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Failure Modes and Effects Associated with Installing and Operating Abatement Technologies for the Reduction of NO_x and SO_x Emissions on Board Ships

Master of Science Thesis

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Gothenburg, Sweden, 2011
Report No. X-11/261

THESIS FOR THE DEGREE OF MASTER OF SCIENCE

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Printed by Chalmers Reproservice
Gothenburg, Sweden, 2011

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Abstract

During the last decade the shipping industry has been subjected to regulation amendments that resulted in a need to reduce ship emissions to air. Nitrogen oxides and sulphur oxides belong to the pollutants that were targeted for reduction. As a consequence, there has been an increased interest in technologies that reduce the amount of pollutants emitted by ships.

The number of installed abatement units is growing, as they are installed new failure modes are introduced among the systems onboard ships. In order to understand the potential hazards involved in installing and operating the technologies, a study of existing solutions was carried out highlighting several potential failure modes with every technology studied.

Since no dedicated rules exits for abatement technologies, and to be able to limit the possible causes and effects of failures associated with the technologies, the failure modes were compared to the current rulebook of the classification society Det Norske Veritas. The aim was to find suitable existing regulations applicable to the studied technologies. The rules were spread through various chapters of the rulebook without focus towards abatement technology.

The results of the technology study revealed various failure modes, among the most common belonged corrosion, increased backpressure and insufficient measures to ensure fail to safe principles. The comparison between potential failure modes and current rules revealed a gap containing unregulated potential hazards.

This background study resulted in a compilation regarding unregulated hazards. It will serve as a basis for rulemaking towards safe installation and operation of abatement technologies.

Keywords: Abatement technologies, Exhaust gas cleaning systems, Failure modes, Regulations, NO_x, SO_x, Ship emissions to air.

Preface

This report is the result of a Master´s thesis carried out from January to June 2011. The thesis comprises 30 credits and completes the Master´s Programme in Naval Architecture at Chalmers University of Technology. The work has been performed at Det Norske Veritas headquarters in Høvik in close cooperation with the Pollution Prevention Group. The working environment has been very stimulating for us and the experienced employees at the office have been a great resource during the work.

We want to thank our examiner at the Department of Shipping and Marine Technology, Associate Professor Karin Andersson for her advice and guidance throughout the project.

We want to thank our supervisor at the Department of Shipping and Marine Technology, Hulda Winnes for her advice and guidance throughout the project.

Further, we want to thank our supervisor at DNV, Helge Drange together with the Pollution Prevention Group for sharing their knowledge, experience and contacts with us.

We would also like to thank administrator Kristin Buntz for all administrative help.

Finally we would like to express our gratitude by thanking everyone at the DNV office who has contributed with information and help during our work.

Høvik, May, 2011

Victor Pettersson
Erik Thune

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List of Abbreviations

CO	Carbon monoxide
CO_2	Carbon dioxide
DNV	Det Norske Veritas
DWI	Direct water injection
ECA	Emission control area
EGR	Exhaust gas recirculation
FMEA	Failure mode and effect analysis
GHG	Green house gas
HAM	Humid air motor
HNO_3	Nitritic acid
IMO	International Maritime Organisation
MARPOL	International Conference for the Prevention of Pollution from Ships
MEPC	Marine Environmental Protection Committee
NaOH	Sodium hydroxide, caustic soda
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
ODS	Ozone depleting substances
PM	Particle matter
ppm	Parts per million
SCR	Selective catalytic reduction
SECA	Sulphur emission control area
SFOC	Specific fuel oil consumption
SO_x	Sulphur oxides
VOC	Volatile organic compounds
WIF	Water in fuel emulsion

1. Introduction

Traditionally pollution associated with the shipping industry has been limited to visible emissions and discharges to sea, such as black smoke and oil spills. The environmental impacts of oil spills and oily discharges have been noticeable and recognised as originating from shipping. The first regulations for these types of pollutions were agreed upon in the International Maritime Organisation (IMO) in the 1950's and have been amended further in different stages ever since [1].

Air pollutants from ships are receiving increased attention, while land-based transport and industry have had stringent rules regarding emissions for decades, the shipping industry is just starting to lower its air emissions. The residual fuels traditionally used in shipping contain large amounts of sulphur, directly proportional to the sulphur oxide (SO_x) emissions of combusted fuel. Due to lack of regulations, the engines have so far been optimized with regard to fuel consumption rather than minimizing emissions such as nitrogen oxides (NO_x).

In 1973 IMO adopted the International Convention for the Prevention of Pollution from Ships, known as MARPOL 73/78 [2]. It was later amended in 1978 and 1997 where by the latter introduced a new Annex to MARPOL, known as Annex VI. The revised Annex VI contains the regulations for the prevention of air pollution from ships and seeks to limit air emissions. Currently NO_x, ozone depleting substances (ODS), SO_x and volatile organic compounds (VOC) are regulated by the Annex [3].

As a consequence of the new air emission regulations engine manufacturers, shipbuilders, ship owners, flag states and classification societies have to act accordingly. A scheduled stepwise strengthening of international regulations of NO_x and SO_x emissions is in progress, as described in Section 4.1 and 4.2.

NO_x is formed when oxygen and nitrogen are present at elevated temperatures, e.g. during combustion. The pollutant can be reduced either by altered combustion to minimise the formation of NO_x or by removing it from the exhaust gases.

To comply with the most stringent emission limits for SO_x there are two main measures to choose from. As stated above, the SO_x emissions are directly proportional to the sulphur content of the fuel, thus a fuel with lower sulphur content, e.g. liquefied natural gas (LNG), results in reduced SO_x emissions. However, instead of changing fuel SO_x can be removed after the combustion using a scrubber, see Section 6.7

Since abatement technologies are feasible solutions to comply with emission regulations coming into force, an increase of installations is expected in the near future. As the number of installations grows there is a need to understand the technologies in order to be able to proactively manage risks that can be associated with their installation and operation. This report seeks to identify and analyse the failure modes and consequences associated with installation and operation of abatement technologies to reduce emissions to air of NO_x and SO_x from ships. The report is carried out in collaboration with Det Norske Veritas (DNV) and is specifically written to compare the potential failure modes and effects with rules and regulations covered in DNV's rulebook.

1.1. Background

Det Norske Veritas is a classification society with long experience of managing risks in the shipping industry. Traditionally risks of interest to classification societies have been associated with ship survivability, propulsion and safety of the crew. As IMO regulations have expanded to include environmental aspects of shipping, DNV has adopted and expanded their environmental regulations and notations as well as established an environmental profile throughout the years.

DNV sees the need of investigating the consequences of installing and operating abatement technology onboard ships. Many of the risks associated with abatement technologies are covered by the Class rules because similar problems can occur with other systems onboard, however there are no rules written solely for abatement technologies and the risks are thus not fully covered. The number of ships installing them is expected to grow as the set forth emission regulations comes into force.

Currently DNV is establishing rules regarding some of the abatement technologies to meet the growing demand. In order to establish rules that keep the risks at acceptable levels it is necessary to combine experience from similar existing systems on board ships with knowledge about the designs on the abatement technology market.

Incidents stretching from minor complications to loss of propulsion that are suspected to have a connection to installed abatement technologies have been reported. Although the suspicions have not always been confirmed, incidents have created further interest in the topic and act as a basis for this report.

1.2. Objective

The objective of this thesis is to:

- Investigate causes for failure and their potential effects.
- Identify existing rules that are applicable for abatement technologies.
- Give an indication of what potential failures that needs to be regulated in class rules with regards to NO_x and SO_x abatement technologies.

The main question to investigate during this thesis can be stated as:

How well are failure modes associated with installation and operation of abatement technologies covered by the DNV rulebook?

1.3. Scope

The scope of this thesis is three general parts providing basic understanding of impact of emissions, the regulations established to reduce NO_x and SO_x emissions and theory about the formation of the pollutants. The focus is then turned towards the core topics of the thesis being abatement technologies, their possible failure modes and applicable rules able to regulate them.

The paragraphs on environmental impact of NO_x and SO_x emissions provides basic information of their effect on human health and environment. The impacts are root causes for the regulations adopted to reduce the emissions from ships. Even though a number of emissions are regulated, only the two (NO_x and SO_x) related to the investigated abatement technologies are studied with regards to impact and regulations.

Secondly the regulations to reduce the emissions are described. A summary of international, national and local regulations is provided to give an overview of the development. The part also touches briefly upon the way the shipping industry will be affected by the regulations and finally the consequences of reducing emissions from ships.

To be able to understand the working principles of the abatement technologies, a brief review of the theory behind the formation of the pollutants is given. The two pollutants of interest are described separately since the formation during combustion differs significantly between the two.

A technology review is provided of the six abatement technologies studied. The review concerns typical working principles, components, system layouts and reduction rates of the different technologies. The review is necessary to be able understand the identified failure modes presented subsequently.

Possible failure modes are analysed for the different technologies. Causes and effects of the failure modes are presented as well as summarising tables presenting the potential failure modes for every technology.

The identified failure modes are compared to the DNV rulebook with the ambition to find rules applicable to the technologies with the ability to prevent them from occurring. Extensive studies of the different chapters in the rulebook have been carried out in order to find applicable rules. As the rules currently have no, or little, reference to abatement technologies references and analyses of the applicability is provided in the section.

The general parts concerning environmental impact of emissions, regulations to reduce NO_x and SO_x and their formation provide necessary background information to fully understand the core parts this thesis. The core parts are providing the required information in order to answer the main question raised in the objective.

1.4. Delimitations

Failure modes will be considered regardless of the probability that the technology will find a market. One possible consequence of using abatement technologies is that they will malfunction and thus lead to violation of MARPOL Annex VI. This is however not the main concern for classification societies, focus will instead be towards possibilities of damaging the ship, its crew or its surrounding. A risk analysis regarding the chance of occurrence will not be carried out, failure modes which can lead to loss of propulsion or other serious damages will be considered unacceptable and should be avoided with all measures available.

It should be noticed that even with the most extensive design efforts to minimise failure modes, external influences such as human factors will always affect the equipment and can lead to unexpected failures. These external influences will however not be regarded in this thesis.

1.5. Method

The thesis has consisted of three main tasks, a literature study complemented with interviews, a failure mode and consequence analysis and analysis of the current regulations of the DNV rulebook applicable to abatement technologies.

The literature study was carried out covering a wide range of topics such as emission reduction theory and existing abatement technology. Interviews were conducted with surveyors, engineers as well as engine and technology manufacturers to complement and enhance the literature study.

Further, failure and consequence analyses were performed for the different technologies revealing several potential failure modes for each technology. These were finally compared to the DNV rulebook in an analysis revealing applicable rules for the different technologies as well as gaps in the current rulebook and some of the failure modes.

2. Methodology

This thesis was built on three main tasks, (i) performing a literature study and interviews, (ii) a failure mode and consequence analysis of the different abatement technologies and (iii) a comparison between failure modes of the different technologies and the rules of the DNV rulebook.

i) The literature study was covering existing rules regarding ships emissions to air, the formation of ship emissions from fossil fuels, existing abatement technologies, emission reduction theory and existing rules in the DNV rulebook applicable to abatement technology. It gave insight in what areas earlier work has been focusing and acted as the basis for further investigations. The literature study was performed as subtasks in the following order:

- Background study
- Study of existing and near future technology
- Study of relevant existing standards and international regulations
- Study of existing regulations in the DNV rulebook.

As literature hereunto have not been focusing directly on linking abatement technologies to potential risks, DNV surveyors and engineers as well as technology and engine manufacturers have had important experience to provide.

To complement and enhance the literature study interviews were conducted. Interviews without standard or structure can be used when a qualitative analysis of the result will be made [4], thus unstructured and unstandardised interviews were performed which focused on the interviewee´s areas of expertise. Open questions were used resulting in answers dependent on the interpretation and experience of the person interviewed. The results mainly served the purpose of finding subjects of interest for further research.

ii) The failure mode and consequence analyses performed for each technology studied were in some senses similar to failure mode and effect analyses (FMEAs) [5], although with some significant simplifications and differences. A FMEA performed in the industry usually concerns a product, design or process, not a technology, and failures are normally ranked after severity, occurrence and possibility to be detected. When the approach is used in product development, actions are normally taken to eliminate or reduce high-risk failure modes. However, the technologies analysed in this report were never ranked. Since the analyses were performed on technologies rather than specific products they tended to become more general. Rather than eliminating failure modes a comparison between failure modes of the different technologies and the DNV rulebook was carried out as described in task iii). The different failure modes identified were finally summarised and presented in a table for each technology.

In order to complete the analyses in this thesis to become full FMEAs the failure ranking of severity, occurrence and possibility to be detected must be carried out. It requires either statistical data or experience to make qualified estimations regarding the ranking, of which neither have been possible to find or perform during this thesis.

iii) A gap analysis may be associated with management tasks but the fundamental principle is based on identifying the current situation and compare it with the desired situation. In other words a gap analysis reveals the gap between the desired state of performance and the current state of performance [6]. The principle of a gap analysis was suitable for the subsequent task of this thesis. As described in task ii) the failure modes were identified. With the failure mode as a basis the DNV rulebook was reviewed in order to find potential rules applicable to the abatement technologies. General and specific rules for different systems were analysed and interpreted in order to find applicable rules able to eliminate or reduce failure modes and their effects. The results revealed rules applicable to the technologies and the gaps, the currently unregulated failure modes. The results were summarised in tables based on the tables from task ii).

3. Environmental Impact of Emissions

Various pollutants are associated with burning of fossil fuels. Typical monitored criteria pollutant species are carbon monoxide (CO), NO_x, ozone (O_3), particulate matter (PM) and SO_x which are related to health problems as well as contribution to acidification, eutrophication and damage to crops [7].

Further, greenhouse gases (GHG) and specifically CO_2 are emitted from the combustion of fossil fuels. The GHG emissions from shipping is rather low, in 2007 shipping contributed to 3.3% of the world total CO_2 emissions [8].

This report however focuses on the technology to reduce NO_x and SO_x. These pollutants have a major impact on the region where they are emitted, thus leading to coastal regions being adversely effected by adjacent shipping. Scandinavia and north-western North America belongs to the most exposed areas where shipping contributes by 25 - 50% to the total nitrate wet deposition. The sulphur deposition is also high in the same areas and shipping contributes by 15-25% to the total deposition, according to S.B Dalsøren et al.[9], According to Cofala et al. [10] NO_x and SO_x emissions from international shipping in Europe accounts for 30% of the land based emissions in the EU-25.

