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PREVENTION OF AIR POLLUTION FROM SHIPS

Washwater Discharge Criteria for Exhaust Gas-SOx Cleaning Systems

Submitted by the United States

SUMMARY

Executive summary:	This document provides two reports submitted to the Correspondence Group on Washwater Discharge Criteria for Exhaust Gas-SOx Cleaning Systems. The reports are attached as annexes to this document to facilitate further considerations
Action to be taken:	Paragraph 4
Related documents:	MEPC 56/4; MEPC 55/23, paragraph 4.46; MEPC 55/4/5; MEPC 55/4/7; MEPC.130(53) and MEPC 55/4

1 The Marine Environment Protection Committee agreed at its fifty-fifth session to establish a correspondence group to further consider the development of criteria for washwater discharge from exhaust gas-SOx cleaning systems following some initial discussion during the Working Group on the Prevention of Air Pollution. The correspondence group's report is submitted under document MEPC 56/4/1.

2 One report was produced by Norway (MARINTEK) on "Washwater Criteria for Seawater Exhaust Gas-SOx Scrubbers" dated October 2006. The report is summarized in paragraph 4 of MEPC 56/4/1 and is attached as annex 1.

3 The other report was produced by Finland (VTT Technical Research Centre) on "Environmental Effects of Caustic Soda and Seawater Scrubbers" dated 23 November 2006. The report is summarized in paragraph 5 of MEPC 56/4/1 and is attached as annex 2.

Action requested of the Committee

4 The Committee is invited to note the information in the two annexes and take action as appropriate.

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ANNEX 1

MARINTEK

MARINTEK REPORT

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TITLE

MARULS WP3: Washwater Criteria for seawater exhaust gas-SOx scrubbers

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Norwegian Shipowners' Association / Research Council of Norway

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ABSTRACT

A set of possible discharge water criteria have been developed based on data from trials using exhaust gas seawater scrubbers conducted in Norway the early nineties and up to date toxicity data and discharge modelling tools.

The proposed criteria have been submitted to IMO as MEPC 55/4/7.

This report provides background information regarding the development of this proposition.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Marine Machinery	Marint maskineri
GROUP 2	Environment	Miljø
SELECTED BY AUTHOR	SOx	SOx
	Scrubber	Scrubber

Preface

This report has been written in cooperation between:

MARINTEK – Energy systems & Environment
SINTEF – Water and Environment and
NIVA – Norwegian Institute for Water Research

Some supporting dispersion calculations has been undertaken by
CFD Norway A/S
SINTEF Materials and Chemistry

Furthermore, information has been exchanged in common interest with Wärtsilä Finland Oy, VTT Technical research centre of Finland and DNV.

The work has been sponsored jointly by Norwegian shipowners and the Research Council of Norway as Work Package 3 of the MARULS project.

Summary

Background

Regulation 14(4)(b) of MARPOL Annex VI requires ships to document that discharges from a possible exhaust gas-SOx cleaning systems (EGCS-SOx) have no adverse impact based upon criteria communicated by the authorities of the port State to the Organization.

IMO Guidelines for on-board exhaust gas-SOx cleaning systems (resolution MEPC.130(53)) contain some information on discharges from the EGCS-SOx. At MEPC 53, however, IMO is in the process of developing more specific recommendations and criteria relevant to EGCS-SOx washwater discharges.

Taking advantage of data from trials using exhaust gas seawater scrubbers conducted in Norway in the early nineties as well as up to date toxicity data and discharge modelling tools, a set of possible criteria have been developed and submitted as a proposition to IMO MEPC 55. This report provides background information regarding the development of this proposition.

Outline of discharge criteria development

The development of discharge criteria consists of three main steps:

.1 Identification of harmful compounds and effects.

.2 Identification of the maximum permissible concentration that can be sustained over time for each of the compounds identified, the Predicted No Effect Concentration (PNEC).

.3 Evaluation of the expected environmental concentration of each discharge compound, designated as Predicted Environmental Concentration (PEC).

A similar procedure is used to assess other possible effects of the discharge such as change in temperature, pH, Dissolved Oxygen (DO), Chemical Oxygen Demand (COD), etc.

The PNEC-concentration is derived from scientific toxicology studies, either by use of species sensitivity distribution curves or by applying safety factors to realistic worst case toxicity levels. These factors are very high when the amount of relevant studies is low and less conservative when the toxicity to several species is better known.

The PEC is usually derived from a study where discharge measurement data and predictions are combined with distribution models.

A risk to the marine environment is indicated if the PEC is higher than the PNEC. However, according to international practice set out by UN, discharges resulting in local concentrations that are higher than no-effects limits for long term (chronic) exposure can be acceptable in the immediate vicinity of the discharge point if the discharge is rapidly diluted.

The concentration of substances and variations in parameters in the discharge water depends on the specific washwater rate, which may vary by a factor of 300 between EGCS-SOx principles.

However, pollutant mass flow may be virtually the same. Hence concentration limits must be related to a nominal washwater rate.

Predicted No Effect Concentrations (PNECs) can be obtained from regulations (such as EU, US-EPA, UK) or in scientific literature when standards are not available.

Differences in sensitivity to contaminants and other environmental stressors between freshwater and marine organisms are small, particularly when compared to the safety factors commonly used to derive PNEC values. For practical risk assessment purposes one may regard freshwater, brackish water and marine species as equally sensitive. PNEC values could thus be suitable world-wide with few exceptions. The principal difference between locations would be the amount of discharge (i.e. traffic density) and how rapidly the water is exchanged.

Port States will have to consider both the extent of ship traffic, and natural dilution effects such as provided by wind, current and rivers when defining their local criteria. To avoid proliferation of criteria it is proposed that IMO develops a set of default criteria that represent typical situations (levels 1, 2 and 3). The port State would then have the opportunity to choose one of the criteria on the list which would significantly ease verification of compliance.

Proposed criteria

Waste water dispersion modelling shows that discharges are rapidly diluted when the ships are in motion. The most critical situation is when the ship is at quay. In this case, it is likely that an average plume dilution of 1:150 may be obtained within the near field (20 m) and within 6-7 minutes. Taking these dilution factors and the PNEC values for the actual scrubber components into account we have estimated the worst case discharge concentrations that may be allowed without the PEC/PNEC ratio exceeding 1 outside the near field.

In those cases where the scrubber discharge measured in trials was lower than the proposed criteria by a factor of ten, that particular substance was considered not to require a discharge criteria. The modelling further indicated that PNEC values can be obtained even with pH=0 and DO = O at outlet, indicating that no regulation would generally be needed for pH and COD.

As previously argued, to avoid proliferation of criteria it is advised that IMO develops a set of default criteria that represent typical situations (Levels 1, 2, 3, etc.). The port State would then have the opportunity to choose one of the predefined criteria on the list which would significantly ease verification of compliance and provide much needed design targets for EGCS-SOx manufacture. The resulting criteria proposition following this logic is shown in Table 1.

Table 1 Proposed discharge water limits (µg/litre)

Criteria level* "Safety Margin"	**1** 1	**2** 10	**3** 100
Nickel	-	30	3
Vanadium	-	-	150
Copper	-	40	4
Lead	-	-	12
THC	4500 (4.5 ppm)	450 (0.45 ppm)	45 (0.045 ppm)

* At nominal washwater rate of 44 kg/kWh (representative of trials and dispersion models used).

These proposals are made based on results from two specific trials. They should be seen in conjunction with experiences from other trials, studies as well as capabilities of water cleaning systems and means of verification. It is anticipated that some revision of the existing EGCS-SOx guideline, particularly chapter 7 (washwater monitoring) and chapter 17 (washwater), could be appropriate when using this approach. An additional cosmetic criterion demanding no visible discharge and absolute limit values irrespective of washwater rate could also be considered.

Selection of predefined discharge criteria by port States

In order to select predefined discharge criteria, the port State would have to identify the rate of water exchange and the anticipated discharge from scrubbers in the area in question. The concentration of contaminants in the area can then be calculated assuming different discharge levels and compared with PNECs as provided above or other as deemed necessary. The port State could then select the least stringent set of criteria which provide sufficient environmental protection.

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1 Introduction

Emissions to air from international shipping are regulated by IMO in MARPOL Annex VI which entered into force on May 19th 2005. Regulation 14 of MARPOL Annex VI limits sulphur emissions by placing a global limit on the sulphur content of marine fuels of 4.5% by mass. Regulation 14 further limits sulphur emissions in certain geographical areas, so called Sulphur Emission Control Areas (SECAs). In these areas, ships may only use fuels containing up to 1.5% sulphur or employ an exhaust gas SOx cleaning system (EGCS-SOx) that delivers an equivalent reduction in sulphur emissions. The SECA regulations will be effective for the Baltic Sea from May 2006 and for North Sea & English Channel from November 2007.

Discharges from exhaust gas SOx cleaning system are regulated in regulation 14(4)(b) which *inter alia* reads: ... *Waste streams from the use of such equipment shall not be discharged into enclosed ports, harbours and estuaries unless it can be thoroughly documented by the ship that such waste streams have no adverse impact on the ecosystems of such enclosed ports harbours and estuaries, based upon criteria communicated by the authorities of the port State to the Organization. The Organization shall circulate the criteria to all parties to the Convention ...*

No port State has, at the time of writing, communicated such criteria to the IMO.

Some guidance to the monitoring and handling of discharges are included as part pf the *Guidelines for on-board exhaust gas-SOx cleaning systems* adopted by IMO in resolution MEPC.130(53).

According to this guideline, the EGCS-SO_x unit's washwater systems should:

(a) eliminate, or reduce to a level at which they are not harmful, hydrocarbons, carbon residue, ash, vanadium, other heavy metals, and other substances contained within EGCS-SO_x unit's washwater that may have an adverse impact on ecosystems if discharged overboard,

(b) ensure that the approach adopted, to control washwater quality and residual waste is not achieved in a way that causes pollution in other areas or environmental media,

(c) also taking into account guidelines to be developed by the Organization.

As of today, the guidelines referred to in bullet (c) of the Guidelines for on-board exhaust gas-SOx cleaning systems have not been developed. At its last meeting, the appropriate committee, MEPC 54, failed to make progress in the development of these guidelines, principally due to lack of information. MEPC 54 thus decided to extend its call for information on this matter.

The lack of IMO guidance and port State criteria makes the specification of EGCS-SO_x unit's difficult. Such criteria are thus urgently needed.

The work contained in this report has been done in an effort to contribute to the development of discharge criteria. The result of this work will be communicated to the Norwegian Maritime Directorate who in turn will submit results to the IMO as deemed appropriate.

EU regulations are not of primary interest in this report which is written in the interest of the IMO process. It should, however, be mentioned that the European Commission has also implemented 1.5% sulphur SOx emission regulation for ships in SECA area through Directive 2005/33/EC. The European Union basically impose the same requirements as IMO within SECA and the additional requirement that:

1. the same 1.5% sulphur limit applies to fuels used by passenger vessels on regular services between EU ports from 19 May 2006;

2. fuel used by inland vessels and by seagoing ships at berth in EU ports is limited to 0.1% sulphur, from 1 January 2010.

Directive 2005/33/EC also opens for exhaust gas SOx cleaning as long as equivalent or higher reduction in sulphur emissions can be demonstrated with no adverse effect on the environment.

2 Exhaust Gas SOx Cleaning Systems (EGCS-SOx)

It is generally acknowledged that EGCS-SOx units, at least in the short term, will be based on the principle of seawater scrubbing with or without the use of a chemical additive. These units have the potential to remove a very high fraction of the SO_2 in the exhaust. The use of such equipment can thus permit much larger emission reductions than is achievable with low the use of sulphur residual fuels.

Exhaust gas scrubbing is a process where the exhaust gas is contacted with a liquid (most often seawater) for selective absorption of SO_2. Once the SO_2 is absorbed into the seawater, the SO_2 is converted by reaction with alkaline material in the liquid to SO_3 and finally SO_4. The conversion of the SO_2 helps the sulphur to stay in the water and allows more SO_2 to be absorbed. For this reason, the alkalinity of the water is important to the efficiency of the scrubber. The alkalinity in seawater is normally a function of salinity according to the relation:

$$\text{alkalinity (mmol/l)} = 0.0697^{*} \text{ salinity (psu)}$$ [1]

This relation may be modified and even reversed in areas of strong freshwater input to the sea where the alkalinity of the freshwater is high due to mineral composition in the watershed. Rivers running trough a calcite area will have increased alkalinity. In such situations the calculation above gives an underestimate of the alkalinity, and hence represents a worst case.

Since the alkalinity of seawater is comparatively low, large quantity of seawater is needed. Even more scrubbing water would be needed in brackish water regions such as the Baltic Sea. The alkalinity of seawater can in certain regions also vary significantly with time due to variations in winds, currents, melting of ice, etc.

Different scrubber designs have been developed to obtain maximum contact area between the seawater and exhaust gas. The exhaust gas may be significantly cooled in the scrubber. To prevent white smoke and ensure a buoyant exhaust, the exhaust may be reheated. One option is

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[1] PSU = Practical Salinity Unit, in practice the same as per mile.

heat exchange between the hot exhaust from the engine and the cold exhaust leaving the scrubber. A principal arrangement of a seawater scrubber is shown in Figure 1.

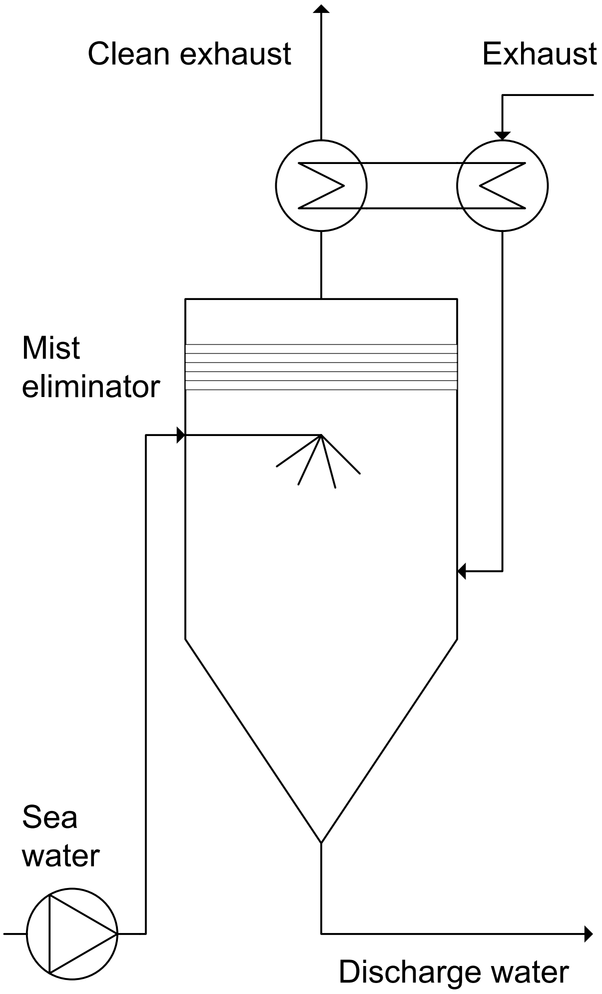


Figure 1 Principal arrangement of seawater scrubber unit

The amount of water needed to clean the exhaust will depend on a number of factors including system design, fuel sulphur content, SOx emission target, alkalinity of the water and use of chemicals. Some field testing experience indicates that pure seawater consumption needed for near-complete (~ 90%) SOx removal will be in the range of 40-100 kg/kWh. This water requirement can be:

- Approximately halved if the system is designed according to current minimum requirements (emission equivalent to 1.5% sulphur fuel)
- Significantly increased in fresh water and brackish water
- Very significantly reduced if alkaline chemicals are added to the seawater

Seawater scrubbing will also remove some of the particulate matter generated during combustion. Seawater scrubbing is also capable of removing some NO_2 from the exhaust. Since the fraction of NO_2 in NOx is usually about 5% (the remainder being NO which is not appreciably affected), the potential for NOx removal is limited. (The use of chemical additives could potentially alter this.)

The principal challenge with seawater scrubbing is not solely to reduce the SOx emissions, but to do so while:

- maintaining a buoyant exhaust;
- maintaining minimum consumption of space, weight and energy;
- maintaining minimum pressure drop in the exhaust;
- keeping discharge water emissions at a level where it is not harmful;
- preventing corrosion;
- preventing water droplets in exhaust.

