Marine Black Carbon Emissions:
Measuring and Controlling BC from Marine Engines

Technical Workshop Background Document

September 7th and 8th, 2016

International Council on Clean Transportation (ICCT) and

Environment and Climate Change Canada (ECCC)

Vancouver, British Columbia, Canada

Abbreviations

AHTS	Anchor Handling Tug Supply
BC	Black Carbon
CAPEX	Capital Expenditure
CCAC	Climate and Clean Air Coalition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DPF	Diesel Particulate Filter
EC	Elemental Carbon
ECCC	Environment and Climate Change Canada
EGR	Exhaust Gas Re-circulation
ESP	Electrostatic Precipitator
EUROMOT	European Association of Internal Combustion Engine Manufacturers
HFO	Heavy Fuel Oil
ICCT	International Council on Clean Transportation
IGF	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LSFO	Low Sulfur Fuel Oil
MDO	Marine Diesel Oil
MEGI	Main Engine Gas Injection
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MT	Metric Ton
NGO	Non-governmental Organization
NO_X	Nitrogen Oxides
OPEX	Operational Expenditure
OSV	Offshore Supply Vessels
PM	Particulate Matter
SLCF	Short Lived Climate Forcers
SO_X	Sulfur Oxides
SSDR	Slow Steaming and De-Rating
UNEP	United Nations Environment Program
WiFE	Water in Fuel Emulsions

CONTENTS

1.0 INTRODUCTION

The International Council on Clean Transportation (ICCT),[1] in coordination with Environment and Climate Change Canada (ECCC), is hosting a technical workshop on marine black carbon (BC) emissions. This workshop is the final of three designed to shape a project on marine BC emissions funded by the Climate and Clean Air Coalition (CCAC) – an international cooperative partnership of over 40 member nations and more than 50 intergovernmental and non-governmental organizations to promote strategies to reduce emissions of short-lived climate pollutants, including BC. Under that project, the ICCT, working with the United Nations Environment Program (UNEP), will develop a refined global marine BC inventory and control technology performance database for use by CCAC member states.

The first workshop, held in Ottawa, Canada, in September 2014, focused on building consensus on a definition of BC suitable for research purposes. Workshop participants agreed that the most suitable definition of BC for research purposes was defined in Bond et al. (2013):

BC is a "distinct type of carbonaceous material, formed primarily in flames, is directly emitted to the atmosphere, and has a unique combination of physical properties." Two properties in particular were considered to be useful for measurement purposes:

- *BC strongly absorbs visible light with a mass absorption coefficient (MAC) value above 5 $m^2\ g^{-1}$ at a wavelength λ = 550 nanometers (nm) for freshly produced particles*
- *BC is refractory, with a volatilization temperature near 4000 K*

The International Maritime Organization (IMO) formally accepted the Bond et al. (2013) definition of BC at MEPC 68 in May 2015.

The second workshop, held in Utrecht, Netherlands, in September 2015, focused on working toward consensus on a standardized BC measurement and reporting approach for voluntary marine BC emissions testing campaigns. Important outcomes from the second workshop were as follows:

- Extensive input from participants on ways to refine a research plan for laboratory and on-board BC testing led by the University of California-Riverside (UCR) in order to make the study results more useful to the marine BC research and policy communities.
- Recommendations on ways to improve a measurement reporting protocol for voluntary marine BC emissions testing campaigns that was developed and presented by the European Association of Internal Combustion Engine Manufacturers (EUROMOT).

Note: the outcomes of the second workshop will be highly relevant to achieving the goals of the third workshop as introduced below, especially the goal to solidify recommendations for marine BC measurement approaches. As such, workshop participants are encouraged to review the second workshop's Workshop Summary Report as background reading material.

The **goals** of this third and final workshop are to: (1) solidify recommendations for marine BC measurement approaches; and (2) identify effective technological and operational strategies to control BC from marine engines. To achieve these goals, the workshop will convene international

[1] The International Council on Clean Transportation is an independent nonprofit organization founded to provide first-rate, unbiased research and technical and scientific analysis to environmental regulators. Our mission is to improve the environmental performance and energy efficiency of road, marine, and air transportation, in order to benefit public health and mitigate climate change.

experts on BC to discuss the results of current marine BC testing efforts as well as operational and technological marine BC control strategies. Workshop participants will: (1) work toward consensus on appropriate marine BC measurement approaches; (2) identify priority marine BC control strategies based on scientific evidence; and (3) discuss policy alternatives that can be implemented by individual countries, the IMO, or other forums, in order to reduce marine BC emissions. Workshop outcomes may inform CCAC member state submissions to the IMO on BC appropriate measurement methods and promising control strategies.

2.0 BACKGROUND

Black carbon is the second largest contributor to human induced climate warming to-date, after carbon dioxide (CO_2), according to Bond et al.'s (2013) landmark four-year study on BC. Black carbon is the primary short-lived climate forcer (SLCF) pollutant from the diesel engines, and marine vessels are a large source of diesel BC emissions. In fact, international shipping was estimated to account for 7-9% of diesel BC emissions in 2000 (Bond et al, 2013; Eyring et al., 2010*)*, growing to 8-13% by 2010 (Azzara et al., 2015). From a climate perspective, marine BC emissions are particularly concerning in the Arctic, where BC deposition to snow and ice reduces albedo, promoting warming and melting. One widely cited 2010 study (Corbett, Lack, & Winebrake, 2010) estimated that, barring additional controls, global BC emissions from marine vessels will nearly triple from 2004 to 2050 due to increased shipping demand, with a growing share emitted in the Arctic region due to vessel diversion. At the same time, emissions from land-based sources are expected to fall due to stricter controls (Johnson et al., 2015), increasing the relative importance of shipping emissions. In addition to its climate impacts, exposure to PM and BC emissions has been linked to negative human health impacts including cardiopulmonary disease, respiratory illness, and lung cancer.

Reducing BC emissions can mitigate climate and health impacts. A number of technologies and operational practices can reduce PM and BC emissions from marine vessels. These include fuel switching, slow-steaming combined with engine de-rating, exhaust gas scrubbers, exhaust gas recirculation, slide valves, water in fuel emulsion, liquefied natural gas (LNG), and diesel particulate filters (DPFs). However, there are challenges in implementing some of these control strategies. For example, many exhaust emissions control technologies require low-sulfur fuel to function properly. While ships operating in Emission Control Areas (ECAs) burn low-sulfur distillate fuels (<1000 ppm S) such as marine diesel oil (MDO) and marine gas oil (MGO), they burn less expensive high-sulfur heavy fuel oil (HFO) with a typical S content of ~25,000 ppm on the open ocean; unfortunately, S contents may need to be on the order of 50 ppm S or less for exhaust gas after-treatment technologies like DPFs to operate properly. Scrubbers are one technology that could be used to reduce PM and BC emissions, but there are potentially serious environmental impacts associated with disposing of polluted scrubber wash-water, as well as substantial installation, operation, and maintenance costs to consider. Furthermore, the effectiveness of scrubbers to reduce BC emissions is not, at present, well understood. Additionally, as of yet, there exists no standardized marine BC measurement protocol, making it difficult to estimate BC emissions reduction potential from some of these control strategies.

