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# Exhaust Gas Cleaning Systems: A Maritime Study

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# Exhaust Gas Cleaning Systems: A Maritime Study

December 14, 2015

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This project proposal is submitted in partial fulfillment of the degree requirements of Worcester Polytechnic Institute. The view and opinions expressed herein are those of the authors and do not necessarily reflect the positions or opinions of Worcester Polytechnic Institute.

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and

Regina Bergner: for being our sponsor and mentor and for guiding us through the maze which is Coast Guard HQ.

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# List of Abbreviations

Abbreviation	Term
APPS	Act to Prevent Pollution From Ships
CATC	Clean Air Technology Center
CEMS	Continuous emissions monitoring systems
ECA	Emissions Control Area
EGCS	Exhaust gas cleaning systems
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency
EQS	European Union Environmental Quality Standards
FGD	Flue-gas desulfurization
GJ	Giga-joules
HFO	Heavy fuel oil
IMO	International Maritime Organization
LNG	Liquefied natural gas
MARPOL	Marine Pollution
MEPC	Marine Environmental Protection Committee
MDO	Marine diesel oil
MGO	Marine gas oil
NO <sub>x</sub>	Nitrogen oxides
PM <sub>10</sub>	Particulate matter larger than 2.5 micrometers and smaller than 10 micrometers
PM <sub>2.5</sub>	Particulate matter '2.5 micrometers in diameter and smaller
SO <sub>x</sub>	Sulfur oxides
TEN-T	Trans-European Transportation Network
USCG	U.S. Coast Guard
VOC	Volatile organic compounds
WHO	World Health Organization

# Dear Reader,

The Interdisciplinary Qualifying Project (IQP), is a defining characteristic of Worcester Polytechnic Institute's (WPI) project based learning curriculum. Traditionally, for an IQP, a group of students will work on a problem for an external organization, create and present a deliverable, and develop a report for the whole process to be turned into WPI and be graded. Students can only hope their work will be used, or that the organization they worked for will follow up on it.

This IQP varies from the traditional IQP, and this distinction is important to keep in mind while reading this report. Unlike other IQPs this report is our deliverable. Unlike other IQPs we are not hoping someone will use our results or that a follow-up will occur, our sponsors already plan on continuing our work after our final submission and have already contracted a revisit to this project years after it is submitted. This has effected the way in which we approached our project and documented our results.

This report is not solely ours, we have been asked by the United States Coast Guard (USCG), to start a comprehensive study that will be completed by Volpe Research Center in Cambridge Massachusetts (A U.S. Department of Transportation facility). In order to better aid in the transition of our report and the co-authoring of the project our team met with the researchers in Cambridge and agreed on how to divide the responsibility for developing different sections of the final report, have regular conference calls, and most importantly, write our sections of the report in the format of the expected final report, in order for Volpe to easily add onto and edit our report and to revisit the topic in future years. You may wonder how this will affect your reading of our report, and this is a very important question.

This report is not structured in the standard intro, methods, results, you might expect from a classic WPI IQP, this is a reference paper organized by topic. The flow of this paper may at first seem foreign and maybe even redundant, but we assure you this is not an oversight but by design. The audience this paper is meant for are looking for specific answers and are not likely intending to read our entire paper. Someone from the USCG engineering department that wants to know about a specific regulation has no desire to read about environmental concerns. For this reason each major subsection is stand-alone, meaning that it can be read independently of the rest of the paper.

The final question you might have is: "What about results?" One of the defining characteristics of an IQP is that it is expect that a project team will process collected data into results and recommendations. While this was not the primary objective of USCG it was important to us. To meet the spirit of an IQP in full we added a results appendix, in which raw data from interviews is presented and the themes and conclusions we draw are listed. In this way we were able to identify interesting gaps in opinion and suggested to Volpe that they follow-up on the knowledge, regulation, technology and other gaps we identified. We thank you for taking interest in our work and hope that this helps you to more fully appreciate and understand the material presented here.

Happy Readings,  
Ryan, John, and Savannah (2017)

# I. Introduction and Background

Recent international regulations restricting marine pollution have had a significant impact in the maritime community. The following section discusses what pollutants are being restricted, the reason for the regulations, and what ship owners can do to comply.

## I.1 Regulatory Triggers

Since 1992, 171 countries have united to create regulations to address climate change problems linked to anthropogenic carbon emissions and the release of industrial chemicals. Marine Pollution (MARPOL) Annex VI is the most recent of these regulations and was triggered by a rising social awareness of the negative effects of marine shipping exhaust pollutants, primarily Sulfur Oxides (SO<sub>x</sub>), Nitrogen Oxides (NO<sub>x</sub>), and Particulate Matter (PM). Sulfur aerosols (SO<sub>2</sub> primarily) have an impact on global and regional climate, ecosystems, agriculture, and human health (Smith, et al., 2011). SO<sub>x</sub>, PM, and NO<sub>x</sub> also lead to problems with the respiratory system, eyes, and heart and the health effects can be fatal. In fact, according to Corbett and colleagues' (2007), the mortality related to ship emissions is estimated to be 60,000 deaths annually. Relative to PM, Figure 1 shows the deaths specifically attributed to PM<sub>2.5</sub> (PM smaller than 2.5 micrometers). What is particularly interesting about this figure and relevant to international maritime shipping is that the deaths due to PM are concentrated in areas that have high concentrations of maritime shipping traffic, especially along the coasts of the eastern United States, China, India and North West Europe.

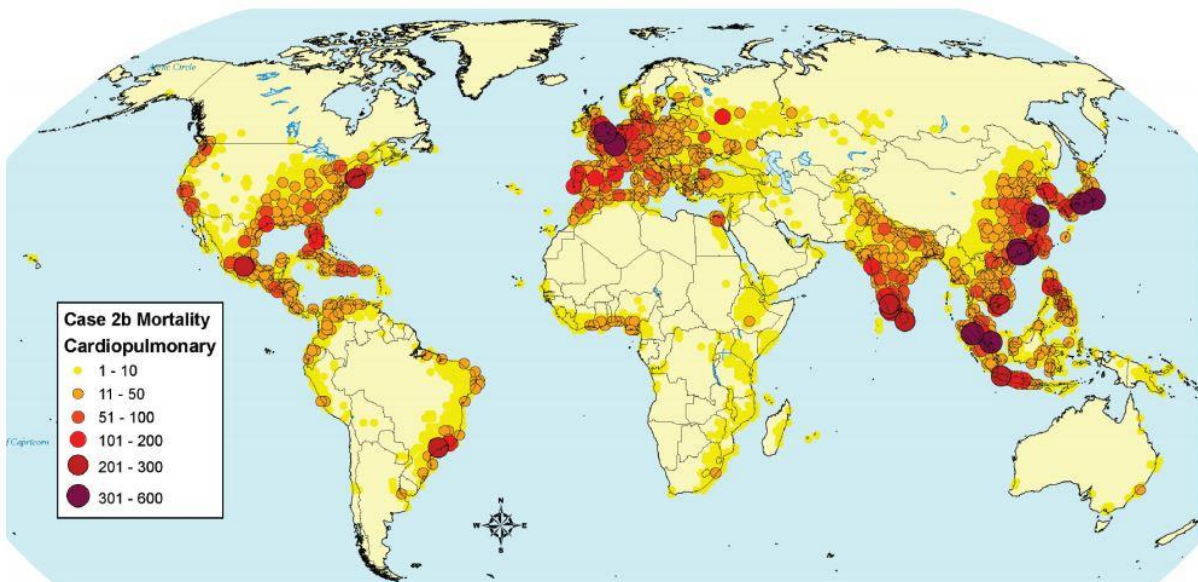


Figure 1: Number of Cardiopulmonary Deaths (Corbet et al. 2007)

To emphasize this point that International maritime shipping is a primary contributor to SO<sub>x</sub> and NO<sub>x</sub> pollutants (Chatterjee and Pratap, 2015), Brunila et al (2015) state that marine shipping contributes nearly 96% of the transportation sector's total SO<sub>x</sub> emissions and is responsible for 50% of all NO<sub>x</sub>

emissions (115, Brunila, Kunnaala-Hyrkki, & Hämäläinen, 2015). Furthermore a study of air pollution on maritime vessels concluded that these vessels emitted approximately 25 million tons of NO<sub>x</sub> in 2007, which is 15% of total global anthropogenic emissions (Chatterjee and Pratap, 2015). To add some perspective, the amount of SO<sub>x</sub> emitted annually from every car in the world is estimated at 88,500 tons while the shipping industry emits 20 million tons of SO<sub>x</sub> annually (Winkler, 2009)

Although global emissions<sup>1</sup> decreased between 1970 and 2000 [the EPA states that NO<sub>x</sub> decreased by 50% and SO<sub>x</sub> by 80%] the rise of commercial China and the expansion of international shipping has resulted in an increase in global emissions since the turn of the century (Smith, et al., 2011; Chatterjee and Pratap, 2015). According to the EPA, if pollutants emitted by maritime vessels are not regulated, current marine NO<sub>x</sub> emissions are expected to double by 2030 (EPA 2015).

The international community is becoming increasingly aware of the negative effects of emissions, knowing the primary source, and knowing the predicted increase within the next 20 years. This new awareness has resulted a movement to reduce the more common and harmful emissions through new international regulation. Currently international regulations set a minimum of 3.5% sulfur content by mass for global fuel. North America and the Baltic Sea have enacted stricter regulations limiting sulfur content to 0.1% of fuel's mass. In the year 2020, however the global standard for fuel will drop to 0.5% sulfur content by mass (IMO 2011).

## 1.2 Primary Pollutants

The three primary pollutants that are addressed in the MARPOL Annex VI regulations are SO<sub>x</sub>, NO<sub>x</sub>, and PM. The following sections describe SO<sub>x</sub>, NO<sub>x</sub>, and PM respectively.

### 1.2.1 SO<sub>x</sub>

SO<sub>x</sub> is one of the primary pollutants that is causing adverse health effects on a global scale. It originates from the sulfur compounds found in marine fuels, as well as other fuels and oils. When the fuel is burned, the exhaust containing the sulfur oxides is released into the atmosphere and reacts with other compounds to form both sulfuric acid and secondary inorganic aerosol gases (Anish, 2011).

The SO<sub>x</sub> that is released into the atmosphere reacts with the atmospheric oxygen and creates sulfuric acid which is then absorbed in clouds and rains down back onto earth's surface as acidic rain and can cause damage to buildings, and infrastructure. Additionally by disrupting the normal pH cycle acid rain can damage sensitive forest soils and watersheds (EPA 2012). SO<sub>x</sub> released into the atmosphere also results in inorganic aerosol gases, which are a type of PM (discussed in section 1.2.3) (EPA, 2015).

In addition to damaging ecosystems and infrastructure SO<sub>x</sub> can have adverse effects on the health of humans, leading to many forms of respiratory irritation, including, but not limited to increased asthma symptoms and bronchoconstriction. The impact of SO<sub>x</sub> on health is increased for children, the elderly, and people suffering from asthma especially during an increased ventilation rate (e.g during exercise). The EPA has reported that when the concentration of SO<sub>x</sub> in the atmosphere increases there is

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<sup>1</sup> For the purposes of this report the term "emissions" will refer to exhaust pollutants (SO<sub>x</sub>, NO<sub>x</sub>, and PM<sub>2.5</sub> in particular)

a corresponding increase in the number of respiratory related hospital visits (EPA, Sulfur Dioxide Health, 2015).

### **1.2.2 NO<sub>x</sub>**

NO<sub>x</sub> refers to a family of seven compounds with the most prevalent being nitrogen dioxide which is generated during the burning of marine fuels (EPA 1999). When released in to the atmosphere, NO<sub>x</sub> can react with carbon and other organic compounds to form ozone, acid rain, and PM<sub>2.5</sub>. The creation of ozone leads to smog and deteriorated visibility along the horizon. Acid rain, as discussed in section 1.2.1 has negative effects on the ecosystem and PM<sub>2.5</sub> emissions result in several health complications as discussed in the following section.

### **1.2.3 PM**

PM is composed of a range of different solid and liquid particles that are released into the atmosphere as a byproduct of fuel burning, and can form in the atmosphere as a result of NO<sub>x</sub> and SO<sub>x</sub> emissions. PM is composed of any type of compound: acids, organic, metals, and general dust (EPA 2015). Particles with a diameter under the size of 10 micrometers but over 2.5 micrometers are considered “inhalable coarse particles” (EPA 2015) and particles under a diameter of 2.5 micrometers are considered “fine particles” (EPA 2015). Figure 2 below compares the size of PM<sub>2.5</sub> and PM<sub>10</sub> with human hair and grains of sand. Both PM<sub>2.5</sub> and PM<sub>10</sub> have the ability to enter deep in your lungs and your blood stream, the EPA links the size of the particles to the severity of their health effects. The health effects of PM include: heart attacks, irregular heartbeat, asthma, decreased lung function, other respiratory problems, cancer, and cause reproductive and developmental harm (EPA 2015). Supporting this claim a study by Lepulle et. al. (2012) has claimed that the reduction of PM in the air can add up to four months onto the average life expectancy and if the annual levels of particle pollution were reduced by 1 µg/m<sup>3</sup>, over 34,000 premature deaths could be prevented (Lepulle, J; Laden, F; Dockert, D; Schwartz, J; 2012).

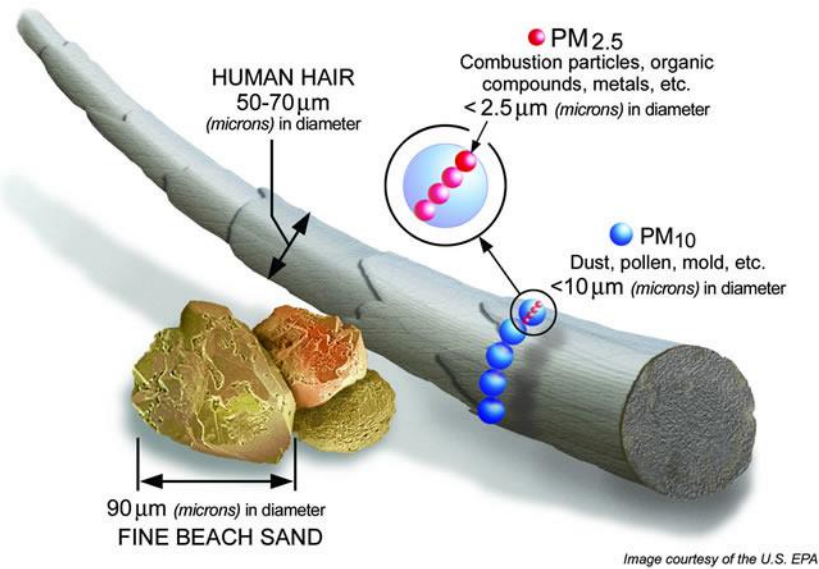


Figure 2: Size Comparison of PM 2.5 and PM 10 (EPA, 2015)

### 1.3 Regulation to Control and Reduce Maritime Emissions

The United States is governed by two primary regulation sources: the International Maritime Organization (IMO) and the United States Environmental Protection Agency (EPA). The IMO passes regulations for the international community, setting a minimum requirement. The EPA takes these regulations into consideration and passes their own more stringent ones. The following sections briefly explain both organizations and the regulations they have passed concerning maritime emissions.

#### 1.3.1 International Maritime Organization and Marine Pollution

The main organization addressing emissions is the International Maritime Organization (IMO), a United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine pollution by ships (IMO, 2015). IMO is made up of 171 member states and is the primary agency with the responsibility of drafting laws relating to international maritime affairs.

In 1973, the IMO passed a resolution known as Marine Pollution 1973/ 1978, (MARPOL 73/78) (Lin, Lin 2005). MARPOL 73/78 was the first of its kind, setting forth conventions and regulations regarding the emissions of commercial shipping vessels, since being passed the resolution has been amended numerous times (Lin, Lin, 2005). The most recent amendment to MARPOL called Annex VI was enacted in 2010, this amendment focuses on reducing both SO<sub>x</sub> and NO<sub>x</sub> emissions in maritime vessels.

#### 1.3.2 Current Regulations of NO<sub>x</sub>

MARPOL Annex VI implemented new regulations to reduce the emission of NO<sub>x</sub>. MARPOL has been increasing NO<sub>x</sub> regulations progressively through tiers, as shown in Table 1, the first tier was

implemented in 2000. Since 2000 MARPOL has implemented two more reductions known as tier 2 and tier 3. After each tier is implemented, ships must produce less than the specified amount of NO<sub>x</sub> emissions measured in grams per Kilo Watt Hours. The amount a ship is allowed to produce is dependent also on the horsepower the engine is capable of producing. These requirements of reducing NO<sub>x</sub> also reduce the amount of PM<sub>2.5</sub> due to the fact that NO<sub>x</sub> is a main contributor to forming PM<sub>2.5</sub> (Authority, 2012).

**Table 1: MARPOL Annex VI NO<sub>x</sub> Emission Limits. Reprinted from International: IMO Marine Engine Regulations (2011)**

Tier	Date	NO <sub>x</sub> Limit, g/kWh		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17.0	45 · n <sup>-0.2</sup>	9.8
Tier II	2011	14.4	44 · n <sup>-0.23</sup>	7.7
Tier III	2016†	3.4	9 · n <sup>-0.2</sup>	1.96

† In NO<sub>x</sub> Emission Control Areas (Tier II standards apply outside ECAs).

### I.3.3 Current Regulations of SO<sub>x</sub>

MARPOL Annex VI has established new regulations for reducing the concentration of sulfur in marine fuel, which reduces the amount of SO<sub>x</sub> in emissions. This regulation has multiple steps as shown below in Table 2. Annex VI's most recent amendment was enacted in 2010 which has put in place the next regulations for the reduction of sulfur in fuel. The next regulation is set to be enacted globally in 2020, with the sulfur limit in fuel being limited to 0.5% by mass (Chatterjee and Pratap, 2015). However, the regulation set for 2020 is dependent upon the availability of fuel with this low of a sulfur content. In June 2017 the Marine Environment Protection Committee (MEPC), a subset committee of the IMO, will have a meeting assessing this availability. If the meeting concludes that 0.5% sulfur content fuel is not widely available as a compliance option then the MEPC can make a recommendation in 2018 to the IMO to raise the maximum content limit for the new regulation.