Discharge of washwater is regulated in ports, harbours and estuaries. In case of scrubbers using chemical additives, temporary storage may be possible; however in case of scrubbers relying on seawater only, storing used washwater on-board, even temporarily, will be difficult due to the large quantities needed and because the washwater will be corrosive. Hence the washwater will generally have to be cleaned (as necessary) and discharged continuously.

As indicated in the introduction to this report, discharge criteria for EGCS-SOx washwater composition must be developed.

3 Principles for the development of EGCS-SO$_x$ discharge criteria

Man-made impact on the marine ecosystem is expressed at all levels of biological organisation, from sub-individual (biochemical and physiological effects), via individual and population levels to the ecosystem level. Covering all these levels of effects in a risk assessment context is impractical and will not necessarily result in a better protection of marine resources.

GESAMP (the Joint Group of Experts on the Scientific Aspects of Marine Pollution in the UN system) has given the following definition of marine pollution: “Pollution means the introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities including fishing, impairment of quality for use of seawater and reduction of amenities” (GESAMP 1991).

Since man made effects on individual organisms not necessary results in effects on a higher ecological level, the definition limits pollution to those perturbations which have an impact on populations and/or ecosystems. This limitation is very important when assessing significant spatial end temporal impacts from scrubber discharges.

In practical terms, this means that discharges resulting in local concentrations that are higher than no-effects limits for chronic exposure can be acceptable if the discharge is rapidly diluted. Part of the challenge when defining discharge criteria is deciding how rapid the dilution must be or – in other words – how large water volume can be permitted to be ‘affected’ without resulting in effects on any marine populations. Naturally, this may vary from one location to another. The following steps must generally be followed in order to develop such discharge criteria:

The first step in the process of the development of discharge criteria is the identification of harmful compounds that must be controlled.

The second step is identifying the maximum permissible concentration that can be sustained over time for each of the compounds identified. This level is often designated as PNEC (Predicted No Effect Concentration). The PNEC-concentration is derived from scientific toxicology studies, either by use of species sensitivity distribution curves or by applying safety factors to realistic worst case toxicity levels. These factors are very high when the amount of relevant studies is low and less conservative when the toxicity to several species is better known.

The third step is to evaluate the expected environmental concentration of each discharge compound, often designated as PEC (Predicted Environmental Concentration). A risk to the marine environment is indicated if the PEC is higher than the PNEC. According to the GESAMP principle the risk will be acceptable if PEC exceeds PNEC only in the immediate vicinity of the discharge point, which may result in effects on individuals but not on populations. However a PEC>PNEC value cannot be accepted for a larger area where the risk for population effects is present.

Port States will have to consider both the extent of ship traffic, and natural dilution effects such as provided by wind, current and rivers when defining their local criteria. To avoid proliferation of criteria it is advised that IMO develops a set of default criteria that represent typical situations (Levels 1, 2, 3, etc.). The port State would then have the opportunity to choose one of the criteria on the list which would significantly ease verification of compliance.

4 Identification of harmful compounds in EGCS-SO_x discharge water

The discharge water from the EGCS-SO_x unit contains material from three sources:

1. the exhaust gas exiting the engine (air, fuel, lubricant and combustion products);
2. the seawater used to clean the exhaust
3. the scrubber itself (possible reaction products and possible chemical additives)

4.1 Harmful compounds from the exhaust gas

The composition of the exhaust gas will vary with engine type, engine age, operating conditions, fuel and lubricating oil composition. Table 1 indicates concentration levels of the main constituents in the exhaust gas from 4 stroke diesel engines. The concentration can vary considerably for some of the constituents depending on engine load (fuel/air ratio) and fuel composition.

Table 2 Typical exhaust gas concentration levels in exhaust gas from 4 stroke diesel engines

Component	Concentration level (Vol.-%)
Nitrogen - N_2	75.6 (74.3-77)
Oxygen - O_2	12.5 (11.25-15.5)
Carbon dioxide - CO_2	6.2 (4.0-6.5)
Water vapour - H_2O	4.5 (4-8)
Argon - Ar	0.9
Nitrogen oxides - NO_x	0.15-0.20
Sulphur oxides - SO_x	0.01-0.15
Hydrocarbon compounds HC,	<0.03
CO,	<0.03
Particulate matter	0.5-1.5 g/kWh on heavy fuel

All substances in Table 2 can be captured or to some extent entrained in the EGCS-SO_x washwater. Of the elements on this list, however, it is mainly the particulate matter and hydrocarbons that is of interest as potentially harmful pollutants. Particulate matter is of concern primarily due to its content of potentially harmful contaminants (cf chapter 4.1.2).

4.1.1 Exhaust gas hydrocarbon compounds

The hydrocarbon compounds are principally derived from fuel that has not been burned or is only partly burned. Hydrocarbon compounds can also originate in lubricating oil. Hydrocarbon compounds are generally biodegradable. Certain hydrocarbon compounds are more harmful than others. In particular, the polyaromatic compounds PAH. Some of the hydrocarbon compounds, and particularly the larger molecules such as PAHs, will contribute to the formation of particles or associate strongly with soot particles. The issue of PAHs is discussed further in conjunction with particulate matter.

4.1.2 Exhaust gas Particulate Matter (PM)

Particulate matter is small, solid or liquid substances that can be collected on a filter in the exhaust stream. The formation of the particles is an accumulation process. The amount and size of the particles will depend upon where and how the particulate matter is collected. There are two fundamentally different standard procedures for the measurement of PM.

ISO 8178 –	where particles are collected after dilution in air which promotes particle growth by condensation
ISO 9096 –	where particles are collected on a hot filter in order to avoid condensed matter

The total amount of PM measured depends on the measurement method and fuel quality. An example is given in Table 3.

Table 3 Particulate mass PM in exhaust gas as a function of the fuel sulphur content

Fuel sulphur content	ISO 8178	ISO 9096
%	g/kWh	g/kWh
1.0	0.6	0.2
2.5	1.2	0.4

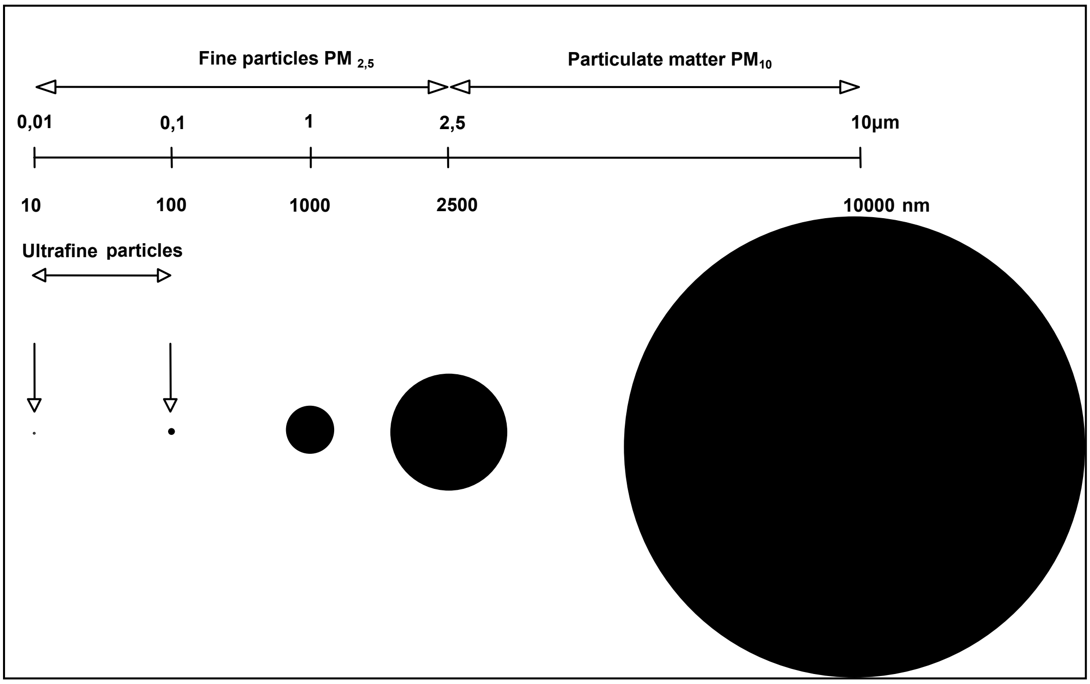
Particulate emissions are affected substantially by the ash and sulphur content of the fuel used. Particle size is variable, but of great importance because it affects dispersion and how harmful they are. Figure 2 illustrates classification and variation in particle size.

The composition of particles of different sizes is different. Generally, the smallest particulates are condensed water, sulphuric acid and hydrocarbons. Intermediate particles contain more carbonaceous compounds, metal oxides, and ash. Larger particles contain relatively less carbonaceous compounds and are dominated by metal oxides and ash.

The particulate matter contains a variable mixture of compounds, most importantly:

- Soot;
- Ashes;
- PAH and PAH-derivatives;
- Aldehydes, alkanes and alkenes;
- Unburned fuel or incombustible elements in the fuel;
- Metal salts like sulphates.

Figure 2 Particulate size and classification



Many of the PAHs and PAH-derivatives, especially nitro-PAHs, have been found to be potent mutagens and carcinogens. Analysis data of particles generated in a medium speed engine using residual fuel oil 380 cSt/50°C at 100% load is shown in Table 4. The analyses refer to dry particles.

Table 4 Analysis of marine diesel particulate matter

Metal oxides and sulphates	65%
Carbon (soot)	25%
Hydrocarbons (fuel and lube oils)	10%
including traces of	
PAH	17 ppm
Plychlorinated biphenyls (PCB)	17 ppm
Chlorophenols	40 ppm
Chlorobenzenes	44 ppm
Polychlorinated dibenzodioxins (PCDD)	3.9 ppb
Polychlorinated dibenzofurans (PCDF)	2.8 ppb

Table 5 gives an example of a measurement performed with the ISO 9096 method of a W6L20 medium speed engine operating on high ash HFO (2.6% S) and 100% load, in %-mass.

Table 5 Elemental composition of particles of different size (%)

		90 nm particles	**8 micron particles**
Silicon	Si	0.5	0.3
Sulphur	S	11.2	11.8
Nickel	Ni	1.9	1.1
Sodium	Na	3.5	0.8
Calcium	Ca	0.3	0.1
Oxygen	O	43.3	34.6
Carbon	C	10.6	41.8
Iron	Fe	0.4	-
Vanadium	V	28.2	9.6
TOTAL		**100.0**	**100.0**

Some fuel constituents are uncombustible. In general, these uncombustible compounds will be emitted from the engine as particulate matter. Therefore, some aspects of the particle composition will mirror the fuel composition.

4.2 Harmful compounds from the seawater used to clean the exhaust

Naturally, any harmful compounds entering the EGCS-SOx unit with the seawater used for scrubbing will be expected to come out as part of the washwater. This is, however, not an additional pollution, and the issue is not generally expected to be problematic, however background levels must be considered when determining discharge limits and monitoring.

4.3 Harmful compounds and effect from the EGCS-SOx

Harmful compounds can enter the washwater as result of chemical reactions in the EGCS-SOx unit. The absorption of SOx will also cause the seawater pH to drop and consume dissolved oxygen.

Chemicals may be added to improve the SOx removal or reduce the water consumption needed to achieve a given SOx reduction rate. This is particularly attractive when the alkalinity of the seawater is low. The most common additives in land-based plants are lime and sodium hydroxide.

Sodium hydroxide (NaOH) can be supplied either as granulate or as concentrated solutions (up to 40%). Handling and dosing is more convenient in the liquid form. The use of NaOH does not result in increased precipitation since sodium sulphate and sulphite are very soluble.

Neutralization with lime or $Ca(OH)_2$ results in the formation of large amounts of gypsum ($CaSO_4$). Although the product is considered harmless to the environment it could create a visible plume after the ship which may be unwanted. Also, the product is insoluble in water and tends to settle in tanks and pipes, particularly where the flow is slow. For practical reasons lime is generally considered unsuitable for use onboard a marine vessel.

Small amounts of wear metals from the scrubber may also show up on analysis of scrubber water.

4.4 Results of discharge water analysis from ECGS-SOx trials

MARINTEK has coordinated two ship trials of ECGS-SOx units. Both units were based on scrubbing exhaust with pure seawater, and neither used any after-treatment of the discharge water. Some key information from these two trials is shown in Table 6.

Table 6 Key information from ECGS-SOx trials coordinated by MARINTEK

Ship	**Kronprins Harald**	**Fjordshell**
Propulsion Engines	Wärtsilä Sulzer 12ZAV40 * 2, 6ZAL40 * 2 (4 stroke)	Sulzer 6RND76, 10400 kW (2 stroke)
Ship Owner	Colour Line	Norske Shell Shipping
Test Year	1991	1993
Description	Part flow prototype using spray, high swirl (cyclone) and packaged bed with counter current water flow.	1:10 scale prototype with inlet venturi/ spray and mist catchers based on inert gas generator. Combined with SCR
Water consumption	64 m^3/h at 8 bar	~ 50 kg/kWh at maximum load (constant water rate)
Measured SO_2 reduction	57% in port (from 70 to 30 ppm) 73% in transit (from 454-121 ppm)	90% over a wide range

The scrubbers and analysis have been made at different operating conditions:

Transit: Loaded ship at service speed
Port operation: Approaching port at reduced speed (4 knots)
Quay side manoeuvring: (0 knots), same power as port operation

Table 7 Discharge water analysis data

Washing water characteristic	**Unit**	**Intake/Outlet**	**Fjordshell**		**M/S Kronprins Harald**	
			Transit	Port operation	Transit	Port operation
Salinity	p.p.t		19.1	19.0	17.4	14.5
Temperature	^{o}C	Intake	12.6	9.8	n.a.	n.a.
		Outlet	23	17.2	n.a.	n.a.
SO_4	g/l	Intake	2.71	2.76	1.4	1.18
		Outlet	2.91	2.82	1.83	1.46
SO_2	mg/l	Intake	n.a	n.a	<0.5	<0.5
		Outlet	n.a	n.a	<0.5	57
pH		Intake	8.01	7.96	8.11	7.95
		Outlet	2.95	3.76	3	2.7
TOC	mg/l	Intake	2.1	n.a.	n.a.	n.a.
		Outlet	2.7	1.5	n.a.	n.a.
COD	mg/l	Intake	n.a	n.a.	n.a.	n.a.
		Outlet	33.3	10	n.a.	n.a.
Particles and soot	mg/l	Intake	0.42	4.3	0.6	2.3
		Outlet	0.68	0.88	14.7	14.7
Hydrocarbons	mg/l	Intake	0.031	0.053	<0.1	<0.1
		Outlet	0.081	0.045	1.0	1.7
AOX	µg/l	Intake	62.5	43.9	17	38
		Outlet	25.3	33.2	700	51
PAH	µg/	Intake	<0.1	<0.1	n.a.	n.a.
		Outlet	<0.1	<0.1	n.a.	n.a.
PCDD	pg/l	Intake	59.8	n.a.	n.a.	n.a.
		Outlet	13.7	n.a.	n.a.	n.a.
PCDF	pg/l	Intake	50.3	n.a.	n.a.	n.a.
		Outlet	291	n.a.	n.a.	n.a.

Table 8 Measurement principles used in trials – discharge water

Parameter	Measurement principle
Water sample particulate material weight	Norwegian Standard NS 4733
Salinity	Titration by silver
pH	Electrodes
SOx	Gravimetry($BaSO_4$)
THC	Gas Chromatography
PAH	Gas Chromatography
AOX	SCAN-W9-89
Cu, Pb, Cd, Ni, V	Atomic absorption, NS 47771
As, Hg, Zn	Atomic absorption – hydride method
Cl	Titration by silver
Cr^{6+}	Photometric (diphenylcarbazid)
PCDD (polychlorinated dibenzo-p-dioxines)	Gas chromatography, Mass spectroscopy, conforming to EN-450001
PCDF (polychlorinated dibenzofurans)	Gas chromatography, Mass spectroscopy, conforming to EN-450001
Temperature	Chromel-Alumel thermocouple
Flow	Electromagnetic flowmeter (Fisher & Porter ND100)

Table 9 Measurement principles used in trials – other parameters

Parameter	Measurement principle
Gas flow	Pitot tube conforming to ISO 3966
CO	NDIR, Rosemount Binos 100, calibrated at 804 ppm
CO_2	NDIR, Rosemount Binos 100, 0-20%, calibrated at 4.13%
O_2	Paramagnetism, Signal 8000, 0-25%, calibrated in air (20.95%)
NO_x	CLA, Signal 4000, Calibrated at 855 ppm
HC	FID, IPM Ratfish calibrated at 84 ppm
SO_2 *	Absorption (H_2O_2), distillation and titration
Particulate material (exhaust)	Collected in dilution tunnel (ISO 8178-1), Weighted in lab using Mettler Microweight AE163
NH_3 *	Absorption (5% H_2SO_4), distillation and titration
N_2O *	Absorption (3M NaOH), drying ($Mg(ClO_4)$)
Noise	Hand portable instrument

* Analysed in laboratory

4.4.1 Acidity

Sulphur dioxide and NO_x are known as the main constituents of acid rain. In the scrubber a very small part of NO_x (less than 5%) will be absorbed, unless specific absorbents (e.g. ammonia) is added to the water. Carbon dioxide does not contribute to the acidity. The acidity of the washwater is therefore mainly due to the sulphur compounds and especially sulphurous and sulphuric acids. Environmental aspects of low pH are discussed in chapter 5.5.

