, such as dust, acid gases, helium, water, and heavy hydrocarbons, which could cause difficulty downstream. The natural gas is then condensed into a liquid at close to atmospheric pressure (maximum transport pressure set at around 25 kPa/3.6 psi) by cooling it to approximately −162 °C (−260 °F) [Wikipedia 2011].

The reduction in volume makes it much more cost efficient to transport over long distances where pipelines do not exist. Where moving natural gas by pipelines is not possible or economical, it can be transported by specially designed cryogenic sea vessels (LNG carriers) or cryogenic road tankers. The energy density of LNG is 60 % of that of diesel fuel.

LNG is principally used for transporting natural gas to markets, where it is regasified and distributed as pipeline natural gas. It can be used in natural gas vehicles, although it is more common to design vehicles to use compressed natural gas. Its relatively high cost of production and the need to store it in expensive cryogenic tanks have prevented its widespread use in commercial applications.

The density of LNG is roughly 0.41 kg/L to 0.5 kg/L, depending on temperature, pressure and composition, compared to water at 1.0 kg/L.

The heat value depends on the source of gas that is used and the process that is used to liquefy the gas. The higher heating value of LNG is estimated to be 24 MJ/L. The lower heating value of LNG is 21 MJ/L or 635 BTU/ft^3. For the purpose of comparison of different fuels the heating value is also known as the energy density expressed in MJ/L or the gasoline gallon equivalent expressed in BTU/ft^3. The energy density of LNG is 2.4 times greater than that of CNG which makes it economical to transport natural gas in the form of LNG by ship. The energy density of LNG is comparable to propane and ethanol but is only 60 % that of diesel and 70 % that of gasoline.

Since LNG is refrigerated natural gas, its long term availability depends ultimately on global gas reserves. The global resource situation for natural gas is better than for oil in terms of reserves-to-production ratio and geographical spread. According to BP's Statistical Review of World Energy *(BP 2008)*, the world's proven gas reserves stood at 177 trillion Sm3 at the end of 2007. This is 60 times the world's gas production during 2007. By comparison, the global oil reserves were similar to gas reserves by energy content, but were only 42 times the world's oil production during 2007.

While 61 % of proved oil reserves were in the Middle East, which has given cause for concern over the political exposure of global oil supply, the corresponding number for natural gas was 41 %. Russia is the world's largest reserve holder and producer of natural gas, a position which Saudi Arabia holds for crude oil. Norway, which is Europe's largest producer of both oil and natural gas outside Russia, currently has increasing gas production but declining oil production. Norway's proved gas reserves at the end of 2007 were 33 times its gas production during that year.

The major ship engine designers, Mitsubishi, Wartsila and MAN Diesel & Turbo, are engaged in the technical development of LNG fuelled engines. Classification societies are active in the development and have issued "Rules for LNG for ships". Also other players in the industry participate in the new venture and have realized that a new market is emerging. A new generation of ship engines can be introduced in the shipping industry, because the engine designers can offer the technology, the ship owners are alert, and the classification companies elaborated rules of LNG for ships. The new generation is strongly needed by the ship owners in order to comply with the TIER 3 restriction of 2016. The ships have to follow the same green route as all other energy consuming sectors started earlier.

Technical challenges still exist in the development of the new LNG engines, because LNG requires much more space and another infrastructure in the ports; including terminals, supply ships etc. The industry invests many efforts in the development of new systems to the handling of LNG from bunkering, storage and supply. In addition to that new materials and injection systems have to be developed.

Beside the technical challenges related to the engine the challenges associated with the supply of LNG are huge. Major ports need to invest into bunkering and storage technologies and yet it is unclear which party will cover the cost for the implementation of the required infrastructure.

In terms of emissions a LNG fueled engine has almost zero SOx emissions, about 80 % less of NOx emissions and also the PM emissions is app. 90 % lower compared to a HFO fueled engine. Nevertheless the methane slip produced by dual-fuel engines needs to be considered and not be swept under the rug.

Dual-fuel engine are showing a methane slip of 1 % to 3 %. The impact of global warming of methane is app. 25 times higher compared to CO_2 on 100 years time scale and app. 70 times higher on 20 years time scale. Methane (CH_4) which is the main component of LNG is a strong GHG and the methane emission of the shipping industry should be calculated along the entire chain from the gas gathering till the funnel of the vessel.

In the oil and gas sector, methane emissions occur throughout system: during exploration, in production, at transport and distribution. From wellhead to end user, the gas moves through hundreds of valves, processing mechanisms, compressors, pipes, pressure-regulating stations and other equipment. Whenever the gas moves through valves and joints under high pressure, methane can escape to the atmosphere. In many cases, gas is vented to the atmosphere as part of normal operations [Hendriks 2001].

3. Exhaust Gas Composition

Significant amounts of the concerning emissions are produced from the main diesel engines used to provide propulsion and generate power. Other sources, such as onboard incinerators and boilers, can contribute to emission levels from ships, depending on their operation, but these are at relatively low levels compared to those produced from the main power and propulsion diesel engines. The emissions levels from marine engines typically depend on five factors, which are:

1. Type of fuel being consumed;
2. engine type;
3. engine efficiency;
4. power and propulsion drive configuration; and
5. operation and workload of the engines.

Marine fuels are heavier, more viscous than their land based equivalents, traditionally with longer carbon chains and higher sulphur mass content. The three most commonly used marine fuels are distilled fuel oils (DFO), commonly also known as gas oil or marine gas oil (MGO); intermediate fuel oil (IFO), also known as marine diesel oil (MDO); and residual fuel oil (RFO), also known as marine fuel oil (MFO) or heavy fuel oil (HFO). DFO is composed of the petroleum fractions that boil off during the refining process, while RFO are those fuels left behind in the refining process. IFO, as the name suggests, is a fuel produced by a mixture DFO and RFO [Cooper 2002; ICF 1999; ISO 2010].

There are three main diesel engine types used in for power and main propulsion [Cooper 2002; Wärtsilä 2005], which are:

- **Two-stroke slow speed diesel engine (SSD)**: the engine is directly connected to the propeller shaft typically without any gearing, typical speeds of 60 - 200 rpm and power ratings up to 80 MW, used on many larger commercial vessels. Typically, a slow speed engines runs on marine distilled or residual fuels with an efficiency of 47 - 51 % depending on the specific make and model of the engine.
- **Four-stroke, medium speed diesel engines (MSD)**: either a single engine or pair of engines connected to the propeller shaft through a reversing gearing with a fixed pitch propeller (FPP), or a reduction gearing with a controllable pitch propeller. Typical speeds of 300 - 1200 rpm and power rating up to 20 MW, commonly found in use on all ranges of ships, but are preferred to be used onboard small or medium displacement vessels.
- **Four-stroke, high speed diesel engines (HSD):** the engine is connected to the propeller through a reversing gearing with a fixed pitch propeller (FPP) or a reduction gearing with a controllable pitch propeller, with typical speeds greater

than 1200 rpm and low power (under one megawatt) commonly used in all types of small vessels.

Marine diesel engines are most efficient running between 75-95 % of the rated engines speed, with optimal efficiency at about 85 % of their rating [Cooper, 2002]. However, if the efficiency of these systems falls outside of these boundaries, this can have a dramatic effect on fuel consumption and emission rates.

Typically in larger ships, slow speed diesel engines are used to provide main propulsion connected to an alternator/or directly driving generator to provide some of the ship's power, while main ships power is provide by a combination of differently rated medium or high speed diesel generators. This maintains high engine efficiencies reducing overall fuel consumption and consequently emissions. In smaller ships, medium or high-speed diesel engines used to provide main propulsion through a reduction and reversing gearbox. In addition, the advent of highly efficient and cost effective electric motors used either as the only propulsion driver or in combination with a diesel engine, has led to the development of efficient hybrid propulsion systems. The exact configuration of main power and propulsion engine arrangement is dependent on the type, needs and operation of the ship.

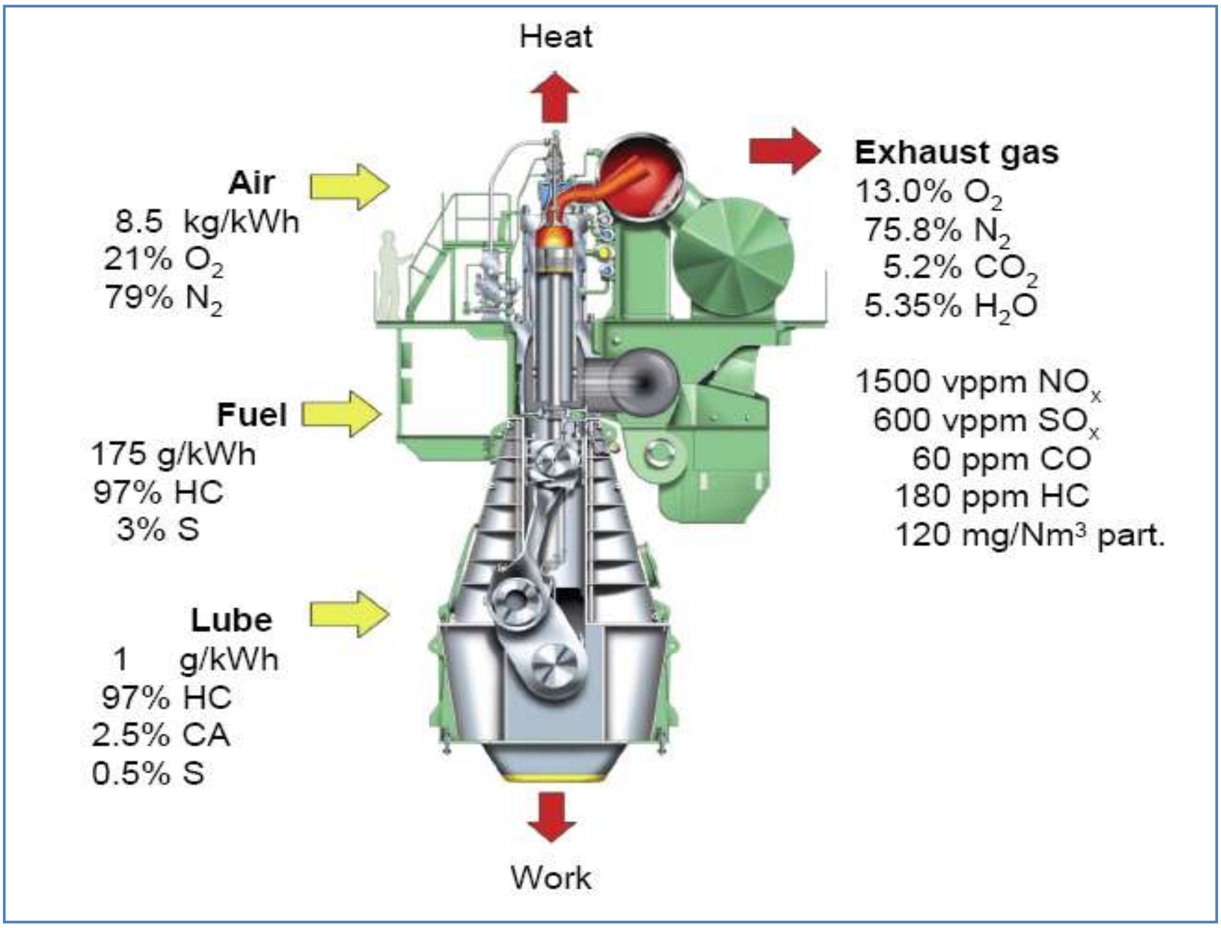
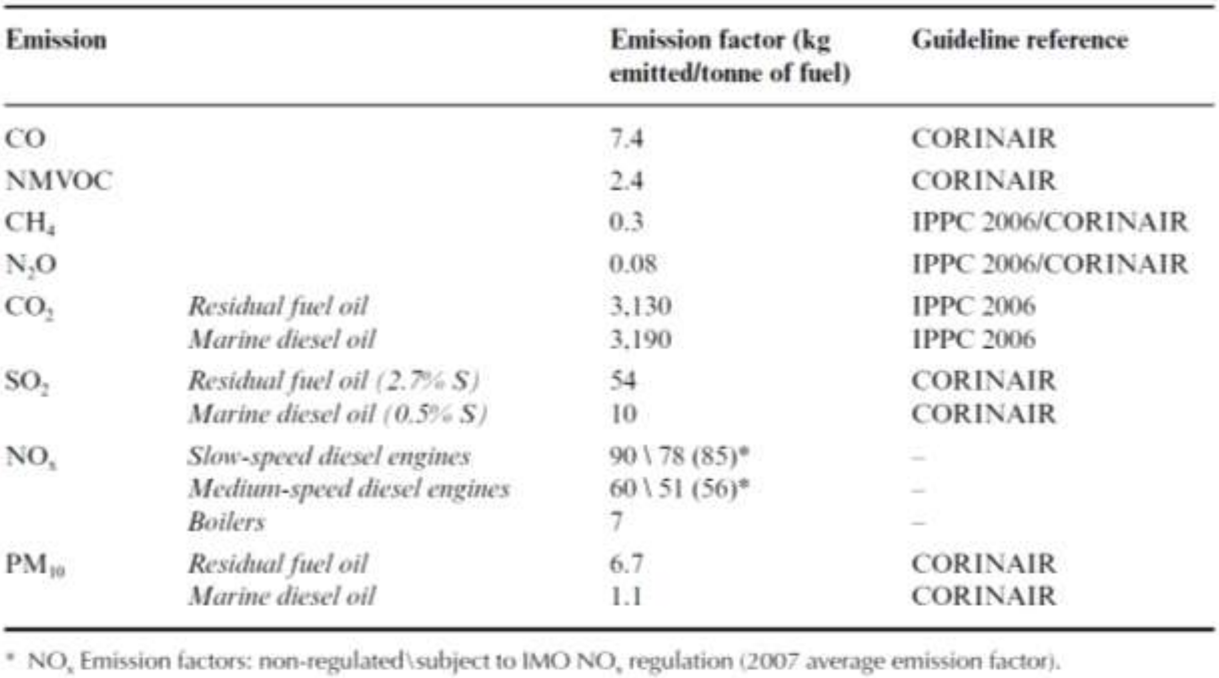


Figure 16: Typical exhaust gas composition – slow speed two stroke engine using HFO

Over the years, several studies performed on collected marine engine emissions data from several ships and engine types to create standard emission factors for the marine industry.

Typically, these emissions factors averaged across the ship and engine types and given in relation to tonne of fuel consumed. The latest IMO study on GHG emissions from ships [IMO 2009] recommends the use of the standard emissions factors shown in Table 6.

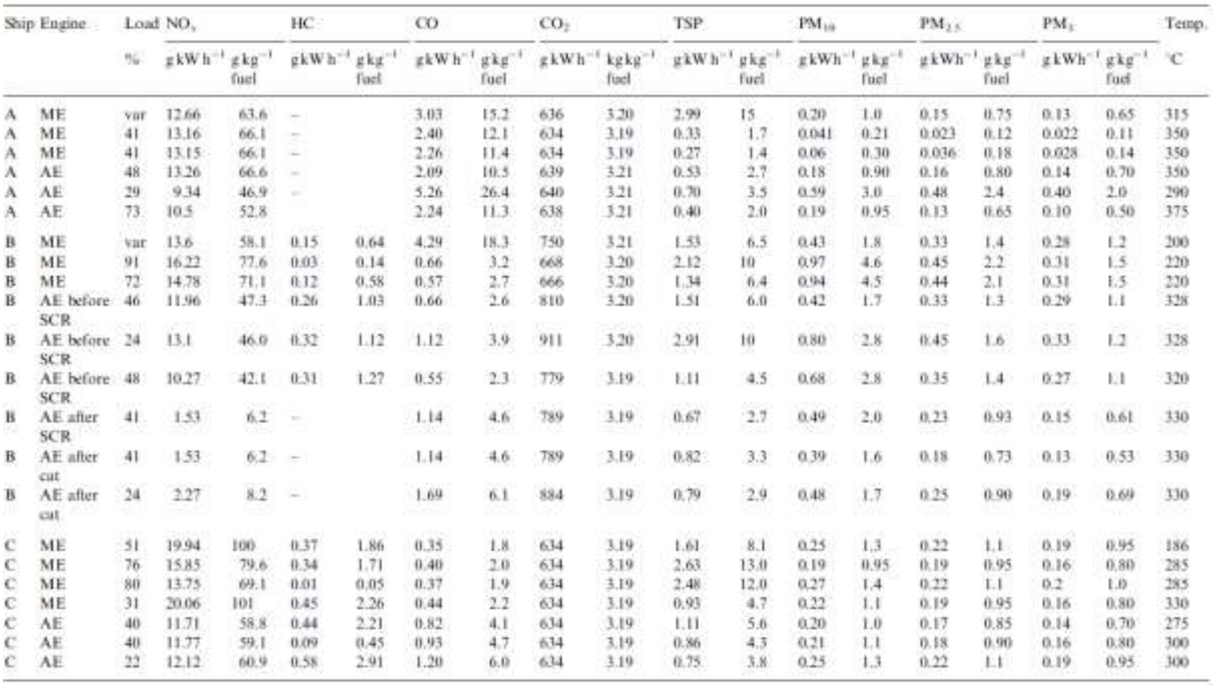


Emission		Emission factor (kg emitted/tonne of fuel)	Guideline reference
CO		7.4	CORINAIR
NMVOC		2.4	CORINAIR
CH_4		0.3	IPPC 2006/CORINAIR
N_2O		0.08	IPPC 2006/CORINAIR
CO_2	*Residual fuel oil*	3,130	IPPC 2006
	Marine diesel oil	3,190	IPPC 2006
SO_2	*Residual fuel oil (2.7% S)*	54	CORINAIR
	Marine diesel oil (0.5% S)	10	CORINAIR
NO_x	*Slow-speed diesel engines*	90 \ 78 (85)*	–
	Medium-speed diesel engines	60 \ 51 (56)*	–
	Boilers	7	–
PM_{10}	*Residual fuel oil*	6.7	CORINAIR
	Marine diesel oil	1.1	CORINAIR

* NO_x Emission factors: non-regulated\subject to IMO NO_x regulation (2007 average emission factor).

Table 6: IMO recommended ships' standard emissions factors [IMO 2009b]

A study with three different engines and measurements being taking at different loads, shows the variation in both power and fuel consumptions dependent emissions factors as shown in [Fridell 2008].



Ship	Engine	Load	NO_x		HC		CO		CO_2		TSP		PM_{10}		$PM_{2.5}$		PM_1		Temp.
		%	g kWh^{-1}	g kg^{-1} fuel	g kWh^{-1}	g kg^{-1} fuel	g kWh^{-1}	g kg^{-1} fuel	g kWh^{-1}	kg kg^{-1} fuel	g kWh^{-1}	g kg^{-1} fuel	g kWh^{-1}	g kg^{-1} fuel	g kWh^{-1}	g kg^{-1} fuel	g kWh^{-1}	g kg^{-1} fuel	°C
A	ME	var	12.66	63.6	–		3.03	15.2	636	3.20	2.99	15	0.20	1.0	0.15	0.75	0.13	0.65	315
A	ME	41	13.16	66.1	–		2.40	12.1	634	3.19	0.33	1.7	0.041	0.21	0.023	0.12	0.022	0.11	350
A	ME	41	13.15	66.1	–		2.26	11.4	634	3.19	0.27	1.4	0.06	0.30	0.036	0.18	0.028	0.14	350
A	AE	48	13.26	66.6	–		2.09	10.5	639	3.21	0.53	2.7	0.18	0.90	0.16	0.80	0.14	0.70	350
A	AE	29	9.34	46.9	–		5.26	26.4	640	3.21	0.70	3.5	0.59	3.0	0.48	2.4	0.40	2.0	290
A	AE	73	10.5	52.8			2.24	11.3	638	3.21	0.40	2.0	0.19	0.95	0.13	0.65	0.10	0.50	375
B	ME	var	13.6	58.1	0.15	0.64	4.29	18.3	750	3.21	1.53	6.5	0.43	1.8	0.33	1.4	0.28	1.2	200
B	ME	91	16.22	77.6	0.03	0.14	0.66	3.2	668	3.20	2.12	10	0.97	4.6	0.45	2.2	0.31	1.5	220
B	ME	72	14.78	71.1	0.12	0.58	0.57	2.7	666	3.20	1.34	6.4	0.94	4.5	0.44	2.1	0.31	1.5	220
B	AE before SCR	46	11.96	47.3	0.26	1.03	0.66	2.6	810	3.20	1.51	6.0	0.42	1.7	0.33	1.3	0.29	1.1	328
B	AE before SCR	24	13.1	46.0	0.32	1.12	1.12	3.9	911	3.20	2.91	10	0.80	2.8	0.45	1.6	0.33	1.2	328
B	AE before SCR	48	10.27	42.1	0.31	1.27	0.55	2.3	779	3.19	1.11	4.5	0.68	2.8	0.35	1.4	0.27	1.1	320
B	AE after SCR	41	1.53	6.2	–		1.14	4.6	789	3.19	0.67	2.7	0.49	2.0	0.23	0.93	0.15	0.61	330
B	AE after cat	41	1.53	6.2	–		1.14	4.6	789	3.19	0.82	3.3	0.39	1.6	0.18	0.73	0.13	0.53	330
B	AE after cat	24	2.27	8.2	–		1.69	6.1	884	3.19	0.79	2.9	0.48	1.7	0.25	0.90	0.19	0.69	330
C	ME	51	19.94	100	0.37	1.86	0.35	1.8	634	3.19	1.61	8.1	0.25	1.3	0.22	1.1	0.19	0.95	186
C	ME	76	15.85	79.6	0.34	1.71	0.40	2.0	634	3.19	2.63	13.0	0.19	0.95	0.19	0.95	0.16	0.80	285
C	ME	80	13.75	69.1	0.01	0.05	0.37	1.9	634	3.19	2.48	12.0	0.27	1.4	0.22	1.1	0.2	1.0	285
C	ME	31	20.06	101	0.45	2.26	0.44	2.2	634	3.19	0.93	4.7	0.22	1.1	0.19	0.95	0.16	0.80	330
C	AE	40	11.71	58.8	0.44	2.21	0.82	4.1	634	3.19	1.11	5.6	0.20	1.0	0.17	0.85	0.14	0.70	275
C	AE	40	11.77	59.1	0.09	0.45	0.93	4.7	634	3.19	0.86	4.3	0.21	1.1	0.18	0.90	0.16	0.80	300
C	AE	22	12.12	60.9	0.58	2.91	1.20	6.0	634	3.19	0.75	3.8	0.25	1.3	0.22	1.1	0.19	0.95	300

Table 7: Fridell et al. study emissions factors [Fridell 2008]

Corbett and Koehler [Corbett 2003] calculated fuel consumption and emissions in metric tonnes per year. The equations developed to calculate fuel consumption and emissions are:

$$Fuel\ Consumption_{tonnes\ /year} = \sum_{subgroup\ \ i=1}^{n} (P_{MW}\ x\ F_{\%MCR}\, x\ t_{hrs/yr}\ x\ \frac{SFOC_{g/kWh}}{1000})$$

and

$$Emissions_{tonnes\ /year} = \sum_{subgroup\ \ i=1}^{n} (P_{MW}\ x\ F_{\%MCR}\ x\ t_{hrs/yr}\ x\ \frac{E_{g/kWh}}{1000})$$

Where P_{MW} is the accumulated power for each subgroup; $F_{\%MCR}$ is the engine load factor based duty cycle profile; $t_{hrs/yr}$ is the average running time of the engine for each subgroup; $SFOC_{g/kWh}$ is the power-based specific fuel oil consumption; $E_{g/kWh}$ is the power-based emissions factor for each pollutant (CO_2, NOx, SOx and PM).

Figure 17 displays the exhaust gas volume (6712 g) generated during the production of one kilowatt hour ($3.6 * 10^6$ Joule) in a 4-stroke engine fueled with HFO containing 2,2 % sulphur. This data are the results of measurements run at the exhaust gas laboratory of the German Lloyd [GL 2008].

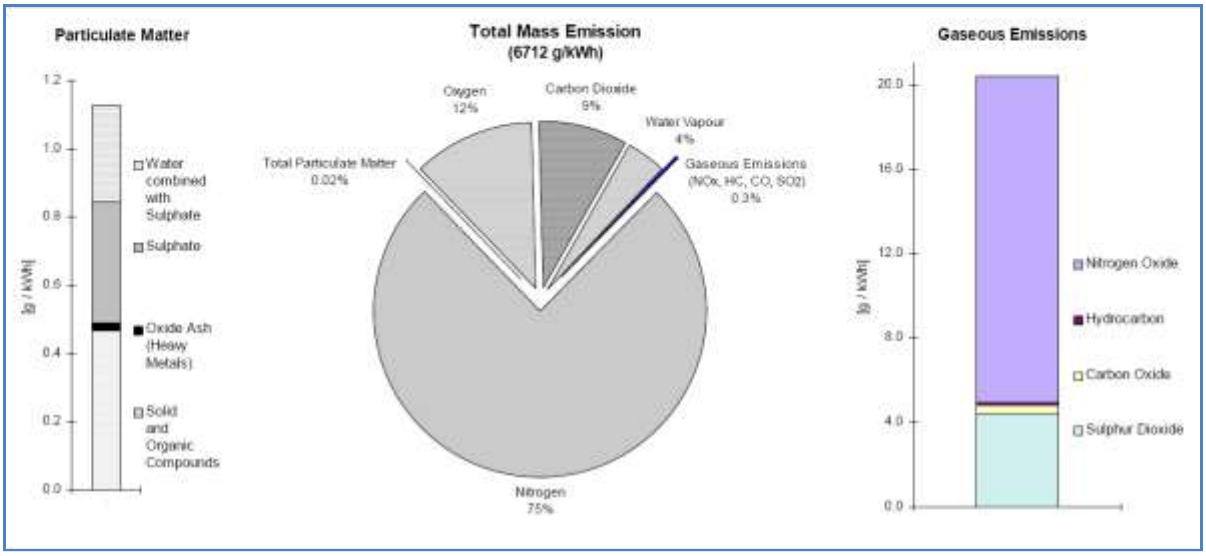


Figure 17: Exhaust Gas Composition of a 4-stroke Diesel Engine (propeller curve, MCR 75 %, with 2,2 % sulphur in fuel)

3.1. Carbon Dioxide (CO2)

Carbon dioxide (CO_2) is considered as one of the major contributors to climate change, leading to global warming, and produced from the combustion of the complex hydrocarbon, mainly paraffin compounds such as cetane ($C_{16}H_{34}$), found in marine fuel oils [EPA 1999;

Hagenow 2010]. The weight fraction of carbon in marine fuel ranges between 86.5 - 87 %, depending on the specific marine fuel used [Cooper 2002]. Other emissions produced by the combustion of marine fuels are carbon monoxide (CO) and volatile hydrocarbons (VOC), including methane (CH_4). However, these emissions are in relatively small quantities compared to CO_2.

Previous ships' emission studies show that CO_2 emission factors are largely independent of the fuel and the engine type. In emission reports reviewed, CO_2 emission factors were found to range from 3100 to 3200 kg/Ton of fuel consumed (3.2% difference depending on study data used) [Corbett 2003; Eyring 2010; IMO 2009; Johnson 2000; Lloyds 1995], the most common value being 3170 kg/ton.

Fuel consumption and thus, engine efficiency are the main drivers in reducing CO_2 emissions. By improving the running of the main power and propulsion diesel engines or using technologies to recover lost energy, engines can be run more efficiently for longer, reducing fuel consumption and CO_2 emissions.

An alternative to relating emission factors to fuel consumption is to give the emission factor corresponding to produced power. In the study by Lloyds Register (Engineer Service), the average CO_2 emissions factor found was to be 660 g/kWh [Lloyds 1995]. In 2000, the US Environmental Protection Agency (EPA) derived a simple formula to calculate the CO_2 emission factor related to power usage [EPA 2000]. The formula based on the factional load of the engine is:

$$EF_{CO_2\,(g/kWh)} = [44.1x(Factional\ Load\ of\ Engine)^{-1}] + 648.6$$

Where $EF_{CO_2\,(g/kWh)}$ is the emissions factor for CO_2; and the fractional load is the current load divided by the maximum engine rated load. It is possible to revert to the emission factor relative to fuel consumption by dividing by the specific fuel consumption (sfc in g/kWh). This is calculated using *sfc* = (14.12/*fractional load*) + 205.717 [60].

The IMO discussed at MEPC 53 and stated in MEPC/Circ.471 a method of CO_2-efficiency indexing of CO_2 emissions related to the amount of cargo carried and the distance travelled for a ship [IMO 2009; MEPC 2005. The method of calculating the index is given in the following equation:

$$EEOI = \frac{\sum_i FC_i\, xC_{carbon}}{\sum_i m_{cargo\,.i}\, xD_i}$$

Where $EEOI$ is the energy efficiency operational index of the ship; FC_i is the fuel consumption during voyage i; C_{carbon} is the carbon content of the fuel; $m_{cargo\,.i}$ is the mass of cargo per voyage; and D_i is the distance travelled per voyage.

It is of common understanding that the anthropogenious emission of CO_2 has to be reduced to stop the overall global warming. The shipping industry contributes with app. 3,3 % to the global CO_2 emission and has defined the goal to reduce this emission significantly by using known technologies and practices on the design of new ships as follows:

- Concept, speed and capability
- Hull and superstructure
- Power and propulsion system
- Low-carbon fuels
- Renewable energy

Also the operation of ships can contribute to the reduction of CO_2 emissions:

- Fleet management
- Logistics and incentives
- Voyage optimization
- Energy management

The above mentioned actions and strategies represent the most effective methods to minimize the arising of CO_2. It is as simple as this: Fuel which is saved does not produce CO_2.

Carbon dioxide is chemically spoken a very slowly reacting compound and thus difficult to be treated by an exhaust gas system [Jürgens 2009].

3.2. Sulphur Oxides (SOx)

Sulphur is a natural compound of crude oil and it appears in different concentrations depending on the source of the crude oil. It can be as high 6 wt %. The sulphur is chemically bonded to the hydrocarbons of the oil. The binding energy is quite high which makes it so difficult and energy consuming to separate the sulphur from the hydrocarbons [Jürgens 2009].

SOx emissions, contributing to water acidification and air toxicity, are heavily dependent on type of fuel used. In the combustion, sulphur contained in the fuel is oxidised to form sulphur dioxide (SO_2) and sulphur trioxide (SO_3) in a ratio of 15:1 respectively. Traditionally, emissions studies have measured the SO_2 in the exhaust gases to determine SOx emissions factors, as SO_3 readily reacts with water to form sulphuric acid (H_2SO_4).

Regulation 14 of the MARPOL legislation stipulates limits to the mass sulphur content of any fuel oil and the ECAs around the world (Baltic Sea area and North Sea) [IMO 2004], amending the previous legislation. Table 8 shows the maximum limits on the sulphur mass content of marine fuel oils as stipulated in MARPOL, through the introduction of low sulphur fuels, and a timeline when these limits are due to come into force.

Outside an ECA Established to Limit SOx and PM Emissions	**Inside an ECA Established to Limit SOx and PM Emissions**
4.50% m/m prior to 1st January 2012	1.50% m/m prior to 1st July 2010
3.50% m/m on and after to 1st January 2012	1.00% m/m on and after to 1st July 2010
0.50% m/m on and after to 1st January 2020*	0.10% m/m on and after to 1st January 2015

*** To be implementation on current timeline subject to technical review (2018)**

Table 8: MARPOL 93/97 Annex VI limits on sulphur content of marine fuel oil

The basic calculation used for the SOx emission factor uses the mass sulphur content of the fuel. The Lloyds Register study showed that the sulphur emission factor (EF_{SOx}) is approximately equal to 20x percentage mass sulphur content of the fuel (S %), i.e. $EF_{SOx\,(kg/Ton)} = 20xS\,\%$ kg/Ton of fuel consumed [Lloyds 1995].

For example, MDO with a sulphur mass content of 2.7 %, the SOx emission rates are 54 kg/Ton of fuel consumed. Similarly, for HFO with a typical sulphur mass content of 4 %, the emission rate is calculated to be 80 kg/Ton, while for MGO (0.5 % typically) it is 10 kg/Ton and low sulphur fuels (0.1 %) it is 2 kg/Ton.

From the Lloyds Register data, simple formulae were derived, equating a time dependent emissions factor ($EF_{SOx\,(kg/hr)}$), in kg/hr, to the factional load (P_i) of the engine. The following equations relate to engines @2000 kW.

For Medium Speed Engines

$$EF_{SOx\ (kg/hr)} = 12.47x10^{-3}\sum_i P_i$$

For Slow Speed Engines

$$EF_{SO_x\ (kg/hr)} = 11.34x10^{-3}\sum_i P_i$$

where P_i = engine power (kW) x engine load (85% MCR) for $i = 1 \rightarrow n$ main engines.

For medium speed engines < 2000 kW

$$EF_{SOx\ (\mathrm{kg/hr})} = 2.31x10^{-3}\sum_i P_i$$

For auxiliary diesel engines (mostly medium/high-speed engines)

$$EF_{SOx\ (\mathrm{kg/hr})} = 2.36x10^{-3}\ x\ A\ x\ C$$

where A is the total auxiliary power (kW) and C is 1,2,3,4 & 5 depending on the gross tonnage of the vessel, < 1000, 1000-5000, 5000-10000, 10000-50000 and >50000 respectively.

To convert the time dependent emissions factors to emission factors relative to fuel consumption, one can simply divide by the rate of fuel consumption for the engine at the given engine load.

Alternatively, the SOx emissions can be calculated using power usage emissions factor derived from 4.2 × percentage mass sulphur content of the fuel, i.e. $EF_{SOx\ (g/kWh)} = 4.2 \times S\ \%$ g/kWh of power produced [Lloyds 1995]. Although, the US EPA report on ship emissions [EPA 2000] derived an equation to calculate the SOx emissions factor relative to the power output of the diesel engines, these present a much high emissions factor compared to measured results and the amount of sulphur contained in the fuel. This considered to the EPA considering sulphur dioxide SO_2 and SO_3 levels in the exhaust gases, the later produced in the hot exhaust gases through the reaction of hydroxide ions with SO_2 gases [Cooper 2002; EPA 2000].

Similar to the requirements of the NOx Technical Code for engines, an Exhaust Gas Cleaning (EGC) unit may be used subject to periodic 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/kilowatt hour) is not required. Instead monitoring the ratio of SO_2 (sulphur dioxide) to CO_2 (carbon dioxide) emissions is permitted.

Sulphur oxide emissions from an engine (or other combustion unit such as a boiler) are almost entirely derived from the sulphur content of the fuel and unlike NOx formation are not related to engine design, operation and combustion conditions [Gregory 2010]. The majority of CO_2 is also derived from the combustion of hydrocarbon fuel and typically makes up about 6 % of a diesel engine's exhaust gas. The SO_2/CO_2 ratio therefore gives a robust measure of SOx emissions in proportion to the sulphur content of the fuel burned, which greatly simplifies monitoring requirements without compromising accuracy. Gas concentrations (parts per million/percent) can be used rather than determining the actual mass flow rate of SO_2 and engine (or boiler) power is not required. It also removes the need to measure parameters such as engine speed and fuel flow as well as various other temperatures and pressures that are required under the NOx Technical Code

Table 9 shows the SO_2 (ppm)/CO_2 (%) ratios that must be measured after an exhaust gas cleaning unit in order to achieve equivalence and therefore compliance with the sulphur-in-fuel limits under regulation 14.

Fuel Oil Sulphur Content (% m/m)	Ratio Emission SO_2 (ppm)/CO_2 (% v/v)
4.50	195.0
3.50	151.7
1.50	65.0
1.00	43.3
0.50	21.7

0.10	4.3

Table 9: Fuel oil sulphur limits recorded in MARPOL Annex VI regulations 14.1 and 14.4 and corresponding emissions values

The Guidelines for Exhaust Gas Cleaning Systems give various SO_2 /CO_2 ratios that must be measured after an exhaust gas cleaning unit in order to achieve equivalence and therefore compliance with the sulphur-in-fuel limits under regulation 14 (see table 9). It has also been discussed in section 3.2 how the ratio is a robust measure of SOx emissions in proportion to the sulphur content of the fuel burned because all sulphur oxides and virtually all CO_2 are derived from the combustion of fuel that is hydrocarbon based and contains sulphur.

Some Exhaust Gas Cleaning Systems however use the natural buffering capacity of seawater to neutralize the acids produced from scrubbing SO_2, which moves the carbonate system equilibrium towards CO_2 release. This could at first be considered to compromise the validity of the SO_2/CO_2 ratio method but a typical air: fuel ratio for a marine diesel engine is typically between 50 to 35 depending on load i.e. the mass of combustion air is 50 to 35 times greater than the mass of fuel to be combusted and CO_2, formed from the fuel and air will typically make-up 6 % of the exhaust [Wright 2000]. It can be shown by calculation [Hamworthy 2007] and has been demonstrated by in-field testing that the CO_2 produced by neutralizing the acidity produced by 1 tonne of residual fuel is minimal, particularly when compared with the CO_2 produced in combusting that tonne of fuel. The validity of the method therefore remains unaffected.

3.3. Nitrogen Oxides (NOx)

NOx is a generic term for mono-nitrogen oxides (NO and NO_2). These oxides are produced during combustion, especially combustion at high temperatures. The three primary sources of NOx in combustion processes:

- thermal NOx
- fuel NOx
- prompt NOx

Thermal NOx formation, which is highly temperature dependent, is recognized as the most relevant source when combusting natural fuels. Fuel NOx tends to dominate during the combustion of fuels, such as coal or oil, which have significant nitrogen content, particularly when burned in combustors designed to minimise thermal NOx. The contribution of prompt NOx is normally considered negligible.

Thermal NOx refers to NOx formed through high temperature oxidation of the diatomic nitrogen found in combustion air. The formation rate is primarily a function of temperature and the residence time of nitrogen at that temperature. At high temperatures, usually above 1600 °C (2900 °F), molecular nitrogen (N_2) and oxygen (O_2) in the combustion air disassociate into their atomic states and participate in a series of reactions.

The three principal reactions (the extended Zeldovich mechanism) producing thermal NOx are:

$$N_2 + O \rightarrow NO + N \qquad (1)$$

$$N + O_2 \rightarrow NO + O \qquad (2)$$

$$N + OH \rightarrow NO + H \qquad (3)$$

NOx emissions are produced by the oxidation of nitrogen in the fuel (≃1.4 % by weight of fuel) to form nitrogen oxide (NO), of which about 5 % is converted to nitrogen dioxide (NO_2) and 1 % forms nitrous oxide (N_2O) in the hot exhaust gases. NOx emissions contributing to water acidification, air toxicity, photo-oxidation and eutrophication and are dependent on the engine type of engine with slow speed engines producing more NOx emissions than higher speed engines.

Regulation 13 of the MARPOL legislation stipulates NOx emission limits are dependent on the engine rating and covers engines of more than 130 kW or not solely used for emergencies. The regulation provides limits for the installation or conversion of engines in three tiers depending on the date of installation or conversion [IMO 2004]. In addition, tier three limits only apply inside ECA as designated by the MARPOL Regulations, and are only applicable to ships less than 24m in length or with a combined propulsion power of less than 750 kW, if demonstrated ship cannot comply safely with the standard. Outside ECA, tier two limits will apply to NOx emissions. The limits in each tier are set based on the speed of the engine and calculated as shown in Table 10 [MEPC 2008].

Engine Rated Speed n (rpm)	**Tier I**	**Tier II**	**Tier III#**
Date of Installation/Conversion	On or after 1st January 2000 Prior to 1st January 2011	On or after 1st January 2011	On or after 1st January 2016
n < 130	17.0 g/kWh	14.4 g/kWh	3.4 g/kWh
130 @ n > 2000	$45*n^{(-0.2)}$ g/kWh	$44*n^{(-0.23)}$ g/kWh	$9*n^{(-0.2)}$ g/kWh
n @2000	9.8 g/kWh	7.7 g/kWh	2.0 g/kWh

 # The regulations for Tier III only apply inside ECA, when not inside ECA limits are set according to tier II guidelines. This regulation is not applied to ships less than 24m in length or has a combined propulsion power of less than 750kW, if demonstrated that the ship cannot comply safely with standard.

Table 10: MARPOL NOx emission limits

Figure 18 shows the calculated NOx emission limits for the three tiers for engines less than 2000rpm rated speed as stipulated in the IMO's MARPOL Annex VI, Regulation 13.

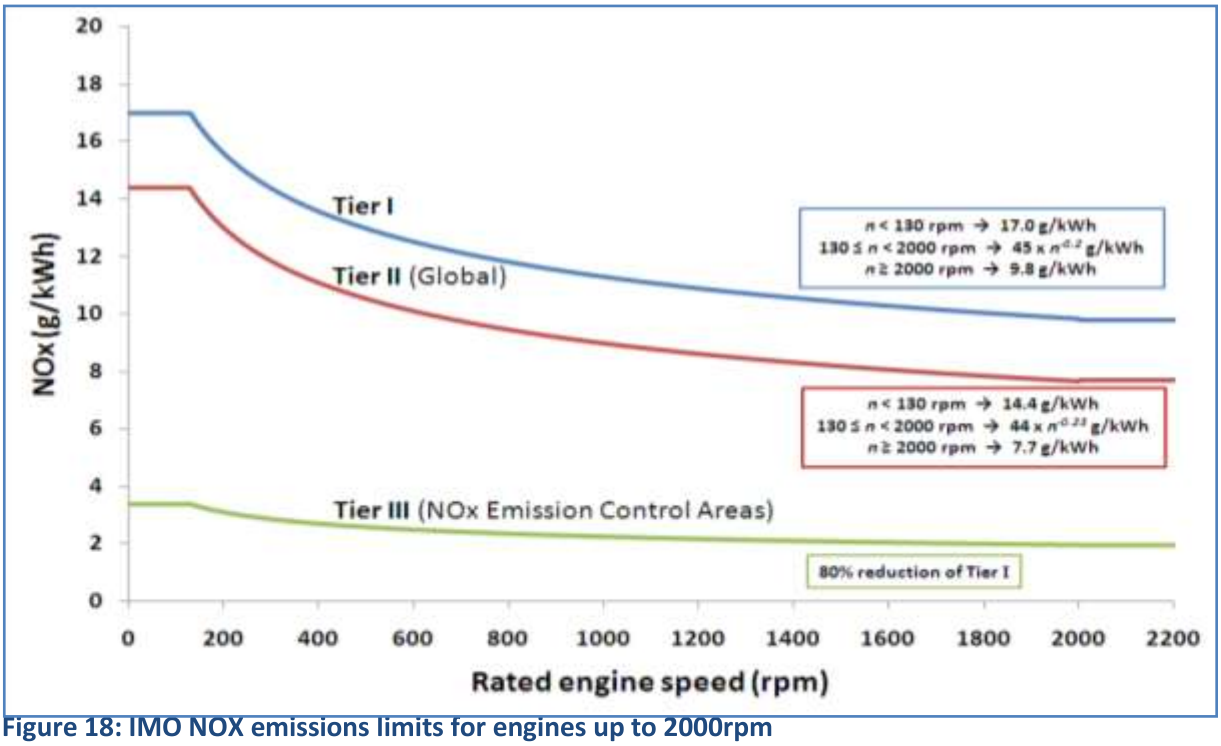


Figure 18: IMO NOX emissions limits for engines up to 2000rpm

NOx emission factors largely depend on the engine type and load, as well as the fuel type. Studies have shown emission rates for NOx are higher for slow speed diesel engine compared to medium speed diesel and high-speed diesel. However, NOx emission rates can vary dramatically from study-to-study. Commonly used emission factors for NOx are 87 kg/Ton for slow speed diesel engine and 57 kg/Ton for medium speed diesel and high-speed diesel [IMO 2009].

Similar to the NOx emission factor dependent on time, the Lloyds Register study showed NOx emissions were dependent on the power factor of the diesel engine [Lloyds 1995]. The equations given for emission rates relative to time were:

For medium speed engines

$$EF_{NOx\ (kg/hr)} = 4.25x10^{-3} \sum_{i} P_i^{1.15}$$

For slow speed engines

$$EF_{NOx\ (kg/hr)} = 17.5x10^{-3} \sum_{i} P_i$$

For auxiliary engines

$$EF_{NOx\ (kg/hr)} = 4.25x10^{-3} x A^{1.15}$$

Where P_i is engine power (kW) × engine load (85 % MCR) for *i* = 1→n main engines; and A is total auxiliary power (kW).