**Table 2: MARPOL Annex VI Fuel SO<sub>x</sub> Limits. Reprinted from International: IMO Marine Engine Regulations (2011)**

Date	Sulfur Limit in Fuel (% m/m)	
	SO <sub>x</sub> ECA	Global
2000	1.5%	4.5%
2010.07	1.0%	
2012		3.5%
2015	0.1%	
2020 <sup>a</sup>		0.5%

a - alternative date is 2025, to be decided by a review in 2018



## I.4 North American Emissions Control Area (ECA)

The EPA has claimed that new regulations were not enough for Americans and thus the IMO allowed for the creation of a zone around North America, known as the North American ECA that would have stricter restrictions than the worldwide regulations. The restrictions placed on the North American ECA will increase the current IMO restrictions for NO<sub>x</sub> by an additional 23 percent, PM<sub>2.5</sub> by an additional 74 percent and SO<sub>x</sub> by an additional 86 percent. These stricter regulations first became enforceable in August of 2012 (EPA, 2010).

This region includes both the Atlantic and Pacific coasts starting in Canadian waters and includes almost all of the water along the American Coast as shown in Figure 3. The United States Coast Guard has been tasked with the responsibility of enforcing these emissions laws within this given area.

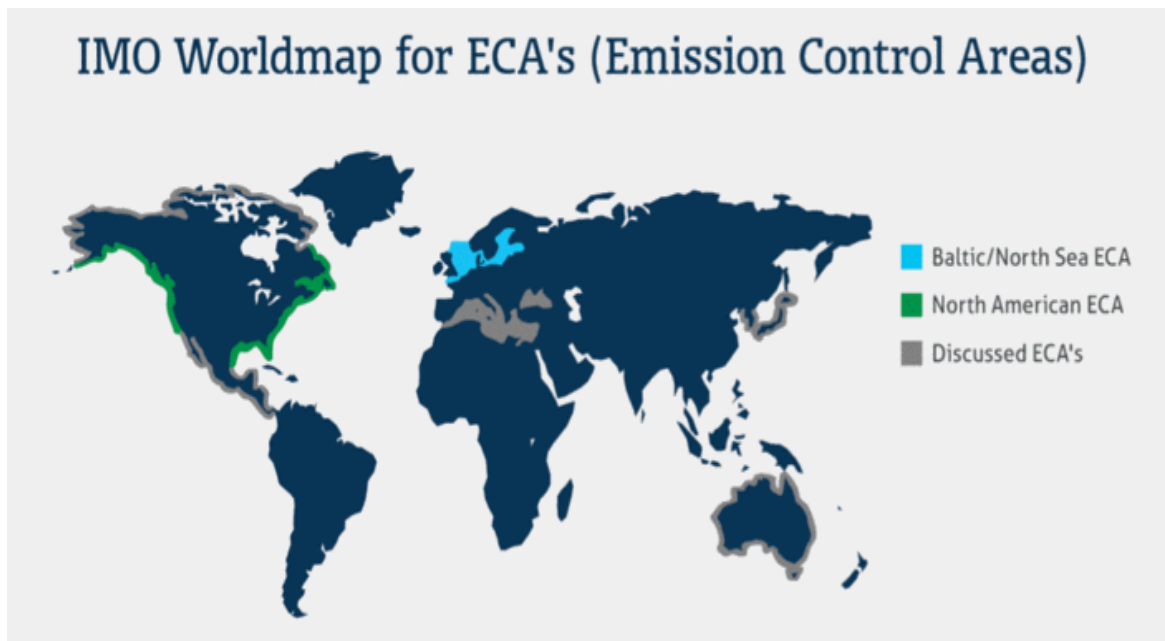


Figure 3: Emission Control Areas of Northern Europe and North America (Maritime Cyprus Admin, 2014)

### I.4.1 Enforcement Trends in the ECA

The United States Coast Guard's enforcement of MARPOL Annex VI regulations within the ECA has caught the attention to the international community. While the EPA argues that stringent regulations and strict enforcement are critical for Americans others find the US measures excessive. "United States: Current Trends In MARPOL Enforcement— Higher Fines, More Jail Time, The Banning Of Ships, And Whistleblowers Galore" is a 2011 news article addressing the enforcement in the North American ECA. The authors attacked US policy rather aggressively stating:

"The United States does not appear to make any enforcement distinction between cases that involve serious pollution problems and those that represent isolated, comparatively minor deficiencies. Similarly, the United States seems unable or unwilling to differentiate between vessel owners and operators who have made good faith efforts to achieve MARPOL compliance within their fleets, and those companies that



ignore their compliance responsibilities.”

While rather opinionated this article does reflect how many view the US policy. The punishments and techniques for the Act to Prevent Pollution From Ships (APPS), MARPOL, and the clean air act are rather unique. One such unique policy allows whistle blowers to be paid up to 50% of the penalty for the APPS violation they reported (Grasso and Linsin, 2011). Grass and Linsin point out that while this reward does increase the amount of violations reported, it also encourages employees to not fix problems. Rather than fixing the problem, employees will record them for months to collect more evidence causing the company to be fined more, thus increasing their own reward.

## **1.5 Compliance Options**

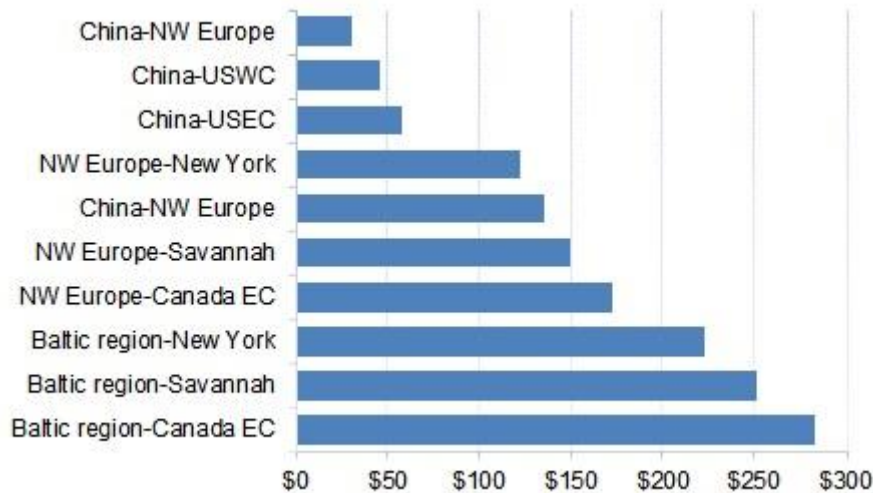
To comply with the new regulations on SO<sub>x</sub> and NO<sub>x</sub>, marine vessels have several different options. Exhaust Gas Cleaning Systems (EGCS) are the form of compliance that this report primarily focuses on (beginning in section 2). Aside from EGCS there are two primary methods for compliance. The first is ultra-low sulfur fuel and the second is liquefied natural gas (LNG). There is also a third possible, but less common, solution known as Non-Thermal Plasma (NTP). All three of these options are detailed in this section.

### **1.5.1 Ultra-low Sulfur Fuel**

Complying with the regulations using ultra-low sulfur fuel is referred to as a primary compliance method, because currently it is the most universally recommended option. Not only is this method the simplest but it requires no delay in compliance. Ultra-low sulfur fuel has two types; marine diesel oil (MDO) and marine gas oil (MGO). MDO has 1.0% sulfur by weight, and MGO has 0.1% sulfur per weight (Caiazza, Giuseppe, Langella, Miccio, Francesco, Scala, Fabrizio, 2013). Ultra-low sulfur fuels are expensive. Chevron claims that ultra-low sulfur fuel costs significantly more than heavy diesel oil, because of the extra treatment it takes to remove the sulfur (as cited in Kilcarr, 2004). This extra treatment process, takes energy and time.

In addition to the more expensive fuel costs, ECAs will include a surcharge for the use of these new fuel types. These new charges (detailed in Figure 4) can range anywhere from \$25 to \$275 depending on the shipping route (MarEX. 2014). A study by the University of Antwerp in Belgium claims that the cost of a single one-way trip would be increase by 25.5% if the ship is going an average speed, and closer to 30% if the ship is moving above the average speed (Notteboom, Delhaye, Vanherle, 2010). These added costs place further financial burden on shipping companies and consumers alike.

In addition to the surcharge, marine gas oil decreases engine speed and requires additional maintenance increasing the cost even more (Brunial, Kunnaala-Kyrkki, and Hämäläinen, 2015). Older ships have trouble using the ultra-low sulfur fuel because of the lower energy content of the fuel. This lower energy content cause issues with load or rapid speed changes. Another issue that older engines are not deigned to run with low viscosity fuel and ultra-low sulfur fuel, having such a low viscosity causes leaks in the engine (ABS, 9 - 11).



**Figure 4: Average Low-Sulfur Fuel Surcharges, Applicable from 1 January 2015 (US\$/40ft container) Drewry Maritime Research ([www.drewry.co.uk](http://www.drewry.co.uk)) as cited in (MarEx, 2014)**

The Trans-European Transportation Network (TEN-T) summarizes MGO implementation in a single paragraph.

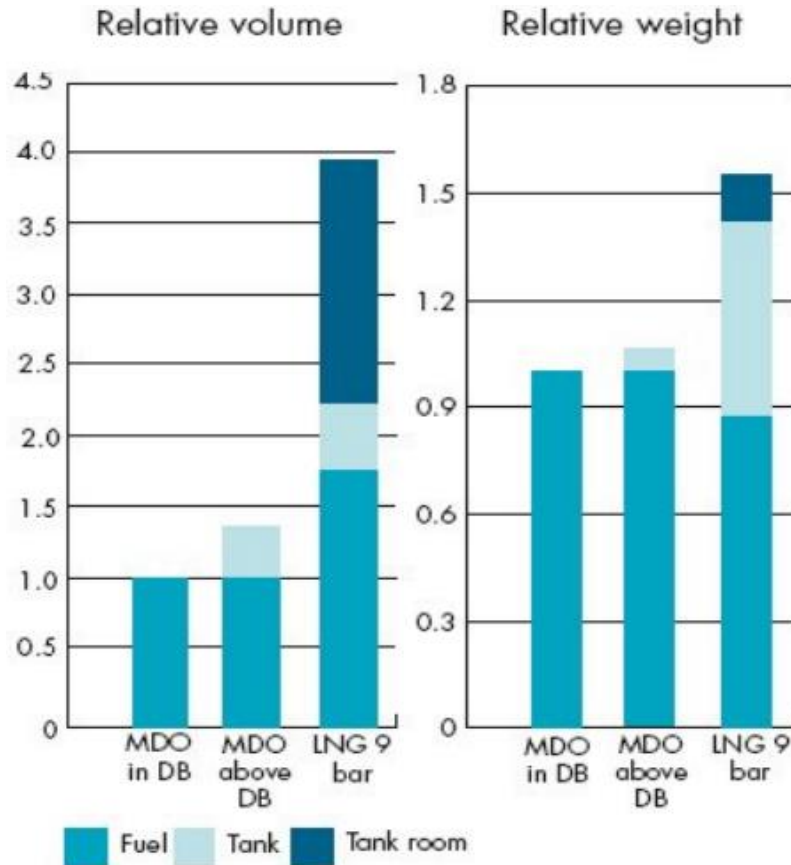
Marine Gas Oil with 0.1 % sulphur or less is readily available and share about the same properties as the diesel fuel used for high speed diesel engines. Using MGO gives low sulphur emissions matching the SECA demands. MGO does not require extra volume for storage tanks, and adjusting the engine to MGO causes in most cases only small investments costs. However, MGO fuel prices are higher than the other fuels.

Although no physical modifications to the engine are needed for ultra-low sulfur fuels, the corresponding investments of surcharges, decreased speed, and increased maintenance make these fuels a less attractive option. Also, the marine gas oil, which reduced the sulfur by 90% and PM<sub>2.5</sub> by 38%, still did not affect nitrogen oxide (Jiang, Kronbak, & Christensen, 2014). Without a reduction in NO<sub>x</sub> this fuel would still need to be supplemented with additional technology to be in compliance with new laws.

## 1.5.2 Liquefied Natural Gas

Liquefied Natural Gas (LNG) provides another possible method to comply with MARPOL Annex VI regulations. The benefit of LNG is that it reduces SO<sub>x</sub> by almost 100% and NO<sub>x</sub> by 85%, compared to ultra-low sulfur fuel, which only reduces SO<sub>x</sub> emissions by 70%-85% (Corbett, James J; Winebrake, James, 2008, 540) and does not affect NO<sub>x</sub> (EPA 2015). LNG is half the price of diesel fuels and the Department of Energy predicts that LNG could be nearly a quarter of the price of crude oil by 2035. The disadvantages of using LNG are that it has half the energy content per unit volume compared to diesel fuel, requiring twice the amount of fuel for the same amount of power output. As a comparison, it takes 13 gallons of LNG to reach an output of one million BTU, but it only takes 6.7 gallons of MGO to reach the same one million BTU output (American Clear Skies Foundation, 2012). More fuel means additional

tanks and insulation for ships switching to this fuel. This would increase the volume of the fuel compartment by 230%, as shown in figure 5 (Bagniewski 2010). In addition, LNG ignites at a much higher temperature meaning that ships would need to have completely new ignition systems installed in their engines or find a way to inject lit diesel fuel into the LNG to get the same results. The only way to implement LNG systems into current ships would be to rebuild them (Bagniewski, 2010).



**Figure 5: Average Fuel Compartment Volume Reprinted from “LNG fuel for ships. A chance or a must?,” by Michal Bagniewski, DNV( Det Norsky Veritas), 4.**

A report from the TEN-T describes the advantages and disadvantages of LNG. The advantages for LNG are: it will resolve all emission issues with NO<sub>x</sub>, SO<sub>x</sub>, and PM, currently costs are competitive, and they allow for dual fuel. Dual fuel means the ship would run on LNG while in ECAs and be able to switch to less expensive high emission fuel as soon as they were no longer within a regulated area, thus saving money. The disadvantages are that “due to its low temperature, LNG has to be stored in cryogenic tanks, which require much more space than traditional fuel oil tanks.” These essential engine modifications make LNG an option but not the immediate choice. If more and more vessels choose this as an option, the question now comes to the supply of LNG. It is extremely difficult to determine how an increase in demand will affect the prices of LNG. An increased demand for LNG could result in an increase of infrastructure, and lower the price of LNG; however, the opposite could occur demand could grow faster than infrastructure can handle and the prices could rise. The study shows three separate

ways that fuel prices could change in one scenario payback for EGCS is half the time of LNG, one scenario they are equal, and the third LNG is paid of faster than EGCS (Authority, et al. 2012).

Despite the complications with retrofitting current ships with LNG technology one company is still attempting to implement LNG technology as their method of compliance. Nova Star sent a permit request to USCG requesting an extension on their compliance date for MARPOL Annex IV. Nova Star intends to put two dual fuel engines on one of their ships. They request the extensions specifically “for developing and evaluating the potential use of LNG engines as an advanced sulfur emissions control technology” (Nova Star, 2015). While Nova Star states their intention to use LNG technology in their own permit request they point out the necessary technology is neither developed nor evaluated.

### **I.5.3 Non-Thermal Plasma**

Non-Thermal Plasma systems (NTP) are unique because unlike other systems that reduce emissions through chemical reactions NTP complies through molecular excitation (Lloyd’s Register Marine, 2015). When molecules are heated to an extremely high temperature they enter the plasma state, at this point the electrons “become excited and increase velocity to a point [that] they leave their orbits and fly out of the molecule’s influence” (EPA, 2005). This effect not only occurs in the presence of intense heat, but also when molecules are introduced to a strong electric field, this is called Non-thermal plasma. While plasma has long been studied (it was discovered over 150 years ago) it was not considered for air pollution applications until the early 2000s. Dec. 14<sup>th</sup> 2000 the EPA proposed regulations to have coal and oil plants regulate their mercury (Hg) emissions by Dec. 15 2003. At the time there was no means of removing HgO (mercury oxide) from the exhaust, this spurred the research into using NTP to break the bonds between the mercury and the oxygen. From 1998 till 2001 26.2 million dollars were put into researching NTP (funded by DOE, Ohio Coal Development office, and FirstEnergy). This funding allowed for a demonstration of the effects of NTP. The Destruction and Removal Efficiency (DRE) of Sulfur Dioxide was 98%, NO<sub>x</sub> was 90%, Total Particulate Matter 99.9%, PM<sub>2.5</sub> 95%, and Mercury 80-90%. (EPA, 2005). When testing the DRE of HgO it was learned that NTP effectively breaks down all oxides. While there is no doubt that NTP would meet every regulation, the installing of a high voltage apparatus (or ionizing beam lasers) can be incredibly difficult, expensive, demands high amounts of energy, and could take up a great deal of space (Lloyd’s Register Marine, 2015). This in addition to the fact that the market is very small and some parts would likely only be produced by a single company and thus be a risk in case the supplier stops producing a part (EPA, 2005).

## 2. EGCS Overview

Exhaust Gas Cleaning Systems (EGCS)s are a secondary form of compliance to MARPOL Annex VI and are being implemented throughout the Maritime industry (particularly North America), because they are generally considered to be cheaper than burning compliance fuel. This section provides an overview of the three primary types of EGCS.

### 2.1 EGCS Systems

The EPA has recommended the use of Exhaust Gas Cleaning Systems (EGCS) to comply with emission regulations. The development and implementation of industrial EGCS began with inventor, Walter Wisting. Wisting filed the first patent for an EGCS in 1965. His patent describes the EGCS like this.

This invention relates to air treating apparatus and more particularly relates to apparatus for acting upon air or a gas to remove contaminants therefrom and to exchange heat therewith....The present invention provides a new and improved air washer which also washes or scrubs air by passing the air to be washed or scrubbed through liquid spray zones” (Wisting 1967).

When The Clean Air Act of 1970, which established national emissions standards, and placed restrictions on stationary and mobile sources of emission pollution, came into effect EGCSs became more prevalent. This increase in oversight and enforcement of emission pollution resulted in many companies, organizations, and even individuals researching and developing new and more effective technologies for pollution reduction, including Wisting’s EGCS invention. The first prototype of an EGCS was installed in 1991 and comprehensive studies have been concluded since. Recently EGCSs have developed from strictly land-based applications to maritime applications. A study was conducted in 2010 on three ships, the *Zaandam*, the *Pride of Kent*, and the *Suula*, where SO<sub>x</sub> EGCS installed. According to the study, these three separate installations showed the viability of integration of EGCS into the maritime environment. As part of the integration the systems were installed in place of an exhaust silencer unit, and function well under marine conditions (EPA, 2011, 2).

The general EGCS works rather simply, it is installed into the exhaust system and the exhaust is pumped through the EGCS. Each EGCS contains numerous chambers and pumps depending on the type of system. Despite being very different all EGCS have, a cleaning chamber, storage tank, and place of discharge. In the cleaning chamber, an alkaline substance is applied to the exhaust gas and a chemical reaction takes place creating a precipitate from the pollutants. The excess alkaline substance along with the newly produced solids are then transferred into a storage tank. The solids settle to the bottom of tank and then the reusable water is separated and treated. Depending on the EGCS type the solids and chemicals are either stored on board or treated a second time and discharged off the ship.