However, there are a number of ongoing voluntary marine BC emissions testing campaigns in the United States, Germany, Finland, Denmark, Japan, and Canada that seek to refine marine BC emissions factors from engines in the lab and onboard vessels. Importantly, many of these studies implement a measurement reporting protocol developed by EUROMOT, which was first presented at the second workshop of this series and subsequently endorsed by IMO Member States at the 3rd session of IMO's Sub-Committee on Pollution Prevention and Response (PPR 3) in February 2016. The EUROMOT measurement reporting protocol makes it easier to compare the results of various marine BC emissions testing campaigns, as researchers record information about the engine, fuel, instrumentation, and sampling approach. The protocol will likely be refined as it is used in these testing campaigns. These studies are also exploring the impact of operational and technological control strategies on marine BC emissions, including fuel switching, slow steaming, and scrubbers, among others.

Additionally, there are a number of non-governmental organizations (NGOs) that are analyzing potential domestic, regional, and international environmental policies to reduce marine BC emissions through the use of cleaner fuels and through extra protections for sensitive areas, including the potential for international agreements to limit marine BC emissions from vessels that operate in the Arctic. These policies would apply operational strategies, technological strategies, or both, to limit marine BC emissions.

3.0 POTENTIAL MARINE BC CONTROL STRATEGIES

Black carbon control strategies can be applied in two ways: before or after the combustion process (*Figure 1*). Pre-combustion, one can reduce BC emissions through fuel switching, fuel treatment, or by modifying engine operations or the fuel delivery systems. Post-combustion, one relies on removing BC emissions from the exhaust gas stream. This section provides a brief overview of potential marine BC control strategies for workshop participants to consider.

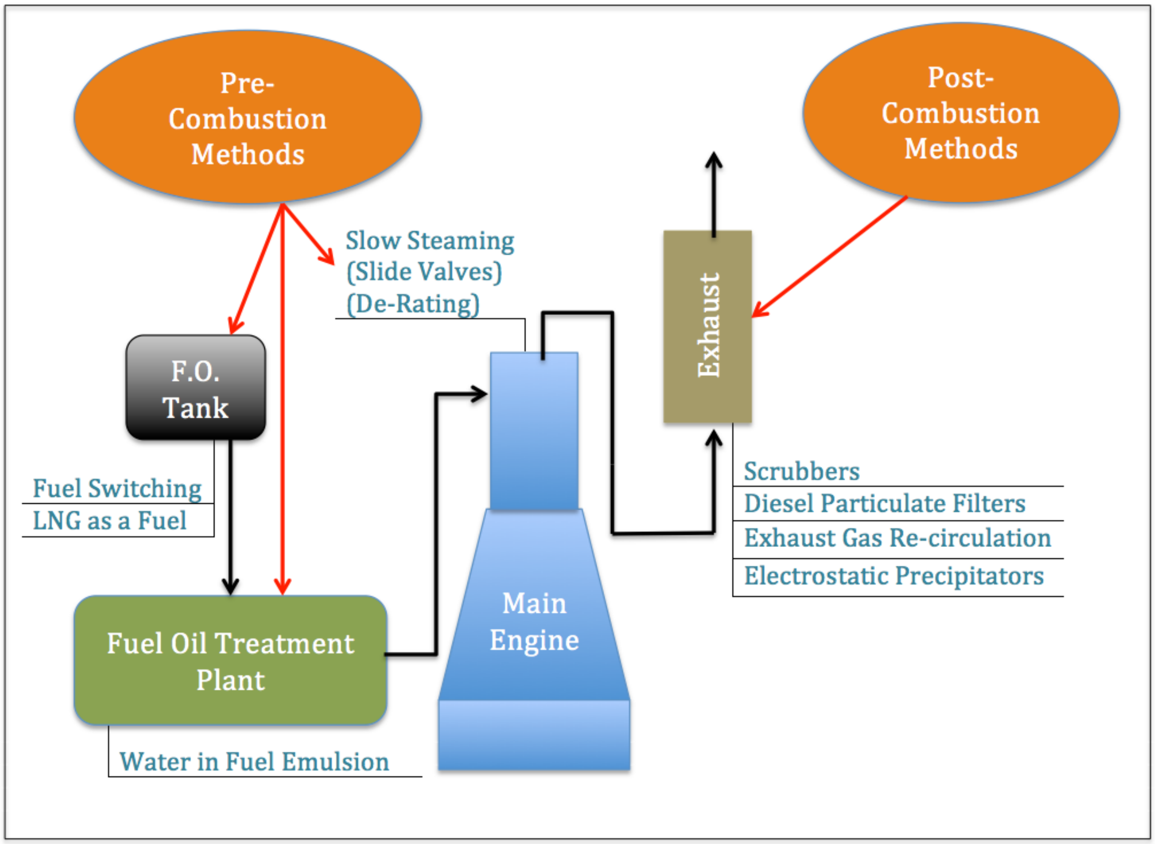

Figure 1: Schematic of potential pre-combustion and post-combustion marine black carbon control strategies

3.1 Fuel Switching

Fuel switching from HFO to distillate fuels like MDO and MGO is proven to reduce harmful air emissions, especially SO_x and PM, in ECAs; however, the impact of fuel oil quality on BC emissions is less clear. For example, Lack and Corbett (2012) found that a switch from HFO to distillates can result in a 30-80% reduction in BC. Other studies suggest that, under certain conditions, BC emission factors are greater with distillate fuels than with HFO, especially at low engine loads (Johnson et al., 2015). However, under typical operating conditions, a switch from HFO to distillates is expected to result in a net decrease in overall marine BC emissions (Lack and Corbett, 2012).

A switch to distillate fuel will be encouraged when the 0.5% fuel sulfur cap enters into force (either 2020 or 2025). However, some vessel owners and operators will continue to operate on HFO and comply by using scrubbers to remove sulfur from the exhaust gas. The BC removal potential from scrubbers is not well understood, but is being examined by some researchers, including the UCR research consortium. Other ships will comply by using emerging low-sulfur residual fuels. It is not clear what BC emissions might be with such fuels compared to high-sulfur HFO; however, researchers, including those with the UCR research consortium, are investigating this question.

