WORKSHOP SUMMARY

Third Workshop on Marine Black Carbon Emissions:
Measuring and Controlling BC from Marine Engines

A technical workshop hosted by:
The International Council on Clean Transportation

In collaboration with:
Environment and Climate Change Canada

Sponsored by:
The Climate and Clean Air Coalition

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Environment and Climate Change Canada
Douglas Jung Building
Vancouver, British Columbia, Canada

CLIMATE & CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

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Acknowledgements

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Executive Summary

This was the third and final workshop designed to inform and guide a two-year project on black carbon (BC) emissions from ports and marine vessels funded by the Climate and Clean Air Coalition (CCAC) and implemented jointly by the International Council on Clean Transportation (ICCT) and the United Nations Environment Program (UNEP). The ICCT has acted as the main implementer of the marine work, which aims to develop a refined global marine BC emissions inventory and a technology performance database for BC mitigation strategies. The workshop was held 7-8 September 2016 in Vancouver, British Columbia, Canada, at the offices of Environment and Climate Change Canada.

The goals of this third workshop were to:

1. Solidify recommendations for marine BC measurement approaches
2. Identify effective technological and operational strategies to control BC from marine engines.

To achieve these goals, the workshop convened 27 in-person participants and one remote presenter representing 19 organizations from industry, government, academia, and civil society. Many participants are recognized as international experts on BC. Workshop participants: (1) worked toward consensus on appropriate marine BC measurement approaches; (2) identified priority marine BC control strategies based on scientific evidence; and (3) discussed policy alternatives that could 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 appropriate BC measurement methods and promising control strategies.

The two-day agenda (Appendix A) included presentations and discussions on the results of current marine BC testing efforts as well as operational, technological, and policy strategies to control marine BC emissions. Four presentation sessions were held on Day 1, in which 11 experts presented on measuring marine BC; the influence of marine fuels on BC; BC control technologies and operational strategies; and potential BC control policies. Group discussions were held on Day 2, in which participants considered marine BC measurement protocols, potential BC control policies, and future research needs.

In the end, workshop participants agreed on a number of conclusions based upon the research presented at the workshop:

Measuring Marine BC

1. For the purposes of this project, **the goal of measuring BC emissions from marine engines is to enable control of BC at the source** (i.e., the marine engine and its exhaust gas stream) rather than in the atmosphere. This means that **precise marine engine BC emissions measurements are needed.**
2. Consistent with this purpose, **the group recognized the value in first developing standardized measurement approaches in an engine test stand configuration**. This would then be **subject to confirmation with on-board (real world) testing of vessels** under typical operating conditions.
3. A marine black carbon **measurement protocol is needed**. An **ad hoc technical committee** working in parallel with IMO policymakers could develop and review such a protocol and may build upon existing protocols for particulate matter (i.e., ISO 8178). The formation of this technical committee is recommended.

4. The **IMO is not the proper venue for specifying a standardized marine BC measurement protocol.** The proper venue is likely ISO, which is referenced in other IMO regulations (e.g., the NO_x Technical Code). The IMO, instead, would reference such a standard measurement protocol in any marine BC emissions standard regulations. A standardized BC measurement protocol could be informed by existing standards for particulate matter (PM), i.e., ISO 8178.
5. **Some instruments are more promising for measuring marine BC emissions** than others, and instruments designed to measure ambient air pollution are not appropriate for measuring marine BC emissions from the source (i.e., the marine engine exhaust).
    a. Photo-Acoustic Spectroscopy (PAS) and Filter Smoke Number (FSN) showed good correlation in some recent in-lab and on-board marine BC emissions studies and appear to be fit for purpose for measuring BC from marine engines. Some Thermal-Optical Analysis (TOA) approaches may be fit for purpose when the fraction of BC to total PM is relatively high. Laser Induced Incandescence (LII) correlated well with PAS, FSN, and TOA in one laboratory test.

Marine Fuels and BC

1. **Alternative marine fuels, such as LNG, emit much less BC than traditional bunker fuels** (e.g., residual and distillate oils), but traditional residual-based bunker fuels dominate the marine fuel sector.
2. **Alterative propulsion technologies could reduce or eliminate BC emissions** (hybrid technologies; hydrogen fuel cells; etc.), but these technologies are still under development.
3. **Black carbon formation is influenced by the physical and chemical properties of marine fuels.** Discussion indicated that the hydrogen-to-carbon ratio or hydrogen content of the fuels may impact BC emissions. However, at present, there are no formulas or models that can predict BC emissions as a function of physical and chemical fuel properties.
4. Evidence presented at the workshop suggests that **shifting from conventional HFO to distillate fuels such as MGO can reduce BC emissions**. More data is needed on the impact on BC emissions from switching from high-sulfur HFO to lower sulfur hybrid fuels created by blending residual and light fraction blends, which are now entering the market.
5. **Black carbon formation is influenced by fuel properties, engine type, and engine load.** Data from onboard testing presented at the workshop showed that BC emission factors decreased, in most cases, as engine load increased.