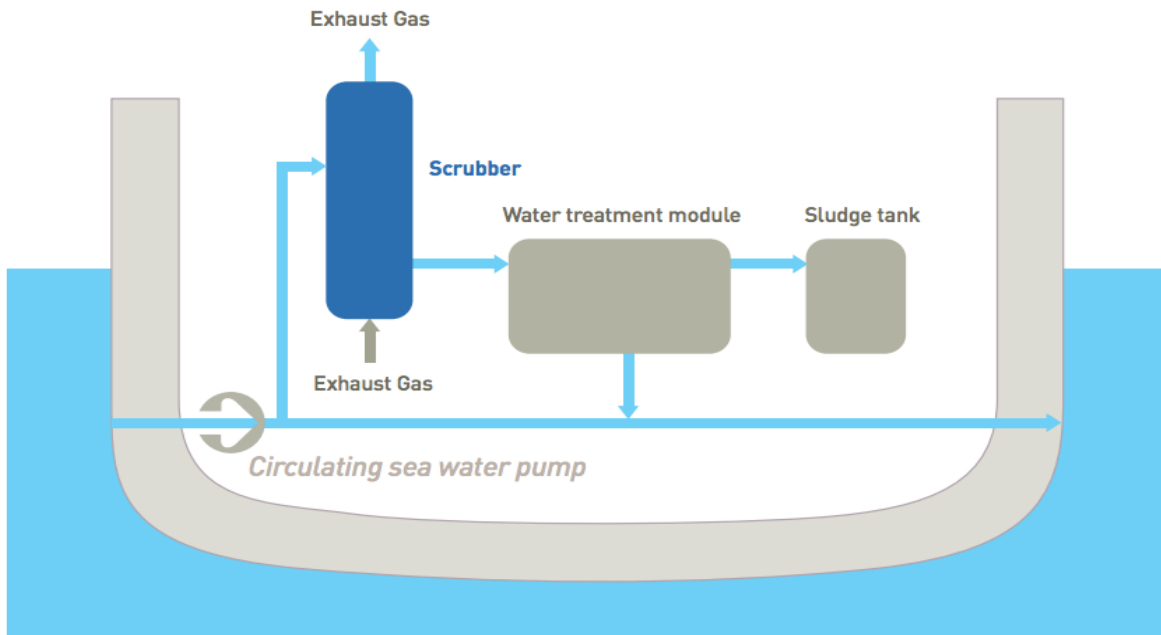
There are three different types of EGCSs: open loop salt-water, closed loop fresh water, and dry (den Boer, E. H., Maarten 't. 2015). Table 3 provides a general summary of these three types of EGCS. If the excess water is mostly recycled, it is referred to as a closed loop system, if it is mostly dumped back into the ocean it is referred to as open loop, and if it removes pollutants through a dry granulate instead

of water, it is considered a dry EGCS.

EGGS manufacturers all claim that the systems have an efficiency of over 97% for sulfur oxide removal (Agranovski, Braddock, Myjojo 1999). Wartsila, an EGCS manufacturing company, has completed studies on their systems showing that the SO<sub>x</sub> emissions, post cleaning, were essentially zero at below measurable values (Wartsila, 2010, 10). The amount of sulfur removed from the exhaust directly relates to the amount of the reagent consumed during the reaction. More details of each EGCS type are provided in sections 2.1.1 through 2.1.3.

### **2.1.1 Open Loop Salt EGCS**

An open loop salt EGCS utilizes seawater's natural alkalinity to neutralize the acidic sulfur in the exhaust gases, resulting in a precipitate. Water is pumped to the EGCS and showered over the exhaust. Depending on the ship's architecture and needs for pollution removal the tanks may be arranged differently or the treatment module may be associated with the engine cooling tanks in a different part of the ship. Figure 6 shows a general diagram of how the open loop system functions. In this diagram, the blue line along the bottom of the vessel's hull is the intake and discharge pump line. The larger blue section above this is the cleaning chamber where the gas is treated one of two ways. One way is to spray the seawater onto the exhaust gas. The second way is to bubble the exhaust through the water. In either case the alkaline calcium bicarbonate naturally found in seawater, reacts with the sulfur in the exhaust, and forms a precipitate of sodium sulfate. The water droplets capture the precipitate and are moved to a treatment chamber or module next to the cleaning chamber. The washwater (the water used to treat the gas) is then separated from the solid and discharged back into the ocean and the solid is stored in a tank for later disposal. The pH of the washwater in the treatment chamber is lower than the original seawater because the reaction leaves an excess of hydrogen ions dissolved in the water. However, because not all of the calcium bicarbonate initially react, the excess reacts with the extra hydrogen ions and the pH becomes closer to neutral (den Boer, 2015, 18). The environmental hazards of this process are discussed in section 3.1 and how these concerns are monitored is discussed in section 4.2.



**Figure 6: Open loop seawater EGCS (Bureau Veritas Marine and Offshore Division, 2014).**

These types of EGCS normally have the highest water flow rate because there is less control over the alkalinity seawater so you need to run more water through to ensure there is enough to react with all the pollutants (as cited in EPA, 2009, 6). The constant uptake and discharge of the seawater allows high volumes to run through the system for maximum efficiency. One advantage of this system it does not need a lot of storage space for the byproduct because seawater is constantly being pumped through the system, treated, and discharged. (Bureau Veritas Marine and Offshore Division, 2014). Based on vendor information, these EGCS systems can be compliant to the .1% sulfur emissions regulation using a maximum 3.5% sulfur fuel. Using this fuel EGCS remove between 70% to 90% of  $PM_{2.5}$ , and 0% to 2.5% of  $NO_x$  from the exhaust gas. It, however, has no effect on  $CO_2$  emissions (Kjølholt, Jesper et al., 2012, 29). A significant issue facing the wet type EGCS is over cooling. If the exhaust is cooled too much during the process then water droplets form inside the exhaust itself and condensation can form on the inside the stack or system. Water droplets and condensation can both create problems with erosion, and even increase the density of the exhaust itself and prevent the exhaust from escaping out the stack (Kjølholt, Jesper; Aakre, Stian; Jørgensen, Carsten; Lauridsen, Jørn; COWI; Parallelvej 2; 2800 Lyngby, 2012, 28).

### **2.1.2 Closed Loop Fresh Water EGCS**

A general closed loop fresh water EGCS, shown in figure 7, involves using freshwater that is stored on the ship. A salt (usually, sodium bicarbonate, ammonia, or caustic soda, shown below as NaOH) is dissolved into the freshwater and then a similar reaction occurs to the open loop EGCS (discussed in section 2.1.1). The now alkaline freshwater is sprayed over the gas or the gas is bubbled through the water. The reaction takes the sodium bicarbonate and reacts with sulfur gas, water, and oxygen to form sodium sulfate and water. Then these byproducts are put into a holding tank or treatment module, as seen in figure 7, where a suction process and then some type of treatment occurs. The treatment of either via a hydro or multi cyclone, coagulation or flocculation, separates the

precipitate and the water (den Boer, 2015, 18). The hydro or multi-cyclone uses centrifugal force to separate larger particles from the water (EPA, 2011, 9). Coagulation is a process where the washwater is subjected to a strong electrical field to electrically precipitate metals and other contaminants (GPI 2015). Flocculation is the gentle stirring or agitation of the washwater to encourage particles to mass together for easier removal (Mazille, Falicien; Spuhler, Dorothee, 2012). After the separation is complete, the washwater is sent back into the buffer tank, as seen in figure 7, to be treated and used again.

As with the open loop system the diagram below only shows one possible configuration. This diagram shows the washwater being discharged overboard and a heat exchanger being used between the seawater and the freshwater. The exchanger is not a necessary part of the system and in other systems, the salt added into the buffer tank allowing the new freshwater to be treated at the same time as the recycled.

This system, according to vendors consistently removes more pollutants than the open loop system. It can remove more pollutants because there is control over the alkalinity. It can become compliant with ECA regulations using up to 5% sulfur content fuel, which is 1.5% higher than open loop. Using this high sulfur fuel is cheaper, however the treatment cost more do to the need to use more chemicals during the treatment process. Additionally, this system removes other pollutants as well. It removes 65% to 90% of  $PM_{2.5}$ , and 5% of  $NO_x$  from the exhaust. It does not usually affect  $CO_2$  emissions, but it can, depending on the amount of the salt used in pre-treating the water (Kjølholt, Jesper et al., 2012, 29).

This system is more complex due to the requirement of pre and post treating the freshwater during the process, is more costly to run and maintain, and uses a finite amount of water creating a higher concentration of hazardous chemicals in the water. Although there is some bleed off into the ocean this system does not present as much of an environmental concern as open loop systems, because a majority of the washwater is treated and recycled back through the system instead of being discharged back into the environment (den Boer, 2015, 18).



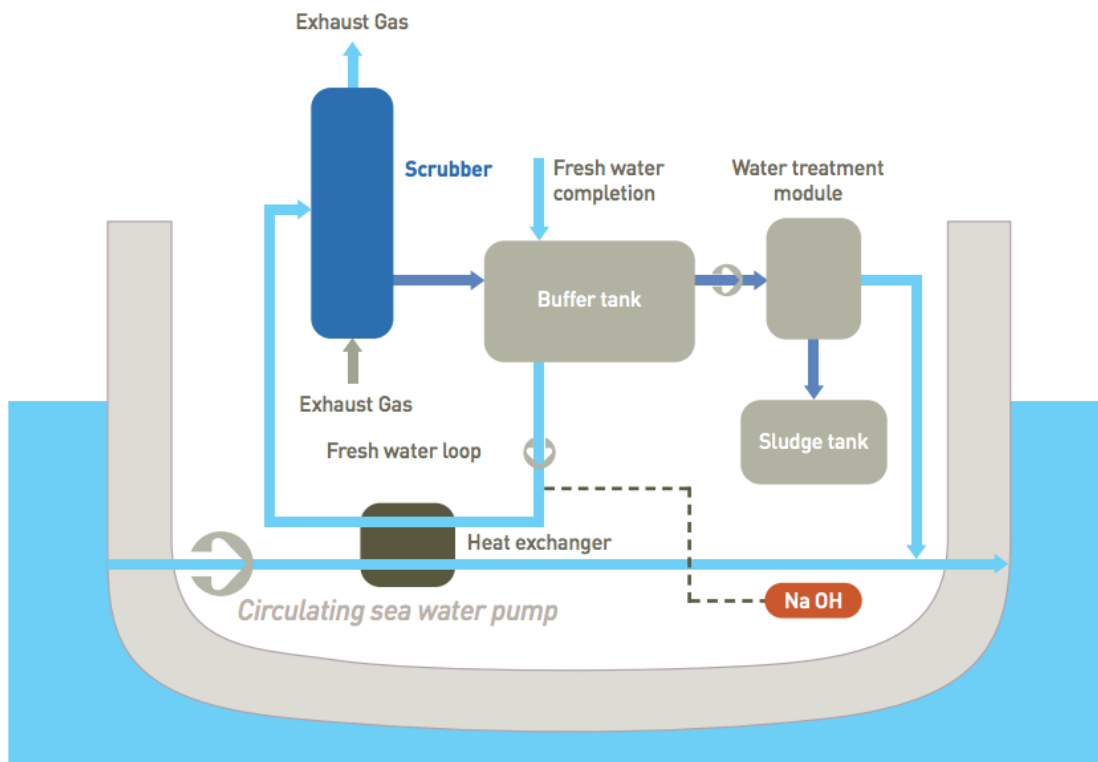


Figure 7: Closed loop fresh water EGCS (Bureau Veritas Marine and Offshore Division, 2014).

### 2.1.3 Dry Calcium Granulate EGCS

The dry calcium granulate EGCS, shown in figure 8, follows the same chemical reaction concept as the other two types. A burnt or hydrated lime or calcium carbonate ( $\text{CaCO}_3$ ) mixes with the exhaust at the reagent injection point as seen in figure 8 and creates calcium sulfite. The calcium sulfite in pellet, or gel form reacts with the oxygen from the air to form calcium sulfate dehydrate, more commonly known as gypsum (den Boer, 2015, 18). The diagram below does not show a storage tank or a place for gypsum to be collected, in the case where it is collected it is usually.

This system has been reported by vendors to remove up to 99% of  $\text{SO}_x$  from the exhaust, and can handle up to 4.5% sulfur fuel content and still achieve the regulation of .1%  $\text{SO}_x$  emissions. This system is able to remove up to 80% of  $\text{PM}_{10}$ , due to the fact that the granulate acts as a physical filter (Kjølholt, Jesper et al., 2012, 43).

One of the benefits of this system is that the alkaline reagent can be recycled and reused in the EGCS many times before it is spent. The reagents are also very cheap and readily available, making the operation costs much lower. It also does not use water so there are less energy costs associated with it.

The gypsum byproduct produced has commercial value, because it can be used in many building materials, more importantly this is the only EGCS type that does not result in a hazardous byproduct. There are tests for quality and other hazardous materials, however this method of scrubbing is the least tested and has only been implemented sparingly (den Boer, 2015, 18).

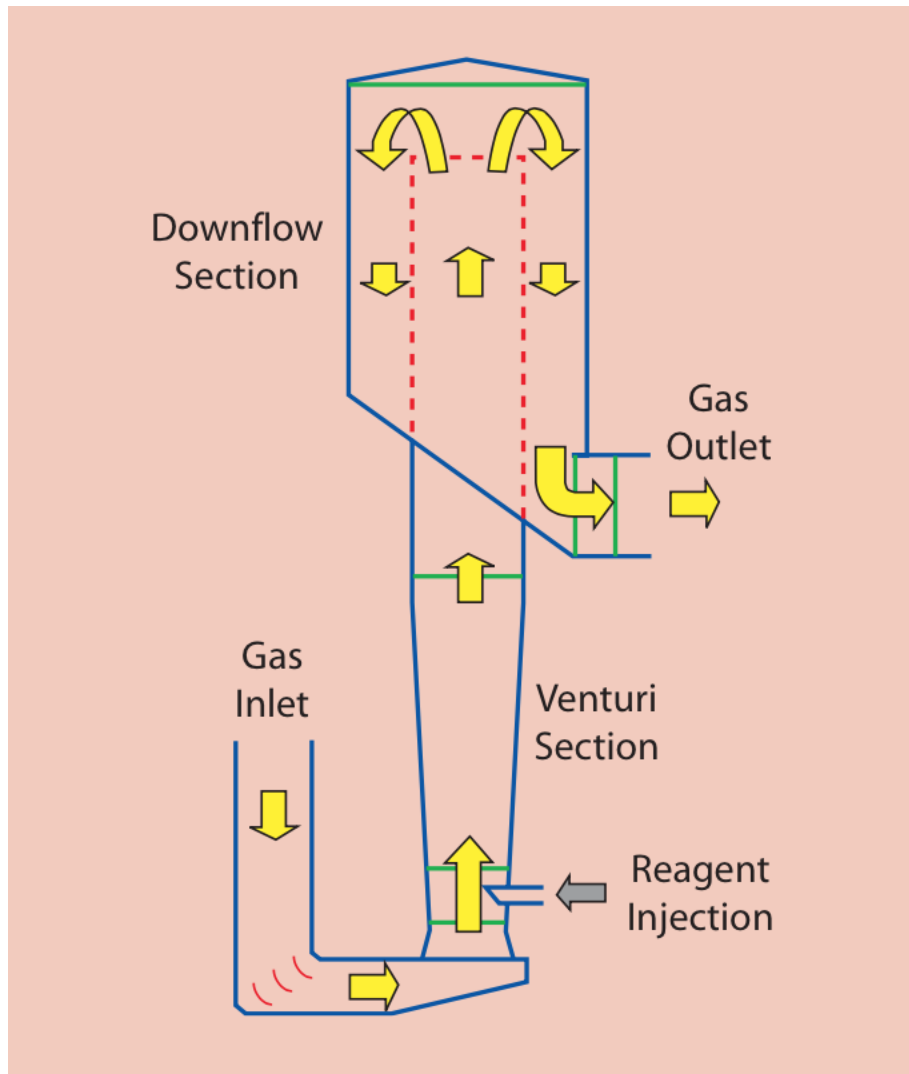


Figure 8: Dry EGCS (Keppel Seghers, 2006)

**Table 3: Comparison of EGCS Types**

EGCS Types	Method of Removal	Resultant	Important Notes
Open Loop (Wet)	Sprays salt water over the exhaust	Acidic sea-water with a sulfate precipitate (washwater)	Washwater is often not cleaned before being returned to the ocean so many ports have made this system illegal
Closed Loop (Wet)	Sprays freshwater treated with sodium bicarbonate over the	Sludge byproduct	Harmful chemicals are stored in high concentration, but released back into environment at low dosage
Calcium Granulate (Dry)	Shower of alkaline chemicals sprayed onto exhaust in a closed system	Turns emissions into a gypsum byproduct	System has undergone limited testing. Gypsum has commercial value.

## 2.2 Verification of Compliance through EGCS

The primary regulation relating to the control and monitoring of emissions on ships is MEPC 184(59) which details the testing, certification, and verification of exhaust gas monitoring systems. The regulations specify the basic operational requirements for any on-board system monitoring. These requirements state the basic on board documentation and records required to show compliance to the system. Scheme A and scheme B divide and outline the options for accreditation and verification of compliance; both require some form of continuous monitoring.

Scheme A states that when the system is initially installed the manufacturer or ship owner needs to be certified with an SECC (SO<sub>x</sub> Emissions Compliance Certificate). This certificate compares the flow rates, sulfur content in the fuel, and the SO<sub>x</sub> emission values outlined in the Technical Manual for the ship with the values the scrubber is rated to handle. The testing of the scrubber can be done prior to or post installation. The comparison needs to illustrate that the range of the ship's output with the scrubber, theoretically or physically, are comparable to if the ship was using 0.1% sulfur content fuel. To make sure that these outputs align, the testing data and the Technical Manual for the ship need to be submitted together. In addition to this testing, a verification process is needed, with periodic testing, to make sure the system is still in compliance. The technical manual must include the verification process for periodic testing that can be done with spot-checking emissions values, or a continuous monitoring system. Included in the verification process outlined in the Technical Manual, testing must be done on: flow rate, water pressure inlet for the EGCS, pressure changes across the system, fuel consumption for the ship and EGCS, and chemical consumption. These parameters are all in place to ensure the EGCS is operating at its maximum efficiency, and that there are no adverse effects to the engine for the benefit of the ship owner, and the MEPC. In addition to all of these values, a process must be outlined in the

Technical Manual in the event the EGCS does not, or ceases to fulfill the requirements necessary. Not only is an onboard Technical Manual required, but also an Onboard Monitoring Manual (OMM) is required to give the details of all the monitoring systems installed. It requires the position, maintenance, and methods of calibration for each system and that the data record is stored securely for a minimum of 18 months and be available for check at any point in time (Lloyd's Register Marine, 2015).