In subsequent Sections, a more detailed description of the consequences of NO_x and SO_x emissions to air will follow.

3.1. Nitrogen Oxides

NO_x emissions have adverse impact on primarily four categories; (i) health effects, (ii) acidification, (iii) photo-oxidant formation and (iv) eutrophication [7].

i) The World Health Organization (WHO) [11] reports that NO_2 can alter lung function and is a toxic gas that has a significant impact on health, even at short-term exposure of higher concentrations. The health risks can be attributed to direct exposure to the gases but probably to an even larger extent to exposure to particles. Fine particles are formed as the gas condensates and reacts with other gases in the atmosphere.

ii) NO_x is one of the primary sources of acidic deposition such as rainfall, acidic fogs, mists, snowmelt, gases and dry particulate matters. Depositions of acidic substances cause several adverse environmental effects including damage to forest and vegetation as well as changes in soil and surface water chemistry [12].

As an example, nitrogen gases such as NO_x enter the atmosphere and rapidly react with moisture in the air to form nitric (HNO_3) acids. The acids are lowering the pH of the rainfall, so called acid rain. Rain in equilibrium with atmospheric CO_2 has a pH of 5.6. However, in industrialized areas acid rain often have a pH below 4.5 and severely acidic deposition may have a pH of less than 4.0 [12]. Eventually the acid rich rain falls over land and sea affecting mainly soil and inland water, especially those with a low buffer capacity, influencing e.g. the growth of plants.

Acidic deposition may also impact buildings, structures and monuments constructed using materials such as steel, limestone, bronze and marble [12].

iii) Photo-oxidant formation is the term used for formation of species like Ozone (O_3) by photo-chemical induced processes. In presence of VOC, NO_x and sunlight net formation of Ozone can occur [7]. Ozone represents one of the major scientific challenges associated with urban air pollution and adversely affects human health as well as crops and forest eco systems [13] [11].

iv) In order to provide conditions for sustainable biomass growth sunlight and nutrients are necessary. The limiting nutrients are usually phosphorus or nitrogen and an existing surplus of the limiting nutrient may lead to luxuriant growth of plant life that is affecting the ecological balance of the waters, known as Eutrophication [14]. It is usually associated with e.g. algal blooming that may lead to decreased biodiversity as well as anaerobic seabeds. Dead organic matter decomposes at the bottom of the sea consuming oxygen that in combination with insufficient water circulation may lead to anaerobic seabeds.

3.2. Sulphur Oxides

SO_x emissions have adverse impact on mainly two categories; (i) health effects and (ii) acidification.

(i) The health effects are the same as those of NOx and hence associated with altered lung function but also respiratory symptoms for asthmatics [11].

(ii) The acidification process is the same as described in Section 3.1. However, SO_x emitted to the atmosphere forms the acid H_2SO_4 as it reacts with moist and this acid is associated with the acidification caused by SO_x emissions [13].

4. Regulations to Reduce Emissions

The International Maritime Organization is a specialised agency of the United Nations which purpose is to regulate international shipping, one of its areas being environmental issues. In 1997, IMO added Annex VI to the MARPOL Convention which regulates emission to air, together with the NO_x Technical Code which is mandatory under MARPOL Annex VI. In 2005, on the Marine Environmental Protection Committee 53rd session (MEPC 53) agreed, in light of the technological improvements, to the revision of the MAPROL Annex VI together with The NOx Technical Code to further decrease the emission levels. This resulted in the MEPC 58 adopting the revised MARPOL Annex VI together with the NOx Technical Code 2008, which got final acceptance on 1 January 2010 and entered into force on 1 July 2010 [3].

MARPOL Annex VI covers a variety of emissions to air. However, the abatement technologies regarded in this thesis are designed to decrease NO_x and SO_x emissions. The regulations governing NO_x and SO_x emissions from ships correspond to Regulation 13 and Regulation 14 of MARPOL Annex VI why these will be shortly described below. The NOx Technical Code provides mandatory procedures for the testing, survey and certification of engines to comply with the MARPOL Annex VI. The Code's content is extensive and its main concern is not the ships' safety why a description of it has been left out from this report.

Designated areas with even stricter emission limits have been formed, so called Emission Control Areas (ECAs) which reduces the environmental impact from shipping, mainly locally. The areas together with other emission reducing initiatives will be discussed further in Section 4.3.

4.1. MARPOL Annex VI Regulation 13 - The Reduction of NO_x Emissions

Regulation 13 of the MARPOL Annex VI regulates NOx emissions and applies to any engine that has a power output of more than 130 kW or is installed, or undergoes a major conversion, on or after 1 January 2000. Assuming an engine falls under this regulation, the emission limits are then dependent on when the ship is constructed. The NOx emission limits are divided into three Tiers and the construction date of the ship determines what Tier that has to be followed.

Tier I applies to ships constructed on or after 1 January 2000 and prior to 1 January 2011, and to ships constructed before 1 January 2000 which undergoes a major engine modification as defined in Regulation 13, paragraph 2.1. If a ship has a power output of more than 5,000 kW, a per cylinder displacement at or above 90 litres and is constructed on or after 1 January 1990 but prior to 1 January 2000 it shall also comply with Tier I.

Tier II applies to all ships constructed on or after 1 January 2011.

Tier III applies for ships constructed on or after 1 January 2016, and solely when sailing in ECAs, unless;

- The ship is less than 24 m and used solely for recreational purposes; or
- The ship has a combined nameplate diesel propulsion power of less than 750 kW and it is demonstrated that the ship cannot comply with Tier III because of design or construction limitations

No later than 2013 a review of the technological developments will be carried out to ensure that Tier III is feasible to implement [3].

The emission limits for the different Tiers depend on rated engine speed and are visualised in Figure 1.

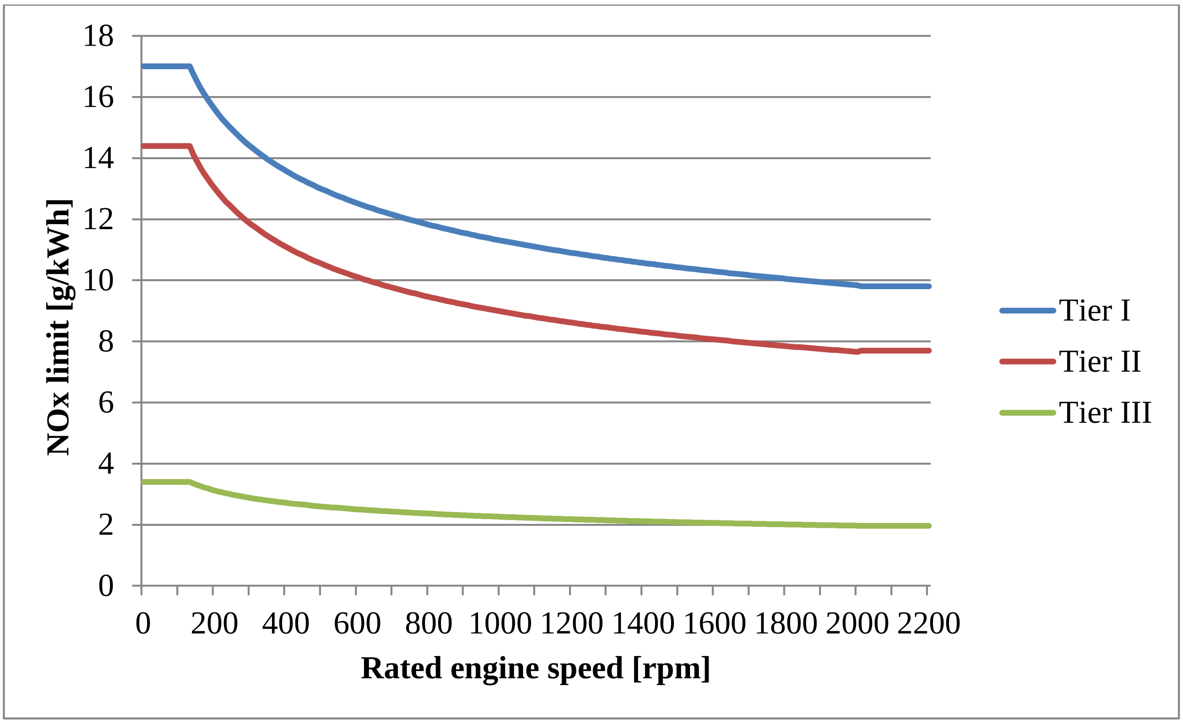

Figure 1. Tier I,II and III emission limits as a function of rated engine speed.

4.2. MARPOL Annex VI Regulation 14 - The Reduction of SO_x Emissions

Regulation 14 in MARPOL regulates the sulphur content in the fuel. Noticeable is however that it is allowed to use abatement technologies to clean the exhaust gas to an equivalent level of sulphur content. Regulation 14 states that the sulphur content of any fuel oil used on board ships shall not exceed the following limits:

- 4.50% m/m prior to 1 January 2012
- 3.5% m/m on and after 1 January 2012
- 0.5% m/m on and after 1 January 2020,

where m/m is given as mass ratio.

Regulation 14 also include specific rules for Sulphur Emission Controlled Areas (SECA), in these areas the sulphur limit should instead not exceed the following limits:

- 1.50% m/m prior to 1 July 2010
- 1.00% m/m on and after 1 July 2010
- 0.10% m/m on and after 1 January 2015,

where m/m is given as mass ratio.

Figure 2 provides an overview of the regulation in order to provide an understanding of the upcoming limit reductions.

Regulation 14 comes with a review provision regarding the 2020 limit that applies to all ships. In 2018 a review will be carried out regarding the availability of low sulphur fuels. If the review finds it impossible to comply with the sulphur levels as of 2020, this limit will be postponed until 1 January 2025 [3].

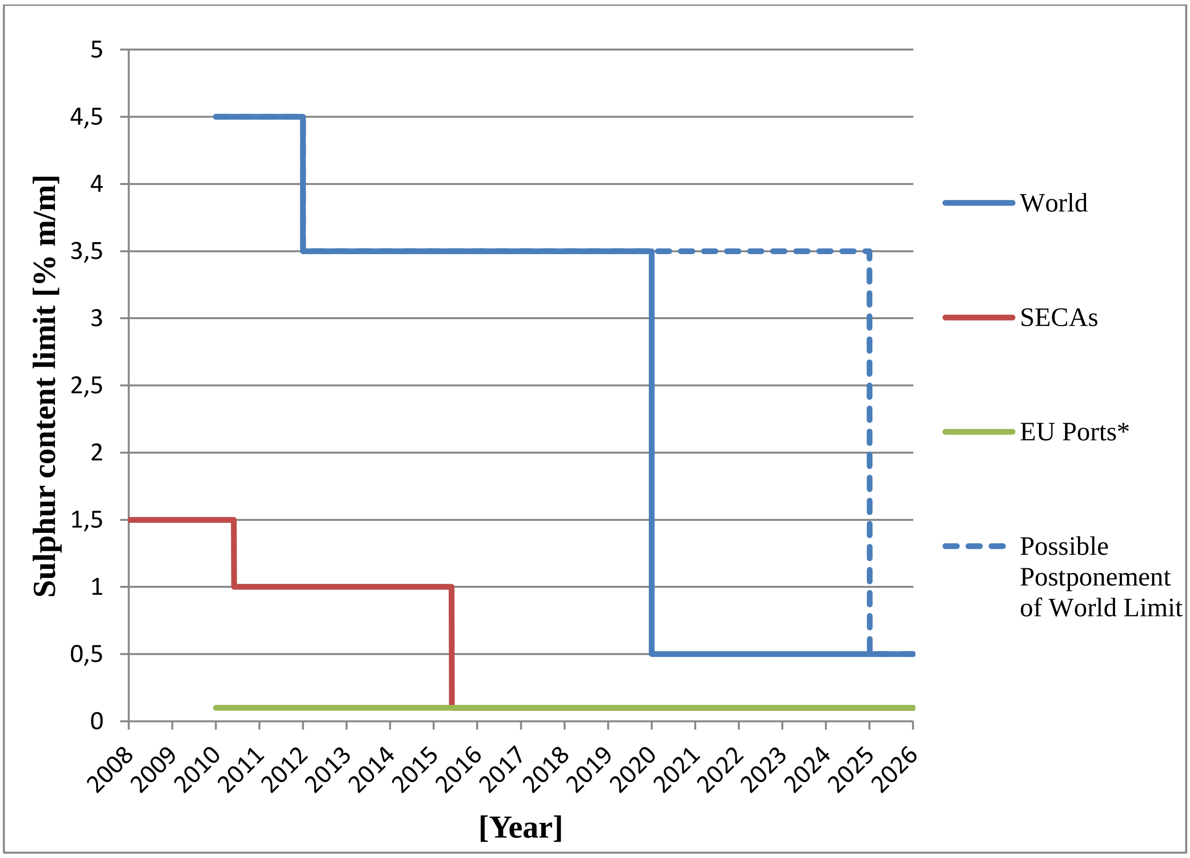

Figure 2. Maximum allowed sulphur content in fuel to be used in different areas.

4.3. Local and National Regulations

On the one hand ECAs are local areas with stricter emission limits on NO_x and SO_x emissions, on the other hand IMO has regulated the limits for nitrogen oxides and sulphur oxides in these areas and hence made them internationally recognized. Nations can, and are, applying for new ECAs that are subjected to discussion within IMO. An ECA in the Pacific and the Atlantic coasts of North America is scheduled to enter into force in August 2011 [15] with a one year grace period. Another ECA is proposed by the United States to include coastal areas around Puerto Rico and United States Virgin Islands in the Caribbean [16]. It is expected to enter into force in 2014 as it is adopted by IMO. Discussions have been raised regarding additional ECAs for the future [17], see Figure 3.

