TECHNICAL REPORT

DET NORSKE VERITAS, NORWEGIAN RESEARCH COUNCIL

TECHNOLOGIES FOR REDUCTION OF POLLUTION FROM SHIPS

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Summary:

This report gives an overview of means for pollution reduction from ships. The report focus on emissions and discharges to environmental problems on the agenda; global warming (CO2: carbon dioxide), acidification (SOX: sulphur oxides, NOX; nitrous oxides), ground level ozone formation (VOC: Volatile Organic Compounds, NOX), air quality (PM; Particulate Matter, CO: carbon mono-oxides, HC: hydrocarbon), toxic effects of tributyltin (TBT) and alien species changing regional ecosystems (discharged through ballast water).

A range of means are identified, particularly for the reduction of NOX and SOX. Alternatives to TBT based antifouling are available although the experience is limited.

This report do not give cost figures for acquisition, operation and maintenance. Moreover, practical limitations in terms of space requirements for the technology, operational limitations, work load, maintenance needs, etc. have not been fully explored. These factors have to be taken into account prior to any recommendations for pollution reduction strategies.

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1 INTRODUCTION

This report aims at giving an overview of technological options for the reduction of pollution from ships. The report does not give a complete and detailed list of all available means, and in particular costs related to options and experiences gained by operators could be improved. The report will be subject to revisions to include new knowledge and experiences as compiled through other projects and activities.

2 EXHAUST GAS EMISSION REDUCTION METHODS

In order to reduce emissions to air from marine engines, different reduction methods have to be initiated. The selected means can be initiated either:

- before start of the combustion process (fuel oil treatment and fuel oil modifications)
- during the combustion process (reduce formation of air pollutants in the combustion process)
- after the combustion process has proceeded (exhaust gas treatment)

When the reduction methods are to be initiated, depends on which component that is to be controlled, for instance SO_X can easily be controlled before the combustion process by removal of sulphur in the fuel, while NO_X can be controlled during the combustion process by reducing the combustion temperature.

Some of the reduction methods can have a negative or positive effect on other exhaust gas components and the specific fuel consumption.

2.1 CO_2 and SO_X reduction

The amount of CO_2 and SO_X in the exhaust gas from an engine is directly proportional with the carbon and sulphur level in the fuel burned.

Reduction of CO_2 and SO_X emissions can be achieved by an engine efficiency increase, or through a change to alternative fuels with lower carbon and sulphur content (for instance Liquefied Natural Gas (LNG)). Introducion of LNG as ship fuel requires new bunkering systems in the ports, which for the time being puts strong limitations on the possible implementation of this technology. There is also a safety aspect to be considered when using LNG /1/.

Methods for reducing the formation of CO_2 or methods for removal of CO_2 in the exhaust gas are not identified. However, reduced fuel consumption and thereby reduced CO2 emissions could be obtained by:

- reduced speed; e.g. a 80,000 dwt ship may reduce CO_2 emissions with 50% when reducing speed with 30% from 24.5 knots to 16 knots /39/
- weather and ocean current routing; up to 7% reduction potential claimed /39/

- propeller maintenance; if the propeller is not cleaned after one year, power consumption is increased by 3% /39/
- retrofitting propeller shrouds; these savings decreases as the speed increases. CLT propellers from Sistemar have proved savings of 10% and a payback in two years /39/.

The SO_X reduction methods and corresponding reduction potential are presented in Table 1.

Table 1 SO_X reduction methods

No.	Reduction method	Description	Reduction potential	Investment costs
1	Limiting the sulphur content in the fuel	The method is intended to control the SO_X emissions by means of reduction of the sulphur content in the fuel before delivery of bunker to the ship	Likely 70% /2/	Approx. 180–400 NOK/tonne fuel for reduction from 3% to 1% sulphur. Further reduction will result in a significant cost increase /2/.
2	Sea water scrubbing	The method is intended to control the SO_X emissions by means of seawater washing of the exhaust gas	80% – 95% /4/	Unknown, but anticipated to be significant lower than for a SCR unit (NO_X)

In order to produce low-sulphur fuels, de-sulphuring of the present types of fuel may be carried out prior to the delivery of the bunker to the ship. This is however an expensive procedure which also results in the production of large quantities of sulphur.

Provisional rules presented in Lloyd's register of shipping/3/ indicates that the emission of SO_X is to be controlled by limiting the sulphur content of fuel used onboard. In the report, no cleaning methods are evaluated and taken into consideration. Bunker oil with low sulphur content is about 15-20% more expensive than regular bunker oil /34/.

Seawater washing of exhaust gases is a well-known method, which is commonly used at onshore installations. For a marine engines, there are identified several types of equipment that can be installed with the purpose of seawater washing of the exhaust gas /4/. A SO_X seawater scrubber can be built in combination with a scrubber to reduce the NO_X emission /3/.

In restricted waters with heavy traffic, cleaning the water from the sea water scrubber may be required to reduce the concentration of sulphur in the seawater.

2.2 NO_X reduction

A number of methods which separately or combined reduce the NO_X emission from marine engines are identified /1/, /2/, /5/. The methods are mostly based on changing the combustion temperature or by cleaning the exhaust gas. The NO_X reduction methods and corresponding reduction potentials are presented in Table 2.