3.2 Slide Valves

Slide valves reduce fuel consumption by eliminating a small channel in the valve called the "sac volume." This allows for efficient combustion even at low speeds (e.g., while slow steaming). Without slide valves, the sac volume retains a small amount of fuel oil after injection, which drips into the chamber and combusts incompletely, wasting fuel and producing higher BC emissions. Slide valves are installed on most new marine engines; if not, they can be retrofitted onto existing engines with relative ease. In fact, slide valves are already in use in a large percentage of the shipping fleet and all new engines manufactured by MAN B&W are currently equipped with slide valves. Slide valves are primarily used as a NO_x reduction technique to comply with IMO regulations for newbuild ships. However, Corbett et al. (2010) explain that slide valves can reduce PM emissions as well, resulting in up to 25% PM reductions, with similar reductions in BC. Slide valves require no added operational or maintenance costs, making them an inexpensive way to reduce NO_x, with potential additional BC reduction benefits. Slide valves provide higher reduction in BC when used in conjunction with slow steaming, which is discussed in the next section.

3.3 Slow Steaming

Slow steaming can reduce BC emissions by reducing a ship's fuel consumption along its voyage, as fuel consumption is directly proportional to cube of vessel speed. Therefore, a 10% reduction in speed results in approximately 27% reduction in demanded engine power but a 19% reduction in overall fuel consumption, as it takes longer to sail a given distance at a slower speed (Faber et al., 2012).

Slow steaming can be achieved with or without de-rating. De-rating is ability of the engine to make adjustments to account for the reduced operating speed to ensure better combustion. A combination of slow steaming with de-rating can reduce marine BC emissions by approximately by 15% (Lack et al., 2012). However, for engines without the de-rating feature, BC emissions may increase due to incomplete combustion. For engines without the de-rating feature, slide valves provide an effective BC reduction option.

3.4 Scrubbers

Open loop wet scrubbers use seawater to remove SOx from the exhaust. Closed loop wet scrubbers use fresh water plus an alkaline solution to neutralize the acids formed in the exhaust gas (Hombravella et. al., 2011). *Figure 2 and Figure 3* (Lloyd's Register Marine) show a schematic description of the two types of wet scrubbing systems. Both systems discharge treated wastewater into the open ocean. Dry scrubbers are also being used nowadays, where the sulfuric acid is neutralized by calcium hydroxide via chemical adsorption.

Lack et al. (2012) explain that wet scrubber systems can reduce BC by 20-55% for low sulfur distillate fuels and 50-75% for high-sulfur HFO. However, scrubbers are one of the most expensive abatement techniques.

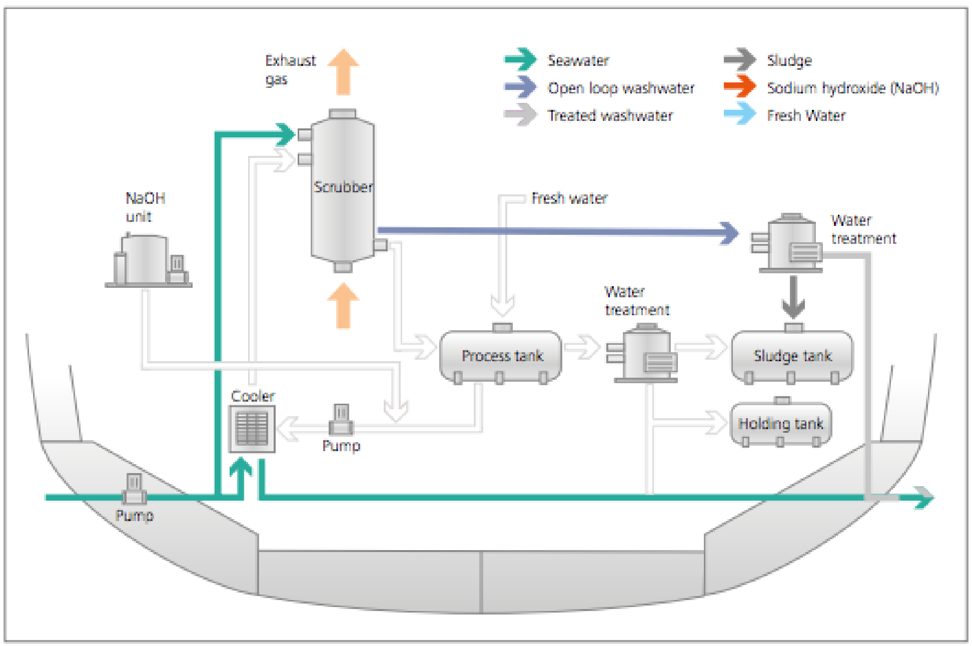

Figure 2: Open Loop Scrubber System

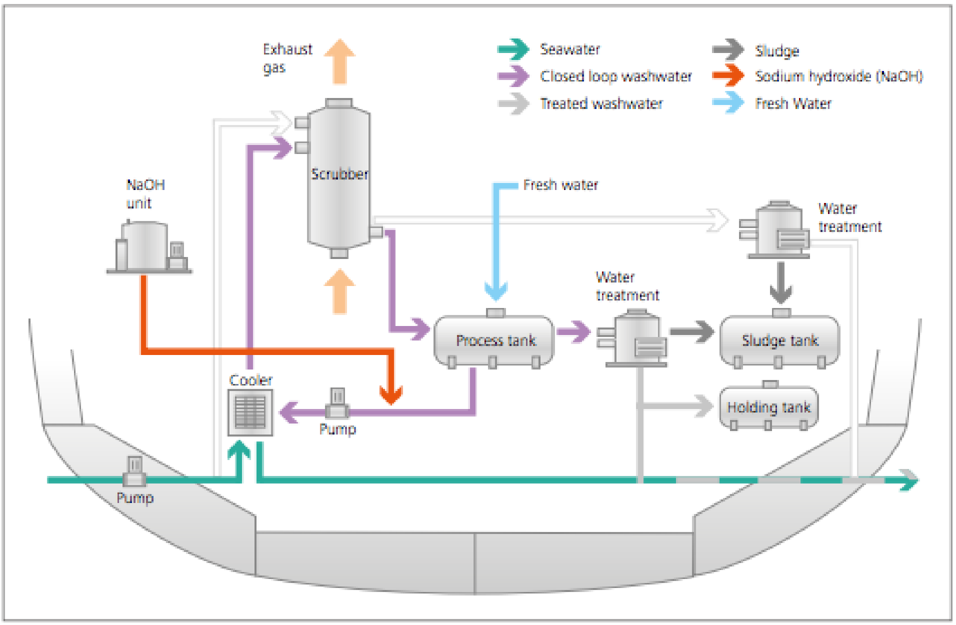

Figure 3: Closed Loop Scrubber System

3.5 Diesel Particulate Filters (DPF)

Diesel particulate filters are the most effective exhaust gas after-treatment systems in terms of BC reduction (95-99%). Diesel particulate filters use silicon carbide ceramic fibers to trap PM or BC. There are two kinds of DPFs: active and passive. Active DPFs use fuel burners or electric regeneration to keep PM and BC from building up and clogging the filter. Passive DPFs use catalysts to regenerate without the aid of any external energy (Corbett et al., 2010). Catalyzed DPFs are not suitable for marine applications due to their inability to work efficiently even at lower fuel sulfur content (50 ppm). For both active and passive DPFs, ash accumulation can be a problem. A report by Dimou et al. (2012) suggests that increased ash deposits not only reduce its soot collecting efficiency but also increases the fuel consumption due to the increased back pressure in the exhaust system. Thus, it is important for DPFs to be regularly maintained.