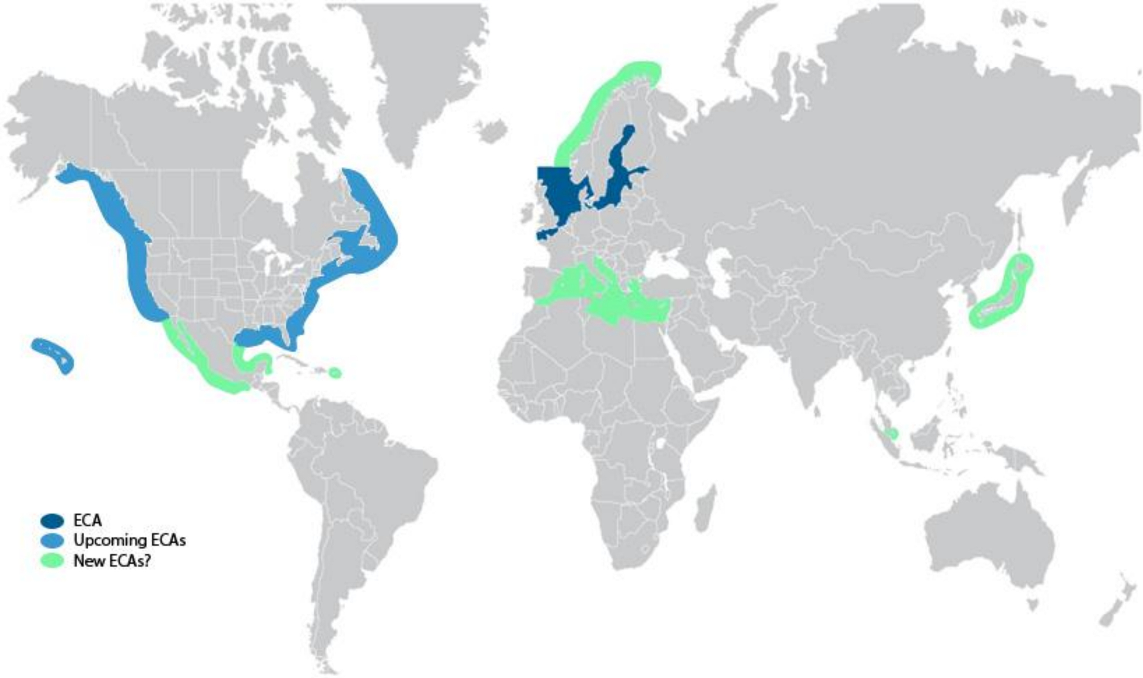

Figure 3. Existing, upcoming and potential emission control areas *[18]*.

To better understand the strategic location of ECAs the shipping density can be seen in Figure 4. Approximately 80-90% of the shipping industry will be affected in some way of the implementation of ECAs [18].

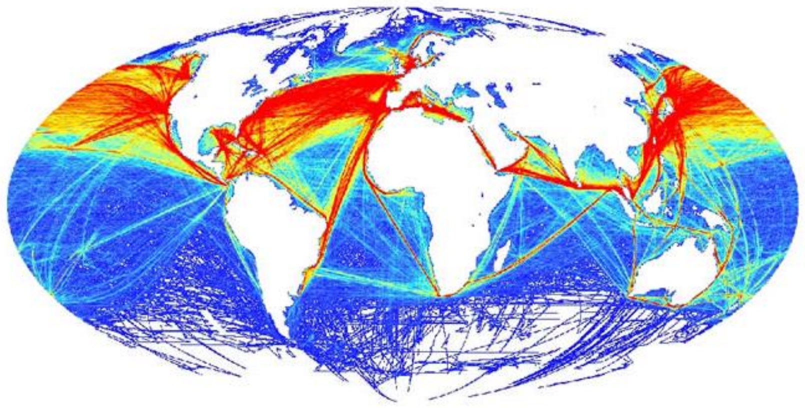

Figure 4. Shipping density around the world*[18]*.

In addition to the IMO regulations, several initiatives have been taken locally. For example, the state of California has since 2007 regulated auxiliary engine fuel of ocean going vessels. The current proposals of amendments requires, from the effective date of approval, auxiliary diesel engines, main engines and auxiliary boilers to run on either marine gas oil (MGO) of 1.5 percent sulphur content by weight or marine diesel oil (MDO) of 0.5 percent sulphur content by weight. The rule regards ocean going vessels within 24 nautical miles of the Californian coast and from 2014 the levels will become 0.1 percent by weight for both MGO and MDO [19].

Since 1 January 2010 European Union directive 2005/33EC requires a maximum sulphur level of 0.1 percent by weigth in European ports and inland waterways, approved abatement technologies are also recognised provided that at least equivalent emission reductions are met.

Also national incentives exists, such as the Norwegian NO_x fund and the Swedish fairway fees, with the objective to further reduce emissions, see [20] and [21] respectively.

4.4. Consequences of Reducing Emissions from Ships

The new limits coming into force in the near future will demand drastic measures to be taken by the shipping industry. Regulation 13 regarding NO_x is not only dependent on the fuel since nitrogen is always present in the engine's charge air. The choice of fuel can decrease the NO_x emissions, e.g. using natural gas which have a lower combustion temperature, but on board measures will probably be needed to comply with Regulation 13 of MARPOL Annex VI. These measures can be adjustment of the combustion or by installing new equipment to remove created NO_x from the exhaust gas. Further theory on the equipment and technologies will be given in Section 6.

The sulphur on the other hand comes from the fuel that is being used. This means that the sulphur can be removed by changing fuels. A fuel change is associated with technical challenges since sulphur works as lubrication and distillate fuels have lower viscosity and can often lead to leakages. Distillates are, at the moment, also very expensive which creates a demand for other ways to remove the sulphur; this can instead be removed from the exhaust gas and can either be stored onboard or discharged overboard, see Section 6.7.

Installations to ensure compliance with the upcoming limits of MARPOL Annex VI demands major changes, either in design or in retrofit, which have to be considered carefully. The demand for abatement technologies have increased significantly the last years and will most likely increase rapidly to comply with the Tier III NO_x limits coming into force in 2016, as well as the lower global limits of sulphur emissions in 2020.

Det Norske Veritas specializes in managing risks and is responsible to ensure the safety of the main functions onboard the ships they classify. The new abatement technologies introduce new failure mode and effects, many of which are not comparable with other systems onboard. Test installations, as well as installations done without approval from a classification society (class approval), have experienced problems with fires and piping system failing which could result in dangerous scenarios with loss of propulsion or even loss of a ship. Consequently DNV needs to ensure that rules are in order to ensure that the new abatement technologies can be installed without jeopardizing the safety onboard.

5. Formation of Pollutants

In order to understand the origin of NO_x and SO_x emissions, and thus how they can be minimized, follows here a short description of the mechanisms behind their formation in combustion engines.

5.1. Formation of Nitrogen Oxides

NO_x is formed through oxidation of nitrogen and refers to NO and NO_2 (sometimes also N_2O and other compounds). Different fuels have different amount of nitrogen bounded which means that the choice of fuel can to some extent lower the NO_x emissions. NO_x created from the nitrogen in the fuel is called Fuel NO_x. However, depending on the fuel, the major contributor to the creation of NO_x is often nitrogen from the air injected into the combustion chamber.

One way of forming NO_x from the nitrogen in the air is so called Prompt NO_x. The formation takes place in the flame zone, where un-combusted hydrocarbon breaks up the nitrogen gas which later ends up as NO_x. This NO_x formation is not very temperature sensitive and is thus regulated by changing the amount of available fuel and the flame front [22] [23] [24].

The third, and usually largest, contributor to NO_x formation during combustion is Thermal NOx and takes place when nitrogen and oxygen are present at elevated temperatures. The formation is increasing exponentially when temperatures reach above approximately 2000°K [25], thus a slower combustion with lower peak temperatures is preferred considering NOx emissions. Studies of thermal NO_x formation have been carried out to formulate equations for the reaction rate and every temperature increase of 90°K above 2200°K will approximately double the formation rate considering that there are enough reactants in the mixture [26]. Generally high local peak temperatures should be avoided, although an overall decrease in temperature will also decrease the thermal efficiency of the engine. Thus it is possible to significantly decrease the NO_x formation by lowering the combustion temperature but simultaneously increase the fuel consumption, often referred to as “the NO_x paradox”.

5.2. Formation of Sulphur Oxides

The production of SO_x is directly linked to the amount of sulphur in the fuel. During combustion most of the sulphur will be oxidised into SO_2, and some to SO_3. According to Wahlström et al. the SO_3 corresponds to typically about five per cent of the sulphur oxide amount [27]. There is not much that can be done during combustion to minimize the SO_x emissions as the sulphur is already present in the fuel, it has to be removed either before combustion or from the exhaust fumes.

6. Abatement Technologies

To understand what failure modes and effects that can follow with different abatement technologies, it is crucial to understand how the different technologies work. Below follows a description of the different technologies, and how they reduce emissions

6.1. Selective Catalytic Reduction

The main function of an SCR is to convert NO_x into nitrogen gas (N_2) and water (H_2O). This is done by injecting ammonia or urea into the exhaust fumes which then reacts inside the catalyst. Both urea and ammonia end up in the same reactions, where urea first decomposes into ammonia with the production of CO_2 as a reaction product. The overall stoichiometric equation for ammonia reacting with NO and NO_2 is as follows [28];

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad (1)$$

$$6NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O \quad (2)$$

To ensure desired reduction, a temperature of above approximately 270°C is required [29], especially if using high sulphur fuels when the ammonia instead can react with sulphur to create ammonium hydrogen sulphate (NH_4HSO_4) at temperatures below 300°C [30]. This means that the SCR typically need a start-up time of around 20-30 minutes after a cold start before the exhaust have reached the desired temperature and the unit can work properly[29]. Because of the required high temperatures, SCR is best suited for four-stroke engines but installations have also been done on 2-stroke engines, with a lower lifetime as a result. Temperatures should however not be too high since the ammonia will then rather burn than react with the NO_x [31]. During optimal operation SCR can more or less remove all NOx from the exhaust gas, manufacturers often guarantee above 90%. However, because of the change in temperature and operational modes, DNV accepts a guaranteed reduction of 75-85% for most applicants which applies for certificates to be used e.g. with regards to the Norwegian NOx fund [32].

The catalyst itself can be made of several different materials, often a ceramic such as titanium oxide is used as carrier together with a base metal such as vanadium or tungsten as active component which are organised into a honeycomb structure.

A SCR installation can often replace the silencer, even if it in many cases has a larger weight and requires more space. In some cases, especially for two-stroke engines, it is favourable to install the SCR in the engine room before the turbo charger to get as high exhaust gas temperatures as possible. This complicated retrofits since the space in the engine room is often very limited [29]. A tank for urea or ammonia with effluent piping is also needed. A schematic SCR system can be seen in Figure 5.

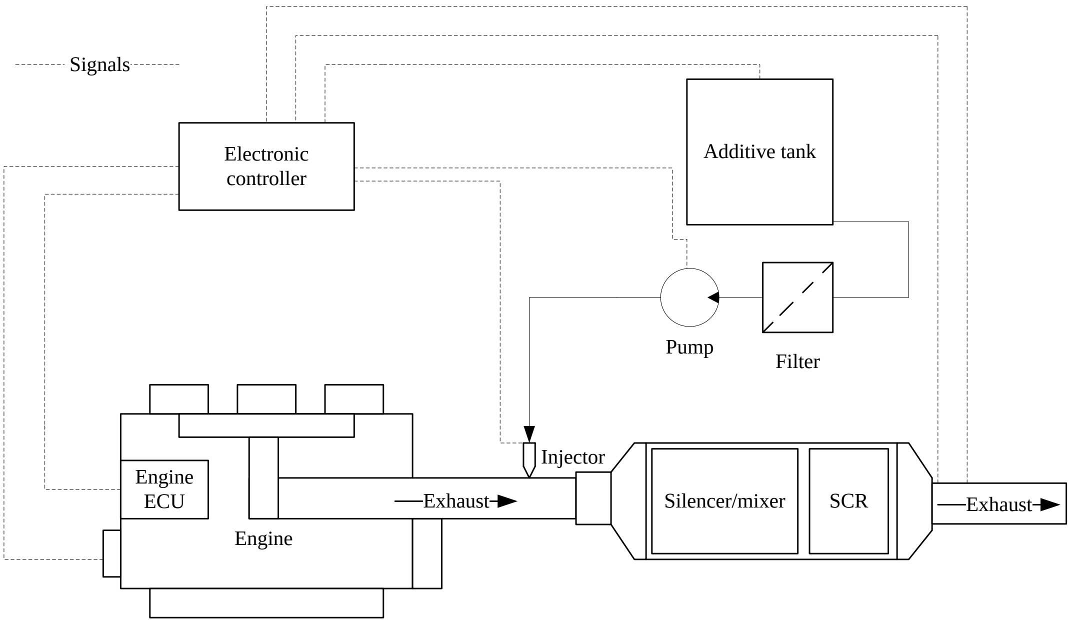

Figure 5. Schematic view of a SCR system.

Cost estimates have been carried out on behalf of the EU-commission by Entec in 2005 and are in presented in Table 1 and Table 2. The costs estimates are to include investment, operational and maintenance cost. Noticeable is that approximately 80 % of the cost is connected to operation and maintenance where the future urea price will have a significant impact.

Table 1. Cost estimates of using SCR with fuel sulphur content up to 4.5%.

Selective Catalytic Reduction (SCR) (Entec, 2005) Ships using RO, Outside SECA			
	Small	Medium	Large
Total annual costs - new build (€/year)	155,842	389,316	909,795
Total annual costs - retrofit (€/year)	170,503	423,408	988,137

Table 2. Cost estimates of using SCR with fuel sulphur content up to 1.5%.

Selective Catalytic Reduction (SCR) (Entec, 2005) Ships using RO, Inside SECA			
	Small	Medium	Large
Total annual costs - new build (€/year)	114,429	293,018	688,499
Total annual costs - retrofit (€/year)	129,09	327,109	766,841

6.2. Exhaust Gas Recirculation

The main principle for reducing NO_x using exhaust gas recirculation (EGR) is to lower the combustion temperature and create a shortage of oxygen. A fraction of the exhaust gas is being recirculated, cooled and injected together with the charge air into the combustion chamber, see Figure 6. As described in Section 5.1 the usually largest source of NO_x formation is Thermal NO_x and EGR uses in two principles to lower the amount of NO_x formed:

- The exhaust gas has a higher specific heat capacity than “clean” air and thus keeps the combustion temperature down [29] [33].
- The exhaust gas works as an inert gas which leads to a decreased concentration of oxygen that can react with the nitrogen which slows the NO_x formation further [29][34].

Because of particles and other impurities being recirculated into the combustion chamber, EGR can be combined with a small scrubber which cleans the recirculated gas to avoid accumulation of hazardous compounds, see Section 6.7. For two-stroke engines there is also an option to instead limit the scavenge air to decrease the purity of the air in the chamber, this however removes the possibility to clean the air from combustion residues that are left in the cylinder and can lead to an increase in wear of the engine.

