European Commission Directorate General Environment

Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments

Task 2c – SO_2 Abatement

Final Report

August 2005

Entec UK Limited

Report for

European Commission
Directorate-General-Environment
Directorate C - Unit C1

Main Contributors

Alistair Ritchie (Entec)
Emily de Jonge (Entec)
Christoph Hugi (Entec)
David Cooper (IVL)

Issued by

....
Christoph Hugi

Approved by

....
Alistair Ritchie

Entec UK Limited

Windsor House
Gadbrook Business Centre
Gadbrook Road
Northwich
Cheshire
CW9 7TN
England
Tel: +44 (0) 1606 354800
Fax: +44 (0) 1606 354810

13554

h:\projects\em-260\13000 projects\13554 pp ship emissions\reports\task 2 final report\task 2 so2 final_final report 16_09_05v2.doc

European Commission Directorate General Environment

Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments

Task 2c – SO_2 Abatement

Final Report

August 2005

Entec UK Limited

Certificate No. EMS 69090

Certificate No. FS 13881

Executive Summary

Introduction

This report forms part of the deliverables under Task 2 of the European Commission contract on Ship Emissions: Assignment, Abatement and Market-Based Instruments.

Task 2 requires an investigation of the costs, emission reduction potential and practicalities of ship emissions abatement technologies. The technologies to be considered are:

- Task 2a: The use of shore-side electricity (see separate report on shore-side electricity);
- Task 2b: NO_x abatement techniques (see separate report on NO_X techniques);
- Task 2c: SO_2 abatement techniques with focus on sea water scrubbing (this report).

This is the report for Task 2c on SO_2 abatement techniques.

This report investigates the costs, emissions reductions and cost effectiveness of specific SO_2 reduction measures on ships. The following three measures are investigated:

1. Sea water scrubbing;
2. Fuel switching from 2.7% sulphur residual oil (RO) down to 1.5% sulphur RO; and
3. Fuel switching from 2.7% sulphur residual oil (RO) down to 0.5% sulphur RO.

The main focus of this report, as required by the project specification, is Sea Water Scrubbing. As such, it has been possible to give only limited consideration to fuel switching within the resources of this study.

Details of Sea Water Scrubbing

Background

One of the most versatile, readily available and cost-effective scrubbing processes is sea water scrubbing, due to sea water's natural alkalinity. Furthermore, sea water already contains large quantities of sulphur and can be considered as a relatively safe sulphur reservoir.

The basic principle of operation for a Sea Water Scrubber relies on hot exhaust gases mixing in a turbulent cascade with seawater whereupon SO_2 in the exhaust is transferred to the seawater. The seawater is re-circulated, and the solid particles removed from the exhaust gas are trapped in a settling or sludge tank where they are collected for disposal.

Early trials of Sea Water Scrubbers

To our knowledge, the first prototype exhaust gas seawater system for ship emission control was installed in 1991. This demonstrated that a reduction of SO_2 emissions up to 92% was possible. At the normal load conditions measured however, the prototype demonstrated a sulphur removal rate in the range of 71% to 73%.

An additional early demonstration of a sea water scrubber (in conjunction with a Selective Catalytic Reduction unit and particle eductor) was installed in June 1993. The results showed an SO_2 removal efficiency of 90%, but the study concluded that the potential for an even higher reduction exists by optimisation of the sea water/exhaust gas capacity ratio.

Development of the EcoSilencer®
Marine Energy Ltd. (MEL) undertook a comprehensive field trial in May 1998. The study also outlined the possibility of recovering the waste heat from the exhaust in the sea water and thereby achieving fuel savings by reducing the need to operate conventional auxiliary boilers. A 96% SO_2 removal rate was observed.

A new prototype scrubber, the EcoSilencer®, was fitted for testing onboard a ferry in August 2001. Independent stack sampling consultants initially showed a 94% SO_2 reduction but around 3 months later this was reduced to 85%.

A more recent round of commercial trials with the EcoSilencer® onboard P&O Line's passenger ferry *Pride of Kent* took place during autumn 2004. The scope, performance and costs of this project will outline the most up-to date assessment of the technique and is discussed in this report.

Impact on emissions
Operating with a 2.5% sulphur fuel, SO_2 reduction rates of 68-94% have been achieved. The scrubbing efficiency is linked to the flow rate of sea water contacting with the exhaust. The worst results experienced, with restricted sea water flow rates, were around 65%. By over supplying the system with water removal rates of 94% were achieved. By operating the system within the existing design parameters removal rates of 75% to 80% can be achieved. A reduction efficiency rate of 75% is assumed in this study. It is also worth noting that MES expect that with improved scrubber design, the EcoSilencer® will be able to sustain around 90% reduction in SO_2 emissions.

Discharge water quality
The quality of the discharge water must comply with the appropriate environmental legislation. The IMO OILPOL has a limit on the concentration of petroleum hydrocarbons which can be discharged overboard, of 15ppm. The EcoSilencer® trial demonstrated that the discharge water from the scrubber contained significantly lower levels of petroleum hydrocarbons than this limit.

The IMO has not specified limits for other components and characteristics of discharge water, such as pH, suspended solids and heavy metals.

Emissions reductions

Table 1 presents the estimated mid range values of emission reduction efficiencies of the SO_2 abatement techniques considered in this study.

Table 1 **Emission reduction efficiencies**

Measure	**% Emissions reduction (-) / increase (+) per vessel**			
	SO_2	**NO_X**	**PM**	**VOC**
Sea water scrubbing	-75%	0%	-25%[1]	±
Fuel switching 2.7->1.5% S fuel	-44%	±	-18%	±
Fuel switching 2.7->0.5% S fuel	-81%	±	-20%[2]	±

Section 3.3 presents details of the impact of these measures on other emissions and noise.

Costs

Table 2 presents the estimated mid range values of cost-effectiveness of the SO_2 abatement techniques, expressed in terms of €/tonne SO_2 abated. The associated uncertainty is considered in Section 1.2.

Table 2 **Costs per tonne of emissions reduced for SO_2 abatement measures based on mid-range values (Note 1) (€/tonne SO_2)**

Measure	**Ship type**	**Small Vessel**	**Medium Vessel**	**Large Vessel**
		(€/tonne SO_2)	(€/tonne SO_2)	(€/tonne SO_2)
Sea water scrubbing	New	390	351	320
Sea water scrubbing	Retrofit	576	535	504
Fuel switching: 2.7% S fuel to 1.5% S fuel	New/retrofit	2,053 (1,230)	2,050 (1,230)	2,045 (1,230)
Fuel switching: 2.7% S fuel to 0.5% S fuel	New/retrofit	1,439 (1,690)	1,438 (1,690)	1,434 (1,690)

Note

1. For fuel switching, there is a wide range of estimated values for the price premia of low sulphur fuels. The main results relate to the use of BeicipFranlab (2003) average fuel price differential information, whilst the figures in brackets represent the use of Concawe estimates.

---

[1] MES measured sludge production from the Pride of Kent as 0.2 g/kWh and particles suspended in overboard water as 0.05g/kWh. Based on a PM emission factor of 0.8 g/kWh in the exhaust for the type of auxiliary engine used in MES's trials, the PM removal rate by the EcoSilencer® can be approximated as around 31%. However since this calculation assumed that all the sludge consists of particulates, and that the suspended solids in the scrubber inflow is negligible, the actual removal rate is likely to be lower than 31%. A conservative estimate of 25% PM reductions was therefore chosen.

[2] Conservative figure. It is estimated that PM removal will be more than 18% but is likely to be significantly less than 63% (US EPA 2003).

More details of estimated costs, including estimated capital and operating costs for different size vessels, specific costs (€/kW capital, €/MWh operating) and total costs scaled up for all EU-flagged vessels are given in Sections 4, 5 and 6.

A comparison of the cost effectiveness of SO_2 abatement measures for ships against SO_2 abatement for other sources is given in Section 5.2.

Contents

1. Introduction

1.1 General

This report forms part of the deliverables under Task 2 of the European Commission contract on Ship Emissions: Assignment, Abatement and Market-Based Instruments.

Task 2 requires an investigation of the costs, emission reduction potential and practicalities of ship emissions abatement technologies. The technologies to be considered are:

- Task 2a: The use of shore-side electricity (see separate report on shore-side electricity);
- Task 2b: NO_x abatement techniques (see separate report on NO_X techniques);
- Task 2c: SO_2 abatement techniques with focus on sea water scrubbing (this report).