From the Lloyds Register study gave the NOx emissions relative to engine power as 17 g/kWh for slow speed engines and 12 g/kWh for medium speed engines [Eyring 2010]. In the EPA report, emission factors relative to engine power were calculated using following equation:

$$EF_{NOx\ (g/kWh)} = [0.19x(Fractional\ Load)^{-1.5}] + 15.5$$

where the fractional load is equal to engine load/engine rated load.

3.4. Particulate Matter (PM)

Particulate air pollution originates from diverse sources. One major source of primary particle emissions is fuel combustion, including that by mobile sources such as diesel and gasoline-powered vehicles. The relative contributions of these different sources to the particle concentration at a given site may vary significantly. Atmospheric particles consist of organic and inorganic substances and are present in liquid or solid forms. They are subdivided according to diameter: coarse particles > 2.5 µm, fine particles < 2.5 µm. A further distinction is to classify particles as either primary or secondary, according to their origin. Particles that are emitted directly into the atmosphere are termed primary particles, whereas secondary particles form during atmospheric reactions. The primary particles contain carbon, hydrocarbons, metal oxides and other solid materials, which are primarily formed during combustion processes. Fine particles also include secondarily formed aerosols, smaller combustion particles and re-condensed organic and metallic compounds with low volatility. Most secondary particulate matter occurs as ammonium sulphates and nitrates formed from reactions involving sulphur dioxide, nitrogen oxides and ammonia. Shipping contributes to both, primary and secondary particles. Natural atmospheric emissions of particulates also derive from volcanic activities [Behrends 2003].

Particulkate matter can be definded by two characteristcs:

- Primary particulates
- Secondary particulates

Flue gases contain soot particles, which are produced by incomplete combustion of fossil fuels. Due to the ability of these particles to serve as condensation nuclei, soot contains polycyclic aromatic hydrocarbons (PAHs), a family of semi-volatile organic pollutants encompassing compounds such as extremely small amounts of anthracene, and some pyrene, or benzo[a]pyrene. Some PAHs from combustion products have been identified as carcinogenic. Combustion-derived PAHs are rapidly transferred from the atmosphere to aqueous systems and accumulate in the sediment.

Secondary particles (including sulphate and nitrate aerosols) are formed from gaseous pollutants (SO_2, NOx, NH_3). Ships emit sulphur dioxide and nitrous oxides through the combustion of fossil fuels. The primary air pollutants sulphur dioxide and nitrogen oxides are oxidised as they are dispersed in the atmosphere, forming sulphuric acid and nitric acid respectively, which may be deposited downwind as acid rain. Secondary particles can be transported over long distances [Behrends 2003].

PM emissions from shipping are difficult to measure accurately due to variations in size and complexity of composition. Depending on size, there are essentially three modes of PMs from marine diesel engines, which are [Fridell 2008]:

- Nucleation, ranging 10 - 100 nm
- Accumulation, ranging 0.1 – 1 µm
- Coarse, ranging 1 – 100 µm

PM emissions are generally composed of sulphate particles ($SO_4^{2-}\ ions$) formed through the degradation of SOx emissions), complex hydrocarbons from un-burnt fuel, graphite soot particles and inorganic particles from engine component wear/erosion [Fridell 2008; Moldanová et al., 2009]. The exact composition of the PM emissions determines their overall size and affect on human health and climate, responsible for cloud formation and, in either a positive or a negative way, for radiative forcing in the environment [Moldanová 2009].

Figure 19 displays the particle composition of a 4-Stroke engine fueled with MDO @ 1,7 % sulphur content vs. MGO @ 0,07 % sulphur content. Because of the significantly lower sulphur content of the MGO the formation of sulphate particles ir relativly low.

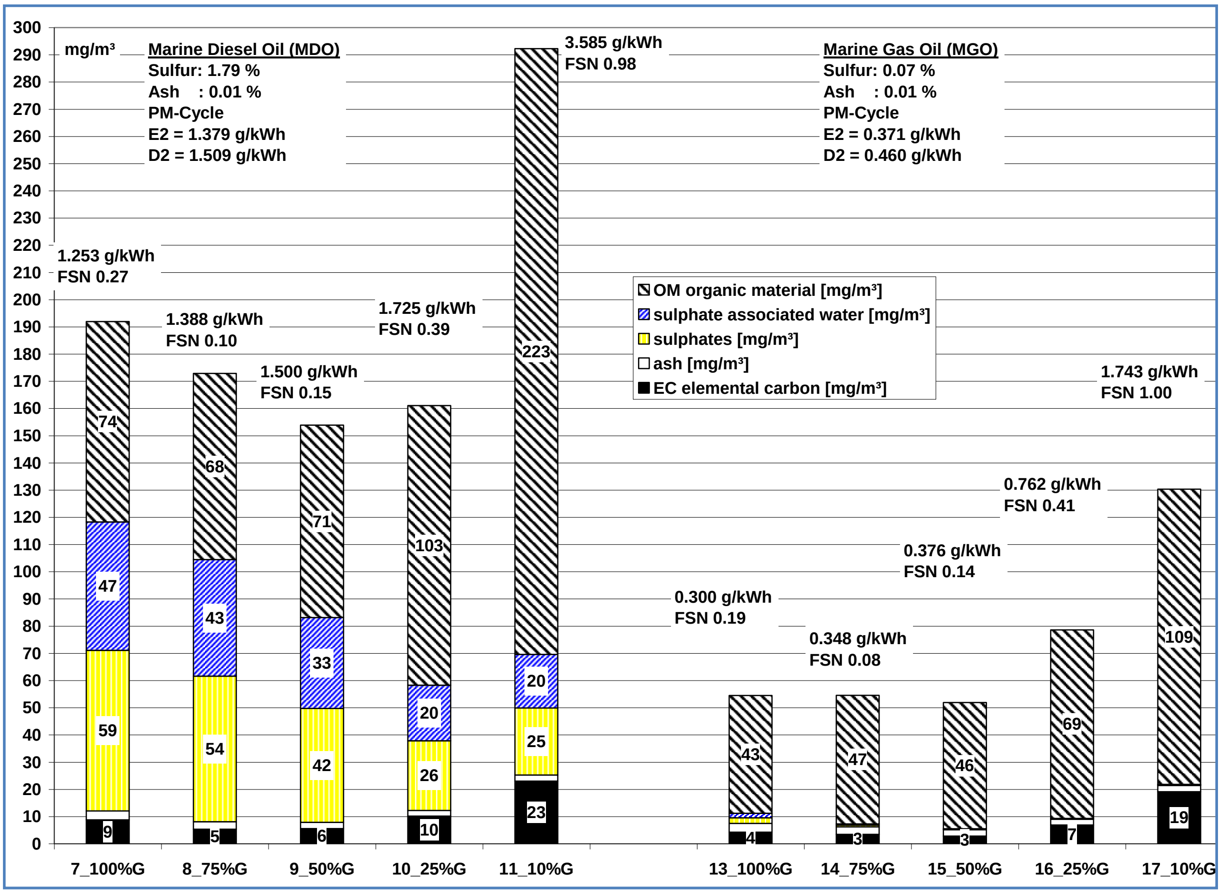


Figure 19: PM reduction by fuel sulphur limitation [Lauer 2009]

Most PM emissions from shipping occur within 400 km of land. Estimates for PM emissions are about 1.7 Teragrams (1Tg = 1000 Tons = 10^9g) is produced annually from shipping, one of the largest contributors of PM emissions to the global environment, as most other major producers of PM emissions have some form of regulation to limit PM emissions [Fridell 2008; Moldanová 2009]. In the marine environment, the only regulation adopted by the IMO and EU concerns the reduction of sulphur levels in fuels, which contribute the formation of PM. However, it is still uncertain how effective this would be in reducing overall PM emissions, as diesel engines run on low sulphur fuels require greater lubrication, which can add PM emissions. Currently, there is no definitive marine legislation setting limits on the levels of PM emissions from ships.

The Lloyds Register study (1995) first stated onboard ship 7.6 kg of PM emissions produced for every tonne of residual fuel oil combusted, while 1.2 kg/tonne produced from the combustion of marine gas oil [Lloyds 1995; Cooper 2002]. In the IMO's study on GHG emissions from shipping gives the emissions factors as 6.7 kg/tonne of residual fuel oil and 1.1 kg/tonne of marine diesel oil for PM_{10} emissions, particles equal to or less than 10µm [IMO 2009b].

In terms of power-based PM emissions, Lloyds Register calculated the emissions factors to 1.5 g/kWh for residual fuel oil and 0.2 g/kWh for marine gas oil [Lloyds 1995]. The US EPA established the power-based PM emission factor relates to the fractional power load by an inverse power factor of 1.5 [EPA 2000; Cooper, 2002]. The equation developed only relates to power-based PM emission factors for marine gas oils, which is:

$$EF_{PM\ g/kWh} = [0.0059xFractional\ Load^{-1.5}] + 0.2551$$

where the fractional load is equal to engine load/engine rated load.

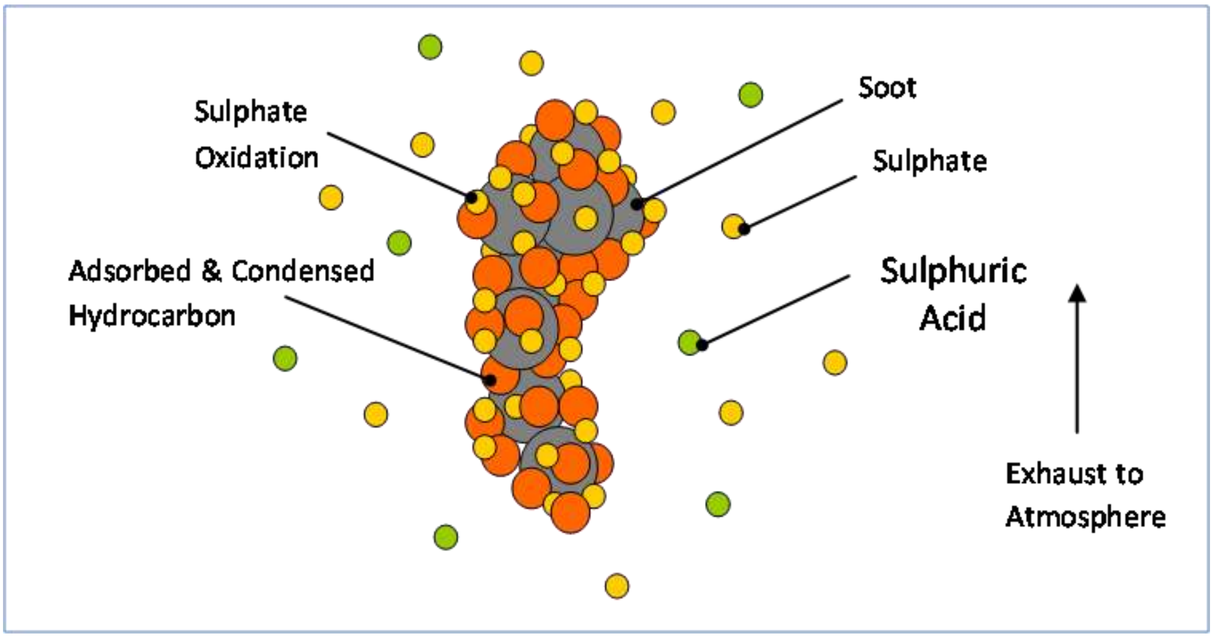


Figure 20: Particulate matter

- PM_{10} is particualte matter with an aerodynamic diameter nominally less than 10 µm
- PM_{10} comprises both coarse particles (PM_{10-25}) and fine particles ($PM_{2.5}$)
- $PM_{2.5}$ is particulate matter with an aerodynamic diameter nominally less than 2.5 µm
- $PM_{2.5}$ fine particles include the ultra-fine particles $PM_{0,1}$
- $PM_{0.1}$ is particulate matter with an aerodynamic diameter of up to 0,1 µm

Info Box 2: Particulate matter definitions

EPA is currently in a program that is evaluating the efficiency of PM_{10} and $PM_{2.5}$ reduction resulting from diesel combustion of low sulphur fuels. It is possible that a PM limit will be added to EGCS requirements. There is uncertainty as to the efficacy of EGCS in the removal of particulate matter, in particular $PM_{2.5}$ [Reynolds 2011].

- 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 air 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 [ISO 2006].
- The purpose of dilution is to reproduce the effects that occur when the exhaust gas from a diesel engine is emitted to atmosphere. The rapid mixing and cooling stops the growth of particulate matter and causes hydrocarbons, sulphates and associated water to condense.
- Smoke spot number is the measurement unit for the degree of filter blackening as defined by DIN 51402 Part 1. The soot content of flue gas is determined by capturing particulate matter on a filter of silica fibre material. The smoke spot is then assessed either visually or by photometer, which compares the intensity of reflected light with that from the original light source enabling the smoke number to be derived by a standard conversion procedure. Photometric measurement is carried out either directly in the stack or by extractive sampling [DIN 1986].
- Under EPA Method 5 particulate matter mass is determined by sampling part of an exhaust stream and weighing material collected on a on a glass fibre filter maintained at a temperature of 120 ± 14 °C (unless otherwise approved). The particulate matter includes any material that condenses at or above the filtration temperature, after the removal of un-combined water [EPA 1989].
- EPA Method 5 (which is similar to ISO 9096 [ISO 2003]) has historically been the method of choice for measurement of stationary particulate matter sources in the United States, since the majority consist of coal fired boilers. In these applications, the particulate matter control measures (e.g. electrostatic precipitators) 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 [BLG 2007].
- ISO 8178 states that particulates defined under the standard are substantially different in composition and weight from particulates or dust sampled directly from the undiluted exhaust gas using a hot filter method (e.g. ISO 9096). It is also stated in ISO 8178 that particulates measurement as described in the relevant part of the standard is conclusively proven to be effective for fuel sulphur levels up to 0.8 % [ISO 2006]. This is because at higher sulphur levels there is a possibility of sulphate loss due to condensation within the test apparatus before the filter [Wright 2000].

Info Box 3: A brief comparison of PM measurement methods

4. Evaluation of thermal energy technology onboard of ships

4.1 Purpose of generating thermal energy

On board of a ship thermal energy is required for a variaty of applications and consumers. Besides the type of vessel is the sailing profile of influence of the heat request. To understand the evaluation of thermal energy technology onboard of a ship, the demand of thermal energy in various scenario's of the vessel is leading in dimensioning the heating system.

The demand of thermal energy is the sum of the total consumers for all applications at a certain scenario. Summarized in the thermal heat balance and meeting the design parameters of the ship, this will determine the standard sizing of the main components of the heating system.

This is traditional way of engineering and dimensioning a heating system onboard of a vessel. In practice the request of heat required will be less than the heat available from the heat which can be recovered from the main engine in seagoing condition. Like shown in the figure below the surplus of heat which is not needed will be by-passed and wasted to avoid overheating of the system. In harbour the demand of heat is generated from the oil fired boiler as shown in the second figure below.

Now the challenge will be to extract as much heat or energy as possible from the main engine in seagoing condition. By connecting systems together, like a refrigerating system of adsorption type or thermal heat storage e.g. are extra purposes of using the additional heat. Finally to reduce the total emission footprint of the vessel in all conditions; seagoing, manoeuvring and port visit.

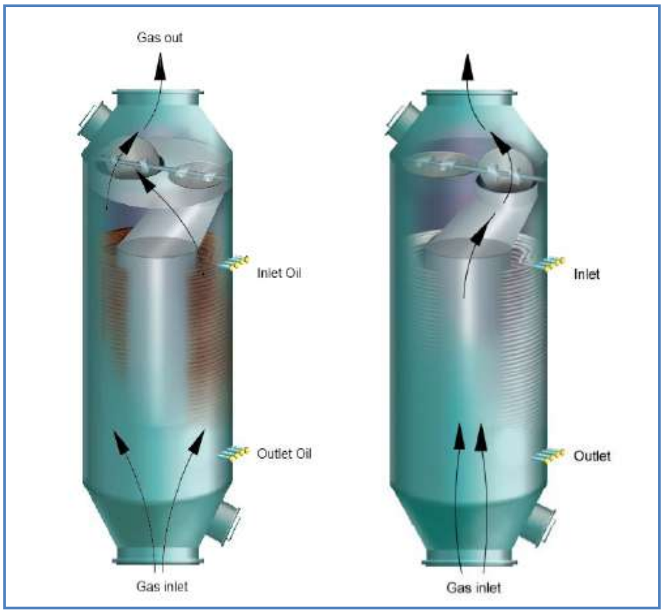


Figure 21: Exhaust gas economizer with by-pass (Heatmaster)

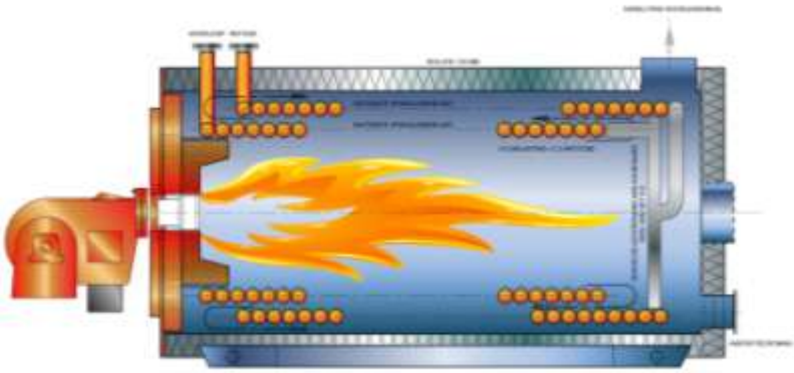


Figure 22: Exhaust gas economizer with by-pass (Heatmaster)

4.2 Thermal energy requirements

To start dimensioning the heating system onboard of a ship a total summary of all thermal energy consumers has to be determined.

4.2.1 Thermal energy consumers

In general thermal energy is supplying the following applications:

1. Central heating of accommodation and work spaces;
2. Domestic hot water;
3. Tank heating;
4. Fuel oil treatment;
5. Pre-heating of the main engine.

In many cases the heating systems are connected to the HVAC (Heating Ventilation and Air Conditioning) systems. Below a typical thermal fluid heating system of a ship with two main engines is displayed. Each main engine is executed with an exhaust gas economiser for seagoing and an oil fired boiler for harbour use.

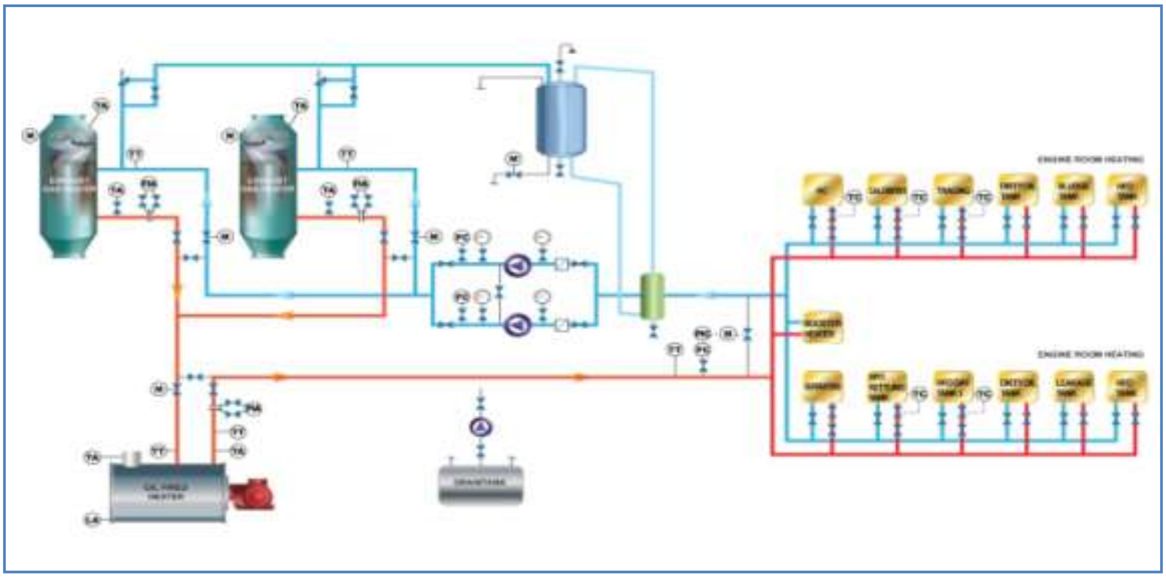


Figure 23: Thermal fluid heating system for a ship with two main engines (Heatmaster)

Further the thermal tracing of Fuel Oil piping systems, de-icing or ice preventing systems, additional fresh water generation and other customised applications can be connected to the heating system. All this is pending on the requirements and duties of the vessel.

For tankers transporting viscous cargo's the cargo heating and tank wash cleaning are additional applications which are consuming large amounts of thermal energy.

New developments like ad-/absorption refrigeration systems and air conditioners, waste heat recovery and heat buffering are subjects of the TEFLES study and will be discussed in deliverable D2.2.

4.2.2 Design conditions of the thermal heating system

Like a building which is standing in the arctic or located in the desert, a different design and dimensioning of the heating (and cooling) system is required. For a ship which is not fixed to one position on this planet, it can meet extreme cold and extreme hot conditions. In all situations the heating system must perform accordingly.

All these extreme conditions, the minimal and maximal ambient temperatures of the outside air, seawater and certain spaces inside the ship are to be specified in the building specification of the ship.

Also the selected fuel type is defined in the building specification. A majority of larger ships are running on HFO (Heavy Fuel Oil). The heat in his case is required to make the fuel oil viscous. Otherwise the HFO pump will not be able to transfer the fuel oil. Different types of heavy fuel oils, ranked to a certain viscosity and corresponding temperature, will require different temperature to meet the pump's suction conditions. The higher the viscosity, the higher the fuel oil / tank temperature. Higher tank temperatures more heat required and a increase of thermal losses. Suction requirement for the HFO transfer are normally between 500 and 1.000 cSt.

Heating times of the fuel oil tanks or the speed what is required to reach the tank temperature will influence the demand of energy for that period. Also the energy required for maintaining the tank temperatures to the set points regarding the energy loss are influencing the energy demand. Special attention has to be taken for the position of the tank in relation to the heat loss. A HFO fuel side tank adjacent to seawater in sailing conditioning will lose a lot more energy than the same tank installed inside the engine room.

All these data are to be summarized in heat balance sizing the heating installation.

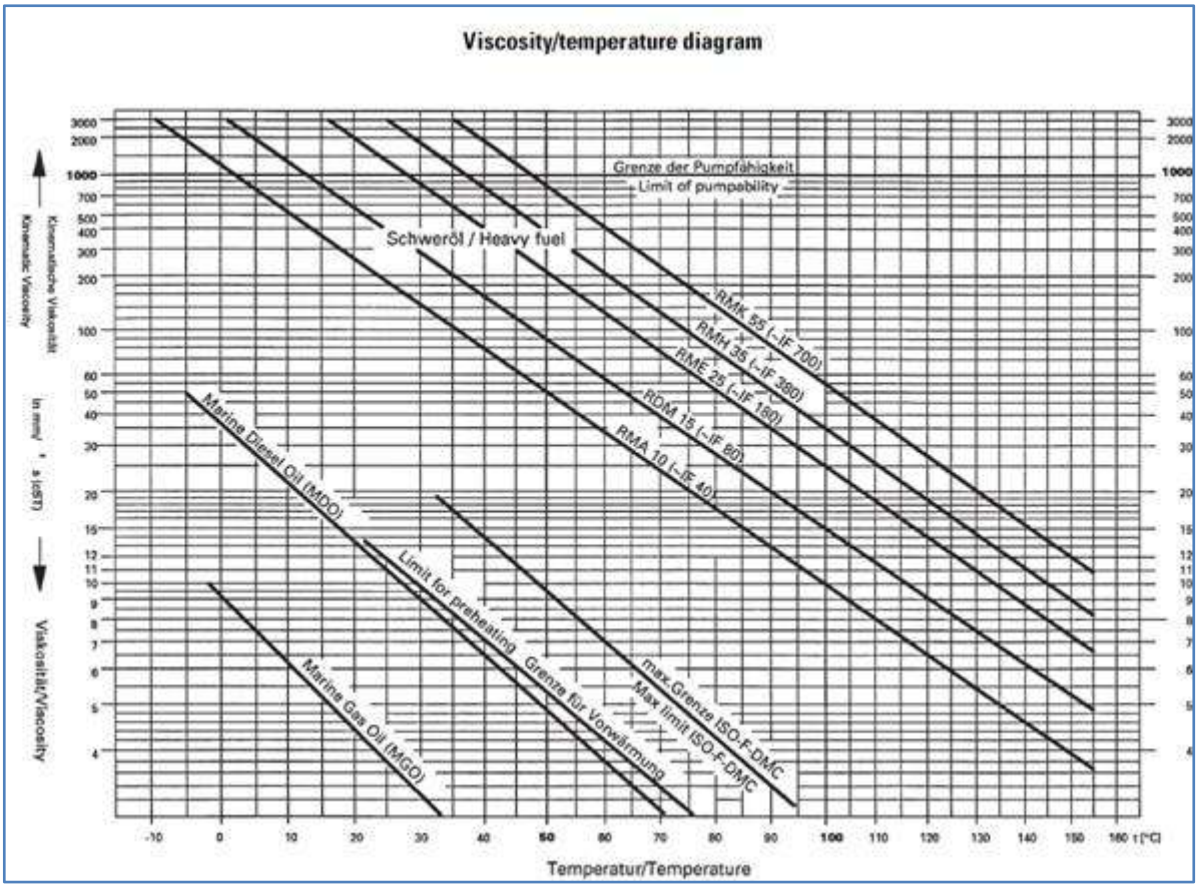
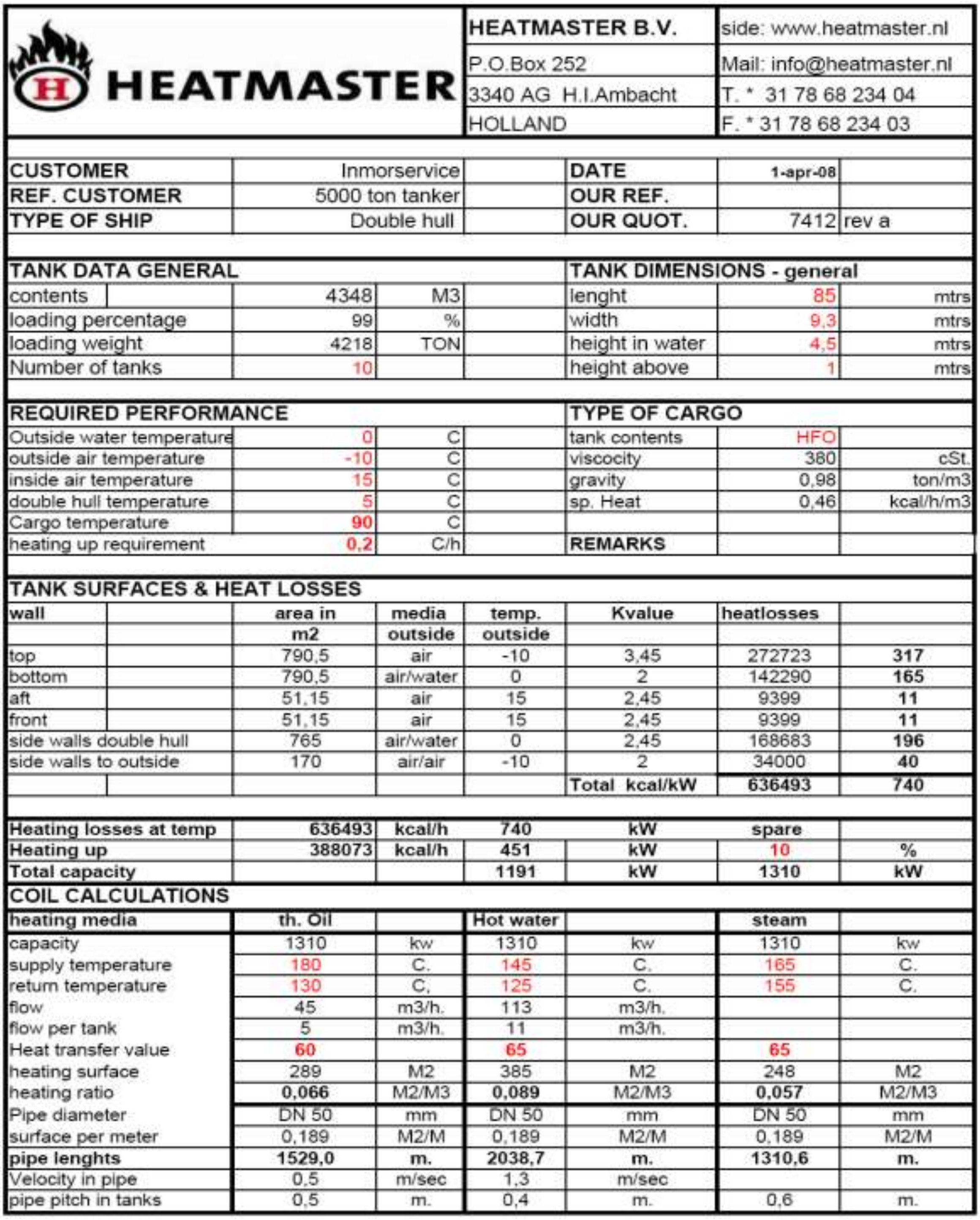


Figure 24: Viscosity / temperature diagram for various types of fuel oil (MaK project guide)

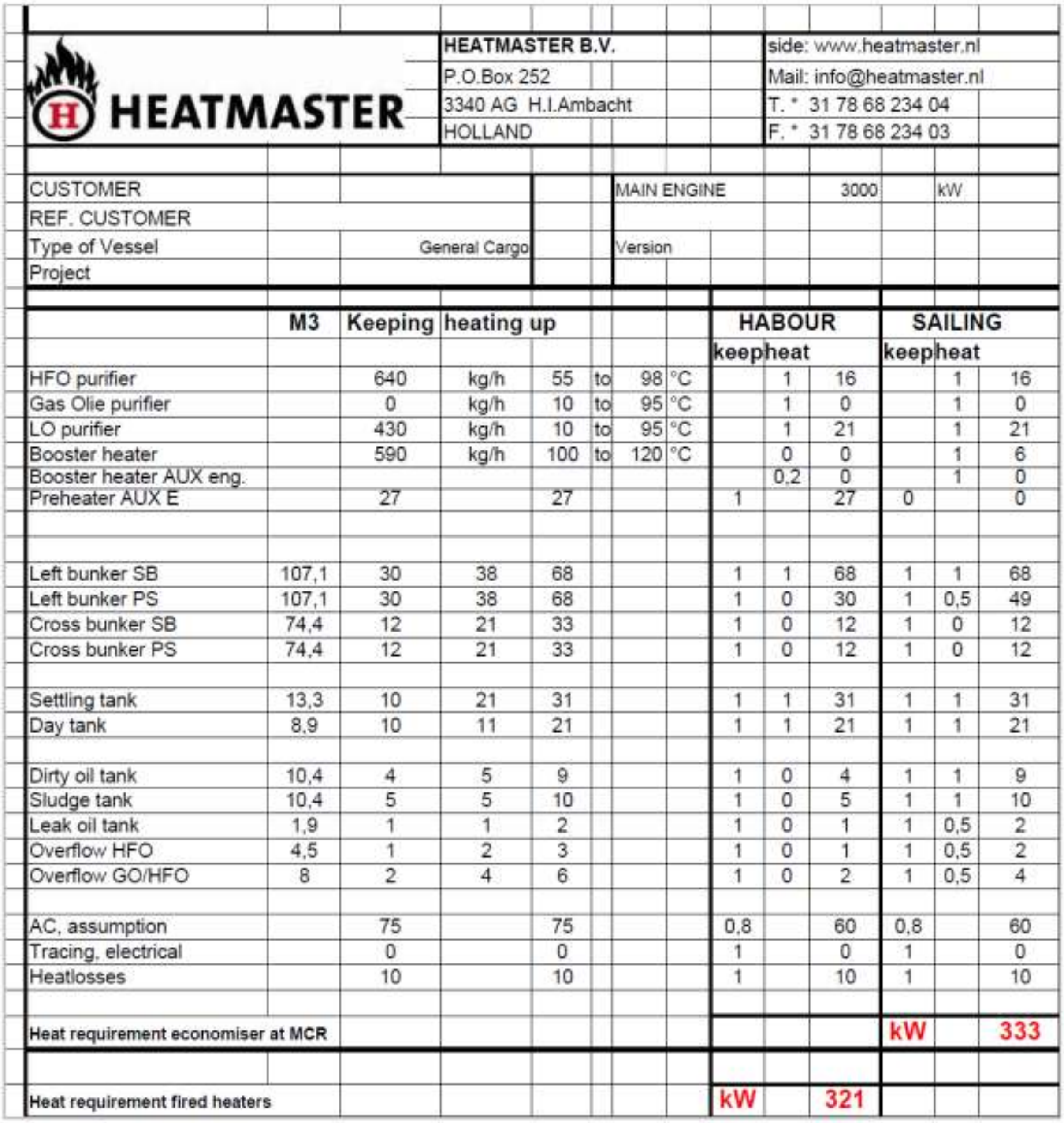
4.2.3 Heat balance

After collecting all data, consumers determined, design conditions fixed, heating times and heat losses of the tanks calculated. The heat balance can be generated. Dividing in a sailing and a harbour duty, the total heat request can be summarized to dimensioning the components of the heating systems.



HEATMASTER					HEATMASTER B.V.	side: www.heatmaster.nl	
					P.O.Box 252	Mail: info@heatmaster.nl	
					3340 AG H.I.Ambacht	T. * 31 78 68 234 04	
					HOLLAND	F. * 31 78 68 234 03	
CUSTOMER		Inmorservice			**DATE**	**1-apr-08**	
REF. CUSTOMER		5000 ton tanker			**OUR REF.**		
TYPE OF SHIP		Double hull			**OUR QUOT.**	7412	rev a
TANK DATA GENERAL					**TANK DIMENSIONS - general**		
contents		4348	M3		lenght	85	mtrs
loading percentage		99	%		width	9,3	mtrs
loading weight		4218	TON		height in water	4,5	mtrs
Number of tanks		10			height above	1	mtrs
REQUIRED PERFORMANCE					**TYPE OF CARGO**		
Outside water temperature		0	C		tank contents	HFO	
outside air temperature		-10	C		viscocity	380	cSt.
inside air temperature		15	C		gravity	0,98	ton/m3
double hull temperature		5	C		sp. Heat	0,46	kcal/h/m3
Cargo temperature		**90**	C				
heating up requirement		**0,2**	C/h		**REMARKS**		
TANK SURFACES & HEAT LOSSES							
wall		**area in m2**	**media outside**	**temp. outside**	**Kvalue**	**heatlosses**	
top		790,5	air	-10	3,45	272723	**317**
bottom		790,5	air/water	0	2	142290	**165**
aft		51,15	air	15	2,45	9399	**11**
front		51,15	air	15	2,45	9399	**11**
side walls double hull		765	air/water	0	2,45	168683	**196**
side walls to outside		170	air/air	-10	2	34000	**40**
					Total kcal/kW	**636493**	**740**
Heating losses at temp		**636493**	**kcal/h**	**740**	**kW**	**spare**	
Heating up		**388073**	**kcal/h**	**451**	**kW**	10	%
Total capacity				**1191**	**kW**	**1310**	**kW**
COIL CALCULATIONS							
heating media		**th. Oil**		**Hot water**		**steam**	
capacity		1310	kw	1310	kw	1310	kw
supply temperature		180	C.	145	C.	165	C.
return temperature		130	C,	125	C.	155	C.
flow		45	m3/h.	113	m3/h.		
flow per tank		5	m3/h.	11	m3/h.		
Heat transfer value		**60**		**65**		**65**	
heating surface		289	M2	385	M2	248	M2
heating ratio		**0,066**	M2/M3	**0,089**	M2/M3	**0,057**	M2/M3
Pipe diameter		DN 50	mm	DN 50	mm	DN 50	mm
surface per meter		0,189	M2/M	0,189	M2/M	0,189	M2/M
pipe lenghts		**1529,0**	**m.**	**2038,7**	**m.**	**1310,6**	**m.**
Velocity in pipe		0,5	m/sec	1,3	m/sec		
pipe pitch in tanks		0,5	m.	0,4	m.	0,6	m.

Table 11: Tank heating calculation of a Tanker (Heatmaster)



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CUSTOMER
REF. CUSTOMER
Type of Vessel General Cargo
Project

MAIN ENGINE 3000 kW
Version

	M3	Keeping	heating up					HABOUR			SAILING		
								keep	heat		keep	heat	
HFO purifier		640	kg/h	55	to	98	°C		1	16		1	16
Gas Olie purifier		0	kg/h	10	to	95	°C		1	0		1	0
LO purifier		430	kg/h	10	to	95	°C		1	21		1	21
Booster heater		590	kg/h	100	to	120	°C		0	0		1	6
Booster heater AUX eng.									0,2	0		1	0
Preheater AUX E		27		27				1		27	0		0
Left bunker SB	107,1	30	38	68				1	1	68	1	1	68
Left bunker PS	107,1	30	38	68				1	0	30	1	0,5	49
Cross bunker SB	74,4	12	21	33				1	0	12	1	0	12
Cross bunker PS	74,4	12	21	33				1	0	12	1	0	12
Settling tank	13,3	10	21	31				1	1	31	1	1	31
Day tank	8,9	10	11	21				1	1	21	1	1	21
Dirty oil tank	10,4	4	5	9				1	0	4	1	1	9
Sludge tank	10,4	5	5	10				1	0	5	1	1	10
Leak oil tank	1,9	1	1	2				1	0	1	1	0,5	2
Overflow HFO	4,5	1	2	3				1	0	1	1	0,5	2
Overflow GO/HFO	8	2	4	6				1	0	2	1	0,5	4
AC, assumption		75		75				0,8		60	0,8		60
Tracing, electrical		0		0				1		0	1		0
Heatlosses		10		10				1		10	1		10
Heat requirement economiser at MCR											kW		333
Heat requirement fired heaters								kW		321			

4.3 Thermal heating systems

4.3.1 Heating media

Knowing the total heat demand in all design conditions of the ship, the heating system can be designed, starting with the selection of the heating medium. Every fluid or vapour has a corresponding thermal conductivity and energy contents. The most common heating media used on board of ships are:

- Steam
- Thermal fluid
- Hot water

The final selection will be made by the shipyard and/or the ship owner after considering all benefits and disadvantages. Initial and operational cost of the installation, tradition and experience with existing installations are also decision points in selecting a heating media.

The most common heating systems used onboard of ships are:

1. Steam generator system 6 - 8 bar.
2. Steam boiler system 6 -8 bar.
3. Thermal fluid system.
4. Hot water systems, supply temperature < 120 °C.
5. Hot water systems, supply temperature < 140 °C.

4.3.2 Comparison of the heating systems

In shipbuilding comprises has to be made. Considering all advantages and disadvantages of the systems a selection can be made based on the below mentioned list per system.

4.3.2.1 Steam generator system

- Known system;
- Almost constant attention needed, most difficult control;
- Cheap system, but more expensive piping due to steam traps, pressure, condensate water;
- Most expensive system in operational cost;
- Highest fuel cost, due to lowest system efficiency;
- Highest risk of corrosion of coils in boiler, repair very difficult (if possible);
- Highest risk of corrosion of coils in cargo tanks.

4.3.2.2 Steam boiler system

- Known system;
- Daily attention needed;
- Total system cost same as thermal fluid system;
- Expensive piping due to steam traps, pressure, condensate water;
- Expensive system in operational cost;
- Costly periodical re-tubing of boiler and piping due to corrosion;
- High fuel cost, due to low system efficiency;
- Highest risk of corrosion of coils in cargo tanks.

4.3.2.3 Thermal fluid systems

- Low maintenance cost;
- Expensive piping due to class rules;
- High reliability;
- Great simplicity: simple system which is fully automatic with little supervision, higher degree of control;
- Not corrosive and no risk of freezing;
- Risk of fire in case of leaking;
- Oil is more expensive than water;
- Low operation cost;
- Low fuel cost.

4.3.2.4 Various hot water systems, < 120 °C system

- Cheapest system available. Cheapest piping;
- Low maintenance cost;
- High reliability;
- Great simplicity: simple system which is fully automatic with little supervision;
- Low pressure (working pressure 1 - 2 bar);
- Not corrosive as it's a closed system and no risk of freezing due to glycol;
- Lowest operation cost;
- Lowest fuel cost;
- Most flexible system, ducts welded on tank bottom, heat exchangers on m/e & aux cooling water possible;
- Longer coil length;
- HFO Booster heater are electrical.

4.3.2.5 Hot water systems, < 140 °C system

- Low maintenance cost;
- High reliability;
- Great simplicity: simple system which is fully automatic with little supervision;
- Not corrosive as it's a closed system and no risk of freezing due to glycol;
- Low operation cost;
- Low fuel cost.

With today's knowledge the environmental impact has to be considered as well in the final selection of the heating medium of the system. Especially with the introduction of the EEDI Environmental Efficiency Design Index, the EEOI Environmental Efficiency Operation Index, the ESI Environmental Ship Index and other local regulations, the ship owner are rewarded in selecting environmental friendly designs.

Also the serious threat of the rising of the fuel prices are becoming more and more important decision parameters for a ship owner to choose an efficient system, combined with heat recovery.

4.4 Heat generation and recovery

As mentioned in the paragraph 4.3.1 describing the various heating media, the heat can be generated or recovered. Rules of the classification society are subscribing always a second or redundant way of supply the heat to the system.

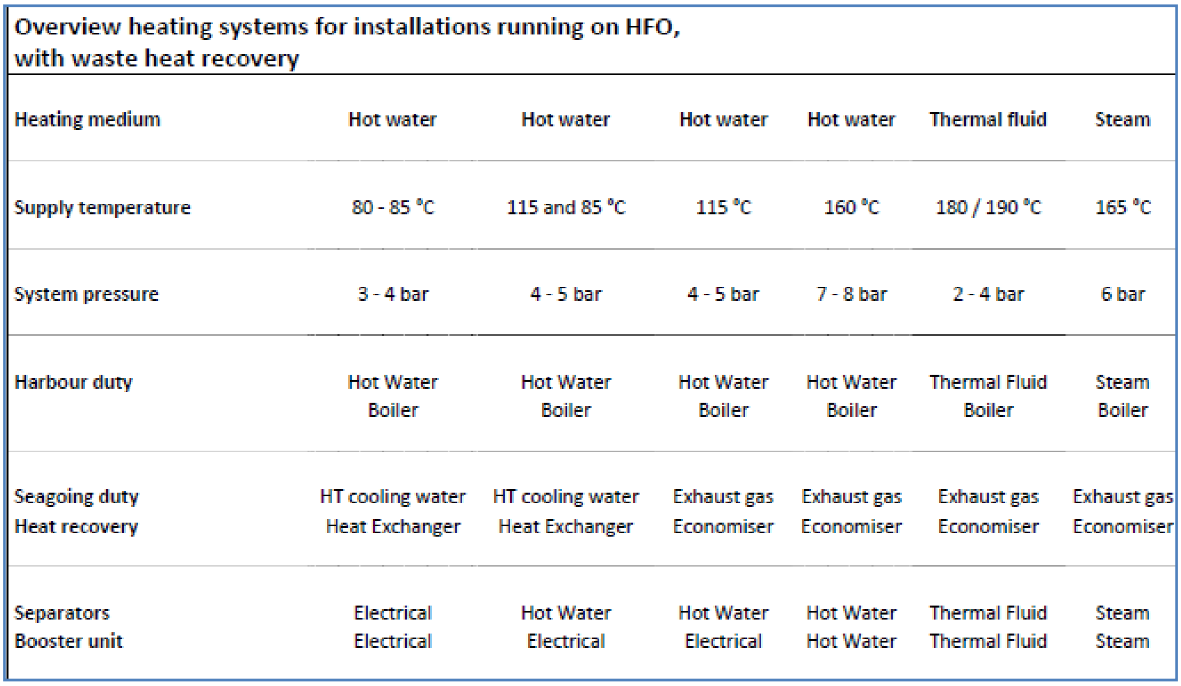
The oil fired boiler can always be fired up, covering the total heat demand in all conditions of the ship. Use of the oil fired boiler will have as drawback the consumption of (distillate) fuel oil with corresponding emissions.