The primary advantage of DPFs as a BC control strategy is its high BC removal efficiency. DPF technology, in conjunction with low sulfur fuel, is expected to reduce marine BC emissions by 80-90% (Faber et al., 2012). Unfortunately, the high S content of most marine fuels is one current barrier to wider adoption of DPFs on marine vessels.

Figure 4 (MOL, 2012) describes the operation of DPFs. There are four DPF elements, one of which is always in the regeneration mode (self-cleaning process – indicated in red).

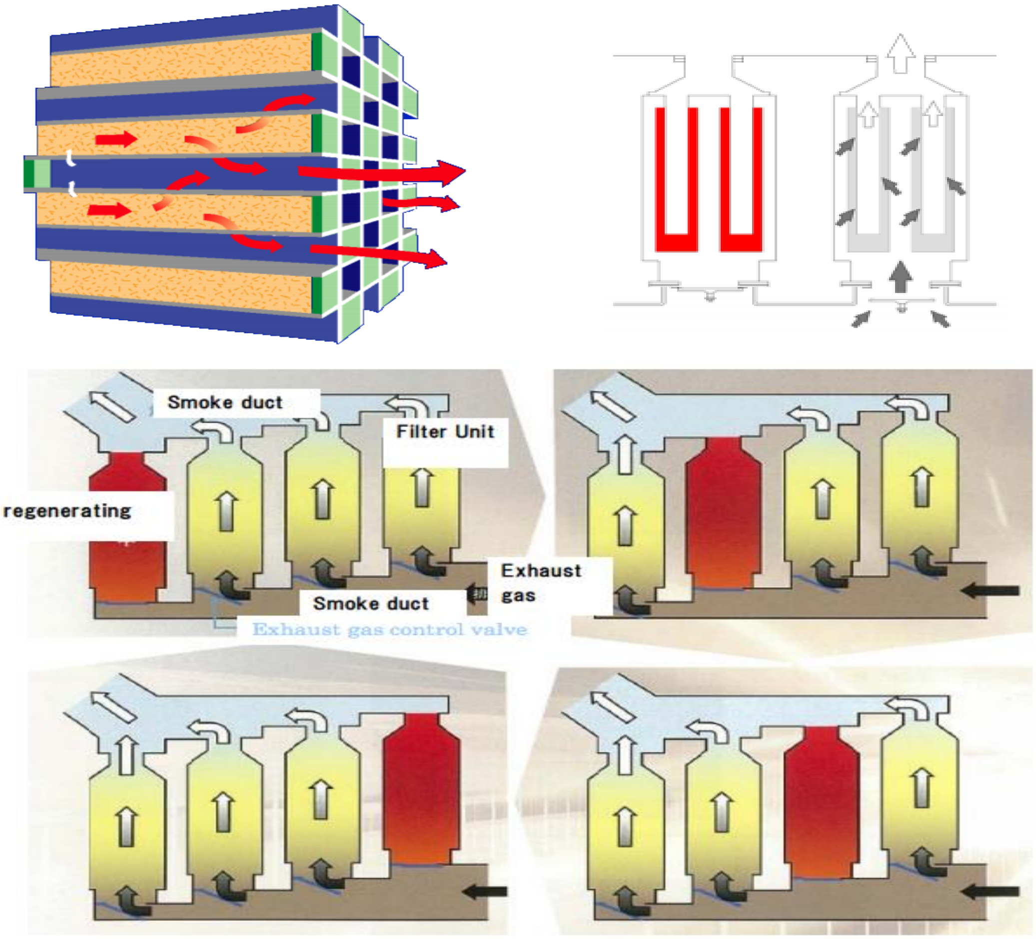

Figure 4: Diesel Particulate Filters (DPFs)

3.6 Exhaust Gas Recirculation (EGR)

Exhaust gas recirculation is primarily used to reduce NO_x emissions by recirculating a portion of the exhaust gas into the intake combustion gas. Unfortunately, lower combustion temperatures and reduced oxygen levels in the EGR process that reduce NO_x emissions also tend to increase the formation of soot, resulting in increased BC emissions.

Thus, EGR is not an effective way to reduce BC emissions unless it is used in conjunction with other processes. For example, Lack et al. (2012) mentions that although the recirculation of exhaust gas results in soot formation, EGR when used in conjunction with an onboard scrubber system helps remove PM and potentially BC.

3.7 Water-in-Fuel emulsion (WiFE)

Water-in-fuel emulsion (WiFE) is a NO_x control technology that may also reduce BC emissions. In WiFE (*Figure 5*), water is continuously added to the fuel supply to create a homogenous mixture. High-pressure water (100 bar) is injected into the fuel stream in atomized form. The homogenizer is placed between the fuel oil supply and circulating pumps, where the frequency controlled high-pressure pump is able to constantly deliver the required amount of water at the desired pressure. On injection, the additional energy required to heat up the liquid water to its boiling point (evaporation), as well as super heating the water vapor, reduces the combustion temperature, thereby reducing NO_x (Landet, 2010). However, WiFE may also reduce BC emissions. Corbett et al. (2010) suggest that WiFE systems can also reduce the fuel consumption of older vessels by improving the combustion efficiency. Additionally, a report by Cottell (2012) indicates a 5-15% fuel consumption reduction by using a 10-15% water emulsion. However, using WiFE in newer vessels may result in a fuel penalty of up to 1% (Corbett et al., 2010).