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Table 2 NO_X reduction methods

No.	Reduction method	Description	Reduction potential	Investment costs
1	Emulsification	The emulsification method is intended to control the NO_X emissions by means of adding water to the fuel oil.	20% – 25% with 20% - 25% water in the fuel /1/.	approximately 250.000NOK for engines less than 3MW
2	Fumigation (humidification)	The fumigation method is intended to control the NO_X emissions by means of adding water to the charge air.	Indicated to be above 70% /1/.	Unknown
3	Direct injection	The direct injection method is intended to control the NO_X emissions by means of direct injection of water or other liquid directly into the engine cylinders.	50% – 60% /1/	75 – 220 NOK/kW
4	Selective catalytic reduction (SCR)	The SCR method is intended to control the NO_X emissions by means of a selective catalytic reduction unit.	85% to 90% /1/	>1000kW, 300-500NOK/kW <1000kW, 500-1500NOK/kW running expenses excluded
5	Selective none catalytic reduction (SNCR)	The SNCR method is intended to control the NO_X emissions by means of catalytic reduction without presence of a catalyst.	Above 95% /1/	In the same range as a SCR unit
6	Engine tuning and injection retard	The engine tuning and injection retard method is intended to control the NO_X emissions by means of: • Reducing the charge air temperature • Retarding the start of the oil fuel injection	10% – 30% /1/	Low cost alternative
7	Exhaust gas re-circulation (EGR)	The EGR method is intended to control the NO_X emissions by means of re-circulation of cooled and filtered exhaust gas to the charge air.	Not known	Not known

The NO_X reduction methods listed above are well known methods used by engine suppliers. However, measurements available for verification of the reduction potential are few, especially when reduction methods are combined. As a consequence, the presented reduction potentials presented in Table 2 are indicative /1/.

2.2.1 Emulsification, fumigation and direct injection of water

Addition of water to the combustion process contributes to reduction of the NO_X emission. The water is added to the combustion process in order to reduce the combustion temperature, which is an important factor in the formation of NO_X. Heating and evaporation of the water causes the temperature reduction and with that the NO_X reduction.

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The emulsification, fumigation and direct injection methods are separated by their method of adding water to the combustion process.

The emulsification method is based on adding water to the fuel oil before injecting the emulsion into the combustion chamber. By adding water to the fuel and mixing by means of a homogeniser, it is claimed that NO_X emissions may be reduced 50% /35/. Injection of water/fuel emulsion results in effective atomising and good distribution of the fuel in the combustion chamber and it results in better combustion with lower fuel consumption, a cleaner engine and a reduction of air pollutants such as NO_X, CO, HC and PM. The emulsification method is suitable for new and existing marine engines.

The fumigation method is based on adding water or steam to the charge air. The method is in an early development phase with limited information available.

The direct injection method is based on injecting water into each combustion chamber. The method requires direct intervention/controls at the engine. Direct injection is not a common NO_X reduction method and there are few references to installations in operation.

2.2.2 Selective catalytic reduction (SCR)

Selective catalytic reduction is the most common method for removal of NO_X in the exhaust gas emitted /1/. The SCR method reduces NO_X to N_2 by using NH_3 (ammonia) or urea as a reactant. The NO_X reduction takes place in a SCR reactor, which holds a catalytic material in small replaceable units. The reactor operates in a temperature range of about 270 – 500 °C.

In addition to the NO_X reduction, reduction of HC, CO and PM may be achieved by including an additional oxidation step in the SCR unit.

The SCR technology is suitable for installation in existing vessels and has the highest implementation rate at four stroke medium speed engines. High-speed engines can favourable take use of the technology while installations at large slow speed engines can be complicated due to lower exhaust gas temperature and high sulphur content in the fuel /1/.

The SCR method is also effective for “small” engines. However suppliers indicates a practical lower limit at 300-500 kW due to expensive installation costs, which gives a high cost per kW.

NO_X emission reduction of 90% is reported by implementation of a SCR plant serving a low-speed engine on a 30 000 dwt bulk carrier /33/. A vessel may bypass the SCR during open sea voyage. Close to shore, the engine feed is switched from heavy fuel oil to gas oil and the exhaust gas is gradually passed through the SCR reactor. When the temperature has raised to the right level, ammonia dosing is started to effect NO_X control.

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The passenger ferry Stena Jutlandica is equipped with a catalyst. The NO_X emissions are assumed to be reduced to about 2 g/kWh. A catalyst with the reduction potential of 80-95% costs between 1.5 and 3 million NOK to install /34/.

ABB Flakt has the longest running catalytic converter in a merchant ship - the Scandilines ferry Aurora. These SCR's have about 50,000 operating hours. NO_X reductions remain at 97-98%. HC reductions are 88% and CO reductions are 53%. Additional operating costs are that of urea, which is used as a 40% aqueous solution with a consume of 14 litres per MWh. Experience with a vessel using HFO with a 2.6% sulphur indicate that this does not appear to harm the catalyst /40/.

The German company TT line had an SCR installed on one of its vessels, but found that operating costs were high and decided therefore not to have SCR on newbuildings /42/.

2.2.3 Selective none catalytic reduction (SNCR)

SNCR is based on NO_X reduction without use of a catalyst, but with presence of a gas that can release free nitrogen atoms. Gases which has that capacity, are among other ammonia (NH_3) and urea ($CO(NH_2)_2$). For these gases, the reduction method is effective in the temperature range of 900 to 1000°C. Negative effects are identified when running the process above or below this temperature range (emission of NH_3 at low temperature and production of NO at high temperature).