BC Control Technologies and Operational Strategies

1. **There are existing technologies that can reduce BC**, notably wall-flow DPFs, LNG engines, SCR systems, low-PM engine recalibration, scrubbers, alternative fuels, etc. DPFs in particular attract considerable attention for BC reductions due to their successful application in other transportation modes, but it should be noted that there is little experience to-date to indicate that DPFs are a practical control measure for large, slow-speed marine diesel engines.
2. **There are operational strategies that can reduce BC**, including slow steaming; engine timing and fuel injection changes at low loads; and connecting to shorepower in port. Slow steaming, which is being implemented across significant portions of the world's fleet today, generally reduces marine air emissions but can lead to higher BC emission factors at low engine loads. The impact of slow steaming on BC emissions per unit distance, however, remains unclear.
3. Diesel fuel with low sulfur content is required for some aftertreatment systems (e.g. DPFs) to prevent frequent plugging. In general, HFO is not suitable for use with wall-flow DPFs unless they can be actively regenerated (i.e., are not catalyzed).

Potential BC Control Policies

1. Policies to control BC emissions could be in the form of **regulations** or **incentives**, or both. When considering policies to control BC, there is value in thinking about concrete actions that can be accomplished in the near-term. Any BC control policy should consider the holistic impacts of such a policy, including its impacts on air quality, human and ecosystem health, and international trade.
2. **There are existing and potential future international ship energy efficiency policies that may reduce BC**, including the Energy Efficiency Design Index (EEDI) and future energy efficiency measures likely to be taken at the IMO. Both the EEDI standards and future IMO actions to reduce carbon would presumably reduce BC by improving vessel efficiency, thereby reducing fuel consumption and BC emissions.
3. **Policies that aim to reduce other air pollutants (e.g., SO_x and PM) from marine vessels could reduce BC emissions.** However, the effect of some policies on marine BC – e.g., the 0.5% global marine fuel sulfur standard – may depend on the physical and chemical properties of fuel used to comply with such a standard.
4. **Other policies could help reduce BC emissions in ecologically sensitive areas, such as the Arctic.** Such policies could include Arctic routing measures, a ban on the use of HFO in the Arctic, or a multilateral Arctic BC agreement to limit BC emissions from ships operating in the Arctic.
5. **Emission Control Areas (ECAs) may have some BC reduction co-benefits but are unlikely to reduce absolute BC emissions** given projected ship traffic growth.
6. **Existing PM policies for engines on smaller marine vessels in the US and Europe are expected to provide BC reduction benefits for those vessels**, especially if such policies drive the adoption of DPFs. Those policies could serve as a model for PM standards for larger marine engines, although the limitations of existing control technologies for such engines must be addressed.

Future Research Needs

The participants noted that the conclusions presented above are, in some cases, based upon limited evidence. Further research is advised on the following topics:

1. **Work to develop a standardized marine BC measurement protocol** through an ad hoc technical committee.
2. **The influence of physical and chemical fuel properties on BC formation deserves additional research.** Simple metrics need to be developed to link fuel chemical properties directly to black carbon emissions (e.g. hydrogen/carbon ratio).
3. **The impact on BC emissions from switching from residual to distillate, renewable, hydrogenated, or blended fuels** deserves more study.
4. Global and regional **marine BC emissions inventories** are needed to inform policymaking.
5. **Demonstration projects** on vessels that show how technical and operational strategies can reduce BC emissions are needed.
6. **Black carbon emissions testing campaigns on smaller vessels** (MSD/HSD) could inform policies that reduce BC emissions near shore and in port.
7. Expanded **BC emissions testing campaigns on newer engines (Tier II+)** is needed to understand how BC emissions from marine vessels will change as the proportion of the global fleet with newer, Tier II+ certified marine diesel engines grows.