There are essentially two different types of EGRs, high- and low pressure. In high pressure EGRs exhaust is taken upstream of the turbocharger turbine and then injected downstream of the compressor. Low pressure EGR instead takes the air downstream the turbocharger’s turbine and injects it upstream of the compressor [35]. Because of the relative high amount of pollutants in ships’ exhaust fumes the high pressure system is usually used to avoid sulphur and other pollutants to damage the compressor. A solution could be, if a scrubber is installed to comply with MARPOL’s SO_x regulations, to take the exhaust gas after it has been scrubbed, however this would demand extensive piping since the after treatment is often situated far from the engine. Alexander Maersk is running with EGR and have above 70% NO_x reduction [36].

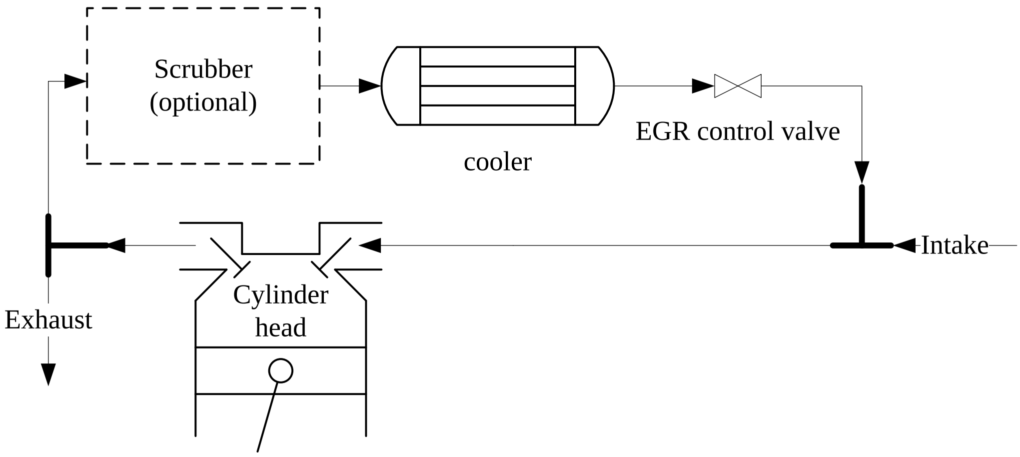

Figure 6. Schematic view of an EGR system.

6.3. General for Technologies Adding Water to the Combustion

Generally it is said that the creation of NOx can be limited using water because of the lower combustion temperatures. However, extensive studies have been done by F.L. Dryer claiming that this cannot be the only explanation to the decreased NOx formation. Using 30% W/F would only add 2% mass to the combustion and the water would only be able to absorb approximately 4% of the heat, still the NOx reduction is much higher than what would be the result from a 4% heat reduction. It is discussed if the explanation lies in the change in speed of the flame front, increased burn rate of fuel droplets leading to a more complete combustion as well as water causing better atomization of the fuel. The investigation shows that the NOx emission would decrease even with constant temperature [37]. There is a lack of consensus in these matters, however a lower temperature will decrease the NOx formation and will in this thesis be seen as the main contributor to lowering NOx emission when using water in the combustion chamber

6.4. Humid Air Motor

Humid air motor (HAM) is designed to lower the temperature during combustion to reduce NO_x emissions. Sea-water is vaporised, removing most of the salts and minerals, by using spill heat from the engine or exhaust gases and is then mixed with the charge air. As a result of the increased heat capacity the combustion temperature is lowered and thus also the NO_x emissions. Other effects such as dilution of the charge-air and dissociation of the water molecules can also influence the NO_x formation but is often said to have marginal effects [38]. An advantage of using HAM is that it is not vulnerable for sulphur in the fuel as many other of the NO_x reducing technologies as well as not demanding fresh water generation or bunkering [39]. The main components of a HAM installation is the humidifier, circulating pump, heat exchanger and often some equipment to control the content of the water, as regard to salts and minerals[38], see Figure 7.

The Viking Line operated ship Mariella have used a HAM system for more than 10 years and measurement have been done that shows a reduction of NOx by 70% in 2001 [38] and from 17 to between 2.2. and 2.6 g/kWh (>84%) in 2006 [40] . An installation on the Norwegian fishing vessel Kvannøy achieves NO_x levels just above Tier III and with the potential of reaching Tier III limits according to MAN [41].

The system can replace the conventional air inter-cooler [29] but still requires relatively large volumes to be reserved for the humidifier and heat exchanger, which also requires high investment costs[42] , however the operational cost are very low compared to other NO_x reducing technologies [41][43].

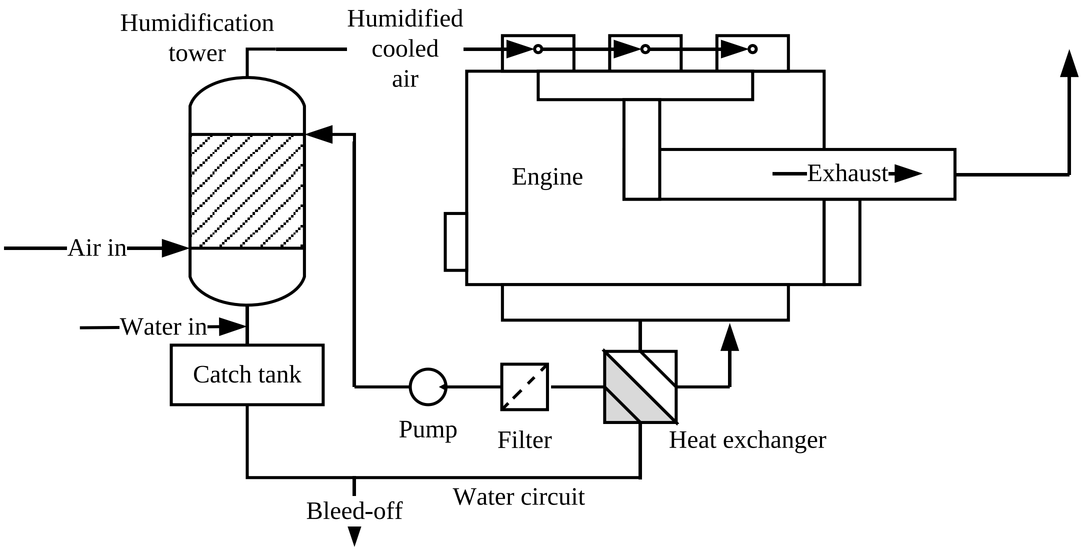

Figure 7. Schematic view of a HAM system.

Entec have made a cost estimation of the NO_x reduction when using HAM, see Table 3. The costs estimates include investment, operational and maintenance cost.

Table 3. Cost estimate of using HAM.

Humid Air Motor (HAM) (Entec, 2005)			
	Small	Medium	Large
Total annual costs - new build (€/year)	43,985	123,9	265,918
Total annual costs - retrofit (€/year)	50,129	151,38	353,957

6.5. Direct Water Injection

Direct water injection (DWI) is similar to the HAM concept with regard to water being used to lower the combustion temperature and thus the NO_x formation. DWI was first developed for air jet engines to improve thrust by allowing high output due to the increased cooling and increased mass-flow from the added water. The main difference between HAM and DWI is that the water is injected in liquid form; it can thus absorb more heat due to evaporation. Since the water absorbs heat and expands during evaporation, DWI also have to potential to improve fuel consumption by transforming heat to mechanical work. This effect is however two-fold since the lower combustion temperature also will have a negative effect on the thermal efficiency of the engine [44]. The injection, see Figure 8, of water can occur either during fuel injection (high pressure) or after the fuel injection (lower pressure).

According to de Jonge et al., typical water-to-fuel ratios used are in the range of 0.4-0.7 which can reduce the NO_x emissions by 50-60% [29]. F. Bedford et al. report NO_x reductions of 24-46% and 39-71% for 30% W/F and 45% W/F mixture respectively depending on load conditions [45]. Other sources report of similar reductions, the amount of NO_x reduced is approximately the same percentage as the water being added [44] [29] [38].

The disadvantage with DWI compared to HAM is that it is usually operated with fresh water which means that a dedicated fresh water generator have to be installed. To use a combined freshwater generator for DWI and other systems will most likely not be allowed by neither classification societies, flag states or IMO. The investment cost may also be a major issue for DWI since this is, according to some, significantly higher than for other water using technologies [42] [46]. Entec on the other hand states it is cheaper than many other NOx reducing technologies[29], see Table 4. It has also been stated that DWI is not suitable to use together with high sulphur fuels which can also be a major drawback for the technology. DWI can be combined with e.g. EGR, to comply with Tier III, but with some challenge since EGR can increase the sulphur content in the combustion chamber further.

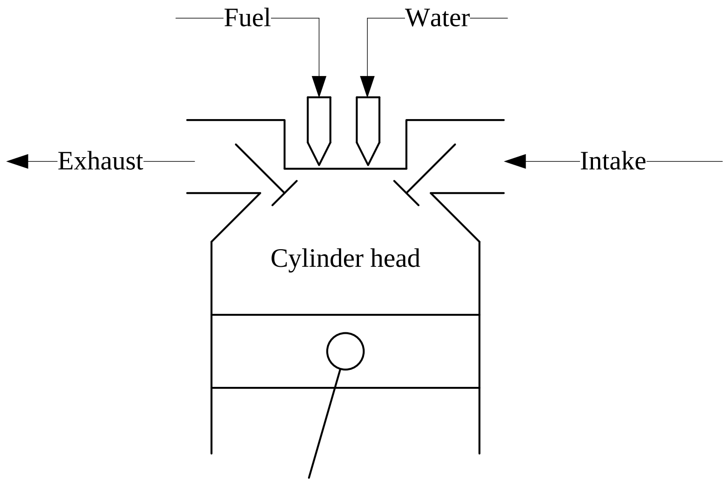

Figure 8. *Schematic view of a DWI system.*

Estimated cost for DWI from Entec, 2005 can be seen in Table 4. The costs estimates are to include investment, operational and maintenance cost.

Table 4. Cost estimates using DWI.

Direct Water Injection (DWI) (Entec, 2005)			
	Small	Medium	Large
Total annual costs - new build (€/year)	48,134	138,351	331,438

6.6. Water in Fuel Emulsion

Water in fuel emulsion (WIF) uses an emulsion of fuel and water to fuel the ship, see Figure 9. The water can be emulsified in different ways e.g. mechanic, ultrasonic or by using high pressure injection. Fresh water has to be produced, to avoid fouling of components particle deposits, together with an emulsifier to produce the emulsion that can then be injected into the combustion chamber.

For best performance the water droplets in the emulsion should be as small as possible to optimize the spray and heat absorption. Emulsion, as opposed to DWI, has shown to also decrease PM emissions and soot. As explanation it is often referred to increased mixing, better oxidation of carbon and reduced formation of soot precursors, however, this phenomena is not fully understood [47] [44].Other positive side effects have also been reported such as decreased lubrication oil consumption and reduced deposits in the downstream equipment [48]. Emulsions are instable and will eventually separate into individual liquid layers; because of this additives are sometimes added for particular fuels to ensure the stability of the emulsion [31].

MAN Diesel & Turbo claims that WIF is not yet feasible because of the high specific fuel oil consumption (SFOC) increase and must be further optimized or used together with e.g. EGR to have enough NOx reduction without unacceptable SFOC increase [49].

M. Abu-Zaid's study regarding a single cylinder using water emulsion indicates that WIF can also increase the thermal efficiency of the engine. Using 20% water in the emulsion showed an increase in brake thermal efficiency of approximately 3.5% over the use of pure diesel for the speed range studied [50]. According to DNV, the NOx reduction follows closely to the water content of the emulsion; however the SFOC will increase if the water content exceeds approximately 30% [51].

Karila et al. have performed a comparison of DWI and WIF with Caterpillar marine engines using heavy fuel and in their report it is concluded that, when using 10-,20- and 30% water in the fuel WIF was the superior method regarding both NO_x and soot emissions [52].

There is also a possibility to bunker with premade fuel emulsions, e.g. the Lubrizol Corp's PuriNOx. The San Francisco Bay Water Transit Authority had a pilot program using "PuriNOx" in one of its ferries which resulted in NOx and PM reduction as desired. PuriNOx uses approximately 20% water and ended up with a 15 % decrease in fuel economy and a power loss of 8 to 12% [53]. Using premade emulsion will inevitable lower the range of the vessel since less energy will be carried in the bunker tanks, proportional to the amount of water in the mixture, that can most likely not be compensated by better brake thermal efficiency.

Notable is that no manufacturer claims to be able to comply with Tier III regulations with just using water emulsion, which means that it has to be combined with other technologies. A risk assessment or FMEA of the combination must then be carried out.

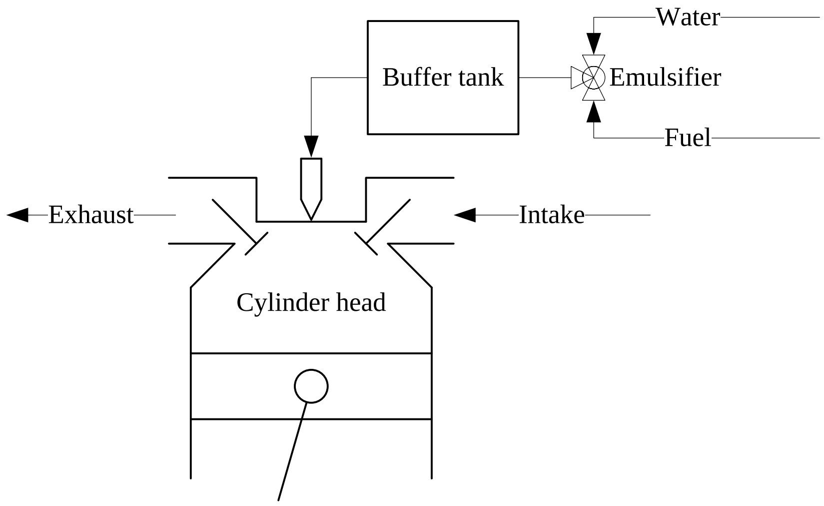

Figure 9. *Schematic view of a WIF system.*

6.7. Scrubber

Scrubbing is at the moment the only feasible measure to remove sulphur from the exhaust gas, instead of running on low sulphur fuels. There are essentially two different types of scrubbing; either using a liquid, wet scrubbing, or by non-liquid additives to react with the sulphur gases, dry scrubbing. So far dry scrubbing systems for marine applications have only been seen in the design stage [54], and is not common in marine installations, hence this thesis will consequently only analyse wet scrubbing.

