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# Reduction of $SO_2$, $NO_x$ and Particulate Matter from Ships with Diesel Engines

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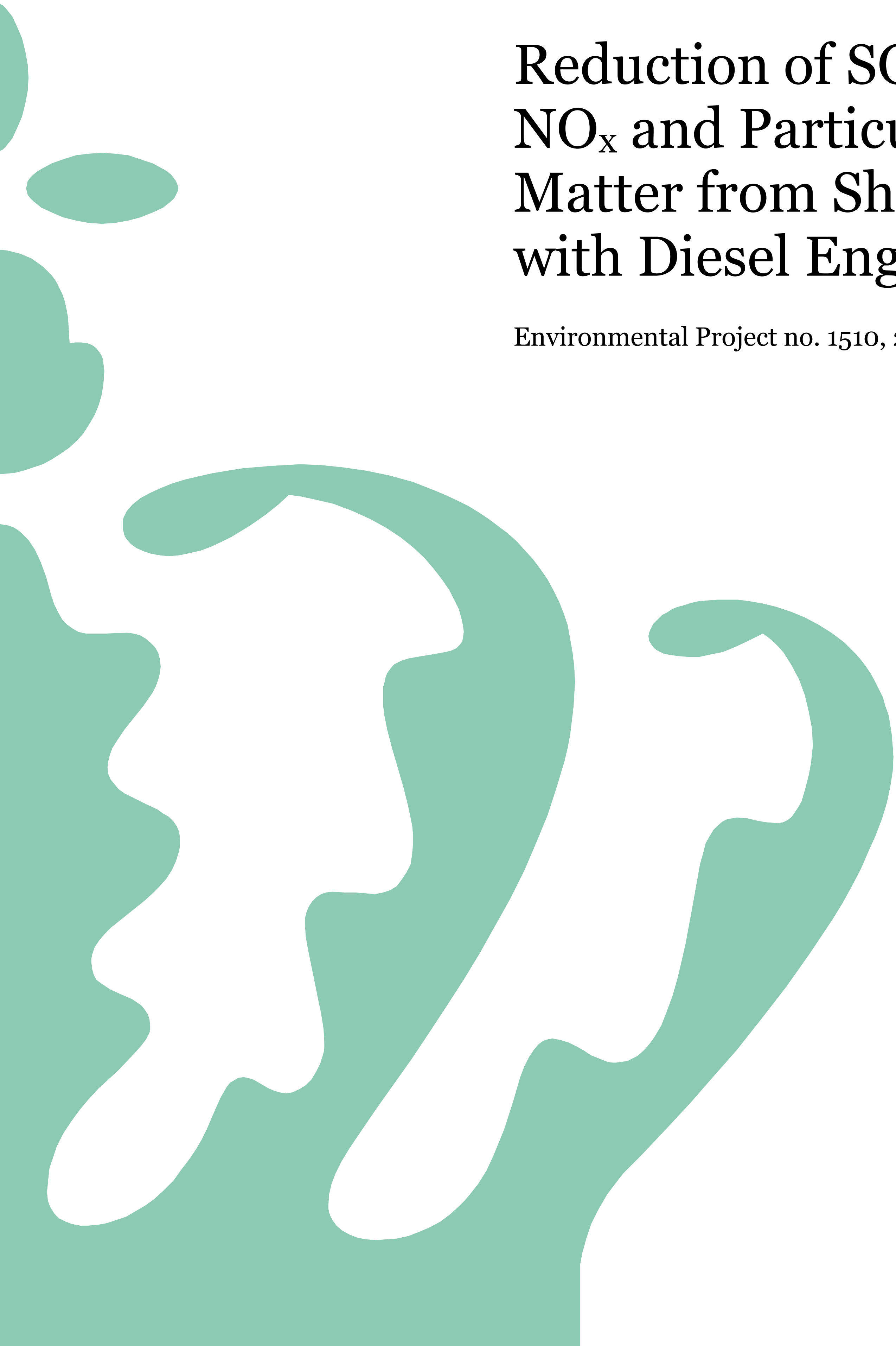

**Title:**

Reduction of $SO_2$, $NO_x$ and Particulate Matters from Ships with Diesel Engines.

