E

MARINE ENVIRONMENT PROTECTION COMMITTEE
74th session
Agenda item 10

MEPC 74/INF.10
8 February 2019
ENGLISH ONLY

POLLUTION PREVENTION AND RESPONSE

Scrubber Environmental Impact Literature Review

Submitted by Panama

SUMMARY

Executive summary:	This document summarizes the key findings of an extensive literature review on environmental impacts of marine exhaust gas cleaning systems (scrubbers) that was commissioned by Panama and undertaken by Professor John Heywood and Dr. Emmanuel Kasseris of the Massachusetts Institute of Technology (MIT), United States, in light of the International Maritime Organization's (IMO) regulations on fuel sulphur limit coming into effect in 2020
Strategic direction, if applicable:	1
Output:	1.12
Action to be taken:	Paragraph 6
Related documents:	Resolution MEPC.259(68); PPR 6/INF.20 and PPR 6/WP.1

Introduction and background

1 This document summarizes the key findings of an extensive literature review on environmental impacts of marine exhaust gas cleaning systems (EGCS), also known as "scrubbers", in light of the International Maritime Organization's (IMO) regulations on fuel sulphur limit coming into effect in 2020. MARPOL Annex VI regulations mandate significant reductions, as of 1 January 2020, in fuel sulphur content or equivalent exhaust gas after treatment (scrubbing) to reduce SO_x content. The full literature review is included in the annex.

2 The submitting delegation views the above-mentioned literature work as being pertinent to the work of the Sub-Committee on Pollution Prevention and Response (PPR), which at its sixth session, reviewed the *2015 Guidelines for Exhaust Gas Cleaning Systems* (resolution MEPC.259(68))(PPR 6/WP.1). The final report of PPR 6 is also relevant.

Summary

3 There is a need to evaluate the environmental impact of marine EGCS in light of IMO's regulations on fuel sulphur limit coming into effect in 2020. According to these regulations, scrubbers are considered an equivalent alternative to using low sulphur fuel. Professor John Heywood and Dr. Emmanuel Kasseris of the Massachusetts Institute of Technology (MIT), United States, performed an extensive literature review on environmental impacts of scrubbers and have concluded that there are two areas where there is cause for concern, or at least justification for further scientific investigation.

4 The first issue is the impact of scrubber effluent discharge on marine life and biogeochemical processes. This is especially concerning when discussing open-loop scrubbers which constitute the vast majority of installed EGCS. Scrubber effluent contains pollutants such as heavy metals and polyaromatic hydrocarbons (PAH), among others. It is also acidic, which can affect ocean chemistry and marine life. Although ocean dispersion modelling of scrubber effluent studies has been very limited, there is an almost complete consensus in the literature that there is cause for concern and justification for further scientific investigation.

5 The second issue concerns whether ships equipped with scrubbers are truly equivalent to ships using low sulphur fuel regarding air emissions. In terms of gaseous sulphur oxides, scrubbers are effective in removing them. In terms of particulate emissions however, there are strong indications in the literature that ships equipped with scrubbers may not be equivalent to burning low sulphur fuel. This is mostly due to the fact that scrubbers may not be as efficient in removing small (less than 100 nm diameter) particulates (nucleation mode) that consist mostly of sulphuric acid, water and condensable organic molecules. There is limited work in this area and it needs to be investigated further. However, there are enough indications that there may be issues with current scrubber designs and regulations in terms of delivering emissions that are completely equivalent to those of low sulphur fuel.

Action requested of the Committee

6 The Committee is invited to take note of the information provided in this document.

***

ANNEX

Environmental Impact Evaluation of Marine Exhaust Gas Cleaning Systems (Scrubbers): A Critical Literature Review

Professor John B. Heywood and Dr. Emmanuel Kasseris

January 28th 2019

Signature of the Authors:

Professor John B. Heywood **Dr. Emmanuel Kasseris**

Summary

There is a need to evaluate the environmental impact of marine Exhaust Gas Cleaning Systems (EGCS-scrubbers) in light of the International Maritime Organization's (IMO) regulations on fuel sulfur limit coming into effect in 2020. According to these regulations, scrubbers are considered an equivalent alternative to using low sulfur fuel. We performed an extensive literature review on environmental impacts of scrubbers and have concluded that there are two areas where there is cause for concern or at least justification for further scientific investigation.

The first issue is the impact of scrubber effluent discharge on marine life and biogeochemical processes. This is especially concerning when discussing open loop scrubbers which constitute the vast majority of installed EGC systems. Scrubber effluent contains pollutants such as heavy metals and polyaromatic hydrocarbons (PAH) among others. It is also acidic which can affect ocean chemistry and marine life. Although ocean dispersion modeling of scrubber effluent studies has been very limited, there is an almost complete consensus in the literature that there is cause for concern and justification for further scientific investigation.

The second issue concerns whether marine vessels equipped with scrubbers are truly equivalent to vessels using low sulfur fuel regarding air emissions. In terms of gaseous sulfur oxides, scrubbers are effective in removing them. In terms of particulate emissions however, there are strong indications in the literature that vessels equipped with scrubbers may not be equivalent to burning low sulfur fuel. This is mostly due to the fact that scrubbers may not be as efficient in removing small (less than 100 nm diameter) particulates (nucleation mode) that consist mostly of sulfuric acid, water and condensable organic molecules. There is limited work in this area and it needs to be investigated further. However, there are enough indications that there may be issues with current scrubber designs and regulations in terms of delivering emissions that are completely equivalent to those of low sulfur fuel.

1. Introduction

With the adoption of the revised Annex VI in October 2008 [Resolution MEPC 176(58)], regulations have been adopted by the International Maritime Organization (IMO), [MARPOL, 2017] and with the European Union's Sulphur Directive [EU, 2016] regarding marine fuel sulfur limits. According to these regulations, as amended [MARPOL, 2017], the maximum sulfur content limit in marine fuel used globally outside Sulfur Emission Control Areas (SECAs), will be reduced from 3.50% currently to 0.50% as of 1.1.2020. MARPOL Annex VI also introduced SECAs (sulfur emission control areas), with the aim of further reducing emissions of sulfur oxides (SOx) in designated sea areas. Inside SECA's, fuel used by ships has been limited to a maximum sulfur content of 0.1% since 1.1.2015.

In Regulation 14.4 (b) of MARPOL Annex VI, it is allowed to use higher sulfur fuel if an Exhaust Gas Cleaning System (EGCS-Scrubber) is employed to remove sulfur oxides from exhaust gas in order to provide equivalency to the prescribed specific SOx emission limits as stipulated in Regulations 14.1 and 14.4.

Almost all commercial EGCS use alkaline water[1] to remove sulfur oxides from engine exhaust gas. Sulfur oxide gases (SO2, SO3) are soluble in water. After dissolving in water sprayed into exhaust gas, they form acids that react with the alkalinity in the water to produce salts. There are two main types of scrubbers-open loop (depicted in Figure 1) and closed loop (depicted in Figure 2). Open loop uses sea water as the scrubbing medium due to its natural alkalinity. Scrubber effluent is mildly processed, essentially, sludge and oil are removed and then it is diluted onboard with more fresh seawater before being discharged back into the sea. Closed loop scrubbers reuse most of the water and maintain alkalinity by adding NaOH, however they still need to discharge some processed effluent and replenish it with make-up water.