Introduction

The International Council on Clean Transportation (ICCT),[1] in coordination with Environment and Climate Change Canada (ECCC), hosted a technical workshop on marine black carbon (BC) emissions. This workshop was 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 50 country partners and more than 60 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:

- *BC strongly absorbs visible light with a mass absorption coefficient (MAC) value above 5* $m^2 g^{-1}$ *at a wavelength* $\lambda = 550$ *nanometers (nm)*
- *BC is refractory, with a vaporization temperature near 4000 K*
- *BC is insoluble in water, in organic solvents including methanol and acetone, and in other components of atmospheric aerosol; and*
- *BC exists as an aggregate of small carbon spherules.*

The first two properties in particular were considered to be useful for measurement purposes. The third property is commonly used to exclude any charring effects in EC/OC determination. 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, the 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). This measurement reporting protocol was subsequently endorsed by the IMO's 3rd session of its Pollution Prevention and Response Sub-Committee (PPR 3) in February 2016.

The goals of this third workshop were to:

1. Solidify recommendations for marine BC measurement approaches
2. Identify effective technological and operational strategies to control BC from marine engines.

[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.

To achieve these goals, the workshop convened 27 in-person participants and one remote presenter representing 19 organizations. Many participants are recognized as international experts on BC. Workshop participants: (1) worked toward consensus on appropriate marine BC measurement approaches; (2) identified priority marine BC control strategies based on scientific evidence; and (3) discussed policy alternatives that could 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.

This workshop was divided into distinct sessions with the intent of providing expert overviews and subject matter presentations covering the range of BC topics. Each session included an opportunity for questions and answers to provide the foundation for specialized breakout group discussions. The topics and goals for each session are presented in Table 1 below.

Table 1. Workshop Sessions and Goals

Day	Session	Topic	Session Goal
Sept. 7	1	Brief Summary of Previous Workshop and Background	*Provide a general overview of the CCAC/ICCT project, highlight the consensus definition agreed to at the first workshop, review recommendations for measuring marine BC from the second workshop, and outline the current IMO context relative to these issues.*
	2	Measuring Marine BC	*Learn about current marine BC testing and research, especially experimental design, instrumentation, results, and measurement reporting protocols.*
	3	Marine Fuels and BC	*Learn about how marine fuel characteristics (chemical and physical) influence marine BC emissions.*
	4	BC Control Technologies and Operational Strategies	*Learn about the technological and operational ways marine BC emissions can be controlled, including challenges and opportunities for their implementation.*
	5	Potential BC Control Policies	*Learn about policy alternatives that can reduce marine BC emissions, including challenges and opportunities for their adoption and implementation.*
Sept. 8	6	Breakout Group and Full Group Discussion: BC Measurement Protocols	*Identify promising BC measurement approaches that are appropriate for controlling marine BC emissions. Capture challenges and opportunities for their adoption and implementation*
	7	Breakout Group and Full Group Discussion: Potential BC Control Policies	*Identify promising potential BC control policies. Capture challenges and opportunities for the adoption and implementation.*
	8	Discussion: Future Research Needs	*Identify future research needs related to measuring and controlling marine BC emissions.*
	9	Summary of Workshop Outcomes	*Agree on key workshop outcomes/conclusions.*

The complete agenda is included as Appendix A. A list of attendees is found in Appendix B. The following sections walk through the main agenda topics and summarize major discussion points and outcomes.

Summary of Workshop Presentations

The workshop began with a series of presentations focused on (1) measuring marine BC; (2) marine fuels and BC; (3) BC control technologies and operational strategies; and (4) potential BC control policies. These presentations can be found on ICCT's website. A summary of the presentations is provided in this section.

Measuring Marine BC

The first presentation session focused on measuring marine BC. The goal of the session was to learn about current marine BC testing and research, especially experimental design, instrumentation, results, and measurement reporting protocols.

Three experts presented: Peter Lauer from MAN Diesel & Turbo (MAN); Dr. Kent Johnson from the University of California-Riverside Center for Environmental Research and Technology (UCR CERT); and Dr. Greg Smallwood from the National Research Council Canada (NRC Canada).

Mr. Lauer (MAN), presented work by marine engine OEMs to measure BC emissions from marine engines using a variety of instruments and fuels. For instruments directly measuring equivalent black carbon (eBC), filter smoke number (FSN, via AVL Smoke Meter 415SE) and MAAP were applied; for elemental and organic carbon measurement, a variety of thermal-optical methods were used. EC/OC methods have been historically developed for analysis of ambient aerosol samples. Various methods for EC/OC determination exist, e.g. EUSAAR or IMPROVE methods in the European Union and NIOSH-5040 method in the US and Canada. In case of the MAN presentation, particulate matter (PM) filter samples were analyzed according to VDI-2465-1/-2, BGI 505-44, NIOSH-5040, and by an improved in-house method based on a combination of both VDI-2465 methods. The work found that many thermal-optical methods were prone to overestimating elemental carbon (EC) emissions due to charring effects, with the NIOSH 5040 protocol used with Sunset instruments and the improved DNV-GL in-house method showing the best correlation for diesel exhaust with direct eBC measurement. Overall, emission factors (EFs) on an order of magnitude lower than cited by Lack et al. were determined for these test engines. Given the relationship identified between BC emissions and fuel quality, the need for a standardized reference fuel for BC emission testing was discussed.