This is the report for Task 2c on SO_2 *abatement techniques.*

This report investigates the costs, emissions reductions and cost effectiveness of specific SO_2 reduction measures on ships. The following three measures are investigated:

1. Sea water scrubbing
2. Fuel switching from 2.7% sulphur residual oil (RO) down to 1.5% sulphur RO
3. Fuel switching from 2.7% sulphur residual oil (RO) down to 0.5% sulphur RO

The main focus of this report, as required by the project specification, is Sea Water Scrubbing. As such, it has been possible to give only limited consideration to fuel switching within the resources of this study.

The main input data used to assess the sea water scrubbing process applied to ships are based on the trials of the EcoSilencer® on the Pride of Kent vessel.

The full methodology and underlying assumptions are outlined in the General report.

Chapter 2 contains the technical description of the sea water scrubbing process and existing case studies. Chapter 3 assesses the expected emission reduction achieved by the three measures and Chapter 4 covers the associated cost to achieve these reductions. Chapter 5 summarises the estimated cost effectiveness of the individual measures and Chapter 6 estimates the cost if these measures are implemented on EU-flagged ships.

1.2 Uncertainty of Results

The two key results of this study are the costs of a measure and the achieved emission reduction by this measure i.e.

$$Cost - Effectiveness_{measure\ i}\,(\text{€/tonne of pollutant}) = \frac{\text{Cost of measure i (€/year)}}{\text{Emission reduction (tonne of pollutant/year)}}$$

Costs of measures: It is estimated that the costs derived in this study are subject to a 30% uncertainty range compared to the best estimate cost figure which are quoted. The key contributors to the uncertainty in the above estimates include:

- Sea water scrubbing on ships has not been commercially exploited and the market prices have not been developed. The quoted costs are estimates based on the experience with the prototypes and discussions with experts;
- Costs for low sulphur fuel mainly depend on supply, demand, sulphur content of explored crude oil and technology. The market for low sulphur fuels for ships (1.5% and 0.5% sulphur levels have been investigated) have not been properly developed and volatility of oil markets is generally high; and
- Inherent variations in costs of retrofitting abatement equipment at different ships due to ship specific factors.

Emission reductions: It is estimated that the emission reduction derived in this study are subject to a 20% uncertainty range compared to the best estimate emission reduction figures which are quoted. This is caused by a number of factors including:

- The variation in possible designs of Sea Water Scrubber;
- The level of maintenance of the equipment;
- The operating modes and load factors of the ship; and
- The variation in sulphur contents of fuels.

Based on these uncertainty ranges it can be estimated that the cost-effectiveness of measures derived in this study are subject to an approximate 35% uncertainty range compared to the best estimate cost effectiveness figures which are quoted.

2. Technical Description

2.1 Background

The use of liquid scrubbers to remove gaseous sulphur dioxide is, at least on land-based combustion units, a well-established practise (from 1930s onwards). More commonly termed as Flue Gas Desulphurisation (FGD), several design options exist including impingement trays, venturi, fan scrubbers and spray towers. These techniques have been demonstrated with many applications such as in the production of pulp and paper, steel, mining and in power generation.

One of the most versatile, readily available and cost-effective scrubbing processes is sea water scrubbing, due to sea water's natural alkalinity. Furthermore, sea water already contains large quantities of sulphur (around 0.1% on weight) and can be considered as a safe sulphur reservoir.

Most land-based scrubber designs are not directly transferable to ships at face value due to size, cost and complexity considerations, and consequently manufacturers of land-based scrubbers have seemed initially reluctant to develop scrubbers for use on board ships. Nonetheless, several sea trials have been undertaken to develop sea water scrubbing for marine applications.

Interestingly, the first use of exhaust gas seawater scrubbers in the marine industry was not directed to the problem concerning SO_2 emission control. Instead, the scrubbers were seen as a cheap means to produce inert gas for reducing the fire hazard in the cargo tanks of tankers while unloading. By the 1970s, their use was widespread. Even in these cases, reductions of particulates (PM) and SO_2 (by as much as 97%) from the exhaust were noted (Zhou and Montgomery, 1999).

The introduction of scrubbers for SO_2 emission reductions onboard ships has however been relatively limited in comparison to other technologies such as NO_x abatement technologies. This has largely been due to the ability to reduce SO_2 emissions by using low-sulphur fuels. However, due to predicted low-sulphur fuel supply limitations, relatively high operating costs and other practical difficulties (Skjolsvik, 2003), the scrubber option is receiving increasing attention as a cost-effective alternative (Gregory and Trivett, 2002).

This study has mainly drawn from the results and findings of the trial of the Eco-Silencer® sea water scrubbing on the Pride of Kent. The basic principle of operation for the Eco-Silencer® relies on hot exhaust gases mixing in a turbulent cascade with seawater whereupon SO_2 in the exhaust is transferred to the seawater. The design aims at achieving a 95% SO_2 reduction depending on water temperature and salinity. To ensure that the surface area for contact between gas and water is high, and sufficient time for absorption of pollutants is provided, a patented, compact mixing process was developed.

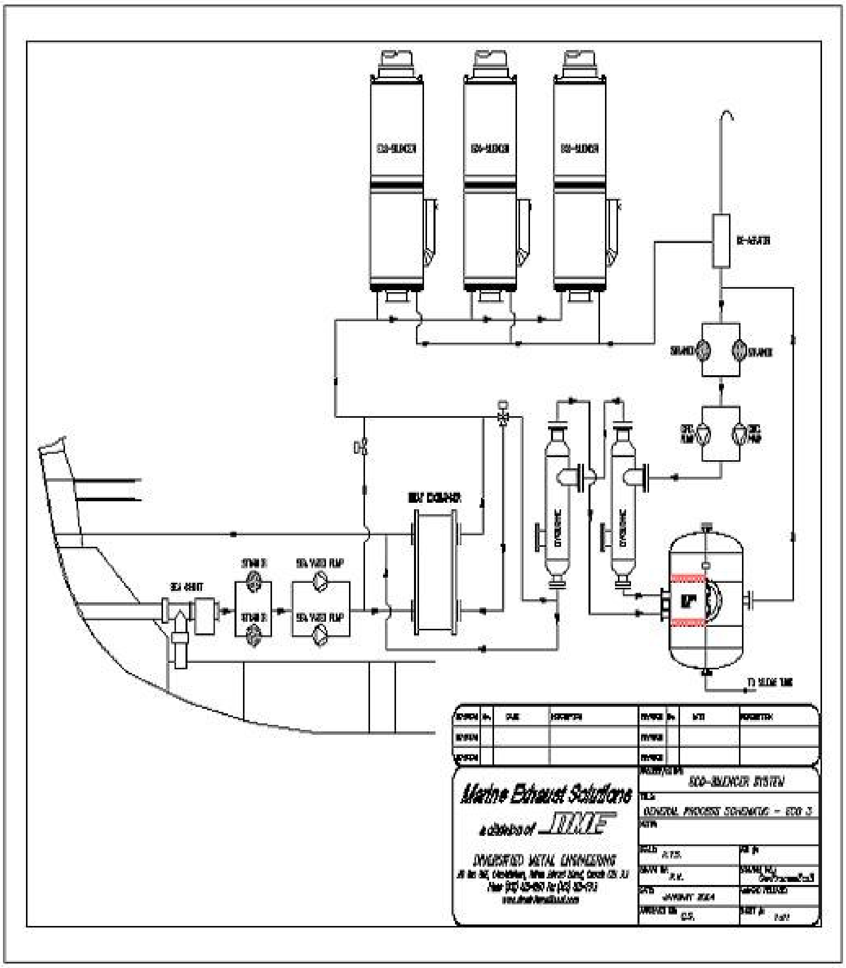
Figure 2.1 shows a schematic scrubbing system. The seawater is re-circulated[3], and the solid particles removed from the exhaust gas are trapped in a settling or sludge tank where they are

---

[3] The rate of pH change in the re-circulating water is a simple indicator of SO_2 removal and may therefore have an implication for monitoring applications.

collected for disposal. Disposal involves either burning the sludge in the ship's incinerator or disposing of it ashore. Filtered and used seawater can then pass onto the ship's existing bilgewater treatment system.[4] Further details of the system can be found in the literature e.g. Gregory and Trivett, 2002; Holness, 2003; DME International, 2004.

Figure 2.1 Schematic of EcoSilencer's® scrubbing recirculation system



---

[4] Bilgewater systems are installed onboard ships to treat bilge water. Bilge water is produced from ship activities such as clearing of cargo tanks and engine rooms. Bilge water contains oil and other contaminants, and treatment of this water produces an oily sludge.