Scheme B states that the scrubbing system does not need to be certified prior to installation, nor does it need to have spot checks for emissions. Scheme B, instead, requires an approved continuous emissions monitoring system that will be subject to periodic checking. The approved system will monitor the ratio of SO<sub>x</sub> to CO<sub>2</sub>, proving the system is in compliance. An OMM for the system ensures the system meets the required calibration and care specifications, and gives the location and details for each sensor. The OMM also requires the data, which includes time, ship location, and emission levels, recorded to be accessible for 18 months to confirm compliance. In addition to an OMM an EGC System Technical Manual is to be approved. This manual outlines: the applicable operating values and limits, a plan of action in the case the system no longer complies with ANNEX VI, and technical details of the engine. Spot checks across the system must be logged daily to verify the system is operating properly (Lloyd's Register Marine, 2015).

## 3. Limitations and Constraints

The systems used for secondary compliance for MARPOL Annex VI have been tested extensively on land, however they have not been tested in a maritime environment. Vessels are different from factories, in many ways they are a mobile source, have less space, dispose byproducts less frequently, and have generally different restrictions and safety concerns. Factories operate in areas where they have designated and safe ways to dispose of waste byproducts, while ships may need to store the waste on board for weeks at a time or discharge the wastes back into the ocean.

Building on land based facilities is much easier than maritime vessels. Adding an exhaust gas cleaning system to a factory is not as difficult as adding one to a marine vessel because the land based factors are more structurally flexible, additions and reinforcements can be made without affecting the structural integrity of the stack or building. Vessels on the other hand are more compact and have to balance in rough waters; any type of alteration needs to be carefully calculated to keep the crew safe. This section covers both the environmental concerns of EGCS by-products, and the engineering constraints with EGCSs.

### 3.1 Environmental Concerns

The main environmental concern raised with the use of EGCS is the byproducts they produce. The two main byproducts of EGCSs are washwater and sludge. Washwater is a byproduct in both open and closed loop EGCSs. Sludge is a byproduct in all different types of EGCSs. The water with the solution that was used to spray the exhaust gas to remove the pollutants is labeled as washwater. Sludge is a part of the wash water that cannot be recycled through the system.

#### 3.1.1 Washwater

The primary byproduct of an EGCS is the washwater that is released back into the ocean or recycled through the system again. The open loop system by design ejects the washwater back into the ocean. The closed EGCS can either bleed off the excess water in the sludge tank back into the ocean, or store the excess water in a holding tank (Kjølholt, Jesper et al., 2012, 27). Regardless of which system at least some washwater is released back into the ocean, this water is treated before discharge with a multi-cyclone, coagulation, or flocculation. The multi-cyclone uses centrifugal force to separate larger particles from the water (EPA, 2011, 9). Coagulation is a process where the washwater is subjected to a strong electrical field to electrically precipitate metals and other contaminants (GPI 2015). Flocculation is the gentle stirring or agitation of the washwater so that particles mass together for easier removal (Mazille, Falicien; Spuhler, Dorothee, 2012). Seawater used to cool the engines is added to the washwater to partially neutralize the pH (As cited in EPA, 2011, 9). Although the water is treated, and partially naturalized, not all of the particles and pollutants are removed the treatment processes are effective for larger particles, but not for all, likewise the pH may be closer to neutral but still will not be exact. The residual chemicals and pH in the washwater are environmental hazards and have caused ports to regulate when and where ships can discharge this water, if they can at all.

Washwater discharged in the desolate open ocean is considered to cause less environmental

damage because the chemicals released will disperse and will not directly affect marine or human life. The concentrations of the metals, and PAH can build-up because there is less water and the tides do not allow this water to be changed out as frequently as needed (den Boer, 2015, 17). A study has shown the negative effects of the acidification of the ocean, while the study does not directly discuss EGCSs it recognizes the effects shipping has on the environment. The study only looked at the total emissions and pollutants currently being emitted from ships. (Hasselov, I-M., D. R. Turner, A. Lauer, and J. J. Corbett, 2013). This does not necessarily show the effects scrubbing washwater has on the environment, however it is important to keep the impact of pH on the ocean in mind since EGCSs directly affect ocean water.

A study done by the Danish EPA in 2012 showed that the levels of pH, sulfur, nitrogen, and solids seawater are not heavily influenced by washwater. Table 4 outlines the chemicals identified in the washwater from an EGCS, using two variations of fuel (1.0% and 2.0% sulfur content by weight) under a maximum (heavy) cargo load, and a minimum (light) cargo load for the ship. As seen in table 4 the concentrations of chemicals do not change drastically after washwater was ejected from the EGCS. (Kjølholt, Jesper et al., 2012). The pH is significantly lower, than the original 7.8 pH level, however this is considered acceptable because after discharge the washwater will dilute in the seawater correcting the pH.

The major concerns, presented by table 4, are the heavy metal concentrations being released into the environment (i.e zinc, nickel, and vanadium) as they do not dissolve and can build up causing harm to biological life. These metals mentioned before come directly from the HFO and are currently removed during the refining process for MGO and MDO will be more commonly removed as the stricter regulations are enacted in 2020. Vessels using EGCS technology use HFO instead of MDO or MGO which is why these chemicals appear in the washwater. The most concerning part of table 4 is the levels of copper and zinc, both copper and zinc are not found in the fuel itself which suggests some other part of the EGCS or ship itself is contaminating the seawater. In addition to table 4, table 5 provide a comparison of chemical concentrations in the fresh, and salt washwater to the Danish Laws on the maximum and acceptable concentration levels, this is significant since the Danish Laws are typically the strictest concerning concentration levels.

**Table 4 EGCS washwater chemical analysis (Kjølholt, Jesper et al., 2012, 53).**

Substance/parameter	Unit	Sea water <sup>1</sup>	Wash water from scrubber (SW-mode) <sup>2</sup>			
			2.2% S, High load	2.2 % S, Low load	1.0 % S, High load	1.0 % S, Low load
<i>Fuel consumption</i>	kg/h	-	3510	1850	3360	1830
<i>General and inorganics</i>						
pH	-	7.8	3.7	5.2	5.5	5.8
Suspended solids (SS)	mg/L	14	14	10	15	12
COD	mg/L	44	52	56	48	46
Sulphur (tot-S)	mg/L	865	900	900	890	870
Nitrogen (tot-N)	mg/L	0.12	0.56	0.34	0.36	0.22
<i>Metals</i>						
Arsenic (as)	µg/L	1.5	<1.0	1.8	<1.0	<1.0
Lead (Pb)	µg/L	<0.20	21	3.6	5.8	3.8
Cadmium (Cd)	µg/L	<0.20	<0.20	<0.20	<0.20	<0.20
Copper (Cu) <sup>3</sup>	µg/L	5.0	260	150	110	150
Mercury (Hg)	µg/L	0.12	0.086	0.092	0.099	0.064
Nickel (Ni)	µg/L	8.9	43	20	19	9.1
Vanadium (V)	µg/L	1.8	180	81	49	25
Zinc (Zn) <sup>3</sup>	µg/L	<2.0 - 8.0	450	150	110	98
<i>Total hydrocarbons (THC)</i>						
Sum, benzene - C35	µg/L	N/A	110	140	330	200
PAH (16 USEPA)	µg/L	N/A	0.96	1.1	1.8	1.6
- hereof naphthalene	µg/L	N/A	0.48	0.51	0.52	0.57
PAH, filtered sample	µg/L	N/A	0.62	0.65	0.78	0.86

N/A = not applicable. All individual components were below the limit of quantification (LOQ), i.e. the content of THC is < 20 µg/L and the sum of PAH < 0.16 µg/L.

<sup>1</sup> Ref. sample. Mean of two samples (taken at day 1 and 2 of the sampling, respectively).

<sup>2</sup> High load = 85-90 % MCR; low load = 40-45 % MCR.

<sup>3</sup> The levels of copper and zinc are much higher than would be expected from the contents in the fuel used. Possibly a contamination source exist, which could possibly be the tap (made of brass or bronze) used for the sampling (despite prior flushing). This hypothesis has not been verified.

**Table 5 EGCS washwater comparison of substance levels (Kjølholt, Jesper et al., 2012, 53).**

Name	SW-washwater Flow-through, HFO 2.2% S with particles* (µg/L)		FW-washwater 2 h circ., HFO 2.2% S without particles (µg/L)	EU EQS / Danish EQS Marine environment (µg/L)**	
	High load	Low load	High load	AA-EQS <sup>1</sup>	MAC-EQS <sup>1</sup>
Sulphur (mg/L)	900	900	9000	-	-
Arsenic (As)	<1.0	1.8	9.8	- / 0.11	- / 1.1
Lead (Pb)	21	3.6	3.8	7.2 / 0.34	na / 2.8
Cadmium (Cd)	<0.20	<0.20	0.094	0.2	0.45 - 1.5
Copper (Cu)	260	150	860	- / 1.0	- / 2
Mercury (Hg)	0.086	0.092	<0.050	0.05	0.07
Nickel (Ni)	43	20	3100	20 / 0.23	- / 6.8
Vanadium (V)	180	81	14000	- / 4.1	- / 57.8
Zinc (Zn)	450	150	420	- / 7.8	- / 8.4
Benzene - C10	<2.0	<2.0	16	8 <sup>2</sup>	50 <sup>2</sup>
C10 - C25	55	52	4400	-	-
C25 - C35	58	88	6600	-	-
Sum, benzene-C35	110	140	11000	-	-
ΣPAH	0.96	1.1	3.8	-	-
Naphthalene	0.48	0.51	0.32	1.2	na

\*Not adjusted for possible background concentration in natural seawater (low for most substances but high for sulfur: 865 mg/L)

\*\*For metals the EQS refers only to the dissolved fraction, not the total content.

<sup>1</sup>AA-EQS = Annual average EQS: MAC-EQS = Maximum allowable concentration EQS

<sup>2</sup>Benzene only.

na = not applicabile (according to EC Directive 2008/105/EC).

In addition to the study done by Danish EPA, USEPA has conducted studies on the three ships installed with EGCS. The three ships, the *Zaandam*, the *Pride of Kent*, and the *Suula* were all a part of a study done on washwater composition and monitoring of pH, turbidity, PAH, metals, sulfides, and nitrites. The results of the study showed that in most cases the washwater pH level would be within the acceptable range. There were two separate instances where it was not, and EPA attributed these to the



buffering content of the water and the lack of dilution prior to discharge. The caveat to these studies is that the EGCS were only installed on auxiliary engines and were not often operating at full capacity. However, it can be inferred that operating at full capacity the EGCS will discharge more washwater with a higher concentration of chemicals, and the effect on pH is uncertain (EPA 2011). The study showed that the pH of the discharge water was well within the limits inside the ship and when the vessel was stationary. EPA also noted that the alkalinity of the water changes depending on the area. They also noted that in brackish or fresh water the amount of water needed to dilute the washwater to an acceptable pH was nearly seven times greater than the amount for saltwater. In addition to this, EPA mentioned that when running in harbors or ports the vessel requires substantial less propulsion power, meaning there is less discharge water in these confined areas (EPA 2011).

### **3.1.2 Sludge**

The washwater is treated, in one of three ways, as noted in section 3.1.1, the non-reusable substance that is collected from this treatment process is referred to as “sludge”. The sludge, mostly composed of oil hydrocarbons, metals, ash, and sulfates, needs to be stored on the vessel for the entirety of the voyage because it cannot be dumped overboard or burned. The concentrations of chemicals in the sludge depends on the fuel quality, the efficiency of the treatment process, and the chemicals added to treat the washwater (Kjølholt, Jesper et al., 2012, 53). Sludge can be either hazardous or non-hazardous depending on the concentration of some chemicals and volatile organic compounds. The classification determines how it is dealt with once the vessel returns to port. In some cases the sludge can be treated with lime, pressed to remove most of the water, and added to a landfills that are equipped to handle sludge properly. (Kjølholt, Jesper et al., 2012, 53).

The larger issue facing the sludge wasted is the transportation from the ship to the treatment facility and then to the landfill. Most ports already have vacuum trucks available for other waste, since the waste is mostly liquid it can be classified as pumpable, because its composition is 30% to 40% water, it would not take a lot to incorporate this sludge as part of the program. Some ports however are farther from treatment facilities and it would require further costs to dispose of the waste (Kjølholt, Jesper et al., 2012, 53). In order for the sludge to be disposed of properly there would need to be an initiative for these treatment facilities to be closer to ports or be ready to handle the waste once EGCS are implemented on ships on a global scale. The governments and processing and transportation companies would need to work together to make the disposal of sludge as easy and environmentally friendly as possible

Unlike wet EGCSs dry EGCSs do not produce sludge, however they do produce a by-product referred to as flue gas desulfurization (FGD) gypsum. Gypsum has a market of its own and to date is being sold and used in products such as wall board, concrete, and agriculture, however depending on the gypsum can be hazardous and must be tested to determine proper disposal method. Generally the environmental concerns for this byproduct are low, as it is able to be recycled across industry lines. The environmental concerns come into play when the material does not pass the tests, and needs to be disposed of in an environmentally friendly way. (FGD Gypsum, 2007)

## 3.2 Engineering Concerns

### 3.2.1 General Engineering Concerns

One of the largest technical issues with the installation of an EGCS are the dimensions and weight of the system. These systems need to be massive to handle the load from the even larger ship engines. The EGCS installed on July 2009 at Moterenwerken Bremerhaven in Germany was 10 meters tall, 4.6 meters in diameter, and weighed 32 tons; in addition to this, roughly 200 meters of piping were installed (Danish EPA, 2012). This weight and size only takes into consideration the EGCS and the piping does not even include the pumps for the piping and the mixing/storage tanks required for wash water, the additional weight and storage for the treatment solution required run an EGCS, or any monitoring technology that is used. The EGCS needs to be integrated into the engine room and the exhaust pipe and because of other structures; there is no room without inhibiting other crucial functions. With limited space, EGCSs traditionally can be installed high up in the exhaust stack meaning even lighter EGCS can be a substantial concern for ships with that have small margins of stability (US DOT, 2011). In addition, sometimes decks and other piping systems need to be reinforced to withstand the weight

Aside from the mechanical difficulty of weight and size, EGCS provide other engineering difficulties both with power required to run and the effects on the exhaust flow. EGCS need to be continuously run and can increase power consumption by 2% of nominal power (US DOT, 2011). This can be taxing on the ship's engine, or in some cases an impossible requirement to meet in addition to the ships other operational needs. Additionally, the extra energy requirement will burn more fuel and increase the emissions from the vessel; this needs to be calculated when installing the EGCS. The exhaust flow can also create issues for the vessel. EGCS require a certain backpressure to continue working and have the exhaust move effectively, if this pressure is not reached, loss of propulsion can result. If the vessel is not operating at 100% power the amount of backpressure drops, to prevent loss of propulsion vessels need to install a way to keep the backpressure above the minimum. Furthermore stacks are meant, in part, to prevent exhaust in the engine room, EGCSs can impede that flow resulting in exhaust accumulation of exhaust both within the stack itself and eventually the engine room, this is both an engineering and health hazard (internal interview).

### 3.2.2 Open Loop EGCS Specific Engineering Concerns

Open Loop EGCSs require regular inspections to ensure operational functions and maintenance. Part of the maintenance is de-fouling and replacing the filters. The filters are for the initial exhaust to remove larger particles and the filters for the washwater intake. In order to supply enough ocean water to a standard system two pumps capable of approximately 50 m<sup>3</sup>/hr per engine megawatt are required. These pumps also require regular inspections and maintenance. In addition to the normal space issues for an EGCS the sludge must be stored. It can be stored in an existing sludge tank (which involves more frequent stops to unload sludge) or the installation of a sludge tank (US DOT, 2011).

### **3.2.3 Closed Loop EGCS Specific Engineering Concerns**

Closed Loop EGCSs require more space than the open loop system because of the extra tanks that are part of the system. In addition to a sludge tank, they require a large buffer tank to allow the freshwater to mix with chemical or salt being used. This chemical has its own set of safety and engineering concerns because it needs to be stored and moved properly. Most tanks storing chemicals like this are stationary and are not mobile and subject to the sloshing of the ocean or lake. Closed loop EGCS also use a heat exchanger to remove heat that is absorbed during the process by the solution. This system also requires more pumps than the open-loop because there are more tanks and there is no simple inlet and outlet.

### **3.2.4 Dry EGCS Specific Engineering Concerns**

Dry EGCSs use a conveyor belt to move reactants and by-products in and out of the system, like any mechanical system the conveyor belt requires routine inspection to spot wearing in the moving parts. Dry EGCSs use large volume blowers to force exhaust through the system to prevent buildup of exhaust. Similar to a closed loop EGCS (3.2.3) a dry EGCS needs to store its reactants and by-product. Unlike closed loop systems, however, the byproduct of a dry EGCS is a solid (gypsum) and not all facilities have equipment to remove it so crew will have to do so manually. (US DOT, 2011)

## 4. Monitoring Technologies

An important all emission compliance technologies is a monitoring system to insure that the emission regulations are being followed. While monitoring and recording emissions are not a part of the Annex VI requirement, monitoring and recording are usually required in order to prove compliance. The following section details what continuous emissions monitoring is, the various ways to do it, and what other monitoring systems are needed for an EGCS system.

### 4.1 Continuous Emissions Monitoring (CEM)

CEM systems are widely applicable and precise so many industries use them to comply with regulations and ensure efficiency. The uses of CEM technologies range from measuring mercury and PM at power plants to measuring acid rain, and now maritime shipping vessels. The definition of a CEM system according to EPA (2015) is:

The total equipment necessary for the determination of a gas or particulate matter concentration or emission rate using pollutant analyzer measurements and a conversion equation, graph, or computer program to produce results in units of the applicable emission limitation or standard.

This definition depends on the type of system being monitored. “In general, stationary source emissions monitoring is composed of four elements, including: 1) indicator(s) of performance, 2) measurement techniques, 3) monitoring frequency, and 4) averaging time” (CFR EPA, 2015). For example, wet EGCS need to be checked every 15 minutes or less and data is reported by averaging the measurements over a three hour period. Thus, the report for an individual day will be nine data points each the result of 12 measurements (EPA Part 60 table 2).

The Coast Guard is looking to implement similar systems on maritime shipping vessels because after Annex VI these systems are the only reliable way to demonstrate that ships are complying with the new regulations inside of the Emissions Control Area (ECA). These systems not only benefit the USCG, but also the ship owners. These systems can also check the efficiency and capacity of an EGCS system when paired with it. This can allow the vessel’s crew to adjust the EGCS’s intake to work as efficiently as possible. It also allows the crew to, if they choose, switch fuels more efficiently prior to entering an ECA. Both of these options allow the ship owner to lower costs as much as possible (Parker Hannifin 2015).