Example: Assuming a fuel with 4 % sulphur (m/m) and a specific washwater consumption of 80 kg/kWh and 100% absorption efficiency a sulphur concentration of 100 mg/l ($3.125 \cdot 10^{-3}$ mol/l) can be expected. If seawater with salinity 35 PSU is used, the pH of the water before dilution can be calculated to about 3.25.

4.4.2 Oxygen demand

It is expected that the oxidation of sulphite (HSO_3^-) to sulphate (SO_4^{2-}) ion is the main contributor to the Chemical Oxygen Demand (COD) of the washing water. However, there may also be other components, e.g. NO_x, uncombusted fuel, VOC or others that contribute to the COD.

Example: Assuming the same condition as in the previous example (4% S and 80 kg water/kWh) and provided that 100% of the sulphur is on the bisulphite form, it can be calculated that the COD resulting from sulphur alone will be 50 mg /l before dilution.

In the Fjordshell experiments the COD was found to be 33 mg/l under transit operation and 10 mg/l under port operation. In the M/S Kronprins Harald experiments COD was not analysed, but under transit operation no SO_2 was detected and under port operation only a small part of the absorbed sulphur was detected as SO_2. The concentration of SO_2 was found to be 57 mg/l, representing only 23% of the total absorbed sulphur. This is equivalent to a COD of 14 mg/l.

The results so far indicate that a substantial part of the SO_2 is oxidized to sulphate during the combustion and/or scrubbing process.

4.4.3 Particulate matter in untreated discharge water

The amount and composition of particles generated by marine diesel engines are influenced by the combustion process and the type of fuel used. Some of the particulate matter will be trapped in the scrubber water, resulting in particulate pollution of the discharge. Particle concentration in the washwater from two different scrubbers were found to vary from less than 1 to about 15 mg/l (Table 7).

Micropollutants are to a large extent associated with particles or suspended in the washwater. The composition of particles may be divided in the three main groups; 1) metal oxides and sulphates, 2) carbon (soot), and 3) other organic compounds.

4.4.4 Metals in untreated discharge water

Table 10 gives examples of concentrations of specific heavy metals found in washwater from scrubbers.

Table 10 Examples of heavy metal concentrations observed in scrubber discharge water

Substance	Unit	Fjordshell	
		Transit load	Port load
Vanadium (V)	mg/l	0.035	0.023
Nickel (Ni)	μg/l	32.8	10.4
Zinc (Zn)	μg/l	6	15
Chromium (Cr)	μg/l	<1	<1
Lead (Pb)	μg/l	5	0.6
Copper (Cu)	μg/l	41.6	15.3
Mercury (Hg)	μg/l	<0.1	<0.1
Arsene (As)	μg/l	<0.1	<0.1
Cadmium (Cd)	μg/l	0.05	0.08
Specific water consumption	kg/kWh	~ 50	~ 150

Generally an increase in the content of heavy metals across the scrubber is observed.

4.4.5 Hydrocarbons

As shown in Table 7, the concentration of hydrocarbons in the washwater varies from 0.05 to 1.7 mg/l.

4.5 General remark – concentrations vs flux

The concentration of pollutants in the discharge water will naturally be reduced when the amount of washwater is increased, and the pH reduction will be smaller. In this case, the water can be considered partly diluted before discharge. However, the mass flow of many pollutants may be virtually the same.

Especially for non-degradable constituents the concentration at the discharge point is less relevant than the long term concentration in a larger area. For this purpose, it is the flux or mass flow of pollutants that is important, not the concentration.

5 Toxicity of scrubber discharges and safe environmental levels

5.1 Risk assessment of discharge components – the PEC/PNEC approach

In order to perform a risk assessment of scrubber water discharges to the sea it is necessary both to evaluate the expected environmental concentration of each discharge compound, the PEC (Predicted Environmental concentration) and the toxic properties of the same compound the PNEC (Predicted No Effect Concentration). If the PEC/PNEC ratio is >1 then a risk to the marine environment is indicated. Usually, as a first approach both PEC and PNEC is estimated conservatively, meaning that realistic worst case assumptions are included in both PEC and PNEC derivation. Therefore if a PEC/PNEC<1 the risk to marine life should be negligible. If a PEC/PNEC>1 is arrived at during the first approach one should investigate whether it is possible to refine the PEC and PNEC estimates and make them more realistic for the actual situation. In this case refinement can be achieved by performing measurements either of actual releases in the case of PEC or performing chronic toxicity studies on relevant aquatic organisms in the case of PNEC. If the PEC/PNEC ratio is still >1 then risk reduction measurements have to be implemented leading to reduction in releases. Such a reduction can either be achieved by treating the effluent or if this is not effective, prohibiting the processes that give rise to the emissions.

5.2 PNEC derivation for relevant metals

The following metals have been found relevant for risk assessment concerning release of Scrubber effluent; Nickel (Ni), Copper (Cu), Zinc (Zn), Quicksilver (Hg), Lead (Pb), Arsen (As), Cadmium (Cd), Chromium (Cr) and Vanadium (Va). Most of these metals have other release sources and have therefore been evaluated with regard to aquatic toxicity both nationally and internationally. The United Kingdom and the United States have developed quality standards for several of these metal compounds and within the EU Directive for existing chemicals (Commission regulation No.1488/94), PNEC values have also been derived. As EU PNEC values may have limited international acceptance, national quality standards may have to be employed when these are lower than the EU PNEC values in order to ensure international acceptance of the risk assessment.

Table 11 contains a summary of available PNEC values for metals which has undergone evaluation within EU existing chemicals regulation. Notice that for some metals both a marine and freshwater PNEC has been derived. Lack of a specific marine PNEC is mainly due to that one has not found scientific basis that indicate a significant difference in the toxicity between organisms in these two compartments. Therefore use of a freshwater PNEC should adequately protect also marine organisms.

Table 11 Metals with PNECs suggested by EU risk assessment program for existing chemicals (regulation no 1488/94)

Metal	PNEC concept	HC5	AF	PNEC(µg/l)
Cd (fresh)	SSD total	0.38	2	0.19
Cu (fresh)	SSD total	8.2	1	8.2
Ni (fresh)	SSD total	6.43	3	2.1
Pb (fresh)	SSD total	14.5	1	14.5
Pb (marine)	SSD total	8.3	1	8.3
Zn (fresh)	SSD added	15.6	2	7.8
Zn (marine)	SSD added	6.1	2	3.5

For those metals not having been assessed in the EU risk assessment program for existing chemicals the data from Crommentuijen *et al* (1997) may be used. The Maximum Permissible Concentrations (MPC) derived by Crommentuijen *et al* (1997) are assessed according to the same methods as in the EU risk assessment program for existing chemicals. The MPC is similarly derived as HC5 in Table 1, but with addition of a mean background level in the environment. In order that these values should be equal to PNEC it is necessary to divide by an assessment factor (AF). It seems that an AF=2 most closely match current practice in EU as indicated in Table 1. Except for As, Cr and V where only freshwater MPCs are available, these estimates include marine tests.

Table 12 shows MPCs for some metals which have not been assessed in the EU risk assessment program for existing chemicals. The data is from Crommentuijen *et al* (1997). The PNEC is derived using an AF=2.

Table 12 MPCs for some metals not assessed in EU risk assessment program for existing chemicals

Metal	**PNEC concept**	**MPC (µg/l)**	**PNEC (µg/l)**
As (fresh)	SSD total	25	12.5
Cr (fresh)	SSD total	8.7	4.3
Hg (fresh)	SSD total	0.24	0.12
Hg (marine)	SSD total	0.23	0.11
V (fresh)	Lowest NOEC AF=1000	4.3	4.3

5.3 Compliance with other water regulation

In order that the PNECs used in the risk assessment are internationally accepted they should also comply with national water quality standards. Both UK, EU (The EC Dangerous Substances Directive (76/464/EEC) and USA EPA have developed national standards for many compounds. These are shown in Table 13 for the relevant metals. The US EPA Water Quality Standards (WQS) are based on a scientific assessment of available ecotoxicological information, and deviate in some cases significantly from the European PNEC values. For Hg, US EPA has taken into account also risk to humans via biomagnification in the food chain. The Environmental Quality Standards (EQS) of EU are established through a similar procedure as US EPA. There is good agreement in levels between these two standards, except again with respect to Hg were EU has a 10x higher value than US EPA.

Table 13 Relevant US EPA and UK Water Quality Standards

compound	**US EPA WQS µg/l freshwater**	**US EPA WQS µg/l seawater**	**EQS (UK) µg/l seawater**
Cd	0.66	8.8	2.5
Ni	56	7.1	30
Pb	1.3	5.6	25
Zn	180	58	40
As	190	36	25
Cr	11	50	15
Cu	6.5	2.9 (1 hr max)	5
Hg	0.012	0.024	0.3
V			100

The derived metal PNECs are all below the shown aquatic WQSs, the only exception being the very low US WQS value for Hg. One should therefore proceed with the risk assessment using the PNECs presented here. In addition Hg should be assessed also using the US EPA derived WQS value of 0.024 µg/l for Hg in order to be able to conclude that also the human endpoint associated with the WQS value is assessed.

5.4 PNEC derivation of organic compounds

The organic compounds that might be of concern as identified in Chapter 0 are hydrocarbons (THC), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and dioxins (PCDD/PCDF). Except to some extent the THC, these compounds together with the metals are associated with the total particulate matter (PM) being trapped in the scrubber water (cf Chapter 4.1.2).

OSPAR (1996) developed Ecotoxicological Assessment Criteria (EAC) for a large range of chemicals to facilitate evaluation of monitoring data on toxic substances in the marine environment. The EAC values were derived essentially in the same way as the PNEC values given above (based on available toxicity test data and use of application factors) and should therefore in principle be applied as PNEC values. This is proposed in the present context. The OSPAR EAC values for the relevant compounds are given in Table 14. Later on OSPAR (2004) provided EAC values for groups of PAH compounds according to molecular size (Table 15). PNEC values for THC, total PAH or sumPAH$_{16}$ and for dioxins are not available from this source.

Most of these organic substances will be adsorbed to particles in the discharge and due to their strong particle association (especially to soot particles) they will to a large extent be particle bound also after discharge. An impact assessment should thus focus on their behaviour as part of the PM, e.g. they might settle to the sediment with other PM over time. The EAC-sediment might therefore be the most relevant assessment criteria, but modelling of PM settling behaviour will be highly unreliable.

Table 14 Ecotoxicological Assessment Criteria (EAC) for PCBs and PAHs as proposed by OSPAR (1996)

Substance	EAC-water (µg/l)	EAC-sediment (mg/kg dw)
PAHs		
Naphtalene	5 – 50 f	0.05 – 0.5 f
Phenanthrene	0.5 – 5 p	0,12 – 1 f
Anthracene	0.001 – 0.01 p	0.05 – 0.5 f
Fluoranthene	0.01 – 0.1 p	0.5 – 5 p
Pyrene	0.05 – 0.5 p	0.05 – 0.5 p
Benzo(a)anthracene	n.d.	0.1 – 1 p
Chrysene	n.d.	0.1 – 1 p
Benzo(a)pyrene	0.01 – 0.1 p	0.1 – 1 p
sumPCB$_7$	n.r.	0.001 – 0.01 p

f: firm p: provisional n.d.: no/insufficient data n.r.: not relevant vs OSPAR monitoring

Table 15 Ecotoxicological Assessment Criteria (EAC) for PAH groups as proposed by OSPAR (2004)

PAH group	**EAC-water (µg/l)**	**EAC-sediment (mg/kg ww)**
2 rings: naphtalene	2.4 p	0.038 p*
3 rings: phenanthrene & anthracene	0.17 p	0.031 p*
4 rings: fluoranthene, pyrene, benzo(a)-anthracene, chrysene	0.69 p	0.141 p*
5 rings: benzo(k)fluoranthene, benzo(a)pyrene	0.03 p	0.021 p*
6 rings: benzo(ghi)perylene, indeno(123-cd)-pyrene	0.016 p	0.0037 p*

p: provisional * sediment normalised to 1% organic carbon

Agreed PNEC values for THC have not been found in the available literature. A value of 40, 4 µg/l has been proposed by Scholten *et al* 1993 for the aliphatic fraction of the oil (the aromatic fraction should be covered by the PAH criteria) and is adopted by the Norwegian Oil Operators Association (OLF) for risk assessment of offshore produced water (Johnsen *et al* 2000). The large wealth of toxicity data on oil hydrocarbons is difficult to condense due to variability in experimental conditions, analytical procedures and oil composition, but there appears to be consensus that chronic environmental impact of oil is observed when concentration of THC exceeds 50 µg/l, which is close to the aliphatic PNEC given above. We therefore propose that the PNEC for THC is set at 40 µg/l.

5.5 PNEC derivation of other discharge compounds

The other discharge components of concern would be pH, total particulate matter (PM), total organic carbon (TOC) and potential chemical oxygen demand (COD). The PM and TOC are both typical features of the seawater and vary considerably in space and time. PM originates from a range of natural (e.g. river runoff, resuspension of bottom sediments, phytoplankton growth intensity) and manmade sources (e.g. industrial and sewage outfalls, land runoff, mining, dredging). PM levels may be extremely patchy in nearshore waters. We consider PNEC values for PM and TOC as of minor importance in the environmental risk assessment.

Review of the literature on pH tolerance indicates that there is little evidence of harm to marine organisms from a decrease of 0.5 –1 pH units from ambient (Knutzen 1981). It is also suggested that marine organisms are more sensitive to a rise in pH than a decrease (Wolff *et al* 1988). Table 13 shows some national EQS (Environmental Quality Standards) values for pH. The strictest is given by the US EPA allowing not more than 0.2 pH unit deviation from what is the normal pH range of the ambient water. This implies a variable PNEC depending on the natural pH-levels which normally range from 7.0 to 8.5 (partially correlated with primary production). Otherwise we would propose a PNEC for pH of 7.0 which according to the UK Water Research Centre should safeguard both fish and shellfish at chronic exposure.

Table 16 Examples of national environmental quality standards (EQS) for pH in marine waters (From Wolfe *et al* 1988)

EQS given by	value
US EPA	6.5 – 8.5 1)
Australia	6.5 – 8.5
China	7.5 – 8.3
Japan	7.8 – 8.3
UK Water Research Centre, protection of shellfish	7.0 – 8.5
UK Water Research Centre, protection of fish	6.0 – 8.5

1) but not more than 0.2 units outside normally occurring range

Although many countries have discharge limits for COD (typically 150-350 mg/l) there are no environmental standards. This is because COD will manifest itself through oxidation and hence by reducing the dissolved oxygen correspondingly. This process takes time which implies that there will be a gradual oxygen consumption taking place concurrent with dispersion and dilution. An assessment will therefore have to evaluate to what extent the COD will contribute to the risk of reduced dissolved oxygen in the receiving waters. A worst (but not entirely realistic) case is that the COD is oxidized immediately.

There is a wealth of literature showing that tolerance to reduced dissolved oxygen in seawater varies considerably dependent on organism, life stage and environmental conditions. A concentration that should safeguard most marine temperate-coldwater organisms are proposed to be 5 mgO_2/l (Bakke *et al*. 2002). Fully saturated cold-temperate seawater contains about 9-10 mgO_2/l.

6 Prediction of environmental concentration

The Predicted Environmental Concentration (PEC) resulting from the operation of scrubbers depends on the dilution of the discharge water. Such dilution is difficult to measure in field; however it can be readily be modelled and numeric dilution models are commonly used to obtain a PEC.