2.2 Experience with Sea Water Scrubbing on Marine Vessels

2.2.1 Early trials of Sea Water Scrubbers in Marine Applications

To our knowledge, the first prototype exhaust gas seawater system for ship emission control was installed in 1991 on Color Line's passenger ferry *M/S Kronprins Harald* serving the Oslo - Kiel route. The tests lasted ca. 1,700 operating hours and demonstrated that a reduction of SO_2 emissions up to 92% was possible (European Commission, 1999). At the normal load conditions measured however, the prototype demonstrated a sulphur removal rate in the range of 71% to 73% for salinities down to 14% (Ives and Klokk, 1993). The discharged wastewater was characterised by a low pH and various toxic organic pollutants and metals mainly associated with the particles. Compared to the initial project targets for pollutant reductions, a vast deviation was demonstrated for particle removal. Also, contradictory to the technology originators expectations, no removal of NO_x was observed.

An additional early demonstration of a sea water scrubber (in conjunction with a Selective Catalytic Reduction unit and particle eductor) formed part of a Kvaerner/Norske Shell project (Marine Engineers Review, 1995). The plant was installed in June 1993 on the Norske Shell tanker *MT Fjordshell* that operates with a 10,800 kW main engine, three auxiliary engines, and two boilers generating around 90,000 Nm^3/hr of exhaust gas. The results showed a SO_x removal efficiency of 90%, but the study concluded that a potential for an even higher reduction exists with an optimisation of the sea water/exhaust gas capacity ratio.

The environmental impact of the particulate-containing wastewater (which included soot, copper, vanadium and nickel) was assessed (Skjolsvik, 2004). It was concluded that efficient mixing in the wake of the ship (dilution by a factor of 2,000:1 within 50 m from the vessel's stern) meant that the exposure time to marine organisms would be small and the toxic effect negligible. Although in harbour operations the dilution would be smaller, the environmental effect of the process water was still presumed to be insignificant.

The overall conclusion from the project team was that the effectiveness of the plant had been proven according to the scrubber design expectations (85-95% SO_2 removal). In addition, the automation of the system had meant little extra work for the crew onboard. As a general conclusion it was reported that the degree of economic justification for the system would depend on the ship's fuel consumption, the price differential between high and low sulphur fuel, the cost of the plant and eventual penalties incurred in lost cargo space. In the *MT Fjordshell* case, the scrubber system was deemed less expensive than the use of low sulphur fuel.

Parallel to trials at sea, some experience with exhaust scrubbers for marine diesel engines have been conducted at laboratory engine test facilities. In one example (Zhou and Montgomery, 1999), high SO_2 reductions (> 95%), CO reductions (around 30%) with signs of NO_x and PM reductions and without significant changes in fuel consumption were observed for a 36 kW Perkins high–speed engine.[5] CO_2 emissions are not effected in any significant way. The cooling effect of the exhaust gases was illustrated in this study (380 °C down to 50 °C) with raised scrubbing water temperatures (11 °C up to 50 °C). This result pointed the way for future material considerations for scrubbers since titanium is free from all corrosion below 80 °C.

---

[5] The impact on CO_2 emissions were not reported.

In a second more recent example, the University of Dundee are involved with a patented scrubber design aimed at removing particulates and SO_2 (Cairns and Graham, 2004). The underlying concept relies on the particulates being filtered from the scrubber liquid, which in turn is heated to re-evolve the SO_2. Water vapour is then condensed out, to leave dry SO_2 gas, which is converted to SO_3 over a vanadium oxide catalyst, and dissolved in water to form sulphuric acid. In this way the pollutant can be converted to a useful by-product.

2.2.2 Development of the EcoSilencer®

Marine Energy Ltd. (MEL) undertook a comprehensive field trial in May 1998 onboard the Canadian ice breaker *Louis S. St.-Laurent* (Trivett et al., 1999). The trials were conducted during 22 days of a 6-week transatlantic voyage. In this system the "i400" pilot plant scrubber treated a partial stream of the exhaust from one of the three auxiliary engines onboard (1,200 kW). In particular, the i400 was built to work at low exhaust back-pressures typical of marine exhaust systems.

The study also outlined the possibility of recovering the waste heat from the exhaust in the sea water and thereby achieving fuel savings by reducing the need to operate conventional auxiliary boilers. Regarding SO_2 reduction, a 96% removal rate was observed with a 70-80% reduction in particulates (for sizes larger than 1 micron) and a 4% reduction in NO. An improved NO reduction was proposed for future scrubber designs using higher concentrations of sea water. Furthermore, three inspections revealed that fouling of the plant was minimal.

MEL's development work continued in co-operation with MAN B&W. A new prototype scrubber, the Eco-Silencer®, was fitted for testing onboard the Canadian RoPax ferry *Leif Ericson,* which used to be known as the Stena Challenger (Gregory and Trivett, 2002, Clarke, 2004) in August 2001. The Eco-Silencer unit was supplied by Marine Exhaust Solutions (MES[6]) a division of DME International in Canada and used on a 1,500 kW auxiliary engine running on heavy fuel oil with a sulphur content of ca. 3.5% by weight. The installation, where the scrubber replaced the exhaust silencer in the funnel casing was carried out during a normal scheduled dock period alongside the terminal (that is no additional time out of operational service was required). In contrast to the i400 prototype, the Eco-Silencer scrubber was a full-scale plant and treated the entire exhaust stream from the engine.[7]

One of the specific aims of the *Leif Ericson* trials was to investigate wastewater quality though a water treatment plant and if necessary apply alternate water treatment components. In addition the owners of the vessel, Canada's Marine Atlantic, were particularly concerned about soot emissions. Crew officers noted a visible improvement in smoke opacity during the tests and measurements confirmed the following reductions: PM_2 reduced by 98%; $PM_{1.5}$ reduced by 74%; PM_1 reduced by 59%; and $PM_{0.05}$ reduced by 45% (Clarke, 2004).

Regarding SO_2 removal, independent stack sampling consultants initially showed a 94% reduction but around 3 months later this was reduced to 85%. Unfortunately most of the test period was hampered with industrial action, and subsequently led to a winter stoppage that led to ice damage within the scrubber. Thus in the spring of 2002 the system was removed (Clarke, 2004).

---

[6] Marine Energy Ltd became Marine Exhaust Solutions on joining DME International in 2000.

[7] Besides SO_2, NO_x and PM removal, the Eco-Silencer also reduces exhaust odour and noise.

The developmental work thus far undertaken, in particular on *Louis S. St.-Laurent* and *Leif Ericson*, has subsequently led to the next round of commercial trials with the Eco-Silencer onboard P&O Line's passenger ferry *Pride of Kent* during autumn 2004. The scope, performance and costs of this project will outline the most up-to date assessment of the technique and is discussed below.

2.2.3 Pride of Kent EcoSilencer® Trials

The results from the EcoSilencer trials on the Pride of Kent are investigated in this study. The results incorporated in this study are the latest results from the trial, covering emission reductions, cost and discharge water quality. Appendix 1 includes the reports by MES on this trial.

The trial comprised of four EcoSilencers® on four 1.2 MW auxiliary engines. The trial lasted over 16 months during which the auxiliary engines were operational for approximately 11,680 hours (≈100% of the time) (MES 2005).

Figure 2.2 The EcoSilencer® incorporated into the exhaust train and installed on the Pride of Kent

2.2.4 Discharge Water Quality

The quality of the discharge water must comply with the appropriate environmental legislation. The IMO OILPOL has a limit on the concentration of petroleum hydrocarbons which can be discharged overboard, of 15ppm. The EcoSilencer® trial demonstrated that the discharge water from the scrubber contained significantly lower levels of petroleum hydrocarbons than this limit (AQS/UKAS, 2004; Westech/AQS, 2004, 1 and 2; MES 2004; MES 2005, and shown in Appendix 1).

The IMO has not specified limits for other components and characteristics of discharge water, such as pH, suspended solids and heavy metals. The US EPA has outlined limits for these components and characteristics, under the Quality Criteria for Water 1986, EPA 440/5-86-001. The EcoSilencer® trial demonstrated that the discharge water met some of the EPA criteria, but exceeded others (AQS/UKAS, 2004; Westech/AQS, 2004, 1 and 2; MES 2004; MES 2005, and shown in Appendix 1). Whether these exceedences can be avoided by alteration in scrubber design would need further investigation.