Different wet scrubbers exist, often in combination where e.g. a *venturi scrubber* is aligned with a *spray scrubber*. The alkalinity determines the sea water's ability to absorb sulphur and depends on the amount of bicarbonate and carbonate ions present.

A venturi scrubber consists of three sections; one converging, one throat and one diverging section. In the converging section the gas flow is accelerated and when water is introduced, either in the converging section or the throat, it is sheared into tiny droplets because of the high velocities. As the gas mixes with the mist of water particles and gas are absorbed by the water and the flow is then decelerated to continue through the exhaust system. The high velocities in a venturi scrubber cause turbulence which increases the pollutant absorption but this also leads to a significant pressure drop, often higher than other types of scrubbers. Similar scrubbers also exist which uses venturi effects but with high injection pressure for the water to create a mist without using the kinetic energy from the air. This can limit the pressure drop created by the scrubber and these are often referred to as jet scrubbers or ejector venturi scrubber [55].

A spray scrubber is usually a tower where the gas enters in the bottom and passes up through the tower while being sprayed with water, but spray can also be perpendicular the flow having horizontal gas flow with spray from above. The alkaline compounds in the sea water neutralize sulphur oxides in the scrubber and can then be either cleaned and kept onboard or discharged to sea in the form of sulphates [56].

It is also possible to use a closed loop while scrubbing; the sludge is then accumulated in a tank. To increase the alkalinity of the water being recirculated it is often treated with an additive, such as NaOH or CaOH. This demands significantly less water than sea water scrubbing, however water has to be cleaned for recirculation.

After the wet scrubber(s) a mist collector is needed to ensure that the polluted mist does not continue out of the funnel.

Studies made on seawater scrubbing show that SO_2 emissions can be reduced up to 95% and PM emissions can be reduced about 80% [57]. The amount of sulphates discharged into the sea is, by some, assumed to be negligible compared to the amount that exists naturally in the sea [58]. Still, it may not be allowed to discharge sulphates in certain port and restricted waters due to risk of accumulation.

Both open and closed loop scrubbing is schematically presented in Figure 10.

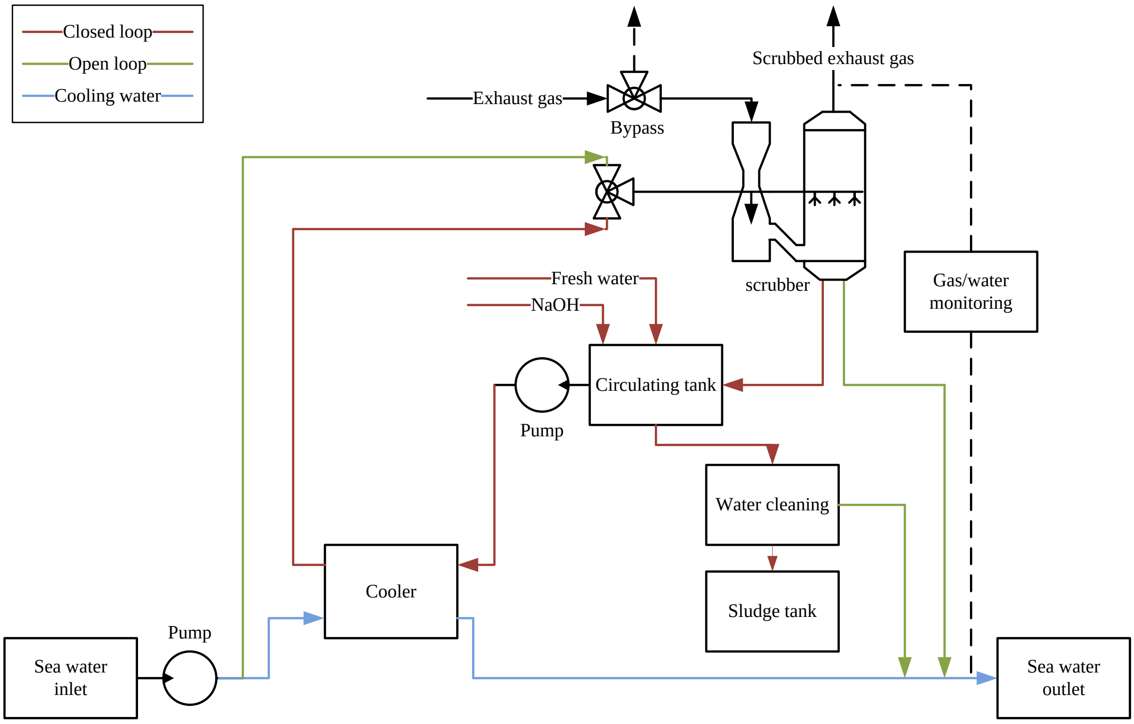

Figure 10. Schematic view combined open and closed loop scrubber systems.

Table 5 compares cost estimates made by Entec of running on low-sulphur fuel compared to removing the sulphur from the exhaust gas using sea water scrubbing [29]. These figures however hold uncertainties since the prices are strongly connected to the fuel price.

Table 5. Cost estimates using scrubber versus changing fuel.

Scrubber (Entec, 2005)			
	Small	Medium	Large
Sea Water Scrubbing Newbuild (€/tonne SO2)	390	351	320
Sea Water Scrubbing Retrofit (€/tonne SO2)	576	535	504
Fuel Switching 2.7% S to 1.5% S (€/tonne SO2)	2,053	2,050	2,045
Fuel Switching 2.7% S to 0.5% S (€/tonne SO2)	1,439	1,438	1,434

7. Results

This section will describe what failure modes and rules that have been identified through literature and interviews. First the potential hazards the installation and operation of using different abatement technologies will be discussed followed by what rules that can be applicable for these technologies.

7.1. Possible Failure Modes Associated with Abatement Technologies

New problems can always occur when installing or changing the parameters in a system. General problems can occur such as stability problems if installing something heavy in the funnel; the following section will however regard the specific failure modes associated with each technology.

7.1.1. Selective Catalytic Reduction

In order for an SCR to function properly the temperature needs to be held within certain intervals, depending on the installation. If the temperature falls below approximately 300°C soot and other deposits can start forming at the catalyst surface [59] as well as the sulphur in the fuel forming ammonium sulphate and bisulphate compounds which can lead to deterioration, erosion, corrosion, clogging and fouling of the catalyst [30][60]. The extensive heat in the catalyst can also lead to sintering of the material which leads to decreased catalytic surface [60]. The catalyst of a SCR, even with good design practice, deteriorates and should be changed within a specific time period; Entec states many newer designs have needed to change the catalyst every 4-5 years when running on residual fuels [29].

Clogging can however occur even for higher temperatures, if the flow velocity is insufficient, or the catalyst is of an inadequately designed, flyash and other deposits can cause erosion, accumulate and cause an increase in back pressure which can lead to stalling of the turbo charger and damage the engine. These deposits may also later ignite causing a fire in the exhaust system [60]. In addition, gypsum can be created by calcium reacting with the sulphur in the SCR which also leads to clogging, this phenomenon is further accelerated from vanadium from the HFO which facilitates oxidation of SO_2 to SO_3 [49] [61].

Handling of the ammonia may also cause injuries as it is toxic. Ammonia has a sharp, irritating and pungent odour that helps to warn crew if there is a leakage. However, if a rapid, large leakage of ammonia can result in lung damage and death. The National Institute of Occupational Safety and Health (NIOSH) states that 300 to 500 ppm for 30 to 60 minutes is the maximum short exposure tolerance, 5000 to 10 000 ppm is reported to be fatal [62].

EU has classed Ammonia as *Toxic*, *Corrosive* and *Dangerous for the Environment* and in The United States it requires a hazardous safety permit if transported in quantities greater than 3,500 Gallons (13,248 litres) [63].

Because of these hazards, and extensive rules, with using ammonia, urea is most often used in marine SCR installations. Urea exists in urine and, except for environmental impact, is not very toxic for the crew or material on board. According to the Material Safety Data Sheet (MSDS) for urea it can cause irritation if contact with skin and eyes and hazardous in case of ingestion or inhalation [64]. Inside the exhaust system urea however decomposes into ammonia, and carbon dioxide, which can then still present risks according to the above text.

Regardless of where urea or ammonia is used there is a risk of backflow to other equipment, at least one case is known where water mixed urea have been injected to a system with several engines connected to the same SCR. The additive did not hydrolyze fully and flowed upstream into an idling engine where it later caused engine failure [61]. Table 6 provides an overview of the mail failure modes identified for SCR.

Table 6. Main failure modes for a SCR system.

Main failure modes	**Cause**	**Explanation**
Increased erosion, corrosion, fouling and clogging	Too low temperature (<300°C)	Sulphur in fuel reacts with ammonia to form sulphate compounds.
Decreased catalytic efficiency	Too high temperature	Sintering of the catalyst --> smaller reaction surface. Ammonia burns instead of reacting with NO_x (rather failure to comply with MARPOL than risking the safety of the ship).
Increased back-pressure due to clogging	Too low flow velocities (above 12m/s recommended)	Soot and other deposits get stuck in the honeycomb chamber.
Loss of propulsion due to engine failure	Additive non-reacting / overdosing	Non-reacting additive pouring upstream into engine(s).
Injured crew	Additive handling	Un-suitable handling/accident handling hazardous additive.

7.1.2. Exhaust Gas Recirculation

The main issue with using EGR onboard ships is that the sulphur in the fuel and other particles is being recirculated. This leads to an increase of these abrasive particles and sulphur compounds which can cause corrosion and an increase in mechanical wear of the engine.

EGR often leads to increased soot emissions because of the lack of oxygen that can oxidize soot. This combined with the recirculation of soot can lead to lowering the engine’s durability because of contamination of the lubrication oil, with decreased viscosity as result leading to inadequate lubrication [29]. Recirculation of sulphur will also increase the acidity of the lubricant which lowers the quality further [65]. During their studies, S. Aldajah et al. concluded that the soot content was between 7% and 12%

in the lubrication oil, presumably depending on the level of EGR, after only 102 h duration of engine testing. This level of soot content is considerably higher than what is typical for diesel engine tests without EGR, in which the soot content of the lubrication oil is often less than 5%. Similarly, acidity of the lubrication oil increased with a factor two to three after the engine test. This change is part of the normal aging process for lubrication oil; however the rate of aging in terms of acidity increase is substantial when using EGR. S. Aldajah et al. also concluded that EGR led to increased noise, even though lower friction coefficient, as well as a wear of the tested equipment was of a magnitude of two counting in volume [65].

The gaseous sulphur species can lead to soot deposits in EGR systems influencing piping, coolers and valves which over time results in reduced efficiency. The sulphur may through sulphuric acid also increase the corrosion in the system [29]. Table 7 summarises the identified failure modes associated with EGR.

Table 7. Main failure modes using an EGR system.

Main failure modes	**Cause**	**Explanation**
Increased wear of engine	Decreased pH, increased soot and accumulation of particles	Sulphur being recirculated leading to increased sulphur concentration in the cylinders. Decreased oxygen levels leading to increased soot formation together with recirculation.
Decreased lubrication	Increased soot content and decreased pH of lubrication oil	The increased amount of particles in cylinder contaminating the lubrication oil.
Corrosion and reduced efficiency	Soot deposits	The sulphur present in the system creates deposits and forms sulphuric acid in the system.

7.1.3. Humid Air Motor

Because of the few components used in a HAM installation there are relatively few failure modes. Overheating of the engine may occur in case pumps, injectors or other equipment fails with a stopped humidification of the charge air as result. HAM usually uses seawater which can bring different impurities, most obvious being NaCl, which could potentially harm piping and other equipment. If the HAM is installed upstream of the turbocharger, which demands accurate balancing, this could increase the need of dust blowing or cleaning equipment to avoid impurities to stick to the turbine blades.

If too much vapour, or condensed water, is being injected this could lead to excessive cooling and quenching of the combustion. Water being incompressible, or even if vaporized, this could potentially cause too high compression ratios and thus damaging the engine [61]. Manufacturers states that the HAM system is turned off 15 minutes before the engine to ensure the cylinders dry up.

All vapour injection systems are claimed to be associated with potentially additional cylinder wear due to disturbed lubrication films according to DNV. On the contrary, cleaner turbo chargers have been reported and lubrication oil consumption has been reduced by up to 40%. The clean engines has increased the service intervals and in other words reduced the maintenance requirements [40]. Some problems were initially reported from the HAM system onboard Vikingline's Mariella. $CaCO_3$ (Calcium carbonate) deposits in the evaporator vessel was reported but were overcome by treatment with an additive [40]. The use of additives can however introduce new risks with the HAM system and needs special consideration.

Since humidified air has higher heat capacity than dry air this can lead to severe burns if a leakage were to occur on personal standing next to the piping. High pressure vapour should not be allowed to spray onto anything that can take damage from.

Different manufacturers claim very different reduction potential of HAM. HAM might have to be combined with other abatement technologies to be able to comply with Tier III which can then cause new risks, e.g. introducing water vapour inside an SCR or EGR.

Table 8. Main failure modes using a HAM system.

Main failure modes	Cause	Explanation
Absence of ignition	Failure of equipment or control system	Excessive vapour condensation in cylinder leading to quenching of combustion.
Increased cylinder wear	Disturbed lubrication films	Contamination at removal of lubrication oil because of the added vapour.
Clogging of evaporator / humidifier tower	Salt, calcium or other mineral deposits	Salt, calcium or other mineral from the sea water vapour accumulating and creating growing deposits.
Damage to equipment or crew	Hot steam leakage	Leakage of high pressure steam could potentially damage crew members or vulnerable equipment.
Engine shut-down/overheating	Pumps/valves failing	Failure of the HAM system would remove the cooling of the engine and thus need to run the engine on low load or in worst case shut-down.

7.1.4. Direct Water Injection

As for the other technologies using water the most imminent failure mode is that water stays in the cylinder. If too much water is injected, this will increase the injection duration which will increase the soot formation. Furthermore this can lead to problems in the exhaust system [27]. If excessive water is injected into the combustion chamber, resulting in liquid water being present after the combustion, the lubrication oil can be contaminated. In a worst case scenario abundance of incompressible water can lead to extreme pressure increase and mechanical failure in the engine, known as hydrolock. If the water supply instead is insufficient, or absent, this would decrease the engine cooling which would result in an increased engine temperature and thus limiting the engine load. In worst case this would require an engine shut off.