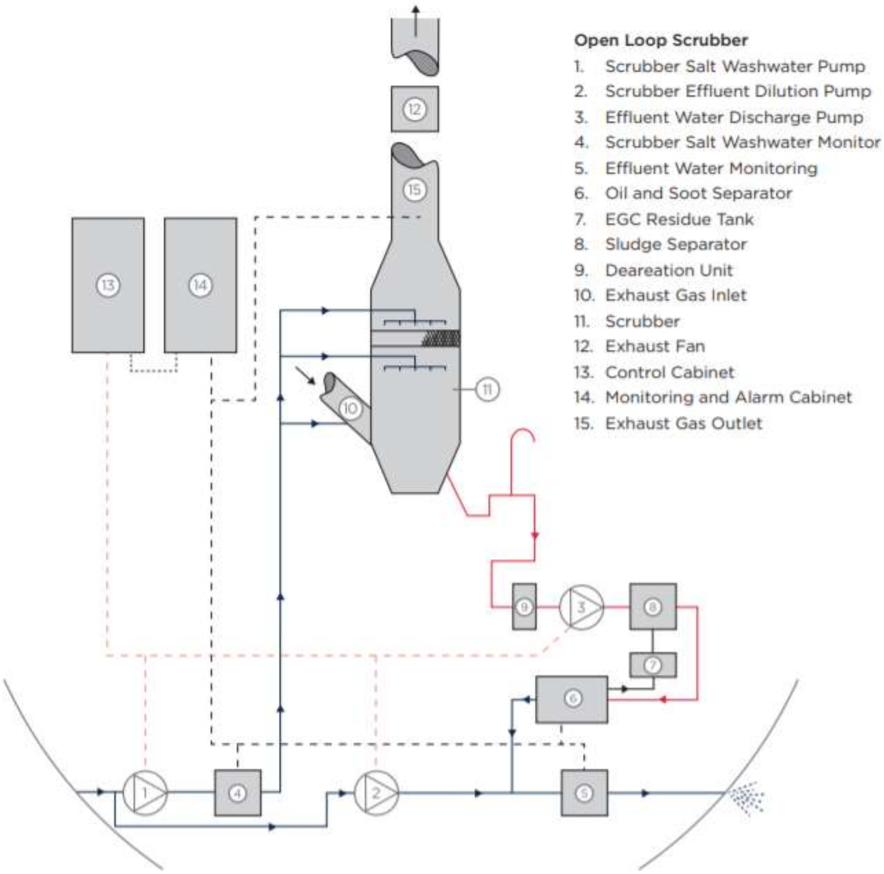


Figure 1: Open Loop EGCS (Scrubber) Source: [ABS]

1 Dry Scrubbers that use a solid alkaline medium instead of water have been proposed but have only been implemented commercially on two vessels - We will focus on wet scrubbing.

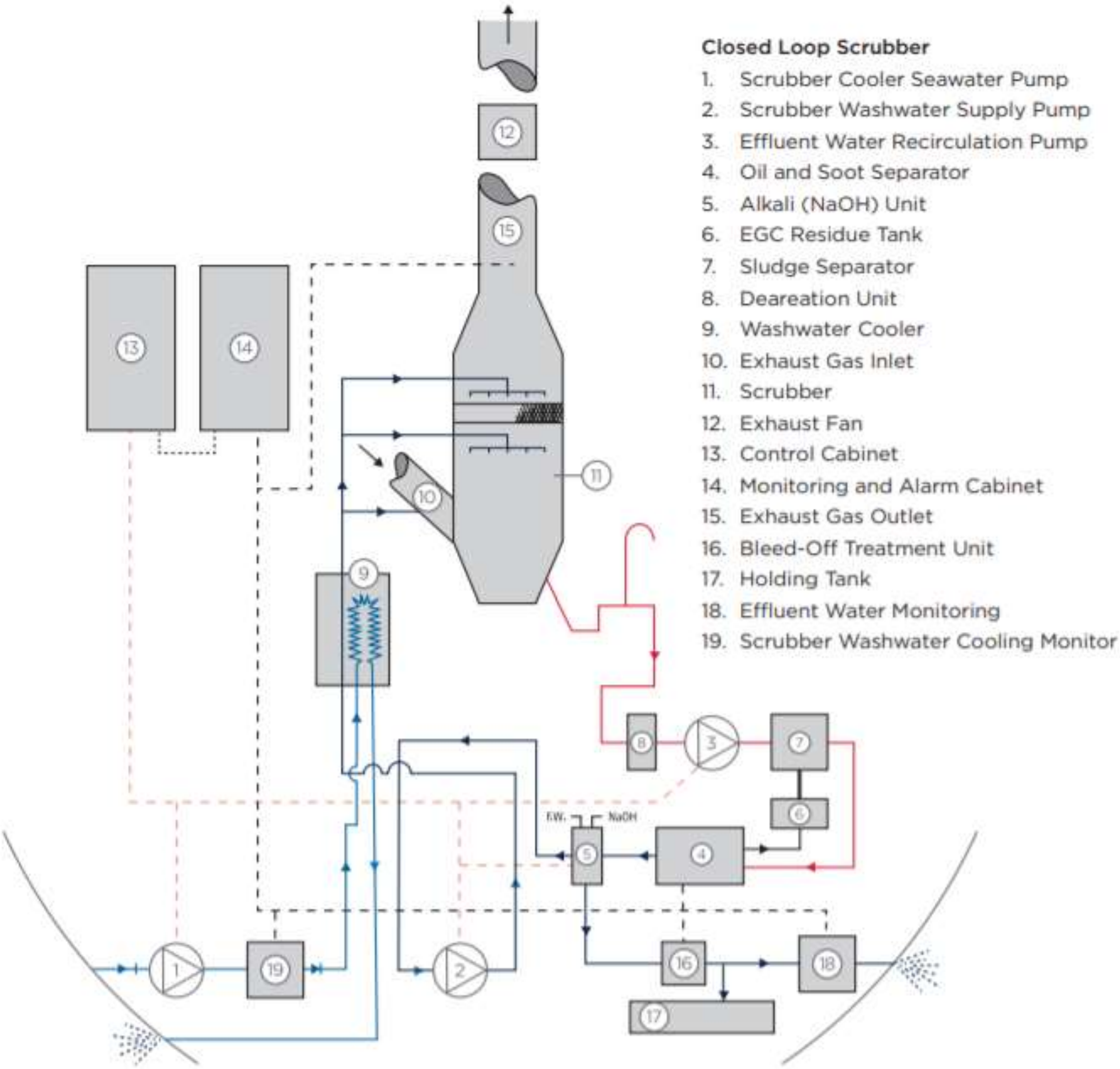


Figure 2: Closed Loop EGCS (Scrubber) Source: [ABS]

2. Impact of Scrubber Effluent Discharge

2.1. Summary of Literature Review on Impact of Scrubber Effluent Discharge

From our assessment of the literature, there is enough evidence to cause concern and warrant further research to evaluate the total environmental impact of discharging scrubber effluent into the sea:

- pH of effluent: EGCS effluent is very acidic, (pH~3) when discharged. Large effluent volume discharges could therefore as a result affect surrounding water pH. This could have adverse health effects on marine life but also potentially affect the ability of the ocean to absorb CO2 [Hassellöv]
- Metals: Scrubber water contains heavy metals from the fuel and oil as well as other sources. These can be toxic to marine life.
- PAH: Polyaromatic hydrocarbons. These are hydrocarbon compounds with multiple aromatic rings that can have serious health effects on marine life.
- PM. Some of particulate matter present in exhaust gases ends up in scrubber washwater. It can have negative health effects.

- Nitrates, temperature/ Eutrophication Agents: Nitrates in washwater come from NOx in the exhaust gases. If nitrate concentration in the ocean water increases too much, eutrophication effects can occur. Temperature rise from warm effluent discharge can cause similar effects [SOLAS study]

Studies have evaluated other substances as potential pollutants in scrubber effluent such as, sulfates, other hydrocarbons, oil, effects on dissolved oxygen etc.

We examined 7 different studies that we could find in the literature. A summary of the findings is presented in Table 1.

As can been seen in Table 1, all but one of the studies examined conclude that there is justification for concern and further study regarding heavy metals and PAH in the effluent. Four of the studies are concerned with acidification due to high effluent pH. Two of the studies state that nitrates could also cause issues.

		pH	**Metals**	**PAH**	**Nitrates**	**Notes**
1	**Danish EPA (2012)**	NOT a problem	NOT a problem	NOT a problem	Not applicable	
2	**US EPA (2011)**	possibly a problem	possibly a problem	possibly a problem	NOT a problem	pH likely not a problem
3	**SOLAS study**	a problem	a problem	a problem	a problem	
4	**UBA**	a problem	a problem	a problem	a problem	temperature also an issue
5	**BSH**	Not available	possibly a problem	a problem	probably NOT a problem	Preliminary findings
6	**NABU**	possibly a problem	possibly a problem	possibly a problem	probably NOT a problem	
7	**DTU**	a problem	a problem	a problem	Not applicable	

Table 1:Summary of Literature findings on Scrubber Effluent Contaminants

The US EPA (2011) study analyzed data from scrubber water chemical analyses from three different vessels and compared them against US NRWQC (US National recommended water quality criteria). The study concluded that for heavy metals and PAH, IMO guidelines washwater limits may not be sufficiently protective, since measured values exceeded US NRWQC. The study also raised some concern over suitability of measurement methods in IMO guidelines. pH is unlikely to be an issue according to the US EPA study although large amounts of dilution water would be needed. Nitrates are not an issue according to the EPA study.