The process of adding a CEM system to a ship is very similar to installing an EGCS because they are both integrated into the exhaust system of a ship (Cage, 1999). There are several different types of CEM systems that can be used in conjunction with the EGCS systems. Each has different styles and methods of measurements as displayed at the end of section 4.1 in Table 6. The different types of CEM systems are hot or cold extraction, dilution, cross stack analyzer, and open path. The basic principle of CEM systems is that they perform tests on the exhaust to immediately determine the emission content. The measurements can be taken through a chemical sampling process or using light. The light system requires the equipment to be calibrated to the specific pollutant type being measured and the system must be zeroed for the most accurate results. The light method however has the potential for cross contamination with water vapor in the exhaust. The wave lengths at which the exhaust absorbs the light

are the same as the wave lengths at which water vapor absorbs light. This can be detrimental to the accuracy and precision of these instruments. Ensuring accuracy and precision of the light system requires a number of tests to confirm the gathered information. The chemical systems however remove water vapor prior to using chemicals to determine the emission content. This reduces the chance of having inaccurate readings; the only CEM system that uses chemical is the hot or cold extractive type (Silberberg 2011).

## **4.1.1 Extractive System**

### **4.1.1.1 Hot or Cold System**

An extractive system (shown in figure 9) is a direct method of monitoring emissions. A sample of the exhaust is pumped directly to an analyzing system. Once the sample is removed, it moves to an environmentally safe area away from the stack. The exhaust is conditioned by a filter on its way from the stack to the extractive system. This filter requires a lot of maintenance because the high temperature and chemicals from the exhaust stack can damage it. The purpose of the filter is to keep larger particles, PM<sub>10</sub> or greater, out of the analyzer and to ensure the gas's temperature does not exceed the dew point of the exhaust. If this dew point is exceeded the exhaust will partially condensate and bring moisture into the analyzer resulting in inaccurate data (Silberberg 2011).

The difference between extractive systems comes from how the gas is conditioned before testing. One type of system is referred to as a "hot-wet" extraction CEM system. It keeps the temperature of the gas high and does not remove water vapor. Another type of extraction CEM is a "cold-dry" system where the gas is cooled, moisture is removed, and then it is tested (EPA 2000).

The advantages of hot or cold extractive systems is they are less expensive and can be easily calibrated for a specific type of chemical. In addition, the distance between the stack and the analyzer means maintenance and calibration for the analyzer can be done more easily. This distance also reduces the sample's exposure to the extreme temperature and exhaust gas concentration, which will allow for more accurate results. Some detriments to the hot or cold system are contained in the extraction, transferring, and conditioning of the gas sample. The line containing the gas might leak, the temperature may not be correct, or the gas may absorb chemicals from the tubing itself which can affect the accuracy of the data collected (EPA 2000).

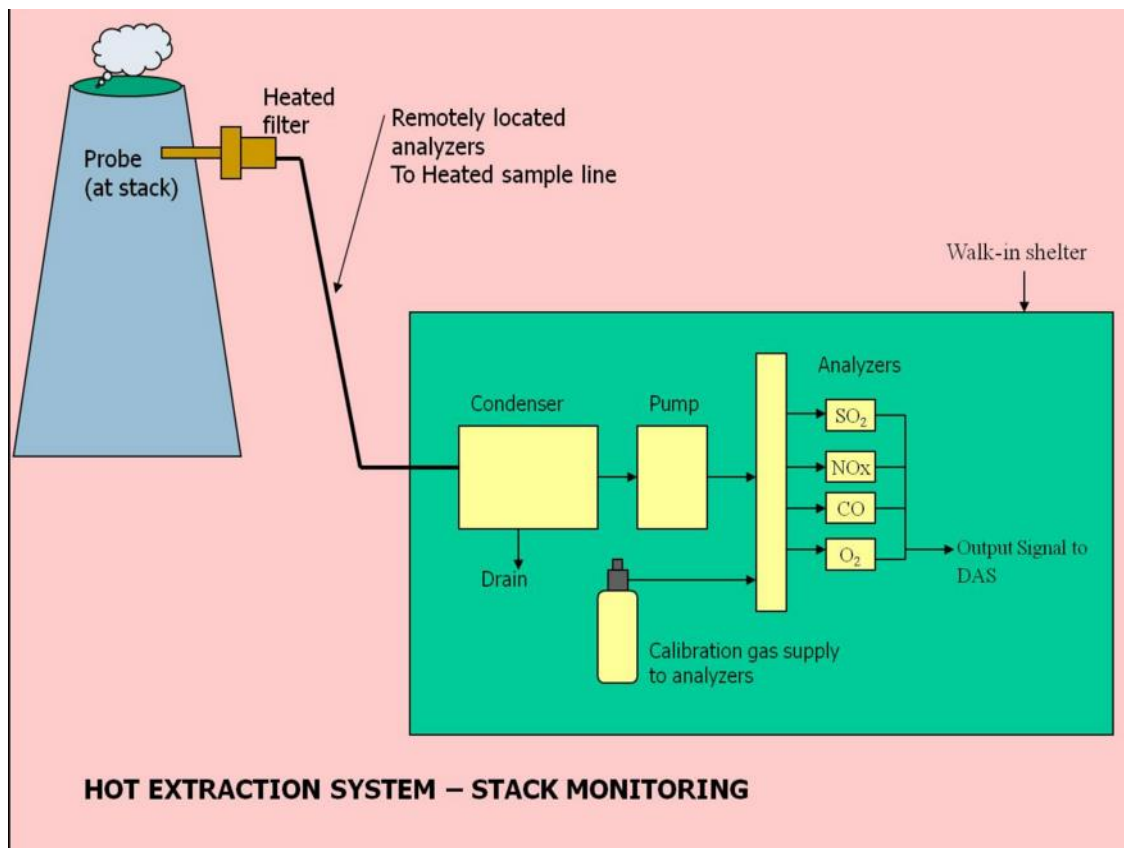


Figure 9: Hot Extraction System (Chemtrols, 2010)

#### 4.1.1.2 Dilution System

Figure 10 illustrates the basic schematic of a dilution system. Dilution systems work the same way as an extractive systems do, where the sample is removed from the stack and sent to a hub to be analyzed. The dilution systems prevent the issue of condensation caused by typical extraction systems by diluting the extracted sample with air to a ratio of 100:1. This process prevents condensation even at the lowest possible temperature it could encounter (Silberg 2011). This method also works on a “wet” basis, because the moisture is diluted but not removed, meaning that it does not need a moisture correction. Without the moisture correction, the numbers are easily compared to flow meter readings (Monitoring Solutions, 2015). After the dilution process, the sample is analyzed. A major drawback to this type of system is that the dilution is hard to manage, additionally the analyzer needs to be hypersensitive to accommodate the lower concentration of gas (Silberg 2011). The hypersensitivity is only an issue when the exhaust has low pollutant concentrations initially. For this reason, a dilution CEM system is usually only used for exhaust with a high pollution content such as from the burning of wood or coal (Monitoring Solutions, 2015).

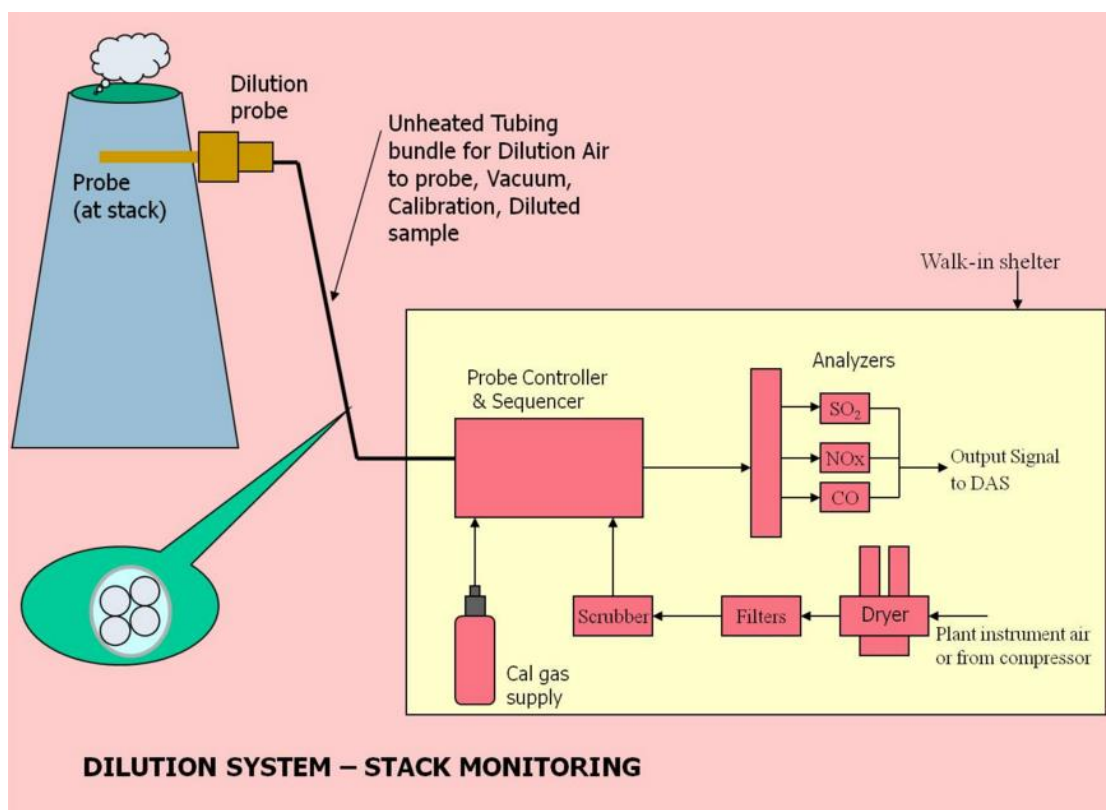


Figure 10: Dilution System Stack Monitoring (Chemtrols, 2010)

#### 4.1.2 In-Situ System

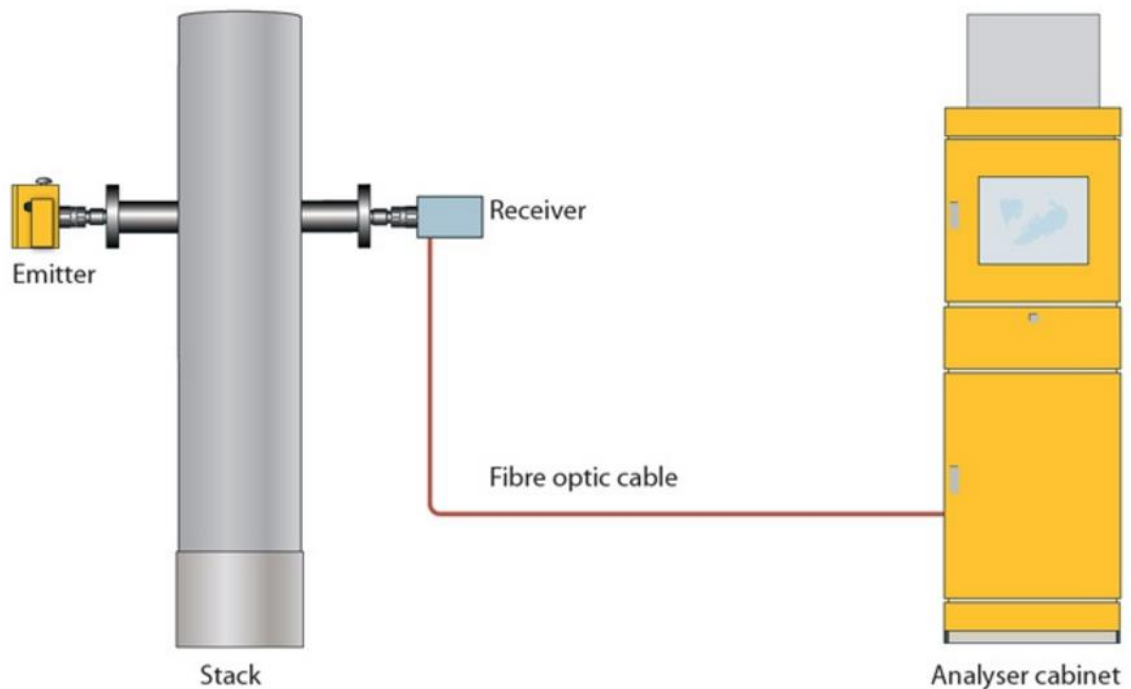
In-situ CEM systems measure the emissions in the exhaust directly from the stack. There are two types of in-situ measurement: path and point. Path measurements use a signal and a reflector to measure the content of pollutants in the exhaust over a larger area and over a period of time the measurements are averaged together. An example of a path analyzer is the cross-stack system detailed in section 4.1.2.1. Point measurements are taken at the exact point the analyzer is located in the stack. It takes only one sample and that is the only measurement it uses. An example of a point measurement is the open-path system, detailed in section 4.1.2.2 (EPA 2000).

The close proximity to the stack makes these CEM systems more expensive, because they are required to be more durable and tightly sealed to protect them from the heat, moisture, and corrosive gasses. The harsh environment and proximity to the stacks make maintenance of in-situ systems challenging. At the same time however, their close proximity reduces the risk of contamination and leaks of gas samples (EPA 2000).

##### 4.1.2.1 Cross Stack Analyzer System

Cross stack analyzer systems as shown in figure 11, do not require high maintenance sample systems because it uses the light method to measure the emissions. The system sends pulses of ultra-violet or fluorescent light through the stack to a receiver (or a reflector). This technique is best at measuring  $\text{NO}_x$ , because when it is exposed to  $\text{O}_3$  it oxidizes to become  $\text{NO}_2$ , which produces light. Controlling the amount of ozone, exhaust, and light that enters a system allows for measurement of the

light produced, and refracted thus the amount of  $\text{NO}_x$ . The cross stack analyzer allows for no modification of the sample which reduces the possibility of contamination or faulty measurements. However, these systems can only be mounted on specific size stacks and it can be difficult to calibrate the system because it only uses light (Silberberg 2011). There are several of these systems in existence however not many of them explicitly state that they analyze  $\text{SO}_x$  and  $\text{NO}_x$  emissions. One company, Consilium, claims they have a cross stack analyzer that will comply with new IMO regulations. Consilium claims that their Opsis system will analyze “ $\text{NO}$ ,  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{NH}_3$ ,  $\text{CH}_4$ ” (Consilium AB Publ. 2013).



**Figure 11: Cross Stack Analyzer (Consilium AB Publ. 2013)**

#### **4.1.2.2 Open Path System**

An open path system as shown in figure 12 has a probe that extends into the stack and has a slit or window to allow the exhaust to pass through. This system operates with a transmitter and receiver similar to cross stack analyzer systems (4.1.2.1). The primary difference between an open path and a cross stack is that the transmitter and receiver are located inside of the probe in an open path system. The exhaust passes through the probe and proceeds to an external chamber where the sample is measured using infrared or ultra-violet light (Silberberg 2011). This system is very easy to calibrate to analyze a specific type of chemical. To reset the system, put another receiver in front of the probe. To calibrate the probe a test gas can be pumped through the open window in the probe. The challenge with this type of system is that there is a second reflector being used to calibrate it. It does not allow it to be calibrated using the existing reflector and therefore does not actually challenge the systems measurements (Silberberg 2011). Very few companies produce this type of analyzer.



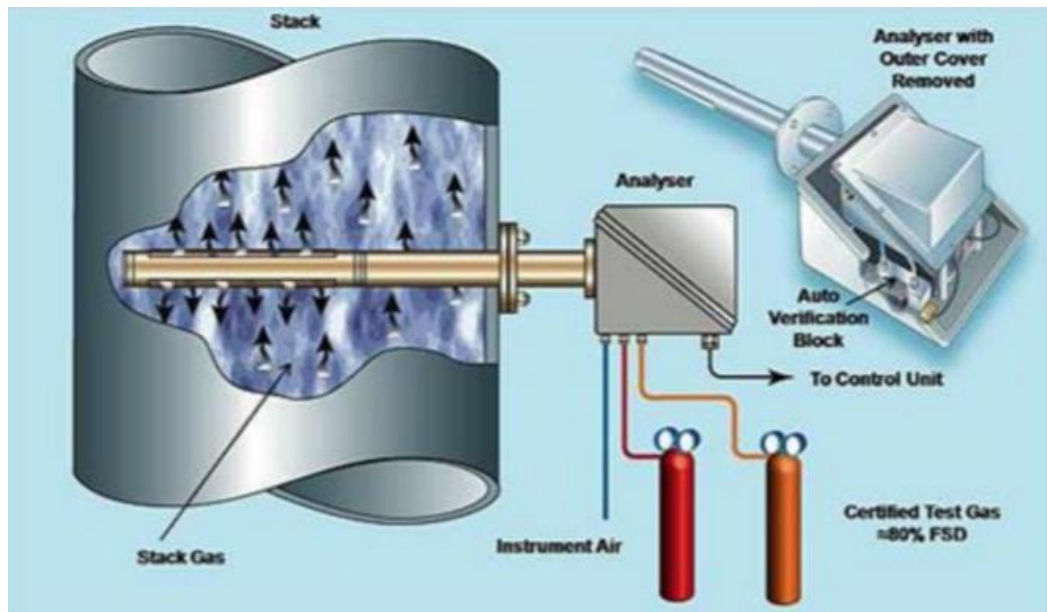


Figure 12: In-Situ Open Path Analyzer

Table 6: CEMS Comparison

Type of CEMS	Style of Measurement	Method of Measurement	Important Notes
Hot or Cold Extraction	Chemical	The exhaust gas is prepared using heat or chilling to remove water vapor and particulate matter and then analyzed using chemicals	The chemicals being tested for can be removed with water vapor. Prepping lines are expensive and require maintenance
Dilution	Chemical	The gas is diluted to remove errors from water vapor and then measured	The sensor needs to be hyper sensitive
Cross Stack Analyzer	Light	Light pulses are sent through the entirety of the stack to measure	Size of stack limits implementation and calibrating system is difficult
Open Path	Light	The gas is blown into a chamber where it is measured using light pulses	Calibration does not challenge system

## 4.2 Washwater Monitoring

Washwater, as detailed in section 3.1.1, is a primary byproduct of EGCS. It can cause environmental concerns if it is not monitored. However, as described by EPA (2011) washwater monitoring is not yet a legal requirement but is encouraged by the IMO and is likely to be required in future regulations.

The IMO guideline recommends pH, PAH [Polycyclic Aromatic Hydrocarbons] concentration, turbidity and temperature should be continuously monitored and recorded when the EGCS is operated in ports, harbors, or estuaries. In other areas, these parameters should be continuously monitored and recorded whenever the EGCS is in operation, except for short periods of maintenance and cleaning of the equipment.