For seagoing the energy wasted through the cooling water and the exhaust gas are normally exceeding the total demand of energy. The level of the energy – or temperature – is determining the use of the heat source. E.g. HT cooling water heat recovery from the main engine (90 °C) cannot supply sufficient temperature for heating the fuel oil or lube oil separators.(resp. 98 and 95 °C) The quantity of heat is not the problem.

For heat recovery from cooling water, conventional heat exchangers are used of the plate or shell and tube type. Also the generation of fresh water by means of an evaporator extracts the energy directly from the HT Cooling water system.

Waste heat recovery from exhaust gas of the main engine, also during seagoing use, are realized by means of the exhaust gas economizer as shown earlier. When using a thermal fluid the output temperature of the fluid will even be sufficient to heat the complete fuel treatment plant, including the fuel oil booster module. This module will supply the Heavy Fuel Oil to the main engine at the required viscosity. Temperatures of the fuel can be as high as 145 °C. In this case no electrical heating is needed.

The waste heat recovery from the exhaust gas and/or the cooling water of the main engine is only applicable when the main engine is running. In many cases for harbor running the oil fired boiler will supply the required heat and possible combined with electrical heating.



Overview heating systems for installations running on HFO, with waste heat recovery

Heating medium	Hot water	Hot water	Hot water	Hot water	Thermal fluid	Steam
Supply temperature	80 - 85 °C	115 and 85 °C	115 °C	160 °C	180 / 190 °C	165 °C
System pressure	3 - 4 bar	4 - 5 bar	4 - 5 bar	7 - 8 bar	2 - 4 bar	6 bar
Harbour duty	Hot Water Boiler	Hot Water Boiler	Hot Water Boiler	Hot Water Boiler	Thermal Fluid Boiler	Steam Boiler
Seagoing duty Heat recovery	HT cooling water Heat Exchanger	HT cooling water Heat Exchanger	Exhaust gas Economiser	Exhaust gas Economiser	Exhaust gas Economiser	Exhaust gas Economiser
Separators Booster unit	Electrical Electrical	Hot Water Electrical	Hot Water Electrical	Hot Water Hot Water	Thermal Fluid Thermal Fluid	Steam Steam

Table 13: Overview heating systems for installations running on HFO, with waste heat recovery (Heatmaster)

4.5 Weakpoints and potential improvements

For vessels running on heavy fuel oils the heat required for keeping the fuel and lube oil systems running can be generated from the cooling water of high temperature part of the main engine and/or from the exhaust gas, also from the main engine.

When using the low temperature hot water systems for heating up the bunkers, the additional energy required of a higher energy level has to be heated up electrically. Every kilowatt consumed for heating purpose has to be generated by the shaft generator of the main engine or from the auxiliary engine. For a four-stroke medium speed main engine the specific fuel consumption will be approx. 190 g/kWh (heavy fuel oil and sea-going). And for the high speed auxiliary a specific fuel oil consumption of 220 g/kWh (distillate fuel oil and harbour duty).

For indication the specific fuel oil consumption of an oil fired boiler, thermal or hot water, will be approx. 100 g/kWh (distillate – harbour duty) for the same kilowatt of energy required for heating the systems.

When trying to achieve a energy efficient system the electrical heating has to reduced or expelled. Not only reducing the consumed quantity, which also benefits the ship owner, the emission footprint will improve significant. For every ton of fuel oil not consumed – no single gram of NOx, SOx, PM and CO_2 are emitted to the environment.

Connecting additional systems to the heating system is also a possibility for reducing electrical consumption. As mentioned in work package 2 the study to connect an ad- / absorption system for the HVAC system to the heating system can reduce the electrical consumption during harbor visit as well during sailing. In this system the electrical consuming compressors needed for air conditioning chillers are exchanged for this new technologies.

Reducing the emission footprint during harbour visit will investigated in the TEFLES program. The footprint is depending on the electrical demand generated via the auxiliary engine(s) and heating of fuel oil and accommodation via the oil fired boiler. Making use of new technologies to store the excess of thermal energy during sailing and extract during harbor visit. Phase Change Materials is one technology available which could be used for marine applications.

Also the investigation of extracting as much as possible useful thermal energy from the exhaust heat recovery is a new dimensioning in designing a heating system. Where normally sufficient thermal energy is recovered, remaining energy is wasted. Even the combination with the exhaust cleaning installation will refigure the design parameters. Due to the extreme low SOx composition in the exhaust gas after cleaning, the risk of sulphur corrosion is serious reduced and making it possible to cool down the exhaust gas to a lower temperature. Or in other words: extracting more high value thermal energy to be applied for new technologies leading to a reduction of the emission footprint of the ship.

These above mentioned potential improvement are part of work package 2 (WP2).

5. After Treatment Technologies for the abatement of Sulphur Oxides (SOx)

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

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

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

The installation of exhaust gas cleaning systems (EGCS) present integration challenges to new builds and retrofits alike. Paragraph 7 provides summary information of several EGCS including footprints, weights, and backpressures. This will provide each operator a baseline on which to begin discussions with suppliers on integration. Key considerations include:

- Weight and stability. Weights will vary significantly by scrubber rating and type. The primary weights of concern are the scrubbers themselves as they are positioned high and even a 20 ton wet weight could be of significant concern for ships that have limited remaining stability margin.
- Water handling systems. These systems can be significant for any of the wet systems, but particularly for open loop and hybrid systems. For example, a 50 MW plant with an open loop scrubber will require 4,500 cubic meters an hour of wash water. This wash water would require about 0.5 megawatts of power to run, and a 760 mm pipe (30 inch diameter).
- Machinery and stack arrangements. In the case of new builds, the EGCS will become a primary component for arrangements and weight allowances. For retrofits, fitting this equipment into existing spaces will be a significant challenge and in some cases may require installation of the scrubber unit in the weather or new above the main deck enclosure.
- Exhaust backpressure. Most engines can tolerate ~3.0 kPa of backpressure without significant degradation of power or adverse affects. Exceeding the allowance will degrade performance by ~ one percent for each additional 3 kPa of backpressure. It should be noted that exhaust piping and silencers may required, depending on the scrubber design. If one is required, then backpressure allowances should be included.
- Electrical power. The demands of these systems can be significant reaching 2 % of nominal power, potentially requiring additional generating capacity.
- Failure modes. Being integral to diesel engine operations, a failure modes and effects or other analysis should be conducted to assure that a scrubber failure will not result in loss of ships service or propulsion power [Reynolds 2011].

5.1. Guidelines for Exhaust Gas Cleaning Systems (EGCS)

The 2009 Guidelines for Exhaust Gas Cleaning Systems - MEPC 184(59) are effective from 1st July 2010. This is in line with the revised MARPOL Annex VI, which permits the use of approved abatement technologies that are at least as effective in reducing emissions as the Annex's sulphur-in-fuel limits.

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

Although scrubbing technology has been successfully used on oil tankers and in shore-side industry for many years, exhaust gas cleaning to meet air pollution limits is a relatively new application for ships. IMO has recognised that as the technology continues to develop so the Guidelines for Exhaust Gas Cleaning Systems may have to evolve and has focussed in particular on the washwater discharge criteria. The current limits are intended to act as initial guidance for implementing Exhaust Gas Cleaning System designs and IMO has strongly requested that washwater samples be collected for analysis and data shared so that the criteria may be further reviewed in the future. For the time being the IMO guidelines are strictly focused on the use of wet scrubbing technologies and do not consider dry scrubbing technologies as offered by Couple Systems. It is likely that the scrubbing guidelines will be enhanced with reference to dry scrubbing technologies.

5.1.1. Overview

Similar to the requirements of the NOx Technical Code for engines, an Exhaust Gas Cleaning (EGC) unit may be used subject to periodic 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/kilowatt hour) is not required. Instead monitoring the ratio of SO_2 (sulphur dioxide) to CO_2 (carbon dioxide) emissions is permitted.

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

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

Fuel Oil Sulphur Content (% m/m)	Ratio Emission SO_2 (ppm)/CO_2 (% v/v)
4.50	195.0
3.50	151.7
1.50	65.0
1.00	43.3
0.50	21.7
0.10	4.3

Table 14: SO_2/CO_2 ratio emission

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

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

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

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

5.1.2. Scheme A

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

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

The exhaust gas cleaning unit must be tested over a prescribed load range with one or more fuel oils to demonstrate its operational behaviour and that the emissions value can be achieved. Testing can be carried out either prior to, or after installation onboard and test data is to be submitted for approval together with the Technical Manual. On approval the SOx Emissions Compliance Certificate is issued. (The Guidelines for Exhaust Gas Cleaning Systems also give the methods by which identical units and those of the same design but of different capacity may be certified without the need for repeat testing.)

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

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

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

5.1.3. 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, then the performance of the EGC unit is within that required without the need for actual exhaust emission measurements, (although daily spots checks of the latter are recommended to ensure compliance).

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

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

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

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

5.1.4. 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 [Wright 2000]. These reach air, land and water based ecosystems when unscrubbed exhaust gases are emitted into the atmosphere. As most Exhaust Gas Cleaning Systems use water to remove sulphur oxides and particulate matter before they reach the atmosphere, the aim of the washwater criteria is to prevent the undesirable effects and components of the air borne emissions simply being transferred to the seas.

5.1.5. 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.

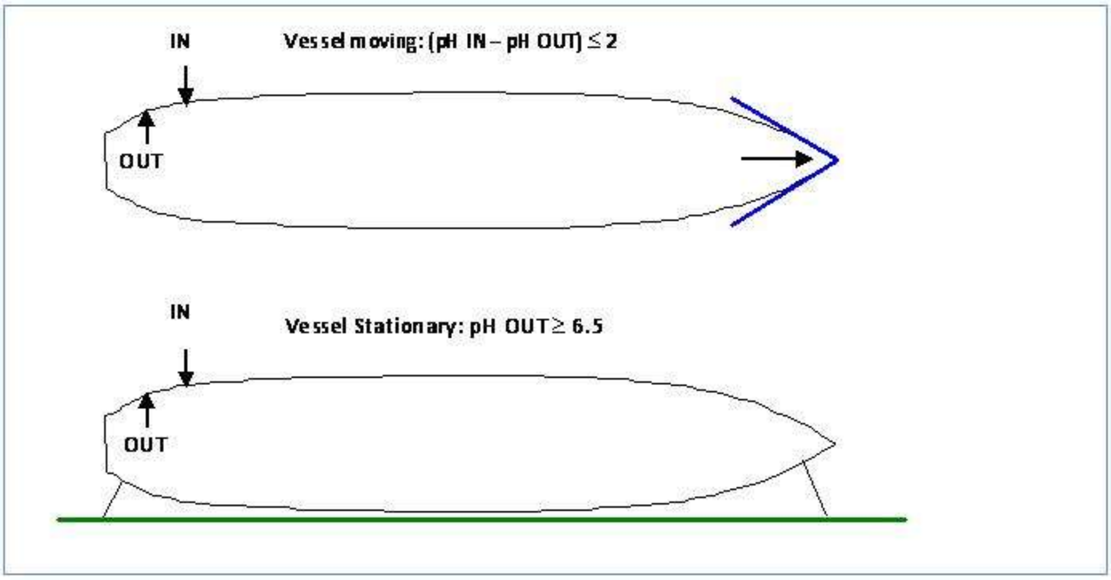


Figure 25: Measurement of position pH – Method 1

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.

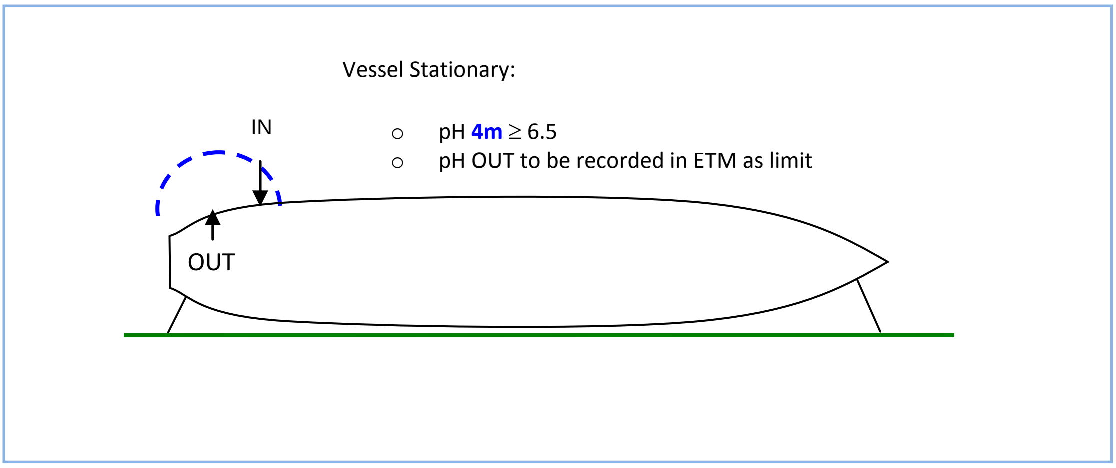


Figure 26: Measurement of position pH – Method 2

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

5.1.6. Polycyclic Aromatic Hydrocarbons (PAH)

Polycyclic aromatic hydrocarbons (PAHs), also known as poly-aromatic hydrocarbons or polynuclear aromatic hydrocarbons, are potent atmospheric pollutants that consist of fused aromatic rings and do not contain heteroatoms or carry substituents [Fetzer 2000]. Naphthalene is the simplest example of a PAH. PAHs occur in oil, coal, and tar deposits, and are produced as byproducts of fuel burning (whether fossil fuel or biomass). As a pollutant, they are of concern because some compounds have been identified as carcinogenic, mutagenic, and teratogenic.

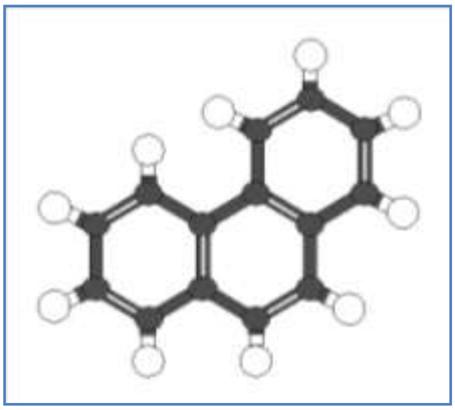


Figure 27: Phenanthrene $C_{14}H_{10}$

A source of PAHs is the incomplete combustion of fuel oils and although engines and boilers are designed to optimise the combustion of fuel, exhaust gases will always contain a proportion of incompletely combusted material. This results in gaseous hydrocarbon and particulate emissions that range from methane to very large complex molecules; a proportion of which will include polycyclic aromatic hydrocarbons. 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 [Hufnagel 2005].

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

The Guidelines for Exhaust Gas Cleaning Systems have PAH discharge limits based on the measurement of phenanthrene, as studies to date have shown no negative influences of washwater on port environments and that this is the most prevalent of the 16 US EPA PAHs to be found in the washwater systems onboard [Hufnagel 2005].

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

Flow Rate(t/MW h)	Discharge Concentration Limit(µg/L PAHphe equivalents)	Measurement Technology
0 - 1	2250	Ultraviolet Light
2.5	900	– ″ –
5	450	Fluorescence*
11.25	200	– ″ –
22.5	100	– ″ –
45	50	– ″ –
90	25	– ″ –

Table 15: PAH discharge concentration limits

By relating the discharge limit to a flow rate different concentrations are acceptable requiring different monitoring technologies to be used. For closed systems with a very low discharge rate ultraviolet light absorption technology is appropriate. UV light at a specific wavelength is emitted and the amount of light absorbed by the PAH is used to determine the concentration in the washwater. At flow rates above 2.5 t/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 particles, and natural oil seeps. There are also seasonal variations in concentration, for example increases can be seen in winter because of the heating of buildings in towns and cities. Low molecular weight PAHs with two or three rings are present normally in dissolved form in water or gaseous in the atmosphere. However the higher the molecular weight the more hydrophobic they behave and the more they are bound to particles. The highest PAH concentrations are therefore found in sediments [Behrends 2003].

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

5.1.7. Turbidity

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

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

5.1.8. 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 5-10% of the NO is then converted to nitrogen dioxide (NO_2) in the presence of excess oxygen. Collectively NO and NO_2 are often referred to as NOx.

When NO_2 is dissolved in water a series of reactions occur which finally result in ionisation to nitrate. Nitrate is an important nutrient in the sea, 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 a lack of oxygen in the water needed for fish and shellfish to survive [Behrends 2003].

Photosynthesis and within limits a fixed ratio of nitrogen, phosphorus and carbon are required for microscopic algae to be produced in marine systems. The production therefore depends not only on the actual amount of nitrogen added but also on the phosphorus. In the open oceans the availability of phosphorus is generally regarded as the limiting factor and additional nitrogen will not have any effects on growth. However in near-shore or harbour situations, where phosphorus is available (e.g. from river inputs, run-off from agriculture or direct input of domestic sewage), addition of nitrate may lead to enhanced biomass production [Behrends 2003].

The level of unscrubbed NOx emissions is mainly governed by the design and operation of an engine, the combustion temperature and to a lesser extent the nitrogen content of the fuel. Although IMO give typical figures of 4 % nitrogen for residual fuel and zero for distillate[IMO 2009] the mechanisms for NOx production occur in differing proportions during the combustion of these fuels [Wright 2000] so there is only a small reduction in NOx emissions from the use of distillate [EPA 2010]). Whilst the majority nitric oxide in NOx is not readily dissolved, the 5 – 10 % nitrogen dioxide is soluble and therefore likely to be at least partly removed during the exhaust gas cleaning process to form nitrate in the washwater. However, when compared with the removal of SO_2, the amount of NO_2 removed by a typical wet Exhaust Gas Cleaning System is relatively small and constant for an engine burning residual fuel and this has been confirmed by in-field testing [Behrends 2003].

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 a hypothetical Exhaust Gas Cleaning System design capable of removing more NOx than the soluble NO_2 fraction 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.

5.1.9. Washwater additives and treatments

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

10.1.6.1 "An assessment of the washwater is required for those EGC technologies, which make use of chemicals, additives, preparations or create relevant chemicals in situ. The assessment could take into account relevant guidelines such as resolution MEPC.126(53), procedure for approval of ballast water management systems that make use of active substances (G9)[MEPC 2005b]and if necessary additional washwater discharge criteria should be established."

Info Box 4: The use of chemicals, additives, preparations or creating chemicals in situ

5.1.10. Washwater treatment plant residues

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 [Wright 2000].

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.

5.2. Wet Exhaust Gas Cleaning Systems

Most wet Exhaust Gas Cleaning Systems have 3 basic components

- A vessel or vessels in close series which enable the exhaust stream from one or more engines or boilers to be intimately mixed with water – either seawater or freshwater (or both). For reasons of available space and access exhaust gas cleaning units tend to be high up in the ship in or around the funnel area. EGC units can be effective silencers, which may allow the existing silencer in an exhaust system to be replaced, saving space
- A treatment plant to remove pollutants from the "wash" water after the exhaust gas cleaning process.
- Sludge handling facilities - residue removed by the washwater treatment plant must be retained onboard for disposal ashore and may not be burned in the ship's incinerators.

The system may be an "open" or once-through type, whereby water is taken from the sea, used for exhaust gas cleaning, treated and discharged back to sea, with the natural chemical composition of the seawater being used to neutralize the results of SO_2 removal. Typically open seawater systems use approximately $45m^3$/MW h [MEPC 2008] for exhaust gas cleaning.

Or, the system may be a "closed" type, whereby freshwater treated with an alkaline chemical such as sodium hydroxide or seawater is used for neutralization and exhaust gas cleaning. The majority of washwater is re-circulated and any losses (in water level and alkalinity) made up with additional freshwater and chemical or seawater. The type of water, amount of recirculation and make-up depends on system design and operating mode. A small quantity of the washwater is bled off to a treatment plant before discharge to sea. Typically closed freshwater systems have a discharge rate of 0.1 - 0.3 m^3/MWh [MEPC 2008] although the system shown can operate with zero discharge for limited periods.

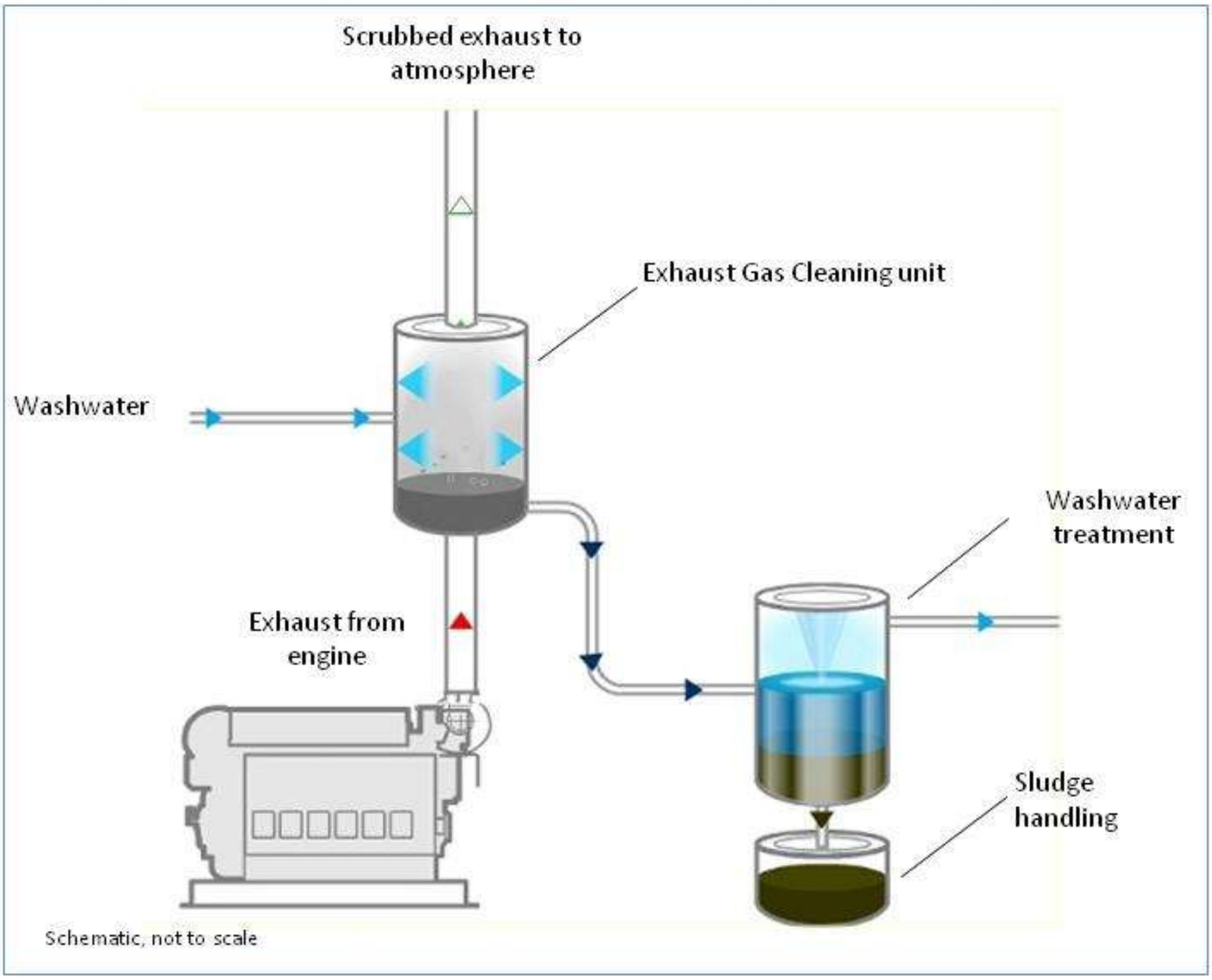


Figure 28: Wet Exhaust Gas Cleaning Systems basic components

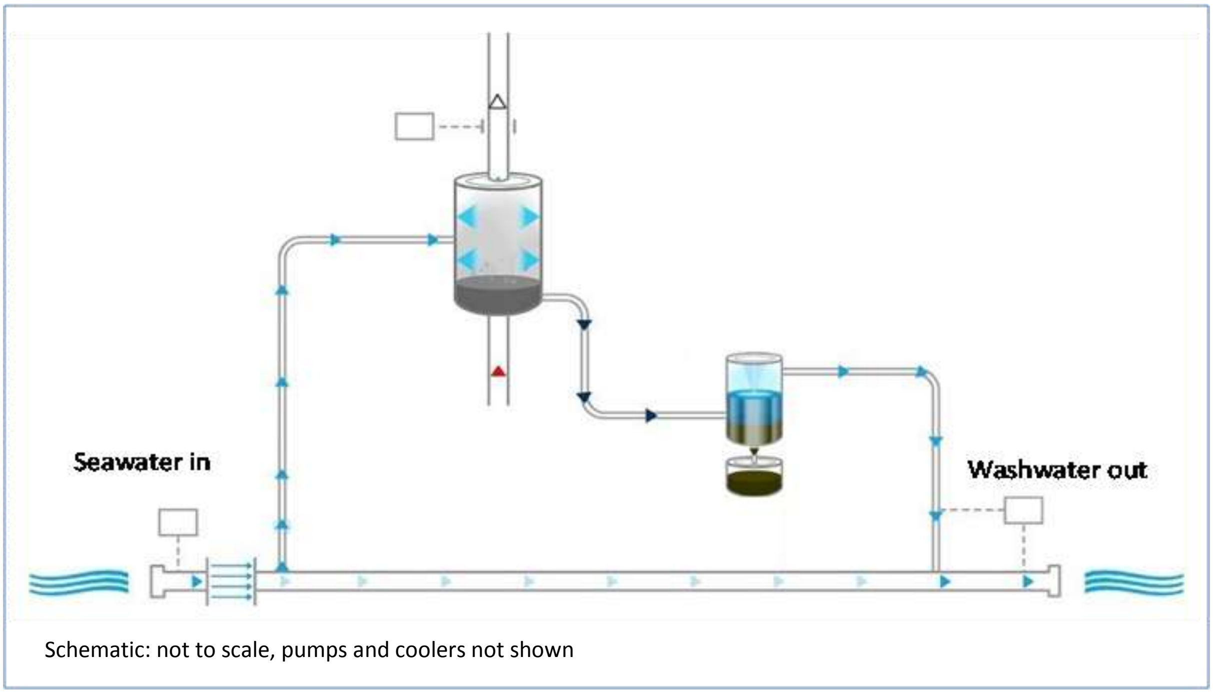


Figure 29: Open Exhaust Gas Cleaning System

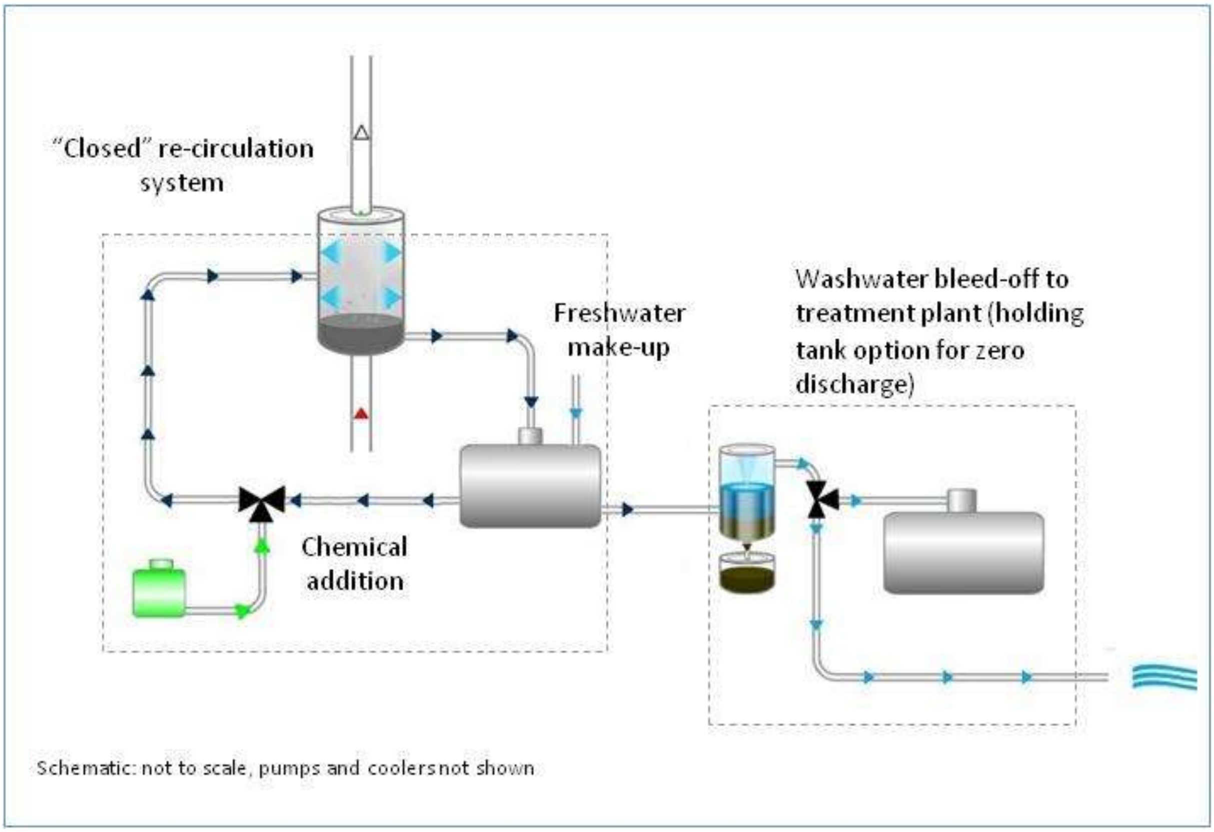


Figure 30: Closed Exhaust Gas Cleaning System

5.2.1 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 'back pressure' outside of the engine builder's limits and adversely affect engine operation. The sulphur oxides in shipping exhausts are virtually all sulphur dioxide - SO_2, a very small percentage of which is further oxidized to sulphur trioxide - SO_3. When dissolved in seawater a reaction occurs whereby the sulphur dioxide is ionized to bisulphite and sulphite, which is then readily oxidized to sulphate in seawater containing oxygen [Karle 2007].

- $SO_3 + H_2O \rightarrow H_2SO_4$ (sulphuric acid)
- $SO_2 + H_2O \leftrightarrow$ "H_2SO_3" (sulphurous acid) $\leftrightarrow H^+ + HSO_3^-$ (bisulphite)
- HSO_3^- (bisulphite) $\leftrightarrow H^+ + SO_3^{2-}$ (sulphite)
- SO_3^{2-} (sulphite) + ½ $O_2 \rightarrow SO_4^{2-}$ (sulphate)

Info Box 5: Relevant chemistry – sulphur oxides to sulphate

The ionization 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 ionization of sulphur dioxide to sulphite is negligible [Karle 2007] and removal becomes limited. (Note: sulphur trioxide reacts very rapidly with water to form sulphuric acid (comprising hydrogen and sulphate ions), which in turn has a great affinity for water. This enables Exhaust Gas Cleaning Systems to be highly effective at removing and neutralizing this minor component).

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

5.2.2 Removal of sulphur oxides – fresh water 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 (NaOH), also known as caustic soda, which is typically sold as a 50 % solution, eliminating the need for solids handling equipment:

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

Info Box 6: Relevant chemistry - aqueous sodium hydroxide

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

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

Info Box 7: Relevant chemistry - sulphur oxides to sulphate

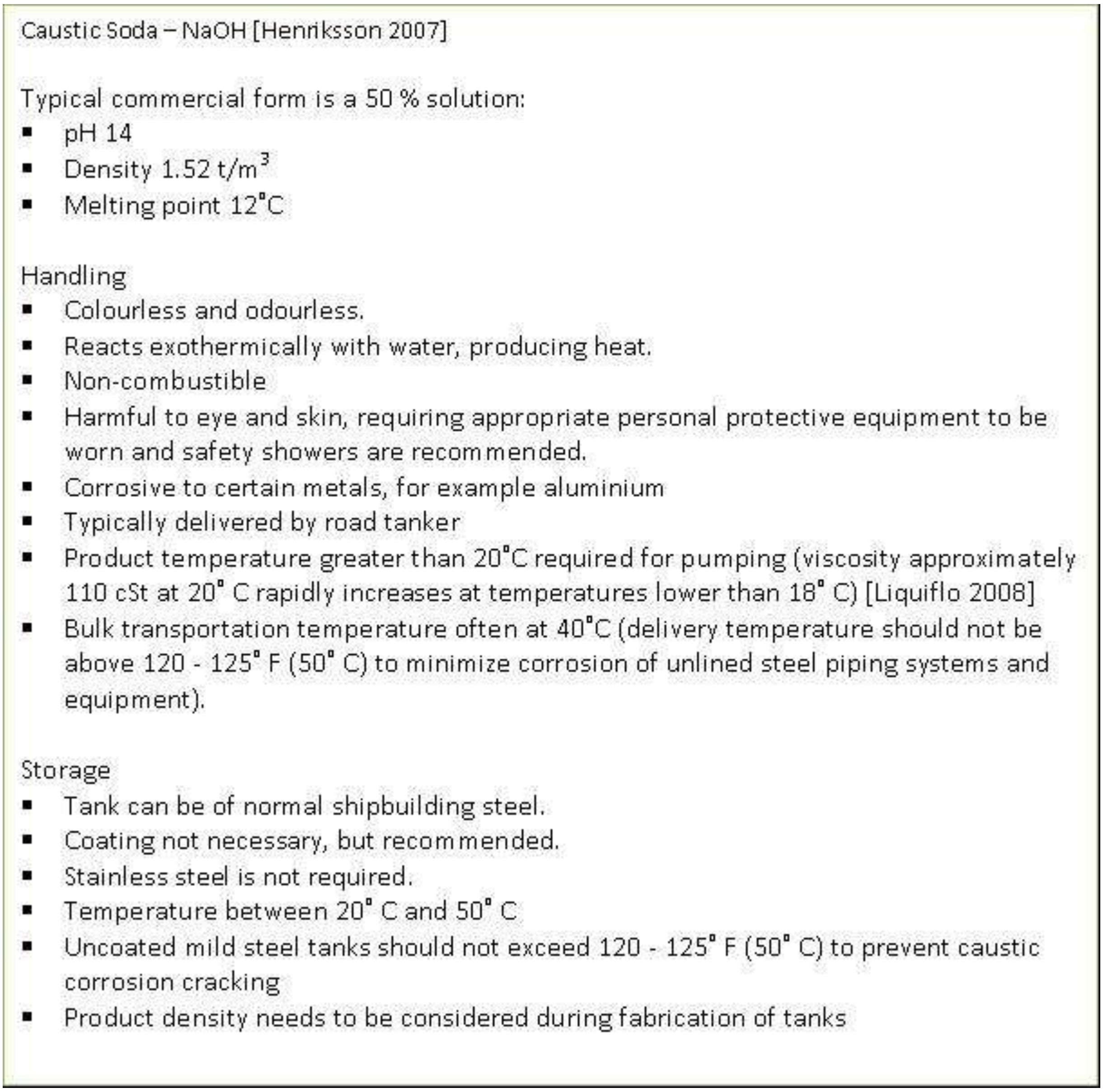
The overall reactions with SO_2 therefore produce a mixture of sodium bisulphite, sodium sulphite, and sodium sulphate. The exact proportions of the sulphur species depend on the pH and degree of oxidation [Schnelle 2002].

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

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

Info Box 8: Relevant chemistry – sodium hydroxide to sodium sulphate

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



Caustic Soda – NaOH [Henriksson 2007]

Typical commercial form is a 50 % solution:

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

Handling

- Colourless and odourless.
- Reacts exothermically with water, producing heat.
- Non-combustible
- Harmful to eye and skin, requiring appropriate personal protective equipment to be worn and safety showers are recommended.
- Corrosive to certain metals, for example aluminium
- Typically delivered by road tanker
- Product temperature greater than 20°C required for pumping (viscosity approximately 110 cSt at 20° C rapidly increases at temperatures lower than 18° C) [Liquiflo 2008]
- Bulk transportation temperature often at 40°C (delivery temperature should not be above 120 - 125° F (50° C) to minimize corrosion of unlined steel piping systems and equipment).

Storage

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

Info Box 9: Caustic soda handling and storage

5.2.3 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 SO_x 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 to freshwater by use of an alkaline chemical such as sodium hydroxide.

$$CO_{2(aq)} + H_2O \leftrightarrow H_2CO_3(Carbon\ Acid) \leftrightarrow H^- + \underleftarrow{+HCO_3^-\ (Bicarbonate) \leftrightarrow H^- + CO2_3^{2-}\ (Carbonate)}$$

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

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

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

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

Info Box 10: Relevant chemistry – seawater neutralization of acidic washwater

Alkalinity does not refer simply to pH, but to the ability of water to resist changes in pH. The buffering components of seawater are primarily bicarbonates and carbonates, but app. 4.0 % of the neutralization is provided by borates and other ions in low concentrations [Hamworthy 2007]. Total alkalinity, is the sum of all these and for the open ocean is usually constant and high at approximately 2200-2300 µmol/l [Karle 2007]. Salinity describes the total salt content of water and for the open ocean this is approximately 3.5 % by weight (the majority salt in seawater being sodium chloride).

- Alkalinity is the capacity of solutes in an aqueous system to neutralize acid [Rounds 2006]
    - Bicarbonates and carbonates contribute 89.8 % and 6.7 % respectively to the total alkalinity of seawater [Millero 1996]
- pH can be considered an abbreviation for power of the concentration of Hydrogen ions. The mathematical definition is pH is equal to the negative logarithmic value of the Hydrogen ion (H^+) concentration, or pH = -log [H^+]
    - pH values are calculated in powers of 10. The hydrogen ion concentration of a solution with pH 1.0 is 10 times larger than the hydrogen ion concentration in a solution with pH 2.0. The larger the hydrogen ion concentration, the smaller the pH:
    - When the pH is above 7 the solution is basic
    - When the pH is below 7 the solution is acidic
- 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 sulphates (> 7.5 %), and salts of magnesium (>3.5 %) calcium (>1 %) and potassium (>1 %).
    - Bicarbonates make-up less than 0.5 % of the salts in seawater [Behrends 2003]
    - Salinity is practically determined from the conductivity ratio of the sampled seawater to a standard potassium chloride solution.

Info Box 11: Definitions – alkalinity, pH, salinity

It is possible for waters to a have high alkalinity and a very low salinity (<0.05 %) depending mainly on the calcium concentration [Henriksson 2007a]. 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 low alkalinity at approximately 500-1300 µmol/l, whereas the southern rivers flow across a region of calcite geology resulting in high carbonate concentrations with consequently higher alkalinity of approximately 1650 -1950 µmol/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 in some cases SO_2 removal efficiency may be reduced [Henriksson 2007a]. The alkalinity of the majority of open sea areas and harbours is however high and therefore suitable for exhaust gas cleaning. In fact many rivers also have a suitably high alkalinity.

AREAS

Alkalinity (µmol/l)

Location	Min.
North Sea	2200
Norwegian Sea	2300
North Atlantic Ocean	2300
South Atlantic Ocean	2300
Mediterranean Sea	2400
Black Sea	2500
Gulf of Mexico	2250
Caribbean Sea	2250
Panama	1800
Panama Canal	1000
Gulf of Alaska	2000
North Pacific Ocean	2100
South Pacific Ocean	2200
Red Sea	2400
Persian Gulf	2500
Arabian Sea	2300
Bay of Bengal	2300
Indian Ocean	2200
Gulf of Thailand	2000
South China Sea	2000
Philippine Sea	2100
Coral Sea	2150
Tasman Sea	2300
Gulf of California	2150

PORTS

Alkalinity (µmol/l)

Port	Min.	Max.	River
Amsterdam	2200		
Antwerpen	2200	4500	Scheldt
Bilbao	2200		
Bordeaux	2300	2400	Gironde
Calais	2800	3100	
Dover	1100	1300	
El Ferrol	2280		
Hamburg	2050	2400	Elbe
Hanko	1600		
Helsinki	1250	1500	
Hull	1350		Humber
Kotka	900	1000	Kymijoki
Miami	2300		
New Orleans	2400	3000	Mississippi
Oslo	1350		
Rotterdam	2200	2700	Rhine
St Petersburg	490		Neva
Travemünde	1800		

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

Info Box 12: Alkalinity in sea areas and ports [Henriksson 2007b]

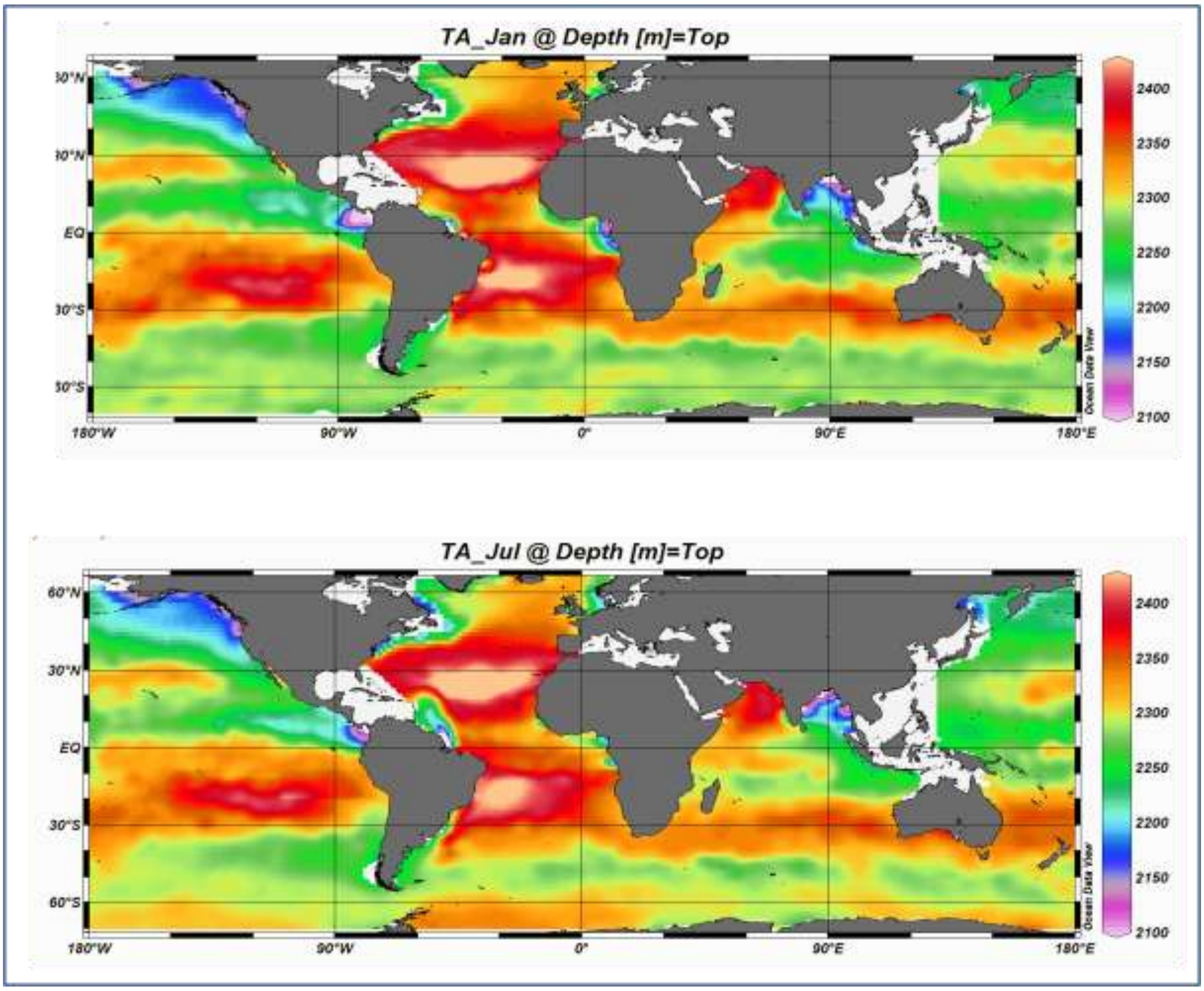


Figure 31: Surface alkalinity of open seas – January and July [Lee 2006]

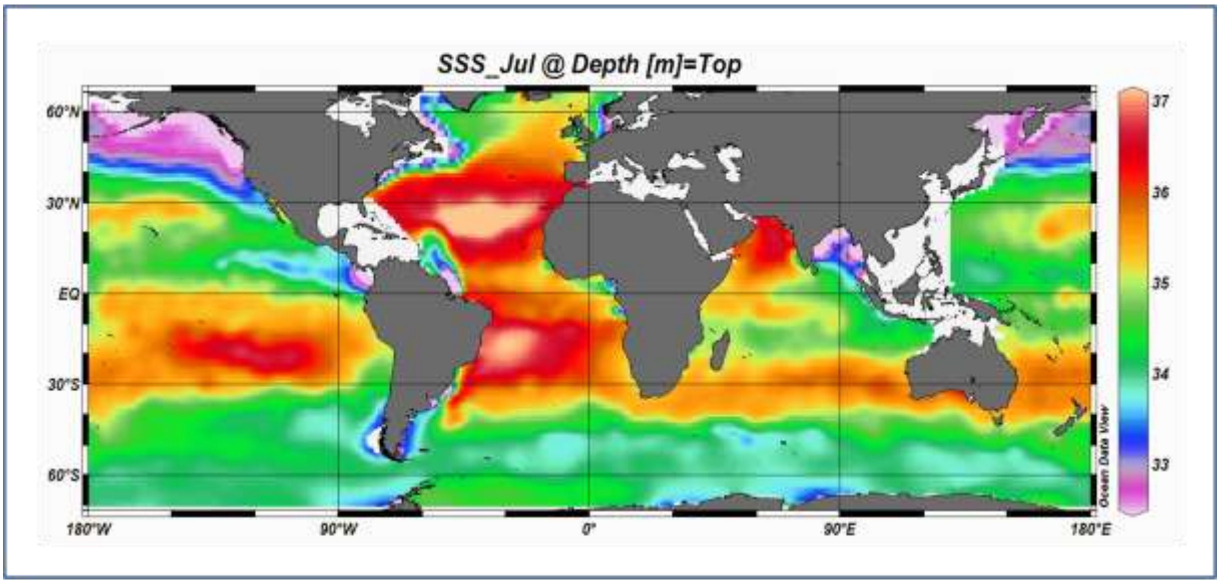


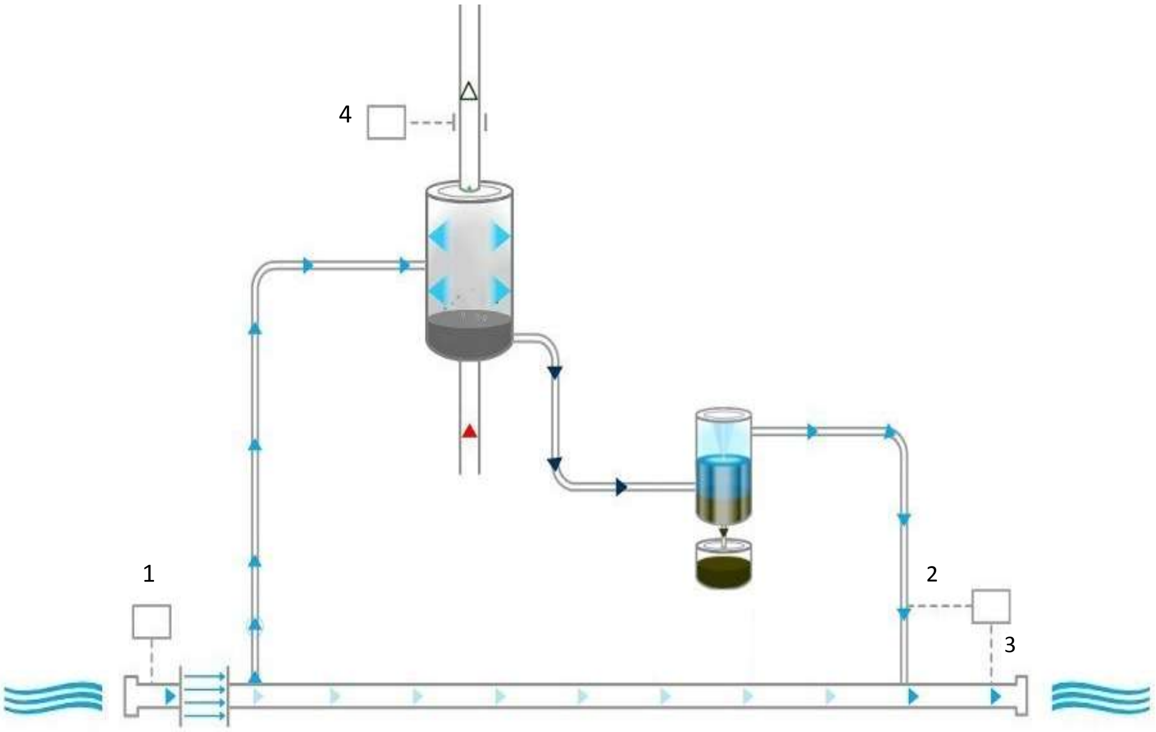
Figure 32: Surface salinity of open seas – July [Lee 2006]

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

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

Info Box 13: 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.