6.1 Modelling of discharge dilution from a single ship

The dilution of the discharge from a single ship has been numerically modelled by SINTEF Material and Chemistry (2006, 1994) and by CFD Norway as (2006). Reports on these studies are included as appendices 1 and 2 to this report. The overall dispersion has been modelled for different scenarios regarding ship size, washwater discharge point and speed, however the results are in accordance and point towards the same general conclusion.

The dilution of the waste water plume after discharge during transit and port operations may be described as a combination of 3 main processes:

- Dilution of the waste water in the exit jet emerging from the outlet;
- Turbulent mixing in the boundary layer along the hull;
- Dispersion in the propeller and the turbulent wake left behind the vessel.

6.1.1 Dilution of discharges from a single ship in open sea

SINTEF (2006) found that the dispersion in the wake behind the vessel was the dominant dilution process. Under the transit operation conditions of a discharge of 440 m^3/hour waste water at 8 m depth 20 m ahead of the stern from a 163 m length vessel at constant speed of 14.5 knots, the process water was diluted by a factor of 1:30 before the effluent passed the stern of the ship and by a factor 1:2000 at a distance 50 m behind the stern. (Appendix 2)

By use of a different numerical model, CFD Norway investigated the dilution of a discharge behind a large container ship. (Appendix 1) Ship particulars are given in Table 17. Discharge point was at the stern just in front of the propellers.

Table 17 Ship particulars

Ship length	L=230 m
Ship speed	24 knots
Propeller (single screw) diameter	7.9 m
Thrust	2600 kN
Shaft power	32 MW
Washwater discharge rate	75 ton/MW (670 kg/s)

Figure 3 shows the dilution as modelled. Some maximum concentrations behind the ship in are given in Table 18.

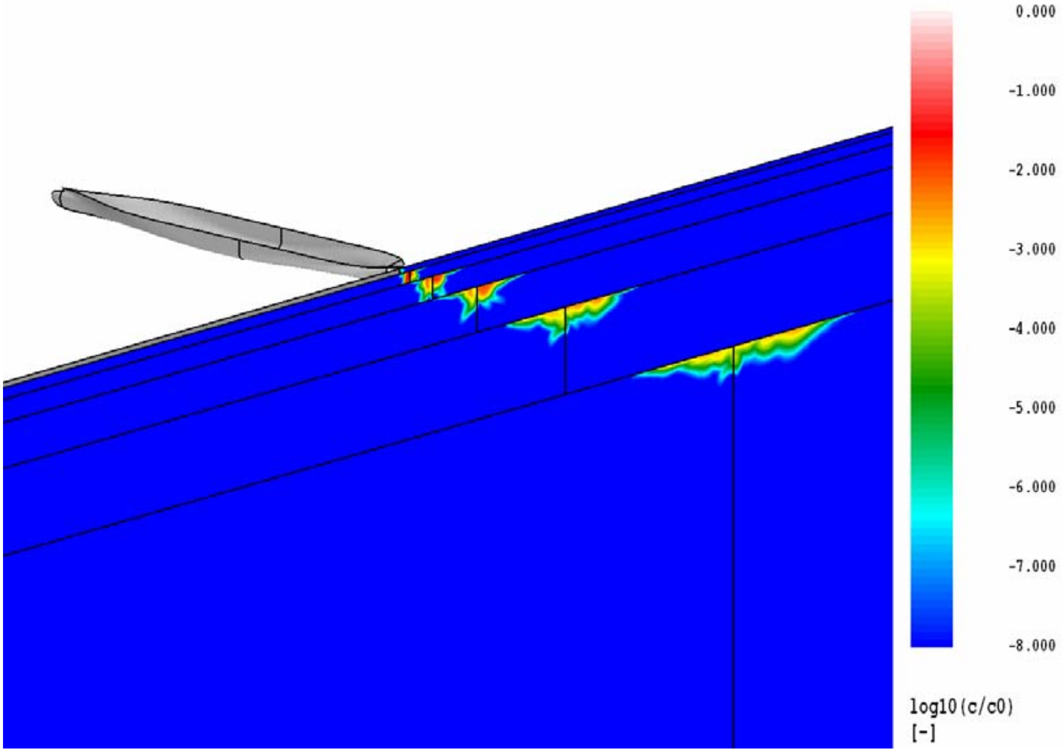


Figure 3 Graphical illustration of dilution of discharge

Table 18 Dilution of original discharge

Distance behind ship		**Maximum concentration**	
x/L	**x [m]**	**log$_{10}$ (c/c$_{0)}$) max**	**c/c$_0$ max**
0.004	0.92	-0.37	0.43
0.035	8.05	-1.28	0.052
0.1	23	-1.59	0.026
0.25	57.5	-1.85	0.014
0.5	115	-2.05	0.009
1	230	-2.15	0.007

C = Concentration, C_0 = concentration at discharge point.

This model estimated dilution by a factor of 1:70 at 57 m behind the stern. If one assumes an additional 1:30 times dilution for a side outlet as used by SINTEF the total dilution at 57 m behind the stern will be 1:2150, i.e. essentially the same as for the SINTEF modelling.

6.1.2 Dilution of discharges from a single ship at port operation

This scenario has only been modelled by SINTEF (2006) for the same vessel as above, but with a speed of 4 knots and a discharge of 130 m^3/h. Under such conditions the dilution factor at 50 m behind the stern was 1:1750, i.e. almost as large as during transit operation.

6.1.3 Dilution of discharges from a single ship at quay side manoeuvring

During quay side manoeuvring the following processes regulate dispersion:

- Dilution of the waste water in the exit jet emerging from the outlet;
- Turbulent mixing during vertical transit of the plume to neutral buoyancy;
- Ambient turbulence such as caused by currents, winds and ship movement.

Dilution at quay side will be strongly influenced by local conditions. One scenario has been modelled by SINTEF (1994) using the same discharge arrangement as for the port operation, speed 0 knots, temperature of the waste water 7.5°C and ambient current speed of 5 cm/s. A dilution factor of 1:100 in the centre of the plume was reached at less than 20 m distance downstream from the outlet, corresponding to an average dilution factor of approximately 1:150.

6.1.4 Summary: Dilution of discharges from a single ship

In summary, the discharges from a single ship are rapidly diluted when the ship is moving. A small area behind the ship will be affected, however. The dilution at quay side is strongly influenced by local conditions, but should be expected to be much slower than when the ship is in moving operation.

6.2 Accumulation of discharges – local and regional effects

The combined effect of the discharges from several ships must be considered in relation to the prevailing local conditions. The most important parameter is the exchange rate of the receiving surface water with neighbouring areas.

6.2.1 The Oslo Fjord Case study – regional effects

In this project we have made an evaluation of the risk that the total ship traffic in the land-locked Inner Oslo Fjord including Oslo harbour would gradually reduce the buffering capacity and other aspects of water quality of the local water masses if all ships were equipped with seawater scrubbers.

The exchange of water in the Inner Oslo Fjord is achieved by an outflow of brackish surface water compensated by an inflow of saline water beneath the surface layer. This exchange is driven by river runoff and winds, and is strongest during periods with northerly wind. The annual mean water exchange of the surface layer (i.e. down to a depth of 10 m) is estimated to 900 m^3/s.

Traffic data for Inner Oslo Fjord are based on data from Oslo and Drammen harbours and is shown in
Table 19.

Table 19 Marine vessels visiting Inner Oslo Fjord 2004

Harbour and ship type	**Number of ships**	**Total dead weight (1,000 tonnes)**
Oslo international	3,003	60,775
Oslo domestic cargo	98	378
Oslo domestic tankers	38	95
Drammen international	938	5,436
Total	4,077	66,684

Local ferries, fishing boats and other vessels smaller than ca 2500 tonnes are assumed to use distillate fuel and hence have no incentive to clean their exhaust.

Average tonnage of visiting ships included is 16,356 tonnes. It is assumed that these ships will have an average main engine power of 5200 kW.

We consider the two different cases 1) transit operation and 2) port operation. Under port operation an engine operation of 30% is expected for a total operation time of 1 hour. Under transit operation an average speed of 14 knots and an engine load of 90% is assumed. The Oslo Fjord is about 80 km long giving a total transit time of 6 hours.

For the calculation of the sulphur emission an average consumption of 0.2 kg fuel per kWh is used. The calculation is based on an average sulphur content of 2.7% in the fuel. One hundred % of the sulphur is removed in the scrubber and discharged to the sea as sulphurous acid.

Estimated sulphur discharge:

Transit operation	$4077 \cdot 5200 \cdot 6 \cdot 0.9 \cdot 0.2 \cdot 0.027/1000 = 618$ t/year
Port operation	$4077 \cdot 5200 \cdot 1 \cdot 0.3 \cdot 0.2 \cdot 0.027/1000 = 34$ t/year
Total discharge	652 t/year =74 kg/h

It is seen from this calculation that the port operation discharge will contribute to about 5.5% of the total sulphur discharge. In addition comes discharge at berth which is not included here.

Neutralization proceeds according to the equation:

$$H_2SO_3 + 2\,HCO_3^- = SO_3^{2-} + 2\,H_2CO_3$$

Each mole of sulphur needs 2 moles of bicarbonate to be neutralized. Provided that the incoming water has a salinity of 20% the alkalinity can be assessed to 1.394 mmol/l. The rate of water exchange necessary to provide enough alkalinity for neutralization of the discharge is:

$$Q = 74/32 \cdot 2 \cdot 1000/1.394 = 3.318\ \text{m}^3/\text{h} = 0.9\ \text{m}^3/\text{s}$$

This is about 0.1 % of the actual exchange, which suggests that the risk of gradual reduction in buffering capacity is negligible.

Based on the same water exchange regime as above for the Inner Oslo Fjord, the modelling of discharge dilution at port operation (chapter 6.1.2), and a traffic load of 6,000 visits/year, SINTEF (1994) calculated the risk of the waste water changing the water quality in the local surface waters. The total waste water discharge from these vessels was estimated to roughly 4000 m^3/day or 167 m^3/hour. This amounts to 0.2% of the annual mean freshwater input to the Inner Oslo Fjord of about 90,000 m^3/hour, and 0.003% of the total mean exchange of surface water between the fjord and the sea outside (6.4×10^6 m^3/hour). These fluxes suggest that the overall equilibrium dilution of the total waste water volume in the surface water of the Inner Oslo Fjord is in the range of 1:38000. This is way above the dilution necessary to reduce the PEC/PNEC ratio to less than 1 for all discharge components of concern, and shows clearly that the risk of gradual deterioration of the water quality of the Inner Oslo Fjord if all vessels were equipped with seawater scrubbers is negligible.

The methods used in the assessments above ought to be of general value. It must, however, be pointed out that such assessments depend entirely on site-specific data on water exchange rates, traffic densities (i.e. discharge water volumes and fluxes) and specific knowledge of the acidity and contaminant content of the actual waste water effluents.

7 Current discharge criteria

The content of petroleum hydrocarbons in discharges of bilgewater from ships is limited by MARPOL Annex I to 15 ppm. This limit is much higher than what would be expected from a regular seawater scrubber. However, this limit is not intended for regulation of scrubber discharges and the limit does not in itself imply that hydrocarbon concentrations up to 15 ppm would be acceptable. In fact hydrocarbon concentrations that are acutely lethal to marine organisms may be as low as 1 ppm.

An effort has been made to identify other discharge standards, criteria or limits of relevance that may exist nationally or internationally. We have looked for standards for the most relevant components such as dissolved oxygen (DO), chemical oxygen demand (COD), pH, total suspended solids (TSS), total organic carbon (TOC), nickel, vanadium, zink, copper, lead, mercury, chromium, and total PAH/PAH_{16}.

The conclusion from structured internet searches and contacts to the Norwegian Pollution Control Authority (SFT) and the Ministry of Environment is that there are few if any such criteria/standards of direct relevance to scrubber discharge from ships.

8 Proposed waste water discharge criteria for exhaust gas scrubbers

8.1 Sensitivity of marine and brackish water organisms to contaminants

Available literature suggests that there may be some systematic, compound-specific differences in sensitivity to contaminants and other environmental stressors between freshwater and marine organisms (Wheeler *et al* 2002). Metals appear to be most toxic to freshwater organisms while organic compounds seem more toxic to marine organisms. These differences are in general not large, and for all practical risk assessment purposes one may regard freshwater and marine species as equally sensitive. Brackish water species are in general more tolerant to natural large environmental fluctuation than their freshwater and marine counterparts, but there is no reason to assume that they also are more tolerant to toxicants. Still it is reasonable to expect that toxicant sensitivity in brackish water organisms does not deviate systematically from that of freshwater and marine organisms. We therefore find no arguments to develop ecosystem-specific waste water discharge criteria for scrubber components to safeguard the inherent organisms of marine and brackish water ecosystems, as long as agreed safety factors are applied to develop PNEC values.

8.2 Proposed waste water criteria for seawater scrubber discharges from vessels at sea

The waste water dispersion modelling shows that a gradual dilution of the plume in the surface water will occur and can be described. There appears to be no discontinuity in this pattern that might serve as a definition of a near field impact area or volume in the wake of a ship. We will therefore rather arbitrarily define that a near field should be limited to 50 m behind the stern. Within this area or volume one must expect that organisms encountering the waste water will be affected, but this should be accepted on basis of the GESAMP principle since this area/volume in all aspects is small compared to the complete water body the ship is moving through. The modelling in transit and port operation shows that a plume dilution of 1:2000 and 1:1700 respectively are achieved at this distance, and within less than 10 seconds. For quay side manoeuvring we have also arbitrarily defined a distance of 20 m from the outlet as the nearfield. It is likely that an average plume dilution of 1:150 may be obtained within the nearfield and within 6-7 minutes.

Taking these dilution factors and the PNEC values for the actual scrubber components into account we have estimated the worst case discharge characteristics that may be allowed without the PEC/PNEC ratio exceeding 1 outside the near field. This should then be proposed as the waste water discharge criteria values. These values are presented in Table 20 and Table 21.

Table 20 shows that even at quay side manoeuvring with the lowest estimated dilution, the waste water may have metal, THC, and PAH content that is 1-3 orders of magnitude higher than those reported as typical for scrubber waste water effluents, and still the PEC/PNEC ratio would be <1 at the border of the near field. The component that comes closest to the proposed discharge criterion is THC, where the quay side criterion is only 3 times higher than the estimated typical discharge concentration, but still on the safe side.

For pH and dissolved oxygen (Table 21) the outlet concentrations would theoretically have to be negative to cause a PEC/PNEC=1 at the border of the near fields. This implies that even with pH = 0 and no dissolved oxygen (DO) in the discharge, the PEC/PNEC ratio would be far below 1 at the border of the nearfield. For DO the table shows that even a COD of 150-350 mg/l (a typical range for national discharge limits for COD) could have been realized within the near field without raising the PEC/PNEC ratio for DO above 1 outside this field.

One should point out that these discharge criteria are very conservative since the PNEC values chosen cover impact during chronic exposure, whereas the anticipated exposure time in the near fields is only 10 seconds during transit and port load and 6-7 minutes at quay side manoeuvring. Also the calculation is based on the strictest PNEC values where alternative values are given by different authorities (cf chapter 6).

Table 20 **Proposed discharge criteria (WDC) for scrubber waste water compounds that are elevated in the waste water (µg/litre). These criteria will ensure that the PEC/PNEC ratio does not exceed 1 at the border of the nearfields in the transit load, port load, and quay side manoeuvring scenarios**

Compound	Most conservative PNEC	Ambient	WDC transit load	WDC port load	WDC quay side manoeuvring	Waste water concentration
Nickel	2.1	0.1	4000	3400	300	32.8
Vanadium	100	2	196000	166600	14700	35
Copper	2.9	0.3	5200	4420	390	41.6
Lead	8.3	0.05	16500	14025	1238	5
Mercury	0.024	0.001	46	39	3	<0.1
Cadmium	2.5	0.03	4940	4199	371	0.08
THC	40	10	60000	51000	4500	1700
PAH	3.3	0.1-0.2	6212	5280	466	0.25

Table 21 **Proposed discharge criteria (WDC) for scrubber waste water compounds that are elevated in the waste water. These criteria will ensure that the PEC/PNEC ratio does not exceed 1 at the border of the nearfields in the transit load, port load, and quay side manoeuvring scenarios**

Compound	Most conservative PNEC	Ambient	WDC transit load	WDC port load	WDC quay side manoeuvring
pH	6.8	7.0	-392	-92	-38
DO mg/l	5	8-10	-9990	-8190	-755

*NOTE: Negative WDC values indicates that PNEC values can be obtained even with pH=0 and DO = O at outlet, indicating that no regulation would generally be needed for pH and COD.