This recommendation echoes the final 2013 Vessel General Permit (VGP), section 2.2.26.2.1, which provides EPA guidelines for the continuous monitoring of washwater. It states:

The data recording system must comply with the guidelines in sections 7 and 8 of MEPC.184(59) and must continuously record pH, PAH (as available), and turbidity. The vessel owner/operator must continuously monitor for PAH discharges where continuous monitoring technologies (e.g., probes/analyzers) are available (availability should include the technology's robustness, reliability and ability to perform over for a minimum of two years). When the EGC system is operated in waters subject to this permit, the washwater monitoring and recording must be continuous. The values monitored and recorded must include pH, PAH (as available), turbidity, and temperature.

The VGP is a regulation that regulates discharges relating to the normal function of a ship 79 feet or longer, including washwater and emissions. According to the VGP, washwater monitoring systems would need to be calibrated at least once a year to within a 5% deviation and the "pH electrode and pH meter must have a resolution of 0.1 pH units and temperature compensation" (Final VGP 2013, 2013).

Resolution MEPC.184(59) outlines regulations that go into detail on washwater monitoring. Both schemes require continuous monitoring of the pH, PAH, and turbidity of the water, and are recorded in respect to the ship's position. If the EGCS uses extra chemicals such as in a dry loop EGCS or a closed loop EGCS or if the washwater is chemically treated prior to discharge, then the ship's crew are required to complete a specific assessment and possibly change their requirements for acceptable discharge levels (Lloyd's Register Marine, 2015).

The pH requirements for the discharged water vary depending on if the ship is stationary or in transit. If the ship is in transit, the pH of the outlet compared with the inlet can only vary by two pH units (Lloyd's Register Marine, 2015). If the ship is in port, the outlet pH can be no less than 6.5 units. The reason for the stricter limits in port is that during transit the lower pH water will automatically mix in the wake of the vessel correcting the pH variation. In port, there is no such water movement. To meet the port restrictions one option is to dilute the washwater with more seawater. A way of saving energy and time would be to use the water already on board used for cooling the engine (Lloyd's Register Marine, 2015).

There are two accepted methods of where to measure pH levels post-discharge. The first is at

the point of discharge (MEPC.184 (56) 10.1.2.1 (i)) and the second is taking the measurement four meters out from the side of the ship (MEPC.184 (59) 10.1.2.1(ii)). Both ways require an external measurement method. The second method has been the subject of dispute, pertaining to if distance from the ship matters when measuring pH levels. The argument for the measurement being taken at the discharge point is that the ocean is so vast that the pH will easily balance itself shortly after discharge. The argument for the distance of four meters consists of the fact that if the pH is not balanced within that distance from the ship then it can have adverse effects on the surrounding environment. However, measuring the pH of the ocean four meters away from a large vessel accurately is a concern.

One company, Alfa Laval filed a request to the EPA and the USCG using a third method of compliance for two of their ships. They have raised issues with both accepted compliance methods. They have stated that, method (i) would require an on-board dilution process that would increase the discharge pump capacity. The significant increase in the pump cannot be done with the limited space and electrical capacity of their ship. Another option to enable them to comply with method (i), is that they could treat the washwater with an alkaline substance prior to discharge. Alfa Laval reports that this option is not feasible due to environmental and technical concerns (Alfa Laval, 2015). Alfa Laval claims that the wording of method (ii) suggests that the measurement is taken four meters from the ship's edge while "on full load at rest in harbor" (Alfa Laval, 2015). They say is impossible for their ship, but gives no follow-up reason.

Alfa Laval believes neither method is acceptable for two of their ships but they have proposed a third method of compliance. Alfa Laval will use jet theory to demonstrate the mixing point of the washwater with the surrounding sea water. Through jet theory Alfa Laval will use principles from fluid mechanics to determine if the washwater is turbulent (turbulent fluids mix with the surrounding fluids). This calculation would allow for the input of a 1) pH reference value, 2) sea water area (calculated via a standard titration curve), and 3) washwater flow rate. By inputting these three values into the equation they would be able to calculate the minimum discharge diameter to have a pH of 6.5 at a distance of four meters out from the side of the ship (Alfa Laval, 2015). This proposed method, and calculations were approved by USCG (Interview with Wayne Lundy (USCG), 10/9/2015).

While Alfa Laval was granted a permit request to be exempt from method (i) and (ii) for two of their ships, other companies have found ways to comply. In Carnival Cruise's request for a permit to research and develop EGCS technology, they stated that they will be monitoring their systems by the regulations stated in Scheme B (Carnival Cruise, 2015).

The PAH limits are determined differently than pH. Only a single type of PAH, phenanthrene which is predominantly found in diesel exhaust, in the washwater is detected because this PAH signals the presence of other PAHs. The regulatory limits of PAH vary depending on the discharge flow rate because the concentration of the PAH varies indirectly with the flow rate. If a ship has a low discharge flow rate then the concentration limits are higher, and vice versa. However, PAH can be created from other things besides the combustion of diesel fuel and can often found in seawater to begin with. To compensate for the initial PAH found in the washwater the net change of PAH concentration is measured by deducting the PAH input value from the PAH output value. There are two methods to measuring the PAH concentration in the water. One is to use ultra-violet light to see the absorption by the PAH at high concentrations with a slow discharge rate. The other is to measure the intensity of the light emitted from the PAH at a lower concentration and a higher flow rate (Lloyd's Register Marine, 2015). The PAH limits as outlined by MEPC.184(59) are allowing a maximum concentration of 50µg/L

above the measured value at the point of intake. This limit however is standardized for a discharge rate of 45 tons/MWh of water (EPA, 2011, 11). Table 8 allows the accurate calculation of the acceptable level of PAH at a specific discharge flow rate.

**Table 7 Discharge Concentration Limit (As cited in EPA, 2011, 11)**

Flow Rate (t/MWh)	Discharge Concentration Limit (µg/L PAHphe equivalents)
0-1	2250
2.5	900
5	450
11.25	200
22.5	100
45	50
90	25

a. Fluorescence technology should be used for any flow rate > 2.5 t/MWh.

Wartsilia, a scrubber manufacturer, installed a scrubbing system for research and development purposes on the vessel “Suula”. They reported, after testing the ships washwater content for PAH, that the current technology available has difficulty making the measurements and calculations needed. The issue stems from the device needing to detect the small amount of PAH in the water while it is flowing and then measure the concentration in the water. Wartisila says that the most reliable way to measure PAH is using on-shore laboratories (Wartsila, 2010, 21). The other particles that are measured in the washwater are the suspended particles, or turbidity. Turbidity is a measure of the cloudiness of the water and can be caused by any undissolved particle in the water. The cloudier the water is the higher the turbidity. The units for measuring turbidity are referred to as formazin nephelometric units (FNU) or nephelometric turbidity units (NTU) (EPA 2011, 11). Both units are slightly different but are calculated the same way. Turbidity is measured through the way light reflects off the particles in the water. Both units measure the light reflected at a 90-degree angle to the source beam. The difference between the units refers to the medium used to measure them. The NTU is measured with white light between ranging between 400 nm to 860 nm in size, and the FNU is measured with infrared light, ranging between 780 nm to 900 nm. One of these units is equivalent to 1 milligram of particles per liter of water (U.S Geological Survey, 2013). According to MEPC.184 (59) the limits for turbidity are 25 NTU or 25 FNU above the inlet. In the event of high inlet turbidity, the precision of measurement and time lapse from the inlet to the outlet proves that a difference limit is unreliable. The MEPC.184(59) advises an average value of the difference of turbidity should be taken over 15 minute increments for 12 hours. Each 15 minute measurement should comply with the same limit of 25 FNU or NTU but the average measurement over the 12 hours can exceed 25 FNU or NTU by 20% (Regulations MEPC.184(59)).

### 4.3 Fuel Consumption Monitoring

Monitoring a vessel’s fuel consumption is one way of monitoring if a ship is in compliance with MARPOL Annex IV. The amount of fuel burned is directly related to the amount of emissions produced. However, monitoring fuel consumption can also allow the ship operators to find inefficiencies in a ship

saving time and money in not only in fuel costs but also in repair costs. There are three ways to monitor and record fuel consumption. The first method is Bunker Delivery Note, which is the primary method for air pollution regulation. The second method is the use of flow meters and the third is tank monitoring. Each of these three methods are detailed 4.3.1 through 4.3.3.

### **4.3.1 Bunker Delivery Note (BDN)**

MARPOL Annex VI regulation 18 states that vessels that are 400 gross tonnage or higher are required to keep a record of fuel oil that they store as a BDN (Bunker Delivery Note) for at least three years. This monitoring of fuel oil is the most commonly used method for air pollution regulation. The BDN, a paper record, supplied by the bunker fuel supplier and must include:

- Name and IMO number of receiving ship;*
- Port;*
- Date of commencement of delivery;*
- Name, address and telephone number of marine fuel oil supplier;*
- Product name(s);*
- Quantity (metric tons);*
- Density at 15 C (kg/m<sup>3</sup>);*
- Sulphur content (%m/m); and*
- A declaration signed and certified by the fuel oil supplier's representative that the fuel oil supplied is in conformity with regulation 14(1) or (4)(a) and Regulation 18(1) of MARPOL Annex VI.*

BDNs simply are a receipt saying that compliant fuel was purchased and rely on the honesty of the vessel owner and operator. Even if the BDN is examined by Coast Guard officials, there are ways that ship owners can manipulate the BDN to show that a vessel is in compliance when it is not. One example of this is when a ship's owner buys the compliant ultra-low sulfur fuel, but instead of burning just this fuel, the ship owner dilutes it with HFO. The BDN would still show that they bought the compliant fuel, but the ship itself would not be in compliance because the dilution of the two fuels would still cause the emissions to be higher than MARPOL Annex IV requires.

### **4.3.2 Flow Meters**

Flow meters are another type of monitoring. Flow meters determine the volume of fuel that passes through the pipes of the ship. Flow can be measured directly in the pipes or indirectly by pressure. This method requires all outward flows of fuel from fuel tanks to be monitored. There are several different types of flow meters: electronic flow meters (volume), velocity sensing flow meters (velocity), inferential flow meters (pressure-based flow meter), optical flow meters (flow rate) and mass sensing flow meters (Faber, Nelissen, Smit 2013).

#### **4.3.2.1 Electronic Flow Meters**

Electronic flow meters are attached to the main engine's fuel supply and monitor the volume of the fuel flowing into the engine. The measured volume is used to calculate the flowrate and is used to monitor fuel efficiency.

### **4.3.2.2 Optical Flow Meters**

Optical flow meters determine flowrate using two light beams spaced a measured distance apart shining into the flow path. These beams are disrupted as the particles common in industrial fuel pass through. Each particle or group of particles that disrupts the beam has a certain signature. When that same signature passes through the second light beam a measurement of time is taken between when the two signatures registered (Faber, Nelissen, Smit 2013). The benefits to this system are that it is entirely non-intrusive, and can be installed outside of the pipe. The electrical and technical portion of the sensor do not directly touch the fuel, preventing corrosion and any potential for damaged or broken parts to block the pipe. The sensor is also much more accurate than other types of flow meters, and can be used in a variety of temperatures. This sensor can also measure temperature and pressure, allowing for easy volume calculations (Flow Research, 2015)

### **4.3.2.3 Inferential Flow Meters**

Inferential flow meters do not directly measure the flow rate in the pipes, but instead measure properties, such as pressure, mass, and velocity, that can be used to calculate the flow rate in the pipes.

#### **4.3.2.3.1 Area Inferential Flow Meters**

When using an inferential flow meter a float is placed in a vertical pipe and the distance the float is displaced measures the flow rate. As this method uses gravity as the opposing force to push the float down; this would not work in a horizontal fuel pipe. The addition of a spring attached to the other side of the float provides a calculable resistance to measure the flow rate (Barbour, Chris et al, 2008). The benefits of this method are that the flow rate can be read on a physical meter, or electronically recorded. The only caveat is that if the fuel coats the spring or float, then the flow meter cannot be used. If the spring or float becomes laden with other substances, the data will not be calibrated correctly (Barbour, Chris et al, 2008).

#### **4.3.2.3.2 Pressure Inferential Flow Meters**

A pressure inferential flow meter does not directly measure the volume or velocity of the fuel. Instead, it measures the pressure differences caused by variable area. A pressure difference is caused through constriction points (variable areas) placed in the pipes. The pressure change, which is proportional to flow-rate, is used to calculate the dynamic pressure of the system. Once the dynamic pressure of the entire system is calculated, the flow rates for the engine can be calculated and monitored (Barbour, Chris et al, 2008).

### **4.3.2.4 Velocity Flow Meters**

Velocity flow meters measure the velocity inside the pipe using a turbine or an ultrasonic meter.

#### **4.3.2.4.1 Turbine Velocity Flow Meters**

The turbine method has a turbine installed in the piping system and the velocity is measured by

the rotational speed of the turbine. This method requires measurements in two places, one measuring the flow of fuel into the tank and one measuring the flow of fuel out of the tank, to calculate the net flow (Faber et al., 2013). The accuracy of this system is low when experiencing large flow fluctuations, or pulsating flow. The parts of this flow meter are directly exposed to the fuel causing excessive wear on the device, and a slight decrease in energy caused by pressure. (Barbour, Chris; Clifford, Thomas; Millar, Dean; Young, Robert, 2013).

#### 4.3.2.4.2 Ultrasonic Velocity Flow Meters

The ultrasonic method measures the velocity using the Doppler effect of ultrasonic waves. The benefit of this type of system is that it is non-intrusive, it only needs to be clamped around the pipe and has zero response time. This system is not affected by pulsating flow rates, but is affected by impurities in the fuel. These systems are also more accurate on larger pipes, making them very useful on large cargo ships or cruise liners (Barbour, Chris et al, 2008).

#### 4.3.2.5 Mass Flow Meters

Mass sensing flow meters calculate the mass-flow rate, which is not affected by impurities, or different temperatures. However, mass flow meters do drop the energy pressure in fuel pipes. For this reason, mass flow meters are more commonly used in pipes that have high pressure.

##### 4.3.2.5.1 Coriolis Mass Flow Meters

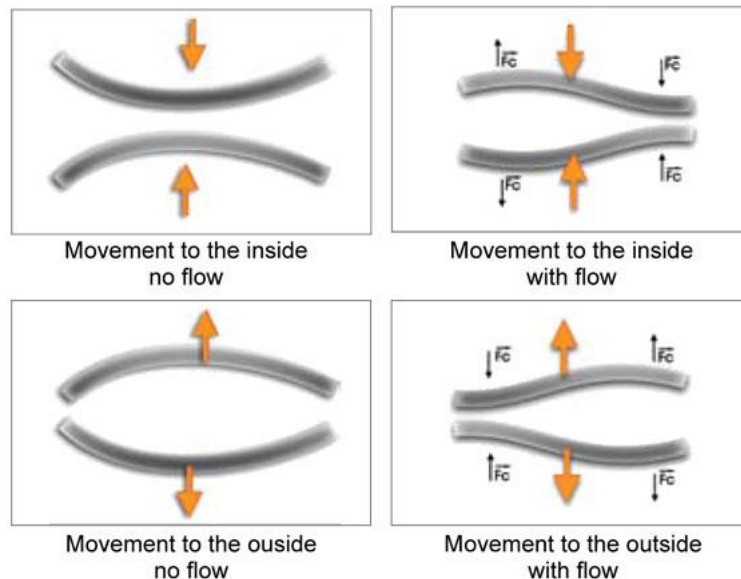


Figure 13: Coriolis Flowmeter (Dunia Instrumentasi, 2014)

Coriolis mass flow meters are attached to a pipe and fuel is redirected into it. The meter consists of a two U-shaped pipes with a smaller diameter than the original pipe aligned vertically. The fluid is diverted into these two pipes from the main pipe. The sections of pipe are vibrating counter to each other as seen in Figure 13. Vibrating counter to each other means one is moving up with the other is moving down. When the pipes are empty, they vibrate parallel to the horizontal and do not twist. When

there is mass in the pipe, the vibration induces the fluid to rotate inside the pipe causing it to twist due to the difference in directional acceleration. As one pipe is moving down, the fluid is rotationally accelerating in one direction, and the other pipe is moving up causing that fluid to rotate in the opposite direction. The magnitude of separation between the two pipes varies directly to the mass flow rate. The advantages of this system are that the separation can be measured directly with a physical meter (Barbour, Chris et al, 2008).

#### 4.3.2.5.2 Thermal Mass Flow Meters

The thermal mass flow meter relies on the assumption that the rate the heat is absorbed by a flow stream varies directly to the mass flow rate. The general principle of this is that as molecules pass by a heat source they absorb some of the heat. More heat is absorbed when more molecules pass by. Thus, the amount of heat absorbed is proportional to the amount of molecules passing by. With the mass of the fluid, and the thermal and flow rate characteristics, the amount of heat dissipated can be calculated to find the mass flow rate (Barbour, Chris et al, 2008). However, these types of meters are most commonly used for pure gases because the composition of the fuel needs to be known to calibrate the flow meter correctly.

#### 4.3.2.5.3 Linear Mass Flow Meters

Linear mass flow meters calculate the flow of fuel in the fuel tank pipes. Its design is based on a hydraulic equivalent of the electrical Wheatstone bridge. A Wheatstone bridge is designed to measure the electronic resistance by the comparison method. A linear mass flow meter, determines the mass liquid flow through a comparison of different levels of pressure in the meter. The different levels of pressure creates a differential pressure output which is linearly proportional to the mass level flow. The linear mass flow meter is able to detect mass level flow, despite changes in the fuels temperature, density or viscosity. It also is able to detect very low flows at very low pressure drops.

#### 4.3.2.6 Volume Flow Meters

Volume flow meters repeatedly trap the fuel and measure the amount of times the fuel is trapped in a given time to measure its volumetric flow. These types of systems have a high energy from pressure loss and are more suited to be used on systems with higher flow rates. These parts are exposed directly to the fuel and could potentially become corroded or worse obstruct fuel flow if broken (Barbour, Chris et al, 2008).