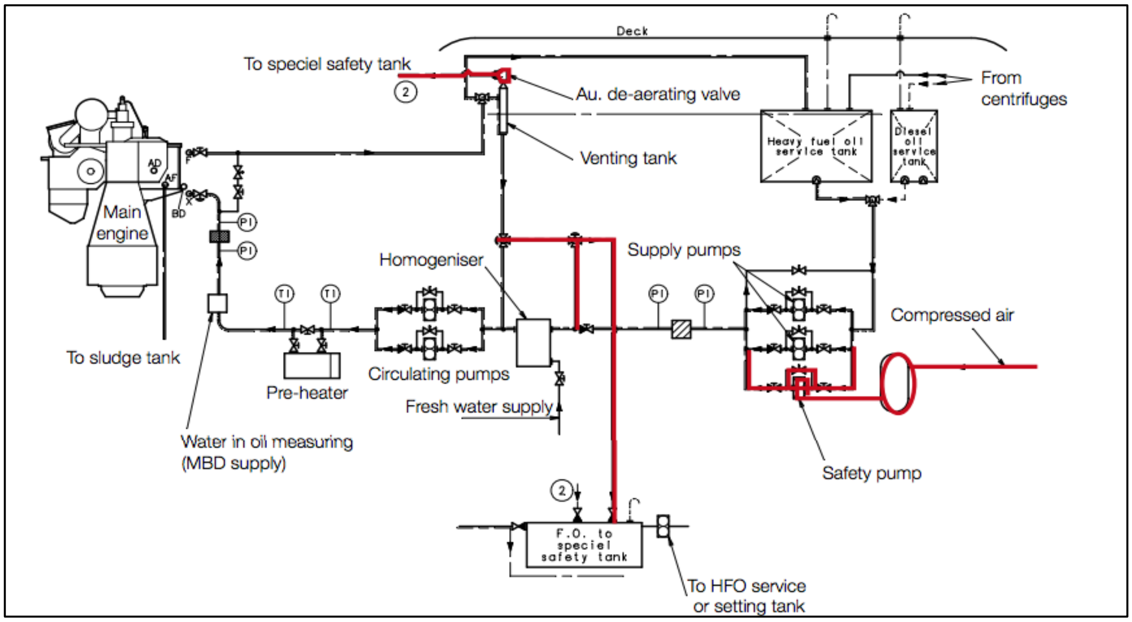

Figure 5: Water in Fuel Emulsion (WiFE) System

3.8 LNG as a Fuel

Liquefied natural gas as a propulsion fuel is one of the most effective solutions to meet IMO fuel sulfur limits, with the added benefit of substantially reduced PM and BC emissions. There are a number of vessels that use LNG fuel today. Dual fuel (LNG and HFO) engines have been used in LNG carriers for over a decade, where system boil-off gas is used as fuel on loaded voyages while HFO is used on ballasted voyages. Initially, the dual fuel engines were 4-stroke engines operating on low-pressure gas injection based on Otto cycle. However, MAN Diesel & Turbo[2] has developed a high pressure injection dual fuel slow speed two stroke main engines based on the Diesel cycle.

The use of dual fuel engines has been mostly limited to LNG carriers, and their use as a replacement of residual and distillate fuel is only possible after proper development of LNG bunkering terminals. Also, retrofitting current non-LNG carriers provides the challenge of creating not only an onboard cryogenic plant but also LNG tanks double the size of residual bunker fuel tanks due to the high expansion ratio of LNG. *Figure 6* shows the arrangement of a two-stroke dual fuel arrangement for a container vessel.[3] The lack of LNG bunkering locations continues to be a barrier to LNG propulsion for marine vessels. Another major stumbling point is developing necessary safety standards to enable bunkering during cargo operations.

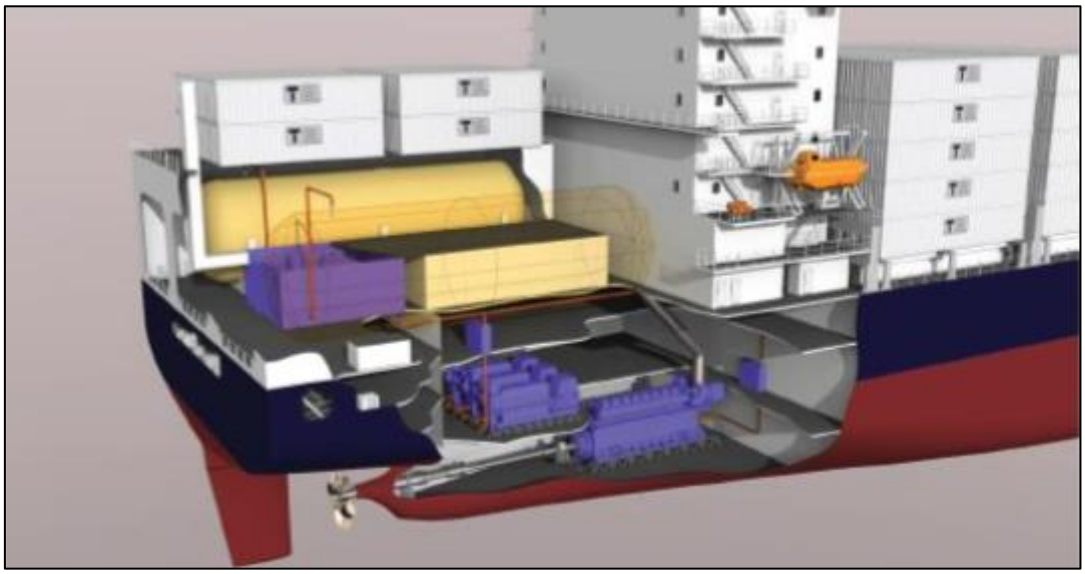

Figure 6: LNG Propulsion Arrangement (ME-GI - MAN B&W) for a Container Vessel

3.9 Electrostatic Precipitators (ESP)

Black carbon particles are statically charged due to rapid airflow around the particle. An electrostatic precipitator (ESP) utilizes this property by passing the exhaust through charged plates, leading to particle precipitation from the exhaust flow. *Figure 7* shows a marine ESP where the gas will flow through between collecting plates charged using high voltage discharge wires (Kaufmann et al., 2014). The rappers located at the top of the system shake the collecting plates once the layer of solid particles on them is relatively thick. The solid particles are collected in the hopper below. The collecting plates for marine purpose are generally made of alloy steel to resist corrosion due to HFO.

---

2 http://www.dma.dk/themes/LNGinfrastructureproject/Documents/Bunkering%20operations%20and%20ship%20propulsion/ME-GI%20Dual%20Fuel%20MAN%20Engines.pdf

3 http://www.lngbunkering.org/sites/default/files/2013%20HEC%20lng%20effect%20on%20ship%20design.pdf

Electrostatic precipitators have a high BC and PM collecting efficiency and do not create any exhaust gas flow backpressure. Some trials have shown BC emissions reductions of 50-80% across all engine loads using ESPs (Lack et al., 2012). However, ESPs are extremely bulky and there is limited deployment of ESPs for marine applications.