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# Abbreviations and Acronyms

| | |
|---|---|
| ALA | Alfa Laval Aalborg |
| CAPEX | CAPital EXPenditures |
| CEAS | MAN two-stroke software program for prediction of engine data |
| CTU | Collecting Tank Unit |
| ECA | Emission Control Area |
| EGC | Exhaust Gas Cleaning |
| EGR | Exhaust Gas Re-circulation |
| E/R | Engine Room |
| EQS | Environmental Quality Standard |
| FW | Fresh Water |
| HZ | Hudong Zhonghua shipyard in China |
| HFO | Heavy Fuel Oil |
| IMO | International Maritime Organization |
| LNG | Liquefied Natural Gas |
| MARPOL | The International Convention for the Prevention of Pollution From Ships |
| MCR | Maximum Continuous Rating (max. engine power) |
| MDT | MAN Diesel & Turbo |
| MEPC | Marine Environment Protection Committee (under the IMO) |
| M/E | Main engine |
| MGO | Marine Gas Oil (a distillate) |
| MW | Mega Watt NTE - Not To Exceed (5.1 g/kWh $NO_x$, for engines below 130 RPM) |
| NECA | $NO_x$ Emission Control Area |
| $NO_x$ | Nitrogen oxides, $NO_2$ and NO. |
| OPEX | Operating Expense |
| PAH | Polycyclic Aromatic Hydrocarbons |
| PM | Particulate matter (ISO 8178) |
| S | Sulphur |
| $S_{eq}$ | Sulphur equivalent: sulphur in the fuel equivalent to the sulphur in the exhaust |
| SCR | Selective Catalytic Reduction |
| SECA | Sulphur Emission Control Area |
| $SO_X$ | Sulphur oxides, e.g. sulphur dioxide, $SO_2$ |
| SS | Suspended Solids |
| SW | Sea Water |
| TC or T/C | Turbocharger |
| WMC | Water Mist Catcher |
| WTS | Water Treatment System |

# Introduction

The focus on the environmental impact from global shipping and exhaust gas emissions from marine engines is increasing every year. Different technologies on marine engines are coming up in order to reduce emissions, i.e. $NO_x$, $SO_x$ and particulate matters, hence a combination of two technologies is described in this project.

Today, the majority of large ships use low cost heavy fuel oil (HFO). Due to the environmental focus on particularly emission of $SO_x$ and particulate matters (PM), IMO has introduced a global cap on the sulphur content in the fuel. This results in a lower degree of freedom for the shipowners in shopping competitive fuels like HFO with higher sulphur contents. By using abatement technologies such as $SO_x$ scrubbers, the shipowners can continue procuring low cost HFO and still comply with sulphur regulations. Normally, HFO has sulphur contents above the future limits.

The most environmentally friendly way to continue the use of HFO in the future seems to be removal of the sulphur after the engine by e.g. scrubbing with sea water or fresh water with addition of chemicals. Removal of sulphur from the HFO at the refineries is a very energy consuming process.

In today’s two-stroke marine diesel engines there are two main ways to reduce the $NO_X$ to the future Tier III criteria ratified by the International Marine Organization (IMO). The Tier III criteria correspond to a 74% reduction of $NO_x$ compared to today’s Tier II criteria. Exhaust Gas Recirculation (EGR) and Selective Catalytic Reduction (SCR) are the two different measures for meeting the IMO Tier III $NO_x$ criteria.

This project is carried out by MAN Diesel & Turbo, Branch of MAN Diesel & Turbo SE and Alfa Laval Aalborg (former Aalborg Industries A/S). Alfa Laval acquired Aalborg Industries A/S by December 2010 after start-up of this project. The project was accepted in August 2010 by the Danish Environmental Agency as a project in group “Environmental effective projects”.