The SNCR reaction process requires relative high temperatures and sufficient reaction time to have the wanted effects. This makes the SNCR method less suitable for combustion engines /1/.

2.2.4 Engine tuning and injection retard

For most of the engines, simple engine specific adjustments may be applied in order to reduce the NO_X emission. Currently, the most interesting adjustments are injection retard and a reduction of the charge air temperature.

Retarding the start of the oil fuel injection reduces the combustion peak temperatures and with that the NO_X emission.

Reducing the charge air temperature does also lower the combustion peak temperatures, which is an important factor in the NO_X formation process. Reduction of the charge air temperature may be achieved by:

- Moving the charge air intake from engine room to open air
- Adjusting the charge air cooler settings, or
- Installing a charge air cooler

The engine tuning and injection retard method has in some cases negative effects on the formation of HC and CO. The injection retard method separately may increase the fuel

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consumption by approximately 3%, and consequently a corresponding increase in CO_2 and SO_X emissions. The increase in the fuel consumption depends on engine type and the delay of the fuel injection.

2.2.5 Exhaust gas re-circulation (EGR)

Re-circulation of the exhaust gas may reduce the NO_X emission significantly /1/. The exhaust gas to be re-circulated, must be cooled and filtered before mixing with the fresh air. The NO_X reduction is achieved by:

- Increase in the thermal capacity for the charge air (reduces the combustion peak temperatures)
- Reduction of the O_2 concentration in the charge air which gives less O_2 to react with N_2.
- Lowering the combustion speed (caused by reduction of the combustion peak temperatures and the reduction of the O_2 concentration)

Re-circulation of exhaust gas is a well-known and tested technique, normally used at incinerator facilities onshore. However there are still some unsolved problems to be solved before EGR can be widespread as a NO_X reduction method for marine engines. The problems are especially connected to combustion of heavy fuels.

There are, at some tests, reported significant increases in the emission of PM when using EGR. This is probably caused by poor combustion conditions/1/.

2.3 Reduction of CO, HC and PM

Methods that reduce the emission of CO, HC and PM from marine engines are identified. The reduction methods and corresponding reduction potentials are presented in Table 3 and Table 4 /1/, /3/.

Table 3 Reduction of CO and HC

No.	Reduction method	Description	Reduction potential	Investment costs
1	Emulsification	Ref. Chapter 2.2.1	CO, 65% /5/.	Ref. Table 2
2	Oxidation reactor	The oxidation method is intended to control the emissions by means of oxidation of carbon to CO_2 and hydrogen to H_2O.	HC, 70% CO, 90% – 95% /1/, /3/.	Unknown

An oxidising reactor can be installed in order to reduce the content of CO and HC in the exhaust gas. The oxidation process transforms these elements to CO_2 and H_2O. An oxidising reactor can be installed in combination with a selective catalytic reduction (SCR) unit (see chapter 2.2.2) /3/.

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The PM in the exhaust gas is a mixture of soot (pure carbon), ashes (metal oxides, sulphate and other non-combustible materials) and unburned fuel (not in the shape of gases) /6/.

Possible methods for reduction of PM in the exhaust gas are presented in Table 4 /3/. Today none of the available methods for control of the emission of PM used on land based installations, have been tested onboard ships.

Table 4 Reduction of PM emissions

No.	Reduction method	Description	Reduction potential	Investment costs
1	Emulsification	Ref. Chapter 2.2.1	75% soot red. at 35% water in the fuel *	Ref. Table 2
2	Cyclones	Use of centrifugal force to remove the PM	Not known	Not known
3	Electrostatic-filters	Use of electromagnetism to remove the PM	Not known	Not known
4	Filter-bags	Use of filter-bags to remove the PM	Not known	Not known

* The portion of soot in the PM may vary. For low sulphur diesel (0.1%) can 45% of the PM be soot while only 25% are soot for heavy fuel with 3% sulphur /6/.

Combustion of lubrication oil causes some of the PM emissions. The lubrication oil contains a lot of additives in order to better the lubrication characteristics. The additives are normally not combustible.

Cyclones, electrostatic filters and filter-bags are well known and tested in the onshore industry. However due to lack of information on the efficiency of such methods when used onboard ships, it is not possible to establish the possible effect when it comes to reduction of this type of emission.

2.4 Alternative power generation

Diesel electric engines may reduce fuel consumption and related emissions. Siemens is producing such engines for fishing vessels and tests made on a supply vessel in the North Sea with diesel electric engines showed savings of about 40% /30/.

Møre og Romsdal Fylkesbåtar have ordered the first gas-driven ferry in the world. The fuel applied will be LNG and the NO_X reduction is estimated to 90% compared with conventional diesel engine propulsion /31/.

Stena Lines HSS catamaran ferries have gas turbine engines with emissions in the range 4-6 g/kWh. These ferries are rebuilt with respect to fuel injection which reduces the emissions to 2 g/kWh /34/. The maximum allowable NO_X emission level for diesel engines is in the range 10-17 g/kWh, depending on rated engine speed /45/.

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2.5 Energy recovery

Instead of wasting the heat energy in the exhaust gas it can be utilised to produce steam for other areas of the ship which would otherwise require the use of oil-fired boilers. However, operators are concerned with the increasing number of soot fires in exhaust gas boilers recorded the recent years /36/. Risk related to soot fires may be reduced by design (temperature difference between the exhaust gas and the water/steam, exhaust gas velocity, water inlet velocity) and soot blowing (up to every two hours).