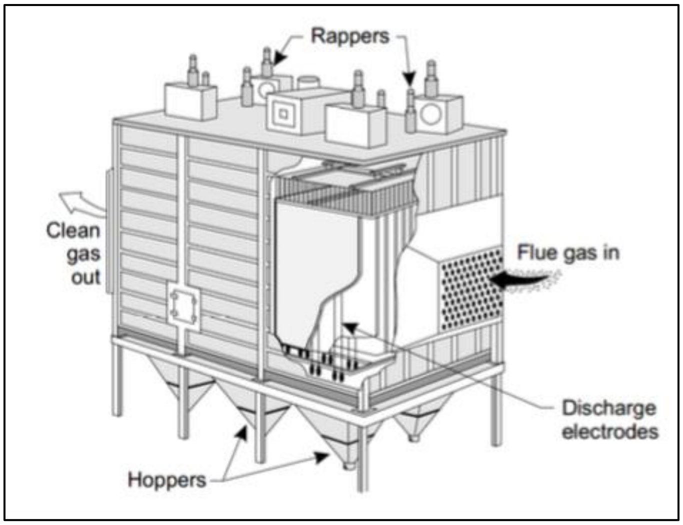

Figure 7: Marine Electrostatic Precipitator (ESP)

3.10 Summary of BC Control Strategy Effectiveness

Figure 8 summarizes marine BC control strategy effectiveness from Azzara et al. (2015). Since many of these technologies have not been tested successfully in full-scale marine applications, the data below provide an approximation of possible BC reductions according to the limited studies that have been carried out. In some cases, the evidence for BC reduction potential is unclear. For example, *Figure8* indicates that EGR can reduce BC emissions 0-20%; however, Lack et al. (2012) suggest that EGR can increase BC.

There is always a potential for synergy between different BC control technologies. For example, Corbett et al. (2010) suggest that combining WiFE (20% water) with slide valves can lead to an almost six-fold reduction in BC emissions when compared to BC reduction by the individual abatement technologies alone.

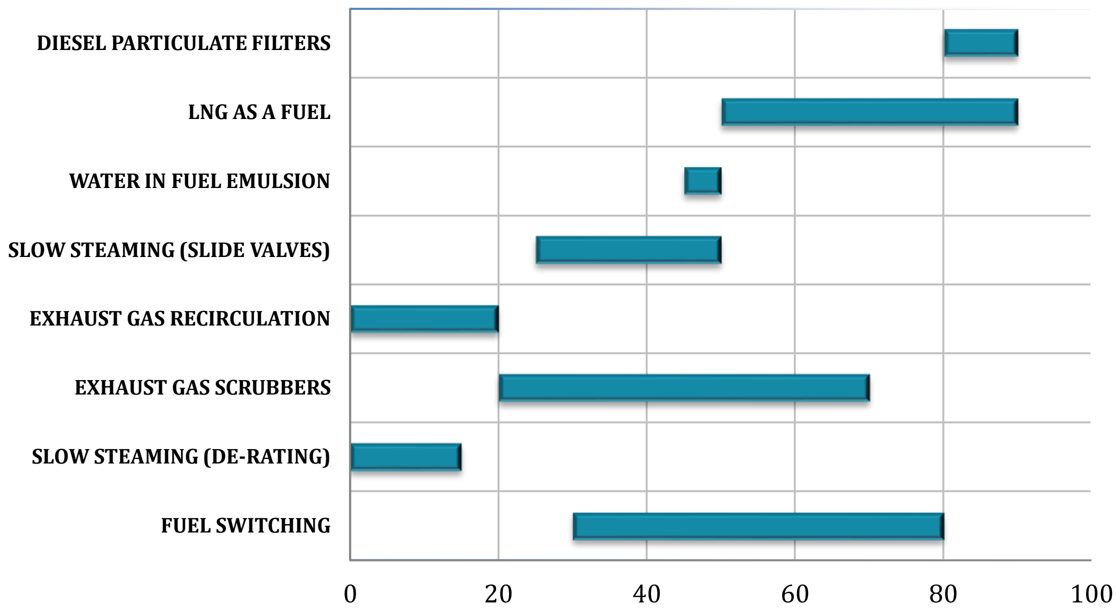

Figure 8: Estimated control strategy BC emissions reduction potential

4.0 COST COMPARISON OF BC CONTROL TECHNOLOGIES

A comparative cost analysis for different BC control technologies is a very complicated process. Numerous factors influence the economic feasibility of a particular technology. Likewise, a particular technology can be suitable for newbuilds but may not be viable as a retrofit option. Furthermore, fuel type and engine type play an important role in the success of BC abatement technologies and strategies.

Few comparative cost analysis of different BC reduction technologies have been carried out to-date, the most exhaustive one being Lack et al. (2012). In this study, the costs of applying BC control measures on an Aframax Tanker was used to compare the relative costs of applying the same measures on different vessel types. The costs of BC abatement measures varies by vessel type and by engine type, as BC control measures might not be applicable to both two-stroke and four-stroke engines.

A comparison of BC abatement measures, as found in Lack et al., (2012), is summarized in *Table 1*. The table shows the relative costs of BC abatement measures by vessel type and engine type, along with comparisons between newbuilds and retrofits. The cost index is calculated with respect to a 120,000 deadweight tonnage (DWT) Aframax Tanker. Subsequently, for other vessels, a cost index exceeding 100 suggests a higher installation and operational expenditure compared to the base vessel, i.e. the Aframax Tanker, and vice-versa for a lower cost index. A few takeaways from the table:

- It is cheaper to install a control technology on a newbuild vessel than to retrofit. This is because for a newbuild we can eliminate additional expenses like drydocking, off-hire, modifications, steel/piping/cabling, etc.

- The appeal of retrofits depends upon the vessel type. For example, for LNG tankers, the cargo itself is a fuel that can be used as a control strategy, thereby requiring relatively few modifications to achieve BC emissions reductions.

- The cost index for smaller vessels like Offshore Supply Vessels (OSV) and Tugs are much smaller due to their operation patterns and size. Application of BC emission reduction technologies on these vessels provides a more economical alternative for research and analysis due to the relatively low capital expenditure requirements.