The SOLAS study is an extensive study of studies that examined existing scrubber effluent measurements from ships and expert opinions from different studies. This study states significant concerns about pH, metals, PAH as well as nitrates/eutrophication. This study also calls for tighter IMO regulations regarding scrubbers and raises issues regarding their implementation. This study was a part of the Surface Ocean - Lower Atmosphere Study (SOLAS) project. This is an international research initiative aiming to understand the key biogeochemical-physical interactions between the ocean and atmosphere.

UBA is a study by the German Federal Environment Agency. It compared measurements of pollutants in scrubber effluent with European Environmental Quality Standards (EQS). Although the values the study picks from the literature of effluent measurements are just below the EQS, the authors calculate the total mass flows of pollutants for typical vessel trips and state significant concerns about pH, metals, PAH as well as nitrates/eutrophication. These concerns are based on the precautionary principle of the European Water Framework and Marine Strategy Directives because of the potential to exceed average EQS values in waters near busy shipping lanes. Also some of the detected substances in scrubber effluent are on the list of persistent, bioaccumulative and toxic (PBT) substances, the discharge of which should be absolutely avoided.

BSH is a study by the German Federal Maritime and Hydrographic Agency (BSH), funded by the German Federal Environment Agency (UBA). Preliminary results were published in December 2018. The study will be completed in 2019. The study performed measurements on scrubber effluent from five ships and calculated based on the measurement data what the total pollutant discharge would be in the case of maximum scrubber installation. This is defined as all vessels for which it makes financial sense in the Baltic Sea, the North Sean and the English Channel being outfitted with scrubbers. Even though results are preliminary, the study concludes that increased application of EGCS-scrubbers will be a new direct pollution source to the marine environment which is a concern, especially for PAH.

NABU is a broader study commissioned by German nature conservation NGO (Non-Governmental Organization) NABU and performed by independent environmental consultancy CE Delft. It examined a similar set of data as UBA and concluded that there is potential to exceed European EQS for metals and PAH and there is potential for sea acidification even when the IMO criteria are met.

The study from the Danish EPA [Danish EPA 2012] is the only one that included ocean dispersion modeling for two high risk locations near Denmark to explore environmental effects if all shipping in that area were to convert to using open loop scrubbers. This is also the only study that concludes that none of the main issues (acidification, metals and PAH) are a concern.

The study from Danish Technical University [DTU] is the only study where living marine organisms (copepods) were subjected to scrubber effluent to examine its effects on survival, feeding and reproduction. The study showed that "A direct exposure to discharge water increased adult copepod mortality and reduced feeding at metal concentrations which were orders of magnitude lower than the lethal concentrations in previous single-metal studies.". In other words, the different pollutants in scrubber effluent have synergistic effects on marine life compared with the effects individual pollutants have. This conclusion becomes very important because water quality standards used in all other studies were based on limits for individual pollutants.

2.2. Additional Details of Studies on Impact of Scrubber Effluent Discharge

US EPA 2011 study
This study evaluated a number of constituents found in EGCS washwater discharges to determine whether these discharges could cause an exceedance of any of US EPA's (United States Environmental Protection Agency) National recommended water quality criteria (NRWQC). The protectiveness of the IMO Guideline washwater limits were also evaluated in terms of whether they adequately mitigate the potential for washwater discharges to result in ecological or human health risk. The study used measured results from vessels that operated scrubbers that complied with IMO regulations as reported in other studies[2]. Based on this evaluation:

[2] Vessels: Zaandam, Suula, Pride of Kent.

Metals and Particulate Matter**:** The study concludes that "*several metals (including arsenic, copper, lead, nickel and selenium) [and PAHs (chrysene, benz(a)anthracene and benzo(a)pyrene)] were measured in washwater discharges at end-of-pipe concentrations that exceeded the NRWQC for that chemical. Accordingly, these parameters have the potential to contribute to an exceedance of water quality standards on a localized scale. The IMO Guideline washwater limits, intended to address turbidity and PAH-phenanthrene equivalents, may not be sufficiently protective based upon the available monitoring data*". (p36)

It is reminded to the reader that IMO guidelines for scrubber effluent discharge do not contain any limits for metal concentrations. The IMO guidelines do however request ship owners to sample and analyze effluent for a suite of metals. Turbidity is monitored as a surrogate for suspended solids. Field measurements have shown that most of the metals are bound to particulates or are particulates themselves which *"were effectively removed by the washwater treatment plant."* (p35) However, *"exceedances of NRWQCs for the several metals parameters, in each of the scrubber trials, suggest that scrubbers may emit washwater with concentrations of metals that could pose a risk to the environment"* (p36).
Finally regarding Particulate Matter (PM), the EPA study raises questions regarding the reliability of using turbidity as a measurement technique for PM *"However, this method of continuous monitoring has not been demonstrated to be a reliable measure of the concentration of PM" (p32)*

PAH: The study concludes that IMO guidelines may not be sufficiently protective-see quote above. Also the EPA study raises question regarding the reliability of the measurement technique for PAH *"However, this method of continuous monitoring has not been demonstrated to be a reliable measure of the concentration of PM".*

pH: Although the EPA study states that pH may be a concern, especially in low alkalinity waters, they conclude that "*The IMO Guidelines washwater limits for pH may be protective".* "*The pH of EGCS washwater discharges may also be a concern, because wet scrubbing involves the transfer of SOx from exhaust gasses to washwater, which is accompanied by a significant increase in acidity. The increased acidity must be neutralized, either by the natural alkalinity in seawater or by adding an alkaline chemical to freshwater. The monitoring data from scrubber trials onboard ships demonstrate that washwater neutralization is generally effective, although large volumes of reaction water may be required in open systems depending on the alkalinity of the water body. The IMO Guidelines washwater limits for pH may be protective, both at sea and in confined harbors."*

Other Pollutants (nitrates, sulfates, hydrocarbons, Chemical oxygen demand): None of these seem to be a concern. *"Total hydrocarbon concentrations in washwater discharges were low or below detection in the scrubber trials, despite the observation of a visible sheen accompanied by sooty deposits in the washwater discharge plume in one of these trials. Two other washwater parameters, nitrate and sulfate, appear unlikely to cause a concern because the quantities of these parameters that have been measured in EGCS washwater discharges should be readily assimilated in marine and estuarine receiving waters. In the case of nitrate, most of the EGCS washwater loading (1 to 3 kg/d/vessel, based on monitoring during trials) would be deposited to the receiving water via the atmosphere if scrubbers were not used"* (p37)

SOLAS study
This study was a part of the Surface Ocean - Lower Atmosphere Study (SOLAS) project. This is an international research initiative aiming to understand the key biogeochemical-physical interactions and feedbacks between the ocean and atmosphere. This study is essentially a bibliographic study of studies.

Metals, PM, PAH, Acidification, Eutrophication
The study concluded that there are potential issues with metals, PM, PAH as well as acidification and eutrophication.

"We conclude, that despite the existing guidelines for levels of monitoring and compliance of scrubber washwater, there is still the risk for acidification, eutrophication, and accumulation of PAHs, PM, and heavy metals in the marine environment, especially in the ecologically sensitive coastal regions, with often already higher background concentrations of contaminants and less dilution compared to the open sea." (p10)

The study also highlights that there is incomplete understanding of the effect of scrubber washwater discharge on marine life and biogeochemical processes and calls for further study.

Finally, the study proposes stricter standards to improve current regulation. *"standards and monitoring guidelines for application of scrubbers need to be improved. IMO member states recently recognized that it is necessary to improve and harmonize procedures in terms of washwater sampling and analysis to ensure comparability in different data sets (MEPC 71/INF.19). Washwater measurements should include monitoring of pH, PAHs, oil, OC (organic carbon), Black Carbon (BC), nitrogen, and heavy metals. Improved inspection protocols but also further technical developments of the scrubber systems, e.g., regarding reduction of biofouling and scrubber sensors failures, are needed to increase the compliance level of national and international regulations as well as enforcement of emission reduction technologies."*

UBA
This study by the German Federal Environment Agency (UMWELTBUNDESAMT- UBA) used data from vessels[3] operating on six sample routes to estimate the quantities of pollutants in total volume of discharged scrubber effluent.