3 SLUDGE TREATMENT

Sludge may be reduced by locating a homogeniser between the day tank and the purifiers. Impurities and water are then homogenised into the fuel and pass through the purifier, thereby reducing the sludge discharged by the centrifuge. However, this method of operation may not meet with the full approval of engine manufacturers (such as MAN B&W) /35/.

Sludge may be treated onboard by use of ship incinerators /14/**,** /15/**.** The sludge then often has to be added diesel to make the sludge pumpable. However many ships do not have incinerators and therefore the sludge has to be delivered ashore in oily waste reception facilities. Such facilities are however not very common all over the world and therefore much of the sludge is discharged into the sea. If a facility exists it is often not used due to high disposal costs for the oily waste /14/, /16/, /17/, /18/.

A facility for treatment of oily sludge may be a barge or a truck to collect the sludge from the ships. After a simple decanting of water and sediments, the remaining oil may be sold as fuel e.g. for brick factories.

3.1 Costs for treatment facilities

The cost for a treatment facility depends totally on the size of the facility. However a general system should consist of a barge to transport both sludge, bilge water, waste lubricating oil and garbage from the ships to a reception facility located in the port. Such a barge should be 40-50 feet and it should be self-driven with about 350 hp. Such a barge will cost approximately 115 mill NOK /17/.

Recommended treatment is settling of sediments, cleaning of the precipitating water and de-watering of the oil phase. This facility consists of a storage tank with capacity of e.g. 250 m^3, a de-watering product tank of 25 m^3 with heating, a small water purification facility and containers for reception of garbage and mixed solid oily waste. The cost for such a facility is in the region 5.5 mill NOK /17/**.**

In addition there is a need for small collection tanks for waste lube oil. On an average 10 tanks may be needed in each port with a capacity of 0.5 m^3. The cost of this is in the region 120.000 NOK.

For ballast water it may be sufficient only to upgrade existing facilities with modern containerised oily water treatment packages consisting of combinations of clusters of hydrocyclones, gravity separation and coalescing filters. A package with capacity of 500 m^3/hour costs about 4,5 mill NOK /17/.

For sewage it is recommended to use the same barge as for oily waste and garbage. Onshore it should be sufficient with use of existing trucks provided by private companies. These may then collect the sewage and transport it to the local sewage treatment plant. Thus there are no direct cost for facilities with regard to sewage.

A feasibility study on treating oily waste aboard the ship by means of aqueous oxidation at high pressure and temperatures is reported in /28/. Wet air oxidation proved to be a very efficient technology for treatment of those residual currents, resulting in destruction efficiencies of greater than 90% of initial COD (chemical oxygen demand) and 99,9% of oil/greases content. High pressure (2-20 MPa) make possible higher oxygen concentrations in water, also assuring that the reaction medium is liquid. High temperatures (150-300 ^{o}C) favour fast oxidation rates, obtaining high elimination percentage in short reaction times. Wet air oxidation has been applied to many different wastes and an extensive review is presented in /29/.

4 ANTIFOULING PAINT

Tributyltin (TBT) is one of the most effective organotin compounds used extensively in antifouling paints. However, the environmental impacts have forced the industry and IMO to consider alternatives. The disadvantages of alternatives may be /37/:

- reduced docking intervals (and increased costs). It should be noted that according to International Paint, the most frequent docking interval today is 24-36 months.
- increased drag resulting in increased fuel consumption and related emissions
- reduced effectiveness of antifouling paint may result in unwanted organisms attached to the hull and brought from one area to another
- environmental impact of copper-based replacements are not well documented

The costs of tin-free copper based alternatives are a factor two higher than TBT paint /37/. Paint based on silicon provides a slippery and very smooth surface. No biocides are needed because the vessel moving through the water washes fouling off. This coating is soft and prone to damage. Careful repair is needed and the paintings are presently not really suitable for larger tankers and bulk carriers. This type of paint can at the moment be applied to high speed vessels (operating around 30 knots), but costs are a factor five above TBT based paint /37/. Alternatives to TBT antifoulings are summarised in Table 5 according to /37/.

International Paint claims that their copper-based Ecoloflex can last five years while rosin-based paints can last three years /41/.

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Table 5 TBT free alternatives to antifouling paints /37/