Schematic: not to scale, pumps not shown

Position 1 washwater system inlet

- pH (optional; depending upon which method is chosen to determine pH at discharge – see section 2.5.1)
- PAH
- Turbidity
- Salinity (optional)

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

- PAH
- Turbidity

Position 3 (before discharge after any pH correction)

- pH

Position 4 (emissions to air)

- SO_2
- CO_2

Figure 33: Position of water quality and emissions monitoring instrumentation

5.2.4 Washwater treatment

5.2.4.1 Wash water

The acidity of the washwater immediately after an EGC unit can be as low as pH3. 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.

5.2.4.2 pH

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 direct to sea. An effective washwater treatment plant is therefore required that is capable of removing both particles and oil.

A number of suppliers 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.

The hydrocyclone is a closed vessel designed to convert incoming liquid velocity into a rotary motion. It does this by means of a tangential inlet near the top of a vertical cylinder. This causes the entire contents of the cylinder to spin, creating centrifugal force in the liquid. The heavy fractions are moved outward towards the wall of the cylinder and downward to the outlet at the bottom of the vessel. The light fractions move toward the central axis of the hydrocyclone and upward to the outlet at the top of the vessel.

Hydrocyclones can be readily sized for the larger flow of open systems and depending on design can provide solid/liquid or liquid/liquid separation. Combinations can therefore be used to separate both particulate matter and oil from the washwater.

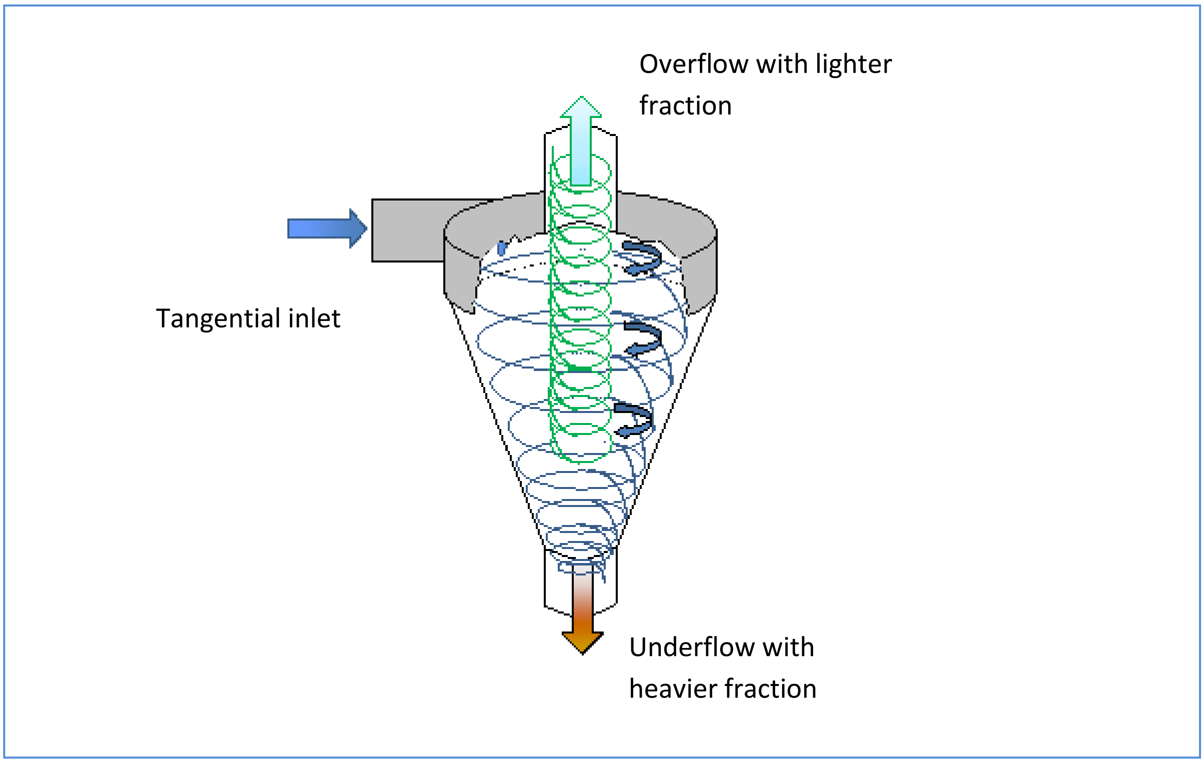


Figure 34: Hydro cyclone schematic

An alternative technology is the multi-stage separation plant using air, chemical addition and filtration, which is suited to the lower discharge rates of closed systems.

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

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

Before discharge the washwater is finally subjected to active carbon filtration, which is effective at removal of organic compounds from water by adsorption.

5.2.5 Effects on seawater composition

5.2.5.1 Sulphate

As seen in section 4.1.1 when SO_2 dissolved in seawater a reaction occurs whereby the sulphur dioxide is ionised to bisulphite and sulphite, which is then readily oxidized to sulphate. Sulphate is a naturally occurring constituent of seawater. It is soluble and has a long ‘residence time’, as it is unaffected by the natural pH, temperatures and pressures found in the oceans. It is therefore said to be ‘conservative’ in that regardless of the total salinity it occurs mixed throughout the oceans in the same ratio to the other conservative constituents such as sodium. 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 [Behrends 2003].

Studies [Karle 2007] and in field testing [Behrends 2005] confirm that the sulphate increase from exhaust gas cleaning will be insignificant when compared with the quantity already in the oceans.

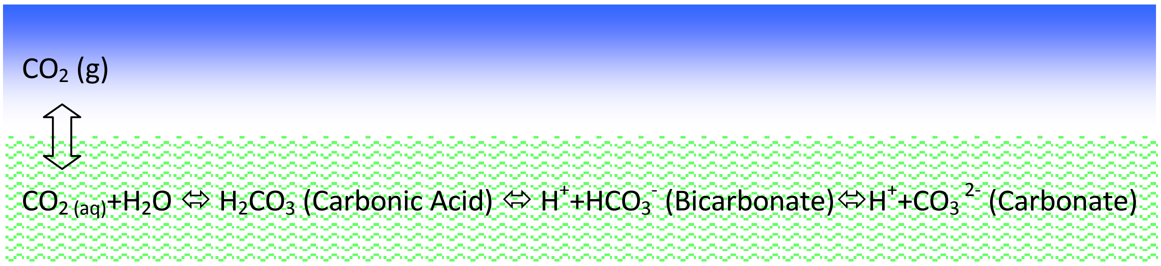
5.2.5.2 Oxygen

The process of oxidising sulphite to sulphate increases the Chemical Oxygen Demand (COD) on water used for exhaust gas cleaning, which could potentially have an adverse impact on aquatic systems when discharged. Using worse case scenarios Karle and Turner [Karle 2007] evaluated the dilution of washwater required to return oxygen levels to within 1 % of those of the ambient water. Using different waters from full seawater to full freshwater and intermediate alkalinities/salinities, it was found that, other than for full open ocean water above 15^{o} 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 modeling 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 [IMO 2008].

5.2.5.3 Acidification

The increase in atmospheric carbon dioxide concentrations from pre-industrial levels of 280 ppm to the present 380 ppm 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 year [Karle 2007].



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

Info Box 14: Relevant chemistry - the ocean carbonate system

There have been various estimates for the quantity of SO_2 emitted by shipping. Using Corbett & Fischbeck's [Corbett 1997] estimate of 8.48 Mt, Karle and Turner [Karle 2007] calculated that if 80 % of the sulphur dioxide were removed by onboard Exhaust Gas Cleaning Systems, 6.78 Mt of SO_2 would be discharged into the oceans each year. However also commented that almost all of the sulphur dioxide transferred to the ocean through the cleaning process would have eventually ended up in the ocean from the emission of unscrubbed exhaust gases.

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

Whilst this would apply for open seas, in enclosed waters with a low level of water exchange there is a potential for acidification in shorter time scales, depending upon factors such as alkalinity and shipping traffic [Karle 2007; Behrends 2003]. Closed freshwater 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.

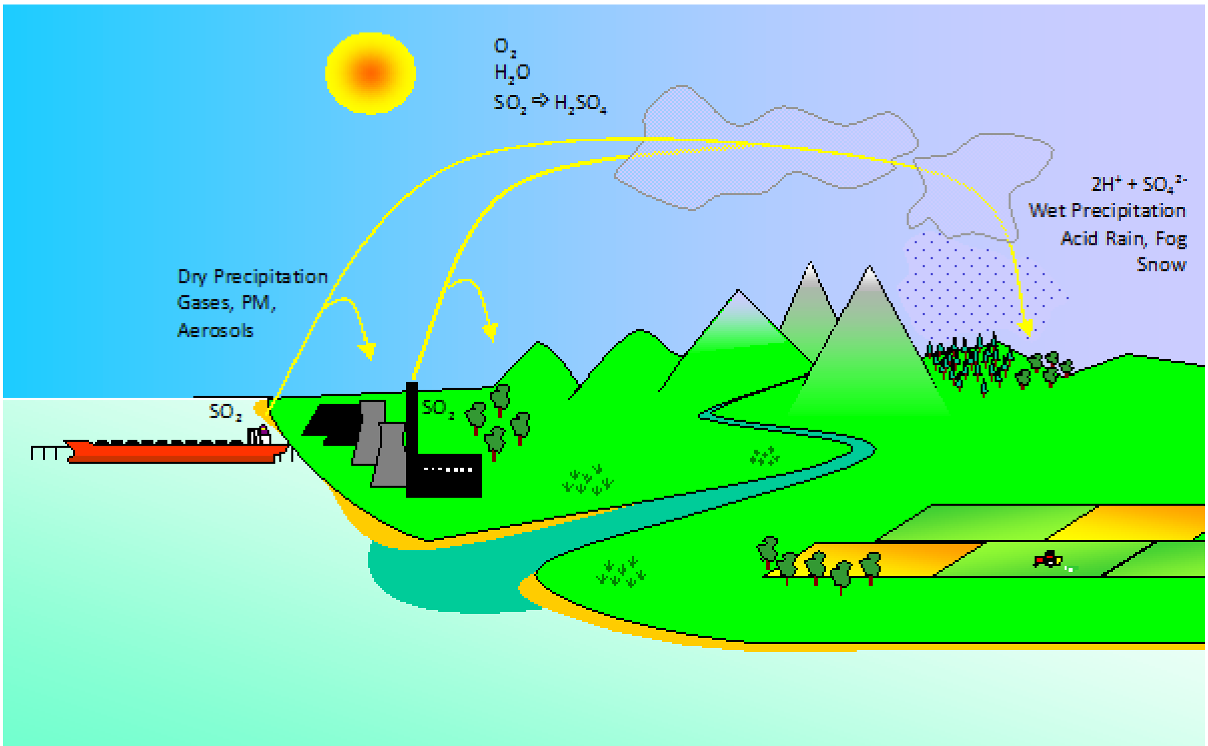


Figure 35: Sulphur oxide deposition without exhaust gas cleaning

Over 95 % of the SOx emitted from the combustion of fossil fuel is sulphur dioxide. SO_2 is a toxic gas, which is directly harmful to human health. It is heavier than air and has a suffocating odor 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 [Wright 2000]. The normal atmospheric background concentration of SO_2 is generally less than 10 ppb, with the EPA reporting that the current annual concentration range is approximately 1 to 6 ppb in the US [EPA 2008].

A secondary effect is the formation of sulphates in the form of aerosols or very fine airborne particles. A significant proportion of the particulate matter derived from fuel oil combustion consists of sulphates, which have been linked to increased asthma attacks, heart and lung disease and respiratory problems in susceptible population groups. This dry deposition can also accumulate onto the ground and surface of leaves, causing damage to plants and trees [Wright 2000].

A third effect occurs further away from the emission source where the sulphur oxides will have converted to acids by aqueous phase reactions in the atmosphere. The acidic aerosols are eventually precipitated as acid rain, snow, sleet or fog in a process referred to as wet deposition. Without man-made pollution rainwater is slightly acidic, at approximately pH 5.6, because of the formation of weak carbonic acid from dissolved CO_2 [Wright 2000; EPA 2007]. Acid rain however has been measured with much lower pH levels. At a mountain site in the eastern USA, a long-term study has shown the mean summertime pH of cloud water ranges from 3.6 to 4.1, while the pH of rainwater ranges from 4.0 to 4.4. The lowest pH value recorded for cloud water is 2.6 while the lowest rainwater pH was 3.1. Chemical analysis has showed 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) [AMC 2011].

Acid rain 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 neutralize acids, in areas where there is not sufficient natural alkalinity the effects are much greater. Acidification of lakes, watercourses and wetlands can cause leeching of heavy metals, which are toxic to aquatic life. Soils can be stripped of essential nutrients and the ability of plants and trees to take-up water impaired. Foliage can be damaged and the process of reproduction inhibited. With a reduced resistance to disease, insect attack and climate effects, deforestation and a loss of vegetation can result. Soils may be washed away leaving a landscape incapable of sustaining many species [Johnson 1981; Wright 2000].

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

In their 2009 joint proposal to IMO, the USA and Canada stated that by designating the eastern and western seaboards of North America an Emissions Control Area, "*as many as 8,300 lives will be saved and over three million people will experience relief from acute respiratory symptoms each year*". It was also stated *"an ECA will result in a 19 per cent reduction in excess [sulphur and nitrogen] deposition in south-western British Columbia and it will eliminate excess deposition over about 13,500 km^2 across Canada*" [MEPC 2009b; MEPC 2009c; EPA 2010b].

5.2.6 Materials of construction

5.2.6.1 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 pipe work and valves include nickel based alloys with a high pitting resistance equivalent number (PREN), titanium and non-metallics such as glass-wound epoxy and suitable plastics. The latter when used for piping systems require class-approved solutions for bulkhead transition and the lower levels of rigidity require close attention to component bracketing to withstand the vibration found onboard ship. Their light weight and ease of assembly does however facilitate retrofit and the service life can substantially outlast metals.

5.2.6.2 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 ^{o}C, as this is above the dew point for sulphuric acid [Wright 2000]. 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 - 400 ^{o}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 acidic liquid carry-over with the exhaust gas, a demister at the EGC unit exit can be used to remove any entrained liquid droplets. In addition a re-heater [Hamworthy 2007; Aalborg 2011; Belco 2011] is used to raise the exhaust gas temperature so that it is no longer fully saturated with water. This prevents water in the gas phase forming vapour and condensing onto cooler exhaust pipe surfaces. On exit from the funnel into the atmosphere the volume of exhaust gas is immediately diluted, which reduces saturation levels, which again prevents water vapour from forming.

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 should preclude the need for the exhaust duct above the EGC unit to be fabricated from higher than normal grade steels.

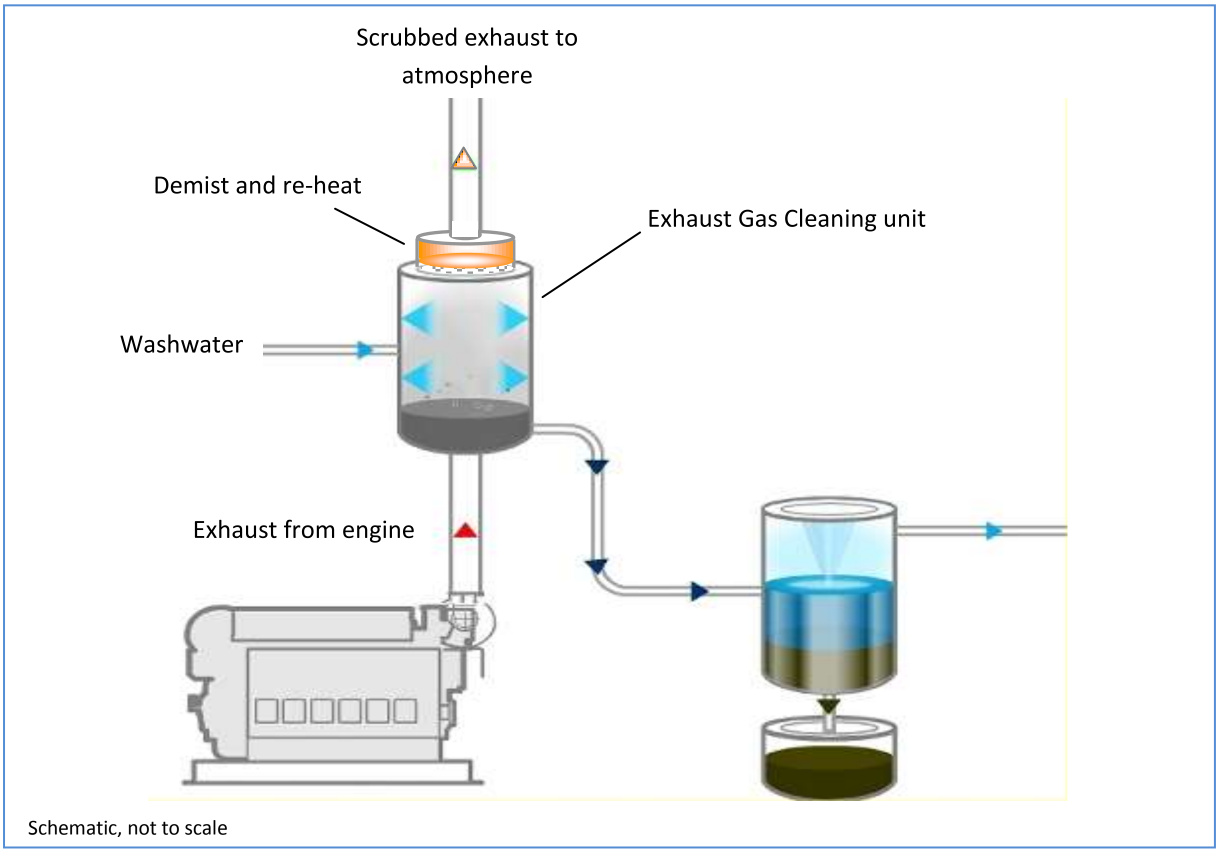


Figure 36: Position of exhaust gas demister and re-heater

5.3 Dry Exhaust Gas Cleaning Systems

The dry Exhaust Gas Cleaning System shown in figure 37 uses a packed bed of granulated hydrated lime (calcium hydroxide - $Ca(OH)_2$) rather than water as the scrubbing medium with calcium sulphate ($CaSO_4$) as the reaction product. It is typically installed after the turbocharger and operates at temperatures of between 240 °C and 450 °C. 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, known as an 'absorber', can be installed before a ship's waste heat boiler or economizer. 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 absorber such that the exhaust gas is constrained to flow horizontally through the packed bed, so optimizing the chemical reaction.

- $SO_2 + Ca(OH)_2 + ½O_2 \rightarrow CaSO_4 + H_2O$
- $SO_3 + Ca(OH)_2 + H_2O \rightarrow CaSO_4 + 2\ H_2O$

Info Box 15: Relevant chemistry – Dry Exhaust Gas Cleaning System

Fresh granulate is stored in a supply silo at the top of the absorber 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 to be located in various locations onboard.

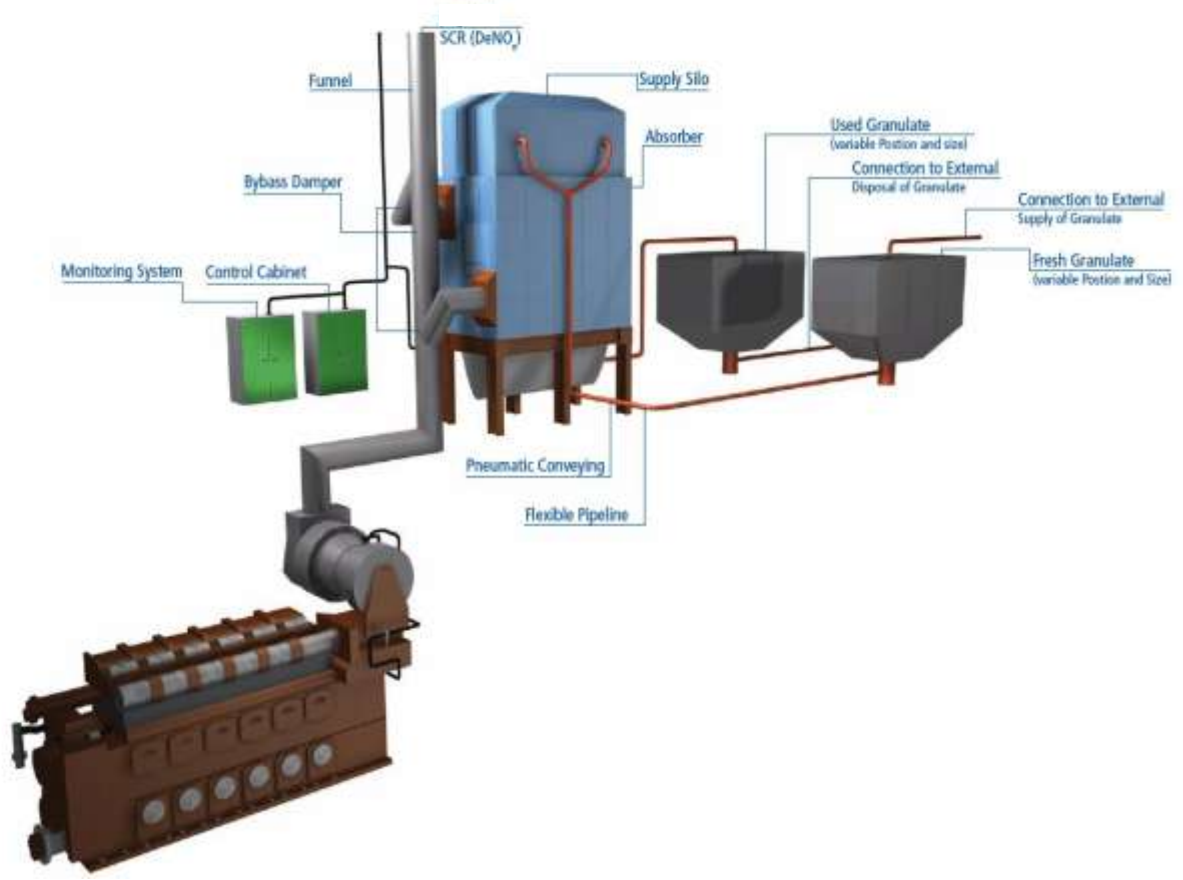


Figure 37: Dry Exhaust Gas Cleaning System

The exhaust gas residence time within the absorber enables a high level of sulphur oxide removal with up to 98 % being quoted for similar shore-side installations [Sargent 2007] and 99 % has been achieved during trials onboard ship [Jürgens 2010].

The flow schematic in figure 38 shows a downstream exhaust fan. Depending on engine builder’s requirements this may be required to compensate for pressure drop across the system so that engine operation is not adversely affected. Dampers enable control of exhaust flow in case it is required to bypass the complete system.

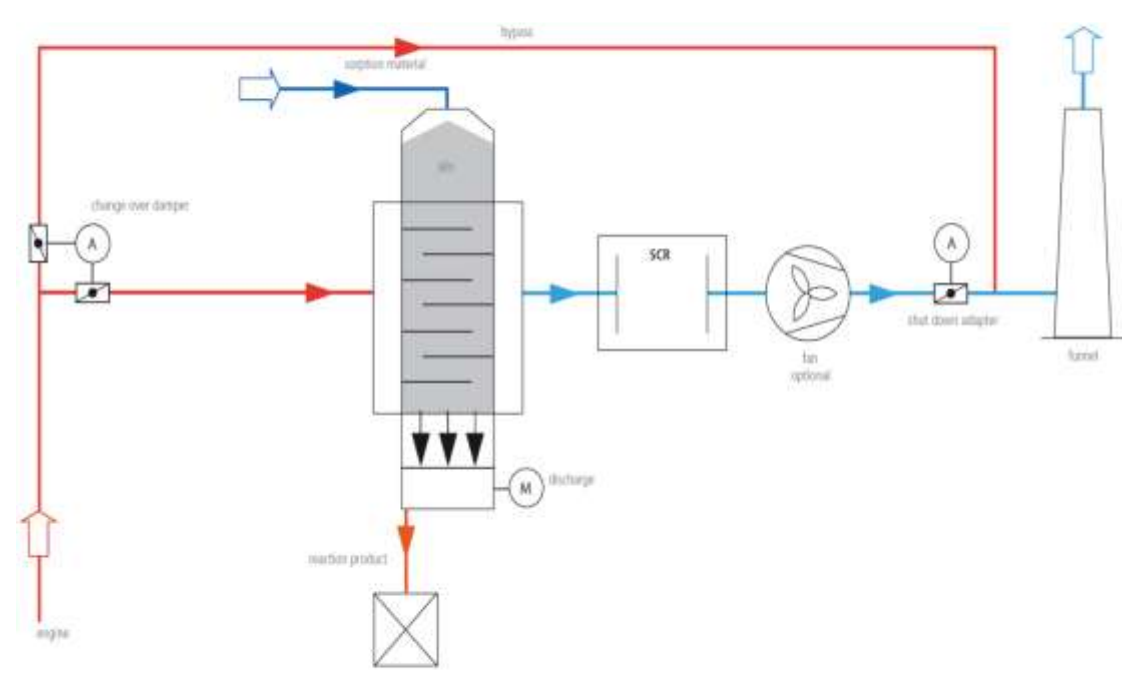


Figure 38: Flow schematic – dry Exhaust Gas Cleaning System combined with SCR

A dry Exhaust Gas Cleaning System facilitates downstream fitting of a Selective Catalytic Reduction (SCR) system. SCR reduces polluting NOx emissions to nitrogen and water and is further explained in the next section; however in marine systems the catalysts for the reaction typically require exhaust gas temperatures of around 350 ^{o}C to function at an optimum. As there is no loss of exhaust gas temperature during the dry cleaning process reheating of the exhaust stream before entry into the SCR reactor is not required.

Exhaust gas entering a SCR reactor with a high level of SO_2 also risks deposition of ammonium sulphates, derived from the urea used in the SCR process. Active parts of the catalyst can be physically blocked and depending on system design and catalyst materials chemical ‘poisoning’ by SOx can also occur. Both mechanisms impair performance and shorten catalyst life. Removing the majority of SO_2 from the exhaust stream therefore has the potential to allow fitting of smaller SCR catalysts, with a significantly longer life expectancy.

5.3.1 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 ships be supplied via strategic logistics centers by truck, in big bags or by use of special containers, with spent product being handled in the same way. 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

6. Technology overview and vendors

The following information was provided by equipment suppliers, and comprises self-certified data on their system particulars and performance. The information should be treated simply as an overview. Although systems are commercially available and have been sold, the market for this particular application is still relatively new. Not all information has been provided for a variety of reasons; in some case the question is not applicable to the particular system, in others it may be considered confidential. It is not intended to make recommendations and importantly each vendor should be contacted to confirm specific details.

6.1 Performance Overview

Of the eight vendors that have provided information for this publication three supply systems that can be switched between an open loop using seawater to a closed loop using freshwater with chemical addition. There are also two solely freshwater and chemical closed loop systems. Of these five, three use a 50 % sodium hydroxide and water solution and one a 40 % sodium hydroxide and water solution.

Two vendors, Hamworthy-Krystallon and Marine Exhaust Solutions (MES) 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.

6.1.1 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 0.1 % S varies between 3 % and no upper limit, although 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 %.

6.1.2 Particulate Matter

The removal of particulate matter varies between 60 % and 95 %. In five cases this has been measured, but at least three different methodologies have been used:

- 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 US EPA presented data [EPA 2009] showing PM_{10} emission rates as dependent upon fuel sulphur levels, with base PM_{10} emission rates of 0.23 g/kWh with distillate fuel (0.24 % sulphur) and 1.35 g/kWh 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 [BLG 2007; Wright 2000]. The latter is primarily used in land based installations in the US and requires the filter to be maintained at a higher temperature so semi-volatile hydrocarbons and sulphates remain in the vapour phase and are not collected during the test. The EPA method therefore considers solid particles dispersed in the exhaust stream whilst ISO 8178 also takes into account the condensable hydrocarbons, sulphates and associated water. Hence the higher the sulphur the higher the particulate matter content by the ISO method.

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

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. The DIN smoke spot method is a considerably more usable in-service technique to a national standard and like the other methods needs to be quoted with the results and the fuel type confirmed. There are 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 [Wright 2000].

As with sulphur oxide removal exhaust gas cleaning unit design is important with regards the efficiency of particulate matter reduction. One vendor - Aalborg Industries 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 400 mm water gauge during tests, and at 400 mm water gauge up to 78 % of particulate matter was removed [DGT 2009].

From this it can be appreciated that the process of removing pollutants has a significant affect on the conditions of pressure and velocity within an exhaust stream, particularly as the volume of gas is much reduced and its density increased by the cooling effect of the washwater. The design of an exhaust gas cleaning unit that can achieve the desired levels of reduction is therefore a careful balance, requiring exhaust conditions to be maintained within engine builders limits, so that engine efficiency and performance also remain unimpaired [Gregory 2011].

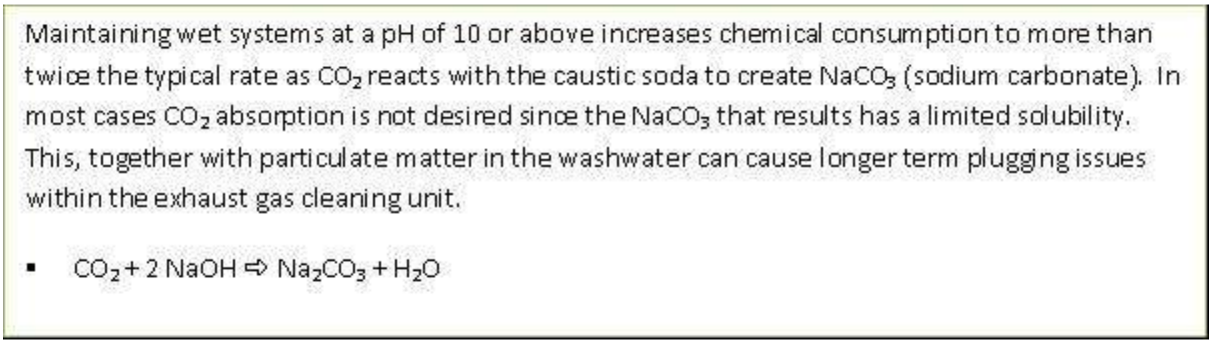
6.1.3 NOx

The wet and dry Exhaust Gas Cleaning Systems for control of SOx emissions have little effect on NO. This is reflected by a number of vendors who advise their system does not remove NOx, although Aalborg Industries, MES and Wärtsilä confirm a reduction of between 2 % and 7 % by measurement onboard. Four vendors, however offer SCR solutions, three as part of an integrated solution. BELCO positions the SCR catalyst upstream i.e. before the exhaust gas cleaning unit], whereas Couple Systems positions the catalyst downstream. Wärtsilä also offer SCR as well as other engine related NOx control techniques [Hellen 2007]. With Selective Catalytic Reduction 80 % to over 90 % NOx can be removed.

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

6.1.4 CO_2

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



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

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

Info Box 16: Relevant chemistry - sodium hydroxide and carbon dioxide reaction

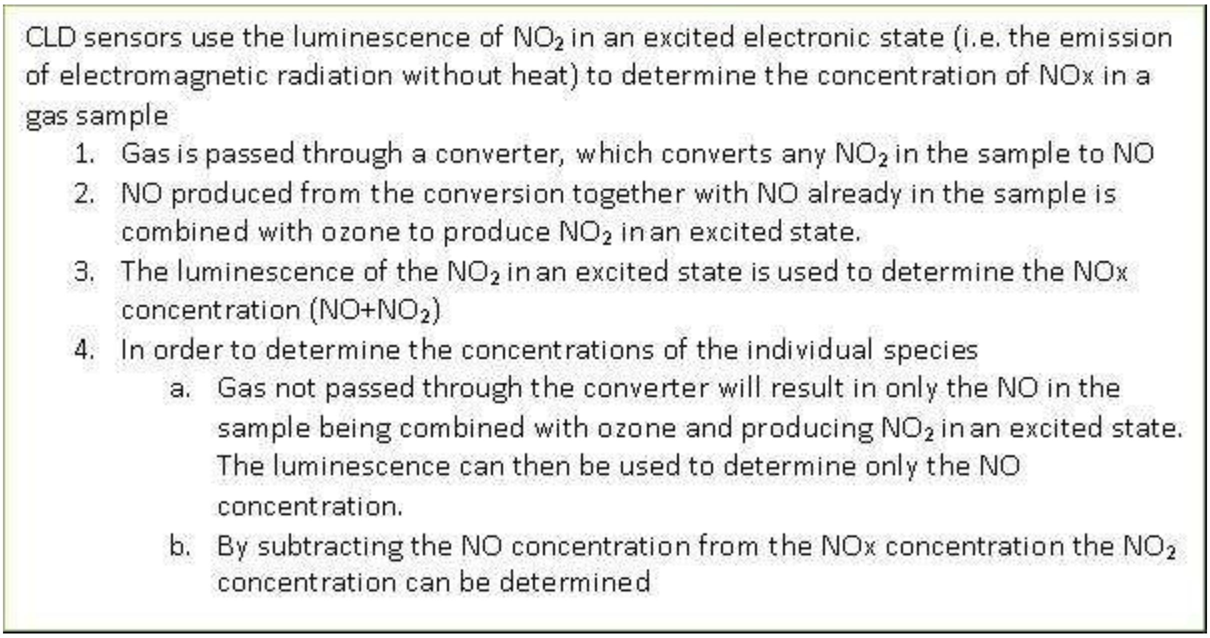
6.1.5 Instrumentation – gaseous emissions

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

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

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

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



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

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

Info Box 17: The basic principle of chemiluminescent detectors

Again, subject to approval, other systems or analyzers may be accepted if they yield equivalent results to the prescribed technology. In establishing equivalency it has to be demonstrated using recognized national or international standards that the proposed alternative will yield equivalent results when used to measure diesel engine exhaust emission concentrations. Other light absorption techniques include Fourier transform infrared spectroscopy, or FTIR and quantum cascade lasers or QCL.

Some sensor technologies require the sampled gas to be dry before analysis to avoid the interference effects of water. As SO_2 and NO_2, for example, are water-soluble it is important that the drying process does not remove any of the gas that is to be measured. Similarly the analysis system including any sampling lines must be kept at a sufficiently high temperature to prevent condensation so that the gas is not lost by dissolution into any condensed water.

The Guidelines for Exhaust Gas Cleaning Systems give various SO_2 /CO_2 ratios that must be measured after an exhaust gas cleaning unit in order to achieve equivalence and therefore compliance with the sulphur-in-fuel limits under regulation 14 (see table 9). It has also been discussed in section 3.2 how the ratio is a robust measure of SOx emissions in proportion to the sulphur content of the fuel burned because all sulphur oxides and virtually all CO_2 are derived from the combustion of fuel that is hydrocarbon based and contains sulphur.

Some Exhaust Gas Cleaning Systems however use the natural buffering capacity of seawater to neutralize the acids produced from scrubbing $SO_{2,}$ which moves the carbonate system equilibrium towards CO_2 release. This could at first be considered to compromise the validity of the SO_2/CO_2 ratio method but a typical air: fuel ratio for a marine diesel engine is typically between 50 to 35 depending on load i.e. the mass of combustion air is 50 to 35 times greater than the mass of fuel to be combusted and CO_2, formed from the fuel and air will typically make-up 6 % of the exhaust [Wright 2000]. It can be shown by calculation [Hamworthy 2007] and has been demonstrated by in-field testing that the CO_2 produced by neutralizing the acidity produced by 1 tonne of residual fuel* is minimal, particularly when compared with the CO_2 produced in combusting that tonne of fuel. The validity of the method therefore remains unaffected.

*For example with the average global sulphur content of ~2.7 %

For Exhaust Gas Cleaning Systems using freshwater Info Box 18 explains how some chemicals have the potential to remove CO_2. The Guidelines also take account of this and state that in justified cases where the CO_2 concentration is reduced by the exhaust gas cleaning unit, the CO_2 concentration can be measured at the EGC unit inlet, provided that the correctness of such a methodology can be clearly demonstrated.

Info Box 18: The effect of exhaust gas cleaning on CO_2 emissions and the SO_2/CO_2 ratio method

6.2 Mechanical Details

6.2.1 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. Onboard wet systems typically consume electrical power at a rate of 1-3 % of the engine operating power (i.e. 10 to 30 kWh per 1 MWh). This will be lower when operating a freshwater and chemical closed loop system. 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 consumption. Higher power consumption may 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 wet exhaust gas cleaning unit is typically around 45 to 50 m^3 per hour per 1 MW of engine power for a open loop seawater system. It is about 20 to 25 m^3 per hour per 1 MW for a closed loop freshwater system with chemical addition to control pH.

Reduced power consumption needs to be balanced against the consumption (and storage and handling) of caustic soda for the wet closed loop system and hydrated lime for the dry system. Caustic soda is typically consumed by ship based systems at a rate of between 6 and 16.5 litres/h per 1 MW of engine power and hydrated lime at a rate of 16 kg/h per 1 MW of engine power when using a 2.7 % sulphur residual fuel.

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

It should be noted that vendors use caustic soda solutions of differing concentrations so although the consumption rates in terms of pure NaOH may be similar, they can be quite different for dilute solutions.

Freshwater consumption is driven by a need to remove sulphate and any chlorides from the closed loop. Water may be condensed out from the exhaust gas in the exhaust gas cleaning unit or lost though evaporation. The loss or gain is dependent on the washwater temperature and therefore again the temperature of seawater used for washwater cooling. There may also be small losses with residue separated by the washwater treatment plant although system designers endeavour to minimise this for reasons of economy. Apart from needing to replace the loss with freshwater, larger than necessary tankage is required to store the wet residue and the costs of handling and shore-side disposal are increased.

For SCR systems that are either standalone or combined with an Exhaust Gas Cleaning System there is a consumption of urea which is app. 22 litres/h per 1 MW of engine power 30 % urea solution).

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

6.2.2 Size and position

Four of the eight vendors of onboard systems can supply exhaust gas cleaning units for the largest sizes of marine engine, as their upper limit is either unlimited, 70 MW or 100 MW. The remaining three can provide individual units sized for 20 to 25 MW engines. Clean Marine’s system allows multiple smaller 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 150 kW and 2 MW, although BELCO advise that sizes suitable for all engines are available.

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

Water 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. Hamworthy-Krystallon also has the option of a de-aeration tank that allows entrapped air and gas bubbles to ventilate thereby avoiding potential foaming at the discharge and lighter, dry particles to float so they can be skimmed off.

The residue collection tank capacity is typically between 0.2 and 1 m^3 per engine. 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. Some storage area will be required if the residue is dewatered, dried and bagged before disposal.

A residue collection tank will be similarly required for closed loop systems. There will also be a process tank for the circulating washwater and a holding tank or tanks in the event zero discharge is required together with caustic soda storage. The capacity of the process tank is a matter of system design. Aalborg Industries require a volume of between 10 and 40 m^3 depending on engine power. The capacity for holding washwater for zero discharge and caustic soda storage is based on the vessel's itinerary and need for autonomy. However caustic soda storage figures of between 5 and 11.5 m^3 per 1 MW of engine power can be considered as indicative of the capacity that may be required.