Water is often injected before the fuel injection which means it does not require as high pressure as the fuel injection, however considerable pressure is required which can cause pressure pulses and lead to excessive water leakage in the case of piping fracture. If the DWI is not injected correctly it can lead to retarded ignition because of the reduced fuel energy density [44].

Table 9. Main failure modes using a DWI system.

Main failure modes	**Cause**	**Explanation**
Hydrolock	Failure of pumps, control system or injection nozzles	Water in liquid face being incompressible leading to increased pressure resulting in engine stop or break down of engine parts.
Increased cylinder wear	Disturbed lubrication films	Contamination at removal of lubrication oil because of the added water.

7.1.5. Water in Fuel Emulsion

As for all the water using technologies it is important to ensure correct water dozing to avoid increased temperatures or risk standing water in the cylinders. Adding water to the fuel also change the behaviour of the fuel, The San Francisco Bay Water Authority reported that the use of PuriNOx can “clean out” the fuel delivery system and increase the risk of fuel filter clogging. Adding water to HFO increases its viscosity which means that measures to tackle this must be taken, either changing injection system or increase the temperature of the fuel [31]. MAN also reports that the engine might need to be strengthened because of the higher fuel oil supply pressure [66]. Attention must also be turned towards distillation of the water being used to avoid harmful compounds to be injected into the combustion chamber. Vanadium in the fuel can react with sodium in the water and other salts can cause fouling of the injectors and other exhaust gas equipment [66].

The fresh water generator is a critical component to keep the main propulsion working when emulsion is used as a fuel. This means that also the fresh water generator should be analysed to ensure the safety of the propulsion. Class might demand an extra fresh water generator dedicated for the emulsifier.

Using emulsified fuels can also lead to ignition delay and increased engine noise. A drawback is also that the water content is constant and might cause problems for e.g. cold starts or other changes in operation conditions [45].

There is one known case where the control system of the water emulsifier has failed. The amount of water mixed with the fuel increased to a level unable to combust in the engine. It lead to complete engine stop with the possibilities of grounding or similar sever damages. In this case however, the crew managed to start the engine again and avoid danger [61].

Table 10. Main failure modes using a WIF system.

Main failure modes	**Cause**	**Explanation**
Engine stop	Incorrect water content in emulsion	Too much water can lead to too much cooling and thus the emulsified fuel will not burn. Too little water will lead to increasing engine temperatures.
Failure of fuel supply system	Change of viscosity Breakdown of the emulsifier	Adding water to the fuel will increase the viscosity and thus create the need of increasing the pressure in the fuel oil supply system, new injection nozzles etc. Irregularities in the emulsifier will thus bring problems. Failure of the emulsifier will stop the water addition, possibility for bypass but then temperature of the combustion and viscosity of the fuel will be drastically changed.

7.1.6. Scrubber

The most apparent risk when using a scrubber is related to the very sulphur it is designed to remove. The quenching with water generates acid condensation on the walls and cause very harsh corrosion conditions; pH can fall below 0 but still with temperatures of 60°C or more. After the quenching region the seawater is reheated and becomes acid due to SO_2 collection. Due to ship movements areas can also be target to “wet/dry” cycles by warm and reducing seawater in an atmosphere rich of oxygen which can cause severe corrosion [67] [40] [68]. SO_3 formed during the combustion (approximately 5% of the total SO_x) will rapidly react with vapour and form sulphuric acid (H_2SO_4) and will generate acid mist that can condensate on surfaces if the temperature falls below the dew point of the acid. An exhaust gas system without a scrubber will also form acid mist due to much higher SO_3 content. However, without a scrubber, the temperature is higher and it will only exist in vaporized face [69].

Even after the sulphur has been discharged into the sea it can cause harm to the ship. A popular material for propellers is Aluminumbronze which are typically vulnerable to corrosion attacks in sulphur polluted water [70]. According to A. Schussler and H. E. Exner accelerated corrosion can occur already at 1 ppm sulphur in sea water [71].

Some scrubbers, primarily when operating closed loop systems, uses additives such as NaOH to regulate the pH of the discharge water. NaOH is a hazardous chemical that should be used with care; it is however used in many industries and home products. Pure NaOH is a highly corrosive, odourless non-flammable white solid. It reacts exothermic when mixed with water and can cause severe damage to human health. Contact to different parts of the body can cause severe damage such as burns/scares (see *Figure 11*), vision loss, pneumonia and can even be fatal if ingested. [72] [73] . This means protective equipment should be used during handling, having first aid equipment in the vicinity and having good ventilation of areas where spill may occur. NaOH is also corrosive to some metals and flammable hydrogen gas is formed when in contact with aluminium. NaOH is also mildly corrosive to glass which can potentially cause problems for system that uses glass reinforced plastic (GRP) instead of metal piping to cope with the otherwise low pH solutions transported in scrubber piping.

Figure 11. Burns on a hand subjected to a solution of sodium hydroxide of less than 10 percent. The photo is taken 44 hours after the incident.

Regarding NaOH and the environment, the EU Commission concluded that no additional measures, besides a proper pH control of waste waters, are needed [74].

Another concern can be raised depending on the conditions in which the scrubber is being used. The scrubber is often installed in the funnel because of shortage of space, this means that water have to be pumped for long distances. E.g. for ships designed to operate in arctic areas where temperature can fall below -50°C this may cause freezing problems and blockage/rapture of the piping system or scrubber [61].

Table 11. Main failure modes using a scrubber system.

Main failure modes	**Cause**	**Explanation**
Water/exhaust leakage	Corrosion of the scrubber	Sulphuric acid condensation on walls.
Water stop/overflow	Water supply failure Water freezing	Water supply valves stuck in open/closed, pumps failing etc. Piping leading to scrubber, often up to funnel, freezing if sailing in arctic areas.
Damage to hull/appendices	Discharge water causing corrosion, primarily on propeller	sulphur in the water causing corrosion, primarily to Aluminium bronze (propeller).
Crew or equipment damage	Additive handling	NaOH being corrosive and cause severe burn if contact with human skin.

7.1.7. Change to Low Sulphur Fuels

Because of regulations, it might be necessary to operate equipment designed for HFO on MDO or MGO.

General piping and pumps may experience leakage and pressure problems with distillate fuels due to the low viscosity [75]. Injectors originally designed for HFO are also known to experience problems due to the low viscosity of distillates. To keep the viscosity within the values specified by the engine manufacturer, insulation of piping etc may be necessary. As a side effect, there might be both an initial cost and a higher operational cost while using distillates [61][75].

MGO also has a low flashpoint (< 60°C) and higher volatility than HFO which can increase the risk of fires unless hot equipment is properly insulated. According to NYKLine MGO has a high detergency and using it as a fuel leads to clogging of FO filters with sludge that is being accumulated in pipelines [75] [76].

Table 12. Main failure modes using low sulphur fuels.

Change to low sulphur fuels	Cause	Explanation
Leakage	Too low viscosity	During changeover the high quality fuel will have lower viscosity than HFO which can thus lead to leakages because of dimensioned for higher viscosity.
Increased wear	Deficient lubrication	Sulphur works as a lubricant and a removal of sulphur will lower the lubrication.

7.2. Existing Rules Applicable to Abatement Technologies

The following section will present existing rules from the DNV rulebook [77] that have been identified as useful in the work towards safe design, installation and operation of abatement technologies. A set of rules common for all technologies will be described followed by those specific for certain technologies.

DNV defines main functions of a vessel as those which are critical to the ships survival and are considered most valuable in case of an accident. The rulebook focuses mainly on measures to ensure that the main functions can perform in all events. The safety philosophy is that a single failure shall not jeopardise the performance of a main function. As stated in Pt.1 Ch.1 Sec.1, main functions in the context of class are;

- strength
- weathertight and watertight integrity
- power generation
- propulsion
- steering
- drainage and bilge pumps
- ballasting
- anchoring

The main functions primarily connected to the use of abatement technologies are power generation and propulsion; the technologies used are either affecting the combustion or the exhaust gas systems. The following rules refer to the DNV rule book if not clearly stated otherwise. In some references to rules there are “Guidance Notes” included, these are not to be seen as mandatory but often clarifies how the rules should be interpret.

7.2.1. Common Rules

The general rules regards safety philosophy and how to minimize risks, such rules exist consistently through the rule book. They are applicable to all onboard systems and should apply also to abatement technologies. Even though an abatement technology system is not regarded a main function, it will not be tolerated that a failure of such system compromises the main functions operability. An example of the safety philosophy is found in:

> **Pt.4 Ch.1 Sec.1**
> *A 200 Safety philosophy*
>
> *201 The safety philosophy shall be based on fail to safe principles. Upon incidents threatening the safety of the vessel or the availability of main functions, the vessel shall be brought into the least hazardous of the possible operating modes with respect to personnel, environment, vessel and cargo, in this order of priority.*

Consequently, the same philosophy reappears in the rules regarding the design principles of machinery systems/components. The rules are considered applicable also to the design of abatement technologies. It may require redundancy of certain components or additional measures to e.g. comply with rules regarding hazardous liquids:

> **Pt.4 Ch.1 Sec.2**
> *A 100 Safety*
>
> *101 All systems/components shall be so designed and installed that they will not constitute unacceptable hazards to personnel, vessel or cargo and such that the environment is not adversely affected. This also applies to installations not supporting main functions.*
>
> *102 In the event of malfunction, the system/component shall enter the least hazardous of the possible failure states taking the overall safety statements in Sec.1 into consideration.*

There are discussions going whether the emission reduction technologies are supporting main functions. Failure of an abatement technology will often lead to loss of propulsion, thus supporting a main function. However if a by-pass exist such that the propulsion will function even if abatement technology is malfunctioning Class will not have as stringent rules regarding these systems. Certain rules apply to systems supporting main functions and may at least partly be applicable to the technologies. Special consideration of designs may result in deviation from the standard interpretation of rules, such deviation is determined by an approval engineer. Examples of rules regarding systems supporting main functions are found in the general machinery rules:

Pt.4 Ch. 1 Sec.2
A 200 Availability

202 Systems/components supporting a main function shall not be used or integrated with other systems/components in such a way that the availability of the main function may be impaired or lost.

203 Systems and components supporting a main function shall be arranged with redundancy so that a single failure does not lead to the unavailability of any main function or inability to start or stop the main function.

Guidance note:
Normally this redundancy is achieved by duplication
---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

205 The redundancy requirement of 203 may be waived upon adequate documentation of reliable performance. Adequate documentation of reliable performance may be based on one or more of the following:

— Extensive and relevant maritime service experience.
— Design based on approved and relevant standards/regulations and service experience.
— Risk based assessment following a predefined standard approved by the Society and associated relevant service experience or testing.

The discussion regarding abatement technologies as supporting main functions emerge once again regarding design, maintenance and operability of the systems:

Pt.4 Ch.1 Sec.2
A 300 Design

301 All systems/components supporting main functions, shall:
a) be designed, built and tested in accordance to the class rules. Components and systems not covered by the rules shall comply with a recognised standard suitable for marine use accepted by class.
b) be designed and built such that maintenance tasks normally expected to be handled during voyage and occurring at short intervals, may be carried out without loss of propulsion or steering.
c) be so designed and built that main functions can be brought into operation from the «dead ship» condition within 30 minutes using only the facilities available on board.

Guidance note:
In order to restore operation from the «dead ship» condition, the emergency generator may be used. It is assumed that means are available to start the emergency generator at all times.
---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

Another general rule applicable to all the technologies regards prevention of inadvertent operations and aims to reduce human errors and their effects:

> **Pt.4 Ch.1 Sec.2**
> *C 300 Prevention of inadvertent operations*
>
> *301 The installation shall be so arranged as to minimize the possibility for inadvertent operation and human errors leading to reduced safety or damage of system/components.*
>
> *302 The installation is to be arranged as to minimize the possibility for sea water, cargo or ballast from reaching dry spaces of the ship, and cargo (oils or chemicals) from being discharged overboard as a consequence of inadvertent operations.*
>
> *303 The installation is to be so arranged that leakage or operation of valves will not directly lead to increased risk of damage to machinery, ship or personnel due to mixing of different fluids.*

Disregarding type of technology, there are risks associated with leakage from fuel change, additives and other fluids and liquids which may be subjected to regulations. It is of importance to evaluate the risk and implement the following regulation if necessary. For some spaces it is required regardless of installation of abatement technology or not:

> **Pt.4 Ch.1 Sec.3**
> *C 400 Ventilation capacity*
>
> *401 All spaces, from which machinery is operated and where flammable or toxic gases or vapours may accumulate, or where a low oxygen atmosphere may occur, are to be provided with adequate ventilation under all conditions.*

It is important to note that there are systems similar to the technologies used for emission reduction, e.g. there are similarities between scrubbers and inert gas systems. Even though there are similarities in theoretical principles and designs, the rules applicable for the systems may however vary. The rules are depending on the consequences of system failure rather than the similarities in the different systems.

7.2.1.1. Electrical, Control and Monitoring Systems

Control and monitoring systems as well as electrical systems are essential parts of most abatement technologies. Several of the abatement technologies are using control and monitoring for dozing of water, urea or other additives. Failure of control and monitoring systems resulting in engine failure are known and presented in Section 7.1 and failures might also lead to violation of Annex VI. However, this type of systems already exists in several installations onboard a ship and there are extensive rules regarding both electrical, control and monitoring systems. Due to one particular rule, the control and monitoring systems of abatement technologies will be governed by the rule chapter for these applications, since they are thought to have impact o the safety of the main functions:

> **Pt4. Ch9 Sec.1**
> *A100 Rule applications*
>
> *102 All control and monitoring systems installed, but not necessarily required by the rules, that may have an impact on the safety of main functions (listed in Pt.1 Ch.1 Sec.1 A200 of the Rules for Classification of Ships), shall meet the requirements of this chapter.*

7.2.2. Selective Catalytic Reduction

The high operation temperature in a SCR system results in a need of insulation of outer surfaces. The surface temperatures of exhaust pipes are already regulated in the rule book. The same rule might be applicable to SCR systems:

> **Pt.4 Ch.3 Sec.1**
> *F400 Exhaust pipes*
>
> *403 All hot surfaces shall be properly insulated. There shall be no surface temperature in excess of 220° C, see D208*

Sulphates can cause several problems to a SCR system as described in Section 7.1.1. To minimise corrosion and erosion it is necessary to regulate the materials used in the installations. The current rulebook contains rules for inert gas plants for oil carriers that can be applicable also to SCR installations:

> **Pt.5 Ch.3 Sec. 11**
> *B 100 General*
>
> *103 Materials shall be selected so as to reduce the probability for corrosion and erosion.*

A regular rule for piping systems further support the importance of the usage of proper materials, the material may vary depending on application according to the rule:

> **Pt.4 Ch.6 Sec.2**
> A 100 General
>
> 101 The materials to be used in piping systems shall be suitable for the medium and service for which the system is intended.