The large safety margin between the trial results and the indicated criteria, and considering the conservative approach used in defining them, indicates that there is no apparent need for scrubber waste water criteria in the open sea. This is in good harmony with MARPOL Regulation 14 which places no restrictions on discharges outside enclosed ports, harbours and estuaries.

8.3 Proposed waste water criteria for seawater scrubber discharges in closed waters

To protect the water quality, the port State needs to limit the total discharges of pollutants within the area of concern. The total discharge of pollutants depend both on the amount of exhaust that is being scrubbed and the discharge criteria.

Even though the Inner Oslo Fjord case concluded that there is no apparent risk for gradual deterioration of the water quality even if all present vessel traffic uses seawater scrubbing of their exhaust, this may not be the case for other enclosed water bodies with high ship traffic. As said earlier each site and situation is unique and has to be evaluated separately to generate site specific waste water discharge criteria, however, the risk procedure used in the Oslo Fjord case is applicable to other enclosed ship traffic areas as well.

As previously argued, to avoid proliferation of criteria it is advised that IMO develops a set of default criteria that represent typical situations (levels 1, 2, 3, etc.). The port State would then have the opportunity to choose one of the predefined criteria on the list which would significantly ease verification of compliance and provide much needed design targets for EGCS-SOx manufacture.

Table 22 Comparison of Possible discharge water limits and worst case trial results (µg/litre)

Criteria level "Safety Margin"	**1** 1	**2** 10	**3** 100	Trial worst case
Nickel	300	30	3	32.8
Vanadium	15000	1500	150	35
Copper	400	40	4	41.6
Lead	1200	120	12	5
Mercury	3	0.3	0.03	<0.1
Cadmium	350	35	4	0.08
THC	4500	450	45	1700
PAH	450	45	5	0.25

As seen in Table 22, there is a considerable difference between the worst case results observed in the trials and proposed criteria in many cases. It is suggested that a limit value is not needed when the worst case observed in the trial is about one order of magnitude or more below the proposed criteria. The resulting criteria proposition following this logic is shown in Table 23.

Table 23 Proposed discharge water limits (µg/litre)

Criteria level[*] "Safety Margin"	**1** 1	**2** 10	**3** 100
Nickel	-	30	3
Vanadium	-	-	150
Copper	-	40	4
Lead	-	-	12
THC	4500 (4.5 ppm)	450 (0.45 ppm)	45 (0.045 ppm)

[*] At nominal washwater rate of 44 kg/kWh (representative of trials and dispersion models used).

The safety margin indicates how much more discharge an area can sustain compared to the unregulated situation, all other aspects being equal.

These proposals are made based on results from two specific trials. They should be seen in conjunction with experiences from other trials, studies as well as capabilities of water cleaning systems and means of verification. An additional cosmetic criterion demanding no visible discharge and absolute limit values irrespective of washwater rate could also be considered.

In order to select predefined discharge criteria, the port State would have to identify the rate of water exchange and the anticipated discharge from scrubbers in the area in question. The concentration of contaminants in the area can then be calculated assuming different discharge levels and compared with PNECs as provided above or other as deemed necessary. The port State could then select the least stringent set of criteria which provide sufficient environmental protection.

9 GLOSSARY

COD	chemical oxygen demand
AOX	absorbate organic chloride
PAH	polyaromatic hydrocarbons
PCDD	polychlorinated dibenzo-p-dioxines
PCDF	polychlorinated dibenzofurans
PEC	predicted environmental concentration
PNEC	predicted no-effect concentration
THC	Total Hydrocarbon
HC	Hydrocarbon
WDC	water discharge criteria
DO	dissolved oxygen
EQS	environmental quality standard
TSS	total suspended solids
TOC	total organic carbon
SPM	suspended particular matter
PCB	polychlorinated biphenyls
EAC	Ecotoxicological Assessment Criteria

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APPENDIX 1
Report CFD-Norway

APPENDIX 2
Memo Sintef Materials & Chemistry

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ANNEX 2

RESEARCH REPORT | **NO VTT-R-08868-06** | **23.11.2006**

Environmental effects of caustic soda and sea water scrubbers

Customer: Wärtsilä Finland Oy

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Summary

Due to Marpol Annex VI, sulphur molecules in exhaust gases must be reduced in heavy fuel oil (HFO) burning engines. The means for sulphur reduction are utilization of low sulphur fuels or treatment of exhaust gas. Because of predicted low-sulphur fuel supply limitations and relatively high operating costs, the exhaust gas treatment with a scrubber is receiving increasing attention as an alternative. A study of environmental effects of scrubber waste water is required since the existing marine regulations do not have any specific requirements regarding the quality of the waste water.

This study contains environmental effects of scrubber maker “A” caustic soda scrubber and maker “B” scrubber with sea water mode and caustic soda mode. The scrubbers installed to main and auxiliary engines are studied.

This is a shortened, public version of a more detailed confidential master report. The master report has been based on information obtained under non-disclosure agreements, and such information has been omitted from this public version for obvious reasons.

Date Espoo 23 November, 2006

Seppo Kivimaa Technology Manager	Saara Hänninen Research Scientist

Distribution (customers and VTT):

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1 Executive summary

Due to Marpol Annex VI and EU regulations, sulphur molecules in exhaust gases must be reduced in heavy fuel oil (HFO) burning engines. In so called sulphur emission control areas (SECAs), ships may only use fuels containing up to 1.5% sulphur or use an exhaust gas cleaning system (SO_x scrubber) that delivers an equivalent reduction in sulphur emission. Because of predicted low-sulphur fuel supply limitations and relatively high operating costs, the exhaust gas treatment with a scrubber is receiving increasing attention as an alternative.

Modern scrubbers also remove a part of the PM and heavy metals from the exhaust gas. The scrubber effluent therefore also contains exhaust particles, hydrocarbons and heavy metals. It is thus an important issue to evaluate whether it is better to send these pollutants in the effluent into the sea or emit them into the atmosphere in the exhaust gas. Most probably, the emissions legislation will in the near future also limit the air polluting exhaust PM emissions at least in harbours which encourages the use of SO_x scrubbers, also efficient in exhaust PM removal.

This study contains environmental effects of scrubber maker “A” caustic soda scrubber and maker “B” scrubber with sea water mode and caustic soda mode. This is a shortened, public version of a more detailed confidential master report. The master report has been based on information obtained under non-disclosure agreements, and such information has been omitted from this public version for obvious reasons.

When calculating the contaminants emitted by ships, the following assumptions were made:

- A concept of "an average ship" was formed to simplify the calculations needed. The average ship has the following main characteristics: Main engine power 10 000 kW, auxiliary installed engine power 1 470 kW, main engine load factor at sea 80%, manoeuvring 20%, auxiliary engine load factor at sea 30% at berth 40%, hours at sea 6 000 h/a, at berth 700 h/a, manoeuvring 20 h/a, fuel consumption 200 g/kWh.
- Emissions in the Baltic Sea region are one of the topics of this study. Of the data sources gone through, the TREMOVE model (Catholic University of Leuven) figures were chosen to be the most valid for the purpose of this study. The fuel consumption, totalling 4 165 826 tonnes in the Baltic Sea region for the year 2005 has been the basis for all calculations concerning the Baltic Sea.
- Data on engine-out emissions and fuel consumption plus specifications of fuel and lubricating oil supplied by Wärtsilä were used. Updates for the average fuel provided by Det Norske Veritas were taken into account. HFO was assumed to be used both in the main and auxiliary engines.
- An engine output of 75% of the full output (MCR) was used for emissions figures, since data were available for this load and the figures were assumed to be very close to those of 80% load, used for bulk calculations. The specific exhaust flow was estimated at 8 kg/kWh at this engine part load.
- The PM emissions results achieved with the ISO 8178 method formed the basis for calculation and analysis of PM emissions.
- The scrubbers do not remove gaseous hydrocarbons and other gaseous pollutants from the exhaust, except for SO_2.

Wash water discharge criteria

During the project, it has become evident that further research is needed before wash water discharge criteria for the scrubbers can be selected, since all issues of environmental effects are not yet completely understood. Additional challenges should not be put on ships equipped with scrubbers compared with those sailing without scrubbers.

As long as this situation with unclear rules prevails, owners continue to be reluctant to invest, and scrubbers will not enter the market. In case of too stringent criteria for heavy metals, legislation will encourage the selection of scrubbers with low particle removal rate, sending most of the particles to the atmosphere, and producing a clean effluent requiring no treatment plant. In case of too stringent criteria for pH, legislation will encourage the selection of scrubbers with limited SOx-reduction rate (cleaning down only to an equivalent of 1.5 % S), sending much of the SOx to the atmosphere. Legislation clearly preventing scrubbers from fully reducing emissions to the air will be deemed inappropriate by scrubber designers, presently in a need for design targets.

Finland and Norway submitted a paper to the IMO for the MEPC (Marine Environmental Protection Committee) 55 meeting in October 2006 (Appendix A). MEPC 55 decided to form a Correspondence Group to establish wash water discharge criteria. The decision will be reached at the earliest in MEPC 56 in July 2007.

The criteria that the Norwegian – Finnish paper suggested is handled below concerning the scrubbers evaluated in this report. It seems that the criteria for copper and lead could be removed from the submission, at least in the case of four-stroke engines, since copper and lead originate mainly from the lubricating oil. The effluent concentrations of Ni, V, and THC may be higher than proposed for limits for IMO in the submission. At open sea, high THC content seems to be mainly a cosmetic weak spot. Dilution in the propeller race is quick and effective. In case the THC was limited down to 15 ppm, an effective separation would be needed. Especially in the closed-loop mode the THC concentrations are fairly high, although the stream flows are low. The effects of scrubbers are, however, altogether positive. One should therefore be careful in setting standards for effluent quality as long as the knowledge about the environmental effects is limited.

To meet the regulations scrubber technology has a clear advantage compared with the use of 1.5% sulphur content fuel. The scrubber decreases also other than sulphur dioxide air emissions. If in the Baltic Sea region all ships would use HFO fuel with sulphur content of 2.7% with maker “B” sea-water scrubber installed there would be 102 000 tonnes less sulphur dioxide air emissions, less 16 000 tonnes particles, 260 tonnes vanadium etc. compared with the situation where all ships would be using fuel with sulphur content of 1.5% without scrubber.

During a one year period (720 h/a) an average ship using HFO fuel with sulphur content of 2.7% and maker “B” sea-water scrubber installed would have emitted 2 600 kg less sulphur dioxide in the air of the harbours' area than a ship using fuel with sulphur content of 1.5%. Furthermore there would be 410 kg less particles and 7 kg vanadium and many other contaminants.

As an example of a situation at ports, the following will show calculation results from the port of Helsinki. There are ca 3 000 cargo ship calls yearly. If all cargo ships would use HFO fuel with sulphur content of 2.7% and with maker ”B” sea-water scrubber installed, a decrease of sulphur dioxide air emissions 365 tonnes, particles 57 tonnes and vanadium1 tonne in the port area could be achieved compared with the situation where all ships would use fuel with sulphur content of 1.5% without scrubber.

Scrubber maker “A” caustic soda scrubber

The caustic soda (NaOH) scrubber by maker “A” removes 90% of SO_2 from exhaust gases produced by a HFO driven diesel engine. Of the PM, approximately 35% is captured by the wash water, including heavy metals. The scrubbing process does not produce any solids, but the reactions take place in aqueous solution. At the scrubber outlet, the wash water pH is some 7.0…7.5.

The effluent of the scrubber of the maker “A” consists of sodium bisulphite, sodium sulphite and sodium sulphate. The effluent also contains impurities like oil, lubricant and heavy metals. The liquid part of the effluent can not be stored on-board ship, except only temporarily.

When using the maker “A” scrubber, the raw effluent concentrations of nickel, vanadium and THC may be higher than is proposed for limits for IMO by the Norwegian and Finnish submission (Appendix A). However, since heavy metals and THC in the effluent reduce atmospheric emissions, an all-inclusive examination of PM, heavy metal and hydrocarbon emissions is desirable to evaluate, whether it is better to also remove those pollutants from the exhaust by a scrubber or emit them into the atmosphere without using a scrubber. In its entirety, the environmental effect of a scrubber may well be positive. Accordingly, too stringent wash water criteria should be avoided that might prevent scrubbers from being installed.

Treatment of the effluent on quay:

- Chemical oxygen demand (COD) caused by the wash water can be essentially reduced by connecting an oxygenation stage into the process. A minimum retention time of approximately six (6) hours is recommended.
- Oil can be removed by means of a system similar to oil separation from bilge water.

In summary, the effluent of the maker “A” caustic soda scrubber is suitable from environmental point of view:

	On quay	**Manoeuvring**	**Open Sea**
pH	yes	yes	yes
THC (oil)	yes (A)	yes	yes
Vanadium	yes (A)	yes	yes
Nickel	yes (A)	yes	yes
COD	yes (B)	yes	yes

A	additional separation with bilge water needed
B	aeration tank needed

Maker “B” scrubber with sea water mode and caustic soda mode

The scrubber of the maker “B” can be operated in two modes, in sea-water mode and in caustic soda mode. In sea-water mode, the natural alkalinity of sea-water is exploited for SO_x abatement. In caustic soda mode, a solution of NaOH and water works as scrubbing liquid.

The maker “B” scrubber can be operated using open or closed wash water circulation (open-loop or closed-loop mode, respectively). Neat sea-water can be used in the open-loop mode when the sea-water alkalinity is sufficient. At decreasing alkalinity, the open-loop mode is boosted with slight NaOH addition. Soda is injected upstream of the scrubber and it will be injected only if there is pH limitation in wash water flow or high efficiency has to be reached.

In closed-loop mode, the scrubber works with a solution of caustic soda and sea or fresh water. The wash water flow is significantly smaller than in the open-loop mode. In the closed-loop soda mode, the quantity of NaOH is stoichiometric. In the open-loop mode, when NaOH must be added, more than stoichiometric amounts of NaOH are needed.

In the closed-loop soda mode, maker “B” utilises a heat exchanger (HE) in the wash water circuit of the scrubber. In the HE, the wash water is cooled. The HE also reduces consumption of make-up water drastically. The bleed-off from the wash water is directed through a possible water treatment unit (WTU) and then diluted, optionally twice, with sea-water before sending it into the sea. It is still unclear, however, whether this kind of dilution is permissible or not.

The sea-water and caustic soda scrubbers of the maker “B” do not remove any gaseous exhaust pollutants, except for sulphur dioxide, 90% of which is removed. Particles are reduced by 60% and so are heavy metals. Hydrocarbons in particles also decrease by 60%.

Generally, maker “B” does not take a stand on wash water after-treatment, but expects assessment from VTT and FIMR. In open-loop mode, maker “B” intends to add caustic soda when required and send wash water into the sea. With a WTU, it is possible to modify and reduce the COD. However, the company sees it difficult to incorporate a WTU into the open-loop mode of the scrubber, since the water flows are huge and the WTU would require a lot of space. Maker “B” also considers that in harbours it will be obligatory to run the scrubber in closed-loop caustic mode in order to maintain pH at 7. With sea-water dilution, a sufficient pH is obtained. It is unclear, however, whether dilution is permissible or not.

When using the maker “B” scrubbers, the effluent concentrations of nickel, vanadium and THC may be higher than is proposed for limits for IMO by the Norwegian and Finnish submission (Appendix A). However, since heavy metals and THC in the effluent reduce atmospheric emissions, an all-inclusive examination of PM, heavy metal and hydrocarbon emissions is desirable to evaluate, whether it is better to also remove those pollutants from the exhaust by a scrubber or emit them into the atmosphere without using a scrubber. In its entirety, the environmental effect of a scrubber may well be positive. Accordingly, too stringent wash water criteria should be avoided that might prevent scrubbers from being installed.

Although the effluent dilutes quickly behind the ship while the ship is moving, in closed port basins the dilution is restricted due to the low basin water volume. This could be a problem in the ports with high number of port calls.

Scrubber maker “B” has a solution where the sea water scrubber can be changed into caustic soda mode. Such a change seems practical in harbours.

Treatment of the effluent:

- The treatment is necessary when the pH of the effluent is lower than 6. It is possible to add NaOH before scrubbing to raise pH near neutral (caustic soda mode).
- The treatment is necessary when the alkalinity of the sea water is low.