Storage of fresh and spent hydrated lime is required for the dry Exhaust Gas Cleaning System. Couple Systems suggest 14 m^3 per 1 MW of engine power as an indicative figure based on continuous combustion of a 2.7 % sulphur residual fuel over a one-month period.

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

6.3 Experience, Testing and Approvals

Two vendors, Wärtsilä and BELCO, (part of the DuPont group) are experienced with exhaust gas cleaning solutions for land based applications. Wärtsilä supply the power generation market with systems for residual fuel burning engines of up to 80 MW. BELCO mainly supply the oil refining industry with systems for a wide variety of applications, using differing fuels with a sulphur content of up to 11 % and producing a flue gas flow of up to the equivalent of a 150 MW combustion unit. BELCO and Couple Systems specifically advise their marine design is based on solutions used in land based industry.

Aalborg Industries and Hamworthy are experienced in the supply of inert gas scrubbing systems to the marine industry.

Four vendors, Aalborg Industries, Clean Marine, Couple Systems and Hamworthy-Krystallon have run trial marine units in shore-side test facilities. Six vendors have fitted Exhaust Gas Cleaning Systems to ships for tests. Hamworthy-Krystallon has conducted trials on ships including the Ro-Ro ferry Pride of Kent and cruise ship Zaandam. The exhaust gas cleaning unit from Aalborg Industries is currently the largest onboard a ship. It is installed on the DFDS Ro-Ro ferry Tor Ficaria and has been in continuous operation using seawater and freshwater for more than 1200 hours as of October 2010. BELCO is awaiting installation of a system for a 3.5 MW engine on a ship. Fuel sulphur content has varied between 1.5 % and 4.07 % and engine powers have been between 150 kW (MES) and 21 MW (Aalborg Industries). Unlike the others Couple Systems' exhaust gas cleaning unit is fitted immediately forward of the accommodation block rather at the funnel.

All trials have been of an exhaust gas cleaning unit fitted to a single engine, except for the Clean Marine trial on M.V. Baru. Here exhaust from the main engine, up to 2 auxiliary engines and occasionally the boiler is commonly collected at the top of the funnel and drawn through the EGC unit by a downstream fan. The typical total power of engines during exhaust gas cleaning has been approximately 6 MW.

Independent reports on emissions to air and water have yet to be published for marine systems however they have been published for industrial systems from BELCO. Independent testing has however been carried out during ship trials for Aalborg Industries, Hamworthy-Krystallon, MES, Wärtsilä and Couple Systems (who will supply details on request).

Wärtsilä has gained Scheme A and Scheme B approval of their closed loop system with a 610 kW engine and Couple Systems has Scheme B approval of their dry system with a 3.6 MW engine. DNV and Germanischer Lloyd undertook the surveys, with approvals granted in 2009 and 2010 respectively. Aalborg Industries has Scheme B approval until October 2011 from the Danish EPA for the system onboard Tor Ficaria.

Apart from the core system components of exhaust gas cleaning unit, water treatment plant, instrumentation and controls, the scope of supply to allow the interconnection of parts and installation on the ship varies from vendor to vendor and as such will be agreed on a project-by-project 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 are often self-contained, should they need to be part of the fabric of the ship then these too may need to be supplied by the ship operator if 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, in which case the shipyard will typically supply all labour, cranes, staging etc. Again the scope will need to be agreed on a project-by-project basis.

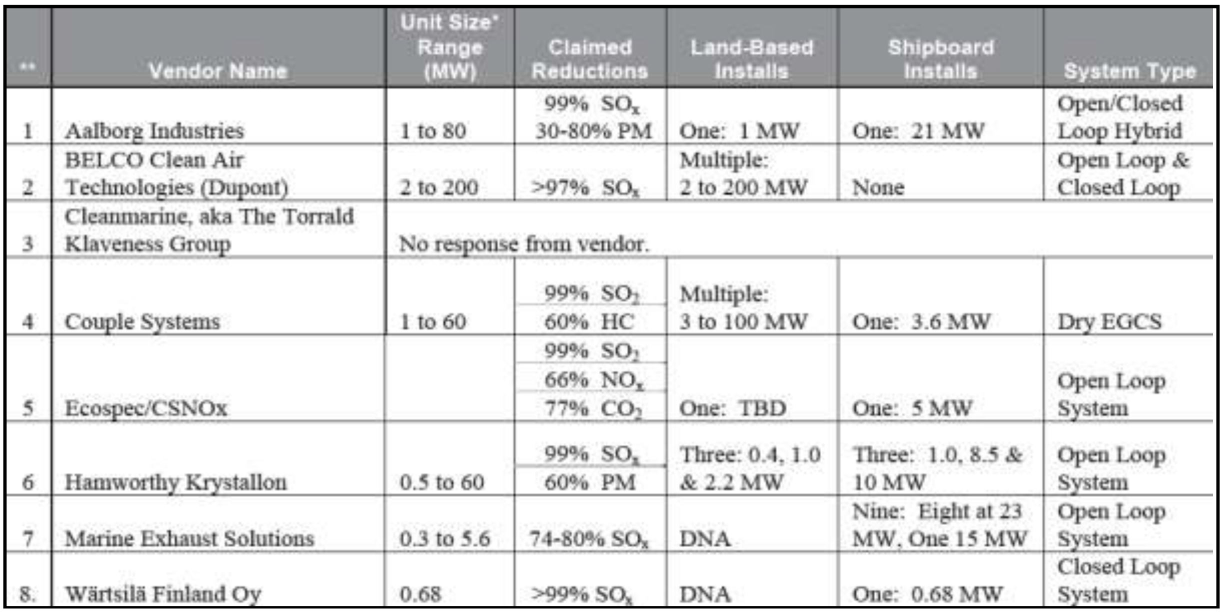
In the case of retrofits dry-docking is not likely to be required unless existing sea chests and hull penetrations for overboard discharge connections cannot be used. Although the exhaust gas cleaning units will need to be fitted with the vessel out of service, it is possible that a significant amount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

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

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

7 Vendor Summary SOx abatement

The following information was provided by equipment suppliers, and comprises self-certified data on their system particulars and performance.

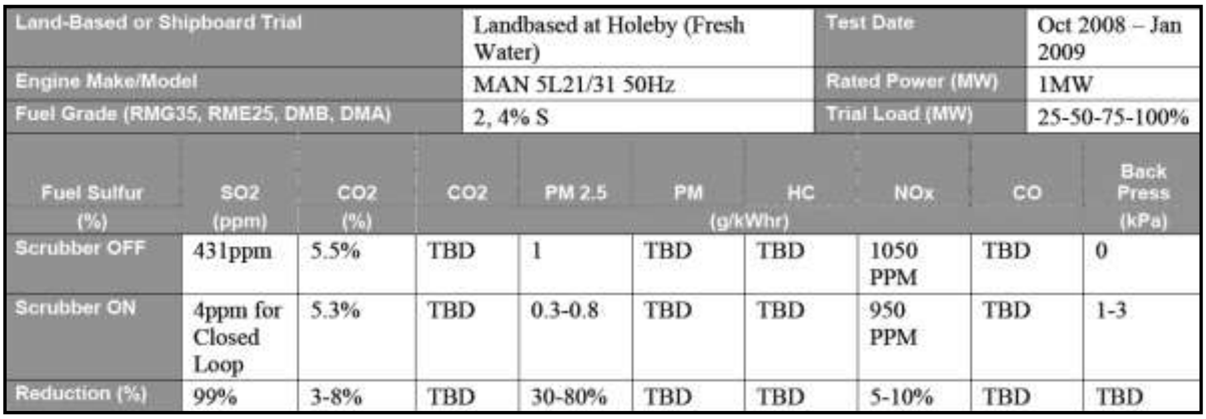


**	Vendor Name	Unit Size* Range (MW)	Claimed Reductions	Land-Based Installs	Shipboard Installs	System Type
1	Aalborg Industries	1 to 80	99% SO_x 30-80% PM	One: 1 MW	One: 21 MW	Open/Closed Loop Hybrid
2	BELCO Clean Air Technologies (Dupont)	2 to 200	>97% SO_x	Multiple: 2 to 200 MW	None	Open Loop & Closed Loop
3	Cleanmarine, aka The Torrald Klaveness Group	No response from vendor.				
4	Couple Systems	1 to 60	99% SO_2 60% HC	Multiple: 3 to 100 MW	One: 3.6 MW	Dry EGCS
5	Ecospec/CSNOx		99% SO_2 66% NO_x 77% CO_2	One: TBD	One: 5 MW	Open Loop System
6	Hamworthy Krystallon	0.5 to 60	99% SO_x 60% PM	Three: 0.4, 1.0 & 2.2 MW	Three: 1.0, 8.5 & 10 MW	Open Loop System
7	Marine Exhaust Solutions	0.3 to 5.6	74-80% SO_x	DNA	Nine: Eight at 23 MW, One 15 MW	Open Loop System
8.	Wärtsilä Finland Oy	0.68	>99% SO_x	DNA	One: 0.68 MW	Closed Loop System

** Unit size refers to diesel engine size served. Boiler units are not considered in this survey.*
*** Vendors are listed alphabetically and not by price or efficiency.*

7.1 Aalborg Industries

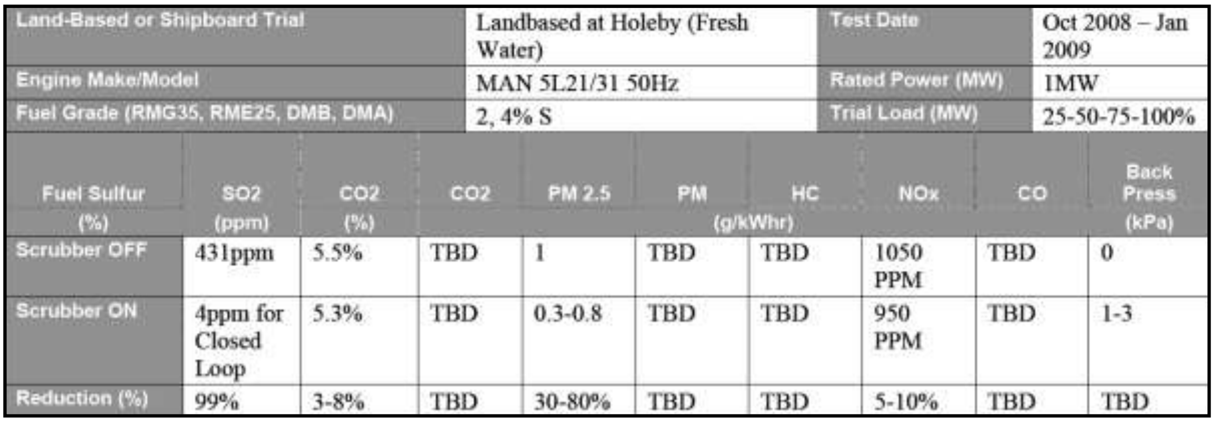
Contact	René Diks, +3 (0)24 352 3100, rdk@aalborg-industries.com Website: www.aalborg-industries.com		
Technology Type(s)	EGC system, Combined Open Loop (Salt Water) and Closed Loop (Fresh Water) No Dry Chemical	**Other Products**	The EGC system can incorporate a venturi system (non standard) to capture PM up to 80%
Exhaust Monitoring IMO Scheme	Scheme B	**Vessel Install Contact**	Olav Knudsen Aalborg Industries
System Availability	1 MW to 50 MW	**Size, Land Based Install**	1 MW, in 2008
Development Phase	Prototype	**Size, Shipboard Install**	21 MW, in 2009
Failure Modes	If an interruption occurs, the bypass valves open and the exhaust gas flow will bypass the EGC system.	**Failure Recovery**	The problem must be solved after which the system will return to normal operation automatically. The EGC can be remotely checked on trouble shooting by Aalborg Industries.



Land-Based or Shipboard Trial	Landbased at Holeby (Fresh Water)	Test Date	Oct 2008 – Jan 2009
Engine Make/Model	MAN 5L21/31 50Hz	Rated Power (MW)	1MW
Fuel Grade (RMG35, RME25, DMB, DMA)	2, 4% S	Trial Load (MW)	25-50-75-100%

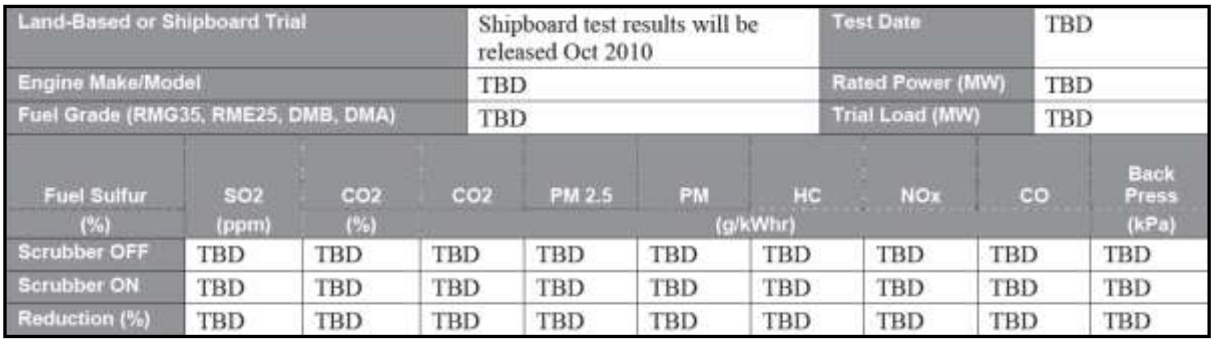
Fuel Sulfur (%)	SO2 (ppm)	CO2 (%)	CO2 (g/kWhr)	PM 2.5	PM	HC	NOx	CO	Back Press (kPa)
Scrubber OFF	431ppm	5.5%	TBD	1	TBD	TBD	1050 PPM	TBD	0
Scrubber ON	4ppm for Closed Loop	5.3%	TBD	0.3-0.8	TBD	TBD	950 PPM	TBD	1-3
Reduction (%)	99%	3-8%	TBD	30-80%	TBD	TBD	5-10%	TBD	TBD

7.1.1 System efficiency trial results



Land-Based or Shipboard Trial	Landbased at Holeby (Fresh Water)	Test Date	Oct 2008 – Jan 2009
Engine Make/Model	MAN 5L21/31 50Hz	Rated Power (MW)	1MW
Fuel Grade (RMG35, RME25, DMB, DMA)	2, 4% S	Trial Load (MW)	25-50-75-100%

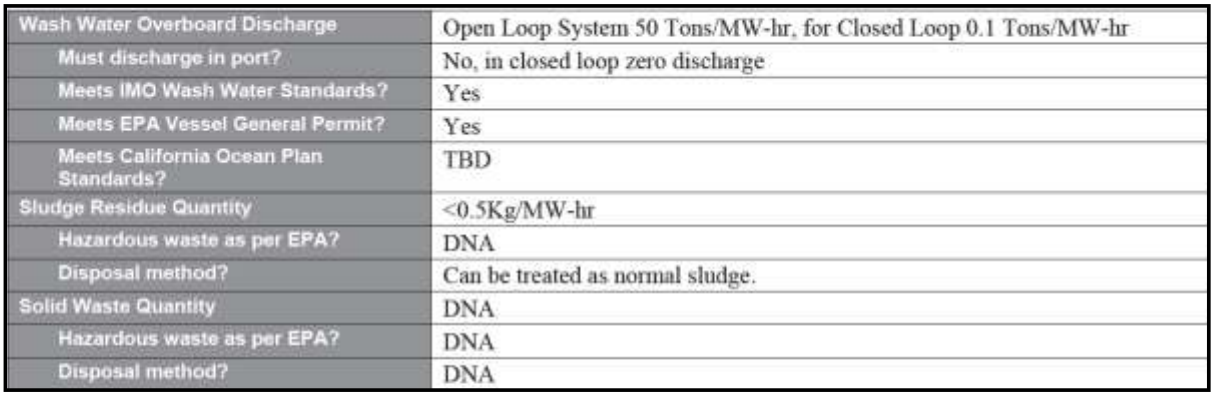
Fuel Sulfur (%)	SO2 (ppm)	CO2 (%)	CO2 (g/kWhr)	PM 2.5	PM	HC	NOx	CO	Back Press (kPa)
Scrubber OFF	431ppm	5.5%	TBD	1	TBD	TBD	1050 PPM	TBD	0
Scrubber ON	4ppm for Closed Loop	5.3%	TBD	0.3-0.8	TBD	TBD	950 PPM	TBD	1-3
Reduction (%)	99%	3-8%	TBD	30-80%	TBD	TBD	5-10%	TBD	TBD



Land-Based or Shipboard Trial	Shipboard test results will be released Oct 2010	Test Date	TBD
Engine Make/Model	TBD	Rated Power (MW)	TBD
Fuel Grade (RMG35, RME25, DMB, DMA)	TBD	Trial Load (MW)	TBD

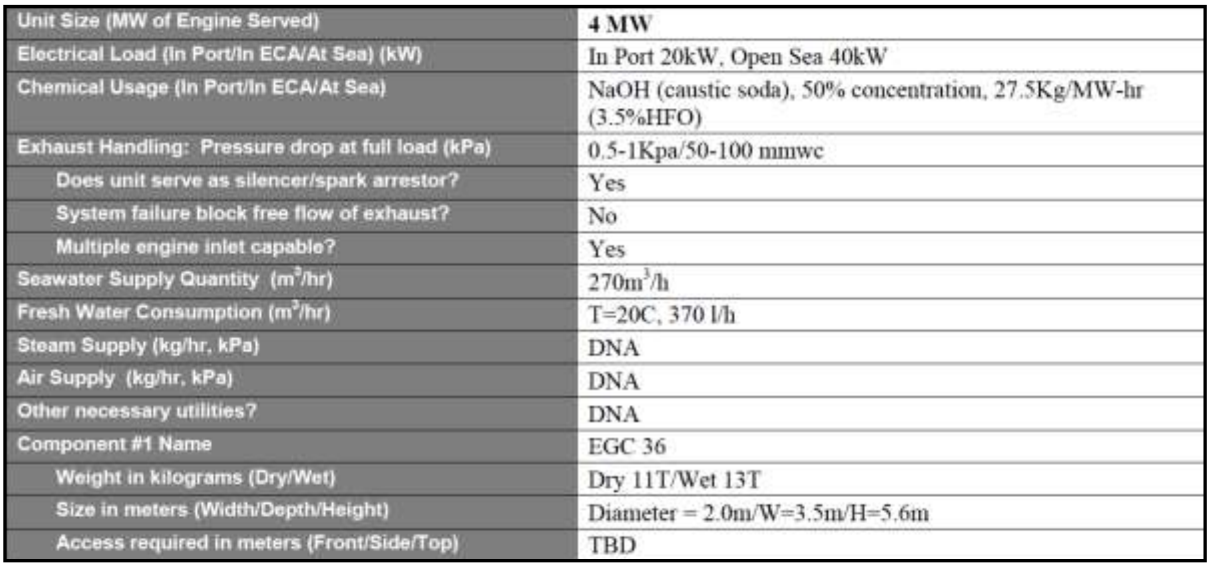
Fuel Sulfur	SO2	CO2	CO2	PM 2.5	PM	HC	NOx	CO	Back Press
(%)	(ppm)	(%)	(g/kWhr)						(kPa)
Scrubber OFF	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Scrubber ON	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Reduction (%)	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

7.1.2 Waste streams

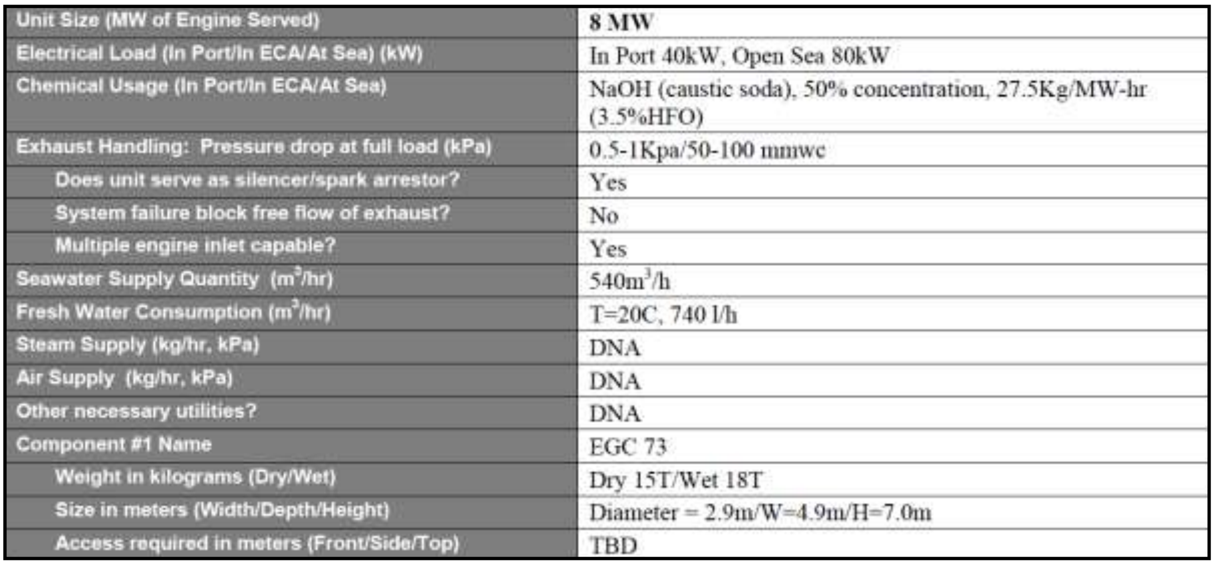


Wash Water Overboard Discharge	Open Loop System 50 Tons/MW-hr, for Closed Loop 0.1 Tons/MW-hr
Must discharge in port?	No, in closed loop zero discharge
Meets IMO Wash Water Standards?	Yes
Meets EPA Vessel General Permit?	Yes
Meets California Ocean Plan Standards?	TBD
Sludge Residue Quantity	<0.5Kg/MW-hr
Hazardous waste as per EPA?	DNA
Disposal method?	Can be treated as normal sludge.
Solid Waste Quantity	DNA
Hazardous waste as per EPA?	DNA
Disposal method?	DNA

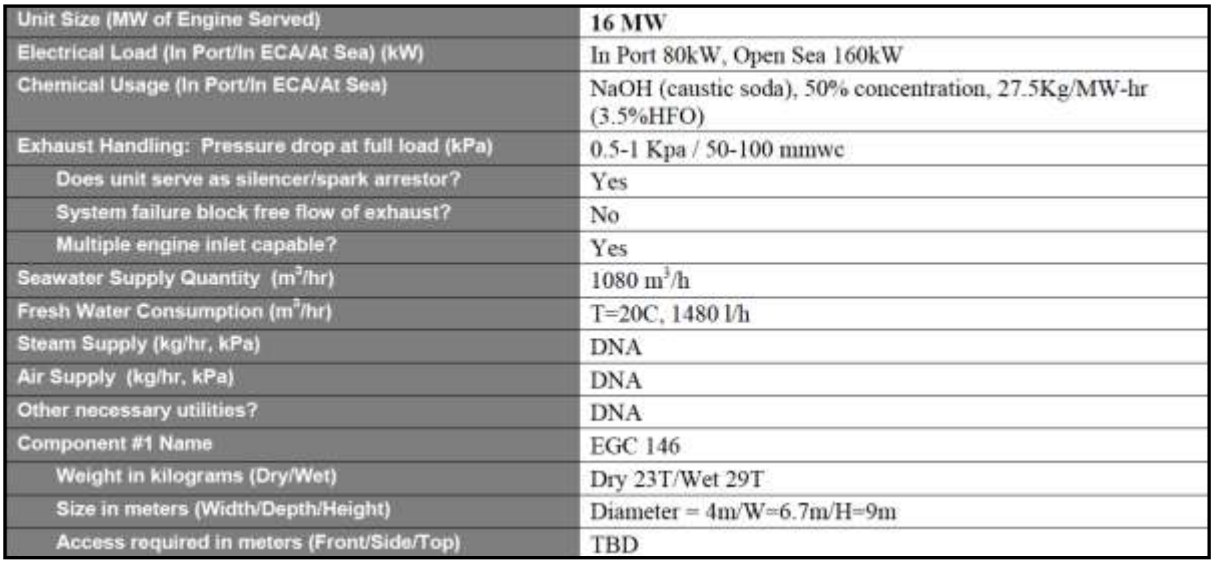
7.1.3 System Details



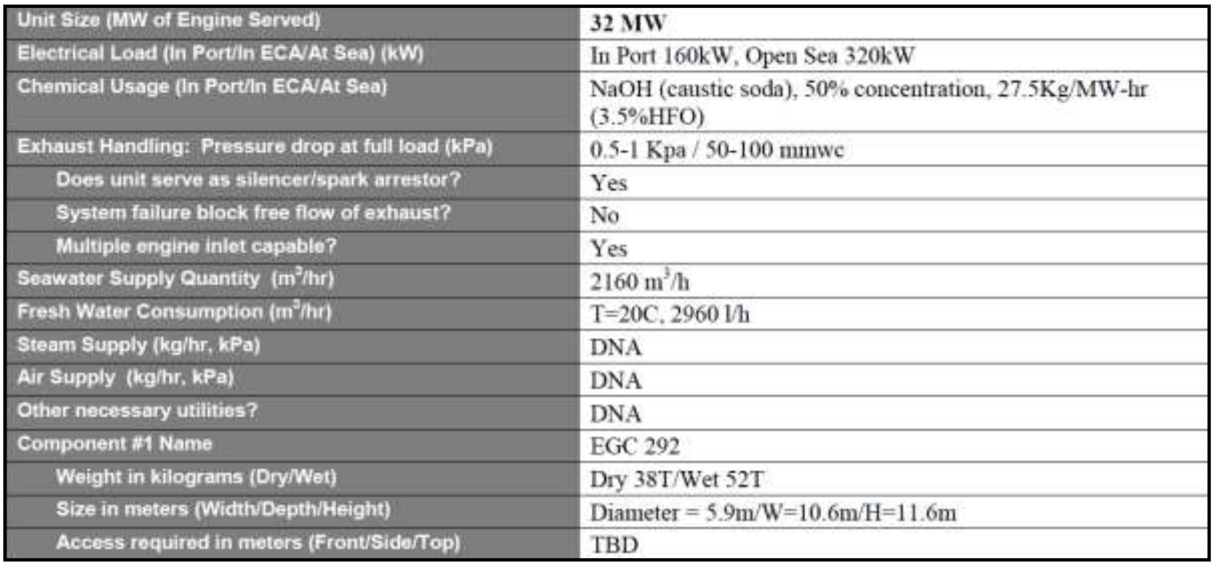
Unit Size (MW of Engine Served)	**4 MW**
Electrical Load (In Port/In ECA/At Sea) (kW)	In Port 20kW, Open Sea 40kW
Chemical Usage (In Port/In ECA/At Sea)	NaOH (caustic soda), 50% concentration, 27.5Kg/MW-hr (3.5%HFO)
Exhaust Handling: Pressure drop at full load (kPa)	0.5-1Kpa/50-100 mmwc
Does unit serve as silencer/spark arrestor?	Yes
System failure block free flow of exhaust?	No
Multiple engine inlet capable?	Yes
Seawater Supply Quantity (m^3/hr)	270m^3/h
Fresh Water Consumption (m^3/hr)	T=20C, 370 l/h
Steam Supply (kg/hr, kPa)	DNA
Air Supply (kg/hr, kPa)	DNA
Other necessary utilities?	DNA
Component #1 Name	EGC 36
Weight in kilograms (Dry/Wet)	Dry 11T/Wet 13T
Size in meters (Width/Depth/Height)	Diameter = 2.0m/W=3.5m/H=5.6m
Access required in meters (Front/Side/Top)	TBD



Unit Size (MW of Engine Served)	**8 MW**
Electrical Load (In Port/In ECA/At Sea) (kW)	In Port 40kW, Open Sea 80kW
Chemical Usage (In Port/In ECA/At Sea)	NaOH (caustic soda), 50% concentration, 27.5Kg/MW-hr (3.5%HFO)
Exhaust Handling: Pressure drop at full load (kPa)	0.5-1Kpa/50-100 mmwc
Does unit serve as silencer/spark arrestor?	Yes
System failure block free flow of exhaust?	No
Multiple engine inlet capable?	Yes
Seawater Supply Quantity (m^3/hr)	540m^3/h
Fresh Water Consumption (m^3/hr)	T=20C, 740 l/h
Steam Supply (kg/hr, kPa)	DNA
Air Supply (kg/hr, kPa)	DNA
Other necessary utilities?	DNA
Component #1 Name	EGC 73
Weight in kilograms (Dry/Wet)	Dry 15T/Wet 18T
Size in meters (Width/Depth/Height)	Diameter = 2.9m/W=4.9m/H=7.0m
Access required in meters (Front/Side/Top)	TBD



Unit Size (MW of Engine Served)	**16 MW**
Electrical Load (In Port/In ECA/At Sea) (kW)	In Port 80kW, Open Sea 160kW
Chemical Usage (In Port/In ECA/At Sea)	NaOH (caustic soda), 50% concentration, 27.5Kg/MW-hr (3.5%HFO)
Exhaust Handling: Pressure drop at full load (kPa)	0.5-1 Kpa / 50-100 mmwc
Does unit serve as silencer/spark arrestor?	Yes
System failure block free flow of exhaust?	No
Multiple engine inlet capable?	Yes
Seawater Supply Quantity (m^3/hr)	1080 m^3/h
Fresh Water Consumption (m^3/hr)	T=20C, 1480 l/h
Steam Supply (kg/hr, kPa)	DNA
Air Supply (kg/hr, kPa)	DNA
Other necessary utilities?	DNA
Component #1 Name	EGC 146
Weight in kilograms (Dry/Wet)	Dry 23T/Wet 29T
Size in meters (Width/Depth/Height)	Diameter = 4m/W=6.7m/H=9m
Access required in meters (Front/Side/Top)	TBD



Unit Size (MW of Engine Served)	**32 MW**
Electrical Load (In Port/In ECA/At Sea) (kW)	In Port 160kW, Open Sea 320kW
Chemical Usage (In Port/In ECA/At Sea)	NaOH (caustic soda), 50% concentration, 27.5Kg/MW-hr (3.5%HFO)
Exhaust Handling: Pressure drop at full load (kPa)	0.5-1 Kpa / 50-100 mmwc
Does unit serve as silencer/spark arrestor?	Yes
System failure block free flow of exhaust?	No
Multiple engine inlet capable?	Yes
Seawater Supply Quantity (m^3/hr)	2160 m^3/h
Fresh Water Consumption (m^3/hr)	T=20C, 2960 l/h
Steam Supply (kg/hr, kPa)	DNA
Air Supply (kg/hr, kPa)	DNA
Other necessary utilities?	DNA
Component #1 Name	EGC 292
Weight in kilograms (Dry/Wet)	Dry 38T/Wet 52T
Size in meters (Width/Depth/Height)	Diameter = 5.9m/W=10.6m/H=11.6m
Access required in meters (Front/Side/Top)	TBD

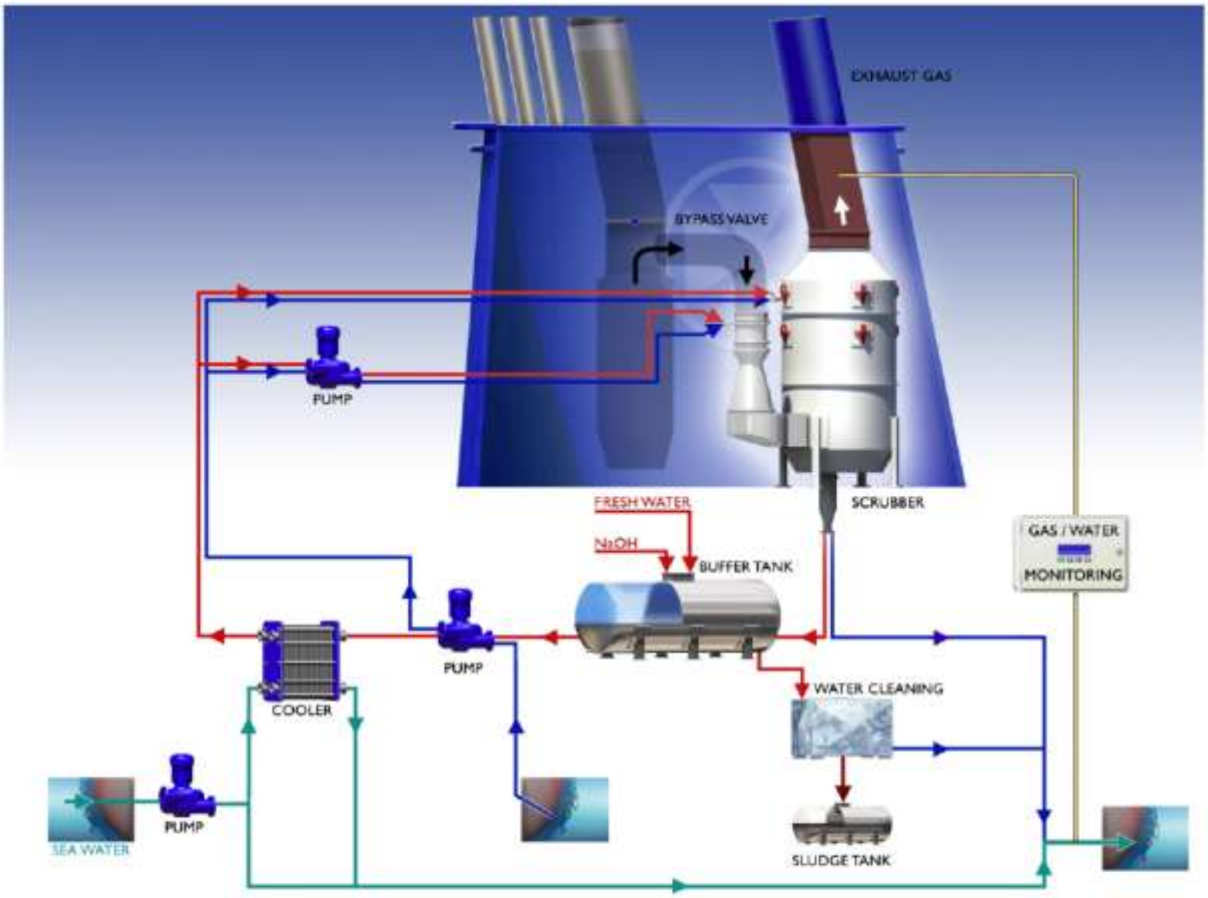


Figure 39: Aalborg system flow chart

7.1.4 System description (provided by supplier)

Aalborg Industries has more than 30 years of experience of supplying scrubbers as an integrated part of Inert Gas Systems (IGS) onboard ships. During 2008, our experiences from these systems in combination with our experiences from supplying exhaust gas boilers after large marine diesel engines were used to design a scrubber test rig to cool and clean the exhaust from a test engine at MAN Diesel test facility in Denmark. The knowledge and experience from these tests were successively used to design an entire exhaust gas cleaning system (EGS) onboard DFDS' Ro-Ro vessel "Tor Ficaria." Installed after the 21 MW MAN engine, it is by far the world's largest exhaust gas cleaning system installed onboard a ship. The design work has been carried out in close co-operation with the marine engineers from DFDS and MAN Diesel.

The EGC system is a combined wet scrubbing system being able to operate in ***sea water (open loop)*** and ***fresh water (closed*** loop). At open sea, the system operates with sea water and saves the use of NaOH and fresh water. In harbours and estuaries with strict discharge criteria, the system can operate on fresh water in a closed loop system. The combined EGC system offers therefore maximum flexibility combined with the lowest operational costs. In addition, our Exhaust Gas Scrubber is:

- A cost-saving solution (able to operate on HFO instead of expensive low sulphur MDO/MGO)
- In compliance with MARPOL Annex VI – MEPC 58 and 59
- Provides a sulphur removal rate >98 % (exceeding the IMO requirements)
- Traps up to 80 % of Particulate Matter (PM)

7.2 Belco Technologies

Contact	Garrett Billemeyer, (973) 515-8902, billemeyer@belcotech.com Website: http://belcotech.dupont.com		
Technology Type(s)	EDV, Open Loop and Closed Loop No Dry Chemical	**Other Products**	Wet Electrostatic Precipitators, Dry Electrostatic Precipitators, Semi-dry Scrubbers, TSS and FSS, SCR Syssterms, LoTOx Systems, LABSORB Regenerative SO_2 Scrubbing Systems.
Exhaust Monitoring IMO Scheme	TBD	**Vessel Install Contact**	TBD
System Availability	2 MW to 200 MW	**Size, Land Based Install**	TBD
Development Phase	Commercial	**Size, Shipboard Install**	TBD
Failure Modes	The Scrubber is designed to run dry and continuously for plus five years. Interrupted operations are not an issue.	**Failure Recovery**	NA

Unit Size* (MW)	Commercially Available (Yes/No)	Land-based Trial (Year/Units)	Shipboard Trial (Year/Units)	Efficiency Results Available (Yes/No)	How Many Hours of Operation?	Notes
List of land-based industrial applications available upon request.						

7.2.1 System efficiency trial results

Land-Based or Shipboard Trial	Shipboard	Test Date	TBD
Engine Make/Model	11,349 kW Engine	Rated Power (MW)	TBD
Fuel Grade (RMG35, RME25, DMB, DMA)	3% Sulfur Diesel	Trial Load (MW)	514 RPM

Fuel Sulfur	SO2	CO2	CO2	PM 2.5	PM	HC	NOx	CO	Back Press
(%)	(ppm)	(%)			(g/kWhr)				(kPa)
Scrubber OFF	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	0.6
Scrubber ON	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	0
Reduction (%)	> 97%	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

7.2.2 Waste streams

Wash Water Overboard Discharge	Dependant on Inlet SOx/Fuel
Must discharge in port?	No overboard discharge
Meets IMO Wash Water Standards?	Yes
Meets EPA Vessel General Permit?	Yes
Meets California Ocean Plan Standards?	Yes
Sludge Residue Quantity	Dependant on engine operation and fuel usage
Hazardous waste as per EPA?	Dependant on fuel source – no solid waste generated
Disposal method?	Occasionally offloaded to waste hauler
Solid Waste Quantity	0
Hazardous waste as per EPA?	We comply with all IMO regulations on waste streams
Disposal method?	None generated

7.2.3 System Details

Unit Size (MW of Engine Served)	TBD
Electrical Load (In Port/In ECA/At Sea) (kW)	TBD
Chemical Usage (In Port/In ECA/At Sea)	TBD
Exhaust Handling: Pressure drop at full load (kPa)	TBD
Does unit serve as silencer/spark arrestor?	TBD
System failure block free flow of exhaust?	TBD
Multiple engine inlet capable?	TBD
Seawater Supply Quantity (m^3/hr)	TBD
Fresh Water Consumption (m^3/hr)	TBD
Steam Supply (kg/hr, kPa)	TBD
Air Supply (kg/hr, kPa)	TBD
Other necessary utilities?	TBD
Component #1 Name	TBD
Weight in kilograms (Dry/Wet)	TBD
Size in meters (Width/Depth/Height)	TBD
Access required in meters (Front/Side/Top)	TBD

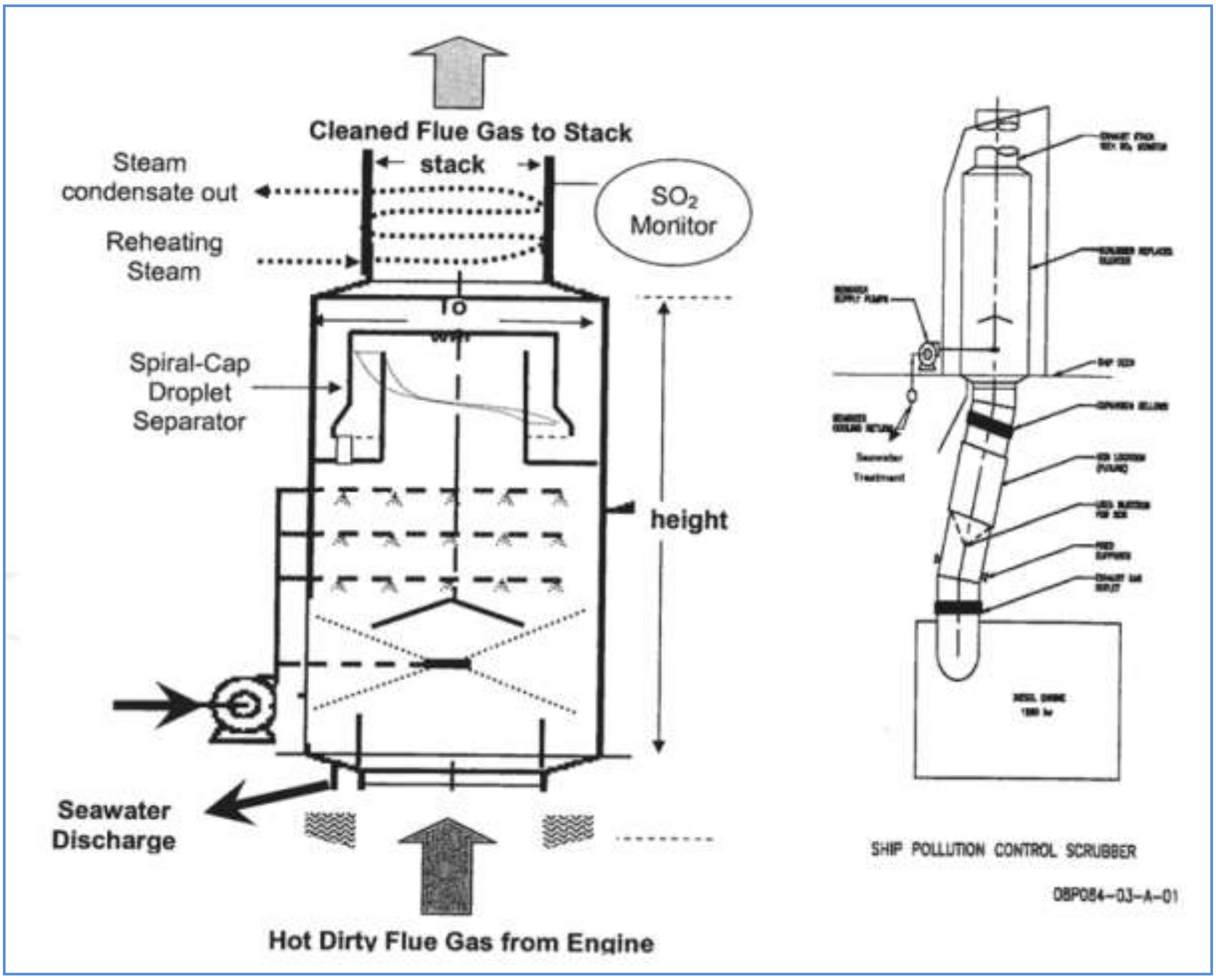


Figure 40: Belco system flow chart

7.2.4 System description (provided by supplier)

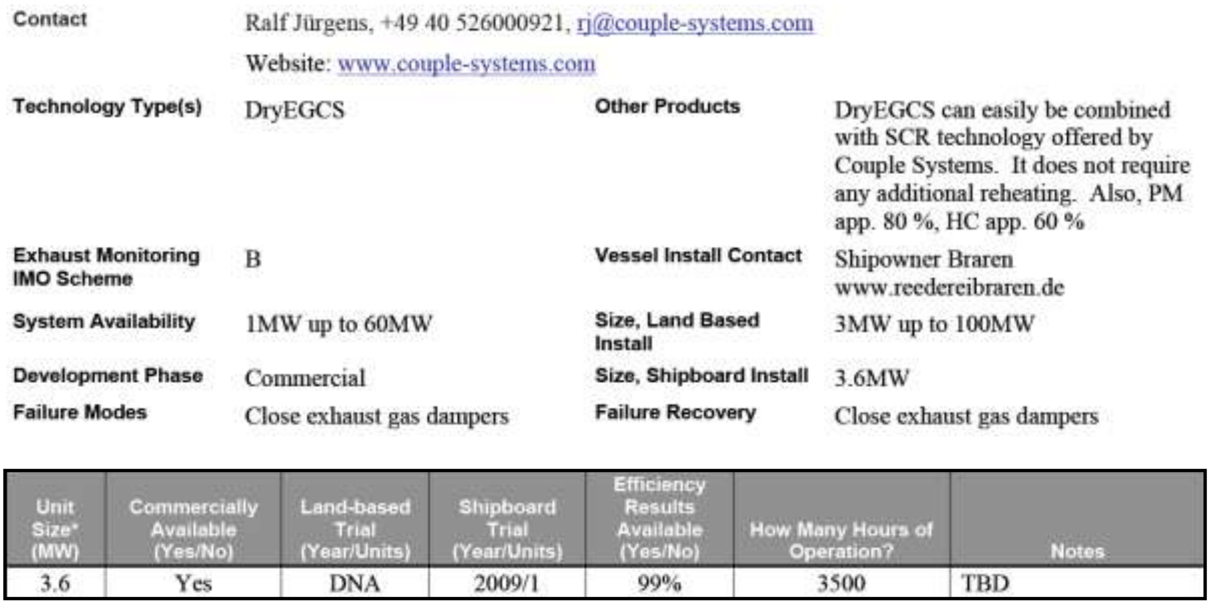
The Benefits of BELCO® Marine Scrubbing Systems include:

- Reliable and cost effective design — designed specifically for your vessels in conjunction with your engineering staff
- Open tower design. Able to operate uninterrupted for many years concurrent with required dry dockings. No concern with plugging or maintenance shutdowns while at sea
- No hot by-pass required
- High efficiency of pollutant removal
- Helps meet all IMO, SECA, EPA regulations, even when using high sulfur fuels • Designed to withstand upset conditions andtemperature excursions
- Designed to operate without shutdowns for periods in excess of 5 years
- Able to use various reagents and regenerative buffers
- Low pressure drop design
- High reliability and durability
- High efficiency

Aftermarket Services and Spare Parts include:

- Proprietary components
- Replacement parts
- Start-up support
- Troubleshooting
- Construction advisors

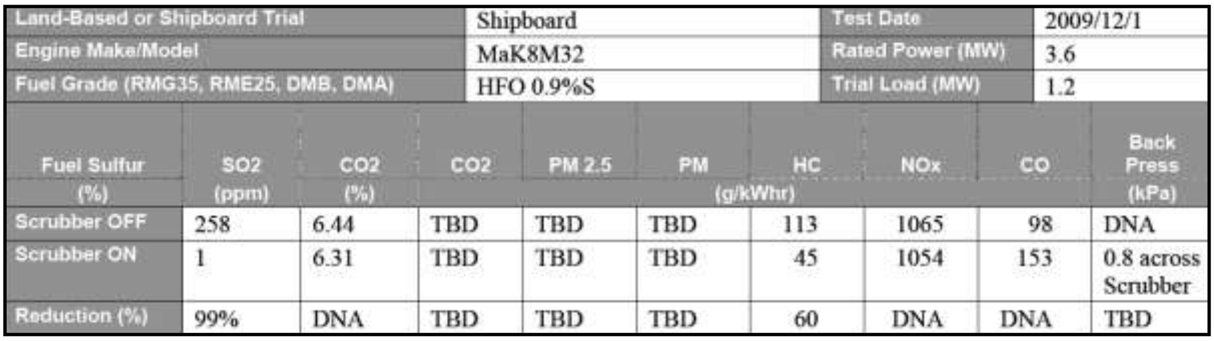
7.3 Couple Systems GmbH



Contact	Ralf Jürgens, +49 40 526000921, rj@couple-systems.com Website: www.couple-systems.com		
Technology Type(s)	DryEGCS	**Other Products**	DryEGCS can easily be combined with SCR technology offered by Couple Systems. It does not require any additional reheating. Also, PM app. 80 %, HC app. 60 %
Exhaust Monitoring IMO Scheme	B	**Vessel Install Contact**	Shipowner Braren www.reedereibraren.de
System Availability	1MW up to 60MW	**Size, Land Based Install**	3MW up to 100MW
Development Phase	Commercial	**Size, Shipboard Install**	3.6MW
Failure Modes	Close exhaust gas dampers	**Failure Recovery**	Close exhaust gas dampers

Unit Size* (MW)	Commercially Available (Yes/No)	Land-based Trial (Year/Units)	Shipboard Trial (Year/Units)	Efficiency Results Available (Yes/No)	How Many Hours of Operation?	Notes
3.6	Yes	DNA	2009/1	99%	3500	TBD

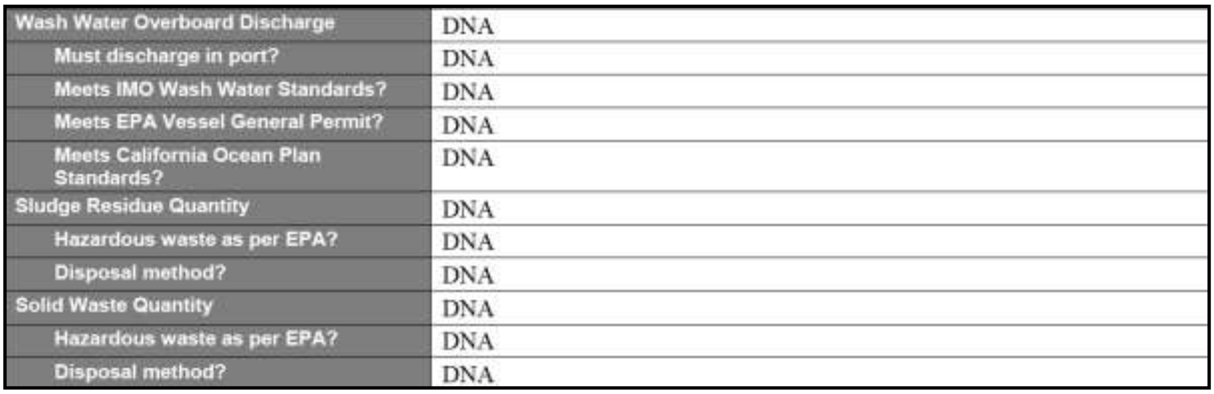
7.3.1 System efficiency trial results



Land-Based or Shipboard Trial	Shipboard	Test Date	2009/12/1
Engine Make/Model	MaK8M32	Rated Power (MW)	3.6
Fuel Grade (RMG35, RME25, DMB, DMA)	HFO 0.9%S	Trial Load (MW)	1.2

Fuel Sulfur (%)	SO2 (ppm)	CO2 (%)	CO2	PM 2.5	PM	HC	NOx	CO	Back Press (kPa)
			(g/kWhr)						
Scrubber OFF	258	6.44	TBD	TBD	TBD	113	1065	98	DNA
Scrubber ON	1	6.31	TBD	TBD	TBD	45	1054	153	0.8 across Scrubber
Reduction (%)	99%	DNA	TBD	TBD	TBD	60	DNA	DNA	TBD

7.3.2 Waste streams



Wash Water Overboard Discharge	DNA
Must discharge in port?	DNA
Meets IMO Wash Water Standards?	DNA
Meets EPA Vessel General Permit?	DNA
Meets California Ocean Plan Standards?	DNA
Sludge Residue Quantity	DNA
Hazardous waste as per EPA?	DNA
Disposal method?	DNA
Solid Waste Quantity	DNA
Hazardous waste as per EPA?	DNA
Disposal method?	DNA

7.3.3 System Details

Unit Size (MW of Engine Served)	4MW
Electrical Load (In Port/In ECA/At Sea) (kW)	12/12/12
Chemical Usage (In Port/In ECA/At Sea)	Calcium Hydroxide, 99%, .05 Tons/MW-hr, 50 Kg/h, 50 Kg/h, 0
Exhaust Handling: Pressure drop at full load (kPa)	1
Does unit serve as silencer/spark arrestor?	Yes
System failure block free flow of exhaust?	No
Multiple engine inlet capable?	Yes
Seawater Supply Quantity (m^3/hr)	DNA
Fresh Water Consumption (m^3/hr)	DNA
Steam Supply (kg/hr, kPa)	DNA
Air Supply (kg/hr, kPa)	DNA
Other necessary utilities?	DNA
Component #1 Name	DryEGCS Absorber
Weight in kilograms (Dry/Wet)	57,000
Size in meters (Width/Depth/Height)	3.85/5.60/7.80
Access required in meters (Front/Side/Top)	0.6/0.6/0.5
Component #2 Name	Supply and Discharge System
Weight in kilograms (Dry/Wet)	24,000
Size in meters (Width/Depth/Height)	2.40/2.40/6.0
Access required in meters (Front/Side/Top)	0.6/0.6/0.5

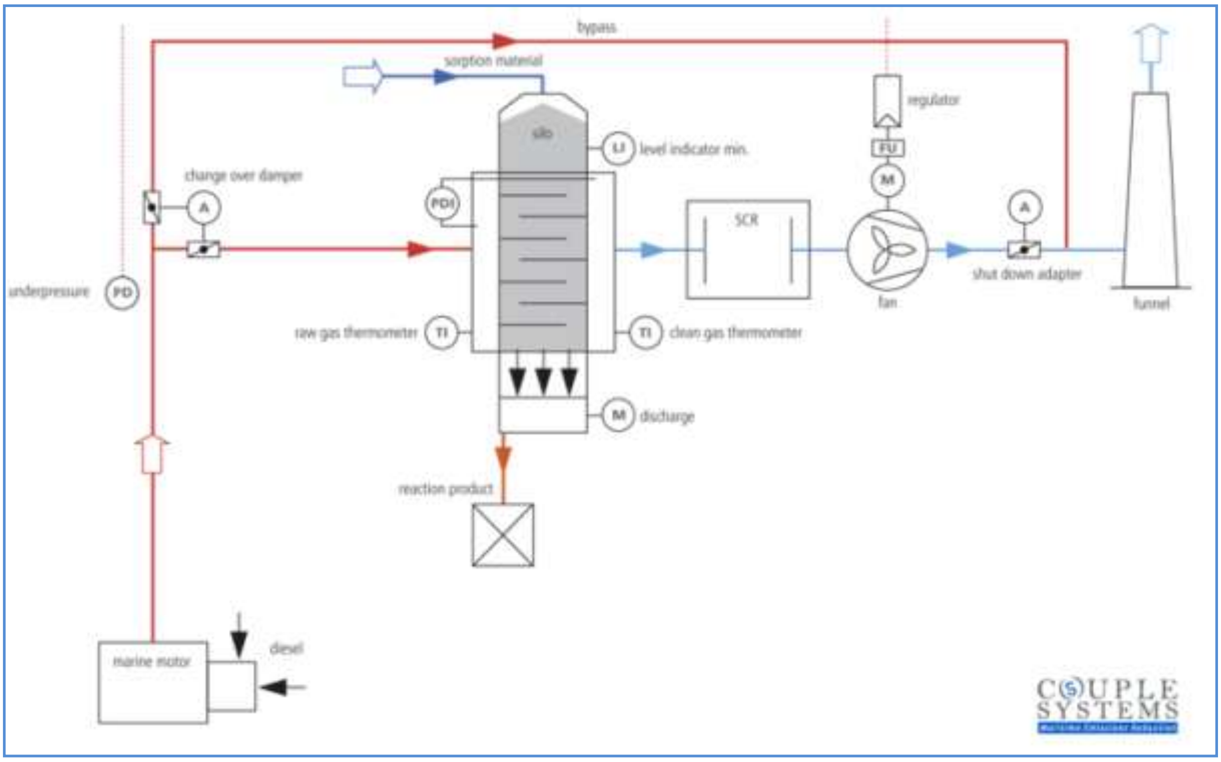


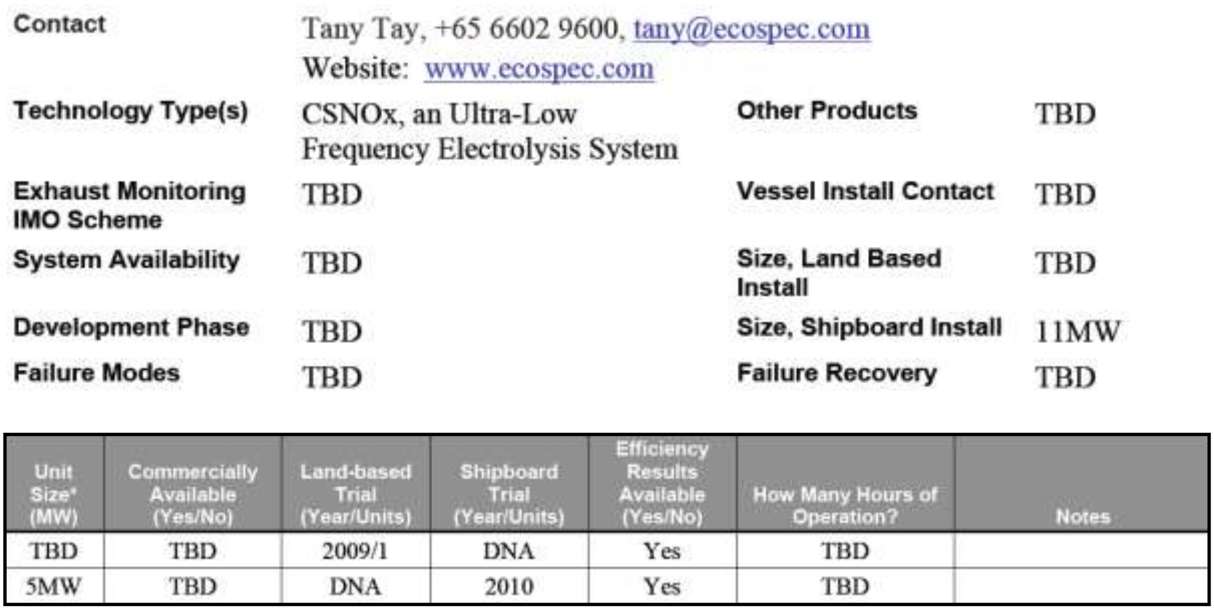
Figure 41: Couple Systems system flow chart

7.3.4 System description (provided by supplier)

Couple Systems GmbH, Bardowick, Germany, brought the worldwide first and only dry system for the desulphurisation of exhaust gases of commercial vessels successfully into service on *MS Timbus*. Motorenwerke Bremerhaven (MWB AG) was able to install the system in less than a week's time with high precision and impeccable workmanship on the cellulose freighter MS Timbus (MaK 8M32, 3.6 MW) of the ship owning company Reederei Braren, Kollmar, Germany. Germanischer Lloyd (GL) has now taken outstanding test readings on the system. This clearly proves the feasibility of the DryEGCS on board ships and the full compliance of the system with the requirements with of Marpol Annex VI. Couple Systems GmbH provides a technical solution, proven and readily available to shipping. A continuation of the HFO-era is ecologically possible. A Return-on-Invest when purchasing a DryEGCS in the light of today's fuel prices, for ships that mainly navigate in the ECA North- and Baltic-Sea, is possible in one year.

The 240 ° to 350 °C hot exhaust gas, which contains SO_2 and SO_3, is fed through a packed-bed absorber filled with lime (calcium hydroxide $Ca(OH)_{2)}$ in the form of granulate pellets. The reaction product is $CaSO_4$ i.e. gypsum. The spherical form of the granulate is retained. The ship's ballast chambers, cargo space, and other open, storage areas on the ship provide storage for recyclables. DryEGCS is dimensioned conservatively so that the collection efficiency is reliably achieved. The loading limit for the calcium hydroxide granulates is about 60 %. Thus the absorbent material retains a considerable residual activity for desulphurization. Alternatively, the residues can be used as mine filling. In this case, costs of approximately US-$ 100 per metric ton can be expected.

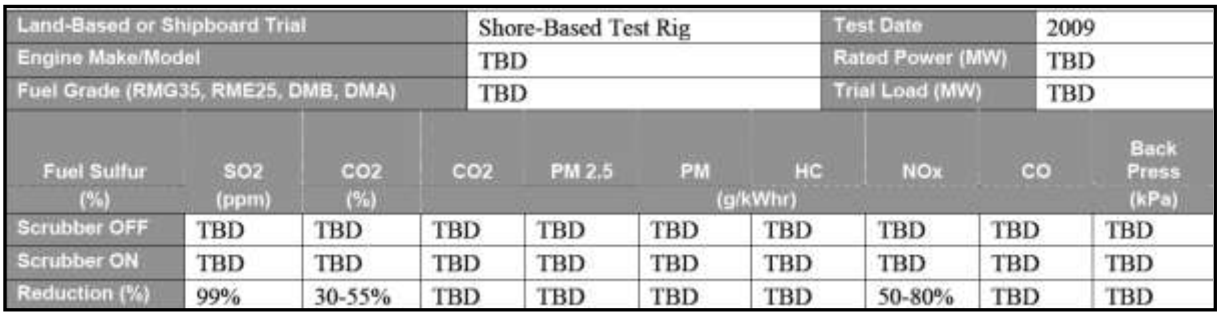
7.4 Ecospec Ltd.



Contact	Tany Tay, +65 6602 9600, tany@ecospec.com Website: www.ecospec.com		
Technology Type(s)	CSNOx, an Ultra-Low Frequency Electrolysis System	**Other Products**	TBD
Exhaust Monitoring IMO Scheme	TBD	**Vessel Install Contact**	TBD
System Availability	TBD	**Size, Land Based Install**	TBD
Development Phase	TBD	**Size, Shipboard Install**	11MW
Failure Modes	TBD	**Failure Recovery**	TBD

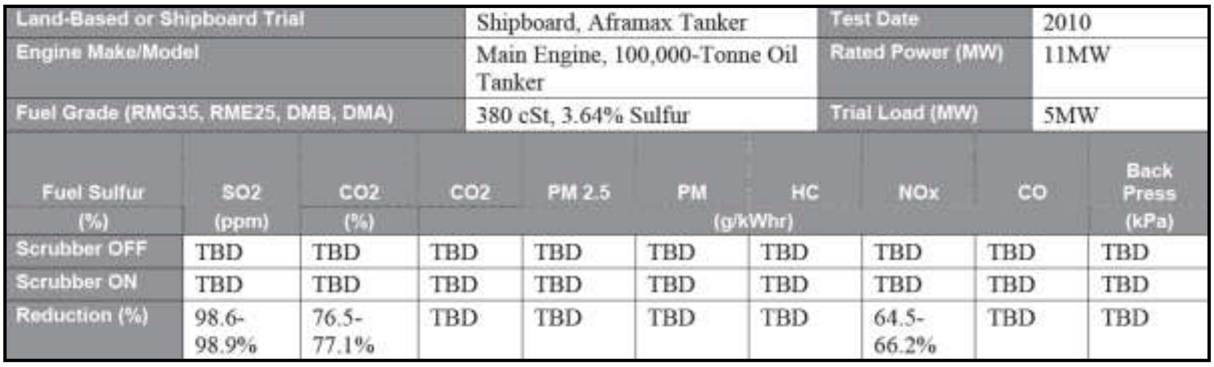
Unit Size* (MW)	Commercially Available (Yes/No)	Land-based Trial (Year/Units)	Shipboard Trial (Year/Units)	Efficiency Results Available (Yes/No)	How Many Hours of Operation?	Notes
TBD	TBD	2009/1	DNA	Yes	TBD	
5MW	TBD	DNA	2010	Yes	TBD	

7.4.1 System efficiency trial results



Land-Based or Shipboard Trial	Shore-Based Test Rig	Test Date	2009
Engine Make/Model	TBD	Rated Power (MW)	TBD
Fuel Grade (RMG35, RME25, DMB, DMA)	TBD	Trial Load (MW)	TBD

Fuel Sulfur	SO2	CO2	CO2	PM 2.5	PM	HC	NOx	CO	Back Press
(%)	(ppm)	(%)	(g/kWhr)						(kPa)
Scrubber OFF	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Scrubber ON	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Reduction (%)	99%	30-55%	TBD	TBD	TBD	TBD	50-80%	TBD	TBD



Land-Based or Shipboard Trial	Shipboard, Aframax Tanker	Test Date	2010
Engine Make/Model	Main Engine, 100,000-Tonne Oil Tanker	Rated Power (MW)	11MW
Fuel Grade (RMG35, RME25, DMB, DMA)	380 cSt, 3.64% Sulfur	Trial Load (MW)	5MW

Fuel Sulfur	SO2	CO2	CO2	PM 2.5	PM	HC	NOx	CO	Back Press
(%)	(ppm)	(%)	(g/kWhr)						(kPa)
Scrubber OFF	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Scrubber ON	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Reduction (%)	98.6-98.9%	76.5-77.1%	TBD	TBD	TBD	TBD	64.5-66.2%	TBD	TBD

7.4.2 Waste streams

Wash Water Overboard Discharge	Yes
Must discharge in port?	TBD
Meets IMO Wash Water Standards?	Yes
Meets EPA Vessel General Permit?	Yes
Meets California Ocean Plan Standards?	Yes
Sludge Residue Quantity	pH 6.7, PAH <1 ppb, Nitrates <0.066mg/l (ppm), Turbidity Δ8.7 NTU
Hazardous waste as per EPA?	TBD
Disposal method?	TBD
Solid Waste Quantity	TBD
Hazardous waste as per EPA?	TBD
Disposal method?	TBD

7.4.3 System Details

Unit Size (MW of Engine Served)	5MW
Electrical Load (In Port/In ECA/At Sea) (kW)	TBD
Chemical Usage (In Port/In ECA/At Sea)	None
Exhaust Handling: Pressure drop at full load (kPa)	TBD
Does unit serve as silencer/spark arrestor?	TBD
System failure block free flow of exhaust?	TBD
Multiple engine inlet capable?	TBD
Seawater Supply Quantity (m^3/hr)	TBD
Fresh Water Consumption (m^3/hr)	TBD
Steam Supply (kg/hr, kPa)	TBD
Air Supply (kg/hr, kPa)	TBD
Other necessary utilities?	TBD
Component #1 Name	TBD
Weight in kilograms (Dry/Wet)	TBD
Size in meters (Width/Depth/Height)	TBD
Access required in meters (Front/Side/Top)	TBD

Figure 42: Ecospec system flow chart

7.4.4 System description (provided by supplier)

ABS, one of the world's leading classification societies, has issued a statement on 8 February 2010 verifying the results of sulphur dioxide (SO_2), carbon dioxide (CO_2), nitrogen oxide (NOx) removal from the emissions of a trading 100,000-tonne Aframax tanker installed with the CSNOx gas abatement system. In the first load point verifications, part of the ongoing IMO Type Approval certification process, conducted during the last week of January 2010 onboard this 100,000-tonne oil tanker, at 50 % gas load (equivalent to approximately 5 MW engine output), ABS issued a Statement of Fact on the performance of CSNOx system with the following results:

Fuel: Type Temperature Sulfur Content
380 cSt 50 °C 3.64 %
Removal SO2 CO2 NOx: efficiencies: 98.6 % - 98.9 % 76.5 % - 77.1 % 64.5 % - 66.2 %
Exhaust gas: Inlet Outlet: 212.3 °C 33.5 °C
Wash water pH PAH Nitrates Temperature Turbidity Quality: 6.7 <1 ppb <0.066mg/l (ppm) 32°C Δ8.7 NTU

This 100,000-tonne Singapore-registered oil tanker, which is owned and managed by leading shipping company Tanker Pacific, set sail from Singapore, travelling to the Middle East via Sri Lanka. Significantly, the removal efficiencies of the CSNOx system allows vessels installed with CSNOx to continue using normal heavy fuel and yet meet the 0.1 % sulfur content as required by the EU Directive effective from 1 January 2010. The removal efficiency for NOx is the absolute reduction percentage. After translating this removal efficiency into the NOx emission requirement as per the Tier 1, 2 or 3 requirements, the CSNOx system is able to remove NOx to such levels that vessels installed with it are able to meet even the strictest Tier 3 requirement. CSNOx truly is a cost-effective and efficient solution for solving the emission issues faced by the ship owners. In addition, the results also affirm CSNOx scalability and suitability for a normal ship's operations.

7.5 Hamworthy Krystallon Ltd

Contact	Heidi Marie Johannessen, +47 6927 9900, hkjohannessen@hamworthy.com Website: http://www.hamworthy.com/en/Products-Systems/Hamworthy-Marine/Emissions-Reduction/Exhaust-Gas-Cleaning/		
Technology Type(s)	Open Loop (Closed Loop under Development) No Dry Chemical Hybrid Wet Solution Available	**Other Products**	The Hamworthy Krystallon SOx scrubber also acts as a Particulates scrubber. Stand alone PM scrubbers also available
Exhaust Monitoring IMO Scheme	Scheme B	**Vessel Install Contact**	TBD
System Availability	0.5 MW to 60 MW	**Size, Land Based Install**	0.4MW, 1MW, 2.2MW
Development Phase	Commercial	**Size, Shipboard Install**	1MW, 6MW, 8.5MW,
Failure Modes	Power loss, multiple supply pump failure, leakage (return pipes or scrubber), clogging of the wet filter.	**Failure Recovery**	If the issue is with the supply or return pump, then the system can be restarted as soon as the pump is repaired.

Unit Size* (MW)	Commercially Available (Yes/No)	Land-based Trial (Year/Units)	Shipboard Trial (Year/Units)	Efficiency Results Available (Yes/No)	How Many Hours of Operation?	Notes
0.5	Yes	2005/1		Yes	500	Test Unit
1	Yes	2008/1	2005/1	Yes	30,000	
2	Yes	2008/1		No	0	Power Plant installation not yet finished
6	No		1993/1	Yes	8000	Initial Hamworthy design
8	Yes		2007/1	Yes	4000	

7.5.1 System efficiency trial results

Land-Based or Shipboard Trial	Land Based	Test Date	2009
Engine Make/Model	DM "MTE40"	Rated Power (MW)	0.9MW
Fuel Grade (RMG35, RME25, DMB, DMA)	TBD	Trial Load (MW)	Various

Fuel Sulfur	SO2	CO2	CO2	PM 2.5	PM	HC	NOx	CO	Back Press
(%)	(ppm)	(%)	(g/kWhr)						(kPa)
Scrubber OFF	340 ppm	DNA	DNA	TBD	TBD	TBD	TBD	TBD	TBD
Scrubber ON	4 ppm	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Reduction (%)	99%	TBD	TBD	DNA	60%	DNA	DNA	DNA	25

Land-Based or Shipboard Trial	Shipboard	Test Date	2009
Engine Make/Model	Sulzer 6ATL25H	Rated Power (MW)	0.8MW
Fuel Grade (RMG35, RME25, DMB, DMA)	IF380	Trial Load (MW)	TBD

Fuel Sulfur	SO2	CO2	CO2	PM 2.5	PM	HC	NOx	CO	Back Press
(%)	(ppm)	(%)	(g/kWhr)						(kPa)
Scrubber OFF	330 ppm	DNA	DNA	TBD	TBD	TBD	TBD	TBD	TBD
Scrubber ON	12 ppm	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Reduction (%)	96.5%	TBD	TBD	DNA	60%	DNA	DNA	DNA	25

Land-Based or Shipboard Trial	Shipboard	Test Date	2010
Engine Make/Model	Sulzer 12VZA40S	Rated Power (MW)	0.8MW
Fuel Grade (RMG35, RME25, DMB, DMA)	IF380	Trial Load (MW)	7.4

Fuel Sulfur	SO2	CO2	CO2	PM 2.5	PM	HC	NOx	CO	Back Press
(%)	(ppm)	(%)	(g/kWhr)						(kPa)
Scrubber OFF	340ppm	DNA	DNA	TBD	TBD	TBD	TBD	TBD	TBD
Scrubber ON	4ppm	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Reduction (%)	99%	TBD	TBD	DNA	60%	DNA	DNA	DNA	25

7.5.2 Waste streams

Wash Water Overboard Discharge	45 Tons/MW-hr
Must discharge in port?	Yes
Meets IMO Wash Water Standards?	Yes
Meets EPA Vessel General Permit?	Yes
Meets California Ocean Plan Standards?	Meets MARPOL Annex VI
Sludge Residue Quantity	<0.1kg/MW.hr
Hazardous waste as per EPA?	No
Disposal method?	1) With ships waste oil, and 2) In portable containers
Solid Waste Quantity	0
Hazardous waste as per EPA?	DNA
Disposal method?	DNA

7.5.3 System Details

Unit Size (MW of Engine Served)	**8 MW**
Electrical Load (In Port/In ECA/At Sea) (kW)	75/120/120
Chemical Usage (In Port/In ECA/At Sea)	0
Exhaust Handling: Pressure drop at full load (kPa)	20 kPa
Does unit serve as silencer/spark arrestor?	Yes
System failure block free flow of exhaust?	Yes
Multiple engine inlet capable?	Yes
Seawater Supply Quantity (m^3/hr)	360 m^3/hr @ 600kPa
Fresh Water Consumption (m^3/hr)	0
Steam Supply (kg/hr, kPa)	450 kg/hr(deplume)@100kPa
Air Supply (kg/hr, kPa)	For instruments only
Other necessary utilities?	DNA
Component #1 Name	2MW
Weight in kilograms (Dry/Wet)	3500/4750 kg
Size in meters (Width/Depth/Height)	1.4/1.4/5
Access required in meters (Front/Side/Top)	600 mm
Exhaust Handling: Pressure drop at full load (kPa)	8 MW
Does unit serve as silencer/spark arrestor?	Yes
System failure block free flow of exhaust?	No
Multiple engine inlet capable?	Yes

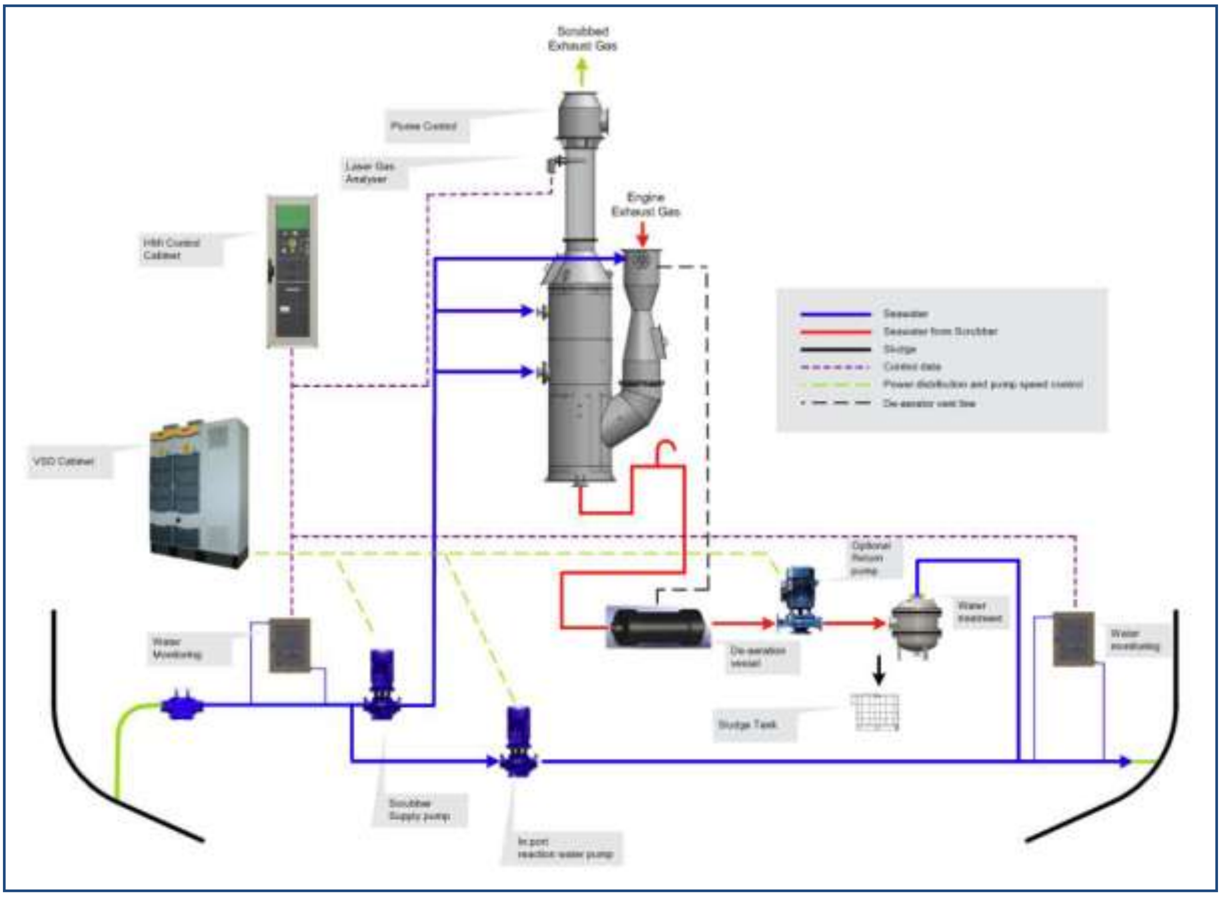


Figure 43: Hamworthy/Kriystallon system flow chart

7.5.4 System description (provided by supplier)

The Hamworthy Krystallon sea water scrubbing technology will remove more than 98 % of sulphur along with the majority of particulate matter from a 3.5 % sulphur residual fuel. The technology is suitable for both new build and retrofits applications, and will deliver ease of operation and low maintenance costs. The technology is available for a wide range of vessel and engine configurations. Hamworthy Krystallon can offer:

1. Pre-installation design support and shipyard supervision
2. A full post-installation commissioning service
3. After sales and service support through Hamworthy’s extensive service network worldwide
4. Access to innovative project financing and fuels supply risk management

The Sea Water Scrubber unit is manufactured from high nickel chrome alloy steels ensuring long lifetime and reliable operation. It can fit into the funnel space being both lightweight and self supporting. Whilst the Scrubber is designed to run cool, operating on a constant supply of sea water, under emergency conditions it can be operated at temperatures of up to 450 °C. It also provides for silencing of the engine exhaust noise, and may therefore replace a typical exhaust gas silencer. The main sea water intake pipe work is manufactured from glass reinforced epoxy. This provides high corrosion resistance, low flow losses, light weight, and ease of installation. Water is transferred around the system via Hamworthy's own trusted centrifugal pumps.

The wash water treatment system will handle the full Scrubber Unit water flow. It is designed to remove both solid particulate matter and liquid hydrocarbon waste products. All exposed materials and wash water transfer pipe work are also manufactured from corrosion proof glass reinforced epoxy. The high efficiency design complies with the requirements of MARPOL Annex VI Regulation 14 Sea Water Scrubbing Wash Water Criteria.

Hamworthy has over 25 years experience of sea water scrubbing through its Inert Gas operation in Moss. Our knowledge and detailed engineering capability allied with Hamworthy Krystallon technology is unique in the marine market place.

7.6 Marine Exhaust Solutions

Contact	Robert Clarke, (506) 214-0535, rclarke@marineexhaustsolutions.com Website: www.marineexhaustsolutions.com		
Technology Type(s)	Seawater Scrubbing System	**Other Products**	J series for PM reduction on diesel fuel engines, NOx reduction unit for MAN Diesel.
Exhaust Monitoring IMO Scheme	TBD	**Vessel Install Contact**	TBD
System Availability	TBD	**Size, Land Based Install**	DNA
Development Phase	TBD	**Size, Shipboard Install**	1.2 to 5.6MW
Failure Modes	Water carryover prevented full time running during tests.	**Failure Recovery**	Run in dry mode until fixed.

Unit Size* (MW)	Commercially Available (Yes/No)	Land-based Trial (Year/Units)	Shipboard Trial (Year/Units)	Efficiency Results Available (Yes/No)	How Many Hours of Operation?	Notes
22.7	No	DNA	2003/8	Yes	11,680	
15.0	TBD	DNA	2001	Yes	TBD	Trials spanned 6 mos.

7.6.1 System efficiency trial results

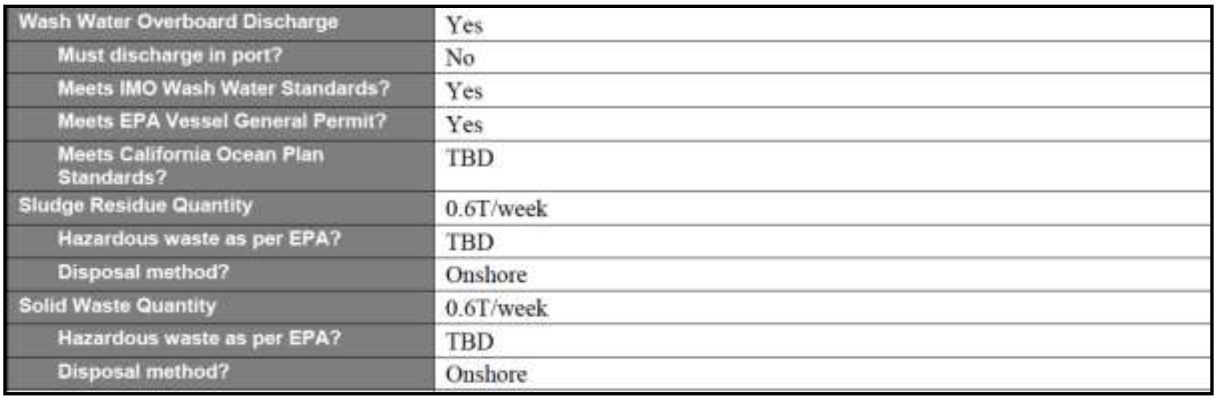
Land-Based or Shipboard Trial	Shipboard, RORO ferry	Test Date	March 2003
Engine Make/Model	Two engine packages, type TBD	Rated Power (MW)	Four 5.6MW mains and four 1.2MW auxiliary engines
Fuel Grade (RMG35, RME25, DMB, DMA)	Heavy Fuel 2.4% Sulfur	Trial Load (MW)	22.7

Fuel Sulfur	SO2	CO2	CO2	PM 2.5	PM	HC	NOx	CO	Back Press
(%)	(ppm)	(%)	(g/kWhr)						(kPa)
Scrubber OFF	235T/yr	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Scrubber ON	59T/yr	TBD	TBD	TBD	TBD	TBD	TBD	TBD	In Limits
Reduction (%)	74-80%	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

Land-Based or Shipboard Trial	Shipboard, Ferry	Test Date	2001
Engine Make/Model	TBD	Rated Power (MW)	1.5MW
Fuel Grade (RMG35, RME25, DMB, DMA)	Heavy Fuel 2.4% Sulfur	Trial Load (MW)	TBD

Fuel Sulfur	SO2	CO2	CO2	PM 2.5	PM	HC	NOx	CO	Back Press
(%)	(ppm)	(%)	(g/kWhr)						(kPa)
Scrubber OFF	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Scrubber ON	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Reduction (%)	90%	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD

7.6.2 Waste streams



Wash Water Overboard Discharge	Yes
Must discharge in port?	No
Meets IMO Wash Water Standards?	Yes
Meets EPA Vessel General Permit?	Yes
Meets California Ocean Plan Standards?	TBD
Sludge Residue Quantity	0.6T/week
Hazardous waste as per EPA?	TBD
Disposal method?	Onshore
Solid Waste Quantity	0.6T/week
Hazardous waste as per EPA?	TBD
Disposal method?	Onshore

7.6.3 System Details

Unit Size (MW of Engine Served)	**TBD**
Electrical Load (In Port/In ECA/At Sea) (kW)	TBD
Chemical Usage (In Port/In ECA/At Sea)	TBD
Exhaust Handling: Pressure drop at full load (kPa)	TBD
Does unit serve as silencer/spark arrestor?	TBD
System failure block free flow of exhaust?	TBD
Multiple engine inlet capable?	TBD
Seawater Supply Quantity (m^3/hr)	TBD
Fresh Water Consumption (m^3/hr)	TBD
Steam Supply (kg/hr, kPa)	TBD
Air Supply (kg/hr, kPa)	TBD
Other necessary utilities?	TBD
Component #1 Name	TBD
Weight in kilograms (Dry/Wet)	TBD
Size in meters (Width/Depth/Height)	TBD
Access required in meters (Front/Side/Top)	TBD

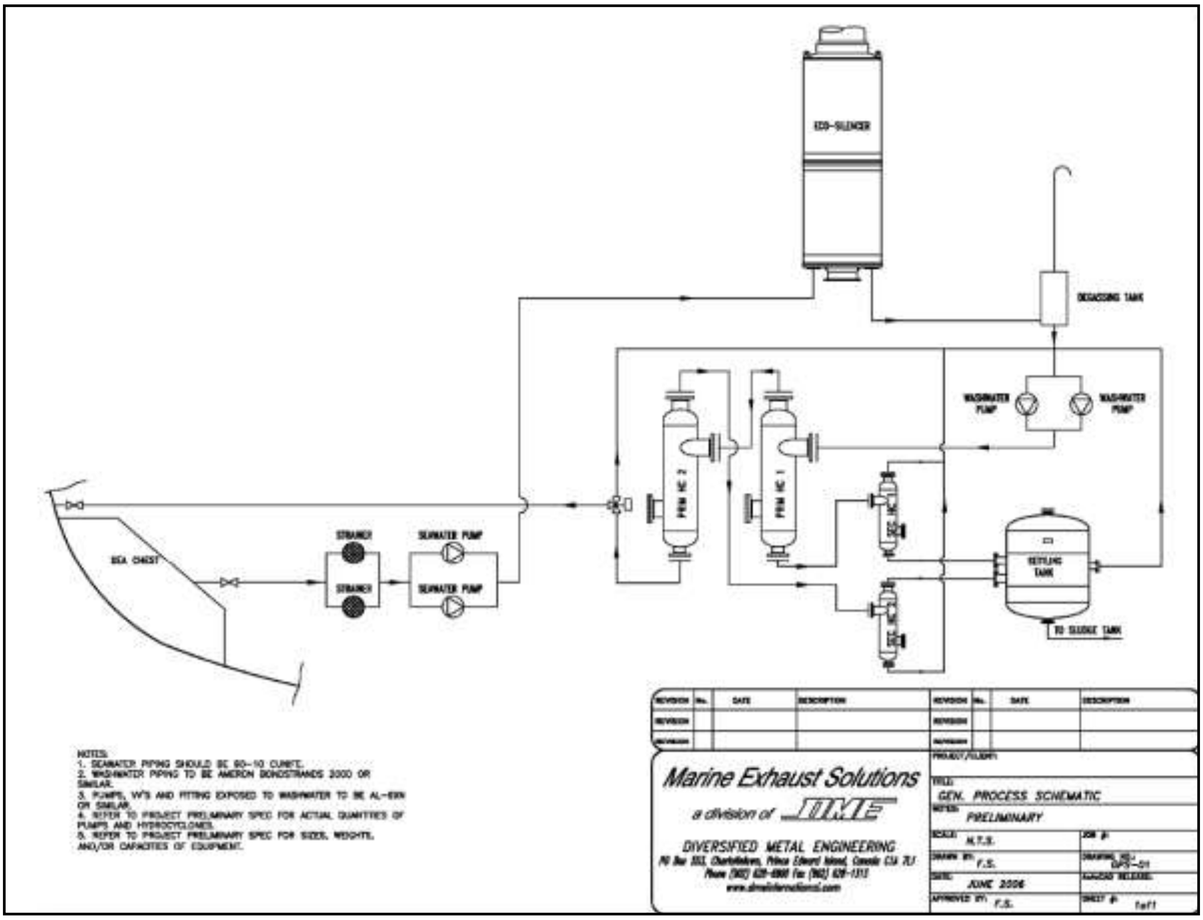


Figure 44: Marine Exhaust Solutions system flow chart

7.6.4 System description (provided by supplier)

Throughout the 16-month trials onboard the RORO passenger ferry, the auxiliary engines were operational for approximately 11680 hours and consumed 6272 tonnes of fuel. During this time, based on a reduction rate of 75 %, the EcoSilencer removed 235.5 of the 314 Tonnes of SO_2. In particular:

- A sustainable SO2 removal level of 74 % – 80 % was obtained with a maximum/minimum range of 94 % to 68 %.
- The target removal of 90 % was only achievable by overcharging the existing water circulation system. Proposed modifications to the circulating water system are expected to result in higher SO2 removal without the necessity of overcharging.
- Tests showed the overboard water discharge complies with USA EPA test criteria.
- Engine performance was not compromised. System backpressures remained within the engines' accepted limits.
- No indication of an increase in engine fuel consumption was noted.
- Soot sludge removal amounted to approximately 0.6 T/week and was easily handled as part of the ships regular onshore waste disposal.