"In terms of total amounts of pollutants discharged*, it is likely that a significant increase of use of scrubbers in the ecologically sensitive coastal waters of the North Sea and Baltic Sea and the confined waters of harbors will have a substantial environmental impact"*

"The present study has demonstrated that wet scrubbers influence the marine environment through pH decrease, temperature increase, pollutant discharges and possibly through the use of active substances. Open scrubbers in particular have a greater environmental impact than closed or dry scrubbers due to their high water consumption and significantly larger amounts of generated washwater. The environmental impact of active substances which are sometimes used in closed systems is completely unresolved."

The study does differentiate between open loop and closed loop scrubbers with the former being significantly worse because of the volume of effluent. *"According to current available knowledge, open scrubbers are particularly impairing because they require a very large amount of water. Thus, the ecological effects of temporary pH decrease, temperature and turbidity increase, and the mass flow of pollutants in the washwater are much higher than in closed systems."*

Heavy Metals, PAH
The study states that "*High values for nickel, mercury, lead and vanadium were detected in effluent. However, they fail to exceed any of the European Water Framework Directive (WFD) and the Marine Strategy Framework Directive (MSFD) Environmental Quality Standard (EQS) for the maximum allowable concentration."*

[3] Vessels: Fjordshell, Pride of Kent', 2 studies on Ficaria Seaways, they used Ficaria for calculations.

However, nickel, mercury and PAHs are all on the list of priority hazardous substances according to WFD (DIRECTIVE 2013/39/EU).

Furthermore, according to the REACH European Directive concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (Regulation EC No. 1907/2006), “No risk assessment is undertaken under REACH for substances that are classified as persistent, bioaccumulative and toxic (PBT) due to their environmental effects, as their distribution and effects cannot be predicted for the long term, and in combination with other substances. An input of these substances must therefore be completely avoided. However, to ensure an adequate level of protection for the environment and human health, the cessation or phasing out of discharges, emissions and losses of priority hazardous substances pursuant to Article 4(1)(a)(iv) of Directive 2000/60/EC should also be aimed at.”

Nitrites/Eutrophication/pH
It is mentioned that nitrates concentration doubles in the effluent compared to the background but is still below the EQS; however, the authors are concerned. The study is also concerned with temperature rise due to effluent that may cause eutrophication and pH levels, which affect marine life.

In conclusion, in this study for the German Environment Agency, even though:

“It seems that the WFD/MSFD environmental quality standards are not likely to be breached at the present time.” [For pollutant concentrations in scrubber effluents]

The study clearly states that “*In principle, the use of clean liquid (diesel) and gas (LNG) fuels is preferable to the aftertreatment of exhaust gases to reduce sulfur dioxide emissions”* and seeks ways to prohibit scrubber use completely in some areas:

“It is necessary to examine whether the use of such systems - including the ecologically precarious open scrubbers, as these cause higher pollutant loads and larger flow rates of washwater – in areas with high protection requirements can be prohibited and the deterioration of the ecological condition may be prevented.”

This is for two reasons:
A) High volumes of effluent are discharged and some of the pollutants are persistent:
“From an ecological perspective, the mass flow rate of pollutants in washwater are just as significant as their concentration. Long-term accumulation is particularly relevant from an ecological perspective when it comes to non-degradable components such as metals.”
“*hence EQS may be exceeded in the future due to accumulation or high shipping volume in certain areas.”*

B) Discharge should be avoided completely based on the precautionary principle of the WFD (avoiding the origin of environmental degradation in the first place).
“The discharges of large amounts of washwater with partially persistent substances, lower pH and elevated temperature, however, are not compatible with the precautionary principles of the WFD/MSFD.”

Finally, the study mentions that:
“There still is great need for research and measurements and, where possible, the development of international activities to prevent environmental degradation by future increase of scrubber discharges.”

BSH

BSH is a study by the German Federal Maritime and Hydrographic Agency (BSH), funded by the German Federal Environment Agency (UBA). Preliminary results were presented in December 2018 at the Sub-committee on Pollution Prevention and Response of the IMO. The study will be completed in 2019. The study performed measurements on scrubber effluent from five ships. The scrubbers on the ships were operated in both open and closed loop mode.

Based on the measurements from the ships, the study will calculate what the total pollutant discharge would be in the Baltic Sea, the North Sean and the English Channel in the case of maximum scrubber installation. This is defined as all vessels for which it makes financial sense to be outfitted with scrubbers. Only results for the North Sea are presented in the preliminary report.

The study also compared ship monitoring data of scrubber effluent water quality with in situ measurements by the authors. They conclude that there are significant discrepancies between ship monitoring data and their measurements regarding PAH and turbidity and advise that more effort is necessary for reliable on board monitoring of washwater discharges.

PAH
Even though results are preliminary, the study concludes that increased application of EGCS-scrubbers will be a new direct pollution source to the marine environment which is concerning, especially for PAH. Concern is expressed for both open loop scrubbers due to the total volume discharged but also for closed loop because they are a highly concentrated source of pollution. The study compares total PAH discharges into the North Sea with riverine sources of PAH and finds EGCS related discharges in the maximum scrubber installation scenario significantly higher.

Heavy Metals
The study did find a significant increase in concentration of some metals in scrubber effluent compared to the background water and does compare the total discharges into the North Sea in the maximum scrubber installation scenario with existing riverine sources but a concrete conclusion is not drawn yet regarding whether these discharges are acceptable.

Nitrates
The study calculates the total discharge in the maximum scrubber installation scenario with riverine sources in the North Sea and concludes that scrubber nitrates are significantly lower than riverine sources.

NABU
This is a broader study commissioned by German nature conservation NGO (Non-Governmental Organization) NABU and performed by independent environmental consultancy CE Delft.

In addition to scrubber effluent impact analysis, the study examined many different aspects of scrubber operation including market analysis and the financial business case. In terms of environmental effects, the study also examined greenhouse gas and air pollutant emissions associated with scrubbers.

Heavy Metals
Regarding effluent, the study mentions that the concentration of various substances found in the washwater of scrubbers is higher than the Environment Quality Standards (EQS) listed in EU Directive 2013/39[4], even though the IMO regulations are likely met.

PAH
The study mentions that *"Although the IMO criteria are met, scrubbers may have an impact on acidification and accumulation of hazardous substances like heavy metals and PAH*".

Nitrates/Eutrophication
The study does not consider them to be a significant source of concern based on amounts discharged.

pH
Even though the study quotes the Danish EPA study which states that pH should not be a problem, it also quotes some more recent studies that imply there may be cause for concern.

Danish EPA 2012
This study is the only one where pollutants were not just evaluated in terms of concentrations of pollutants in effluent [EPA, NABU mostly] or concentrations in effluent and total amount per ship discharged over a typical trip [UBA, BSH], but also evaluated the total impact from all ships in a geographical area. The study focused on just the Baltic Sea since it is of interest to the Danish EPA.

This study focused on two areas in the Baltic Sea (Aarhus Bight and Kattegat) that were considered relatively vulnerable due to high ship traffic, low alkalinity and/or low flushing. The modeling of effluent dispersal (mixing) is determined based on the principles of Time Scale for a water body.

The authors calculated that in a scenario where all ships were outfitted with scrubbers, heavy metal and PAH concentrations in seawater would still stay below the current European EQS (annual average) in terms of average annual concentrations. Scrubber effluent was therefore not considered likely to have a considerable negative impact on the marine environment. In terms of acidification the analysis was extended to the most vulnerable area of the Baltic due to low alkalinity, the Bay of Bothnia, and everywhere the impact of total scrubber effluent discharge on pH was marginal.