Product	Key words
Intersleek 425, International Paint	- used for fast ferries since 1996 - full ship trails conducted on another version which is effective around 15 knots, particularly good for schedule ships which do not stop for long, especially cruise ships - coating will last for 5 years
Hempasil SP-EED, Hempel	- now being trialled , promising long term performance - coating is anticipated to be effective for 5-10 years
Sigmaglide, Sigma	- successful application to US naval vessels (aircraft carrier and submarine)
BIOX, Kansai	- applied to water inlets of power stations, too expensive for ships
Intersmooth Ecoflex, International Paint /38/	- self polishing co-polymer (SPC) based on copper acrylate - may be effective up to five years - applied by more than 1200 ships above 4,000 dwt since 1990 - results indicate effectiveness corresponding to TBT-SPC - currently 10 ships with a five year system
Globic SP-ECO 8190, Hempel	- based on fibre composite formulation (hydrolysable zinc carboxylate polymer salt binding technology - tested on a wide range of low to medium speed coastal vessels with medium to long idle periods - a corresponding alternative (8199) is available for medium to high speed deep sea vesselswith short idle periods - it has demonstrated a level of fouling control performance higher than conventinal tin-free systems
Sea Quantum, Jotun	- SPC tin free alternative based on sophisticated silyl polymer, full five year system - tests by means of sea trails on many types of vessels over the past 4 years with excellent results (86% success rate) - another year with testing before product launched to market - ships in regular traffic in northern waters have highest success rate
Sigmaplane Ecol, Sigma Coatings	- self polishing tin-free antifouling based on copper oxide - commercially in use for six years - one version for high activity vessels with short stationary periods - one version for medium activity vessels with occasional stationary periods of 5 to 20 days - effective life of around three years
TFA 10, Camrex Chugoku	- self-polishing copper oxide antifouling with gumrosin as the base - has shown a success rate of 80-85% (which is about the limit of this technology) - Seatender is the companies special copper oxide antifouling for specific use (warm water, deep sea, application over old TBT)
Sea Grandprix, Camrex Chugoku	- first used commercially in 1995, now on 500 ships - same controlled polishing rate as TBT copolymer but is copper bound copolymer - linear release, no leached layer, no skeletal layer - foul-free performance of 90-95%
ABC3, Ameron	- contains cuprous oxide and biocides and performs at least as well as tin based paint - cheaper than TBT based paints - used on US Navy vessels since 1983 and on commercial vessels since 1986 - effective life of up to 5 years - ABC4 is without biocides but life time reduced to 36 months
Exion, Kansai	- zinc acrylate polymer reacting with seawater and working by ionic exchange - the result is a dissolution process that is as even and controlled as that of TBT - product tested on ocean going vessels last three years; container vessel, Mobil and Shell tankers - early days of testing, good results, aiming for 5 year life time

5 ALIEN SPECIES IN BALLAST WATER

Species of bacteria, plants and animals can survive in the ballast water and sediments for several weeks. When discharged, new colonies may establish that can significantly alter the ecological balance. Some states have established controls of the discharge. Ballast water exchange have to be logged and reported. Mid-ocean ballast water exchange prior to arrival is the preferred option. However, this may conflict with the safety of the ship as ballast water exchange may impact both the stability and the hull strength of the ship /43/.

Intertanko and the International Chamber of Shipping have developed guidelines for ballast water exchange. The Model Ballast Water Management Plan describe a step by step procedure for ballast water exchange at sea to reduce the risk of introducing alien species while maintaining the safety of the ship (stability and hull strength) /43/.

A pre-study has been carried out to evaluate the feasibility of combining the principles of bio-geography and those of risk assessment to prevent the transfer of harmful aquatic species /32/. The idea is to develop a decision support system that gives advice for ballast water management according to biological conditions at ballast water uptake compared with the conditions in approaching port area.

A summary of current treatment methods are given in Table 6 /44/.

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Table 6 Treatment methods for ballast water /44/

Treatment method	Advantages	Disadvantages
In-transit exchange - flushing with oceanic water	- effective at removing a wide range of taxa from ballast water when carried out correctly - no chemical by-product disposal	- may require design modifications - not all ships can comply - may not remove organisms from sediment - may be unsafe in bad weather - only suitable for longer voyages
In-transit exchange - emptying and refilling	- effective on a wide range of taxa when carried out correctly - no chemical by-product disposal	- may not remove organisms from sediment - may be more unsafe than exchanging ballast water by flushing
Heat treatment	- effective on certain taxa at temperatures of 35-45 ^{o}C - no chemical by-product disposal	- may be taxa-specific - depends on ambient sea temperature, duration of voyage and volume of ballast water - thermal effluent may affect discharge area
Filtration/screening	- can remove wide range of organisms - no chemical by-product disposal	- engineering modifications required - filters for small organisms may be costly - filters must be backwashed to prevent clogging
Biocide compounds	- widely used in water treatment - lots of scientific data available	- may generate toxic by-products - chemical by-products must be disposed of - chemicals may be costly - safety concerns when handling a ship

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6 EMISSION REDUCTION METHODS FOR HC GAS

The amount of VOC emissions from ship's oil cargo on a specific trade depends on the cargo characteristics, the design of the cargo handling system and inert gas/venting system, the configuration of cargo tanks, and operational procedures and weather conditions. Some terminals have reception facilities for VOC gas during loading /7/. VOC gas may also be applied as inert gas /19/.

Apart from optimising loading and discharging procedures, little has been done to recover VOC in connection to offshore loading. Work to develop a VOC recovery process has taken place since 1993, with the target of 70% recovery. Several recovery process concepts are available, and are divided into three main categories /7/:

- Condensation through compression and cooling
- Absorption, either directly into the cargo oil or via “wash oil”
- Hydrate process

The VOC gas is then be recovered into the cargo oil. Moreover, attempts are made to use condensed VOC gas directly as fuel /19/.

The Norwegian Shipowners' Association will consider the following technical potential for reducing NMVOC emissions /12/:

- Vapour Emission Control System (VECS), i.e. closed systems to the greatest possible extent for loading and unloading
- Increased tank pressure while sailing
- A higher degree of filling of cargo tanks
- Optimised Crude Oil Washing (COW)

The NORSOK standard recommends that shuttle tankers and offshore and onshore loading systems shall be designed for minimal emissions of methane and NMVOC, e.g. by considering /13/:

- Sequential loading/discharge of oil from tankers
- Optimised geometry of tanks with respect to evaporation of hydrocarbons
- Loading/discharge rate with respect to evaporation
- Optimised oil temperatures, RVP and TVP
- Recovery units for hydrocarbon vapour.