- Minimal system maintenance was required. Routine maintenance consisted of, periodical boroscope type inspections, water circulation pump maintenance and periodical cleaning of the level measuring probes.
- Further trials are needed to confirm the design modifications that will achieve the targeted 90 % SO_2 removal rates for the main engines. The challenge of scaling the system design from a single unit at 1500 kW to eight units at 22700 kW as well as manufacturing, shipping and installation within the four months available proved to be greater than anticipated. A lack of time to properly model the design for the main engine units resulted in installing a system that required additional modifications to become operational.

The final result demonstrates that the EcoSilencer is a reliable, low maintenance sea water scrubbing system that achieves reductions in SO_2 emissions that far exceed those mandated by MARPOL Annex VI.

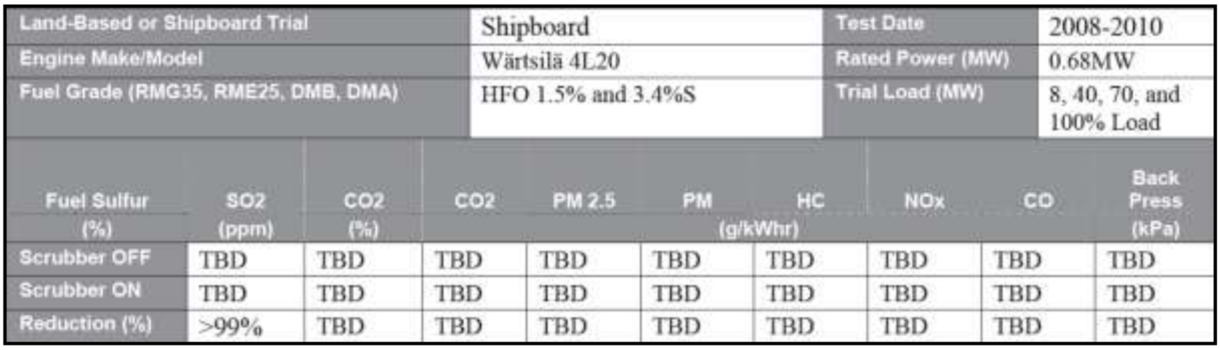
7.7 Wärtsilä Finland Oy

Contact

Technology Type(s)	Closed Loop, High Sulfur SCR	**Other Products**	Wärsilä NOx Reducer
Exhaust Monitoring IMO Scheme	A and B	**Vessel Install Contact**	TBD
System Availability	TBD	**Size, Land Based Install**	TBD
Development Phase	Commercial	**Size, Shipboard Install**	0.68MW
Failure Modes	TBD	**Failure Recovery**	TBD

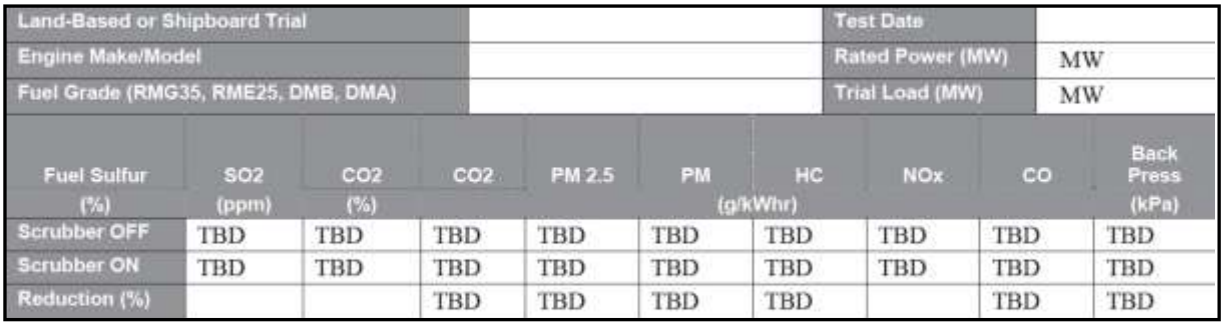
Unit Size* (MW)	Commercially Available (Yes/No)	Land-based Trial (Year/Units)	Shipboard Trial (Year/Units)	Efficiency Results Available (Yes/No)	How Many Hours of Operation?	Notes
.68MW	Yes	TBD	2008/2	Yes	TBD	IMO Certification

7.7.1 System efficiency trial results



Land-Based or Shipboard Trial	Shipboard	Test Date	2008-2010
Engine Make/Model	Wärtsilä 4L20	Rated Power (MW)	0.68MW
Fuel Grade (RMG35, RME25, DMB, DMA)	HFO 1.5% and 3.4%S	Trial Load (MW)	8, 40, 70, and 100% Load

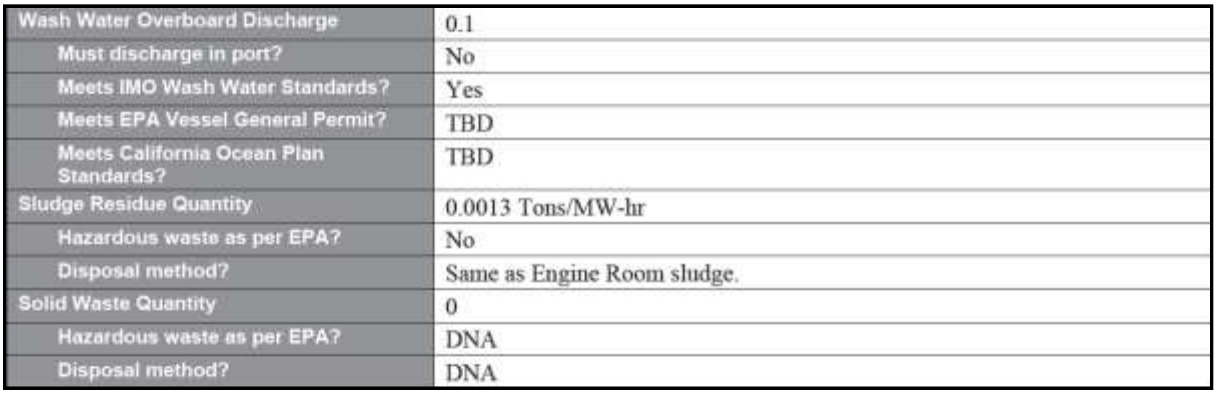
Fuel Sulfur (%)	SO2 (ppm)	CO2 (%)	CO2	PM 2.5	PM	HC	NOx	CO	Back Press (kPa)
			(g/kWhr)						
Scrubber OFF	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Scrubber ON	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Reduction (%)	>99%	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD



Land-Based or Shipboard Trial		Test Date	
Engine Make/Model		Rated Power (MW)	MW
Fuel Grade (RMG35, RME25, DMB, DMA)		Trial Load (MW)	MW

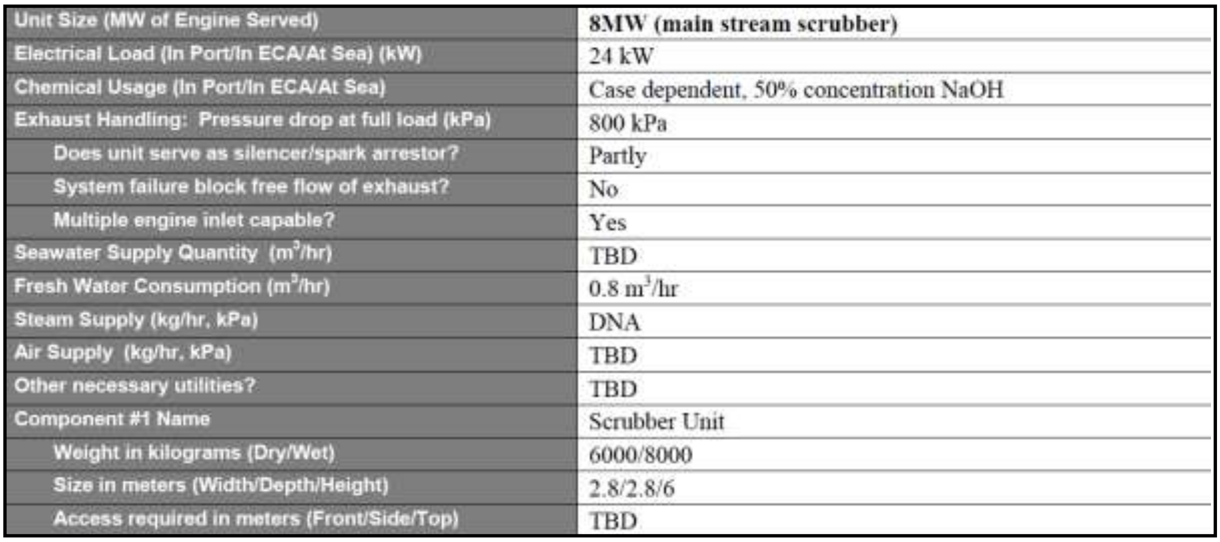
Fuel Sulfur (%)	SO2 (ppm)	CO2 (%)	CO2	PM 2.5	PM	HC	NOx	CO	Back Press (kPa)
			(g/kWhr)						
Scrubber OFF	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Scrubber ON	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
Reduction (%)			TBD	TBD	TBD	TBD		TBD	TBD

7.7.2 Waste streams



Wash Water Overboard Discharge	0.1
Must discharge in port?	No
Meets IMO Wash Water Standards?	Yes
Meets EPA Vessel General Permit?	TBD
Meets California Ocean Plan Standards?	TBD
Sludge Residue Quantity	0.0013 Tons/MW-hr
Hazardous waste as per EPA?	No
Disposal method?	Same as Engine Room sludge.
Solid Waste Quantity	0
Hazardous waste as per EPA?	DNA
Disposal method?	DNA

7.7.3 System Details



Unit Size (MW of Engine Served)	**8MW (main stream scrubber)**
Electrical Load (In Port/In ECA/At Sea) (kW)	24 kW
Chemical Usage (In Port/In ECA/At Sea)	Case dependent, 50% concentration NaOH
Exhaust Handling: Pressure drop at full load (kPa)	800 kPa
Does unit serve as silencer/spark arrestor?	Partly
System failure block free flow of exhaust?	No
Multiple engine inlet capable?	Yes
Seawater Supply Quantity (m^3/hr)	TBD
Fresh Water Consumption (m^3/hr)	0.8 m^3/hr
Steam Supply (kg/hr, kPa)	DNA
Air Supply (kg/hr, kPa)	TBD
Other necessary utilities?	TBD
Component #1 Name	Scrubber Unit
Weight in kilograms (Dry/Wet)	6000/8000
Size in meters (Width/Depth/Height)	2.8/2.8/6
Access required in meters (Front/Side/Top)	TBD

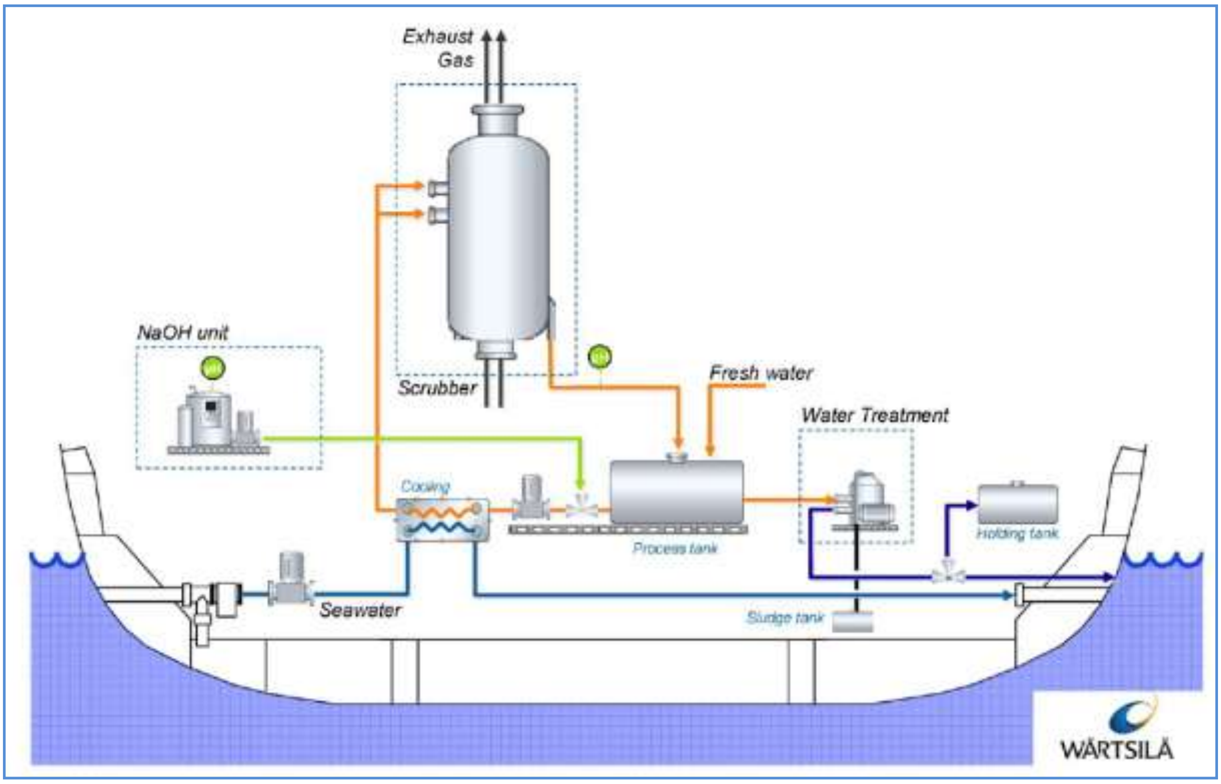


Figure 45: Wärtsilä system flow chart

7.7.4 System description (provided by supplier)

Wärtsilä has developed a feasible scrubber solution, both for new installations and as a retrofit to existing ships. Combustion units can be diesel engines of any make, type, or application, 2-stroke or 4-stroke. In the case of Integrated Scrubber, also flue gases of oil-fired boilers can be cleaned. The SOx removal efficiency of Wärtsilä scrubber system is over 97 %, making possible to operate with 3.5 % sulphur fuel and still comply with 0.1 % sulphur fuel limit. There are different scrubber configurations available. The scrubber system is equipped with an automation system for operation, monitoring, and safety control. Wärtsilä scrubber system has been approved by classification societies.

The Wärtsilä fresh water scrubber is based on closed loop system. Within this process, sulphur oxides in the exhaust gas stream are captured and neutralized by scrubbing water. The scrubbing water is based on fresh water boosted with alkali, typically sodium hydroxide (NaOH). The chemical process sulphur oxides resulting from the exhaust gas are neutralized to sulphates in the scrubbing water. The scrubber system is entirely built of highly corrosion resistant materials. Scrubbing water circulation flow rate is related to the actual dimensions of the scrubber module and design performance of the system. Scrubbing water is buffered in a process tank or wet sump for controlling the quality of the solution. This water is circulated with circulation pump from process tank or wet sump via the cooling heat exchanger to scrubber and back. A small bleed-off is extracted from the scrubbing water circulation to remove the accumulated impurities and led to treatment unit. Clean effluent from the treatment unit is monitored full-filling IMO quality requirements and can be discharged overboard. If operation in zero discharge mode is requested, the effluent can be led to a holding tank for scheduled and periodical discharge.

8 Selective Catalytic Reduction (SCR) of Nitrogen Oxides (NOx)

Emissions of nitrous oxides (NOx) affect human health and the environment in a number of ways and are a serious source of atmospheric pollution in the EU. Ship engines are a major source of NOx emissions which cause acidification and eutrophication (over fertilization) of the sea and on land thus affecting biodiversity of land and coastal waters. The Baltic Sea area is particularly affected.

NOx also results in the formation of nitrate aerosols which lead to increased levels of atmospheric particulate matter (PM) and is a significant factor in the formation of ozone, a major health hazard in Europe and a cause of vegetation damage and reduced crop yields.

EU Governments have, in recent years imposed stringent restrictions on emissions of NOx from a wide range of industrial and commercial activities including road vehicle transport, but relatively little has been done to reduce emissions from ships which now account for more than a quarter of total emissions of nitrogen oxides in Europe. 75 % of the urban population of southern Europe and 40 % of that in Northern Europe live in cities where the ozone level exceeds the EU air quality standard. Exposure to high levels of ozone and PM results in 370,000 cases of premature death annually.

Under current growth trends, emissions from international shipping in European sea areas are projected to increase by nearly 40 per cent between 2000 and 2020. If no additional abatement measures are taken, by 2020 the emissions from shipping around Europe are expected to equal or even surpass the total from all land-based sources in the 27 EU member states combined. As a consequence, the number of annual deaths from ozone and PM exposure in Europe is likely to stay high.

NOx emission standards for international shipping are set by the International Maritime Organisation (IMO). New regulations were introduced by the IMO in 2008 which strengthen somewhat the NOx requirements worldwide for all new ships built after January 01, 2011.

In addition, the IMO decided that in designated sea areas called Emission Control Areas (ECAs), significantly more stringent rules will apply to all new ships built after 01 January 2016 when sailing in these ECAs. Affected ships will have to reduce emissions of NOx by about 80 per cent from the current limit values. There are currently no NOx-ECAs in place, but the countries surrounding the Baltic Sea are cooperating through the Baltic Marine Environment Commission (HELCOM) to prepare a proposal to the IMO to designate the Baltic Sea as a NOx ECA. (it is currently a Sulphur Controlled Area or SECA).

In March 2009, The United States and Canada jointly proposed that most areas of their coastal waters – extending 200 nautical miles from the coast – be designated as an ECA for the control of sulphur oxides, of particulate matter and of NOx emissions. After being approved in principal by the IMO last July, the proposal is set for formal adoption in March 2010.

A problem in the context of the new IMO NOx standards is that they only apply to new ships. Ships tend to have a life of 25 – 35 years before being scrapped so the turnover of the fleet is slow. In addition it is feared that the new regulation could be evaded by operators only deploying older ships in ECAs. Thus in order to not only limit the growth in ships' NOx emissions, but actually to reduce them, there is a need to cut emissions from existing vessels and to speed up the introduction of efficient NOx abatement technologies in new ships built before 2016.

8.1 Legal framework

The legal framework has been described in chapter 3.3. This report does not display market-based instruments like the Norwegian NOx fund or other NOx-differentiated en-route charges.

Regulation 13 of MARPOL Annex VI sets out a schedule for the reduction of nitrogen oxide (NOx) emissions from marine diesel engines. Tier III of these reductions (emissions to be (2 - 3.4 g/kWh), depending on engine speed) is to be introduced for engines installed after 2016 and could require ships to use exhaust after treatment to achieve the required standard when operating in an emission control area.

8.2 Technology overview

Three technologies are identified that can achieve emissions that meet the stringent ECA requirements: Selective Catalytic Reduction (SCR), Humid Air Motor (HAM) and engines fuelled by gas (LNG = liquefied natural gas). This report focuses only on the SCR technology.

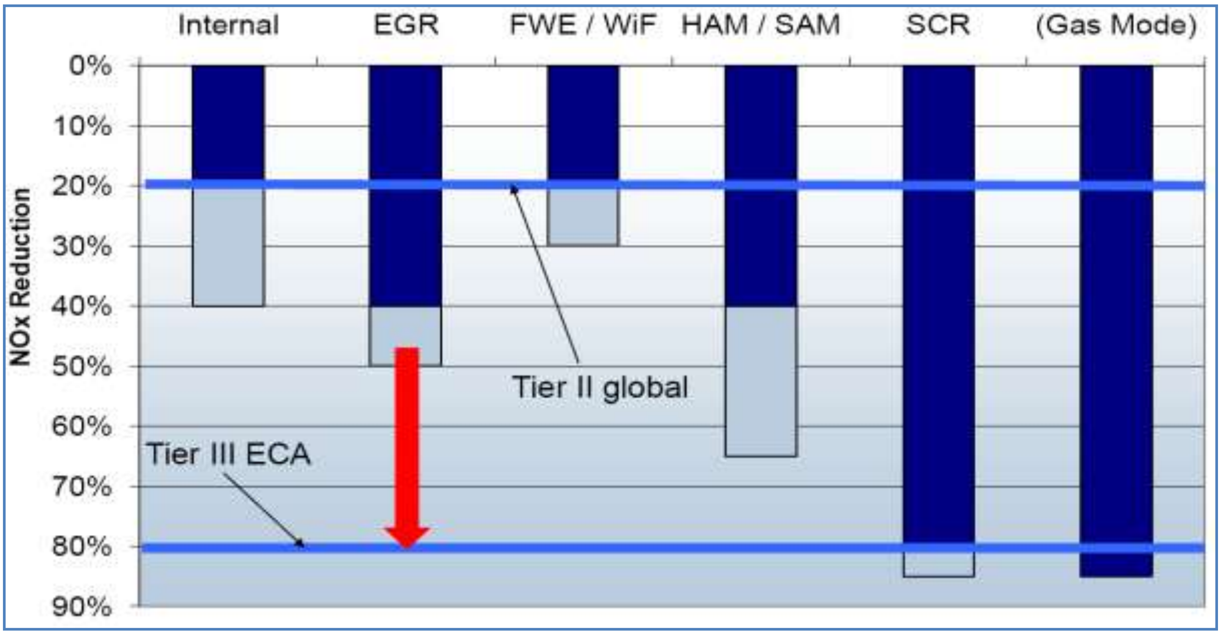


Figure 46: Potential of NOx reduction of various technologies [Jürgens 2010]

When comparing the abatement costs with the monetized health benefits from reducing NOx by these technologies, it is concluded that the benefits are about five times the average cost, provided that a payback period of ten years is allowed. There are also other, less expensive, technologies that can reduce emissions, which are relevant when considering the economic efficiency of retrofitting old engines.

Nitrogen oxides are reacted stoichiometrically with ammonia or urea as reducing agent to form nitrogen (N_2) and water vapor (H_2O) which occur naturally in the atmosphere. The major part of the nitrogen oxides, which is generally present as NO, is reacted according to the following reaction:

$$4NO + 4\,NH_3 + O_2 \rightarrow 4\,N_2 + 6\,H_2O \qquad (4)$$

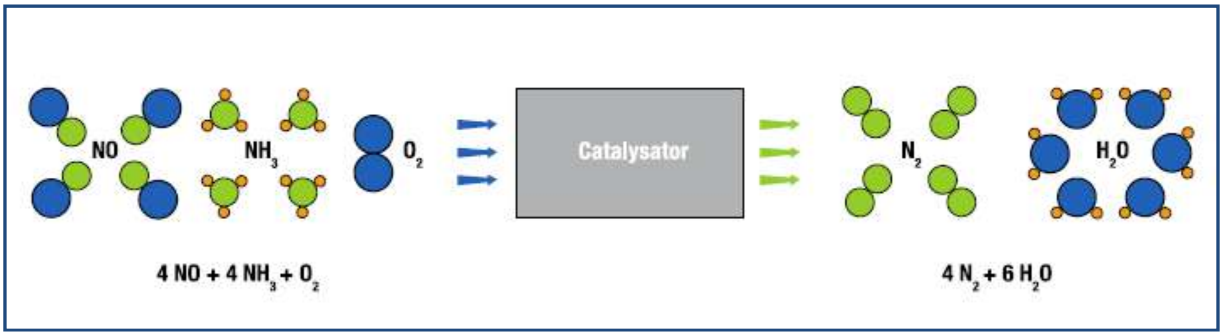


Figure 47: Typical NO reduction with stoichiometrically dosed NH_3

As long as a mixture of NO and NO_2 is present, the following somewhat faster reaction proceeds in parallel:

$$NO + NO_2 + 2NH_3 \rightarrow 2\,N_2 + 3\,H_2O \qquad (5)$$

In principle, these reactions can also be carried out without catalyst in a small temperature range around 900 °C. However, under these conditions a significant proportion of the ammonia is burned to form nitrogen oxides, which severely impairs the efficiency in respect of ammonia consumption and the achievable NOx conversion.

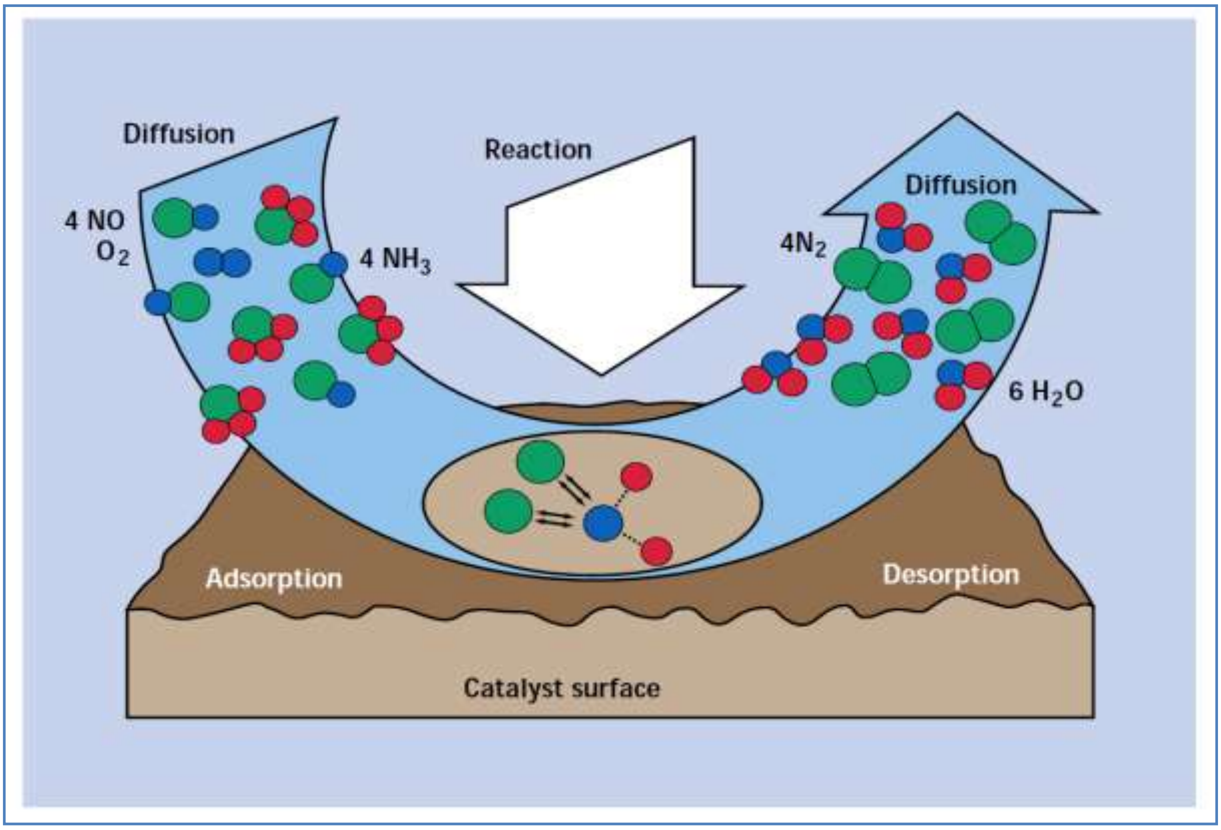


Figure 48: Principle of the selective catalytic reaction of nitrogen oxides with ammonia and oxygen

The SCR process makes it possible to reduce the level of nitrogen oxides by means of the reactions shown in a broad temperature range between about 160 °C and just under 600 °C, depending on flue gas conditions and catalyst type. High selectivities of almost 100 % are obtained in the reaction of ammonia and, if required, NOx conversions of well above 90 % can be achieved. Furthermore, the SCR process is extremely flexible in terms of the fuel used and the loading of the upstream combustion process.

The SCR process enables the highest degree of removal of all DeNOx processes to be achieved in an economical way. In addition, it is at present the best available technology, and therefore helps to secure the future.

Traditional fields of application for the SCR technology are power stations, gas turbines, waste incineration plants, chemical plants, cogeneration plants and glass works. SCR catalysts are being increasingly used in the combustion of wood and other biomass as well as in mobile combustion engines. In the marine industry are at present app. 500 SCR systems installed downstream of main engines as well as downstream of auxiliary engines.

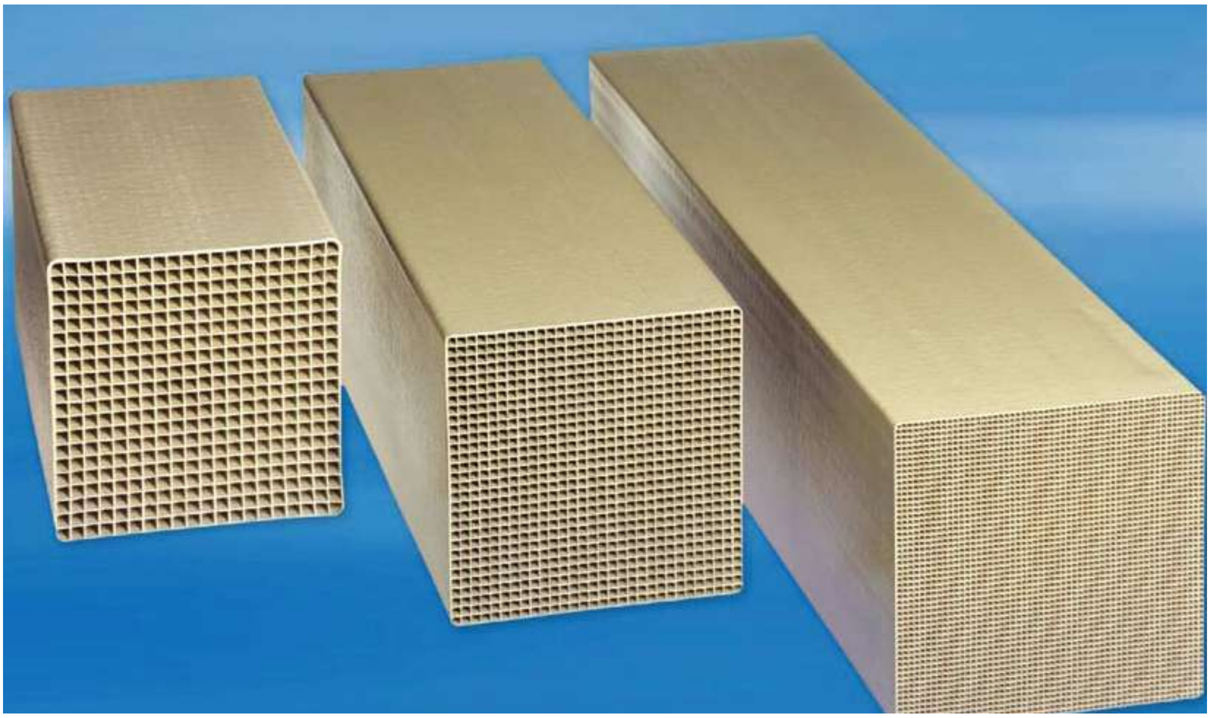


Figure 49: SCR ceramic elements with different pitches

Typically the ceramic elements are installed into the housing of the SCR system (see figure 51).

Figure 50: SCR ceramic elements during installation

Figure 51 displays the complete arrangement of an onboard installed SCR system including the required periphery.

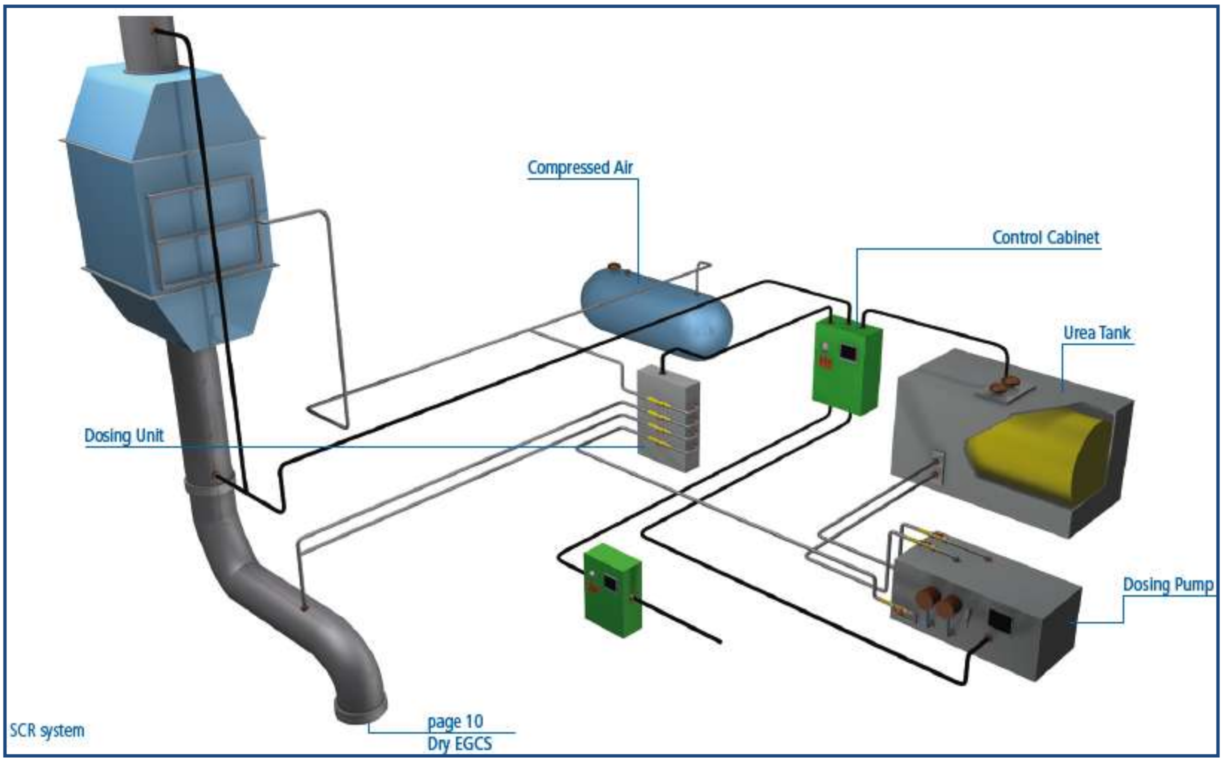


Figure 51: SCR system including periphery

Usually the SCR catalysts are based on titanium dioxide (TiO_2) in form of catalytically active anatase. The ceramic honeycomb with its defined pore structure comprises about 80 % of TiO_2. This support material is acid-resistant and is therefore particularly suitable for use in acid flue gases. The catalytic properties can be tailored to the specific application by means of the most catalytically active component vanadium pentoxide (V_2O_5) and the co-catalyst tungsten oxide (WO_3).

The catalyst can be matched to the particular dust loading of the flue gases by selection of the width of the channels. This prevents plugging of the catalyst channels. In addition, the catalyst structure counteracts losses in activity, since a slight amount of abrasion always exposes fresh active material at the catalyst surface and makes it available for NOx removal.
In general, each catalyst layer contains individual, retractable catalyst elements. Sample elements can be taken out during reactor shutdowns in order to determine the actual catalytic and physical state. For the case of dust-containing flue gases, the catalyst modules are arranged vertically in the reactor – high dust SCR. For low-dust flue gases, a horizontal arrangement of the catalyst modules could be used – low dust SCR.

The high-dust configuration is most widespread in coal power stations for NOx emission controls. This arrangement is also becoming increasingly important in modern waste incineration plants and is the design of choice for marine diesel engines. The SCR reactor is installed directly downstream of the boiler. Here, the operating temperatures are generally in the optimum range for the SCR process, i.e., 320 - 430 °C. The dust loadings in the flue gas are usually is the range of 7.5 – 15 g/m^3.

In the low-dust crude gas configuration the catalysts are installed directly downstream of the Dry Exhaust Gas Cleaning system. The flue gas temperatures here are usually sufficient for the catalytic reaction without further heating. The further flue gas purification elements such as gas scrubbers are arranged downstream of the SCR reactor.

Since in the low-dust clean gas configuration the SCR reactor is located at the end of the flue gas cleaning plant (downstream a wet scrubber), there are generally no longer any catalyst poisons present in the flue gas. However, the exhaust gas has to be reheated which makes the configuration of an SCR downstream of a wet scrubber plant difficult and energy-consuming and yet has not been build. In case a combination of wet scrubbing and SCR is desired the SCR must be installed upstream of the wet scrubber either before the turbo charger or immediately before the scrubber. In both cases the operation of the SCR is difficult and requires a huge load of maintenance.

During the design phase of a marine SCR a couple of parameters need to be considered. First, an appropriate arrangement variant is selected. The choice depends on the flue gas temperature and the flue gas composition. Furthermore, the possible presence of catalyst poisons is of importance.

The choice of the channel width in the catalyst elements is specific to the application. The dust content and the maximum tolerable pressure drop in the flue gas are decisive in making the choice, since the channel width influences the total pressure drop in the flue gas purification system and thus capital and operating costs for the blower if there is a blower installed in order to overcome the pressure drop of the entire exhaust gas system.

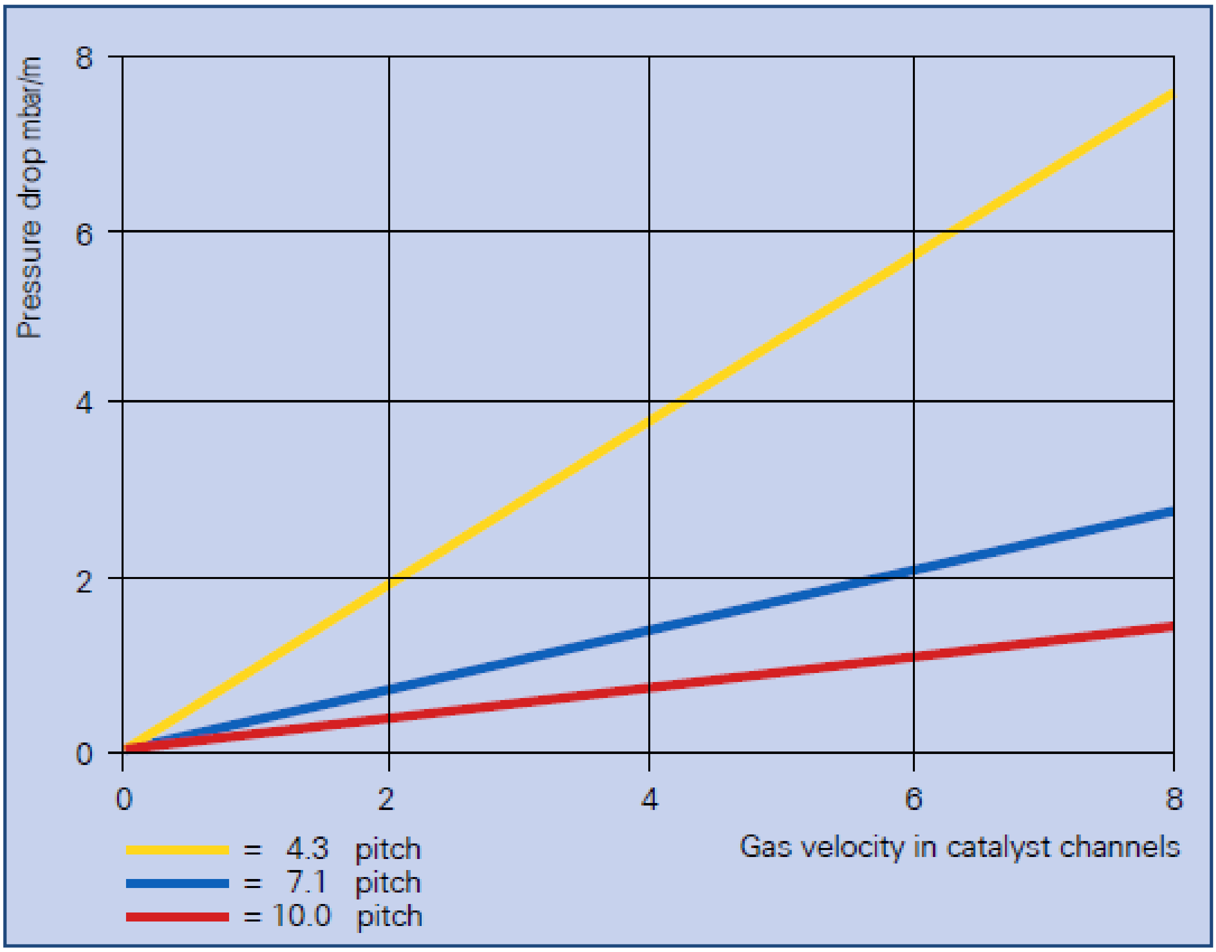


Figure 52: Pressure drop for various catalyst geometries as a function of the gas velocity in the catalyst channels at constant temperature

During operation of an SCR reactor, the temperature must not fall below the minimum working temperature. The minimum working temperature is the temperature below which the formation of ammonium salts on the catalyst has to be reckoned with. This salt formation depends on the SO_3 and NH_3 concentrations in the presence of water (H_2O) and the corresponding temperature is in the range from 160 °C to 320 °C. The ammonium salts are ammonium hydrogen sulfate (NH_4HSO_4) and/or ammonium sulfate ($(NH_4)_2SO_4$), which are formed according to the following reactions.

In presence of an excess of NH_3:

$$2\ NH_3 + SO_3 + H_2O \rightarrow (NH_4)_2SO_4 \quad (6)$$

In case of an excess of SO_3:

$$NH_3 + SO_3 + H_2O \rightarrow NH_4HSO_4 \quad (7)$$

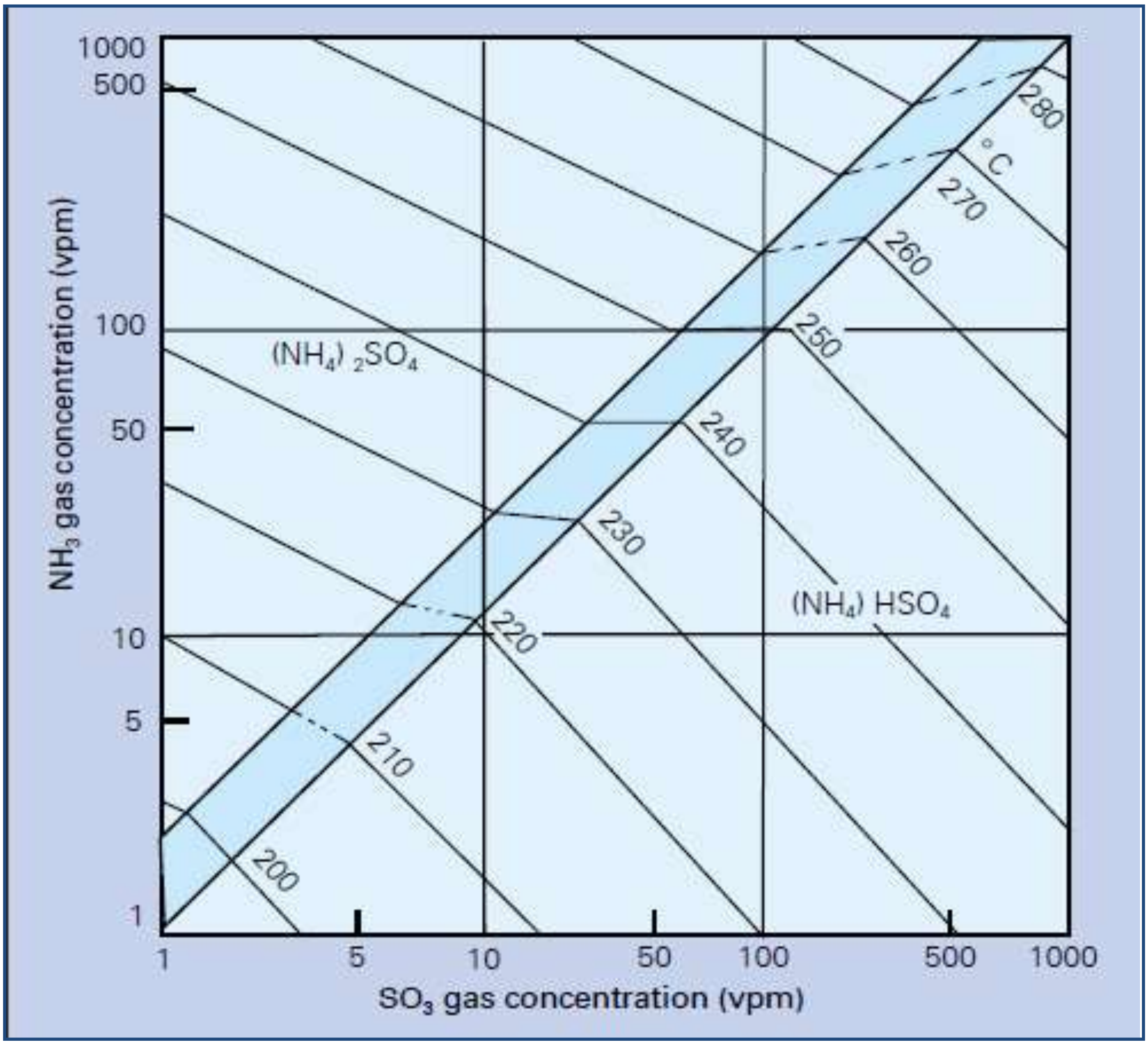


Figure 53: Temperature- and concentration-dependent formation of ammonium sulfate ((NH_4)2SO_4) and ammonium hydrogen sulfate (NH_4HSO_4) from SO_3 and NH_3

To ensure reliable operation of the SCR reactor, the operating conditions are generally selected such that the lowest operating temperature is above the minimum working temperature. The deposition of the catalyst surface with ammonium salts is reversible. However, the formation of ammonium salts is not the only effect of sulfur oxides. SO_3 together with water (H_2O) forms sulfuric acid (H_2SO_4). The reaction is:

$$SO_3 + H_2O \rightarrow H_2SO_4 \qquad (8)$$

The formation of SO_3 should be minimized because of possible corrosion if the temperature falls below the dew point of the acid. Particular attention must therefore be paid to the formation of SO_3.