Table 1: Comparative Cost-Index for BC Control Technologies (Lack et al., 2012)

Type of Vessel	**DWT (Range)**	**Engine Type**		**Cost Index**					
				SSDR	**WiFE**	**LNG**	**HFO-Distillate**	**DPFs**	**Scrubber**
Aframax Tanker	80,000 - 120,000	2-stroke	Retrofit	100	100	100	100	100	100
			New Builds	71	48	89	71	69	90
Container Vessel	120,000 - 180,000	2-stroke	Retrofit	433	358	561	440	429	494
			New Builds	530	530	605	536	530	531
Cape Size Bulk Carrier	150,000 - 180,000	2-stroke	Retrofit	93	92	105	93	92	93
			New Builds	94	95	107	94	93	94
Very Large Gas Carrier	75,000 - 80,000	2-stroke	Retrofit	141	144	156	141	141	139
			New Builds	137	138	157	138	137	137
Cruise Ships	120,000 - 150,000	4-stroke	Retrofit	419	381	508	423	416	450
			New Builds	341	468	534	472	467	469
OSV/AHTS	3,000 - 8,000	4-stroke	Retrofit	122	139	121	121	123	108
			New Builds	100	100	114	100	100	100
Tug	200 - 500	4-stroke	Retrofit	41	44	44	41	42	39
			New Builds	38	38	43	38	38	38

Another cost comparison has been carried out by Corbett et al. (2010). They showed that slide valves provide the most economical alternative, with an installation cost of $0.39-1.68/kW (year 2008$). Unfortunately, slide valves have a shorter lifespan of only 2.5 years as compared to WiFE and DPFs, which can last 20 years. However, DPFs and WiFE are more expensive, with WiFE costing up to $21.8/kW together with an operational and maintenance cost of $19.6/kW.

Another comparison in the same report distinguishes scrubbers as the most expensive BC abatement method – $255,676/MT of BC reduced. While the most efficient BC reduction option is to use slide valves – $5,842/MT of BC reduced. The report did not consider LNG or slow steaming with de-rating.

Table 2 provides an estimated cost comparison in US$/MT BC for different technologies, assuming that the ship is operated in a BC emissions control region for 25% or 100% of the time, respectively.

Table 2: Cost-effectiveness estimates for BC control technologies (Corbett et. al., 2010)

Technology	**Cost (US$/MT BC) (25% in region)**	**Cost (US$/MT BC) (100% in region)**
Slide Valves	23,368	5,842
WiFE (20%)	43,560	18,020
Emulsified Fuel	283,972	283,972
DPF	363,298	133,519
Sea Water Scrubber	735,928	255,676
WiFE (20%) + Slide Valves	137,842	16,753

5.0 POLICIES TO CONTROL BC

There are no formal international, national, or sub-national policies that directly control marine BC emissions. However, some existing policies indirectly control BC. Additionally, some potential future policies could control marine BC emissions, both directly or indirectly.

5.1 Existing Policies

5.1.1 Energy Efficiency Design Index (EEDI)

Following the IMO's first GHG study, IMO adopted Resolution A.963 (23) in 2003 that focused on reducing GHG emissions from ships. The resolution urged IMO's Marine Environment Protection Committee (MEPC) to identify and develop mechanisms to limit or reduce GHG emissions from international shipping. In 2011 technical and operational measures to reduce GHG emissions from new and existing ships, respectively, were adopted. New ships (built 2015+) are required to meet new technical standards for energy efficiency called the Energy Efficiency Design Index (EEDI). These standards become increasingly stringent over time, culminating with ship designs becoming 30% more efficient by 2025, compared with their design efficiency over a 10-year baseline (roughly 1999-2008 for most vessel types). All ships, not just newbuilds, are required to implement a Ship Energy Efficiency Management Plan (SEEMP) to reduce GHG emissions and obtain an International Energy Efficiency (IEE) Certificate to demonstrate compliance.

The EEDI and the SEEMP can indirectly control BC emissions by reducing fuel consumption and, therefore, net BC emissions. However, the EEDI has been criticized as being ineffective at driving improved technical energy efficiency for ships beyond those improvements market forces would incentivize.

5.1.2 Marine Fuel Sulfur Standards

The marine fuel sulfur standards in MARPOL Annex VI Regulation 14 may help reduce marine BC emissions. Regulation 14 calls for a global marine fuel sulfur cap of 0.5% S m/m in 2020, with a potential delay to 2025, depending on the results of a fuel availability study to be presented at MEPC 70 in October 2016. The current global marine fuel sulfur limit is 3.5% S m/m. Under this same regulation, ships operating in ECAs are required to use low sulfur fuels (<0.1% S). There are currently four ECAs designated by IMO where marine fuel sulfur content is limited: North America; the U.S. Caribbean; the North Sea; and the Baltic Sea.

A shift from high-sulfur residual fuels to lower sulfur distillate fuels may help reduce BC, as evidence suggest that, on the whole, distillates produce less BC than residuals (Lack et al., 2012). However, the magnitude of potential BC emissions reductions from a switch to distillate is still uncertain. Additionally, ship operators can comply with the global and ECA fuel sulfur limits by using exhaust gas cleaning systems, like scrubbers, to remove sulfur oxides while continuing to operate on high-sulfur residual fuels. In this case, there is likely little, if any, BC reduction.

5.2 Potential Future Policies

5.2.1 Black Carbon Standard for Marine Engines

The IMO could establish a BC standard for marine engines, as they have done for other pollutants – e.g., NO_x. However, there are many potential methods for measuring BC emissions from marine engines, each with some limitations. Given that BC can be more difficult to measure than total PM, the IMO could instead establish a PM standard for marine engines; however, such a standard would need to be sufficiently stringent to result in BC emissions reductions and not just organic carbon reductions. Thus, it seems that the best way to ensure BC reductions would be to set a BC emissions standard and to specify the measurement and reporting protocols for determining compliance with the standard. At the second workshop, participants agreed that setting a BC emissions standard for marine engines would require the use of protocols that result in consistent, precise results.

5.2.2 Heavy Fuel Oil Use Prohibition

As discussed earlier, a switch from residual fuels, like HFO, to distillate fuels may reduce marine BC emissions. Some environmental NGOs have been calling for a prohibition on the use of HFO in the Arctic. While there is no current ban on HFO use in the Arctic, the IMO banned the use or carriage of HFO in the Antarctic beginning in 2011. The Antarctic was designated as a Special Area under MARPOL Annex II, resulting in a prohibition on the use and carriage of HFO. Despite similar navigation hazards and environmental sensitivities in the Arctic, no such prohibition on the use of HFO exists. The global 0.5% sulfur cap will force a shift away from HFO to distillate fuels in all areas of the world, but some fraction of vessels will choose to install scrubbers to comply with the standard and continue to operate on HFO, with limited, if any, marine BC reduction benefits.

5.2.3 Avoiding Particularly Sensitive Areas or an Arctic ECA

In addition to creating a Special Area in the Arctic as a counterpoint to the Antarctic, there are two other options available under IMO: the designation of a Particularly Sensitive Sea Area (PSSA) or the creation of an Arctic ECA. Either of these could be used to potentially limit BC emissions by restricting the type of fuel that can be burned or by requiring the use of BC emissions control technologies or operational strategies that reduce BC emissions. Another potential tool is the designation of certain parts of the Arctic as Areas to be Avoided (ATBA), which could suggest voluntary measures such as speed restrictions, or fuel restrictions, which may provide some reduction in emissions.