6.1 Design and operation

The factors influencing the emissions can be controlled to a varying degree through measures related to design and operation, as briefly described below:

- Minimise agitation in cargo tanks during loading. This could be achieved through narrow cargo tanks, application of splash bulkheads, minimisation of ship rolling and pitching, low flow velocity and application of baffle plate to ensure smooth inert gas inflow, and minimisation of temperature gradients between cargo oil and bulkheads /27/. The oil inlet should be below oil surface /19/.

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- Application of a vapour emission control system (VECS), whereby the total tank atmosphere displaced from the cargo tanks during loading is piped to a HC recovery plant onshore or onboard. Some emissions will take place, particularly of methane and other light components, as a processing plant is never 100% efficient /8/.
- Application of a system for sequential transfer of tank atmosphere, whereby increased HC partial pressure in the tank atmosphere will reduce evaporation during unloading and loading /8/.
- High pumping rates during loading and unloading reduce the time where the oil surface is exposed to an unsaturated tank atmosphere. Sequential loading and unloading of tank sections with high pumping rates when loading/unloading all tanks parallel has an even lager effect /8/.
- Breaks in loading /unloading when tanks are partly filled will cause increased evaporation and emission. Increased evaporation will take place during sea voyages with partly filled tanks /8/.
- Increase of the VOC partial pressure in cargo tanks during loading by applying a pressure control value in the vent riser, and higher than usual opening pressure of P/V values would reduce the emissions (up to 1,7 bara) /27/. Evaporation is reduced with a high VOC partial pressure in the tank atmosphere.
- Ships with double bottom or double hull will need shorter timed for stripping and for Crude Oil Washing (COW), resulting in somewhat reduced emissions /8/.
- Ships with double bottom/hull will have lower stability and/or lower roll period than single hull sips, resulting in higher emission on a loaded voyage in heavy weather. Double bottom/hull gives small changes in cargo temperature during the voyage. Maintaining a high cargo temperature causes a higher evaporation during unloading. On the other hand, stable cargo temperature during the sea voyage diminishes the need for topping of inert gas /8/.
- Procedure for topping of inert gas pressure in cargo tanks on a sea voyage will influence the emissions. A too high inert gas pressure will result in venting when VOC evaporate during voyage. By allowing an over-pressure in tanks (0,1-0,13 bar) the emissions of VOC are reduced /22/.
- Emissions will be lower when loading/unloading take place at a terminals where the cargo temperature is equal or lower than the steel temperature in the ship's deck, than if the opposite is the case /8/.
- Emissions are highly dependent on the cargo oil vapour pressure (TVP): some crudes are spiked with light hydrocarbons. For a given RVP (Reid Vapour Pressure) the true vapour pressure is dependent on the cargo temperature, and consequently the TVP is reduced if the cargo could be cooled before loading /8/.
- Emissions during crude oil washing (COW) increases with the duration, pumping rate and vapour pressure of the washing oil. Evaporation may be minimised by recirculation of the washing oil, reduced washing time and pumping rate through increased cleaning efficiency, and high VOC concentration in tank before COW is started /27/.

6.2 Sequential loading/unloading

By sequential loading/unloading and transfer of the tank atmosphere from one tank to the next, the partial HC pressure in the tank atmosphere is kept close to the true vapour pressure of the oil and the VOC evaporation is reduced. The VOC emissions will then be reduced. Moreover, the

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filling of each tank will take less time, thus reducing the VOC evaporation because HC saturation of tank atmosphere will take place more rapidly in a less air volume. The principle is shown schematically in Figure 1.

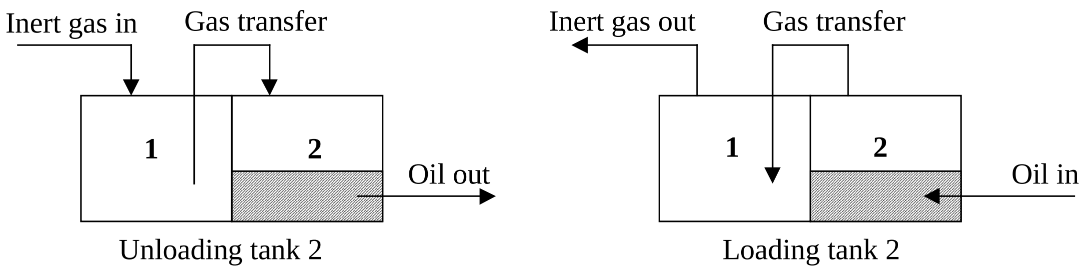

Figure 1 Sequential loading/unloading and transfer of tank atmosphere /19/

Two model simulations made with shuttle tankers /19/ indicate that VOC emissions may be reduced from 0,11% and 0,16% of loaded oil amount to 0,07% and 0,084%, respectively, by sequential loading/unloading. The reduction potential by sequential loading is then of the order 30-50%. However, this is the result from two cases and the results should be applied carefully as the VOC emissions depend on a range of factors /20/.

The above results corresponds to case studies reported in /21/. Three procedures for a VLCC was analysed with Arabian heavy oil for both loading and unloading:

- Conventional loading/unloading; tanks are loaded/unloaded in parallel
- Sequential loading/unloading without tank atmosphere transfer
- Sequential loading/unloading with tank atmosphere transfer

The reduction of VOC emissions was estimated to about 45% with sequential loading/unloading and tank atmosphere transfer compared with a conventional loading/unloading. The reduction was 15% if the tank atmosphere was not transferred /21/.