DTU
This study by the Danish Technical University is the only one where marine life, copepods to be exact, was subjected to real scrubber effluent water diluted with seawater. The study showed that "*direct exposure to discharge water increased adult copepod mortality and reduced feeding at metal concentration which were orders of magnitude lower than the lethal concentrations in previous single-metal studies. In contrast, reproduction was not influenced by dietary uptake of contaminants. Scrubber water constituents could have synergistic effects on plankton productivity and bioaccumulation of metals, although the effects will depend on their dilution in the marine environment".*

The important consequence of this finding is that even in cases where dispersion studies and actual water measurements prove that in a certain geography, pollutant concentrations would be below the EQS for a single pollutant, even if all ships were outfitted with scrubbers, the combined effect of different pollutants could still be harmful to marine life.

[4] For scrubber effluent, this study used data from measurements on vessels MV Ficaria Seaways MS Zaandam MT Suula Pride of Kent.

2.3. Conclusions on Scrubber Effluent Discharge Environmental Impact

The scientific literature was evaluated regarding the environmental effects of scrubber effluent. Out of seven studies evaluated, six state that there is an issue with discharge of scrubber effluent due to the concentration of heavy metals and PAH in the effluent[5]. The same studies, with the exception of US EPA and the BSH study, state that there are potentially issues with water acidification. The US EPA does not completely dismiss issues with acidification but states that it will likely be manageable. Most studies call for stricter IMO guidelines regarding effluent discharges [EGCS 2015 Guidelines].

Most studies compare the plume concentration of metals from on-board measurement studies to different maximum allowable environmental standards. However, there are only a few tests available and there is some ambiguity in which values should be chosen. National and intergovernmental standards of different countries and other supranational entities (European Union) are different for different pollutants. For this reason, the UBA study does not base its recommendation on the likelihood of exceeding plume concentrations as other studies do. It bases its conclusion on the likelihood of average annual concentrations of pollutants being exceeded in some locations due to very high total volume of effluent discharged. It also bases its recommendation on the discharge of persistent, bioaccumulative and toxic (PBT) substances, the discharge of which should be absolutely avoided.

Danish EPA is the only study that considers scrubber effluent discharge not an ecological concern. It is also the only study that undertook ocean dispersion modeling. While the fact that dispersion modeling was included certainly adds credibility to the study, only two locations were examined. It is likely that there are other geographic locations where conditions are worse in terms of pollutant accumulation. Furthermore, as the DTU study has shown, understanding of the combined effects of scrubber water pollutants on marine life is limited. There are likely significant synergistic effects. When there are more than one pollutants as is the case with scrubber water, pollutant concentrations that cause ecological issues can be orders of magnitude less than single pollutant concentrations that cause similar marine life effects.

It is obvious that there are significant questions on acceptability of scrubber water discharges as well as a need for further study. A lot more work needs to be completed on the combined effects of the different pollutants on marine life and ocean chemical processes before new water quality standards are set. Additionally, since low sulfur requirements in marine fuels after 2020 are global, dispersion modeling needs to be completed for many more locations around the world to examine whether average concentrations of pollutants and acidification are acceptable.

3. Air Pollution Equivalence of Scrubber Equipped Vessels to Vessels Burning Low Sulfur Fuel

3.1. Summary of Literature Review on Air Pollution Equivalence of Scrubber Equipped Vessels to Low Sulfur Fuel Burning Vessels

EGCS systems have been proven to effectively remove gaseous sulfur oxide emissions from flue gas to levels that make SOx emissions equivalent to using low sulfur fuel [ABS, UC Riverside, Fridell and Salo, Hansen, others].

[5] The BSH study is preliminary. It has not yet drawn a final conclusion regarding heavy metals but is already expressing concern regarding PAH. All other six studies are concerned with both metals and PAH.

EGCS systems also remove part of the exhaust gas particulates. However, from our review of the literature, there is enough evidence to suggest that emissions of exhaust gas particulates for a vessel using a scrubber could be significantly worse than a vessel using low sulfur fuel: thus at a minimum, this comparison at least warrants further investigation. This is because:

A) Scrubbers may not remove all the additional particulate mass that a higher sulfur fuel generates.
B) Scrubbers may not remove the small diameter, nucleation mode, particulates effectively.
C) Small diameter particulate emission has significant implications. These particulate cause adverse health effects. Additionally, including them in the air emissions sulfur balance may result in not being in compliance with the low sulfur air emissions rule.

In more detail:

3.2. Details of Scrubber Air Pollution Equivalence Literature Review

3.3. Scrubbers do not remove all the additional particulate mass that combustion of a higher sulfur fuel generates

The literature clearly establishes that higher fuel sulfur content leads to higher engine out particulate mass (PM) emissions. Plots of PM vs. fuel sulfur content from many measurements are included in [Zetterdahl and Lack et al]. Many official publications from prominent organizations confirm this [US EPA 2009] and it is part of the rationale for reducing fuel sulfur content for all fuels (not just marine).

While there is some literature on engine-out emissions from marine engines using different types of fuels [e.g. Ushakov, Kasper, Zetterdahl, Winnes and Fridell, Van], publications comparing particulate emissions using a scrubber and high sulfur fuel vs. using a low sulfur fuel without a scrubber are limited. A summary of results can be seen in Table 2. It should be mentioned that the [ABS] and [EGSA] numbers are not detailed studies but just single quoted numbers in more general documents.

It is clear from Table 2, that only in some of the tests[6] ([Hansen],[Fridell and Salo]) was the achieved reduction in particulate mass definitely enough to make the vessel with a scrubber burning high sulfur fuel equivalent to low sulfur fuel use without a scrubber.

[Hansen] reports 31-53% percent PM reduction for the on-board tests and 45-55% PM reduction for rig tests of a similar scrubber. Both systems used jet injectors for the water. When a venturi pre-unit was used in rig tests, the particulate removal efficiency increased to 79% which would be sufficient to make it equivalent to a low sulfur fuel. However, the venturi pre unit causes an additional pressure drop of 400 mm WC (Water Column) to the flue gas which may be unacceptable as it increases fuel consumption.

Most importantly however, examining the literature reveals that there are significant issues with how particulate measurements are performed. In the US, the US EPA 40 CFR 1065 protocol for engine particulate measurements mandates a dilution ratio of 6-20 and a sample temperature of 47^{o} C. In Europe, the ISO 8178 is used and as a result, much higher temperatures (above 250^{o} C) and dilution ratios higher than 20 are used. Because marine fuel contains so much sulfur, the particulate matter could contain a large sulfate (H2SO4*H2O) fraction. For high dilution ratios and sampling temperatures, this fraction is evaporated and not

[6] [EGSA] also quotes high enough numbers although it is not a detailed study but just a number in a general document.

measured [UC Riverside, Ushakov, Zetterdahl]. This is explained well in Figure 3 from [Zetterdahl] where the same sample is measured with high dilution ratio and high temperature and low dilution ratio and low temperature.

From all the measurements presented in Table 2, only the UC Riverside study used low dilution ratio and low temperature which in a large part explains the very low PM removal efficiency measured. Particulate emissions (PM 2.5) measurements before and after a marine scrubber on board two different vessels by [UC Riverside] can be seen in Figure 4. It is clear that in these tests, the sulfate (H2SO4*6.65H2O) component of PM is very significant. Most importantly, particulate mass is not reduced in the scrubber significantly as some of the water in the flue gas condenses as sulfate particulates. In vessel 3, PM actually increases somewhat after the scrubber.

Source	**PM reduction**	**Notes**	**Equivalent to 0.1% S fuel ?**	**Measurement Conditions: Dilution**
Hansen	31-55%	jet spray	NO	high dilution/high temperature
	79%	venturi	YES	high dilution/high temperature
Fridell and Salo	75%		YES	high dilution/high temperature
EGCS Handbook	60-90%	no details provided	likely	high dilution/high temperature
ABS	30-60%	no details provided	NO	N/A
Zhou	36%		NO	high dilution
UC Riverside	2-12%		NO	low dilution/temperature

Table 2: Literature Summary Regarding Scrubber particulate matter (PM) reduction efficiency

With the help of particle size distribution diagrams seen in Figure 4, the measurements of UC Riverside can be explained further. The low particle removal efficiency is due to nucleation mode particles not growing enough as they go through the scrubber so that they can be effectively removed by the cyclonic action of the scrubber or its demister.