#### 4.3.2.6.1 Oval Gear Volume Flow Meters

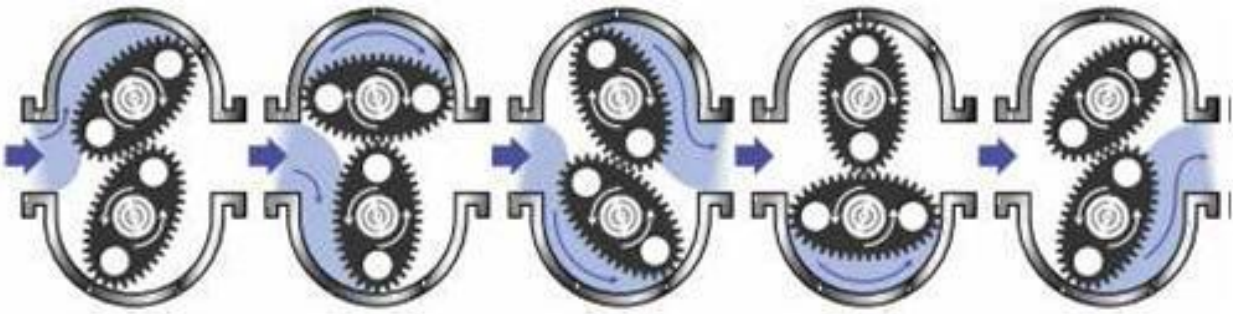


Figure 14: Oval Gear Flow Meter (Mauter, Erica; Wesorick, Steve; Kaplan, Kelsey; Roberts, Andrea; Chen, Henry, 2014)

Oval gear flow meters direct the water into an egg shaped sections of the pipe like in Figure 14. The gears inside are firmly interlocking, and when one is vertical, the other is horizontal. When the water enters the chamber, it rotates the gears and disrupts the flow. The amount of times the gears trap the fuel and rotate in a certain amount of time is used to calculate the volumetric flow rate. (Barbour, Chris et al, 2008). This kind of meter has a very high accuracy and can be easily repeated. The viscosity does not affect the accuracy or the function of the system and it requires very little maintenance. The only disadvantage is that it is susceptible to water based fluids (Mauter, Erica et al., 2014).

#### 4.3.2.6.2 Reciprocating Piston Volume Flow Meters

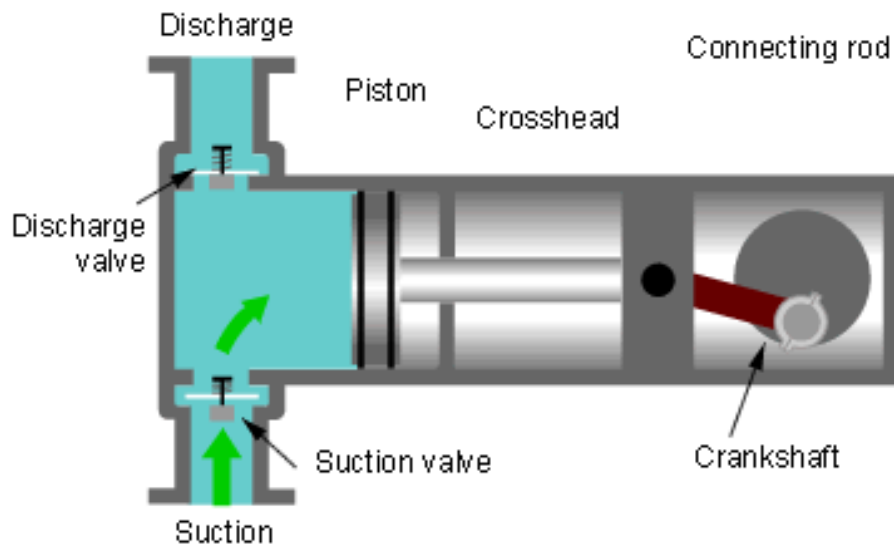


Figure 15: Reciprocating Piston (Air Compressor Spy, 2015)

The reciprocating piston, as seen in Figure 15, attaches to a side of the pipe, and has a piston inside of a chamber attached to a crank. As fuel flows through the pipe, the pressure displaces the piston. The amount the piston displaces is carefully calculated. An electromagnetic sensor measures the

piston's movement by a magnet in its center. The displaced amount compared to the rotation of the piston gives the volumetric flow rate of the pipe (Mauter, Erica et al., 2014).

#### 4.3.2.6.3 Nutating Disks Volume Flow Meters

Nutating Disc meters directly measure the volumetric flow of the pipe by having the fuel pass through the system and alter the position of the disc. Figure 16 gives a side view of the inside of the meter. The fuel flows into the chamber and cause the disc to rotate as it passes over it. The rotating disc causes the shaft on top of the disc to rotate and drives a magnet. The rotation is transmitted through to the exterior of the meter with another magnet and operates the transmitter (Mauter, Erica et al., 2014). These meters are advantageous when using high temperature because of the durable materials it is composed of; bronze, carbon, and aluminum. This meter type is commonly used for fuel and oil (Niagara Meters, 2011).

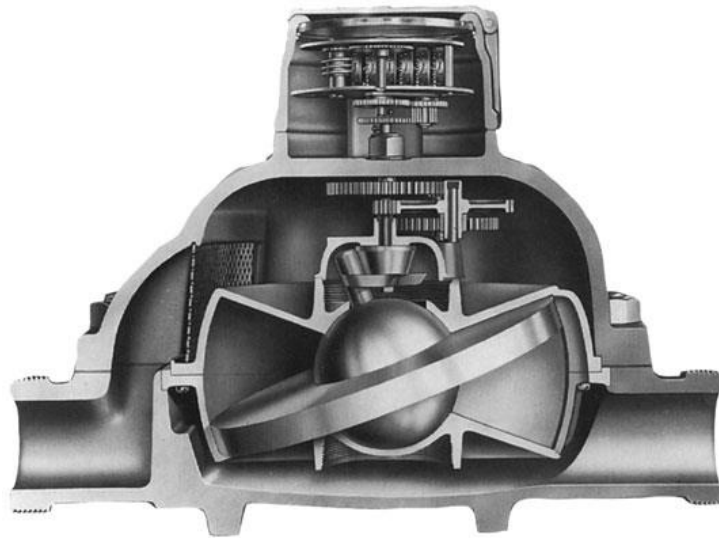


Figure 16: Nutating Disk Meter (Niagara Meters, 2011)

### 4.3.3 Tank Monitoring

Tank monitoring is another way to monitor fuel consumption. The level of the fuel left in the tank can be monitored and calculated using three different methods. The three different methods are electronic sounding, mechanical sounding, or manual sounding. Each determines the depth of the fluid from the surface of the fuel to the bottom of the tank. Once the depth of the fluid is determined, the ship's sounding tables are used which converts the tank's level to the volumetric quantity in the tank (Faber, Nelissen, Smit 2013).

#### 4.3.3.1 Electronic Tank Monitoring

Electrical tank monitoring, also called electronic sounding, is used to determine the amount of fuel in the tank. To determine the tank's content value, a submersible pressure transducer is located either inside the sounding pipe of the tank, or inside the tank itself. The submersible pressure

transducer is a pressure sensor. The pressure sensor takes continuous pressure measurements and sends the reading to a receiver. The receiver, by use of a programmable logic controller circuit and the known density of the fuel, calculates the tank's content value. The content value allows the ship operators to monitor the level of fuel left in the tank (Faber, Nelissen, Smit 2013).

#### 4.3.3.2 Mechanical Tank Monitoring

Mechanical tank monitoring is also called mechanical sounding. It determines the quantity of fuel in the tank directly through the use of a level gauge glass and float level sensor as shown in figure 17. A level gauge glass, also called a float chamber, is a column of pipe connected to the tank. There is a float containing a magnet located in the float chamber and as the liquid level changes the float rises and falls. The float is connected to an indicator via magnet. The fuel level inside the tank can be seen inside the indicator tube, which is attached to the outside of the float chamber, as the indicator rises and falls with the float. (Schollosser, Wesorick, Kaplan, Nalbandian, Chen, 2014).

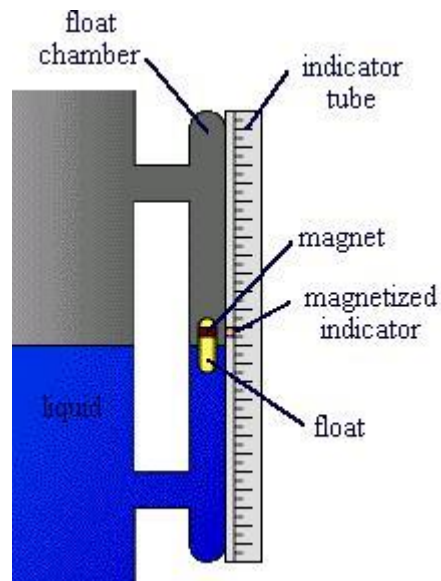


Figure 17 Level Gauge Glass (Schollosser, Wesorick, Kaplan, Nalbandian, Chen 2014)

#### 4.3.3.3 Manual Tank Monitoring

Manual tank monitoring, also called manual sounding or ullage measurement, determines the quantity of fuel in a tank a sounding tape. A sounding tape as shown in figure 18, is a tape measure with a heavy weight bob attached to one end. The heavy weight is dropped down into the tank and the user reads off the measurement from the handle of the sounding tape.



Figure 18: Sounding Tape (Aditib, 2010)

	Equipment needed	Costs/burden for ship operator/owner	Monitoring& verification costs/burdens	Monitoring of other pollutants
Bunker delivery note and period stock-takes of fuel tanks	None	No equipment cost. No running costs. Data reporting costs/burden could be high as a result of use of paper records.	Reporting the data is an extra burden. Costs will be higher as a result of use of paper records and lack of automation possibilities.	SO <sub>x</sub>
Bunker fuel tank monitoring on-board	Yes, but already present on larger ships	Equipment: USD 1,000-1,300 per tank. Maintenance of device. Data reporting costs/burden modest if automatically monitored.	If tanks are automatically monitored and results electronically recorded then costs will be modest. Costs may have to be incurred to prove that device works properly.	(SO <sub>x</sub> )
Flow meters for applicable combustion processes	Yes, but already present in ships with modern fuel systems	Equipment: USD 15,000-60,000. Maintenance of device. Data reporting costs/burden modest if automatically monitored.	If flow is automatically monitored and results electronically recorded then costs will be modest. Costs may have to be incurred to prove that device works properly.	(SO <sub>x</sub> )

Figure 19: Comparison of Fuel Monitoring System's Cost (CE Delft, Delft)

	Accuracy	Completeness	Consistency	Verifiability
Bunker delivery note and periodic stock-takes of fuel tanks	1-5%	All fuel used on-board is captured, provided that all BDNs are presented, every bunker operation is covered by BDNs and BDNs are not falsified.	Difficult to ensure: All BDNs have to be presented, every bunker operation has to be covered by BDNs and BDN need not to be falsified.	Data can be verified by <ul style="list-style-type: none"> <li>- cross-check with other data on-board</li> <li>- cross-check with BDNs of bunker fuel suppliers</li> <li>- plausibility checks</li> </ul> Could turn out to be difficult if BDN copy illegible and/or issued by subcontractor of fuel supplier.
Bunker fuel tank monitoring on-board	Limited to very inaccurate (if manually). Electronically: 2-5%	All tanks need to be monitored to capture all fuel used on-board.	Difficult to ensure: Different methods can be applied with different care. All tanks need to be monitored frequently enough.	Data can be verified by <ul style="list-style-type: none"> <li>- cross-check with other data on-board</li> <li>- controlling devices on-board</li> <li>- plausibility checks</li> </ul> Verification is easier than for BDN if tanks are monitored automatically.
Flow meters for applicable combustion processes	- 3 %	All outward flows of all tanks need to be monitored to capture all fuel used on-board.	Easier to ensure than for BDN and tank monitoring since only automatic measurement.	Data can be verified by <ul style="list-style-type: none"> <li>- cross-check with other data on-board</li> <li>- controlling devices on-board</li> <li>- plausibility checks</li> </ul> Verification is easier than for BDN since monitoring is done automatically.

Figure 20: Comparison of Quality Fuel Monitoring Systems (CE Delft, Delft)



# 5. Summary and Reflections

## 5.1 Summary

Beginning in the fall of 2017 we started studying Exhaust Gas Cleaning Systems (EGCSs) for the United States Coast Guard (USCG). At that time we were under the impression that they did not know much about EGCSs and that they wanted us to make a recommendation on which system is the best for maritime applications. The process of making this recommendation would have included making a rubric to cross reference vessel types to EGCS types. After conversations with our sponsor, we learned that we were instead working on a comprehensive study on the availability of EGCS technology.

Our original project goal would have been nearly impossible to complete due to the complexity of the marine vessels. The process of making recommendations for this initial project goal would have included making a rubric to cross reference vessel types to EGCS types. This issue also arose with the revised project, because of the complexity of the vessels and how new the EGCS technology is; there is a lack of organized information available. Where the information was available, it was often either difficult to access or purposely stated in a vague manner because the companies researching the technology do not want to share the details of their systems. Regardless, we knew our work was going to make an impact so we strove to give the Volpe Center and USCG as much information as we could and the tools to further their study after we were finished.

If this project was to be redone, the main thing we would change is the influence third parties played in the pace of our progress. Because of miscommunications and slow response times we were unable to be as effective as we believe we could have been. Although the interviews that we conducted provided us with abundant amounts of information and provided a new perspective, if we had been able to contact more people and give them more time to respond to our phone calls and emails, we would have been able to make our conclusions stronger and our contribution to the project even more significant. However, we believe the perspective we did add to this paper will benefit USCG. The fact our work will not be just a suggestion to be considered by our sponsor, but rather the base work for an official government study gives us considerable pride.

This project has taught us: how to work as a team, how to handle bureaucracy, how to navigate company policies, and how to effectively communicate and network with people with different levels of understanding and knowledge about our topic. As a group we have learned to explain slowly and thoroughly, just because we understand the material does not mean our audience can do the same. This project has taught us to take a step back, edit and discuss our work critically as a third party.

We are very interested in seeing how our work will benefit the Volpe Center's study when it is published. We are hoping that with the ground work we have completed, they can take it a step farther and do even more for USCG. We also hope that our report or the Volpe Center's will be shared not just internally in USCG but potentially nationally or even worldwide to benefit the maritime shipping industry.

## **5.2 Reflections**

### **5.2.1 Ryan Cavanaugh's Reflection**

This project has taught me a lot about communication. Communication between individuals can be flawless, but if their larger organizations or departments do not communicate then things go much less efficiently, and create unnecessary problems. With this is the importance of making sure everyone is on the same page, and that everyone is aware of the input other stakeholders are giving. This can not only be seen inside the project, but also on a greater level between regulating bodies and industry. This can be solved through thoroughness, if your work is thorough and everything is written out then the questions on direction, or why something is important can be answered. My writing, because of this thoroughness, has developed substantially.

### **5.2.2 Jonathan Comden's Reflection**

The thing I learned from this project was to have confidence. With both the USCG and Volpe having their own opinion and structures and our advisors each having their own ideas and we were forced to pick a middle ground and defend it from all sides. We took in everyone's advice and reached our own conclusions from that. Our final product is not what anyone had envisioned, but I believe it is the best it can be and that it reflects the best points from all the guidance we received.

### **5.2.3 Savannah Redetzke's Reflection**

Over the course of this project, I have had many opportunities to learn both in terms of my writing, editing ability and my team dynamics. I have learned that I cannot do everything, as much as I might want to. I also have learned that while I do have skills that can be of use to this group, other members have strengths that I do not. This is the main function of a team, for different strengths to be brought together and I feel that we have accomplished this.

# Appendix A: Methodology

## A.1 Mission Statement

This project aims to give the background information for a study that will give the USCG the means to effectively and accurately assess the availability exhaust gas cleaning technologies for maritime applications.

## A.2 Methods

- 1) We determined the compatibility and benefits of monitoring technologies with EGCS technology by interviewing members of the maritime industries, through research into the technologies available, and analysis of previous studies.
- 2) We reported on the alternate means of compliance to MARPOL Annex VI by looking to official organizations, such as the EPA and USCG as well as various research institutes, and private industry.
- 3) We provided a background to MARPOL Annex VI, the social issues involved, and the development of emissions control technology, through research of previous studies and various articles.

## A.3 Interview Process

When possible, the interviews were conducted verbally with verbal consent to site by sector. Once we had consent, the goals for our project were outlined, and we told the interviewee our intended outcome for the interview. We proceed to conduct semi-structured styled interviews because this enabled us to ensure each person was asked the same questions allowing for comparable results while also allowing a loose enough environment that the participant could suggest things we have not thought of, provide additional information, and propose new resources to us.

If it was not possible to conduct a verbal interview, we sent an e-mail to participants asking for a written reply stating their willingness to participate and if they comfortable being cited by sector. Once participants replied willing to be interviewed and cited we sent them the questions (Appendix B). The downside to the email option was that there was less leeway to ask questions during the interview limiting the information gained to only our questions. We attempted to prevent this by inviting interviewees to include other thoughts were not direct answers to our questions. Questions used during interview process are listed in Appendix B the results of the interviews are listed in Appendix C.



# Appendix B: Questions for Maritime Industry

The following are the base questions used during the interview process no individual was able to answer every question either due to lack of knowledge or due to trade secret.

1. Do your ships or does the shipping sector you represent use exhaust gas cleaning systems (EGCS) or air scrubbers? What percentage of your fleet or your members do you think use scrubbers?
2. Do you (or your members) hold any MARPOL Annex VI Regulation 3 Exemptions permits or do you plan to apply for them?
3. Do you (or your members) hold any MARPOL Annex VI Regulation 4 Exemptions permits or do you plan to apply for them?
4. What is your primary strategy or what is the strategy you recommend for complying with ECA requirements?
5. What are the major engineering or materials issues involved in retrofitting a scrubber?
6. What do you see as the primary advantages of air scrubbers?
7. What are the primary disadvantages of scrubbers?
8. What concerns do you have about using or not using scrubbers as a compliance strategy?
9. What is the expected payback time on an installed scrubber? What other cost considerations are involved?
10. Do you have business concerns about your competitor's compliance strategies?
11. Did you consider using LNG or dual-fuel engines?
12. What specific problems have you experienced?
  - 12.1. Engineering?
  - 12.2. Materials?
  - 12.3. Technical?
  - 12.4. Scheduling and contracting?
  - 12.5. Economic?
  - 12.6. Legal?
13. Do you have monitoring systems installed with the scrubber? In port? At sea?
  - 13.1. Emissions
  - 13.2. Washwater
  - 13.3. Fuel consumption?
14. How do you currently measure and record emissions data?
  - 14.1.1. What system do you use?
  - 14.1.2. Is it a retrofit? Who installed it?
  - 14.1.3. How well do you like this system?
15. What are your opinions on continuous monitoring?
  - 15.1. Is this process necessary to the function of the air scrubbers?
  - 15.2. Should all ships do this?
16. What problems have you run into with monitoring systems? What testing do you do to ensure accuracy? Can this testing be done easily? How is it done - on board? Remotely?

17. How much maintenance is involved? What are annual scrubber maintenance costs? What are monitoring costs?
18. Are you considering upgrading this system? If so to what and why?
19. Do you have to report this data and to whom? Has there been any problems in doing so?
20. Is there anything that this system does not measure, SO<sub>x</sub>, NO<sub>x</sub>, and PM in particular?