Dr. Johnson (UCR CERT) presented an overview of their emissions testing work since the previous workshop, which has focused on on-board testing of two marine vessels: a newer (2012) container ship with a Tier II (2011) engine, and a container ship with a SO_x scrubber treating both main and auxiliary engine emissions. The measurement methods covered in the testing were PAS, FSN (AVL Smoke Meter 415SE), and TOA (NIOSH 5040). The testing found very low BC emissions from the newer engine operating on 300 ppm S marine gas oil (MGO) fuel, on the order of 0.0024 g/kg fuel at 57% load, with emissions peaking at 27% load (~0.05 g/kg fuel) but lower at very low (8%) loads (~0.02 g/kg fuel) associated with vessel speed reduction. The research found on the order of 30% BC reductions associated with the scrubber, with reductions depending on engine load and also the emission source. The research found a generally good correlation between PAS, FSN, and TOA methods, with the exception of emissions from the main engine alone, which were dominated by high OC fractions. A clear trend towards lower BC EF values was observed with increasing engine size.

Dr. Smallwood (NRC-Canada) presented initial results of a German-Canadian research consortium investigating various instrumentation approaches and the relationship between fuel quality and BC emissions. Since detailed data were not available at the time of the workshop, the focus here was on the measurement protocol itself, including the modes used (engine speed vs. load points, cycling of the engine, etc.) A miniCAST system to generate BC nanoparticles was also used to assess instrument comparability in advance of the engine tests comparison. The effective density of the small (50 nm) particles was increased when comparing samples that underwent thermal denuding compared to the untreated samples, suggesting that organic coatings were an important fraction of the particles emitted. Data were still being processed, with initial results expected to be presented to PPR 4 in January 2017.

Marine Fuels and BC

The second presentation session focused on the relationship between marine fuel quality and BC emissions. The goal of the session was to learn about how marine fuel characteristics (chemical and physical) influence marine BC emissions. Two experts presented: Päivi Aakko-Saksa from VTT, Finland and Wayne Miller from UCR CERT.

Ms. Aakko-Saksa (VTT) presented emissions testing work conducted at VTT in November 2015 on a medium speed engine using the AVL Smoke Meter, PAS, and MAAP with four fuels and multiple test points. Sample pre-treatment, through the use of a thermal denuder and catalytic stripper, was also performed. The work found that variation in the BC emissions between instruments is smaller than differences between fuels and engine loads. Thermophoretic losses were generally high, with many challenges associated with instruments requiring high dilution ratios to measure raw engine exhaust, notably instruments designed for ambient air quality measurement (MAAP and aethalometer). Sample pre-treatment by CS or TD adds complexity and showed ambiguous results. Distillate fuel was found to reduce BC emissions relative to HFO. Under certain circumstances HFO burned cleaner than the 0.5% sulfur (S) residual fuel blend, potentially due to the higher quantity of metallic compounds present in the HFO impurities that facilitated more complete combustion or even catalyzed combustion.

Dr. Miller (UCR CERT) presented a more statistical approach relating fuel properties (sulfur content, carbon residue, calculated aromaticity, etc.) to BC emissions and found that none of these simple fuel properties were primary drivers of BC mass emitted. Dr. Miller presented results for three engines (Detroit Diesel, 2-stroke, 187 kW; MAN, 4-stroke, 6300 kW; and Hyundai/MAN, 2-stroke, 68,530 kW). Generally, higher BC emissions were seen for the HFO and a low-sulfur residual fuel (13 ppm S) compared with distillate fuel. This may be because the marine residual fuels are sourced from refinery streams that have a significant content of poly-aromatic compounds. Since the known mechanisms of BC formation are commonly associated with aromatic content, future work should investigate aromatics as a driver. Discussion indicated that the hydrogen-to-carbon ratio or hydrogen content of the fuels may have an impact on BC emissions, and that hydrogen-to-carbon ratio (or hydrogen content) may be useful instead of, or in addition to, aromatics in correlating to BC emissions.