Sulfate components as a fine particulate mist in scrubbers is a well-known phenomenon. Essentially, some of the SO2 in the exhaust gets oxidized to SO3 because of excess combustion air and when temperature drops in the scrubber, it combines with water to form a fine mist. This can be eliminated by adding a reheat system after the scrubber. The EPA had published an analysis of reheat systems for scrubbers back in 1980 [US EPA 1980]. Also the Association of Exhaust Gas Clean-Up Systems manufacturers has included the phenomenon in their EGCS Handbook [EGCS 2012], as well as the option to add a reheat system to eliminate it with an associated energy penalty. The EGCS Handbook also acknowledges the effect of measurement standards on particulate matter condensable components but states that they have been using ISO.

This phenomenon may imply that other measurements in Table 2 except UC Riverside are skewed and present higher values of particle removal efficiency than what the scrubber actually achieves. This is because a significant number of the particles will go undetected both before and after the scrubber if the measurement is performed at high temperatures and dilution ratios.

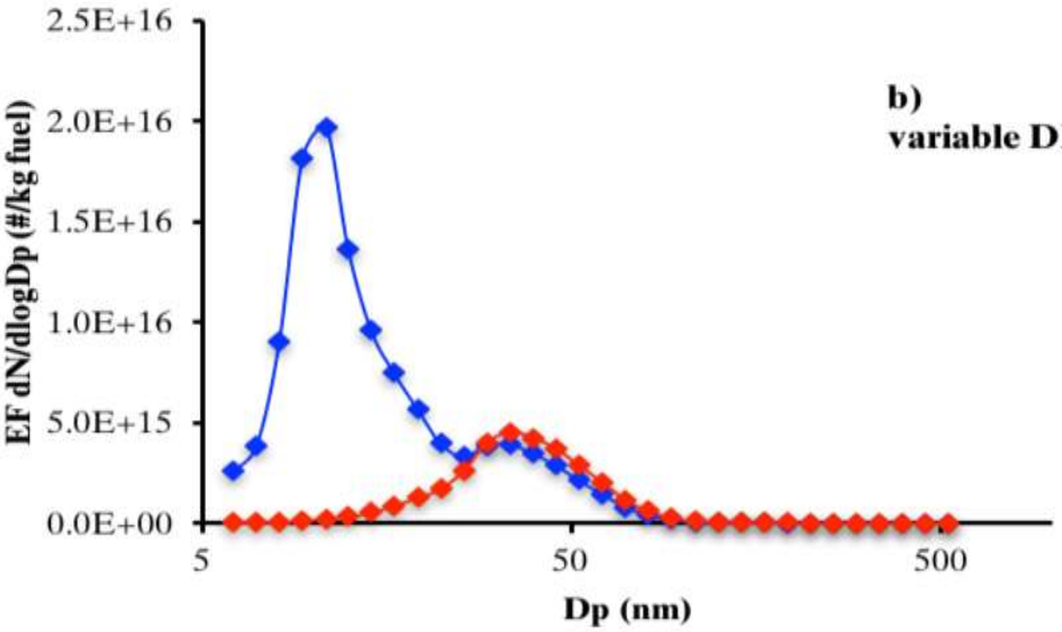


Figure 3: The effect of sampling conditions on particle number emission factor distribution. The blue line shows a measurement with low temperature dilution at a low dilution ratio. The red the same measurement using high dilution ratio and high temperature dilution air. [Zetterdahl]

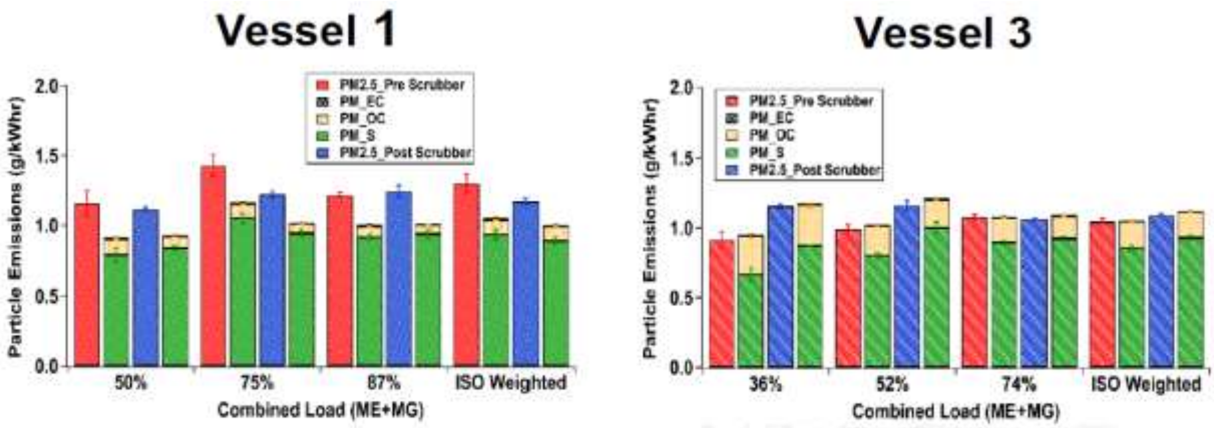
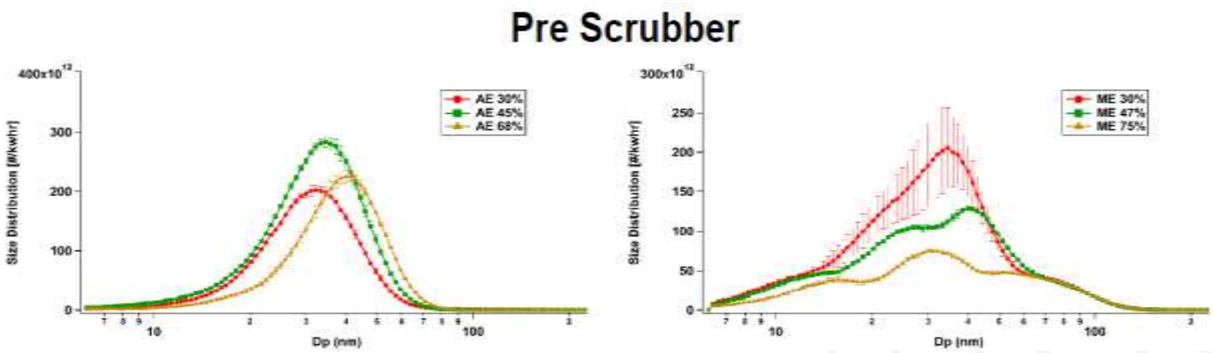


Figure 4: Particulate mass emission factors for two different vessels. Source: [UC Riverside 2017]. The sulfate (S), organic carbon (OC) and elemental carbon (EC) content of pre scrubber and post scrubber particulate mass is displayed. [UC Riverside]



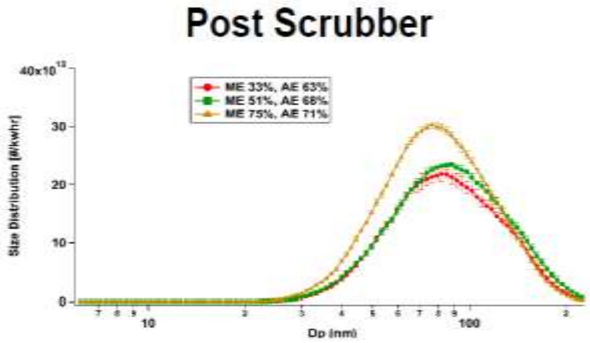


Figure 5: Particulate size distribution for the two engines before the scrubber: (auxiliary-AE) upper left, main (ME) upper right and post scrubber at the bottom for the [UC Riverside 2017] measurements

3.3.1. Scrubbers likely do not remove the small diameter, nucleation mode particulates effectively

It was already explained that there is some evidence in the literature that small particulates (nucleation mode) that contain high amounts of sulfuric acid may not be effectively removed by scrubbers. This is further supported by Figures 6 and 7. The particulate mass removal efficiency vs. aerodynamic diameter for the scrubber system in [Zhou] can be seen in Figure 6. It is clear that the removal efficiency is low for small particulates. The particulate number concentration before and after the scrubber for two fuels measured using different instruments [Køcks] can be seen in Figure 7. This study expands on the same measurements (Vessel: Ficaria Seaways) reported in [Hansen]. It clearly shows that even with a 1% sulfur fuel, the number concentration of particulates is lower before the scrubber than for the 2.3% fuel after the scrubber which suggests that even though there is reduction in fine particulates in the scrubber, more get through than if a lower sulfur fuel were burned.