The material should not only resist corrosion and erosion, it shall also be heat resistant. The heat resistance is important from two points of view. From the current rulebook it is important with proper heat resistance in components where fire may cause outflow of flammable or health hazardous fluids, which can be the case for a SCR installation. Heat resistance is also necessary for the catalyst efficiency. Sintering of the catalyst material is possible in the temperature range of an operating SCR and thus it is important to choose heat resistant material. The following rule from general machinery systems would hence be applicable to SCR:

Pt.4 Ch.1 Sec. 4
A 100 Materials

103 Materials with low heat resistance are not to be used in components where fire may cause outflow of flammable or health hazardous fluids, flooding of any watertight compartment or destruction of watertight integrity.

Clogging of the catalyst can be a problem as described in Section 7.1.1 and soot blowing equipment may be the solution. Soot cleaning arrangements exists for SCRs as well as gas boilers and economisers. Thus the rule regarding the arrangement of soot cleaning should be applicable to SRC systems where problems with clogging may occur:

Pt.4 Ch.7 Sec.3
C 200 Soot-cleaning arrangement

201 Water tube exhaust gas boilers or economisers of a design where soot deposit may create a problem regarding fire hazard, e.g. exhaust gas boilers with extended surface tubes shall have a soot-cleaning arrangement for use in the operation mode. In such cases, the soot cleaners shall be equipped with automatic start and arranged for sequential operation and possibility for manual over-ride.

Guidance note:
For extended surface tubes, soot deposits may create a problem when exhaust gas velocity is less than 12 m/s at normal operating condition.
---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

SCR systems have had incidents regarding leakage of urea from the injectors back to the cylinders of idling engines when the engines have been connected to the same catalyst, see section 7.1.1. A rule to prevent it would affect the designs of the catalysts although designs preventing urea from entering the engine have already been seen among manufacturers. Some existing rules could together reduce the chances of urea entering an engine. The first rule refers to mixing fluids which might be a matter for consideration but would in this case be of secondary importance in comparison to the urea leakage for SCR installations:

> **Pt.4 Ch.1 Sec.2**
> *C 300 Prevention of inadvertent operations*
>
> *303 The installation is to be so arranged that leakage or operation of valves will not directly lead to increased risk of damage to machinery, ship or personnel due to mixing of different fluids.*

Regarding the high pressure injectors of additives into the catalyst it might be necessary to take measures to reduce the chance of leakage, especially if the additive is considered hazardous. Existing regulations regarding pressurised fuel oil systems can act as a basis for the pressurised part of the SCR system:

> **Pt.4 Ch.3 Sec.1**
> *B 700 Fuel oil system*
>
> *701 All external high pressure fuel delivery lines between the high pressure fuel pumps and fuel injectors shall be protected with a jacketed piping system capable of containing fuel from a high pressure line failure. A jacketed pipe incorporates an outer pipe into which the high pressure fuel pipe is placed forming a permanent assembly. The jacketed piping system shall include a means for collection of leakage and arrangements shall be provided for an alarm to be given, in the case of a fuel line failure.*

Leakage prevention as described above is only partly the solution, together with an existing rule ensuring proper measures are taken when several engines are connected to one catalyst unit the chances of urea leaking into engines are further reduced. The existing rule prevents exhaust gases from entering a stopped engine but the similarities to the urea leakage problem is fundamentally the same:

> **Pt.4 Ch.3 Sec.1**
> *F400 Exhaust pipes*
>
> *402 Exhaust pipes from several engines are not to be connected, but shall have separate outlets, unless precautions are taken to prevent the return of exhaust gases to a stopped engine.*

For technologies that, like SCR, use additives a separate tank is necessary. Sounding pipes for such tanks are necessary. With the main function to determine the level of liquid in a tank sounding pipes will also be able to detect leakages that otherwise could be hazardous to personal. The piping rule for sounding pipes should therefore be applicable to SCR systems:

Pt.4 Ch.6 Sec.4
K 500 Sounding pipes

501 All tanks, cofferdams and pipe tunnels shall be provided with sounding pipes or other approved means for ascertaining the level of liquid in the tanks. Spaces which are not always accessible, shall be provided with sounding pipes. In cargo holds, sounding pipes shall be fitted to the bilges on each side and as near the suction pipe rose boxes as practicable.

Finally, the currently voluntary class notation CLEAN include guidance notes for NO_x reducing technology that should be applicable to SCR systems. It regards temperature limits in which the SCR is able to operate and open to certain documentation and procedures to ensure reliable and safe operation of the technologies:

Pt.6 Ch.12 Sec.2
B 200 NO_x Emissions

Guidance note:

Selective Catalytic Reduction (SCR)
Any requirements related to engine performance where SCR-systems are fitted should be identified and addressed in the required documentation as specified in Sec.1 C100. The relevant documentation should also identify operational temperature limits. The reducing agent and the relevant consumptions should be specified by the manufacturer. If other agent than urea-solution is used, this will be subjected to special consideration.

In the case where the NOx emission level is used to verify or control the reduction agent injection rate, the level should be detected by an analyser. Measuring equipment used for this purpose should be according to NOx Technical Code 2008 (edition 2009).

7.2.3. Exhaust gas Recirculation

Due to recirculation of particles and sulphur, corrosion can be a problem for EGR units. Thus the rule Pt.5 Ch.3 Sec.11 B103 in Section 7.2.2 might be applicable also for EGR units. For the same recirculation reason, as described in Section 7.2.2, EGR systems are known to change the lubrication characteristics of the lubrication oil. To ensure proper engine lubrication the DNV rulebook already include regulations requiring that the lubrication oil characteristics are recorded, which could be applied also for rules regarding EGR systems:

Pt.4 Ch.3 Sec.1
B 1600 Type testing data collection

1602 The following external particulars shall be recorded:
…
— fuel and lubrication oil characteristics.

An EGR system subjected to deposits or other problems leading to malfunction can result in unfavourable fuel-to-air ratios and increased concentration of particles in the combustion process that ultimately can lead to misfiring and other harmful engine operation conditions. A present rule under the machinery, drivers - section can thus be applicable also to EGR systems:

Pt.4 Ch.3 Sec.1
E 100 General

103 Engine exhaust gas monitoring shall serve the following purposes:

b) Detection of harmful misfiring operation for engines with cylinder power > 130 kW

It shall be possible to detect misfiring operation where such running conditions could be harmful to the engine and or power transmission.

Apart from the fact that a smaller scrubber unit often is included in an EGR system some additional rules associated with turbochargers in the current rule book have been found useful. If a situation occurs resulting in a malfunctioning EGR system the engine must still be able to operate, at least at reduced speed. Rules regarding damaged turbo chargers exist requiring the engine to be able to operate at a speed of approximately 40%:

Pt.4 Ch.3 Sec.1
B 1700 Type testing program

1702 2) *Operation with damaged turbocharger*
For crosshead propulsion engines, the achievable continuous output shall be determined in the case of turbocharger damage. Engines intended for single propulsion with fixed pitch propeller shall be able to run continuously at a speed (r.p.m.) of approximately 40% of full speed along theoretical propeller curve when one turbocharger is out of operation.

Finally, an EGR unit may be subjected to detrimental vibrations, and should hence be tested in accordance with turbo installations:

Pt.4 Ch.3 Sec.1
B 1200 Turbocharger

1205 The rotor vibration characteristic shall be measured and recorded. The result shall be within the maker's specification.

7.2.4. Humid Air Motor

It is important that the humid charge air do not condensate in the cylinders. Usually HAM systems have taken measures to avoid unvaporised fluid entering the engine but due to the consequences of water ingression in the engine it is of importance to state it in a rule. Current regulations for charge air and coolers might be applicable also for HAM systems:

Pt.4 Ch.3 Sec.1
B 800 Charge air system and cooler

801 The charge air system shall be designed to prevent water entering the engine. Water draining from a cooler leakage shall be possible.

Guidance note:
A hole in the bottom may be sufficient.
---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

Further rules regarding prevention of water ingression to the engine exits. The heat exchanger used in a HAM system can be regulated using rules for water cooled heat exchangers when applicable:

Pt.4 Ch.8 Sec. 3
D 200 Cooling and anti-condensation

202 *Water cooled heat exchangers*
a) Where cooling of equipment is arranged through air-water heat exchangers, these shall be arranged to prevent entry of water into the equipment, whether by leakage or condensation. Leakage alarm shall be provided.

c) The construction and certification of the air-water heat exchangers shall comply with the requirements for pressure vessels, see Pt.4 Ch.7.

The characteristics of the lubrication oil can be affected by a HAM system, a rule similar to that proposed above for EGR, Pt.4 Ch.3 Sec.1 B 1602, should be applicable. Additives have been used for HAM systems and should be subjected to special consideration until further knowledge about the chemicals is gained.

General redundancy rules, such as Pt.4 Ch. 1 Sec.2 A 203, can be applicable to the pumps in a HAM unit; redundancy requirements might be necessary to ensure reliable operation and minimising the risk of overheating.

The currently voluntary class notation CLEAN include guidance notes for NO_x reducing technology that should be applicable to HAM systems. It regards engine modifications and opens to certain documentation and procedures to ensure reliable and safe operation of the technologies:

> **Pt.6 Ch.12 Sec.2**
> *B 200 NO_x Emissions*
>
> ***Guidance note:***
>
> *Engine modification and adjustments*
> *NOx reductions by modification of engine parameters, water injection, fuel/water emulsification and/or by adjusting engine settings in order to influence the combustion characteristics, should be specified by the engine manufacturer and carried out under his supervision. The chosen combination of modifications and adjustments should aim to avoid an increase in the engine's fuel consumption. The engine shall not be adjusted outside the allowable ranges as specified in the Technical File (where applicable) unless a Direct Measurement and Monitoring*

7.2.5. Direct Water Injection

The failure modes identified for direct water injection are related to water dozing and changed lubrication characteristics and thus presented for other technologies. The rules applicable to DWI are therefore already touched upon above.

Regarding water in the engine there are no known measures to prevent it from happening other than the use of properly regulated control systems to ensure proper water injection.

For the lubrication oil the same rule, Pt.4 Ch.3 Sec.1 B 1602, is applicable for DWI as for EGR and HAM systems above and finally, the guidance note of Pt.6 Ch.12 Sec.2 B 200 is also applicable to DWI, see Section 7.2.4

7.2.6. Water in Fuel Emulsion

As recently stated for both HAM and DWI guidance note of Pt.6 Ch.12 Sec.2 B 200 is applicable also to water in fuel emulsion. Apart from the guidance note, only one applicable rule is found in the current rulebook. A WIF system shall not cause detrimental vibrations as regulated in the piping rules:

Pt.4 Ch.6 Sec.3
A 100 Piping systems

103 The support of the piping system shall be such that detrimental vibrations will not arise in the system.

7.2.7. Scrubber

As for most of the abatement technologies scrubbers will be subjected to corrosive environments. To ensure reliable operation the material used shall be suitable for the purpose it is intended for and thus be protected against corrosion. Existing regulations, such as Pt.5 Ch.3 Sec.11 B 103 and Pt.4 Ch.6 Sec.2 A 101 above, are yet again applicable. Further, in existing regulations of inert gas production and cleaning scrubber corrosion protection is mentioned:

Pt.5 Ch.3 Sec.11
D 400 Gas cleaning and cooling

401 A gas scrubber shall be fitted for the purpose of effective cooling and cleaning of the gas. The scrubber shall be protected against corrosion. Devices shall be fitted to minimise carry-over of water and solids. For flue gas system the scrubber shall be fitted on the suction side of the fans.

The water supply of the open loop seawater scrubber is crucial for the abatement capacity of the system. As much as 45 m^3/MWh of water is pumped through a scrubber to scrub the flue gas and to dilute the discharge. Rules regarding pump capacity exists for inert gas production and is essential to the scrubber systems since failing to reduce SO_x to allowable limits, or failing to dilute the discharge to a legislated pH, will result in violation of Annex VI. Thus the water supply rule shall be applicable also to scrubbers:

Pt.5 Ch.3 Sec.11
D 500 Water supply

501 Both the gas scrubber and the water seal shall be supplied with cooling water from two pumps, each of sufficient capacity for supplying the system at maximum inert gas production, and without interfering with any essential service on the ship. One of the pumps shall serve the inert gas scrubber exclusively.

In an open loop seawater scrubber the scrubber water pumped onboard will be discharged overboard as effluent. Certain rules for the discharge already exist for inert gas plants. The inert gas plant rules should be applicable also to scrubbers:

Pt.5 Ch.3 Sec.11
D 600 Water discharge

601 The water effluent piping from scrubber, valve(s) included, shall be protected against corrosion.

602 Distance piece between overboard valve and shell plating shall be of substantial thickness, at least shell plate thickness, but not less than 15 mm.

603 If water discharge is obtained by means of discharge pumps, a pumping arrangement equivalent to the supply shall be provided.

604 Discharge pipes from the water seal shall lead directly to sea.

Continuing with water supply regulations, piping design principles regulating sea inlet and discharges shall also apply to scrubber inlet and discharge systems:

Pt.4 Ch.6 Sec.3
A 300 Valves on ship's sides and bottom

301 All sea inlet and overboard discharge pipes shall be fitted with easily accessible valves or cocks secured direct to the shell or sea chest. Scuppers and sanitary discharges shall be arranged in accordance with Pt.3 Ch.3 Sec.6 K, as applicable.

Due to the vast amount of water pumped through a scrubber system it might be necessary to ensure adequate supply of water, even during ships movement. A current piping rule might thus be applicable to scrubber systems:

Pt.4 Ch.6 Sec.3
A300 Valves on ship's sides and bottom

308 Sea inlets shall be so designed and arranged as to limit turbulence and to avoid entry of air due to the ship's movements.