The project was organised with a steering committee with senior managers from MAN Diesel & Turbo and Alfa Laval Aalborg. A project reference group was formed with participants from the Danish Environmental Protection Agency and Danish Shipowners´ Association. The Project management was carried out by MAN Diesel & Turbo.

MAN Diesel and Turbo (MDT) is a leading provider of marine engines and power plant systems and MDT has for several years been involved in development of the $NO_x$ reducing technology Exhaust Gas Recirculation (EGR) which through this project is further extended into the level of engine integration in order to obtain compact design.

Alfa Laval Aalborg (ALA) is a leading provider of boilers, economisers and scrubber systems. ALA has for several years been developing scrubbers (EGC scrubber) for reduction of $SO_2$ and particulate matters (PM) from the exhaust gas emitted by marine diesel engine burning HFO with sulphur content.

The objective of this project is to examine competitive, environmentally friendly and practical technologies for reduction of $NO_x$, $SO_2$ and particulate matters from large two-stroke diesel marine engines. The project focuses on EGR and EGC scrubber and how the two technologies can be combined and which synergy effects there are. The project includes studies on retrofit of EGC scrubber, engines with integrated EGR and combined EGR and EGC scrubber.

ALA has made the study on retrofit of EGC scrubber covering screening of ships and design parameters for case studies on EGC scrubber retrofit. A Scandlines ferry operating between Rødby and Puttgarden was used for the retrofit study.

MDT has investigated how to make engine integrated design of the EGR system. Two different engine sizes are covered; a smaller size for typically bulk carriers and a large size engine typically used in container vessels.

ALA and MDT have been cooperating closely during the case study on combination of EGR and EGC scrubber. The Chinese shipyard Hudong Zhongua has been involved in this sub-project providing yard expertise in design and economical aspects of combining these two technologies.

# Summary and Conclusion

The global focus on reduction of emissions from marine diesel engines has increased significantly during the last couple of years. In particular, the ratification of MARPOL Annex VI requirements for $NO_x$ and $SO_x$ emissions has been a solid driver for the development of technologies for $NO_x$ and $SO_x$ reduction in large two-stroke marine diesel engines. Additionally, there is a general focus on emission of Particulate Matter (PM) from diesel engines for which reason this part is also included in this project.

The overall objective of the project is to examine how emissions as $NO_x$, $SO_x$ and PM from ships can be reduced by combining two well-known but very different technologies; EGR (Exhaust Gas Re-circulation) for $NO_x$ reduction and EGC scrubber (Exhaust Gas Cleaning scrubber) for $SO_x$ and PM reduction.

It has been the intention of the project to investigate the options for competitive, environmentally friendly and practical technologies for reduction of $NO_x$, $SO_x$ and PM from large two-stroke diesel marine engines.

The project is divided into three sub-projects covering the following items:

- **Retrofit of EGC scrubber** is a study on EGC in order to identify design parameters and to create a calculation tool for layout of EGC. Screening of ships for retrofitting of EGC and a case study on a selected ship is included.

- **Engine with Integrated EGR** is a design study of how to integrate the EGR system on two different two-stroke diesel engine sizes, covering design strategy and requirements for EGR components.

- **Combined EGR and EGC scrubber** is a case study on the combination of EGR and EGC scrubber targeting synergy effects and installation requirements. The project covers investigation of how the two technologies can be combined including auxiliary equipment and economical evaluation.

Retrofit of EGC scrubber covers a study of the potential market relevant for EGC scrubber retrofit. The purpose of the EGC scrubber is to reduce $SO_x$ and PM emissions. It is estimated that it could be relevant for approximately 3,000 ships to install an EGC scrubber system. These ships are a mixture of oil tankers, chemical tankers, bulk carriers, container vessels, RO-RO ships, ferries, cruise ships and others. The engine sizes for these different ships are typically ranging from few MW and up to about 40 MW. A calculation tool for design of scrubbers has been developed. This tool is essential when designing new EGC scrubbers and to judge the influence of different parameters that can vary significantly from case to case. As a case study, the possibility for retrofit of EGC scrubber on Scandlines ferry M/V Prins Richard has been investigated. Drawing material for installation of a EGC scrubber on one of the vessels 3.5 MW engines has been made. Based on these, an offer from a yard has been given for the work involved. The entire EGC scrubber system and installation can be paid back after approximately 15,000 operating hours. The payback time will be better for another case with a larger engine.