2.2.5 Sulphuric Acid Mist after Scrubber Treatment on Ships

Potential problems associated with Sea Water Scrubbing are thought to include the possibility of scrubber emissions falling out as acidic precipitation in the vicinity of the chimney and then causing local acidification problems including potential corrosion of materials and exposure to individuals. This was a problem of early land based flue gas desulphurisation (FGD) plants but the problem is now well understood and there exist technical solutions to mitigate this problem[8].

When fuels containing sulphur are burned, mainly sulphur dioxide (SO_2) is produced, but also a small fraction of sulphur trioxide (SO_3). The chemical process under consideration for the formation of sulphuric acid is:

$2SO_2 + O_2 \dashrightarrow 2SO_3$

$SO_3 + H_2O \dashrightarrow H_2SO_4$

At temperatures >340°C present during combustion processes, sulphuric acid (H_2SO_4) is not present, only sulphur trioxide (SO_3). When gases are cooled, however, sulphur trioxide will react very readily with any available water to form sulphuric acid. If sulphuric acid forms in a gas sample, as long as it remains in the vapour phase it generally causes little or no problem. However when the concentrations of water and sulphuric acid are sufficiently high to form acid mists at ambient temperature, corrosion problems are likely to occur.

When sulphur dioxide is present in gas samples at concentrations of a few hundred ppm or less as it will be after the scrubber treatment (approx. 300ppm), formation of acid mist is normally not reported to be a problem unless the ambient temperature is quite low. However because after a scrubber treatment the exhaust gas stream will have a high water content and will be

---

[8] Land based flue gas desulphurisation (FGD) plants have typically reduction rates of 92% for SO_2. They usually use a reheat system to reduce plume visibility (caused by moisture in the exhausted gas stream) and to increase the discharge plume buoyancy, thereby preventing it from grounding too close to the power station. Such a reheat system also has the effect of reducing the propensity for acid mist formation. The cleaned flue gas is reheated using either an indirect steam heater or heat extracted from the dirty gas on the inlet side of the scrubber (which is usually at about 110-140°C), using a regenerative gas heater.

cooled down in the scrubber and after leaving the chimney by entrained ambient air there might be conditions that allow forming sulphuric acid mist[9].

SO_3 acid dew points are around 125 to 170°C depending upon the water vapour (not liquid droplet) content and SO_3 content of the flue gas. Scrubbed gas will be very close to the ambient scrubbing water temp (5-20°C). Prior to exiting the scrubber, flue gases usually pass through an impingement type droplet separator (deflector baffles within the gas stream) to reduce the entrained water droplet concentration of the discharged gas to around 50 mg/Nm^3. The flue gases are then usually reheated (by say 20-30°C) to eliminate visible steam plume. Consequently the flue will generally be below the SO_3 acid dew point. To accommodate this, appropriate acid-resistant construction materials are usually employed downstream of the scrubber system.

Provided the exit velocity of the flue gas is sufficiently high and reheat has been applied, sufficient plume buoyancy can be achieved to minimise the potential for local plume grounding and possible acid deposition. This can be verified during design using atmospheric dispersion modelling techniques.

The formation of acid mist will start in a similar way to the process of forming clouds with very small droplets. Typical initial cloud drops have a diameter of about 0.002mm but need only about 0.01m/s lift to stay aloft or would fall with a terminal velocity of only 0.01m/s without uplift.

For a ship travelling at sea there is very little probability that the mist will impact on the ship under normal conditions i.e. the upward lift in the exhaust plume is more than big enough to keep the mist aloft for long enough for the ship to travel out of the fallout zone. Any mist falling into the sea will be neutralised in the same fashion as is happening in the scrubber and is of little environmental concern.

For a ship at berth under most normal conditions except still wind conditions there is only a small probability that the mist will impact directly on the ship. However at berth there are other surfaces at risk when the wind blows from the sea and where this mist lands on metal surfaces, it can create a point of corrosion. Additionally, on non metallic surfaces it may cause a reddish brown stain. It is reported that it might even “corrode” non-metallic materials such as fibreglass and plastics.

According to MARPOL Annex VI port states are permitted to set environmental criteria for the use of scrubbers in enclosed ports and coastal areas, and sulphuric mist may be one of the criteria they will wish to consider.

In general, based on these comments sulphuric acid mist formation is currently not thought to be a significant problem for scrubber treatment on ships, though it is a potential issue to be further looked into for specific conditions and cases, e.g. at berth.

However it does not diminish the environmental benefits of scrubbers to reduce SO_2 emissions into the air. On the contrary, SO_2 reductions may be enhanced as the described process could lead to a further reduction of SO_2 in the exhaust gas and the ambient air.

---

[9] By lowering the temperature of the gas sample sufficiently (typically down to 60°-75°C) while it still contains significant amounts of water, sulphuric acid can be forced to condense.

3. Emissions Reductions

3.1 Emissions Reduced by Sea Water Scrubbing (SWS)

As mentioned earlier, the Pride of Kent EcoSilencer trials represent the most up-to-date assessment of Sea Water Scrubbing at the time of writing.

Trial results are based on tests undertaken by the monitoring company Westech's subsidiary Air Quality Solutions (AQS). The results of AQS's trials were supplied by MES (AQS/UKAS, 2004; Westech/AQS, 2004, 1 and 2; MES 2004; MES 2005).

Operating with a 2.5% sulphur fuel, SO_2 reduction rates of 68-94% have been achieved (Westech/AQS/MES 2004). The scrubbing efficiency is linked to the flow rate of sea water contacting with the exhaust. The worst results experienced, with restricted sea water flow rates, were around 65% (MES 2004, 1). However the test results attached in Appendix 1 demonstrate that higher rates are achieved. By over supplying the system with water removal rates of 94% were achieved. By operating the system within the existing design parameters removal rates of 75% to 80% have been sustained. It is also worth noting that MES (2004) expect that with improved scrubber design, the EcoSilencer® will be able to sustain around 90% reduction in SO_2 emissions. A reduction efficiency rate of 75% is assumed in this study.

These tests were undertaken on 2.5% sulphur fuel, and are therefore likely to have shown a slightly higher SO_2 removal rate for engines using 2.7% sulphur fuel, the assumed baseline average for RO in this study. However since there is no data available for scrubbing efficiencies for engines using 2.7% sulphur, the scrubber efficiencies for 2.5% sulphur fuel are assumed.

Measurements of NOx reductions recorded very low NOx removal rates. Therefore it is assumed that NOx removal is likely to be insignificant (Westech/AQS 2004, 1). VOC emission reductions were not measured.

Since the EcoSilencer® scrubs the exhaust, it is likely to be able to remove PM, however this was not measured during the trial. A mass balance approach was used to estimate PM reduction experienced on the Pride of Kent.

The Pride of Kent trial was undertaken on 1,200 kW auxiliary engines. For one engine running at 65% load, MES measured sludge production from the Pride of Kent as 0.2 g/kWh (MES 2005). Particles suspended in overboard water were measured as 450 to 790 µg/L. Using the average value of 620 µg/L, a water outflow of 60 t/h per unit, the amount of particles contained in the overboard water are equivalent to 0.05 g/kWh. Total particles removed were therefore up to 0.25 g/kWh.

Based on a PM emission factor of 0.8 g/kWh in the exhaust for the type of auxiliary engine used in MES's trials, the PM removal rate by the EcoSilencer® can be estimated at around 31%. However, this calculation assumed that all the sludge consists of particulates, and that the suspended solids in the scrubber inflow is negligible. Therefore particulate removal may be less, and a conservative estimate of 25% is used in this study. Reduction rates confirmed by future measurements might therefore further improve the overall environmental benefits of this system.

It should be noted that MES (2004, 1) expect that the EcoSilencer® is capable of PM reductions of the order of 80%. MES is planning further EcoSilencer® trials to test PM reduction efficiency (MES 2005).[11]

Table 3.1 outlines the emission reduction efficiencies assumed for the assessment of the sea water scrubbing technology, based on the EcoSilencer® trials.

Table 3.1 Assumed reduction efficiencies of the sea water scrubbing technology (SWS)

	NOx	SO_2	VOC	PM	sfc
Reduction efficiencies SWS	0%	75%	Unknown	25%	0% (note 1.)

Note 1: The scrubber causes only a small backpressure on the engine, from which MES have not measured any impact on engine efficiency and fuel consumption (MES 2004).

Table 3.2 depicts the expected SO_2 emission reduction per year for the different vessel sizes. The underlying assumptions are summarised in the General Report.