Some scrubber systems use a closed loop where the residue is accumulated in a tank. For these systems and others that uses accumulation tanks, drip trays and waste tanks shall be arranged to handle possible leakage as safety arrangements. The rule is also applicable to tanks for additives if such are used:

Pt.4 Ch.7 Sec.3
B 400 Safety arrangements

406 System tanks and vessels where water may accumulate, shall be arranged with drain cocks.

408 Drip trays with drains to a waste oil tank shall be arranged under all plant components where leakage may occur.

The scrubber washing system can possibly be compared with the water cleaning system that can be used in an exhaust gas boiler. Thus the rules regarding drainage for such systems can be applicable also to scrubbers:

Pt.4 Ch.7 Sec.3
C 200 Soot-cleaning arrangement

202 Exhaust gas collecting pipes shall be provided with drain. The drainage system shall be capable of draining all water when the water washing or water fire extinguishing system in the exhaust gas boiler or economizers are in operation. Necessary protection shall be made, so that water can not enter into any of the engines. The drainage shall be led to a tank of suitable size.

Due to the large amounts of water pumped through a scrubber system, and since additives might be used that bring health risks, the rule Pt.4 Ch.1 Sec.4 A 103 in Section 7.2.2 might be applicable also to scrubbers. A leakage in a scrubber system could cause flooding of a compartment, be hazardous to the crew, or both depending on the situation. Finally, for scrubber installations using additives a dedicated tank for the chemical is needed. Sounding pipes will, as in Section 7.2.2, be able to determine the chemical level in the tank as well as detect potential leakages, thus Pt.4 Ch.6 Sec.4 K 501 is applicable also for scrubbers.

7.3. Regulations and Failure Modes Overview

Table 13 to Table 18 summarises earlier sections to give a better overview of the identified failure modes and regulations applicable to regulate them.

Table 13. Main failure modes and regulations for a SCR system.

Main failure modes	**Cause**	**Explanation**	**Rule**	**Rule**	**Rule**
Increased erosion, corrosion, fouling and clogging, also for downstream equipment	Too low temperature (<300°C)	Sulphur in fuel reacts with ammonia to form sulphate compounds.	Pt.5 Ch.3 Sec. 11 - material choosing	Pt.4 Ch.7 Sec.3 - Soot Blowing	Pt.6 Ch.12 Sec.2 - B 200 NOx Emissions Clean Notation
Decreased catalytic efficiency	Too high temperature	Sintering of the catalyst --> smaller reaction surface. Ammonia burns instead of reacting with NOx (rather failure to comply with MARPOL than risking the safety of the ship).	Pt.6 Ch.12 Sec.2 - B 200 NOx Emissions Clean Notation		
Increased back-pressure due to clogging	Too low flow velocities (above 12m/s recommended)	Soot and other deposits get stuck in the honeycomb chamber.	Pt.4 Ch.7 Sec.3 - Soot Blowing		
Loss of propulsion due to engine failure	Additive non-reacting / overdosing	Non-reacting additive pouring upstream into engine(s) / turbo.	Pt.4 Ch.3 Sec.1 F400 Exhaust pipes - separate outlets / precautions		
Injured crew	Additive handling	Un-suitable handling/accident handling hazardous additive.	Pt4.Ch3 Sec 1 B 700 Fuel oil system - double piping	Pt.4 Ch.6 Sec.2 A 100 General – suitable material	

Table 14. Main failure modes and regulations for an EGR system.

Main failure modes	**Cause**	**Explanation**	**Rule**	**Rule**	**Rule**
Increased wear of engine	Decreased pH, increased soot and accumulation of particles	Sulphur being re-circulated leading to increased sulphur concentration in the cylinders. Decreased oxygen levels leading to increased soot formation together with recirculation.	Pt.5 Ch.3 Sec. 11 - material choosing		
Decreased lubrication	Increased soot content and decreased pH of lubrication oil	The increased amount of particles in cylinder contaminating the lubrication oil.	Pt.4 Ch.3 Sec.1 - B 1600 Type testing data collection - lubrication		
Corrosion and reduced efficiency	Soot deposits	The sulphur present in the system creates deposits and forms sulphuric acid in the system.	Pt.4 Ch.7 Sec.3 - Soot Blowing	Pt.4 Ch.3 Sec.1 - E 100 General - Detection of misfiring	Pt.4 Ch.3 Sec.1 - B 1700 Type testing program - should be able to run with one turbo charger damaged at 40% could say same for EGR

Table 15. Main failure modes and regulations for a HAM system.

Main failure modes	**Cause**	**Explanation**	**Rule**	**Rule**	**Rule**
Hydrolock	Failure of equipment or control system	Excessive vapour condensation in cylinder leading to condensation.	Pt.4 Ch.3 Sec.1 - B 800 Charge air system and cooler - prevent water entering cylinder	Pt.4 Ch.8 Sec. 3 D 200 Cooling and anti-condensation - avoid condensation in the equipment	
Increased cylinder wear	Disturbed lubrication films	Contamination at removal of lubrication oil because of the added vapour.	Pt.4 Ch.3 Sec.1 - B 1600 Type testing data collection - lubrication		
Clogging of evaporator / humidifier tower	Salt, calcium or other mineral deposits	Salt, calcium or other mineral from the sea water vapour accumulating and creating growing deposits.	Pt.4 Ch.7 Sec.3 - Soot Blowing		
Damage to equipment or crew	Hot steam leakage	Leakage of high pressure steam could potentially damage crew members or vulnerable equipment.	Pt4.Ch3 Sec 1 B 700 Fuel oil system - double piping		
Engine shut-down/overheating	Pumps/valves failing	Failure of the HAM system would remove the cooling of the engine and thus need to run the engine on low load or in worst case shut-down.	Pt.4 Ch. 1 Sec.2 A 200 Availability - redundancy	Pt.4 Ch.3 Sec.1 - B 1700 Type testing program - should be able to run with one turbo charger damaged at 40% could say same for EGR	

Table 16. Main failure modes and regulations for a DWI system.

Main failure modes	**Cause**	**Explanation**	**Rule**	**Rule**	**Rule**
Hydrolock	Failure of pumps, control system or injection nozzles	Water in liquid face being incompressible leading to increased pressure resulting in engine stop or break down of engine parts.			
Increased cylinder wear	Disturbed lubrication films	Contamination at removal of lubrication oil because of the added water.	Pt.4 Ch.3 Sec.1 - B 1600 Type testing data collection - lubrication		

Table 17. *Main failure modes and regulations for a WIF system.*

Main failure modes	**Cause**	**Explanation**	**Rule**	**Rule**	**Rule**
Engine stop	Incorrect water content in emulsion	Too much water can lead to too much cooling and thus the emulsified fuel will not burn. Too little water will lead to increasing engine temperatures.			
Failure of fuel supply system	Change of viscosity Breakdown of the emulsifier	Adding water to the fuel will increase the viscosity and thus create the need of increasing the pressure in the fuel oil supply system, new injection nozzles etc. Irregularities in the emulsion will thus bring problems. Failure of the emulsifier will stop the water addition, possibility for bypass but then temperature of the combustion and viscosity of the fuel will be drastically changed.	Pt.4 Ch.6 Sec.3 A 100 Piping systems – Avoiding detrimental vibrations		

Table 18. Main failure modes and regulations for a scrubber system.

Main failure modes	**Cause**	**Explanation**	**Rule**	**Rule**	**Rule**
Water/exhaust leakage	Corrosion of the scrubber	Sulphuric acid condensation on walls.	Pt.5 Ch.3 Sec. 11 - material choosing		
Water stop/overflow	Water supply failure Water freezing	Water supply valves stuck in open/closed, pumps failing etc. Piping leading to scrubber, often up to funnel, freezing if sailing in arctic areas.	Pt.5 Ch.3 Sec.11 - D 500 Water supply	Pt.4 Ch.7 Sec.3 C 200 Soot-cleaning arrangement - 202 - System to collect all water if overflow	
Damage to hull/appendices	Discharge water causing corrosion, primarily on propeller	Sulphur in the water causing corrosion, primarily to Aluminumbronze (propeller).	Pt.5 Ch.3 Sec. 11 - material choosing		
Crew or equipment damage	Additive handling	NaOH being corrosive and cause severe burn if contact with human skin.	Pt4.Ch3 Sec 1 B 700 Fuel oil system - double piping	Pt.4 Ch.6 Sec.2 A 100 General – suitable material	

8. Discussion

The initial ambition of this thesis was to carry out a risk assessment on different abatement technologies for the reduction of NO_x and SO_x emissions. Limited data exist regarding probability of failure, maybe because manufacturers are reluctant to share information during the development stage of a product. Carrying out own tests and gather statistical information was outside any feasible time frame or budget dedicated for this project. Because of this the work instead ended up with analysing failure mode and their effects on the safety of the ship. The more limited work required to asses failure modes without including the probability of occurrence however opened up to analyse additional technologies.

Information has been gathered from manufacturers as well as independent sources such as state authorities. Interviews have been conducted resulting in gained knowledge about specific incidents that are believed to have a connection to the installed abatement technologies, but due to the reluctance of the stakeholders to publish such information this have had to been left out of the thesis. These examples could have been useful to justify some of the identified failure modes but have instead been used as a basis for further research in the specific areas. The results being presented are believed to give an unbiased picture of potential failure modes as they are understood today.

The thesis is believed to still serve its purpose by giving a picture of what failure modes that can occur when installing and operating abatement technologies. Together with the following analysis of what rules that needs to be added to have a comprehensive rulebook this thesis can be used for consideration when writing further rules.

9. Conclusions

This chapter will try to answer the main question of this thesis that was raised in Section 1.2; "*How well are the failure modes associated with installation and operation of abatement technologies covered by the DNV rulebook?"*

Each abatement technology will have its own section since they present different failure modes.

9.1. Selective Catalytic Reduction

As seen in Table 13, SCR is rather well covered by existing Class rules written for other technologies. The main problems with SCR, which can be expected during normal operation, are clogging and the formation of acids in the catalyst. The first problem with clogging is known from other equipment situated in the exhaust system but is still seen as a major problem since it can lead to e.g. fire in the exhaust gas system. The pressure drop over the SCR should be controlled and a soot-blower should be installed. Since redundancy is most likely unfeasible for a whole SCR, a by-pass over the SCR should preferable also be demanded.

The temperature problem is not covered by any specific rule at the moment, different engine loads or other circumstances can lead to a decrease in temperature. To ensure that this does not happen without notice a sound rule could be to control the temperature and possibly also demand corrosion resistant materials to be used downstream of the catalyst.

While urea is used, and not ammonia, the additive is concluded not to present any serious hazards as long as ordinary safety precautions is taken as when transporting urea or other chemicals.

9.2. Exhaust Gas Recirculation

EGR does not imply any imminent risk of loss of propulsion, as long as there is a shut-off valve, since this is an external installation that can be turned off. The main problems are increased wear of the engine and deposits in the EGR, as can be seen in Table 14. This can lead to fires as well as requiring shorter survey intervals. Soot-blower or other precautions to avoid deposits should be required, otherwise the conclusion is that no additional rules are required as long as the EGR follows the general rules for material, machinery and piping. If the EGR is combined with a scrubber to decrease engine wear the scrubber should follow the same rules as for a stand-alone scrubber.

9.3. Humid Air Motor

As for the EGR, HAM might disturb the lubrication and thus increase the wear of the engine. The failure mode that would introduce the most critical effect is that water condensate in the cylinder which can lead to engine stop, or in worst case mechanical failure of engine components, see Table 15. This is not regulated and is not a failure mode that can be acceptable, there is thus a need of additional rules that control the water temperature going in the cylinder to ensure that no liquid follows the charge air. To ensure that all the water is leaving the cylinder after combustion, the engine pressure should be monitored together with the exhaust gas temperature. The voluntary class notation CLEAN states that the installation should be carried out together with the engine manufacturer, however the installation might be done without wanting the CLEAN notation and could thus introduce a lack of rules regarding this matter.

As for the vapour supply there are existing rules for transporting hot steam in pipes. The risk of clogging the humidifier tower is presumably dependent on the design; measures should be taken to ensure that unacceptable deposits will not accumulate, either by design or by using a cleaning system.

9.4. Direct Water Injection

According to Table 16, the main failure mode is that too much water is injected leading to absent ignition. There are rules regarding how fuel injection and piping should be designed, these rules should also apply for an installation where DWI is used. There is not a lack of knowledge, rather a lack of specific rules for injection of water into the cylinder.

As for the potential increase in lubrication oil usage this is not considered to be an issue for Class and should thus be left as an issue for the manufacturer.

9.5. Water in Fuel Emulsion

Considering water injection there is no clear rules that can ensure the safety of the installation, as can be seen in Table 17. WIF could be compared to what needs to be complied with during a change of fuel. Rules for the emulsifier is needed together with either redundancy of the equipment or rules regarding switchover to run on pure fuel, without the water. To ensure the safety during operation, the quality of the emulsion should be monitored.

9.6. Scrubber

Scrubbers have previously been used in inert gas systems and the failure modes of these installations are thus fairly well covered, as shown in Table 18. The main change from these installations is that the exhaust gas scrubbers clean all the exhaust gas and a failure of the scrubber could affect the engine performance. This means that the scrubber should either have redundancy for the essential components or be equipped with a by-pass valve. Apart from this, large water pump installations and handling of hazardous additives are no new phenomena and there are rules written for these matters.

One of the more uncertain problems is what damage the discharge water can cause to the hull and appendices. A requirement on discharge water could reduce the oxidation of the appendices, especially propellers, and help to avoid serious failures but will also affect the installations severely. This is an area where more data is required regarding the influence of sulphur on the propellers before such a demanding requirement could be implemented, thus this is not recommended to implement without further investigation.

10. Recommendations

Overall, most of the failure modes are similar to other situations that can be found on board a ship and the ramifications are very well known. The water technologies are the ones which have had least attention dedicated to them and thus furthest from having a comprehensive coverage in the rulebook. It is recommended that DNV carry out an investigation determining to what extent water technologies needs to be regulated to ensure safe operation of such installations.

For exhaust gas cleaning system it would be preferable if the ramifications of sulphuric acids and other compounds were to be investigated further by a third part; at the moment most information is from the manufacturers themselves which might not always unbiased in discussions regarding their technologies.

Formulating comprehensive rules for technologies where there is only limited experience is also a challenge. To help the approval engineers to consider all the risks, it is recommended that with all installations that are filed for approval a failure modes and effect analysis should be carried out by the manufacturer as currently is required for e.g. control systems.

The most important reflection is not that unacceptable risks are introduced because of the lack of rules from DNV's part rather than difficulties for the manufacturers to know which systems will be approved and which will not. Even if it would mean restating existing rules it is still recommended to develop chapters in the rulebook which are dedicated to these new technologies to facilitate for both the manufacturers, surveyors and approval engineers.

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