BC Control Technologies and Operational Strategies

The third presentation session focused on BC control technologies and operational strategies. The goal of the session was to learn about the technological and operational ways marine BC emissions can be controlled, including the challenges and opportunities for their implementation. Three experts presented: George Lin from Caterpillar (CAT); Jiacheng Yang from UCR CERT; and Dr. Mike Geller from the Manufacturers of Emission Controls Association (MECA).

Mr. Lin (CAT) introduced technologies developed and sold by Caterpillar that influence BC emissions from medium and high-speed marine engines. One technology, Flexible Camshaft Technology (FCT), retards intake timing and advances start of injection to improve transient response at low loads and to reduce PM below the visibility limit. Natural gas and dual fuel engines can reduce BC emissions by up to 90%while also reducing GHG emissions if methane slip is minimized. Selective catalytic reduction (SCR) systems with Vanadium-based catalysts have shown to provide about 15% BC reductions, although larger (up to 80% reductions in PM) along with substantial gains in fuel efficiency are possible if engine recalibration is combined with higher urea dosing rates in order to meet Tier III NO_x limits.

Mr. Yang (UCR CERT) described and evaluation of the impacts of an exhaust gas cleaning system (EGCS) on marine BC emissions that was conducted as a part of UCR's emissions testing campaign. The scrubber system that was evaluated could be used either as an open or closed loop system and was used to meet sulfur emissions regulations in the North American Emission Control Area (ECA). Testing was performed on a container ship engine using 1.9% sulfur fuel with PAS, FSN (AVL Smoke Meter), and TOA (NIOSH 5040) methods. Gaseous SO_2 emissions were controlled to a level equivalent to 0.1% sulfur fuel, but removal of the PM sulfur and particles under 50 nm was low. Overall, about 10% in $PM_{2.5}$ and 20 to 40% of BC was removed, depending on main engine load. No statistically significant difference was found in the BC measurement results across various instruments, although confounding effects were seen, including high sulfur fuel content, organic carbon charring, and dilution ratio influencing the EC/OC split.

Dr. Geller (MECA) provided an overview of the use of diesel particulate filters (DPFs) to control PM and BC emissions from marine engines. DPFs have been employed to control PM emissions from millions of on-highway and nonroad engines around the world. While it was once thought that Tier 4 standards for nonroad engines, including locomotives and C1/C2 marine engines, would force DPFs, many engines are being certified without them by employing SCR systems and in-cylinder emission controls instead. The European Commission's proposed 2019 Stage V off-road and inland waterway engine standards, which include a particle number standard, are likely to force filters on many propulsion and auxiliary C1/C2 marine engines. Overall, DPFs are very effective in controlling BC, although there are limitations to their use for marine engines, notably space constraints, fuel quality (i.e. low sulfur fuel has generally been needed to avoid catalytic poisoning), back pressure, filter maintenance, etc. Solutions to address these constraints include Vanadium-based catalysts, active regeneration, and reverse pulse flow approaches. A prominent example of a new application is a combined SCR-DPF-scrubber system on the Queen Victoria cruise ship, providing 80 to 92% soot removal.

Potential BC Control Policies

The fourth presentation session focused on potential BC control policies. The goal of the session was to learn about policy alternatives that can reduce marine BC emissions, including challenges and opportunities for their adoption and implementation. Three experts presented: Sian Prior, a contractor with the European Climate Foundation (ECF); Tom Brewer from the International Centre for Trade and Sustainable Development (ICTSD); and Jan Hulskotte from the Netherlands Organization for Applied Scientific Research (TNO).

Dr. Prior (ECF) provided an overview of policies with the potential to control the impact of BC emissions on the Arctic. Possible control strategies include routing restrictions, the expansion of existing ECAs, the designation of Particularly Sensitive Sea Areas (PSSAs), a MARPOL Annex VI PM or BC emission standard, and restrictions on the use of HFO under the Polar Code. The latter approach is a current focus of environmental NGOs given its dual benefit of reducing air and climate pollution and the risks associated with HFO spills in Arctic waters.

Dr. Brewer (ICTSD) provided an alternate perspective, focusing on the possible use of a "club-like approach" to control Arctic BC emissions. He surveyed various groups with a potential influence on those emissions, including UNFCCC, CCAC, Arctic Council, IMO, along with ancillary trade organizations/agreements like WTO and TPP, concluding that there may be benefits of a freestanding agreement independent of these groups. He introduced the concept of an Arctic Black Carbon (ABC) agreement under which operators would need to meet certain environmental requirements in order to operate in the Arctic. He highlighted several key elements of an ABC approach, notably shareable and excludable benefits and smaller membership to facilitate decision making. The ABC agreement would include elements of both regulation and technology transfer.