# Appendix C: Interview Results

After writing the main portion of the report we better understood what information we needed to complete each respective section. We began conducting interviews to fill the gaps we found. Although, due to confidentiality any information that could be used to identify the individual will be omitted from the WPI submission. The final submission being made to the Volpe research center and USCG will present information by sector; in this section, the interviews are divided into sector and kept in their raw note form. After all the data from each sector has been presented we analyze the data in a short summary. At the end of the appendix we include suggested points of research gaps for Volpe to continue researching.

## C.I Non-technical administrators

Non-technology Administrators are defined as anyone in an administrative or executive role that is not a technician or involved in managing technicians.

### C.I.1 Non-technology administrator 1

**Interview Date:** 12/1/15

**Omissions:** Information regarding background and permit status

#### EGCS

- Dual fuel with a scrubber system is the most popular if you have the capital to pay for it
- EGCS are built to IMO regulations not to EPA regulations

#### LNG/ Duel Fuel

- Problem with just installing a LNG tank, is that LNG is not available at all ports, if a company wants a global vessel, it has to adapt to different ports which makes the duel fuel with a scrubber popular

#### CEM/ Monitoring

- There is disconnect between IMO wash water monitoring regulation and EPA wash water monitoring regulations.

### C.I.2 Non-technology administrator 2

**Interview Date:** Unknown

**Omissions:** None

#### Area of Expertise

- Your [interviewee's] knowledge is based on an overview of the company, not the technical aspect of the ship

## **EGCS**

- Primary method of compliance is burning complaint fuel
- Installing first EGSC system, don't know the effects of installation as of yet
- Rationale for installation is that it is "common knowledge" the EGCS is cheaper since .1% sulfur content fuel is 30-40% more
- You expect full payback for system in savings
- Installation of EGSC system is expected to be 6 weeks (dry dock)

## **Regulations**

- You have not applied for Reg 3. or 4 exemptions since to date you do not feel you need them

## **LNG/ Dual Fuel**

- You are looking into LNG and dual fuel technology

## **CEM/ Monitoring**

- Hard time finding CEMs, validate our struggles to navigate the market and it's applications to Maritime Applications
- Emissions are not currently measured since you are not required to measure them.

## **C.1.3 Non-technology administrators 3**

**Interview Date:** 12/4/15

**Omissions:** Area of operation, business details, ship operation

## **EGCS**

- EGCS seemed like best option – applied for permits
- Was concerned with the retro fit specifically, how it would all fit in the vessel
- Uses closed loop freshwater scrubber
  - Caustic Soda is a dangerous chemical and no one has domestic experience using it on a ship
  - Volume and size of the tanks were an issue
  - How do you get caustic soda on the ship safely, efficiently
  - Needed to install insulation because caustic soda freezes at 50F (often chilly in the great lakes)
  - Needed to install eye wash stations and showers for crew and have one on shore for the truck driver
  - Normally would use air pressure to pump it aboard but the tanks were above the truck so they couldn't get enough head on the line, had to install new piping and pumps to fill the tanks
- Scrubbers are a complicated system and he had a very high learning curve with them
- Discharging systems are important and complicated need to comply with VGP
- A lot of trial and error for the treatment and discharge
- The fuel cost delta makes using EGCS a better option
- Used ensolve system did not like it switched to centrifugal – not for compliance reasons but for simplicity and economical reasons – ensolve had filters that needed a lot of maintenance

## **Regulations**

- Does not hold reg 3 or 4 permit – simply has Coast Guard R+D permits
- Application is an easy process (App -> Q+A -> permit)

### **LNG/Duel Fuel**

- Converting to ultra low sulfur fuel (Light oil) was incredibly expensive
  - Needed new fuel pumps and injectors, even fuel coolers to manage viscosity within the engine
  -
- Very confident in all systems – scrubber and meters

### **CEM/ Monitoring**

- Monitors emissions with CEMS right in the stack – measurements every 4 minutes
- Monitors pH and turbidity with UV or fluorescent light but one type does not work could not remember which
- They verify all their meters with lab testing periodically and had a team on board the boat to get it accredited, and all are calibrated with test gas once a year
- All meters send the data into a hard drive

## **C.1.4 Non-technology administrator 4**

**Interview Date:** 12/9/15

**Omissions:** Information about fleet and company

### **EGCS**

- The EGCS project is focused on retrofitting existing ships
- Major EGCS engineering issues include: adjusting the standard EGCS system, creating entry routes for the equipment's installation and the space constraints
- Primary advantages of EGCS is the efficiency that the EGCS removes the SOx without a major impact on the fuel supply infrastructure of the company
- Primary disadvantages of EGCS is the installation cost and the continuous monitoring challenges
- The payback time of a EGCS system depends on the ship's operating patterns but is estimated at roughly 3-5 years
- The maintenance of these EGCS include routine inspections and maintenance in general and special daily attention to water analysis systems
- The Annual costs of this system is not defined, but does include the energy cost of seawater pumps
- Operational experience has led to a series of modifications to the system, including a modification to reduce of risk of carryover and to increase the washwater discharge pH levels on some ships

### **LNG/Fuel Switching**

- Retrofitting existing ships to use LNG is very difficult because of the requirement for added tankage to accommodate the LNG
- Limited use of LNG is possible for a single engine in a large ship but the complete conversion of existing ships is limited only to new buildings

- Another concern about LNG is the availability of LNG in most North American Ports
- There is consideration for dual fuel engines for some new builds,
- Some trials are being planned for few existing ship's engines using LNG, but the costs of LNG and of conversion is high and the area of advantageous use are limited

### **CEM/ Monitoring**

- Has monitoring systems for emissions, washwater and fuel consumption installed with EGCS on their ships
- The monitoring systems that they use are three major exhaust gas analyzer makers, two major water analysis system makers
- The monitoring systems have been both installed on retrofitted ships and new builds.
- The Company collects data for each operating EGCS unit every 3 minutes and is stored on a stand alone computer onboard. This produces an enormous amount of data over a year.
- The amount of data is nearly 40,000 records for one ship or 2 million records per year for 50 ships with three operating EGCS units
- Data management is an issue and this company is working with the EPA and CG to come up with practical options for this
- The other challenges with monitoring systems are: achieving high consistent levels of reliability in monitoring systems
- To provide a check to their monitoring systems, they provide calibration training to the onboard EGCS engineers and others, require routine calibration checks and re-calibration, and constant checking of any anomalies against other installed and hand help devices
- They believe that a type approval approach is the best path going forward, I.e. converting Scheme A to a Type Approval
- Monitoring systems measure SO<sub>2</sub> and CO<sub>2</sub> but normally NO<sub>x</sub> or PM

### **Regulations**

- Uses EGCS mainly to comply with the ECA requirements
- Originally had 32 ships with Regulations 3.2 permits, many have now expired
- A number of the ships have transitioned from exemptions to equivalencies with EGCS within regulations 4
- The mixed regulatory environment brings a level of uncertainty to ship's staffs that inhibits the use of EGCS systems

### **C.1.4 Conclusions about non-technical administrators**

A key point that all four non-technical administrators stated in interviews is that EGCS is the cheapest option for compliance. EGCSs are cheaper than burning complaint fuel and LNG is not feasible at this time. There are two important points that can be noted about the differences between non-technical administrators that had worked with EGCSs versus administrators who had not worked with them. First, the non-technical administrators that do not currently have EGCSs see no reason to have CEM technologies since it is not a legal requirement, however the two administrators with an EGCS and

a research and development permit, continuously measure emissions every 3-4 minutes. Secondly, administrators that do not currently have EGCSs installed had nothing negative to say about them. Whereas the administrators with experience were able to provide a lot of insight into additional problems; most of which have little to do with the how the system functions it, but other aspects of continuously operating an EGCS (such as training, dangers and complications with handling the solution).

## C.2 Technical Division

Technical division is defined as technicians and engineers and the admin who manage them.

### C.2.1 Technical Division I

**Interview Date:** 12/2/15

**Omissions:** Area of expertise, EGCS trade secret details, LNG information

#### Regulations/ Permits

- The regulation process allows for companies to make bold moves to pioneer this equipment still with risk but not as much as without the permits
- Hoping the guidelines put into place later for washwater and emissions will reflect the commitment and risk the companies are making now
- All of the CLIA ships are foreign flags and work with the coast guard for the permit process – often coordinated by the flagstate – coordination can always be improved
- IMO is doing extensive discussion on open loop type in ports and bay areas – i.e. Baltic and Mediterranean
- Hopes foreign states keep IMO regulations to make things easier

### C.2.2 Technical Division 2

**Interview Date:** 12/2/15

**Omissions:** Job details

#### EGCS

- General knowledge of scrubbers is limited to MEPC.184 (59)
  - Would love to know more to educate himself and other ships
  - Great opportunity to inform and thus boost compliance methods and knowledge → push market forward
- Currently he is unsure if there are retrofits in the fleet
- He has questions from clients regarding dong trials with scrubbers and currently some are conducting trials (unsure of what type of trials) 3 ships are doing trials
- Another client is contracted to put 5 or 6 scrubbers on their ships by the year 2017

- Contracted because scrubbers are customized so they need to be manufactured ahead of time to meet specific ship
- Concern from client because does not want to put scrubbers on and then have 2020 limit changed *see below*
- Does not want to dry dock ships and spend oodles of money to not have to
- Nervous about EGCS because of the expensiveness of it

### **LNG/Fuel Switching**

- Technical issues with Ultra low sulfur fuel – engine stopping – safety bulletin sent to us by USCG

### **Regulations and Monitoring**

- Mixture of boil off natural gas and HFO for compliance – EU certified method of compliance
  - Largest problem with mixture method is no real way to check compliance because no bunker delivery notes for low sulfur fuel
  - Ensure compliance via application and calculations % blending [ECD stroke 769 stroke EU annex 1 + 2]
  - All data is recorded this way
  - IPP equivalency certificate regulation 18.? And appendix 5 (BDN Notes) of Annex VI
- 1 client applied for trials with USCG – accepted and worked with boil off natural gas and HFO [3.5% or 4.5%]
- 2020 regulations to be 0.5% sulfur by content IF AVAILABLE
- June 2017 at MEPC conference the availability of 0.5% fuel will be checked and a recommendation will be made by 2018 on if 0.5% is a reasonable limit

## **C.2.3 Technical Division 3 and 4**

**Interview Date:** 12/6/15

**Omissions:** Ship Details

### **Engine Control Room:**

- CEMs monitoring interface – all collected measurements in real time (every 3 minutes)
- Scrubber touch screen interface showing the emissions, load capacity, and washwater flow rate

### **Engine Room:**

- Seawater pump and discharge
  - Removed an incinerator and sea chest to be installed
  - Had delivery filters and monitoring system to monitor pH and intake flow
  - Intake pumps can run dry without damage (because they are centrifugal)
- Dilution tanks were just pipes, pH was monitored and controlled, diluted with engine cooling water
- Clean exhaust was measured with cross stack analyzer (light system)



- Maintenance cannot be down consistently, need to have a few days to change everything out and is contracted
  - The engineers have no paperwork for specifications or any replacements parts
  - Do not fix sensors themselves
- Scrubber touch screen interface showing the emissions, load capacity, and washwater flow rate
- Constant learning curve, they have no training on these things and cannot adequately problem solve because are not familiar with system
- Engineers are constantly visually checking the system – leaks are a huge deal because salt builds up and can damage other functions of the ship
- Engineers are not trained with the sensors

### **C.2.4 Conclusions about Technical Division**

Key points that were emphasized by all members of the technical division were that EGCSs do not operate smoothly (i.e. installation and maintenance require more work that was anticipated). Most of the technicians put emphasis into the importance of CEM technology to the operation of the system not because it is required but because there is no way to know if the EGCS is working without CEM systems. Finally, half of the technicians expressed concerns about both the current ECA regulations and future IMO regulations. They hope that these regulations can be met with the currently installed EGCS systems or with limited modification to maximize their initial investment and prevent another major investment.

## **C.3 Consultants**

Consultant are defined as anyone who's role is to advise the Maritime community either in installation of emissions control technologies, operation of emissions control technologies, or compliance options for MARPOL Annex VI.

### **C.3.1 Consultant I**

**Interview Date:** 12/1/15

**Omissions:** Current Project Details,

#### **EGCS**

- The largest technical concerns were with space – how to get everything to fit inside the ship
- The inlet pumps for the washwater (SEAWATER) are incredibly difficult to include in a retrofit because holes need to be cut into the hull to inlet water
  - These are often not centrifugal and need to be below the waterline
- The balance of the ship will be off because of the sheer weight of this system
- The engine also needs to be able to power the EGCS
- There was the huge potential for washwater contamination
- Deck reinforcement
- CHECK THE SUMMARY DOCUMENT TECHNOLOGY REVIEW IMO TIER 3

- Major concern with particulate matter filters if they fail they have the chance of completely stopping the engine – unacceptable for major safety reasons
- Only way to be installed would be to include a bypass
- In his opinion there are so many things to consider a retro fit is incredibly tough
- New builds are much easier to incorporate
- Has not heard of NO<sub>x</sub> effects from EGCS but SCRs work well with that

#### **CEM/ Monitoring**

- Monitoring CO<sub>2</sub> and SO<sub>x</sub>

### **C.3.2 Consultant 2**

**Interview Date:** 12/1/15

**Omissions:** Current Project Details

#### **EGCS**

- Scrubbers create sludge in limited amounts, there is a provision in Annex VI, regulation 17 which requires that there are facilities that sludge must be deposited at
- Coast Guard has a database that should have all the certification of adequacy for the sludge deposal facilities, however it is not on the website so where are these facilities?
- The location of the facilities and if they are available is a concern for ships that use scrubbers
- Scrubber has to fit in stack, some ships have had to enlarge their stacks to accommodate
- Some carry chemicals to treat the pollutants, so safety measures must be put in place for these chemicals in addition to these chemicals needing to be replaced
- Scrubbers require more maintenance (such as cleaning the scrubber), though it is minimal and the crew requires training on how to operate the scrubber as well as be able to monitoring it to ensure it is working correctly
- There is a possibility of it not working when you need it to so the ship might be required to carry low sulfur fuel in addition to the scrubber
- Using Scrubbers can lead to long term savings and cost
  - Don't have to buy low sulfur fuel, can by the cheaper higher sulfur fuel
- Paying back a scrubber depends solely on the price differential of fuel

#### **LNG/Fuel Switching**

- Allows for no fuel switching (between low and high sulfur fuels), which can cause problems with the marine vessel, such as engine failure
- In addition, if a ship does use fuel switching, it has to carry 2 different types of fuel

### **C.3.3 Consultant 3**

**Interview Date:** 11/24/15

**Omissions:** Details of EGCS installation, Permit status

## Areas of Expertise

- Helps company implement strategies for installing EGCSs

## EGCS

- EGCS was supposed to clean PM and SO<sub>x</sub> but it didn't
- EGCS required a lot of modifications and maintenance
- EGCS was an operational hassle and didn't work in field tests
- EGCS take up too much space on ship and the retrofitting includes reinforcing the decks
- The cost of running the EGCS is larger, it also requires fuel to run
- Storing of the effluent, such as wash water, tanks are required

### C.3.3 Conclusions about Consultants

The key opinions that were expressed by all the consultants is that the EGCSs do not work as advertised. A particular emphasis was put on the regular and continuous maintenance that is involved with these systems. The consultants also discussed the difficulties with retrofitting a ship. As well as, the fact the payback time of an EGCS was not guaranteed and depends on fuel prices, and the complexity of the retrofit. Furthermore, two of the three consultants expressed concern about several hidden dangers associated with EGCSs, including the potential for engine failure, the storage of sludge, and the storage of chemicals.

## C.4 Overall Analysis and Suggestions for Volpe

By dividing the interview responses into sectors and analyzing them independently we are able to see general trends emerging. First, the more one works with EGCSs the less one likes them, non-technical administrators that have no experience with an EGCS think it is simple cost effective fix; consultants and technicians that have extensively worked with the systems state they are difficult to install, run and that the payback time is not as black and white as advertised. Secondly, all three groups have very different perspectives concerning EGCSs, non-tech administrators view EGCSs simply as a business decision, consultants express alarm at the dangers involved in installation and running, and technicians simply view it as another system that they are charged with maintaining. While these natural biases seem obvious it is important to consider them while interviewing individuals. Thirdly, the most common trend that all sectors mentioned was the level of maintenance required for EGCSs and the additional equipment required to handle chemicals.

There are several interesting results that we noted from our interviews that warrant a closer look and we would recommend that Volpe look into them during their research. The first is the gap in opinions about CEM technology, consistently those planning to install EGCS systems do not consider them necessary, while all those currently operating EGCS systems talk about CEM technology as if they were required. The second result was what problems happen to what ships and why? All our interviews provided insight into different problems about the installation of EGCSs, however these problems were not consistent and interviewees did not provide details about their ships. This led to us having an

inability to determine what types of ships have what problems. The third result was that several individuals stated the LNG is not viable because North America does not have enough LNG ports. However, others have stated that LNG is most popular in North America and that North America is going to start exporting LNG. Why is there such a difference in opinion?

# Appendix D: Conversion Table

<b>SI* (MODERN METRIC) CONVERSION FACTORS</b>				
<b>APPROXIMATE CONVERSIONS TO SI UNITS</b>				
<b>Symbol</b>	<b>When You Know</b>	<b>Multiply By</b>	<b>To Find</b>	<b>Symbol</b>
<b>LENGTH</b>				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yard	0.836	square meters	m <sup>2</sup>
ac	acres	0.405	hectares	ha
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>
<b>VOLUME</b>				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>
NOTE: volumes greater than 1000 L shall be shown in m <sup>3</sup>				
<b>MASS</b>				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
<b>TEMPERATURE (exact degrees)</b>				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
<b>ILLUMINATION</b>				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>
<b>FORCE and PRESSURE or STRESS</b>				
lbf	poundforce	4.45	newtons	N
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa
<b>APPROXIMATE CONVERSIONS FROM SI UNITS</b>				
<b>Symbol</b>	<b>When You Know</b>	<b>Multiply By</b>	<b>To Find</b>	<b>Symbol</b>
<b>LENGTH</b>				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
<b>AREA</b>				
mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
ha	hectares	2.47	acres	ac
km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m <sup>3</sup>	cubic meters	35.314	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
mL	milliliters	0.034	fluid ounces	fl oz
<b>MASS</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz

## SI\* (MODERN METRIC) CONVERSION FACTORS

### APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>TEMPERATURE (exact degrees)</b>				
°C	Celsius	1.8C+32	Fahrenheit	°F
<b>ILLUMINATION</b>				
lx	lux	0.0929	foot-candles	fc
cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	fl
<b>FORCE and PRESSURE or STRESS</b>				
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>

\*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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