A further guide parameter for the design of the catalyst is the ammonia slip. This is the amount of ammonia which leaves the SCR reactor in the gas phase without having reacted. The catalyst volume is therefore determined not only by the desired degree of NOx abatement but also by the ammonia slip.

Catalysts are subject to aging processes during operation. The current degree of aging is determined by regular examination and sampling. This enables the optimum replacement or recharging time for the catalyst to be determined. The residual activity of a specific SCR reactor is generally determined by regulatory requirements, but these can also be tightened in accordance with the principle of best available technique. In an optimally designed SCR reactor, the actual activity must be sufficient to keep the NH_3 slip below the maximum permissible value.

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

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 speed engines, which have exhaust temperatures above 300 °C at normal load. Slow speed crosshead engines have lower exhaust temperatures because of their two-stroke design and a 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.

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 is mixed thoroughly with the hot exhaust gas in a specifically designed duct before entering the catalyst. Whilst in the duct the urea combines with water in the exhaust stream and from the injected solution, then decomposes to form ammonia (NH_3) and some carbon dioxide (CO_2). On contact with the surface of the catalyst the NOx components, nitric oxide (NO) and nitrogen dioxide (NO_2) react with the ammonia and oxygen from the exhaust to form nitrogen and water.

- $4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$
- $2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$

Info Box 19: Relevant chemistry – Selective Catalytic Reduction

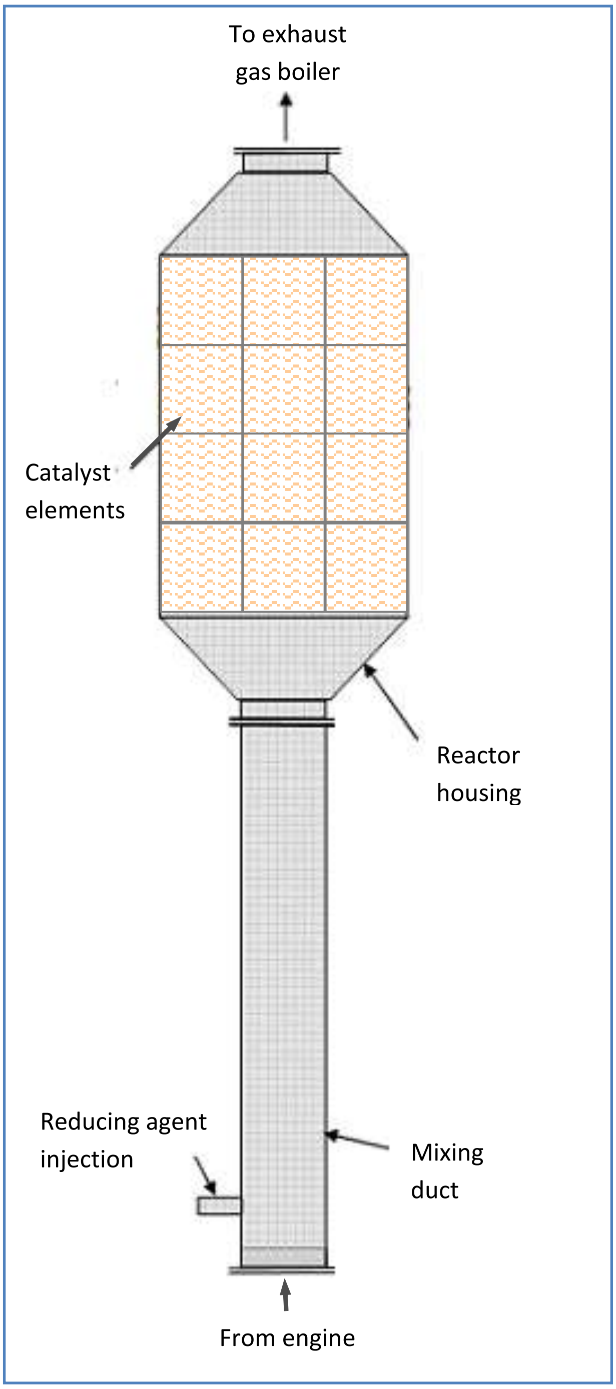


Figure 54: Selective Catalytic Reduction unit

SCR efficiency is such that NOx emissions can be reduced up to 95 % i.e. <1 g/kWh can be achieved and the quantity of CO_2 produced from the urea is negligible when compared with that produced by the fuel oil combustion.

The reactor housing can be designed so that it also acts as a highly effective silencer and for retrofits it can be usually sized to replace the existing silencer in an exhaust system. The catalyst element within the housing is typically composed of replaceable blocks arranged in layers.

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

Info Box 20: Spent SCR catalyst disposal

The blocks have multiple gas paths, providing an optimal area in contact with the exhaust whilst not imposing an unacceptable obstruction to flow. The blocks may be manufactured from various ceramic materials such as titanium oxide coated with an active component such as vanadium pentoxide (V_2O_5), together with tungsten oxide 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.

It is important to tightly control the rate of urea injection in order to restrict the release of un-reacted ammonia to atmosphere, which is referred to as ‘ammonia slip’. A characteristic curve of NOx emissions across the engine load range can be established to programme into the injection control equipment with enhanced feedback by continuous monitoring of the NOx emissions after the reactor. Urea injection may be automatically stopped at very low engine loads and in some designs an extra oxidation or ‘slip’ catalyst may be fitted after the SCR system to reduce the release of ammonia to atmosphere.

In addition to tightly controlling urea injection it is vital to ensure that the temperature of the catalyst is maintained at the design level to maximise NOx reduction and prevent both ammonia slip and a reaction with sulphur trioxide (SO_3) in the exhaust stream. Typically, a minimum of 320 °C – 360 °C is required.

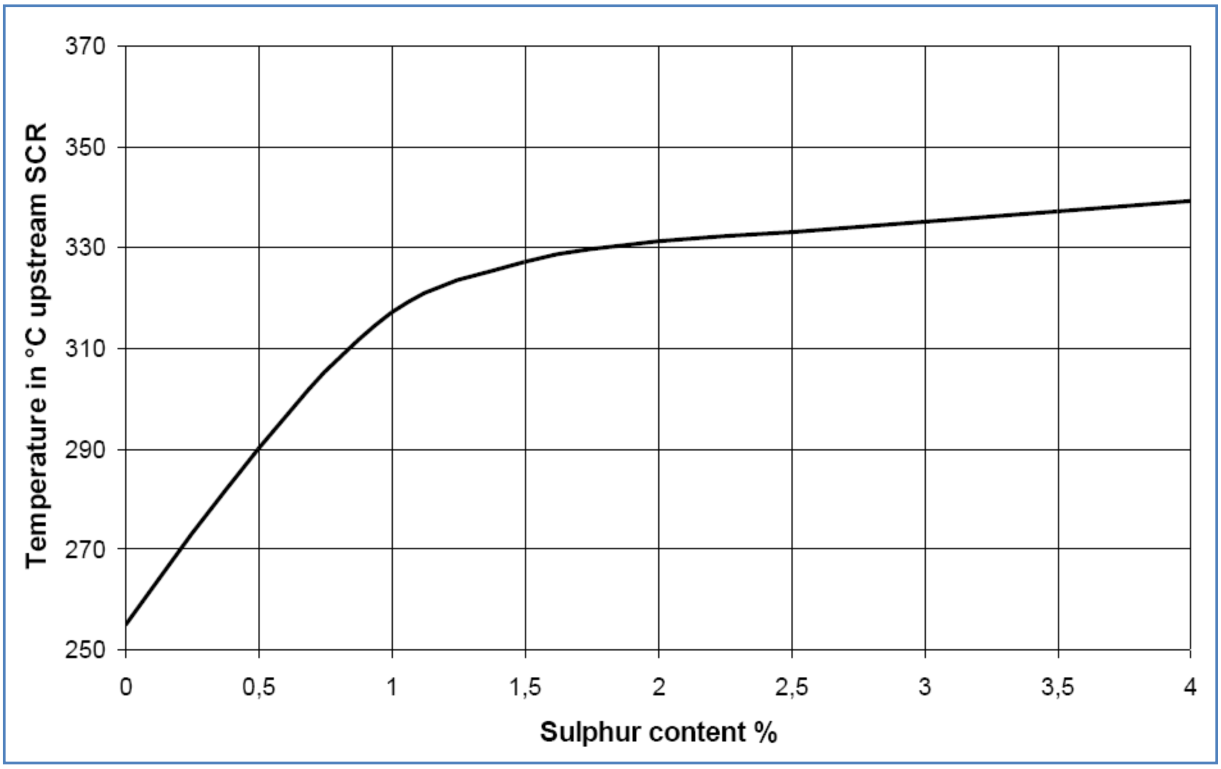


Figure 55: Needed minimum temperature at SCR inlet to avoid ammonium sulphate formation

At lower temperatures the formation of ammonium sulphate, $(NH_4)_2SO_4$, a dry powdery compound can result. Ammonium bisulphate, $(NH_4)HSO_4$ is also formed. This is an adhesive and corrosive compound that reduces the effective area of the catalyst and is deposited in downstream components of the exhaust system impeding gas flow and the transfer of heat. Higher NOx emissions ensue and conditions overall can deteriorate with more ammonia slip and further fouling from the adherence of combustion derived particulate matter.

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 the catalyst surfaces.

Because the rate of reduction of NOx can be limited by the NO reductions in the reactor, an upstream oxidation catalyst may be fitted. This converts some NO to NO_2 and allows manufacturers to use a smaller reactor and/or operate at lower temperatures [EPA 2003].

In addition to the NO to NO_2 conversion, oxidation catalysts can effectively convert other pollutants into simpler, less toxic compounds, such as carbon dioxide and water. These pollutants include carbon monoxide (CO), hydrocarbons, the soluble organic fraction of particulates (derived from unburned or partially combusted fuel oil and engine lubricant), and several hydrocarbon derivatives, including polycyclic aromatic hydrocarbons (PAHs) [Kozak 2005].

The sulphur content of the fuel has to be considered for systems using an oxidation catalyst because sulphur dioxide can be oxidised into 'sulphates' and increase emissions of particulate matter. Sulphates in the form of aerosols or very fine airborne particles have been linked to increased asthma attacks, heart and lung disease and respiratory problems in susceptible population groups [Wright 2000], so this is obviously undesirable. Whilst in a typical diesel engine exhaust a very small percentage of SO_2 is oxidised to $SO_{3,}$ this can be significantly increased by a catalytic system, particularly at higher engine loads and exhaust temperatures [EPA 2003]. A proportion of the SO_3 formed will react with some of the water vapour present to form sulphuric acid (H_2SO_4). The remainder will undergo either oxidation and condense as sub-micronic droplets or will oxidise onto the particulate matter formed during combustion [Wright 2000]. The sulphates formed include those of ammonia and metals [Huggins 2002] derived from the combusted fuel.

Generally in order to maximise the effective life of catalysts, fuel oil with a low sulphur content (typically 1% maximum) or an upstream SOx Exhaust Gas Cleaning System*, which does not impact exhaust temperature has to be used. This helps to reduce ammonium bisulphate and sulphate deposition in the reactor and chemical 'poisoning' of the catalyst. Depending on the materials of construction sulphur-containing compounds can be adsorbed onto and chemically react with active parts of catalysts which can prevent contact with the exhaust gas, and performance is degraded. Other poisons include alkalis, phosphorus and certain heavy metals. This requires adherence to manufacturers recommendations in terms of the fuel oil type, composition and ash content (for example biofuels can have a high level of alkali metals). Recommended lubricating oil specifications for engines also have to be followed.

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

8.3 List of vendors

All vendors listed under .3 utilize the above describe SCR technology. Sizes of the ceramic elements and the individual formulation of the catalytic active agents may vary.

Name	Web page	Typical application	Comments
Canopus Marine Solutions AB	www.canopusmarine.com	Supplier of SCR systems for new and old ship engines.	Uses CFD to design SCR systems. Supplier experienced in designing and commissioning SCR equipment for several applications and installations.
Couple Systems GmbH	www.couple-systems.com	Supplier of maritime SCR systems for new and old ship engines.	Also supplier of DeSOx systems
D.E.C Marine AB (ex Munters)	www.decmarine.com	Supplier of maritime SCR systems for new and old ship engines.	Company has more than 70 ships in their reference list, first was in 1992
Dansk Teknologi	www.dansk-teknologi.dk	Supplier of SCR systems for new and old ships. Claims no additional fuel consumption for their Digital Airless Multipoint Urea injection system, and no additinal space compared to the existing silencer	Has delivered SCR systems to the Danish Navy. Supplier has measured a NOx reduction of more than 80% (IMO E2 cycle weighted)
H+H Umwelt- und Industrietechnik GmbH	www.huhgmbh.com	For new and old ship engines of different sizes. Supplies different types of SCR solutions	Company has more than 110 ships in their reference list.
Johnson Matthey Catalysts (Germany) GmbH	www.matthey.com	Johnson Matthey manufacturers and supplies pollution control systems using expertise in catalyst and systems engineering to reduce emissions of NOx, particulates, CO and non-combusted fuel from stationary and mobile engines including ship engines and boilers.	Johnson Matthey Catalysts Germany has an extensive experience with SCR application. Since 1995 more than 150 SCR systems have been successfully installed on ships.
MAN Diesel SE	www.manbw.com	For new and old maritime engines of various sizes	SCR reduces NOx levels with approx. 80%
Mecmar AS	www.mecmar.no	For new and old ship engines of different sizes, especially experience with military vessels	Supplier estimates a reduction of 80% with ammonium as reduction medium.
Pon Power AS (Caterpillar)	www.pon-cat.com	For new and old ship engines of different sizes	Implemented on 10 vessels and on more than 20 new buildings.
STX Europe Florø	www.stxeurope.com	Retrofit of NOx removal systems for all types of vessels	
Wärtsilä	www.wartsila.com	For new and old ship engines of different sizes	The supplier estimates a NOx-reduction by 80-90%. The first unit was ordered in 2006.
Yarwil AS	www.yarwil.com	For new and old ship engines of different sizes	Supplier estimates a reduction of down to 0.15g/kWh. Yarwill supplies both SCR systems and urea.

9 Exhaust Gas Recirculation (EGR)

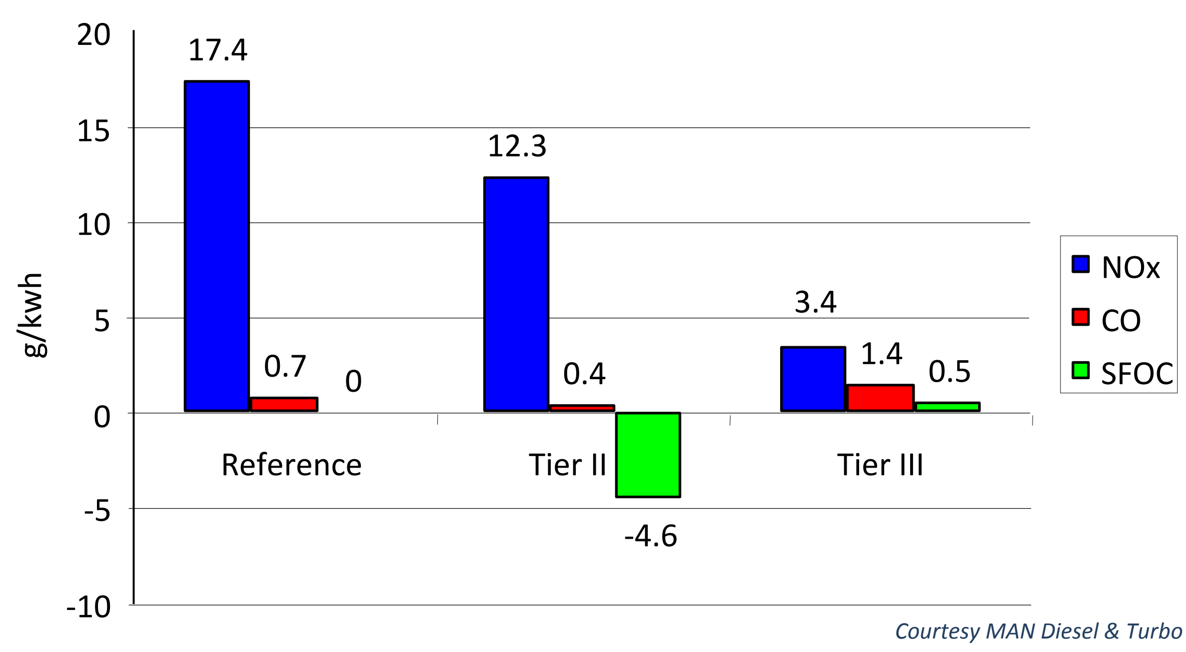
During the process of combustion in an engine a series of complex reactions occur which cause some of the nitrogen in the charge air and most of any nitrogen in the fuel to oxidise and form nitric oxide (NO).

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 ^{o}C and rises exponentially above 1500 ^{o}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 [Wright 2000].

On leaving the combustion chamber some of the nitric oxide is oxidised to nitrogen dioxide (NO_2) and together these 2 gases form NOx in the ratio of approximately 90 – 95 % NO to 5-10 % NO_2 [Wright 2000].

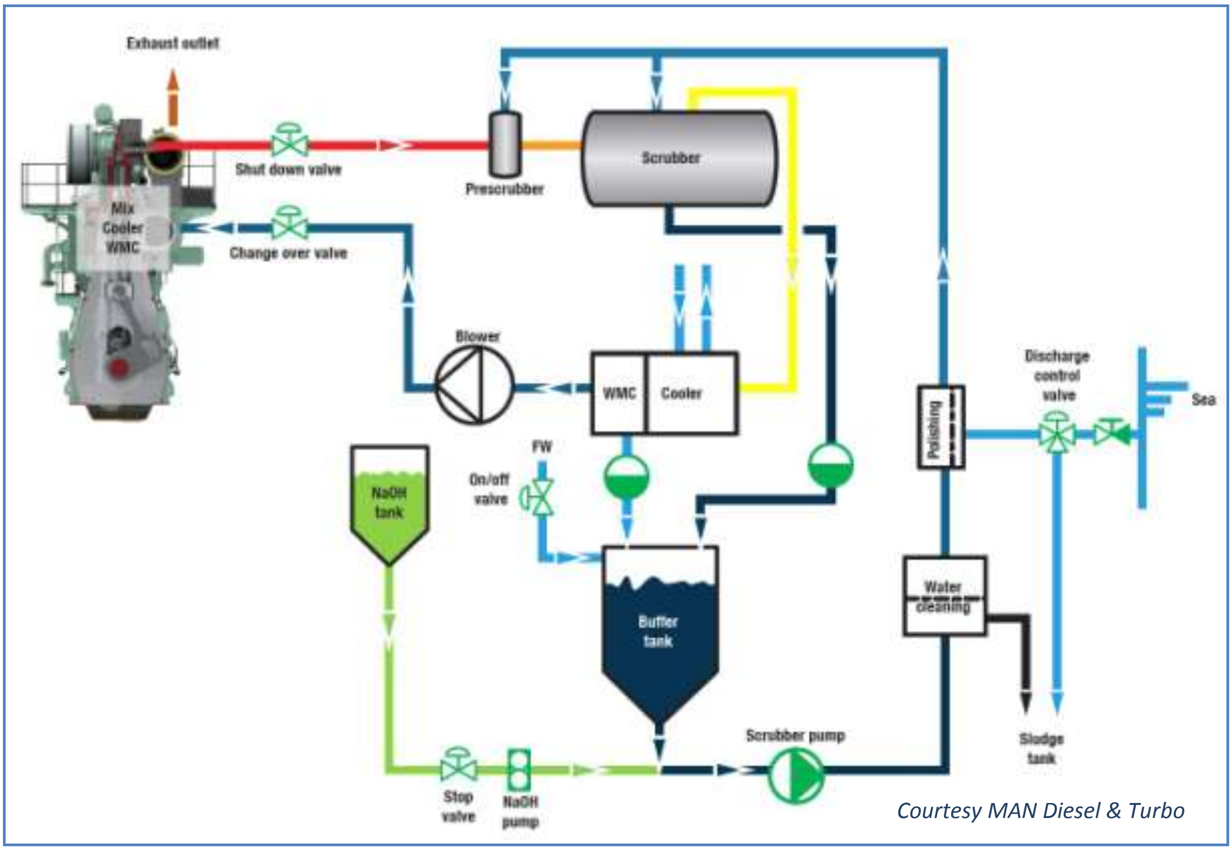
Primary methods of NOx control focus on the process of emission formation and consider the design of an engine and its operational adjustment. This includes the pressure, timing and rate of fuel injection, fuel nozzle configuration, exhaust valve timing, scavenge air temperature and pressure and compression ratio. Another ‘at-engine’ method of NOx control is Exhaust Gas Recirculation (EGR), 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 re-circulated 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 set-up can compensate for a large part of this penalty, which appears to make IMO’s Tier III NOx limit practically achievable. Operation at low engine loads, which can be a problem for other NOx reduction technologies such as SCR, also does not seem to pose a problem for EGR.



Courtesy MAN Diesel & Turbo

Figure 56: Results of EGR tests on 2-stroke test engine adjusted to achieve Tier II & Tier III compliance (Power for the EGR blower is not included in Specific Fuel Oil Consumption values. Other emission values (PM, HC) remain basically unchanged)



Courtesy MAN Diesel & Turbo

Figure 57: EGR system (Color of gas flow indicates temperature)

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

The scrubber removes sulphur oxides and particulate matter from the re-circulated 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 ^{o}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 re-circulated gas by 0.4 - 0.7 bar, before it is introduced to the scavenge air.

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

Between 45 % and 65 % of SO_2 is removed by the scrubber and particulate matter reduction efficiency is believed to be very high. However standard methods of PM measurement are not suited to the high-pressure exhaust conditions at the scrubber and so a new technique for testing is being developed.

A long-term service test has been initiated on the container vessel Alexander Maersk with a specific focus on testing the engine condition, control and safety systems and the materials used for the scrubber and coolers.

Courtesy MAN Diesel & Turbo

Figure 58: EGR system scrubber unit

10. Potential of Scrubbers and SCRs with respect to Particle Filtration

10.1 Particle Filtration Mechanism

In many land-based industries several processes for the collection and separation of particles are applied. However many of them (i.e. electrostatic precipitators, cyclones, fabric filters etc.) have the main function to collect particles. For reasons of size, weight and pressure loss these technologies cannot be integrated into the exhaust gas system of a marine engine. Another constraint is the temperature of the exhaust gas specifically of a 4-stroke engine which makes the operation of fabric filter impossible.

In gas filtration, the primary collection mechanisms are diffusional interception, inertial impaction and direct interception. The influence exerted by each of these collection mechanisms is strongly dependent upon particle size and flow conditions.

10.1.1 Direct Interception

If the particles in a fluid stream are larger than the pore size of the filter medium, the particles will be removed as a result of direct interception. A significant proportion of particles whose diameter is smaller than the filter pore size will be removed by bridging effects and partial occlusion of pores by collected particles. The removal of particles in a gas stream by direct interception becomes more effective with increasing particle diameter.

10.1.2 Inertial Impaction

Particles in a fluid stream possess a certain mass and velocity, and thereby possess a certain momentum. As the fluid and entrained particles pass through a filter medium, the fluid stream will take the path of least resistance to flow and will be diverted around the pore walls. Because of their inertia, the particles will tend to continue in the previously established flow direction and impact upon the filter medium. This collection mechanism is important for particles larger than 1 µm.

10.1.3 Diffusional Interception

Gas molecules are in a state of random motion. Particles smaller than 0.3 µm suspended in a gas are continually bombarded by the gas molecules, causing the particles to undergo a random walk about their path of flight (Brownian Motion). The deviation of the suspended particles from the fluid flow lines due to Brownian Motion increases the likelihood of the particles striking the filter membrane and being removed. Brownian Motion decreases with increasing particle size; diffusion is most effective at small particle sizes (0.3 µm) and becomes less important as particle sizes increase.

10.2 Particle precipitation inside a dry scrubber

Dry scrubbing is a technique for removing vapour components of gas flow using a hot gas filter. The technology described under 7.3 not only absorbs gaseous exhaust gas components such as SO_2 and SO_3. It can also remove particles. The granulate used inside the DryEGCS acts like a deep bed filter. The transportation and capture of the particles in the granulate layer are due to hydrodynamic, gravitational, molecular, Brownian or electrical forces acting alone or in combination.

Several tests haven shown that a filtration efficiency of 80 – 90 % is achievable while the pressure loss of the systems remains below 10 mbar. The velocity profile of the packed bed is relevant for the filtration efficiency. Figure 59 displays the correlation.

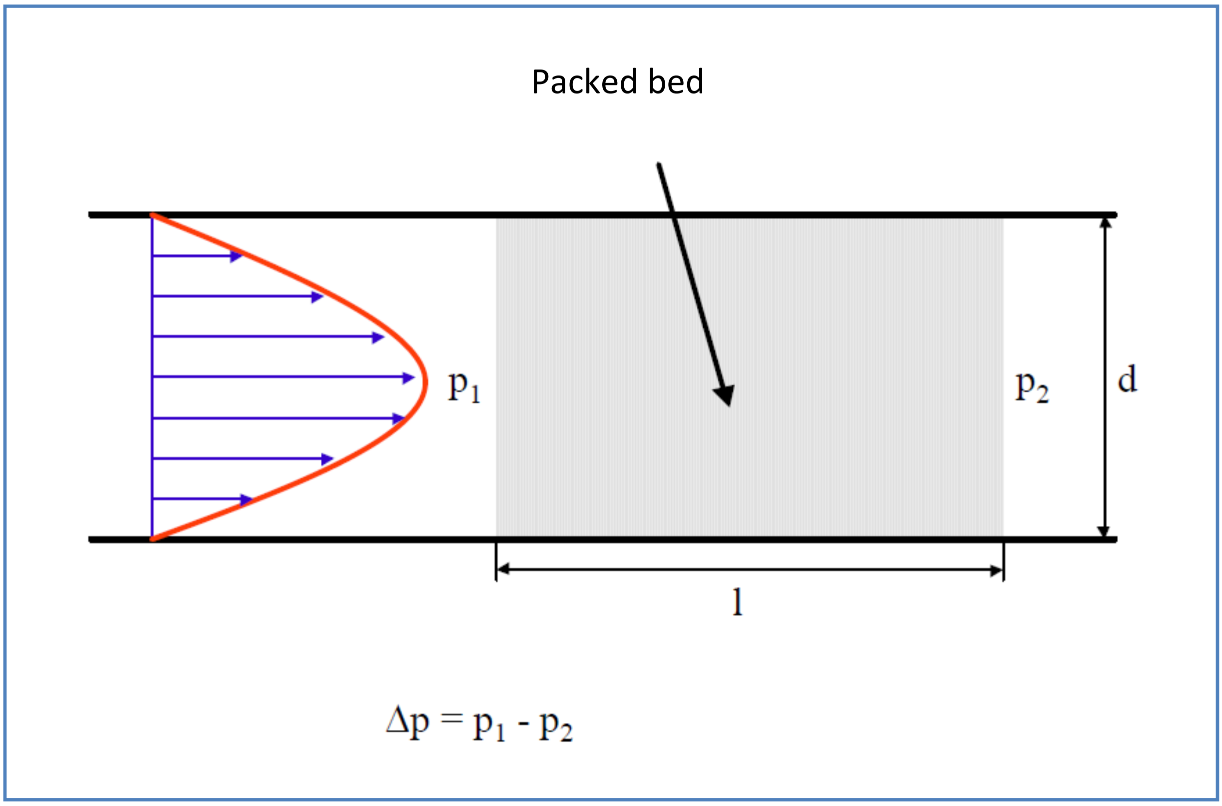


Figure 59: Velocity profile of a packed bed dry scrubber

10.3 Particle precipitation inside a wet scrubber

All of the wet scrubbers listed under 7.0 depend on inertial impaction. However, the velocities of the particle-laden gas stream and the liquid targets vary substantially. Accordingly, there are substantial differences in the ability of particulate wet scrubbers to collect particles less than approximately 5 micrometers. This is illustrated in Figure 59. If a significant portion of the particulate matter mass is composed of particles less than 5 micrometers, care is needed to select the type of scrubber that is effective in this size range.

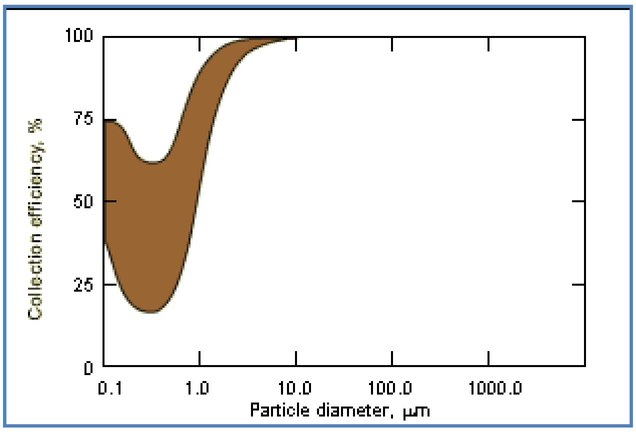


Figure 60: Efficiency of several types of particulate wet scrubbers

It should be noted that some types of wet scrubbers have limited capability to remove particles in the less than 0.3 micrometer range. Methods of particle collection in this very small size range take advantage of these particles' tendencies to diffuse slowly due to their interactions with gas molecules (Brownian diffusion). In other words, these particles are so small that their movement is influenced by collisions with individual molecules in the gas stream.

Many types of particulate wet scrubbers can provide high efficiency control of particulate matter. One of the main advantages of particulate wet scrubbers is that they are often able to simultaneously collect particulate matter and gaseous pollutants. Also, wet scrubbers can often be used on sources that have potentially explosive gases or particulate matter. They are compact and can often be retrofitted into existing plants with very limited space.

One of the main disadvantages of particulate wet scrubbers is that they require make-up water to replace the water vaporized into the gas stream and lost to purge liquid and sludge removed from the scrubber system. Wet scrubbers generate a waste stream that must be treated properly.

Typically the scrubbers achieving relatively high particle filtration efficiency are working as a venturi scrubber. A typical venturi throat is shown in Figure 61. Particulate matter, which accelerates as it enters the throat, is driven into the slow moving, large water droplets that are introduced near the high velocity point at the inlet of the venturi throat. The adjustable dampers in the unit illustrated are used to adjust the open cross-sectional area and thereby affect the speed of the particles entrained in the inlet gas stream.

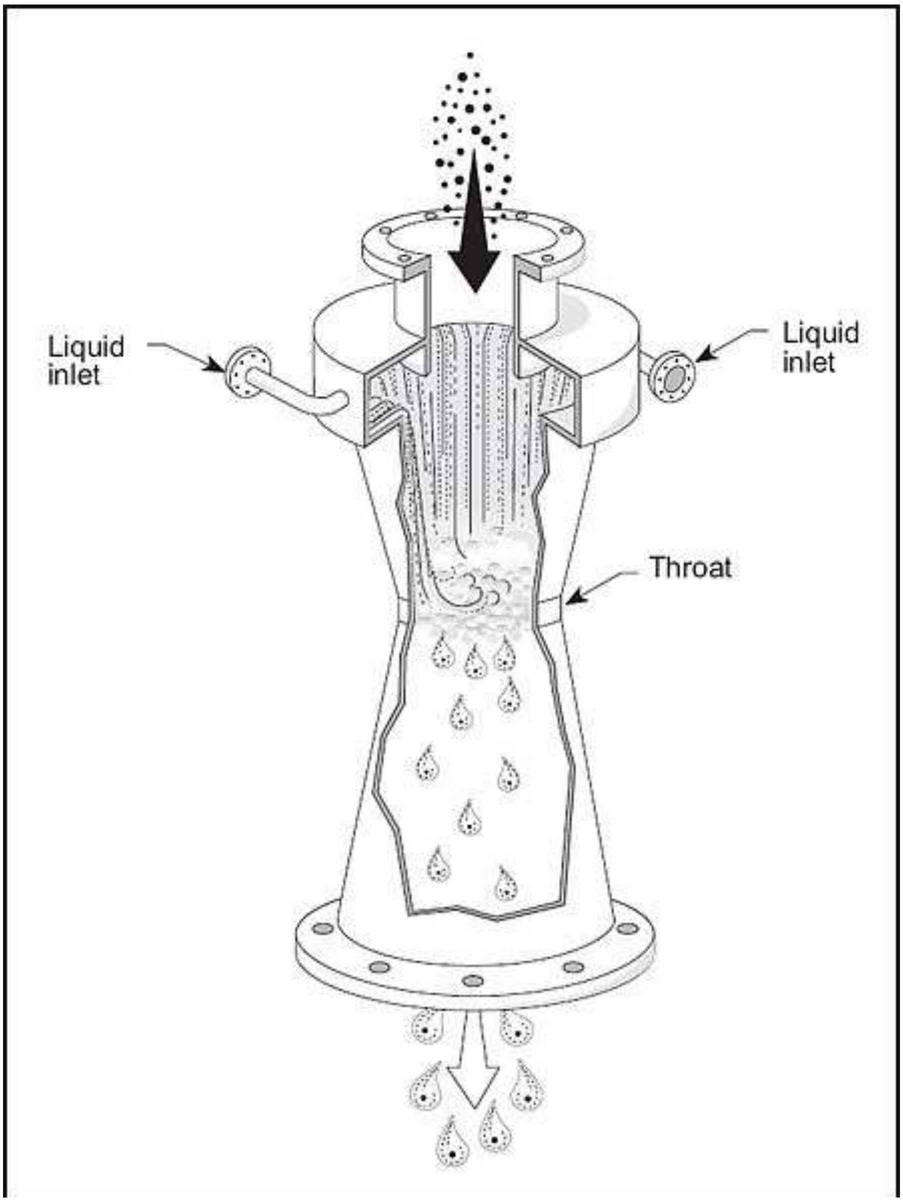


Figure 61: Principal design of a venture scrubber

Venturi scrubbers consist of three sections: a converging section, a throat section, and a diverging section. The inlet gas stream enters the converging section and, as the area decreases, gas velocity increases. Liquid is introduced at the entrance to the converging section. The inlet gas, which is forced to move at extremely high velocities in the small throat section, shears the liquid from its walls, producing a tremendous number of very tiny droplets. In the throat section, particle and gas pollutant removal occurs as the inlet gas stream mixes with the fog of tiny liquid droplets. The inlet stream then exits through the diverging section, where it is forced to slow down. Venturi scrubbers can be used to collect both particulate and gas pollutants.

An important disadvantage of a venture scrubber is the high pressure loss of the system. Aalborg reported that their system operates at 40 mbar pressure at 70 to 80 % particle filtration efficiency.

10.4 Particle precipitation inside a SCR catalyst

Selective Catalytic Reduction (SCR) is commercially used for reduction of NOx emitted from marine engines fueled with HFO, MDO or MGO. NOx is reacted with ammonia to generate nitrogen and water. A V_2O_5-WO_3/TiO_2 (VWT system) catalyst of monolithic type is used. During commercial operation, however, the catalyst is influenced by deposition or interaction of compounds in the flue gas resulting in a reduced chemical activity as well as decreased lifetime of the catalyst. This leads both to environmental and economical drawback.

Particles such as metal ashes, soot and salts are collected inside the SCR which leads to clogging of the active surfaces of the catalytic wash coat (see figure 62). This SCR has been operated downstream a main engine operated with HFO with 0,9 % sulphur content.

Figure 62: SCR element clogged by particles

In order to remove those sediments and agglomerates typically a soot blower operated with compressed air or water steam is installed (see figure 63). However the cleaning capability is limited and after some time the ceramic elements need to be cleaned off manually after disassembly.

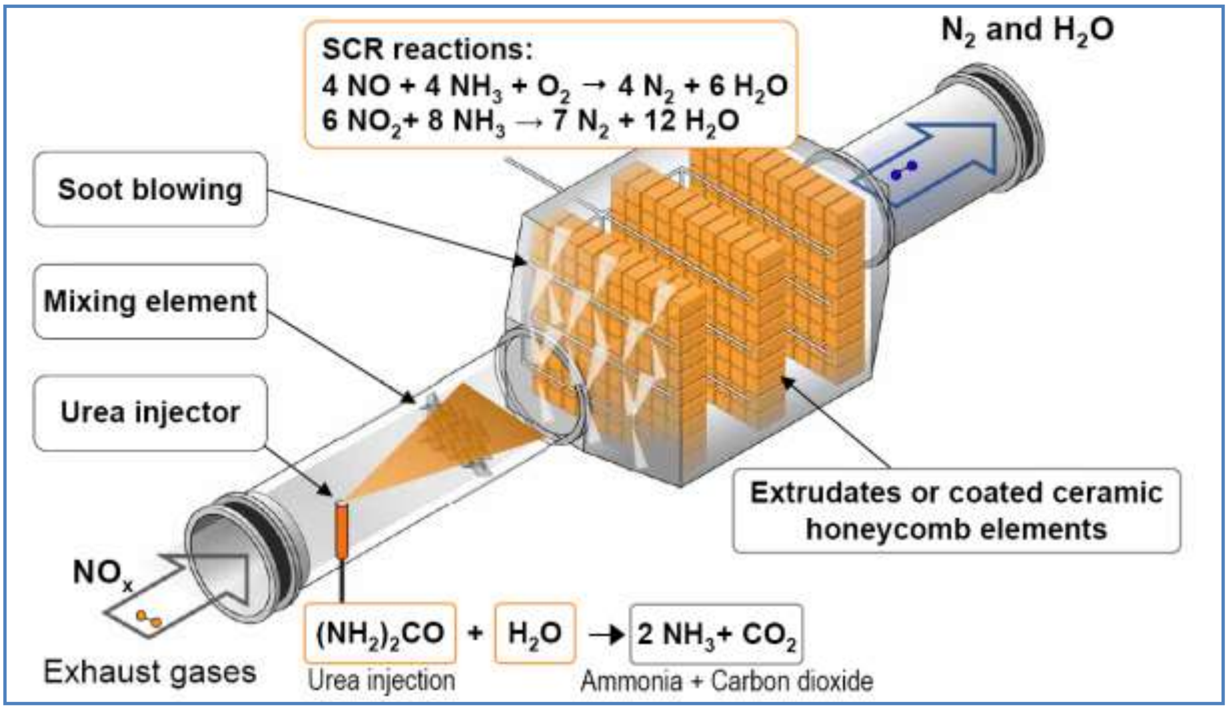


Figure 63: SCR catalyst with soot blowing device

For the optimum function of an SCR installed onboard it is recommended to have a particle filtration plant arranged upstream the SCR. This guarantees a long life time with a high reduction rate of NOx.

11. Potential Efficiency Improvement

Today we are seeing in the shipping industry the generation 1.0 of scrubber and SCR technologies. All scrubbing plants and SCRs installed onboard of various vessels are moving on a learning curve and the results will lead to further technical improvements in terms of efficiency, weight, size and the consumption of operational supplements.

11.1 Scrubbing Technology

Potential areas for improvements are not in the field of scrubbing efficiency. All systems described in this report are achieving satisfying results and thus meet the legal requirements. More important are improvements regarding operational parameters such as pressure loss, weight and space. Also the complexity of some of the systems is worth to be looked as the abatement systems should rather run by themselves as opposed to be supervised continuously during operation.

11.2 Wet Scrubber

Areas of improvement are:

- Pressure loss
- Size
- Weight
- Reheating system
- Monitoring system for wash water
- Protection against corrosion
- Energy consumption
- Wash water treatment plant

11.3 Dry Scrubber

Areas of improvement are:

- Size
- Weight
- Protection against corrosion
- Supply and disposal system for fresh and used granulate

11.4 SCR Technology

Areas of improvement are:

- Pressure loss
- Size
- Weight
- Reheating system
- Monitoring system for urea dosing
- Protection against corrosion
- Mechanical stability (vibration)
- Urea supply

12. Conclusions

The challenges for the shipping industry are quite huge. Not only the exhaust gases of marine diesel engines need to become cleaner but also ballast water treatment as well as the use of toxic-free paintings are the topics on the ship owners to-do-list.

Due to the technological improvements of other transport modes, the share of shipping in emissions to air has increased all the time. Quality of heavy fuel used in vessels gives a revealing example of environmental issues in maritime transport. In 1970s the vessels burned practically the same fuel as other big machines and vehicles everywhere. While environmental rules were getting tighter on land, the crude oil was purified and the cleaner part was used in land and the rest at sea. Today, the price of ship fuel is even lower than that of crude oil, it is practically considered as waste. In other words, shipping has been taking care of the problem waste of oil distilleries without thinking of its costs. Now it is time to pay these costs.

If actions for the improvement of environmentally friendly ways of shipping increase the costs for transportation then many people are willing to pay an extra fee for it. A bottle of wine shipped from Australia to Europe would cost only a few cents more in the supermarket.

The implementation of MARPOL Annex VI (and EU 2005/33) was the right decision and gradually lowering the sulphur content in marine fuels as well as the reduction of NOx emissions is the right strategy. However, regulations for the protection of the environment are only as good as their enforcement. Flag States and Port Authorities are now committed to build up the required infrastructure to control vessels regarding compliancy with the regulations.

Also a mind shift amongst ship owners is requested. Many ship owners claim that shipping is the most environmental mean of transport which is not correct. Shipping is the most energy-efficient mean of transport which is a huge difference. Another problem is that in many cases the ship owner does not pay the fuel bill but the charterer. However actions to improve the efficiency of the engine and by that reducing consumptions and emissions have to be paid and financed by the ship owner but the charterer is taking advantage of it.

A very typical situation is when the ship owner would invest into the retrofit of a scrubber system onboard which would enable the vessel to operate with HFO instead of MGO. The financial benefit of such a retrofit would go straight into the pocket of the charterer while the ship owner has to finance the investment without taking advantage of it. Here the shipping industry needs to develop agreements which could bring the ship owner and the charterer into a win-win-situation.

Abatement technologies for the shipping industry these days represent a totally new market segment. The political decisions have defined the framework and now all players in the market are applying the rules of demand and supply. Over the next 5 years it is likely that abatement technologies as well as technologies to improve the overall energy efficiency of a vessel will become a standard in the shipping industry.

In terms of exhaust emissions it is absolutely clear that simply adopting land-based technologies for the marine industry is not necessarily the way to success. The safety of the vessel and the crew is the over-ruling goal and must not be jeopardized. Any intervention to the propulsion system of a vessel contains a certain level of risks. Abatement technology not only has the purpose to clean up the engine's emissions. It has also the obligation to not interfere with the performance of the engine.

Today we are seeing in the shipping industry the generation 1.0 of scrubber and SCR technologies. All scrubbing plants and SCRs installed onboard of various vessels are moving on a learning curve and the results will lead to further technical improvements in terms of efficiency, weight, size and the consumption of operational supplements. And all these technologies will be one part of the solution not the single solution.

In both technological fields (scrubbing and SCR) we are seeing a decent amount of suppliers which is good for a healthy competition regarding technical and economical improvements.

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