6.3 Absorption

Since exhaust gas is used as the inert gas in the tanks, the principal challenge for NMVOC recovery is to separate the hydrocarbons from the inert gas. This could be made by means of membrane separation or absorption methods /7/.

An absorption process was tested out in 1996 with a shuttle tanker on the scale of 1:10, with good results /9/. The tests gave recovery of 70-80% (field-dependent), which accords well with the target for the project. If the project is continued, a prototype must be tested out before it is possible to say definitely whether the project was successful. The process consists of direct

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absorption of the gas in a side flow of cargo oil. Hydrocarbons are absorbed to a greater degree than for the inert gas. Oil containing the absorbed NMVOC is returned to the main flow. Absorption takes place in a conventional absorption column. The side flow, typically 10-20% of the main flow, is cooled before passing through the column. Work is done to replace the absorption column by a modified two-cycle turbine, which would give significant savings in space and weight, besides increasing the energy recovery potential.

Absorption and return to the cargo oil depends on the oil's ability to retain the gas, i.e. on the stability of oil produced and loaded. Alternative means of disposal being examined for recovered NMVOC are re-injection in the oil cargo, collection in a separate tank and possible use of collected NMVOC as engine fuel for the ship.

A commercial version of the described absorption process for a floating production unit will cost about NOK 6.5 million, while the estimated cost of a full-scale unit for a shuttle tanker is about NOK 28 million.

6.4 Vapour Emission Control System

Vapour Emission Control System (VECS) implies a closed piping system for gas return from ship-to-shore, or from a shuttle tanker to a FPSO. In the latter case, conventional VECS will reduce VOC emissions with 35% /24/. The shore-based system is connected to the deck line by a crossover line and a house with standardised flanges. The system onshore comprises a detonation arrester and other safety equipment, and a compressor for the transfer of the gas mixture from the jetty to an incinerator or a vapour recovery unit. Fuel gas is mixed into the gas stream for enrichment before burning of the lean gas /10/.

New recovery technology installed at the Sture Terminal reduces the NMVOC emissions with 90% /24/. The process is based on transporting the gas to shore (VECS), and then use a recovery unit consisting of an absorption column. Absorption of NMVOC take place using cooled Kerosene. A commercial version of the described process will cost about NOK 24.3 million /11/.

Using sequential loading (transfer of tank atmosphere sequentially from one tank section to another), reduced the energy consumption per recovered unit, compared with conventional loading (large HC fraction combined with less transferred gas volume to shore).

6.5 VOC applied as fuel

Shuttle tankers operating on the Norwegian continental shelf with short voyages to and from the fields may cover the required energy by the energy contained in the VOC gas /23/. The energy potential in the VOC gas for a ULCC on a voyage from the Persian Gulf to the North West of Europe may amount to 50% /22/.

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A joint project between Man B&W and Statoil has the objective to test out the use of VOC gas as fuel for shuttle tankers. The key technologies to achieve this are a VOC handling system and a high-pressure gas-injection engine (Figure 2). The VOC handling system collects and stores the non-methane part of the VOC, i.e. mainly propane, butanes and higher hydrocarbones, which are condensed and separated from the gaseous VOC (inert gas, methane and ethane) which, at this stage, will be submitted to the atmosphere. In a later development phase, also these gases will be captured and used as engine fuel /23/.

The liquefied VOC are stored in an insulated tank at low temperature and atmospheric pressure. It is supplied to the engine at high pressure and is primarily injected directly into the combustion chamber immediately after the injection of a small amount of fuel oil, acting as a pilot oil and securing stable, safe combustion. The special VOC injection valves are operated by a mechatronic system, featuring computer control which allows for the greatly varying properties of the VOC fuel /23/.

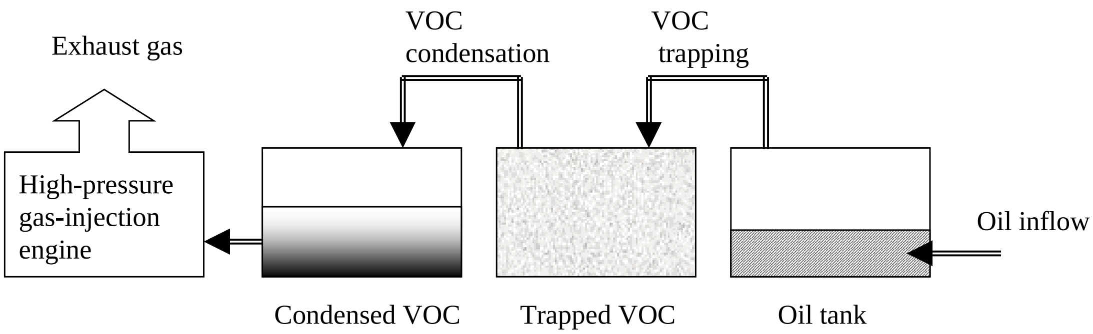

Figure 2 Schematic presentation of the technology for use of VOC as fuel /22/

Up to 90% of the vessel's heavy fuel oil (HFO) consumption may be replaced by VOC, leading to substantial cost savings as well as cleaner exhaust gas /23/:

- 50 - 90% reduction of SO_X emissions (directly proportional to the HFO substitution percentage)
- 50 - 90% reduction in particulate emissions, due to lighter and more volatile fuel, which causes less smoke formation
- 20 - 30% reduction of NO_X emissions du to more uniform mixing
- some reduction of CO_2 emissions due to higher hydrogen/carbon ratio in VOC fuel compared with HFO.