In summary, the effluent of maker “B” sea water scrubber is suitable from the environmental point of view:

	On quay	**Manoeuvring**	**Open Sea**
pH	yes (C)	yes	yes
THC (oil)	yes (A)	yes	yes
Vanadium	yes	yes	yes
Nickel	no?	yes	yes
COD	yes	yes?	yes

A additional separation with bilge water needed
C additional NaOH required / change in caustic soda mode operation

The effluent of maker “B” caustic soda scrubber is suitable from the environmental point of view:

	On quay	**Manoeuvring**	**Open Sea**
pH	yes	yes	yes
THC (oil)	Yes (A)	yes	yes
Vanadium	Yes (A)	yes	yes
Nickel	Yes (A)	yes	yes
COD	Yes (B)	yes	yes

A additional separation with bilge water needed
B aeration tank needed

2 Introduction

Due to Marpol Annex VI and EU regulations, sulphur molecules in exhaust gases must be reduced in heavy fuel oil (HFO) burning engines. Under Annex VI, the maximum allowable sulphur content of marine fuel is now 4.5%. A sulphur limit of 1.5% in marine fuels was, however, set to take effect on May 19, 2006 in sulphur dioxide (SO_x) emission control areas (SECAs) including the Baltic Sea. This was agreed in the International Maritime Organization (IMO) Marpol Annex VI ship bunker fuel treaty which entered into force in May 2005. The North Sea and English Channel is a second SECA where the new rules will not enter force until November 2007 (Figure 2.1), but IMO is likely to designate additional SECA regions in the months ahead (Safety at Sea, 2005).

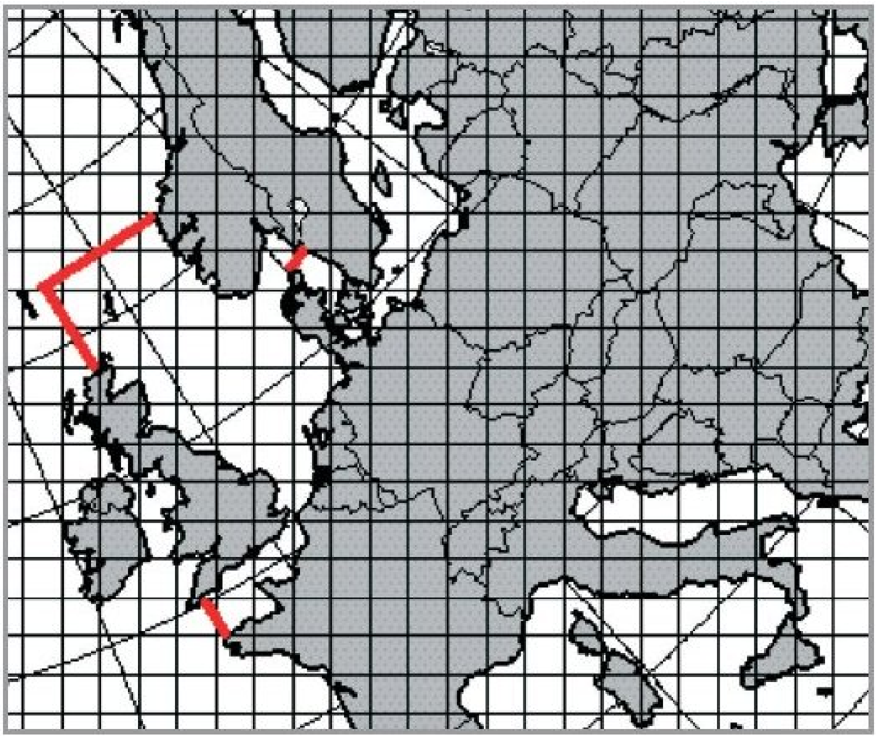

Figure 2.1 Geographical boundaries for the Baltic Sea SECA and the North Sea Area and the English Channel SECA (DNV 2006).

The means for sulphur reduction are utilization of low sulphur fuels or treatment of exhaust gas. Because of predicted low-sulphur fuel supply limitations and relatively high operating costs, the exhaust gas treatment with a scrubber is receiving increasing attention as an alternative.

A study of environmental effects of scrubber waste water is required since the existing marine regulations do not have any specific requirements regarding the quality of the waste water. The IMO EGCS-SO_x Guideline states that EGCS-SO_x unit's wash water systems should:

a) eliminate, or reduce to a level at which they are not harmful, hydrocarbons, carbon residue, ash, vanadium, other heavy metals, and other substances contained within EGCS-SOx unit's wash water that may have an adverse impact on ecosystems if discharged overboard,

b) ensure that the approach adopted, to control wash water quality and residual waste is not achieved in a way that causes pollution in other areas or environmental media.

This study was originally meant to contain environmental effects of scrubber maker “A” caustic soda scrubber, maker “B” scrubber with sea water mode and caustic soda as well as maker “C” sea water scrubber. Later it became clear that required information will not be received from maker “C” and it was decided to leave it out from the study.

This is a shortened, public version of a more detailed confidential master report. The master report has been based on information obtained under non-disclosure agreements, and such information has been omitted from this public version for obvious reasons.

In this project, the scrubbers installed to main and auxiliary engines are studied. The study consists of the following tasks:

1. Existing material concerning the maritime traffic and HFO ship emissions in the Baltic Sea region was examined. Relevant information was gathered and analyzed, main and auxiliary engines included (ship movements, port calls, ship types, engine power classes, HFO consumption, emissions, use of energy etc.). Information mentioned above was defined for an individual average ship (average ship according the report “European Commission Directorate General Environment, Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments, Task 2 – General Report”, August 2005) and for the total maritime traffic in the Baltic Sea per annum.
2. Amount of port calls and average duration in the selected ports in known and possible future sulphur emission control areas was studied to evaluate the efficiency of each scrubber in ports.
3. Known and potential contaminants from the substances in exhaust gas were identified.
4. Annual amount of contaminants emitted by individual average ship and by the total maritime traffic without scrubbers in ports and in shipping channels in the Baltic Sea area was calculated using the data from Tasks 1 and 3.
5. Annual amount of contaminants removed from exhaust gases by scrubber and generated by scrubber to the wash water in an individual average ship and in the total maritime traffic in ports and in shipping channels in the Baltic Sea area was calculated for each scrubber.
6. Annual amount of contaminants removed from scrubber waste water by onboard treatment plant in an individual average ship and in the total maritime traffic in the Baltic Sea area was calculated for each scrubber.
7. Rough evaluation of the percentage of contaminants falling into sea from the amount emitted to air is given.
8. Potential environmental impacts of contaminants falling into the Baltic Sea and selected ports, or entering the sea with the waste water were evaluated as well as compliance with the target set in the IMO EGCS-SOx Guideline.
9. In case of non-compliance with the wash water criteria, the required improvement was clarified.
10. The sensitivity of other denominated and prospective SECAs compared with the Baltic Sea was evaluated.

The engine-out emissions are based on the information received from Wärtsilä. Updated data on the average fuel was received from Det Norske Veritas. Performance data given by the scrubber manufacturers form the basis for calculations of the stack emissions and wash water quality. Exhaust particle characteristics were examined based on literature and tests at VTT.

Utilising this background information and performed calculations, the aim of the study was to clarify

- the total gaseous pollutants emitted into the atmosphere by ships equipped with the scrubbers in question
- the total pollutant concentrations in the scrubber wash water for each scrubber concept
- effects of the wash water on the environment
- the possible need for wash water treatment unit in case of each scrubber.

An average ship was studied having a main engine output of approximately 10 MW. The heavy fuel oil used in the study was assumed to have an average sulphur content of 2.7% by mass. Both the main and auxiliary engines were assumed to burn heavy fuel oil.

3 Maritime traffic and emissions

3.1 Maritime traffic and emissions in the Baltic Sea region

Knowledge of total emissions from ships in different sea areas is rather poorly known compared to e.g. knowledge of road traffic emissions. Road traffic has long been a major environmental problem and much has been done to abate the emissions. This has its ground on the fact that emissions from road vehicles come directly to places where people have their activities whereas emissions from ships are commonly far away.

While road traffic emissions have strongly decreased, the share of maritime traffic emissions of the total traffic emissions has strongly increased. For example SO_2 emissions (2 476 t) from ships in Finnish ports are 36 times higher than SO_2 emissions from road traffic in the whole Finland (68 t).

Worldwide knowledge of ship emissions in harbours is poor. However, emissions in Finnish ports are well known because of the port register in the Finnish Maritime Administration and the MEERI emissions model developed in VTT (Mäkelä 2005).

Emissions in the Baltic Sea region are one of the topics of this study. There are only a few studies that have assessed traffic and emissions in this area. As the Baltic Sea area is not an administrative body in itself there are presently only a few bodies interested in the emissions of the area (mainly HELCOM and EU). The SECA definition has raised the importance of the Baltic Sea as an 'en bloc'.

Maritime emissions are problematic because ship emissions from international traffic are not allocated to any instance and thus the regulations are extremely difficult to get in force. Presently the bunker fuels and emissions from them are only a part of the global emissions calculation and only a matter of the overall interest. Knowing the importance to regulate also bunker fuels EU has made an initiative for the allocation of emissions to the different stakeholders. Finland has taken an active role in this activity. This process increases the need for emission inventory but for this study the ongoing research activities only partly managed to produce emission data in time.

Existing knowledge of the maritime emissions in the Baltic Sea region is presented in the Table 3.1. However, the time frame and data content is quite dispersed because of the heterogeneous data sources available.

Table 3.1 Ship activity data and emissions in the Baltic Sea area from different data sources

	TFB 1987 [t/a]	TREMOVE 1995 [t/a]	SMA 1998	TREMOVE 2000 [t/a]	BMT 2001 [t/a]	TREMOVE 2005 [t/a]
Calls		101 057	350 700	114 489		129 714
FC	2 157 000	3 241 684		3 674 645	5 301 000	4 165 825
CO_2	6 910 000	10 305 755		11 682 197		13 243 724
NOx	163 300	230 337		261 042	365 000	284 767
SO_2	85 600	172 086		195 073	232 000	221 151
S %	2.0	2.7		2.7	2.2	2.7
PM	6 100	18 960		21 482		24 340
VOC	4 300	8 629		9 779		11 082

Emissions in the Baltic Sea area were for the first time published in a thorough Swedish TFB report from the year 1993 concerning the year 1987 (Alexandersson 1993). This publication does not include information on port calls. The emission calculation method presented in the report has also been used in the Finnish MEERI model developed by VTT. MEERI is a calculation system for energy and emission inventory of Finnish ports and waterborne transport inside the economic region of Finland (Mäkelä 2005).

The Swedish Maritime Administration estimated the number of port calls to be 350 700 for the year 1988 (SMA 1999, page 36). The figure seems to be rather high but as it includes the dense ferry traffic in the Baltic Sea region this could be acceptable.

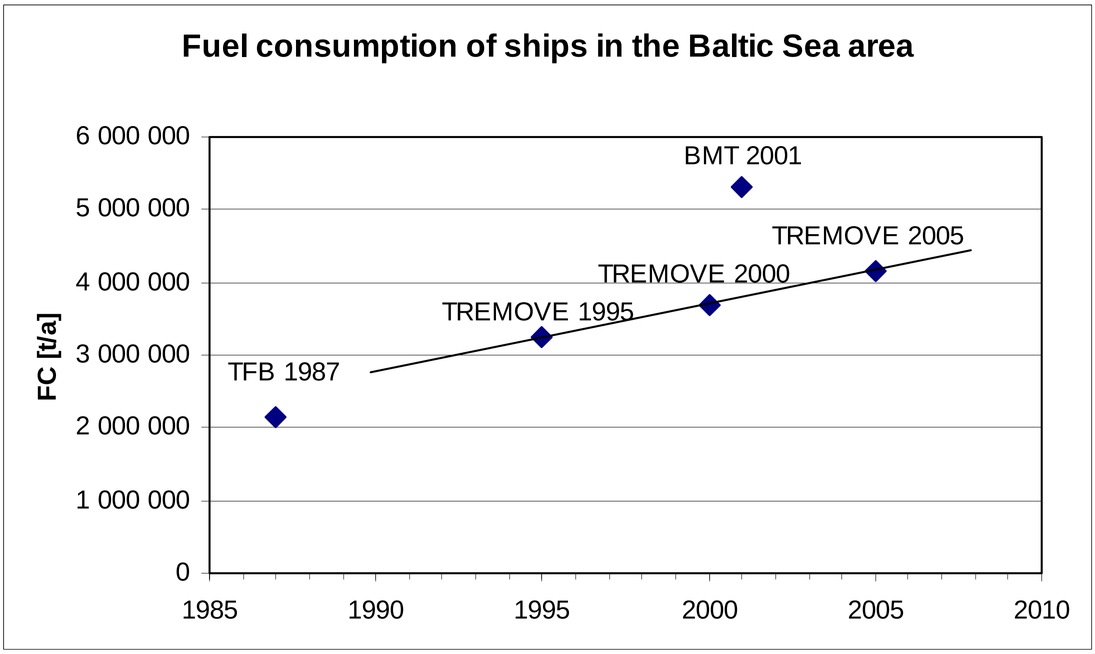

Figure 3.1 Fuel consumption in the Baltic Sea area from different data sources

Entec UK Limited carried out an extensive EU project about ship emissions inside the EU for the year 2000. The Final report (Entec 2002) presents ship calls, energy consumption and emissions at North Sea / Baltic Sea but not separately at the Baltic Sea.

In the EU's CAFE-program (Clean Air for Europe), the Catholic University of Loeven has developed a Europe wide model for transport called TREMOVE. The model includes a maritime transport sub model and emissions calculation procedures (TREMOVE 2006). The model uses the same data set for the ship movements as Entec (for the year 2000). However, TREMOVE splits the data for the Baltic Sea. TREMOVE has a forecast from 1995 up to 2020 (Table 3.1 and Figure 3.1). According to the model description ferry traffic is included in the model. However, comparison of the number of port calls for Finland in the TREMOVE model to the same information in the MEERI model reveals that port calls include almost solely cargo ships. In spite of this fuel consumption and NO_x emissions in both models are very close to each other.

BMT Murray Fenton Edon Liddiard Vince Limited (BMT 2000) presents fuel consumption, NO_x and SO_2 emissions for the year 2001 to the Baltic Sea region. Figures seem to be rather high compared to other data sources.

Of the data sources above, the TREMOVE model figures have been chosen to be the most valid for the purpose of this study. Fuel consumption is the most useful information. Emissions of ship engines correlate well enough with the fuel consumption irrespective of ship type or engine power. In this study the total fuel consumption according to the TREMOVE model (totalling 4 165 826 tonnes) in the Baltic Sea region for the year 2005 has been the basis for all calculations concerning the Baltic Sea. Considering the simplified calculation method and the nature of this study the figure is accurate enough.

3.2 Average ship

In this study emissions were calculated with a rather simplified method. Main elements were the ship activity data to produce fuel consumption data and the emission factors (g/kg fuel). For the calculations an average ship was used. The basis for the definition is described in the EU-report (Entec 2005). Table 3.2 shows the characteristics of the average ship. Both the main and auxiliary engines were assumed to be HFO driven engines.

Table 3.2 Characteristics of the average ship used in calculations (Entec 2005)

		Main engine	**kW**	**10 000**
		Auxiliary engine (inst.)	**kW**	**1 470**
		Number of AE		**4**
ME	Load factor	at sea	%	80
	Load factor	at berth	%	20
	Load factor	manoeuvring	%	20
AE	Load factor	at sea	%	30
	Load factor	at berth	%	40
	Load factor	manoeuvring	%	50
	Time	at sea	h/a	6 000
	Time	at berth	h/a	700
	Time	manoeuvring	h/a	20
ME	Operation time	at berth	%	5
ME	Specific fuel cons.		g/kWh	200
AE	Specific fuel cons.		g/kWh	200

ME = main engine, AE = auxiliary engine

The Entec report describes three different kinds of an average ship: small, medium and large. The medium ship type was chosen for this study because its engine power corresponds to the Wärtsilä engine the emission measurement results of which were used in this study. Another name for the average ship could be equivalent ship because in port emission calculations of this study the actual port calls were converted to average ship calls. The average (or equivalent) ship calls are usually less than the actual ship calls because normally the average size of ships visiting the port is smaller than the one described above (mainly the engine power installed). The conversion of actual calls to average ship calls is highly uncertain because ports did not give information suitable for conversion.