Table 3.2 SO_2 emissions reduction, EcoSilencer®, (reduction efficiency 75%)

		Vessel	
Current	Small	Medium	Large
SO_2 reduction (t/year)	129	423	1,058

3.2 Emissions Reduced by Fuel Switching

Creation of SO_2 emissions from fuel combustion is directly related to the sulphur content of fuels. Therefore the reduction efficiency of fuel switching is related to the reduction in sulphur content of the fuels.

It is likely that fuel switching will be done by using low sulphur residual oil (RO) rather than using marine distillate (MD). This is because the premium for low sulphur fuel is €$_{2000}$20-89 per tonne for RO (BecipFranlab 2003) and around €110 and €130 per tonne for switching to 0.2% and 0.1% sulphur MD[10] respectively. Therefore the following two scenarios were further considered:

---

[10] Prices from BeicipFranlab are converted to €$_{2000}$. Prices assumed for RO and MD are €113 per tonne and €227 per tonne respectively (Jiven 2004). Although fuel prices rose for the remainder of 2004, for

1. switching from 2.7% sulphur to 1.5% sulphur and
2. switching from 2.7% sulphur to 0.5% sulphur.

A reduction in the sulphur content of fuels will reduce PM emissions, however this is difficult to quantify with the extent of currently available data and many emission measurement methodologies do not include PM reductions from a reduction in the sulphur content of fuel (Cooper 2004). A US EPA study (US EPA 2003 3) estimates PM reductions for dropping from 2.7% to 1.5% sulphur fuel as 18%. PM reductions for dropping from 2.7% to 0.5% sulphur fuel will therefore be most likely greater than 18%, but less than the 63% reduction seen from switching to marine distillate (US EPA 2003 3). As a working assumption, a figure of 20% PM reduction is used in this study. The actual reduction will depend on various factors including the source of crude oil and the nature of the petroleum refining operations used to produce the RO.[11]

Reduction in VOC is not quantified. Since it is assumed that the fuel will still be RO, the specific fuel consumption is not expected to change significantly. Table 3.3 outlines the reduction efficiencies assumed in this study for fuel switching. Table 3.4 summarises the expected SO_2 emission reduction per year for the different vessel sizes.

Table 3.3 Assumed reduction efficiencies of Fuel Switching

	Fuel S %	NOx	SO_2	VOC	PM	sfc
Fuel Switching 1	2.7 -> 1.5	0%	44%	unknown	18%	0%
Fuel Switching 2	2.7 -> 0.5	0%	81%	unknown	20%	0%

---

example, the cost of 0.2% sulphur MD in June 2004 was €325 per tonne, such high prices are not expected to last. Specific fuel consumption used is 200 g/kWh.

[11] EU air quality limits for PM concentrations come into force in 2005 for PM10 (less than 10µm in diameter), and include 24 hour limits and annual average limits. These limits do not distinguish between the primary particles which are directly emitted, and the secondary particles which are formed when SO_2 and NOx emissions oxidise in ambient air. In the context of the forthcoming Clean Air for Europe strategy the Commission is considering setting new air quality limits for PM2.5.

Table 3.4 Saved emissions by Fuel Switching

			Vessel		
	Fuel S %	**Reduction**	**Small**	**Medium**	**Large**
Fuel Switching 1	2.7 -> 1.5	SO_2 (t/year)	76	251	627
Fuel Switching 2	2.7 -> 0.5	SO_2 (t/year)	140	459	1,149

3.3 Other Emissions (CO, CO_2, CH_4, N_2O and noise)

The effects of the EcoSilencer® on other emissions such as CO[12], CO_2[12], CH_4 and N_2O have not been measured. It can be assumed that since the specific fuel consumption of engines are unlikely to be impacted by use of an EcoSilencer®, and that the use of an EcoSilencer® will not impact upon combustion conditions, that there may be no significant impact on emissions of these pollutants except where a scrubbing effect may potentially take place.

An EcoSilencer® is designed to replace engine silencers. The EcoSilencer is quoted to increase noise attenuation since noise will encounter a silencer containing significant quantities of water (MES 2004).

Fuel switching is not expected to have any significant effects on the emissions mentioned in this heading.

---

[12] Although reductions of CO of 30% have been measured on test facilities (see Section 2.2.1), we are not aware of measurement of CO emissions from full scale practical application. CO_2 emissions are not effected in any significant way.

4. Costs

4.1 Sea Water Scrubbing

4.1.1 Capital Costs

An estimation of capital costs for the scrubbers installed on the Pride of Kent is shown in Table 4.1. MES (2004) estimate that new build installations would cost 20-40% less than retrofitting, therefore this study assumes an average cost reduction of 30% for new build installations.

Table 4.1 Estimation of specific EcoSilencer capital costs

Costs from the Pride of Kent	Capital Costs (current)
Retrofit Capex (€/kW installed)	168
New build Capex (€/kW installed)	118

These capital costs include a waste water treatment system and demisters required to reduce carryover of scrubbing water into the exhaust. If carryover was not reduced, the SO_2 removal efficiency of the scrubbers would be impacted. The EcoSilencer® system passes the scrubbing water through several stages of cyclone separation to remove solids, oils and any associated contaminants. The Pride of Kent trials (Westech/AQS 2004, 3 and 4) showed that this equipment enabled oily wastes to be removed to 0.042 ppm, which is significantly below the IMO's OILPOL limit of 15 ppm.

MES (2004) estimate that with a significant quantity of EcoSilencer® units manufactured, capital costs per unit could be considerably reduced. MES (2004) estimate future Capex costs for retrofit could be as low as €120/kW. It is interesting to note that capital costs for stationary sea water scrubbing systems cost around €100/kW (Lurgi 2004)[13].

4.1.2 Economies of Scale

Cost estimations from MES (2004) were based on a 27 MW size engine. MES have not provided costs for smaller engines, and therefore details are not available on possible economies of scale.

---

[13] Based on €3.5-5 million for a 40 MW system (Lurgi 2004). An important cost difference between stationary and marine costs relates to water treatment. Stationary SWS systems use concrete lagoons to aerate the scrubbing water before discharging back into the sea. These lagoons add significant costs, whereas onboard ships it is likely that the existing bilgewater treatment system can be used at minimal additional costs. The cost estimate quoted by Lurgi does not include costs for waste water treatment lagoons.

4.1.3 Lifespan

The EcoSilencer® will be subject to significant temperature differentials and to both reducing and oxidising environments. One end of the silencer will be subjected to hot and dry conditions where the exhaust enters, and cold and humid where the seawater and exhaust are mixed. DME (2004) state that the material specification will have a minimum lifespan of 15 years. This study will therefore assume that the equipment lifespan is 15 years.

4.1.4 Operating and Maintenance Costs

General Operating and Maintenance Costs

Experience of operating and maintenance costs on the Pride of Kent were that costs were minimal (MES 2004, 1). These minimal costs relate to costs for pump operation, maintenance and sludge disposal (see below). To reflect likely costs, cost estimates are made as shown in Table 4.2. These costs are estimated as a fraction of new build capital costs.

Table 4.2 Operating and maintenance costs

Vessel size	Small	Medium	Large
O&M costs per year (% of new build capex)	3%	2%	1%

Sludge Disposal

To meet water discharge specifications, the wastewater from the scrubber needs to be cleaned to remove particles and oil. This water treatment process produces an oily sludge, which needs disposal. Although oily sludges are produced from other ship activities, such as such the clearing of cargo tanks or engine room bilges, operation of a sea water scrubber will increase the volume of oily sludge generated.

Oily wastes which have been removed from scrubbing water are stored and disposed of in port. Ports charge for the disposal of oily wastes, however the majority of ports have an fixed (‘direct’) fee for sludge disposal which allows disposal of a certain amount of waste (Hayward and Dzanic, 2003). If this limit is not exceeded, sludge from the scrubber will not add extra costs. For example, the Port of Rotterdam charges an indirect fee for ships based on main engine capacity, which covers the disposal of a certain amount of oily waste.

Results from the Pride of Kent EcoSilencer® trials demonstrated a small sludge production rate of 0.2 kg/MWh (MES 2004,3). Such a small sludge production rate would produce small sludge quantities per journey. It is likely that this amount of additional sludge production per journey from operating a SWS system will not make a ship exceed the amount of sludge disposal allowed under a direct fee. Table 4.3 shows an example for the port of Rotterdam and a journey duration of 550 hours. Since any sludge disposal costs will be relatively small, it is assumed this is covered by the estimated operating costs shown in Table 4.2. However it was claimed that there might be an issue with the acidity of the sludge that might cause additional disposal problems and costs. The characteristic of the seawater scrubbing sludge and its disposal would therefore need to be further investigated to better understand any potential additional cost implications.