At first glance, the question of whether small particulates grow enough to be removed in scrubbers seems not completely resolved in the literature. Looking at the results by [Fridell and Salo] in Figure 8, also measured on Ficaria Seaways, it would seem that not only did the scrubber remove enough particulates to make particulate mass finally emitted equivalent to a low sulfur fuel (Marine Gas Oil- MGO) but it eliminated enough small particulates so that in terms of particulate number emissions the high sulfur scrubbed case is better than the low sulfur marine gas oil (MGO) case. However, this measurement was performed using a high temperature (250C) and a dilution ratio higher than 64, so the volatile component of particulate number, which is the most important part of it, was likely to a large extent, lost.

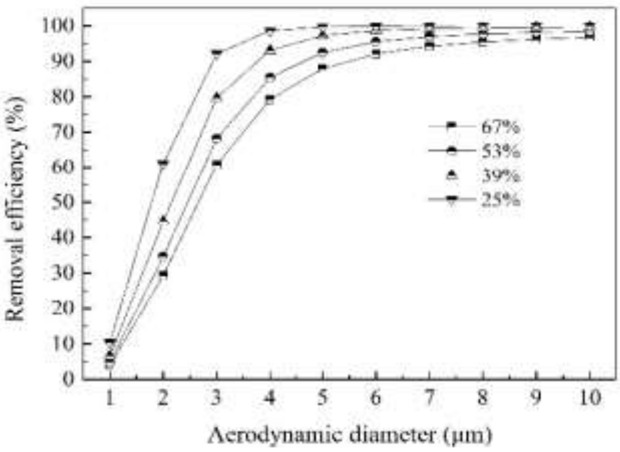


Figure 6: Particulate size removal efficiency for a scrubber vs particle aerodynamic diameter [Zhou]

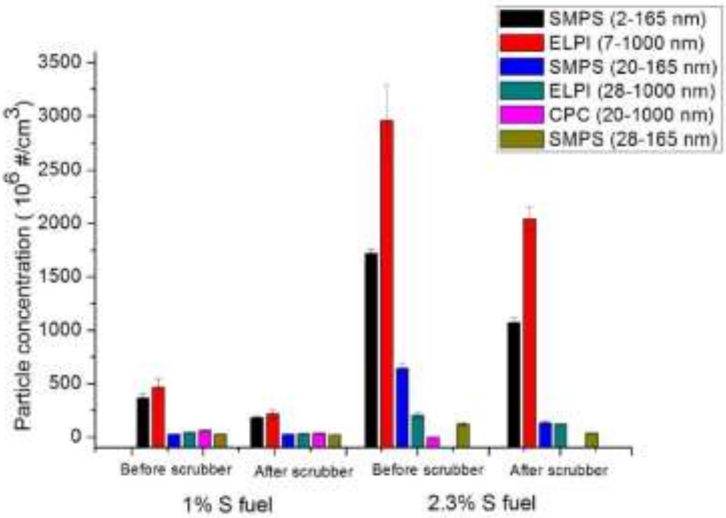


Figure 7: Particulate number concentration before and after the scrubber for two fuels measured using different instruments [Køcks]

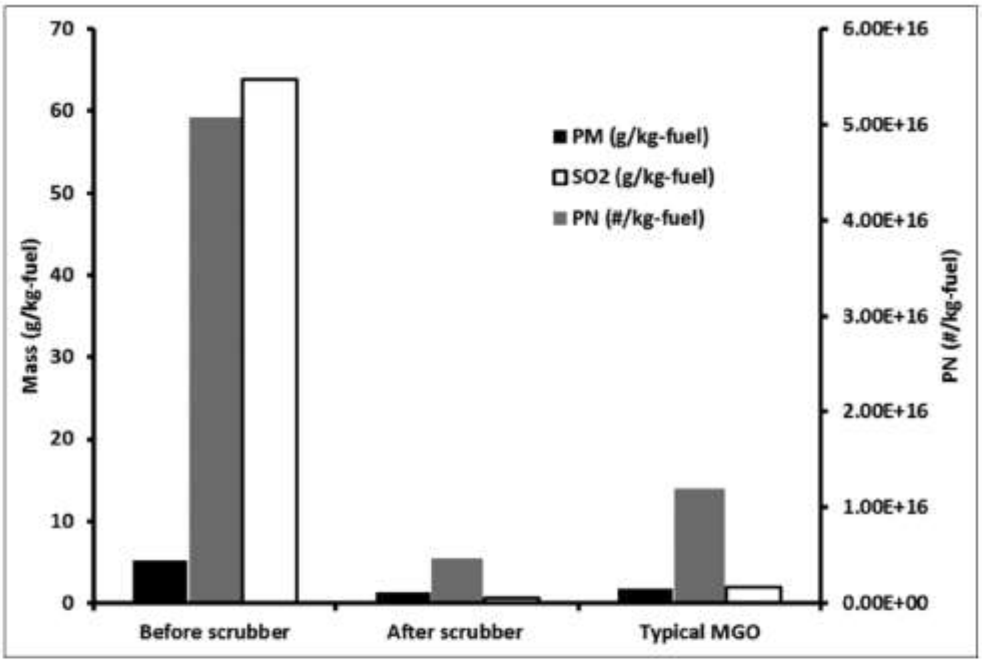


Figure 8: Particulate mass and number concentration before and after the scrubber and typical MGO numbers [Fridell and Salo]

3.3.2. Scrubbers likely do not remove the small diameter, nucleation mode particulates effectively: Implication for health effects and equivalence to low sulfur fuel

The first reason small particulates are important is because health effect studies have shown that the smaller particulates are more harmful. [US EPA 2009].

The second reason is that if sulfur content in the particulates is included in the sulfur balance, the total sulfur related air emissions of the vessel may not be equivalent to 0.1% fuel. This can be seen in Figure 9 from [UC Riverside]. It can be seen in Figure 9, that if the sulfate particulates component of particulates that are not removed by the scrubber and are emitted are included in the balance, the vessels are no longer in compliance in terms of the low sulfur rule. This is likely more of an issue with compliance in SECA's where emissions have to be equivalent to 0.1% sulfur fuel than the global 0.5% fuel sulfur equivalence rule.

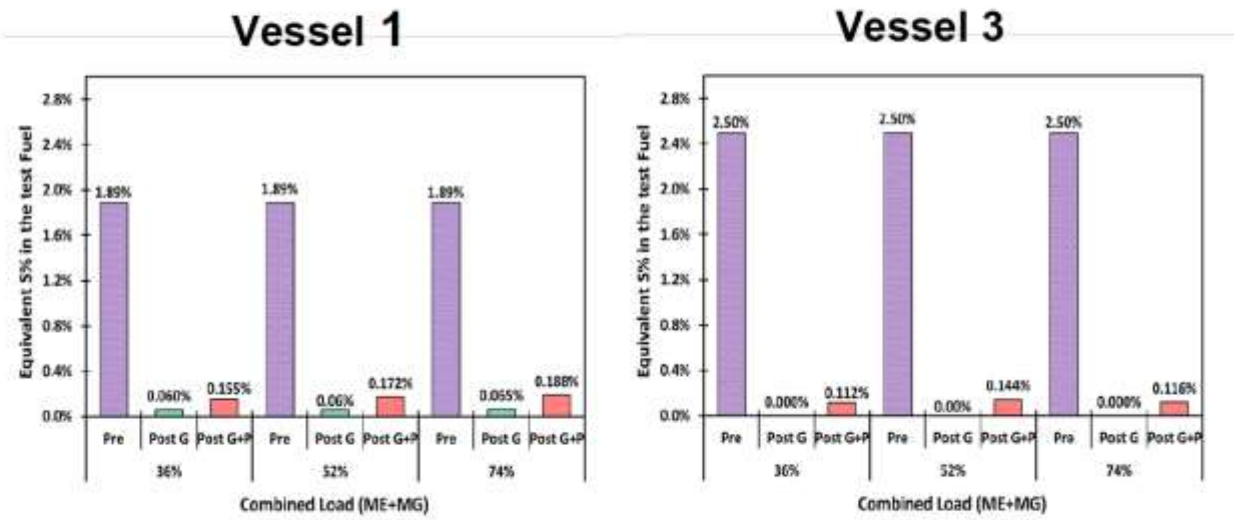


Figure 9: Sulfur air emissions balance for two vessels in [UC Riverside] if only SOx in gaseous phase is included and if the H2SO4 in particulates is added. Equivalent fuel sulfur content numbers are presented. [UC Riverside]

3.4. Conclusions on Scrubber Air Pollution Equivalency

There is no doubt in the literature that the use of EGCS (scrubbers) in marine applications is effective in removing SOx (SO2 and SO3). However, a closer examination reveals that there may be significant issues regarding exhaust particulate emissions. This is because:

A. Particulate matter reduction by EGCS systems may not be sufficient to make emissions equivalent to low sulfur fuel.

A.1. Even without examining measurement protocols, many of the reported measurements on particulate matter reduction are less than the ~75% needed to be equivalent. Details of the scrubber design do matter.