3.3 Contaminants emitted by ships - emission factors

For the purpose of this study the natural source of information on contaminants emitted by ships was Wärtsilä. Measured values (Henriksson 2006b) were converted to emission factors as g/kg, see Table 3.3. Using these factors in calculations total emissions e.g. for the Baltic Sea region appears to be about the same as in the other information sources. In addition, Wärtsilä produced detailed information on such contaminants that are not publicly available. The emission reduction factors for scrubbers were received from the scrubber manufacturers.

Table 3.3 The following emission factors were used in calculations (Henriksson 2006b)

Compound	g/kg fuel	Compound	g/kg fuel
NO_x (as NO_2)	68	Iron	0.00756
CO	2.1	Calcium	0.0356
THC (as CH_4)	2.1	Magnesium	0.0010
CO_2	3190	Zinc	0.002975
Particles	6.4	Phosphorus	0.00090
Vanadium	0.10345	Chromium	0.0000045
Sodium	0.010275	Tin	0.0000045
Nickel	0.03315	Lead	0.0000145
Aluminium	0.003015	Copper	0.0000075
Silicon	0.00406		

Fuel specifications of (Henriksson 2006b) formed the basis for calculations, but fuel updates of Det Norske Veritas were also taken into account (Tveit 2006). Both the main and auxiliary engines were assumed to burn heavy fuel oil. As to the average and high-ash fuels, species concentrations of separated fuels were adopted. Separation reduces the contents of sodium, aluminium, silicon, iron, calcium and magnesium in the fuel. The worst fuel was also taken defined as “before engine”, i.e., as separated. The nickel concentration was, however, modified to correspond to the nickel concentration of the high-ash fuel. Effects of lubricating oil on exhaust composition were included in the study.

An engine output of 80% of the full output power was used, since the marine engines usually operate at the most economic load. Regarding exhaust emissions, measurement results obtained at an engine load of 75% formed, however, the raw data for calculations, since these emissions data were available. Additionally, a specific exhaust gas flow of 8 kg/kWh and fuel consumption of 200 g/kWh were assumed for the basis of the emissions and wash water calculations.

For calculation of the emissions of particulate matter (PM), or dust, the results achieved with the ISO 8178 measurement method were exploited, since these PM figures also include condensed volatile fractions, unlike the ISO 9096 that mostly contains solid material due to the very high sampling temperature. The use of the ISO 8178 was argued for by the fact that the exhaust gas cools down very rapidly in the scrubber and, most probably, volatiles are condensed on the particles. True, there are limitations even in the use of the ISO 8178 method, since according to the ISO 8178 standard, the dilution measurement technique is only validated up to 0.8% sulphur in the fuel (Lauer 2005). Mr Göran Hellén confirmed, however, that it is more reasonable to use the ISO 8178 than ISO 9096 in the scrubber wash water study (Hellén 2006).

As to PM, Suominen (2006b) also writes that the ISO 8178 method is definitely the better way to try to evaluate particulate matter in the gas before and after the scrubber compared with the ISO 9096 method. Because of having the cooling effect (< 52 °C) in the sampling stage by means of air dilution it, however, does not totally match with the scrubber reality either. In actual scrubber installations, the gas cools by means of non-diluted raw gas contacting with water that evaporates in fully saturated conditions. Condensation can be boosted there due to the higher partial pressures of the condensable components. Anyway, the ISO 8178 is most likely the best way to be applied, partly since there are data about the PM concentrations well available even for HFO fired engines.

It should also be noted that the poor reproducibility of the PM emission results with ISO 8178 forms one challenge. The dominating fractions are condensable hydrocarbons, sulphur oxides and its crystallisation water. The amount of these components is very sensitive to temperature and specific features of the combustion process plus sampling chain. So, one must be aware of that the variation range of the results even with the same type of fuel can be very large. The method is not universally applicable for sulphur containing fuel oils. (Suominen 2006b)

In addition to the calculated exhaust pollutants, some other harmful species may exist in the exhaust that may cause problems in the system or environment. For example, mercury also exists in heavy fuel oils and, thus, most likely even in exhaust gases. Mercury is not a standard testing parameter and no statistics were available at DNV Petroleum Services. Nevertheless, the mercury content in HFOs is within a range of parts per billion. At least North Sea-crude contains mercury and it has led to difficulties due to mercury deposits in process piping. (Tveit 2006)

3.4 Proportion of contaminants falling into sea from the amount emitted to air

Information concerning deposition of particles on marine areas is really scanty. This deposition estimation for ship particle emissions has been done by applying simple box model for the plume properties and for distribution of emitted particles. Particulate composition and size distribution as well as the relevant emission parameters for an average ship were given by Wärtsilä.

Additional simplifying assumptions used here were:

Neutral weather conditions, wind speed varying from 5 to 15 m/s.
Roughness length for sea assumed to be 0.001 m (Seinfeld et al 1998).
Deposition velocities for particles are based on (Seinfeld et al 1998).

Results (Table 3.4) are given as particle lifetimes (63 % of the substance removed from atmosphere = concentrations 1/e from original) in atmosphere based on the simplified box-modelling where the box height is taken to be the effective plume height (Table 3.5).

Table 3.4 Particle lifetime (hours) in atmosphere for different size classes and wind speeds (Seinfeld et al 1998)

Diameter (nm)	Deposition velocity (cm/s)	Life Time(h) U = 5m/s	Life Time(h) U= 10 m/s	Life Time(h) U= 15 m/s
20 -40	0.05	**60**	**24**	**17**
30-60	0.02	**150**	**61**	**43**
800-900	0.015	**200**	**81**	**57**
2000	0.03	**100**	**41**	**29**
5000-6000	2	**1.5**	**0.6**	**0.4**

Table 3.5 Effective plume height (m) as a function of the ambient wind speed at (z=23 m) (Karppinen et al 1998)

Wind speed	Effective plume height (m)
5	**108**
6	82
7	67
8	56
9	49
10	**44**
11	37
12	35
13	33
14	32
15	**31**

Speed of the ship is not taken into account. It does not have a great influence on the estimated lifetimes of particles in air; however, it affects greatly the spatial distributions of concentration and deposition.

The effective wind speed used in plume rise calculations is also affected by the relative direction of ship and wind. However, the biggest uncertainty lies in the exact values of the deposition velocities (for details see Seinfeld et al 1998) and other weather and particle composition related uncertainties (e.g. stability, occurrence of rain).

The dispersion of pollutants is always affected by surrounding terrain characteristics, so at least the roughness parameter used would be changing if the estimates are made near the coast line/harbour instead of the assumed open sea conditions.

It is very difficult to assess the amount of particles falling in to the sea, because of strong effect of weather conditions, but a rough approximation is that under dry weather conditions only size class 5000 – 6000 nm will totally fall to the sea (65% is falling within radius of 22 km), whereas smaller particles are carried from some hundreds to some thousands kilometres away.

3.5 Conclusions

To assess the environmental effects of scrubbers, two spatial target areas were chosen: The Baltic Sea area and nine selected ports world wide. Furthermore, an average ship was considered.

Knowledge of total emissions from ships in different sea areas is rather poorly known compared to e.g. knowledge of road traffic emissions. Road traffic has long been a major environmental problem and much has been done to abate the emissions. Emissions in the Baltic Sea region are one of the topics of this study. There are only a few studies that have assessed traffic and emissions in this area. Of the data sources concerning the Baltic Sea area, the TREMOVE model figures have been chosen to be the most valid for the purpose of this study. Fuel consumption is the most useful information. Emissions of ship engines correlate well enough with the fuel consumption irrespective of ship type or engine power. In this study the total fuel consumption according to the TREMOVE model (totalling 4 165 826 tonnes) in the Baltic Sea region for the year 2005 has been the basis for all calculations concerning the Baltic Sea. Considering the simplified calculation method and the nature of this study the figure is accurate enough.

A concept of "an average ship" was formed to simplify the calculations needed. The basis for the definition of the characteristics of an average ship was adopted from the work done by Entec Ltd in the year 2005. The average ship has one main engine (10 MW) and four auxiliary engines (installed power 1470 kW), it spends 6 000 hours at sea, 700 hours at berth and 20 hours manoeuvring during one year.

Information about port calls and ships' average duration in selected ports was gained for further evaluation of potential environmental impacts in the port areas. When the number of port calls and time at berth is known, a rough estimate about the emissions in ports, as well as the influence of scrubbers on these emissions, can be calculated. The information can also help to estimate the magnitude of the emission issue globally.

In the beginning there was a list of 15 ports of which the information was asked for. Altogether nine ports were chosen for further analysis since at least the number of port calls was known in these ports. Required information was received only from Rotterdam, Antwerp and Hull & Goole. Time at berth has been estimated in the other six ports.

For the purpose of this study the natural source of information on fuels used and contaminants emitted by ships was Wärtsilä. Emissions results recorded at an engine load of 75% were utilised, since they were available, even though a main engine load factor at sea 80% was used in calculations. Measured emissions values were converted to emission factors as g/kg.

Fuel updates of Det Norske Veritas were also taken into account. Both the main and auxiliary engines were assumed to burn heavy fuel oil. For calculation of the emissions of particulate matter (PM), or dust, the results achieved with the ISO 8178 measurement method were exploited, since these PM figures also include condensed volatile fractions, unlike the ISO 9096 that mostly contains solid material due to the very high sampling temperature. The emission reduction factors for scrubbers were received from the scrubber manufacturers.

Finnish Meteorological Institute estimated the proportion of contaminants falling into sea from the amount emitted to air. A rough approximation was that under dry weather conditions only size class 5000 – 6000 nm will totally fall to the sea, whereas smaller particles are carried hundreds, or even thousands, of kilometres away.

4 Identification of contaminants in exhaust gas

4.1 Principles for identification

According to international law, marine pollution is defined as direct or indirect introduction by humans of substances or energy into the marine environment (including estuaries), resulting in harm to living resources, hazards to human health, hindrances to marine activities including fishing, impairment of the quality of sea water and reduction of amenities.

On the other hand EGCS-SOx (Exhaust Gas Cleaning System) Guidelines states that wash water systems should:

(a) eliminate, or reduce to a level at which they are not harmful, hydrocarbons, carbon residue, ash, vanadium, heavy metals, and other substances contained within EGCS-SOx wash water that may have an adverse impact on ecosystems if discharged overboard.

(b) ensure that the approach adopted, to control wash water quality and residual waste is not achieved in a way that causes pollution in other areas or environmental media.

The exhaust gas in the diesel engines contains several harmful substances emitted in the air. The main constituents are listed below (Henriksson 2006b). The Table 4.1 shows the main constituents emitted by ships in the Baltic Sea area.

Table 4.1 The main constituents emitted by ships in the Baltic Sea (total amount, tons/year).

Constituent	tons/year	Constituent	tons/year
NOx (as NO2)	283,208	Silicon	17
CO	8,714	Iron	31
THC (as CH4)	8,714	Calcium	148
CO_2	13,288,985	Magnesium	4.2
SO_2	224,955	Zinc	12
Particles	26,661	Phosphorus	3.7
Vanadium	431	Chromium	0.019
Sodium	43	Tin	0.019
Nickel	138	Lead	0.060
Sulphur	112,477	Copper	0.031
Aluminium	13		

4.2 Conclusions

Three kinds of deSOx-scrubbers with different modes for sea water and caustic soda operations have been compared with respect to marine environmental effects. Environmental Quality Standards (EQS), as used by some leading countries within EU as well as in USA and Canada, are used as basis of evaluation by applying different values for EQS .With proposed instructions and recommendations all types (maker ”A” caustic soda, maker ”B” seawater and maker ”B” caustic soda) are suitable for sulphur emission reduction with significant decrease of other contaminants as particles, heavy metals (V and Ni) and THC (total hydrocarbons). The values for PAH (polyaromatic hydrocarbons) could not be stated with confidence. Being components of THC, these were after proposed treatment under the limit of 15 ppm for oil. The restrictions for use without notable harm for marine ecosystem will follow from some process operations using concentrated caustic soda (low water volume) and thus leading to enrichment of metals, oily residues and soot in residual sludge. These wastes are guided for secondary treatment by precipitation, processing with bilge waters and delivered for port facility waste water treatment systems. Some modes of operation with soda will create waste water with high COD (chemical oxygen demand), which should be treated by aeration. Low pH when using sea water version should be buffered close to pH 6, before discharging back to sea. Low alkalinity in some ports and at some sea areas with brackish water will further restrict the use of sea water scrubbers because of low pH of effluent.

Literature data and simple material balance calculations with model values for average ship in operation at sea and in harbour confirmed the ship's role as significant contributor of sulphur to the atmosphere, and vanadium and nickel to sea water. When using scrubbers, these effects could remarkably be reduced. New connections between vanadium and nickel with marine life were noticed. These potential effects may favour some species with nitrogen fixation properties as bluegreen algae, some vanadium enriching species as invading fouling organisms (ascidians or tunicates), as well as some methanogens contributing to greenhouse gases and influencing to sulphate reduction. These effects may lead to gradual changes of marine ecosystem at community level.

Since much of vanadium and nickel will end to the sea with or without scrubbers, the above effects will not concern scrubbers as such. However, ship traffic is significant contributor of these metals basin wide and even globally, and these new ideas should be seen as supporting guiding action for scrubber manufactures for overall reduction of pollution with unforeseen effects by these metals.

5 Maker “A” caustic soda scrubber

5.1 Evaluation of environmental impacts

Maker ”A” caustic soda scrubber is efficient in SOx removal (90%), in particle reduction (30-40 %) with hazardous metal removal about 35% for V and Ni. The high efficiency is achieved by closed loop installation and by injection of soda lime. Using soda in process will favour high pH in effluent (7-7.5) which is desirable to marine environment. Even the stringiest regulations by EPA are thus fulfilled. Some problems may follow with chemical oxygen demand (COD), which is reported to be 5 –8 g/l, and thus very high. In order to reach the target 250 mg/l, secondary treatment by aeration may be needed, as proposed by maker ”A”.

Due to closed loop high amounts of solids will be produced with high concentrations of metals. Oil residues including lubricants and noxious hydrocarbons (PAH) are also present. These give the black soot-like appearance for the residue, and should be treated by port facilities. It is also not allowed to predilute high concentrations with other effluents from the process including sea water, because it is against the EU waste discharge policy. Since the volumes of effluent water are small, collecting it into holding tank for treatment on land in some port under SECA would be preferable. It is recommended that this should be the practice in future and even it lands some extra costs for users when compared to non-scrubber ships, it will accomplish the environment protection idea of the scrubber in full.
This kind of scrubber will concentrate metals as V and Ni in effluent water. The levels are far above the limits for any kinds of waste water criteria. However, if mixing is very rapid and the effluent is introduced in continuous manner into wake efficiently mixed by ship’s propellers when moving at open sea, some mitigating approximations could be used. It has been estimated that dilution 1:2000 will be achieved after the stern by 50 m (Entec 2005 task 2c), which can be assumed to take place rapidly without causing any harm for marine life. If this degree of dilution is taken as basis of calculation, the reported values for effluent are 36 µg/l for V, and 12 µg/l for Ni, the EQS values being 100 µg/l and 15 µg/l, respectively. So they are under the limit values, and thus approved. The dilution 1:2000 can be compared to traditional dilution requirement of about 50-100 that has been used for many years for outfall design in the coastal waters of several European countries (Larsen 2000). It is conceivable that the mixing by ship’s propellers at sea takes place more rapidly than mixing of coastal plumes by natural conditions only.

The influence of effluents from different kinds of scrubbers (including coal power plants and other flue gas deSOx installations), on marine life have been investigated by different manufactures and by others. In these studies it has been stated that the sulphate solids are the natural part of sea water and will not cause harm for marine ecosystems. It has also been demonstrated in two years study that the bottom fauna of a fjord is not affected by abundance or diversity in notable amount by deSOx effluent. Also the residual sulphite causing some COD-effects is rapidly converted in to harmless sulphate under natural conditions.

The only PAH compound which could be detected in the scrubber wash water residue was phenantrene. For all other PAHs the concentration levels were too small to be detected. Although phenantrene is not one of the most carcinogenic PAHs, it has been proven to induce cancer.

The emission of waste water from the scrubber was reported to be 1 626 511 m^3 for whole Baltic Sea fleet during a year. This waste water contains about 5 g of particles, originating from the exhaust gas, per litre.