Table 4.3 Accepted oily waste under direct fee, Port of Rotterdam

Main engine capacity	Maximum amount of oily waste under indirect fee (m^3)	Estimated oily sludge production (m^3) from SWS for a journey of 550 hours[14].
Small (< 6,000 kW)	3	<0.5
Medium (>= 6,000 - <15,000 kW)	3-10	0.5-<1.5
Large (>= 15,000 kW)	15-20	1.5-<10

4.1.5 Total Costs per vessel

Table 4.4 summarises the current costs for sea water scrubbing based on the EcoSilencer® data collected from the Pride of Kent trials by MES (2004).

Table 4.4 Costs for sea water scrubbing

	Vessel		
	Small	Medium	Large
New build capex (€)	418,656	1,350,048	3,386,880
Equipment lifespan (year)	15	15	15
Annualised costs (€/year)	37,700	121,460	304,630
Capex per kW installed (€/kW)	118	118	118
Retrofit capex (€)	598,080	1,928,640	4,838,400
Equipment lifespan (year)	12.5	12.5	12.5
Annualised costs (€/year)	61,750	199,090	499,440
Capex per kW installed (€/kW)	168	168	168
Operating and Maintenance (O&M) costs (€/year)	12,560	27,001	33,869
Opex per MWh (€/MWh)	0.8	0.5	0.3
Total annual costs - new build (€/year)	**50,260**	**148,461**	**338,499**
Total annual costs - retrofit (€/year)	**74,310**	**226,091**	**533,309**

---

[14] Assumed density of sludge of 1,300 kg/m^3

4.2 Fuel Switching

4.2.1 Capital Costs and Lifespan

For fuel switching techniques, vessels have the option of either entirely switching to alternative fuels (including the same fuel type but at a different sulphur content) or operating on dual-fuel mode, with separate fuel storage tanks for each fuel (or split storage tanks). It should be noted that the focus of the cost analysis in this study is on EU-flagged vessels, and an assumption is made that they spend a large proportion of their time, on average, in EU waters. As such, the dual – fuel compliance approach is assumed to be less important for these vessels. However, it is likely that some vessels (in particular, foreign-flagged vessels and internationally EU-flagged vessels) would not want to incur the additional expense of low sulphur fuel if they didn't have to. For these vessels, if they wanted to reduce sulphur by fuel switching, they could either add an additional fuel storage tank, or split an existing storage tank. Some relevant technical issues of operating in dual-fuel mode are discussed in Entec's 2002 report for the European Commission on ship emissions (Entec, 2002).

Therefore this study is considering only the cost to vessels which permanently switch to use lower sulphur RO, rather than vessels which alternate between fuels with different sulphur levels. Therefore for the purposes of the cost estimates in this report, it is assumed that it is not necessary to install an additional fuel tank and associated equipment. In addition, it can be assumed that there are no significant operating issues associated with switching between fuels and no capital costs for fuel switching are taken into account.

4.2.2 Operating Costs

Increases in operating costs for fuel switching relate to the premium in fuel costs. Table 4.5 outlines the cost premiums based on the BeicipFranlab report (2003). It can be seen that there is a wide range of possible price premiums dependant upon supply, fuel demand, production costs and inherent uncertainties in such estimations especially over a longer time period. The table also sets out latest estimates from Concawe for fuel price premia (lower for 1.5% and higher for 0.5%). Note that these costs have been corrected for inflation and converted to Euros in year 2000. The specific fuel consumption assumed is 200 g/kWh. This study uses the mid-range values of the Beicip-Franlab range as the main values, but also presents results calculated with the Concawe values in brackets ().

Table 4.5 Fuel cost premium for low sulphur RO

Fuel switch		BeicipFranlab (2003)	Concawe	Main values used in this study
2.7% S RO-> 1.5% S RO	Price premium of fuel (€$_{2000}$/t)	20 to 80	(30)	50
	Specific Premium (€$_{2000}$/MWh)	-	-	10
2.7% S RO-> 0.5% S RO	Price premium of fuel (€$_{2000}$/t)	40-88.5	(75)	64
	Specific Premium (€$_{2000}$/MWh)	-	-	13
2.7% S RO -> 0.2% S MD	Price premium of fuel (€$_{2000}$/t)	-	-	110
2.7% S RO -> 0.1% S MD	Price premium of fuel (€$_{2000}$/t)	-	-	130

4.2.3 Total Costs for Fuel Switching

Table 4.6 and Table 4.7 summarise the cost for fuel switching from 2.7% sulphur down to 1.5% and 0.5% sulphur respectively.

Table 4.6 Total costs, Fuel switching, 2.7 -> 1.5% Sulphur RO (figures in brackets show results using Concawe price premium)

	Vessel		
	Small	Medium	Large
Capex (no Capex assumed)	0	0	0
Operating and Maintenance (O&M) costs (€/year)	156,907	513,694	1,282,237
Opex per MWh (€/MWh)	10	10	10
Total annual costs - new build (€/year)	**156,907**	**513,694**	**1,282,237**
	(94,000)	**(308,000)**	**(770,000)**
Total annual costs - retrofit (€/year)	**156,907**	**513,694**	**1,282,237**
	(94,000)	**(308,000)**	**(770,000)**

Table 4.7 Total costs, Fuel switching, 2.7 -> 0.5% Sulphur RO (figures in brackets show results using Concawe price premium)

	Vessel		
	Small	**Medium**	**Large**
Capex (no Capex assumed)	0	0	0
Operating and Maintenance (O&M) costs (€/year)	201,737	660,464	1,648,590
Opex per MWh (€/MWh)	13	13	13
Total annual costs - new build (€/year)	**201,737**	**660,464**	**1,648,590**
	(236,500)	**(773,000)**	**(1,930,000)**
Total annual costs - retrofit (€/year)	**201,737**	**660,464**	**1,648,590**
	(236,500)	**(773,000)**	**(1,930,000)**

5. Cost Effectiveness

5.1 Cost effectiveness of SO2 abatement techniques for ships

Table 5.1 and Table 5.2 depict the derived cost effectiveness for the three measures to reduce SO_2 emissions.

Table 5.1 Cost Effectiveness of SO_2 Reduction Measures in €/tonne abated (note 1) (figures in brackets show results using Concawe price premium)

Measure	New/Retrofit	Emission	Small (€/tonne SO_2)	Medium (€/tonne SO_2)	Large (€/tonne SO_2)
Sea water scrubbing	New	SO_2	390	351	320
Sea water scrubbing	Retrofit	SO_2	576	535	504
Fuel switching: 2.7% S fuel to 1.5% S fuel	New	SO_2	2,053 (1,230)	2,050 (1,230)	2,045 (1,230)
Fuel switching: 2.7% S fuel to 1.5% S fuel	Retrofit	SO_2	2,053 (1,230)	2,050 (1,230)	2,045 (1,230)
Fuel switching: 2.7% S fuel to 0.5% S fuel	New	SO_2	1,439 (1,690)	1,438 (1,690)	1,434 (1,690)
Fuel switching: 2.7% S fuel to 0.5% S fuel	Retrofit	SO_2	1,439 (1,690)	1,438 (1,690)	1,434 (1,690)

Note 1: Fuel switching costs are based on mid-range value of BeicipFranlab price premia

Table 5.2 Cost Effectiveness of SO_2 Reduction Measures in €/tonne fuel used (note 1) (figures in brackets show results using Concawe price premium)

Measure	Ship type	Unit	Small (€/tonne fuel)	Medium (€/tonne fuel)	Large (€/tonne fuel)
Sea water scrubbing	New	Fuel	16	14	13
Sea water scrubbing	Retrofit	Fuel	24	22	21
Fuel switching: 2.7% S fuel to 1.5% S fuel	New	Fuel	50 (30)	50 (30)	50 (30)
Fuel switching: 2.7% S fuel to 1.5% S fuel	Retrofit	Fuel	50 (30)	50 (30)	50 (30)
Fuel switching: 2.7% S fuel to 0.5% S fuel	New	Fuel	64 (75)	64 (75)	64 (75)
Fuel switching: 2.7% S fuel to 0.5% S fuel	Retrofit	Fuel	64 (75)	64 (75)	64 (75)

Note 1: Fuel switching costs are based on mid-range value of BeicipFranlab price premia

5.2 Comparison of cost effectiveness of SO2 abatement measures for ships compared with SO2 abatement for other sources

In the context of EU policy development, emissions reductions should be sought where they are most cost-effective in achieving environmental objectives, taking into consideration all emission source groups. This section compares the marginal abatement costs of additional abatement measures for ships with the corresponding costs of additional abatement measures for other sectors.