A.2. For high sulfur fuels, exhaust particulates contain a significant fraction of fine, condensable sulfate particles (also some organic content). Therefore, high dilution, high temperature particulate measurement protocols widely used likely overestimate the particle removal efficiency of a scrubber as they do not measure the condensable component.

B. It is likely that EGCS systems do not remove most of the small particles. Scrubbers are essentially based on cyclonic separation and demisters. It looks therefore that there is a significant possibility that they are unable to remove fine particles unless they grow into larger ones. Interpretation of results in this area is difficult because of the significant effect of measurement protocols. However, there are strong indications that perhaps the only way to eliminate these particulates is by using reheat systems in the exhaust which would result in a fuel consumption penalty.

C. The effect of small scale particulates on human health is significant. Furthermore, accounting for the sulfur in sulfate particulates may affect regulatory compliance for vessels using scrubbers.

Research is far from conclusive in this area. Certainly, more work is needed. However, there are enough indications that there may be issues with current scrubber designs and regulations in terms of delivering emissions that are completely equivalent to those of low sulfur fuel.

References

ABS (2017) American Bureau of Shipping ADVISORY ON EXHAUST GAS SCRUBBER SYSTEMS

BSH (2018) German Federal Maritime and Hydrographic Agency **"**Chemical characterization of discharge water from exhaust gas cleaning systems (EGCS) and a first estimate of total discharges to the North Sea, the Baltic Sea and the English Channel", submitted to the IMO SUB-COMMITTEE ON POLLUTION PREVENTION AND RESPONSE, 6th session, 14 December 2018,

Danish EPA (2012) Danish Ministry of the Environment, Environmental Protection Agency Environmental Project No. 1431, 2012 Assessment of possible impacts of scrubber water discharges on the marine environment

DTU (2017) M. Koski et al Ecological effects of scrubber water discharge on coastal plankton: Potential synergistic effects ofcontaminants reduce survival and feeding of the copepod Acartia tonsa/ Marine Environmental Research 129 (2017) 374-385

EGCSA 2012 A practical guide to exhaust gas cleaning systems for the maritime industry EGCSA Handbook 2012, Exhaust Gas Clean-up Systems Association

EU (2016). Directive 2016/802/EU of the European Parliament and of the Council of 11May 2016 Relating to a Reduction in the Sulphur Content of Certain Liquefied Fuels (codification), OJ L132/58, 21.05.2016.

Fridell and Salo (2016) Eric Fridell and Kent Salo 'Measurements of abatement of particles and exhaust gases in a marine gas scrubber' Proc IMechE Part M: J Engineering for the Maritime Environment 2016, Vol. 230(1) 154–162

Hansen (2012). Danish EPA. Exhaust Gas Scrubber Installed Onboard MV Ficaria Seaways: Public Test Report, Environmental Project No. 1429, s.l.. Author: Peter Hansen

Hassellöv (2013) Hassellöv, I.-M., Turner, D. R., Lauer, A. & Corbett, J. J., 2013. "Shipping contributes to ocean acidification". Geophysical Research Letters, Volume 40, pp. 2731-2736.

Kasper et al (2007) "Particulate Emissions from a Low-Speed Marine Diesel Engine" Aerosol Science and Technology, 41:24–32, 2007

Køcks (2012) M. Køcks "Shipboard characterization of a wet scrubber system: Influence on particle number concentration, particle size distribution and chemical composition" 16th Conference on Combustion Generated Nanoparticles, 2012 available at http://www.nanoparticles.ch/conference_archive.html

Lack et al (2009) "Particulate emissions from commercial shipping: Chemical, physical, and optical properties" JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, D00F04, doi:10.1029/2008JD011300, 2009

MARPOL (2017). MARPOL Consolidated Edition 2017. London: IMO.

MEPC.259 (68) (2015) EGCS Guidelines, 2015 Guidelines for exhaust gas cleaning systems (resolution currently under review)

NABU (2015) Eelco den Boer, Maarten 't Hoen Scrubbers - An economic and ecological assessment Delft, CE Delft, March 2015

SOLAS study (2018) Sonja Endres et al, "A New Perspective at the Ship-Air-Sea-Interface: The Environmental Impacts of Exhaust Gas Scrubber Discharge", Front. Mar. Sci., 24 April 2018

UBA (2015) Federal Environment Agency (Germany)-Umweltbundesamt Impacts of scrubbers on the environmental situation in ports and coastal waters Beate Lange et al, TEXTE 65/2015 Project No. (FKZ) 33913 Report No. (UBA-FB) 002015/E

UC Riverside (2017) University of California, Riverside, 'Marine Scrubber Efficiency and NOx Emissions from Large Ocean Going Vessels' Presented by: Jiacheng (Joey)Yang Co-Authors: Kent C. Johnson, J. Wayne Miller, Thomas D. Durbin, Yu Jiang, Georgios Karavalakis, David R. Cocker III,2017 International Emissions Inventory Conference August 14thto August 18th, 2017 Baltimore, MD
US EPA (1980) "Stack Gas Reheat Evaluation", EPA-600/7-80-051, March 1980
U.S. EPA (2009). U.S. EPA Integrated Science Assessment (ISA) for Particulate Matter (Final Report, Dec 2009). U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-08/139F, 2009.
U.S. EPA (2011). Exhaust Gas Scrubber Washwater Effluent. Washington, DC. EPA-800-R-11-006
Ushakov (2013) Sergey Ushakov, Harald Valland, Jørgen B Nielsen & Erik Hennie (2013) Effects of high sulphur content in marine fuels on particulate matter emission characteristics, Journal of Marine Engineering & Technology, 12:3, 30-39
Van et al (2018) Effect of sulphur and vanadium spiked fuels on particle characteristics and engine performance of auxiliary diesel engines
Winnes and Fridell (2009) Hulda Winnes & Erik Fridell (2009) Particle Emissions from Ships: Dependence on Fuel Type, Journal of the Air & Waste Management Association, 59:12, 1391-1398, DOI: 10.3155/1047-3289.59.12.1391
Zetterdahl (2016) Maria Zetterdahl Particle Emissions from Ships Measurements on Exhausts from Different Marine Fuels PhD Thesis, Department of Shipping and Marine Technology, Chalmers University, ISBN 978-91-7597-383-8
Zhou (2017) Jinxi Zhou, Song Zhou and Yuanqing Zhu, "Characterization of Particle and Gaseous Emissions from Marine Diesel Engines with Different Fuels and Impact of After-Treatment Technology", Energies 2017, 10, 1110; doi:10.3390/en10081110

List of Acronyms

EGCS: Exhaust Gas Cleaning System
EQS: Environmental Quality Standard (EU)
IMO: International Maritime Organization
MGO: Marine Gas Oil
MSFD: Marine Strategy Framework Directive (EU)
NGO: Non-Governmental Organization
NRWQC: National recommended water quality criteria (US)
PAH: Polyaromatic Hydrocarbon
PM: Particulate Matter
PBT: Persistent, Bioaccumulative and Toxic substance
REACH: Registration, Evaluation, Authorization and Restriction of Chemicals
SECA: Sulfur Emission Control Area
SOLAS: Surface Ocean - Lower Atmosphere Study project
US EPA: United States Environmental Protection Agency
WC: Water Column
WFD: Water Framework Directive (EU)

___