A PSSA, Arctic ECA, or similar mechanism could be one step toward global marine BC controls. While the IMO, in general, has declined to regulate regionally before regulating globally, that pattern is overridden by the many Special Areas created under various MARPOL Annexes and should not prevent the recognition of the Arctic as a Special Area or create unnecessary complications for the restriction of emissions of BC. However, although an approach based on a network of Special Areas or other designation would provide some protection and BC mitigation, it would not be comprehensive and the policies could vary between areas, making travel between countries and ports difficult due to a patchwork of regulations.

5.2.4 *Multilateral Agreements*

Countries could potentially come together through international agreements to curb marine BC emissions. One idea from Dr. Thomas Brewer, Senior Fellow at the International Centre for Trade and Sustainable Development (ICTSD), is for an "Arctic Black Carbon (ABC) Agreement." Such an agreement could include Arctic states; ship owners and operators; international organizations such as the CCAC and IMO; and other stakeholders. The agreement could include a "license" to operate in Arctic waters. In order to obtain such a license, the ship owner and operator would need to agree to limit marine BC emissions in some way, be it through technological or operational practices or both, in order to ply Arctic waters. The ABC Agreement could be among Arctic states, but it could also be a building block toward a larger agreement to reduce marine BC emissions in other parts of the world. Additional details of a potential ABC Agreement will be presented by Dr. Brewer at this workshop.

6.0 CONCLUSION

Even though BC is the second largest contributor to human-induced climate change after CO_2, there are no international regulations on marine BC emissions to-date. Despite the threat marine BC emissions pose to the environment and human health, there is insufficient clarity on both the appropriate measurement techniques and the priority control strategies for marine applications. However, effective and efficient marine BC control strategies do exist.

At this workshop, participants are asked to:

1. Work toward consensus on appropriate marine BC measurement approaches
2. Identify priority marine BC control strategies based on scientific evidence
3. Discuss policy alternatives that can be implemented by individual countries, the IMO, or other forums, in order to reduce marine BC emissions

Workshop outcomes may inform CCAC member state submissions to the International Maritime Organization (IMO) on BC appropriate measurement methods and promising control strategies.

7.0 References

Aakko-Saksa P., Timo, M., Harri, P., Hilkka, T., Panu, K., 2016. *Black carbon measurements using different marine fuels.* CIMAC 91, 1–17.

Azzara, A., Rutherford, D., Minjares, R., 2015. Needs and opportunities to reduce black carbon emissions from maritime shipping (Working Paper 2015-2). International Council on Clean Transportation.

Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Berntsen, T., DeAngelo, B.J., Flanner, M.G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P.K., Sarofim, M.C., Schultz, M.G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S.K., Hopke, P.K., Jacobson, M.Z., Kaiser, J.W., Klimont, Z., Lohmann, U., Schwarz, J.P., Shindell, D., Storelvmo, T., Warren, S.G., Zender, C.S., 2013. *Bounding the role of black carbon in the climate system: A scientific assessment: Black Carbon in the Climate System.* J. Geophys. Res. Atmospheres 118, 5380–5552. doi:10.1002/jgrd.50171

Corbett, J., Lack, D.A., Winebrake, J.J., Harder, S., Silberman, J.A., Gold, M., 2010. *Arctic shipping emissions inventories and future scenarios.* Atmospheric Chem. Phys. 10, 9689–9704. doi:10.5194/acp-10-9689-2010

Corbett, J., Winebrake, J., Green, E., 2010. *An assessment of technologies for reducing regional short-lived climate forcers emitted by ships with implications for Arctic shipping.* Carbon Manag. 1, 207–225. doi:10.4155/cMT.10.27

Cottell, E.W., 2012. Emission Control Technology for Engines and Boilers Pays for Itself in Fuel Savings [WWW Document]. URL http://www.nonoxltd.com/whitepaper.html (accessed 8.8.16).

Dimou, I., Sappok, A., Wong, V., Fujii, S., Sakamoto, H., Yuuki, K., Vogt, C.D., 2012. *Influence of Material Properties and Pore Design Parameters on Non-Catalyzed Diesel Particulate Filter Performance with Ash Accumulation*. doi:10.4271/2012-01-1728

Faber, J., Nelissen, D., Hon, G., Wang, H., Tsimplis, M., 2012a. Regulated slow steaming in maritime transport: An assessment of options, costs and benefits. CE Delft.

Faber, J., Nelissen, D., Hon, G., Wang, H., Tsimplis, Mi., 2012. *Regulated Slow Steaming in Maritime Transport : An Assessment of Options, Costs and Benefits.* Delft.

Hombravella M., A., 2011. *Study of Exhaust Gas Cleaning Systems for vessels to fulfill IMO III in 2016.*

Johnson, K., Welch, B., Crocker, D.R., Russell, R.L., Yu, J., 2015. *Black Carbon and Other Gaseous Emissions from an Ocean going vessel Main Engine operating on Two Fuels* (No. ARB contract # 12-425). California Air Resource Board.

Kaufmann, E., Bouman, D., Theunis, A., Kleiberg, X., Megen, R. van, 2014. *Black Carbon Reduction. Rotterdam Mainport University of Applied and Sciences.*

Lack, D.A., Corbett, J., 2012. *Black carbon from ships: a review of the effects of ship speed, fuel quality and exhaust gas scrubbing.* Atmospheric Chem. Phys. 12, 3985–4000. doi:10.5194/acp-12-3985-2012

Lack, D.A., Thuesen, J., Elliot, R., 2012. *Investigation of appropriate control measures (abatement technologies) to reduce black carbon emissions from international shipping.* Study Rep. Prep. Litehauz ERRIAZ.

Landet, R.D., 2010. *PM emissions and NOx-reduction due to water in fuel emulsions in marine diesel engines.*

Lloyd’s Register Marine, n.d. Y*our options for emissions compliance: Guidance for shipowners and operators on the Annex VI SOx and NOx regulations.* Lloyd’s Register Marine.

MAN Diesel & Turbo, n.d. *Exhaust Gas Emission Control Today and Tomorrow, Application on MAN B&W Two-stroke Marine Diesel Engines*. MAN Diesel & Turbo.

MAN Diesel & Turbo, n.d. *ME-GI Dual Fuel MAN B&W Engines: A Technical, Operational and Cost-effective Solution for Ships Fuelled by Gas*. MAN Diesel & Turbo, Copenhagen, Denmark.

MOL, 2012. *MOL Introduces Technology to Eliminate Particulate Emissions from Vessels 2.*