The marginal abatement costs of additional abatement measures for all sectors considered in the CAFÉ modelling work were supplied by IIASA, at the time of undertaking the research for this study, and represent measures beyond those that are estimated to be implemented under the CP_CLE scenario, i.e. the measures represent 'beyond BAU' measures and are under the maximum technically feasible reduction scenario – MTFR.

The data is presented in the following figures for SO_2. Each figure shows the cost curve for the specified year, which is comprised of large numbers of individual 'beyond BAU' measures ranked in order of cost effectiveness. The curve starts at the left of each figure, at zero emissions reduction. As more and more 'beyond BAU' measures are taken into account, emissions are reduced with compliance costs increasing (ie as the cost curve moves to the top right of the figure).

Each measure represents an individual point on the curve. The slope of the curve indicates the cost effectiveness at any given point.

Overlaid onto each figure are text boxes and arrows indicating the approximate relative position in the cost curve where the additional measures for ships considered in this report would fit, if they were included in the cost curves. It should be noted that the specific measures themselves are not currently integrated into the cost curves and therefore their impact on remaining emissions and incremental costs is not explicitly taken into account in the cost curves that are presented here.

These figures simply enable the relative cost effectiveness of additional measures for ships to be considered in comparison to the cost effectiveness of 'beyond BAU' measures already included in the RAINS model.

It should be noted that in these figures the fuel switching costs are based on mid-range value of BeicipFranlab price premia.

Figure 5.1 **Cost curve for SO_2 for 2010 showing position in cost curve where additional measures for ships would fit (all measures for ships are for medium size vessels) (Source: IIASA, 2004)**

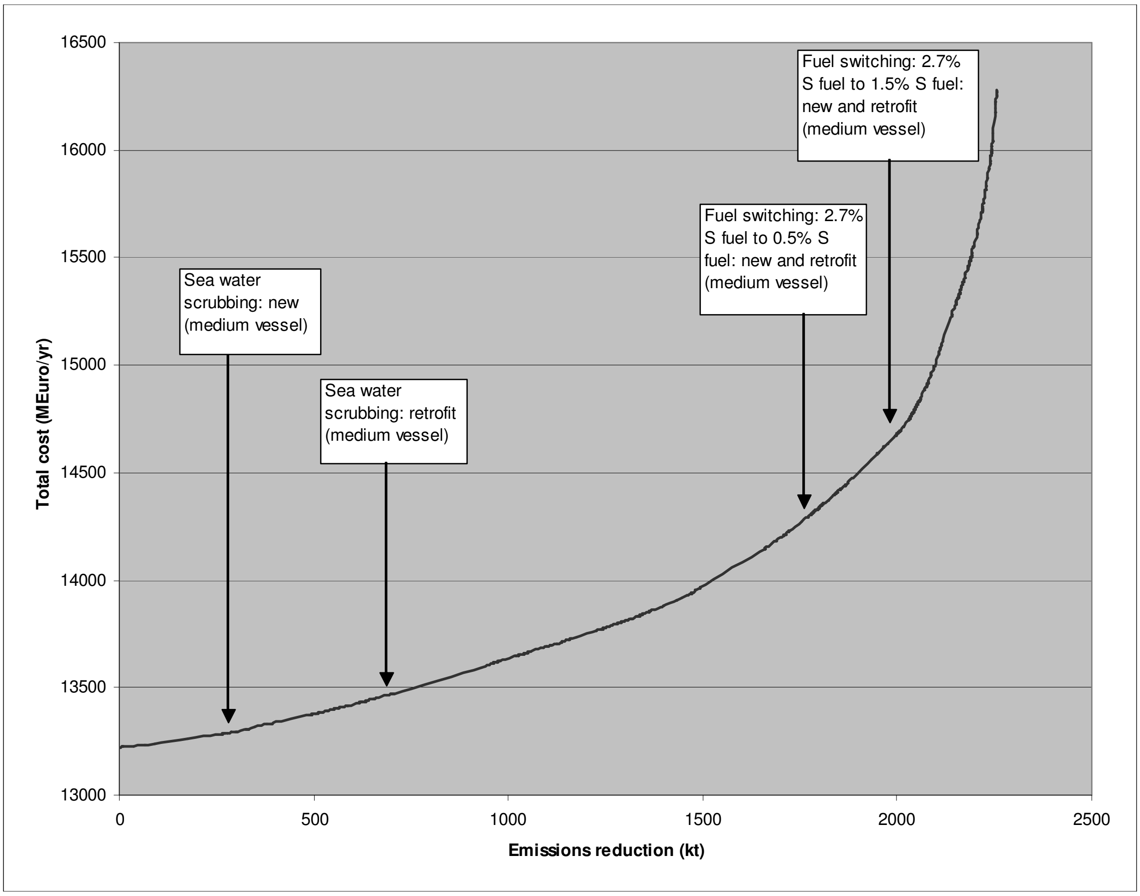
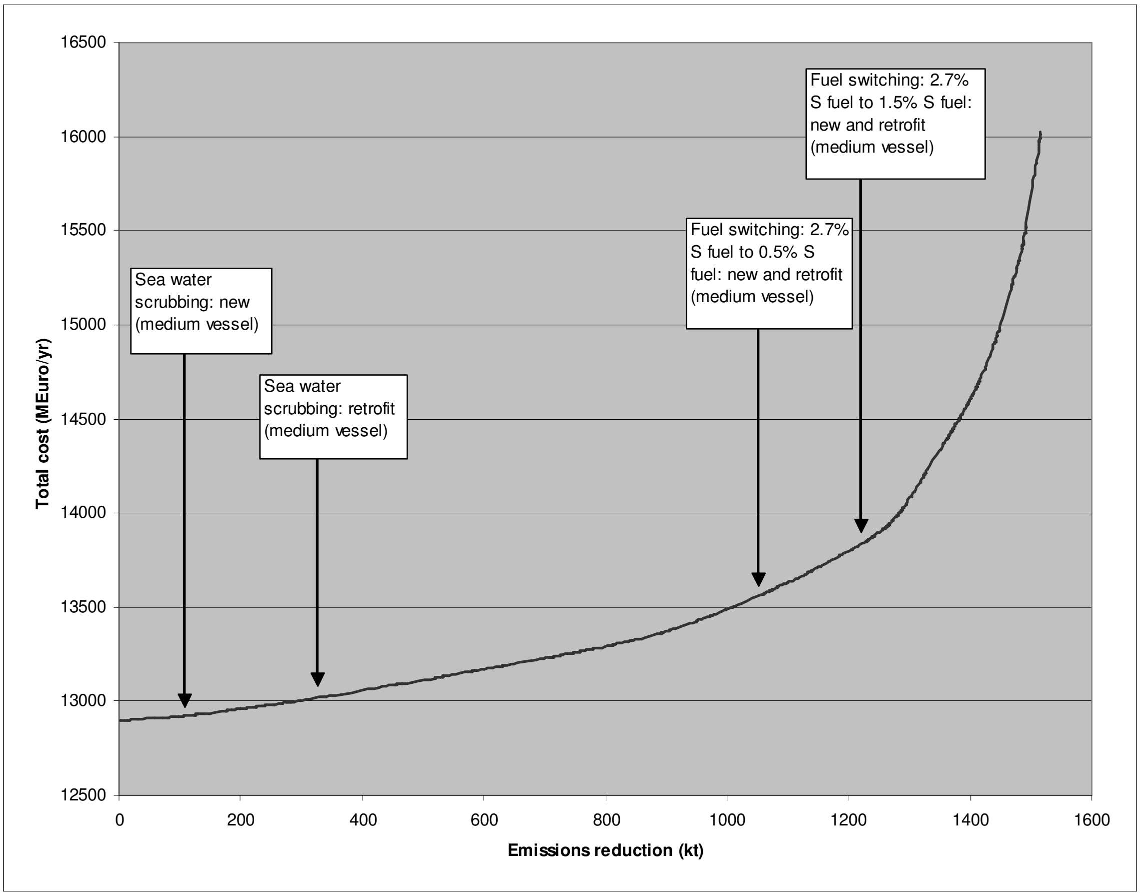


Figure 5.2 **Cost curve for SO2 for 2020 showing position in cost curve where additional measures for ships would fit (all measures for ships are for medium size vessels) (Source: IIASA, 2004)**



It is evident that the potential additional measures for SO_2 for ships are spread along the cost curve: sea water scrubbing being one of the more cost-effective measures on the left of the cost curve, whereas fuel switching is positioned further towards the right.