Using phenantrene as an example, the strong adsorption of PAHs to particulate matter can be seen. The solid-liquid partitioning value of phenantrene in this system is approximately 1400. This value is based on the reported concentrations of 338 µg/kg in the residue and 0.24 µg/kg (originally 0.24 µg/l) in the filtrate. Therefore the particle emissions have more significance in the calculations.

Estimation of the total emissions of other PAHs is hampered due to the undetectable levels in wash water residue. The difference in quantification limits between water and particles was considerable: for e.g. benzo[a]pyrene it is 500 µg/kg (solid): 0.015 µg/kg (water) or about 33000-fold. It can, however, be estimated that the other PAH compounds would behave quite similar to phenantrene in partitioning between the water and solid phases.

For phenantrene, the emission for the above-mentioned Baltic Sea traffic can be calculated at 0.14 kg in expelled water and 0.96 kg in expelled solids, i.e. maximum ca. 1.1 kg per year. For benzo[a]pyrene, the maximum emission for similar conditions would be 1.4 kg in total. However, this is a upper-limit value deduced from the lowest B[a]P concentration (0.5 mg/kg) that can be observed. With regard to total PAHs, the total yearly emissions in scrubber waste water over the Baltic Sea are ca. 28.7 kg. These values as such can not be regarded as alarmingly high, but nevertheless have a substantial overall contribution to total PAH input (overall budget of PAHs) into Baltic Sea environment.
Lastly, the emissions of dissolved organic carbon (DOC; 520 g/m^3) and total organic carbon (TOC) in the residue (215 g/kg) yield a total of 296 t of DOC and 612 t of TOC, respectively, over the Baltic Sea yearly. Such input of DOC and TOC may have some effect on dissolved oxygen, but according calculations only marginal.

More over, the concentration of TOC in the scrubber wash suspension (215g/kg) exceed e.g. the maximum allowed concentrations in Finnish landfill waste (30g/kg) (http://www.finlex.fi/fi/laki/alkup/2006/20060202). In contrast, the total PAH concentration in scrubber waste water (9.9mg/kg) does not exceed the corresponding limit (40 mg/kg). These results are somewhat ambivalent and should be treated with total load of TOC to marine environment. Calculations with the above TOC (612 t) and dispersed in the whole water volume of 21000 km3 will give TOC concentration which is four to fife orders less than the ambient TOC level. Thus effects of TOC emissions can be largely ignored.

How high concentrations the PAHs and DOC/TOC actually are produced in the receiving waters can not be exactly deduced from the data available. Although dilution of the scrubber waste water takes place, the scrubber emissions produce temporarily locally concentrated plumes of PAHs compared to case where exhaust gases enter the atmosphere only (i.e. without use of scrubbers).

5.2 Possibility to reach the target

In summary, with the instructions and recommendations below, maker ”A” caustic soda SOx-scrubber can be interpreted to fulfil the criteria presently applied by EQS norms within EC and USA. With the present knowledge it is improbable that marine ecosystem will be notably harmed with scrubber waste at open sea area. In the manoeuvring situation it is also improbable that marine ecosystem will be harmed, but on quay it needs further treatment before discharging effluent to the sea. The effluent of maker ”A” caustic soda scrubber is suitable for environmental point of view:

	On quay	**Manoeuvring**	**Open Sea**
pH	yes	yes	yes
THC (oil)	yes (A)	yes	yes
Vanadium	yes (A)	yes	yes
Nickel	yes (A)	yes	yes
COD	yes (B)	yes	yes

A additional separation with bilge water needed
B aeration tank needed

5.3 Conclusions

Maker ”A” caustic soda scrubber is efficient in SOx removal (90%), in particle reduction (30-40 %) with hazardous metal removal about 35% for V and Ni. The high efficiency is achieved by closed loop installation and by injection of caustic soda. Using soda in process will favour high pH in effluent (7-7.5) which is desirable to marine environment. Even the stringiest regulations by EPA are thus fulfilled. Chemical oxygen demand (COD), is very high (5 –8 g/l). In order to reach the target 250 mg/l, secondary treatment by aeration may be needed, as proposed by maker A. This type of scrubber produces oily sludge, which as such is not allowed to be discharged into water at port. The recommended manner is to give the black soot containing sludge for port waste water facilities.

The effluent concentrations of nickel and vanadium may be higher in the maker ”A” scrubber than is proposed for IMO by the Norwegian and Finnish submission (Appendix A). There are, however, problems in the proposal. First, it sets limits for effluent heavy metal concentrations but does not limit the pollution flow of heavy metals into the atmosphere. The higher the PM removal efficiency of the scrubber is, the worse is the effluent quality, but the fewer pollutants are escaping into the atmosphere. An all-inclusive examination of PM and heavy metal emissions is therefore desirable. Second, the proposal compares the suggested limits with the measurement results, obtained some 15 years ago with a scrubber, probably not as effective as current devices. Third, the fuel used in those trials is unknown.

6 Maker “B” sea water scrubber

6.1 Evaluation of environmental impacts

Sea water scrubber removal efficiency for particles is high, about 60%. For the metals considered here the efficiency can be calculated to be about 60%. For vanadium and nickel the actual concentrations being 87 and 28 µg/l, respectively. They are under or near the EQS values (100 and 15 µg/l applied by this study). The problem with the sea water scrubber may be pH of the effluent, which is rather low 4.4-5.5 for undiluted and diluted mode, respectively. According to the most national regulations it is forbidden to discharge the effluent with pH below 6. However, the inherently low pH of the effluent can be increased up to 6 by adding NaOH into the scrubber wash water upstream the scrubber.

Effluent water volume in the sea water scrubber is relatively high and even higher when the sea water alkalinity is low. Discharging great effluent volumes in the port areas is questionable as such and especially if the pH of the effluent is low. This may restrict the use of the sea water scrubber in ports and especially in those Baltic Sea ports where the alkalinity level is low. Water volume could be somewhat reduced and effluent pH raised by using NaOH injection. Using low sulphur fuel in the auxiliary engines would solve the problem when at berth (main engines not running). Although the effluent dilutes quickly behind the ship while the ship is moving, in closed port basins the dilution is restricted due to the low basin water volume. This could be a problem in the ports with high number of port calls.

Maker “B” has a solution where the sea water scrubber can be changed into caustic soda mode. In harbours, closed-loop caustic soda mode must be definitely used to restrict the sea-water flow rate and to maintain the pH at 7. With sea water scrubber, oil is not a problem; since the limit for THC (15 ppm) is not exceeded (the actual values calculated are 2.5 and 1.8 ppm for undiluted and diluted mode respectively).

6.2 Possibility to reach the target

By the instructions below, maker ”B” sea water scrubber is suitable for SOx removal and fulfils the present EQS criteria with scrubber waste at open sea area. In the manoeuvring situation it is also improbable that marine ecosystem will be harmed, but on quay it needs further treatment before discharging effluent to the sea. The effluent of maker ”B” sea water scrubber is suitable for environmental point of view:

	On quay	**Manoeuvring**	**Open Sea**
pH	yes (C)	yes	yes
THC (oil)	yes (A)	yes	yes
Vanadium	yes	yes	yes
Nickel	no?	yes	yes
COD	yes	yes?	yes

A	additional separation with bilge water needed
C	additional NaOH required = caustic soda mode

6.3 Conclusions

The problem with the sea water scrubber may be pH of the effluent, which is rather low 4.4-5.5 for undiluted and diluted mode, respectively. According to the most national regulations it is forbidden to discharge the effluent with pH below 6. Based on this, the effluent should be treated by NaOH additions to pH 6 before discharging into the sea. At berth the great water volumes needed may cause difficulties. In other respects there will be no problems.

The effluent concentrations of nickel and vanadium may be higher in the maker “B” sea-water scrubber than is proposed for IMO by the Norwegian and Finnish submission (Appendix A). There are, however, problems in the proposal. First, it sets limits for effluent heavy metal concentrations but does not limit the pollution flow of heavy metals into the atmosphere. The higher the PM removal efficiency of the scrubber is, the worse is the effluent quality, but the fewer pollutants are escaping into the atmosphere. An all-inclusive examination of PM and heavy metal emissions is therefore desirable. Second, the proposal compares the suggested limits with the measurement results, obtained some 15 years ago with a scrubber, probably not as effective as current devices. Third, the fuel used in those trials is unknown.

Because it is, thus, unclear, whether an effluent WTU is capable of removing nickel and vanadium from the effluent, one must be careful in including discharge criteria for those compounds in the regulations.

7 Maker “B” caustic soda scrubber

7.1 Evaluation of environmental impacts

For caustic soda scrubber the removal efficiency of particles is calculated to be the same as with sea water type, viz. 60%. In this type the effluent pH is not a problem. Values for undiluted and diluted mode are reported to be 7.6 and 7.9 and will equal the EQS values.

Particle removal efficiency is high (60%), and V and Ni are removed at 60% efficiency. The actual concentrations of vanadium and nickel in the effluent are 133 and 43 µg/l, respectively. They will exceed slightly the EQS values 100 and 15 µg/l at discharge moment, but will decrease rapidly with mixing.

The values for THC (oil) are under the limit 15 ppm, viz. 4.8 and 2.8 for undiluted and diluted mode, respectively. This type of scrubber produces oily sludge, which as such is not allowed to be discharged into water at port (at port it is zero tolerance for oil). The recommended manner is to give the black soot containing sludge for port waste water facilities. The secondary treatment as precipitation and centrifugation e.g. with bilge water are needed, and any noticeable aesthetic trouble for the environment should be avoided. Also the chemical oxygen demand (COD) will be under 250 mg/l after initial dilution by 2000.

7.2 Possibility to reach the target

With the instructions below, maker ”B” caustic soda scrubber is suitable for SOx emission removal, and can be used without notable harm for marine life at open sea area and manoeuvring but on quay it needs further treatment before discharging effluent to the sea. The effluent of maker ”B” caustic soda scrubber is suitable for environmental point of view:

	On quay	**Manoeuvring**	**Open Sea**
pH	yes	yes	yes
THC (oil)	yes (A)	yes	yes
Vanadium	yes (A)	yes	yes
Nickel	yes (A)	yes	yes
COD	yes (B)	yes	yes

A	additional separation with bilge water needed
B	aeration tank needed

7.3 Conclusions

For caustic soda scrubber the removal efficiency of particles is calculated to be the same as with sea water type, viz. 60%. In this type the effluent pH is not a problem. Values for undiluted and diluted mode are reported to be 7.6 and 7.9 and will equal the EQS values. The scrubber produces oily sludge, which as such is not allowed to be discharged into water at port. The recommended manner is to give the black soot containing sludge for port waste water facilities.

The effluent concentrations of nickel and vanadium may be higher in the closed-loop caustic soda scrubber of maker ”B” than is proposed for IMO by the Norwegian and Finnish submission (Appendix A). There are, however, problems in the proposal. First, it sets limits for effluent heavy metal concentrations but does not limit the pollution flow of heavy metals into the atmosphere. The higher the PM removal efficiency of the scrubber is, the worse is the effluent quality, but the fewer pollutants are escaping into the atmosphere. An all-inclusive examination of PM and heavy metal emissions is therefore desirable. Second, the proposal compares the suggested limits with the measurement results, obtained some 15 years ago with a scrubber, probably not as effective as current devices. The fuel used in the trials is unknown.

Because it is, thus, unclear, whether an effluent WTU is capable of removing nickel and vanadium from the effluent, one must be careful in including discharge criteria for those compounds in the regulations.

8 Rough evaluation of the sensitivity of other SECAs compared to Baltic Sea

8.1 Sulphur dioxide emission control areas

Due to Marpol Annex VI and EU regulations, sulphur molecules in exhaust gases must be reduced in heavy fuel oil (HFO) burning engines. Under Annex VI, the maximum allowable sulphur content of marine fuel is now 4.5% but a 1.5% sulphur limit in marine fuels was set to take effect on May 19, 2006 in sulphur dioxide (SOx) emission control areas (SECAs) including the Baltic Sea, as agreed in the International Maritime Organization (IMO) Marpol Annex VI ship bunker fuel treaty which entered into force in May 2005. The North Sea and English Channel is the second SECA where the new rules will not enter force until November 2007. IMO defines the areas as follows:

- The Baltic Sea area means the Baltic Sea proper with the Gulf of Bothnia and the Gulf of Finland and the entrance to the Baltic Sea bounded by the parallel of the Skaw in the Skagerrak at 57°44.8´.
- The North Sea area means the North Sea proper including seas therein with the boundary between:
    - the North Sea southwards of latitude 62° N and eastwards of longitude 4° W;
    - the Skagerrak, the southern limit of which is determined east of the Skaw by latitude 57°44.8´ N; and
    - the English Channel and its approaches eastwards of longitude 5° W and northwards of latitude 48°30´ N.

IMO is likely to designate additional SECA regions in the months ahead (Safety at Sea, 2005). These could be the Mediterranean Sea as well as east and west coasts of the United States. A number of facts should be evaluated for comparison of SECAs with respect to vulnerability of local ecosystems, some being trivial some under hot scientific debate. These include:

- openness to receiving water body
- geography (basin shape, subdivisions)
- hydrology (runoff, its areal distribution, depth)
- meteorology (climate, temperature, prevailing winds)
- environmental loading (catchment area/sea area-ratio, residence time)
- stress factors:
    - natural:
        - temperature, salinity, ice cover
        - alkalinity, pH-buffering capacity, oxygen level
    - pollutional:
        - biodegrability, temperature, ambient levels

8.2 Comparison between SECAs

Three different potential SECAs (the North Sea, the Mediterranean Sea and coastal area of California) are compared shortly below for these stress factors with respect to the Baltic Sea. Other possible future SECAs are Tokyo (voluntary, implemented 2006), Hong Kong (planned, completed 2007), US east and west coast, Gulf of Mexico and Great Lakes (completed 2010-2012). These latter ones are not treated here.

The Baltic Sea is assumed to be most vulnerable because of restricted water renewal, low oxygen level, the shallowness, relative long residence time (25-30 year), brackish water with low salinity and alkalinity, high external loading (wide catchment area, dense population), northern climate, prevailing south-western winds along the basin configuration, biodiversity and bioaccumulating chemicals.

The North Sea, on the other hand, is heavily traded by ships, comparable to US east- and west coast planned for new SECAs. Geomorphology without remarkable sub basins favours more wide distribution of hazardous substances. Even to be rather shallow it will tolerate more acid wastes because of higher alkalinity. The biodiversity is also higher because of higher salinity. Water exchange and vertical mixing are more efficient and higher temperature favours biodegrability of oily wastes. Pollution from ships does not go directly to sea (spreading 400-1200 km inland, generally applicable for other coastal areas).

The Mediterranean Sea is a semi enclosed sea with mean depth about 1500 m, and water residence time about 80 years. Average temperature is high (13-15 ^{o}C), alkalinity and salinity are high and vertical mixing comparatively efficient. More pressure is focused on the northern coast because of population structure, biased river runoff (92% of total), and harbour density. The greater volume (about 170 times the volume of the Baltic Sea) as well as the open coastline will reduce the near pollution effects. Still, the prevailing northerly winds will direct the atmospheric pollution load to the sea. Also, the area is highly contaminated with oil (PAH load from ships estimated to be 1000 t/a). The acidity problems by shipping are not so relevant when compared to Baltic Sea or the North Sea. Main target is Adriatic Sea. EC shows some reluctance for new SECAs, requiring a learning period.

The Californian coast (24 nm). This area is directly connected to the sea. Thus the initial mixing area is narrow, and the wastes are efficiently diluted. Alkalinity is also high. Westerly winds will direct the SOx load from ships to inland. Area is more tolerable against pollution from ships. Proposed regulations for auxiliary engines and abatement technologies will reduce SOx and particle emissions by 70-80 % giving improvement of local environment. More restrictions for main engines and fuel will follow 2010-2015.

8.3 Conclusions

The environmental pressure concerning sulphur limitation will originate from complex hybrid of pollution load, traffic routes, basin geomorphology, hydro-meteorology and ecosystem structure. Thus the rules from case to case do not usually apply for all areas and the evaluation of the situation by local authorities is needed. As a main rule it will be still stated the following: The SOx –scrubber proved to be safe for the most vulnerable area as the Baltic Sea will be applicable for other SECAs with the present level of sulphur limitation. It is still possible that the effects tolerated on community level will be fatal for sensitive species as for some fishes and oysters, which have more strict requirements for oxygen and pH levels and will differ from the environmental standards used by this report.

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