Dr. Hulskotte (TNO) presented an analysis of projected marine BC emissions in European waters through 2050 using the POSEIDON model that employs BC EFs that reflect a review of the extant literature on marine BC EFs. He highlighted that marine emissions inventories continue to struggle with uncertain BC EFs, the refinement of which is a central goal of the CCAC work. Using the model, he projected BC emissions in the North and Baltic Seas along with Mediterranean areas under various scenarios, including the implementation of the 0.5% global S cap starting in 2020, the application of a NO_x ECA, and multiple possible futures for LNG deployment. Overall, it is expected that PM emissions will fall due to these policies, but BC emissions are not expected to be reduced in absolute terms in European waters despite these existing control policies due to future growth in the shipping sector in these areas.

Summary of Workshop Discussions

The outcomes of workshop discussions can be organized into the following topics: measuring marine BC; marine fuels and BC; BC control strategies; and potential BC control policies. The conclusions of workshop participants based on the evidence presented and discussed at the workshop are reflected in the text that follows.

Measuring Marine BC

1. **For the purposes of this project, the goal of measuring BC emissions from marine engines is to enable control of BC at the source** (i.e., the marine engine and its exhaust gas stream) rather than in the atmosphere. This means that **precise marine engine BC emissions measurements are needed** to compare emissions across marine engines and vessels.
2. Consistent with this purpose, **the group recognized the value in first developing standardized measurement approaches in an engine test stand configuration**. This would then be **subject to confirmation with on-board (real world) testing of vessels** under typical operating conditions.
3. A marine black carbon **measurement protocol is needed**.
    a. An **ad hoc technical committee** working in parallel with IMO policymakers could develop and review such a protocol and may build upon existing protocols for particulate matter (i.e., ISO 8178). **The formation of this technical committee is recommended.**
    b. The **IMO is not the proper venue for specifying a standardized BC measurement protocol.** The proper venue is likely ISO, which is referenced in other IMO regulations (e.g., the NO_x Technical Code). The IMO, instead, would reference such a standard measurement protocol in any marine black carbon emissions standard regulations. A standardized BC measurement protocol may be built upon existing standards for PM (i.e., ISO 8178).
    c. The **value of sample conditioning (e.g., applying a catalytic stripper, thermal denuder, or similar, before measuring BC) is ambiguous**, especially for laboratory testing, and results in high BC losses that must be accounted for. Further research is required.
4. **Some instruments are more promising for measuring accurate marine BC emissions** than others.
    a. PAS and Filter FSN showed good correlation in some recent in-lab and on-board marine BC emissions studies and appear to be fit for purpose for measuring BC from marine engines. Some TOA approaches may be fit for purpose when the fraction of BC to total PM is relatively high. LII correlated well with PAS, FSN, and TOA in one laboratory test.

   b. Two instruments that are **not recommended** for measuring marine BC emissions at the source are the MAAP and the Aethalometer. These instruments are used for measuring BC in the atmosphere at low concentrations and require high dilution before measuring, introducing considerable uncertainty in marine BC emission factors.
   c. One recent study suggests that when measuring marine BC emissions with multiple instruments, applying correction factors, i.e. simulating a common calibration, can help improve intercomparability between instruments and assess impacts of other factors such as fuel properties, sampling protocols (removal of organics and sulfates, dilution, etc.), and aftertreatment options.

Marine Fuels and BC

1. **There are existing alternative fuels** (e.g., LNG) **that emit much less BC than traditional bunker fuels**.
2. **Alternative propulsion technologies could reduce or eliminate BC emissions** (e.g., electrification, hydrogen fuel cells), but these technologies are still under development and are not widely deployed or available for many engine types.
3. **Black carbon formation is influenced by the physical and chemical properties of marine fuels.** Discussion indicated that the hydrogen-to-carbon ratio or hydrogen content of the fuels may impact BC emissions. However, at present, there is no formulas or models that can predict BC emissions as a function of physical and chemical fuel properties.
6. Evidence presented at the workshop suggests that **shifting from conventional HFO to distillate fuels such as MGO can reduce BC emissions**. More data is needed on the impact on BC emissions from switching from high-sulfur HFO to lower sulfur hybrid fuels created by blending residual and light fraction blends, which are now entering the market.
7. **Black carbon formation is influenced by fuel properties, engine type, and engine load.** Data from onboard testing presented at the workshop showed that BC emission factors decreased, in most cases, as engine load increased.
   a. At lower loads (e.g., 25%), metallic impurities in HFO may promote more complete combustion (or even catalyze combustion) compared to residual-distillate blends, reducing BC formation *at that particular load point* compared to other fuels, such as distillates. However, overall, the evidence to date suggests that distillate fuels produce less BC than residual fuels under typical vessel operating conditions.