For further comparison, the indicative average marginal abatement costs supplied by IIASA for sectors in the RAINS model with ‘beyond BAU’ SO_2 measures are shown in Table 5.3. This includes all RAINS sectors except the shipping sector, due to the more specific ship emissions abatement estimates derived in this study. Within each sector in the table, the quoted marginal abatement cost represents an average across all fuel types, abatement techniques and countries. Hence, individual measures may differ significantly from the quoted figures.

Table 5.3 Indicative average marginal abatement costs for sectors with 'beyond BAU' SO_2 measures supplied by IIASA for 2010 and 2020

Sector	2010 Cost Curve - marginal cost (Euro/t)	2020 Cost Curve - marginal cost (Euro/t)
Fuel production & conversion: Combustion	2704	2704
Combustion in residential-commercial sector	2004	2004
Industry: Combustion in boilers	5609	6445
Industry: Other combustion	2139	2627
Power & district heat plants: Exist. other	3838	4365
Power & district heat plants: New	8946	8659
Industrial. Process: Cement production	8691	8691
Industrial. Process: Coke oven	1144	1144
Industrial. Process: Lime production	5839	5839
Industrial. Process: Other non-ferrous metals prod. - primary and secondary	2786	2786
Industrial. Process: Pig iron, blast furnace	1083	1083
Industrial. Process: Paper pulp mills	1099	1099
Industrial. Process: Petroleum refineries	1070	1070
Industrial. Process: Agglomeration plant - sinter	941	941
Industrial. Process: Sulfuric acid	972	990
Other transport: rail (solid fuels), heating (stationary combustion)	5245	5245
Waste: Agricultural waste burning	686	686
Waste: Flaring in gas and oil Industry	6286	6747
Waste: Open burning of residential waste	1586	1586

It can be seen from a comparison of Table 5.3 with Table 5.1, that the shipping sector is one of the more cost effective sectors (per tonne SO_2 abated) for achieving additional 'beyond BAU' SO_2 emissions reductions, with sea water scrubbing being a particularly cost-effective technique relative to other techniques in the cost curve.

It is emphasised, however, that whilst the potential position of a measure in a single-pollutant cost curve is a useful gauge of its relative cost-effectiveness, it is not necessarily indicative of its relative cost-benefit performance, due to the generally greater distance of ship emission sources to nearest receptor populations and environments.

The scope of this particular study does not extend to a cost-benefit analysis, however this would be important in any further policy development related to potentially tighter standards in the shipping sector. If such work was to be done, it would clearly be necessary to consider the costs in more detail (including relevant wider economic impacts) and to quantify the health and environmental benefits of any potential emissions reductions (including impacts on other pollutants). In such an analysis, the location of ship emissions relative to receptor populations and environments would need to be taken into account.

6. Scale up for all EU-Flagged Ships

As mentioned in the General Report only commercial ships > 500 GT are included in this study. Assumptions on numbers of existing ships in the EU-flagged fleet and the world fleet are shown in Table 6.1.

Table 6.1 Number of ships in the EU-flagged and world fleet

Number of EU-flagged vessels >500GT	7,150
Number of ships in world fleet >500GT	31,000

The costs for applying the technologies to the EU-flagged fleet are shown in Table 6.2. This table illustrates costs per year for applying each measure to all applicable existing ships. The additional costs per year for each new build ship are presented in Section 4 for each abatement measure.

Table 6.2 Costs for applying measures to existing vessels in the EU-flagged fleet (estimates based on CONCAWE fuel prices in brackets)

	Vessels			**Total**
	Small	**Medium**	**Large**	
Fraction of total EU-flagged ships	55%	35%	10%	100%
SWS, annualised costs for retrofitting all existing ships (€millions/year)	292	566	381	1,239
Fuel switching, annualised costs for switching to 1.5% S fuel for all existing ships (€millions/year)	617 (370)	1,285 (770)	917 (550)	2,819 (1,690)
Fuel switching, annualised costs for switching to 0.5% S fuel for all existing ships (€millions/year)	793 (930)	1,653 (1,940)	1,179 (1,380)	3,624 (4,250)

Appendix 1
Pride of Kent Trials Air and Water Emission Monitoring Reports

Table of Content

1. DME Project 1497 June 2004

CONTENTS

1. PROJECT OVERVIEW

DME (Marine Exhaust Solutions) of Charlottetown Canada contracted Air Quality Solutions to conduct an emission measurement programme on their installation on board the P & O Ferry ‘Pride of Kent’ based from Dover England.

The installation performs exhaust gas scrubbing for SO_2 removal direct from the diesel engine exhaust gases.

The emission tests were carried out from the 1st June until the 3rd June 2004. Velocity tests were carried out on the 15th June 2004.

The purpose of the test programme was to measure actual air emissions from inlet and outlet locations in accordance with DME requirements.

The test source was identified as follows:

- Stack (Inlet/Outlet)

The test programme included the determination of the following emissions:

- SO_2
- NOx

Co-ordinating the field testing were:

Mr Chris Skawinski	Marine Exhaust Solutions (DME)
Mr Chris Green	Air Quality Solutions

The results of the tests are summarised in section 2.

2. SUMMARY OF TEST RESULTS

Calibration of each analyser system was carried out daily before and after each test.

Date	Location		Comment
01/06/04	Inlet	Outlet	Preliminary Data
02/06/04	Inlet	Outlet	Validation Test
03/06/04	Inlet	Outlet	Process adjustment response
15/06/04	Outlet(s)		Velocity Tests

Fuel: Heavy Fuel 2.4% Sulphur

Location: Auxiliary

Test No:	*Engine Load (kW)	*Water Level PID (mm)	*Backpressure Range (mmH2O)	SO2 (Avg)	NO/NOx (Avg)
Validation test,					
14:00-15:00					
inlet	625	250	280-300	526.0	1008.1
outlet	625	250	280-300	31.9	972.6
Validation test					
14:00-16:30					
inlet	625	250	280-300	526.0	1008.1
outlet	625	250	280-300	45.8	976.8

*Operating details provided by DME

DME Comparison Inlet Outlet.xls

inlet weds (2)am.xls

inlet weds am.xls

inlet weds pm.xls

outlet weds pm.xls

Calibration Check Thursday (Inlet).xls

Calibration Check Thursday (Outlet).xls

DME Velocity Data.xls

Conclusions

- Test duration 150 minutes
- Data logged @ 15 second intervals
- Average SO_2 value before scrubbing 526.0ppm
- Average SO_2 value after scrubbing 45.8ppm
- Best average continuous rate of SO_2 removal 94 %
- Best maximum continuous rate of SO_2 removal 95.1%
- Worst average continuous rate of SO_2 removal 91%
- NO_x average removal rate: 2%

Comment

Inlet/outlet SOx and NOx monitoring conducted at the same time during the test.

Sampling Locations

Typical Equipment Set Up

3 METHODOLOGY

3.1 Sampling Procedures

The sample gas was extracted from the scrubber inlet and outlet ducts as requested via a filtered/heated sample system into a gas conditioning system to remove moisture, the resulting dry gas was than transferred to the Horiba PG 250 analyser system and data logger, measurements were recorded at 15 second intervals.

Equipment List

G212	Gas sample probe (2 off)
H311	Heated sample line (2 off)
GC03	Gas conditioning/flow control system (2 off)
12418	Horiba PG 250 (2 off)
DRM 3	Data Logger (2 off)
SB003	Stack Kit
SB004	Stack Kit

3.2 November 2004 Test Results Summary

54 Hillstrom Avenue • Charlottetown
Prince Edward Island • CANADA C1E 2C6
TEL: 902.628.6900
FAX: 902.628.1313

MARINE EXHAUST SOLUTIONS INC.

Test Results for Marine Exhaust Solutions EcoSilencers for auxiliary motors onboard the Pride of Kent.

November 2004

Independent Testing by: Westech

Test Date	EcoSilencer Unit	% SO2 removed	Equivalent %SO2 fuel rating *	Comments
24 Nov 2004	Auxiliary motors			3 Auxiliary units on line & under load
	Stbd Inner	68% - 74%	0.8% - 0.65%	
25 Nov 2004	Auxiliary motors			1 Auxiliary units on line & under load
	Stbd Inner	76% - 80%	0.6% - 0.5%	
26 Nov 2004	Auxiliary motors			2 Auxiliary units on line & under load
	Port Outer	76% - 80%	0.6% - 0.5%	

*Based on nominal bunker sulphur content of 2.5%.