A full scale test of this concept is planned executed in 1999 /22/, /23/.

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6.6 Condensation of VOC gas

Condensation of VOC gas is not a new technology, but has been used for several years on gas tankers /26/. However, the energy requirements for direct condensation may amount to 1.5 - 2 MW. In order to supply shuttle tankers with a recovery system based on condensation of VOC, Kværner Maritime and Kværner Ship Equipment have developed a system which require 380 kW during loading and 450 kW during voyage /25/.

The VOC are collected from the oil tank during loading by means of a fan and a compressor. The VOC gas is cooled against a cold brine, whereby the main parts of the propane and the heavier components are condensed. The condensed VOC are stored in a tank for later pumping into the oil when loading or for use as fuel (Figure 3). A technical/economical optimal process plant will have a recovery rate of about 75% /25/. However, by increasing the cooling capacity a recovery rate of about 95% may be obtained /25/, /26/.

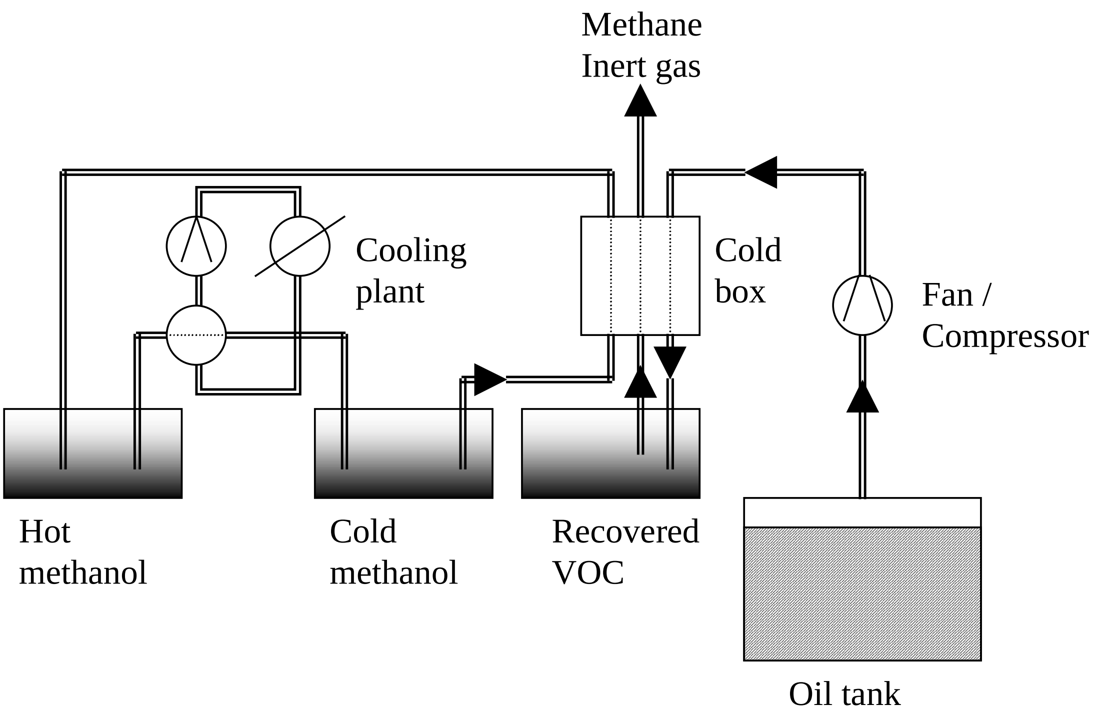

Figure 3 Schematic presentation of a condensation process plant /25/

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7 CONCLUSIONS

This report gives an overview of some technologies and procedures that may be applied to enhance the environmental performance of ship transportation. Emissions to air may be reduced by technical (hull shape, propeller, antifouling systems, engine efficiency) and operational (reduced speed, weather routing) means that reduce fuel consumption. These are the main reduction means for CO_2 emissions with a potential in the range 10-20%.

Propulsion systems based on alternative fuels (e.g. LNG, hydrogen) will reduce air emissions considerably, but the experiences are limited.

SO_X emissions may be reduced with 70-90% by low sulphur content in fuel and/or sea water scrubbing.

NO_X emissions may be reduced with 10-30% by engine adjustments and with 80-90% by catalytic reduction methods.

CO emissions may be reduced with some 60-90% by emulsification and oxidation reactor techniques. The latter means will reduce HC emissions with some 70%.

PM emissions are reduced by means of emulsification, cyclones, filter bags and electrostatic filters. The reduction potentials related to these methods are not known.

Sludge production can be reduced with homogenisers. Sludge can be burned in onboard incinerators, or otherwise delivered ashore. Reception facilities are few.

A range of alternative antifouling systems are identified. Copper-based alternatives seems to be the most likely alternatives.

Ballast water treatment facilities are basically on the research stage. Risk based ballast water management options (incl. continuos and open sea exchange) seems to be the present alternatives.

VOC emissions from tankers may be reduced by recovery plants (condensation, absorption, control systems) with a reduction potential of 50-90%. Sequential loading/unloading may reduce VOC emissions with some 40-50%.

The potential for pollution reduction from ships is significant. The costs related to acquisition, operation and maintenance of the various means are not addressed in this report. Prior to recommended strategies for pollution reduction, a cost/benefit analysis have to be carried out.

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