BC Control Technologies and Operational Strategies

1. **There are existing technologies that can reduce BC**, notably wall-flow DPFs, LNG engines, SCR systems, low-PM engine recalibration, scrubbers, alternative fuels, etc. DPFs in particular attract considerable attention for BC reductions due to their successful applications in other transportation modes, but it should be noted that there is little experience to-date to indicate that DPFs are a practical control measure for large, slow-speed marine diesel engines.
2. **There are operational strategies that can reduce BC**, including slow steaming; engine timing and fuel injection changes at low loads; and connecting to shorepower in port. Slow steaming, which is being implemented across significant portions of the world's fleet today, generally reduces marine air emissions but can lead to higher BC emission factors at low engine loads. The impact of slow steaming on BC emissions per unit distance, however, remains unclear.
3. Diesel fuel with low sulfur content is required for some aftertreatment systems (e.g. DPFs) to prevent frequent plugging. In general, HFO is not suitable for use with wall-flow DPFs unless they can be actively regenerated (i.e., are not catalyzed).

4. **It may be easiest to start controlling BC from ships that use high speed and medium speed diesel engines** (e.g., harbor craft and smaller vessels), given that DPFs and other potential BC control technologies have been deployed on land-based mobile sources (e.g., heavy-duty trucks and locomotives) with similar engines and that these engines are typically operated on lower sulfur fuel. While DPFs are a well-established technology for on-road engines, there are significant challenges for use on large marine vessels, notably space, fuel quality, backpressure, filter maintenance, etc.
    a. Standards in place in the US and Europe for smaller vessels with heavy-duty or locomotive derivative engines (C1/C2) could drive DPF adoption of such technologies for use in high and medium-speed marine diesel engines.
    b. Additionally ultra-low sulfur diesel fuel is also available for these smaller vessels.

Potential BC Control Policies

1. Policies to control BC emissions could take the form of **regulations** or **incentives**, or both.
    a. When considering policies to control BC, there is **value in thinking about concrete actions that can be accomplished in the near-term.**
    b. **Any BC control policy should consider the holistic impacts of such a policy**, including the co-benefits of reducing BC (e.g., total PM reduction), but also the danger of limiting BC emissions in one area (e.g., the Arctic), but driving increased BC emissions in another (e.g., closer to human populations). Potential impacts on international trade should also be considered.
2. **There are existing and potential future international ship energy efficiency policies that may reduce BC**, including the Energy Efficiency Design Index (EEDI) and future energy efficiency measures likely to be taken at the IMO. Both the EEDI standards and future IMO actions to reduce carbon would presumably reduce BC by improving vessel efficiency, thereby reducing fuel consumption and BC emissions.
3. **Policies that aim to reduce other air pollutants (e.g., SO_x and PM) from marine vessels could reduce BC emissions.** However, the effect of some policies on marine BC – e.g., the 0.5% global marine fuel sulfur standard – may depend on the physical and chemical properties of fuel used to comply with such a standard. For example, research presented at this workshop showed that fuel blends that could meet such a sulfur standard may emit more BC emissions than high sulfur HFO, in some cases.
4. **Other policies could help reduce BC emissions in ecologically sensitive areas, such as the Arctic.** Such policies could including Arctic routing measures, a ban on the use of HFO in the Arctic, or a multilateral Arctic BC agreement to limit BC emissions from ships operating in the Arctic.
5. **Emission Control Areas may have some BC reduction co-benefits but are unlikely to reduce absolute BC emissions** given projected ship traffic growth.
6. **Existing PM policies for engines on smaller marine vessels in the US and Europe are expected to provide BC reduction benefits for those vessels**, especially if such policies drive the adoption of DPFs. Those policies could serve as a model for PM standards for larger marine engines, although the limitations of existing control technologies for such engines must be addressed.

Future Research Needs

Workshop participants identified the following future research needs related to marine BC emissions:

1. **Work to develop a standardized marine BC measurement protocol** through an ad hoc technical committee.
2. **The influence of physical and chemical fuel properties on BC formation deserves additional research.** Simple metrics need to be developed to link fuel chemical properties directly to black carbon emissions (e.g. hydrogen/carbon ratio).
3. **The impact on BC emissions from switching from residual to distillate, renewable, hydrogenated, or blended fuels** deserves more study.
4. Global and regional **marine BC emissions inventories** are needed to inform policymaking.
5. **Demonstration projects** on vessels that show how technical and operational strategies can reduce BC emissions are needed.
6. **Black carbon emissions testing campaigns on smaller vessels** (MSD/HSD) could inform policies that reduce BC emissions near shore and in port.
7. Expanded **BC emissions testing campaigns on newer engines (Tier II+)** is needed to understand how BC emissions from marine vessels will change as the proportion of the global fleet with newer, Tier II+ certified marine diesel engines grows.

Appendix A: Final Workshop Agenda

Third Workshop on Marine Black Carbon Emissions:
Measuring and controlling BC from marine engines

September 7 and 8, 2016

Agenda

Workshop Goals:

- Solidify recommendations for marine BC measurement approaches
- Identify effective technological, operational, and policy strategies to control black carbon emissions from marine engines.

Day 1

Time	Activity	Details
9:00-9:30 am	**Registration and Coffee**	
9:30-9:45 am	**Welcome Remarks and Review of Agenda** Richard Holt, ECCC Dan Rutherford, ICCT	
9:45-10:00 am	**Brief Summary of Previous Workshops and Background** Dan Rutherford, ICCT	- Project background - Definition of BC - Measuring BC - IMO Context
10:00-11:15 am	**Session 1: Measuring Marine BC** Ralf Oldenburg & Peter Lauer, MAN Kent Johnson, UCR Greg Smallwood, NRC-Canada	-Setup -Instruments -Results -Reporting protocols
11:15-11:30 am	**Break**	
11:30 am-12:30 pm	**Session 2: Marine Fuels and BC** Päivi Aakko-Saksa, VTT, Finland Wayne Miller, UCR	- Engines - Fuels - Instruments - Results
12:30-1:15 pm	**Lunch** (Provided)	
1:15-2:30 pm	**Session 3: BC Control Technologies and Operational Strategies** George Lin, Caterpillar Jiacheng Yang, UCR Mike Geller, MECA	- Technologies - Operational strategies - BC reduction potential - Implementation challenges/opportunities
2:30-2:45 pm	**Break**	
2:45-4:00 pm	**Session 4: Potential BC Control Policies** Sian Prior, ECF Contractor Tom Brewer, ICTSD Jan Hulskotte, TNO	- Policy alternatives - BC reduction potential - Implementation challenges/opportunities
4:00-4:15 pm	**Day 1 Closing Remarks** Dan Rutherford, ICCT	- Closing remarks - Logistics for dinner - Preview of Day 2 agenda
4:15 pm	**Adjourn**	
6:30-9:30 pm	**Group Dinner** Vancouver Harbor Sunset Dinner Cruise 501 Denman Street, Vancouver, V6G 2W9	-Cruise begins 7:00 p.m. sharp. **Please arrive at 6:30 p.m. to board.**

Day 2

9:00-9:30 am	**Coffee**	
9:30-9:45 am	**Recap of Day 1**	- Brief recap of Day 1 - Instructions for Breakouts
9:45-11:15 am	**Breakout Groups** (concurrent) 1. BC Measurement Protocols 2. BC Control Policy Alternatives	Goal: Identify areas of consensus and questions for the larger group to discuss after lunch
11:15 am-12:15 pm	**Groups Report Out**	Report out to include larger questions or issues needing more input
12:15-1:00 pm	**Lunch** (Provided)	
1:00-2:00 pm	**Discussion 1: BC Measurement Protocols** Facilitated by ICCT	Outcome: Identify promising BC measurement protocols related to controlling marine BC; capture challenges and opportunities
2:00-3:00 pm	**Discussion 2: Potential BC Control Policies** Facilitated by ICCT	Outcome: Identify promising potential BC control policies; capture challenges and opportunities
3:00-3:15 pm	**Break**	
3:15-4:00 pm	**Discussion 3: Future Research Needs** Facilitated by ICCT	Outcome: Identify future research needs related to controlling marine BC
4:00-4:30 pm	**Summary of Workshop Outcomes** Dan Rutherford, ICCT	Outcome: Agree on key workshop outcomes
4:30-4:45 pm	**Closing Remarks** Paul Izdebski, ECCC Dan Rutherford, ICCT	
4:45 pm	**Adjourn**	

Appendix B: Attendee List

Third Workshop on Marine Black Carbon Emissions:
Measuring and controlling BC from marine engines
7-8 September 2016
Vancouver, British Columbia

Attendee List

	Name	Organization	Email
1	Alissa Boardley	Transport Canada	Alissa.Boardley@tc.gc.ca
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