Engine with integrated EGR covers a comprehensive work with engine integrated EGR design that is successfully carried out providing two different designs of EGR engines. The purpose of EGR is to reduce $NO_x$ emission. A 6S80ME-C9.2 EGR engine with a power rating of 27 MW and a 6G50ME-C9.2 EGR engine with a power rating of 10 MW were designed. The design strategy was to keep the same outline of the engine as the standard engine for Tier II, so that yards do not have to change the conventional way of engine room arrangement. The design turned out successfully keeping the same footprint as a standard engine. Only the galleries have to be extended a little and some minor space for EGR auxiliary connections is necessary.

Options for downsizing and simplification of the engine-mounted EGR unit will be carried out in the future, due to the fact that on small engines it is challenging to find the necessary space for the EGR unit on the engine.

In the Combined EGR and EGC scrubber project, a number of combinations of EGR and EGC scrubbers were examined in order to identify the influence on running conditions, system complexity and economy. The purpose of the combined system is to remove $NO_x$, $SO_x$ and PM. A case study on a 4,900 teu (20 foot equivalent containers) container vessel with a 6S80ME-C9.2 EGR engine is completed in cooperation with the Chinese shipyard Hudong Zhongua.

The case study showed that EGR and EGC scrubber can be combined in a beneficial way with positive synergy effects on ship installation and economy. The case study shows that the benefit of installing EGR and EGC scrubber as a combined system is a potential reduction in first cost with 5-20%.

With the combined solution, the ship owner can maintain the use of low cost fuel and meanwhile comply with the requirements for $NO_x$, $SO_x$ and PM in the ECA areas. The operating cost savings by operating on low cost heavy fuel oil with EGC scrubber and EGR systems compared to operation on higher cost marine gas- or diesel oil is 17% to 30%, giving a first cost investment payback time less than two years.

Besides compliance with $NO_x$ and $SO_x$ requirements, the PM emission is estimated to be significantly reduced by combining EGR and EGC scrubber. A reduction of up to 80% in Tier III mode is estimated compared to PM from a standard Tier II engine. Operating the engine in Tier II mode with the EGC scrubber in operation will reduce the PM up to 70%.

# Resumé

Den globale fokus på at nedbringe emissioner fra skibes dieselmotorer har igennem de seneste år været kraftigt forøget. Særligt IMO's ratificering af MARPOL Annex VI kravene til reduktion af $NO_x$ (nitrogenoxider) og $SO_x$ (svovloxider) har stor betydning for udviklingen af teknologier til reduktion af $NO_x$ og $SO_x$ udledningen fra store totakt marine dieselmotorer. Herudover er der generelt fokus på partikelemissioner fra forbrændingsmotorer hvorfor denne del også er inkluderet i projektet.

Formålet med dette projekt har derfor været at undersøge hvordan emissioner af $NO_x$, $SO_x$ og partikler fra skibe med dieselmotorer kan nedbringes ved at kombinere to kendte, men væsentligt forskellige teknologier EGC scrubber (Exhaust Gas Cleaning scrubber) og EGR (Exhaust Gas Recirculation).

Det har været hensigten med projektet at undersøge mulighederne for frembringelse af økonomisk konkurrencedygtig, miljømæssig fordelagtigt og praktisk anvendelig teknologi til reduktion af $NO_x$, $SO_x$ og PM emission fra store totakt marine dieselmotorer.

Projektet er inddelt i tre del-projekter omhandlende følgende emner:

- ”Retrofit of EGC scrubber” er et studie på EGC scrubbere for at fastlægge designparametre og udvikle et beregningsværktøj til udlægning af EGC. Screening af skibe egnede til retrofitting af EGC samt case studie på et udvalgt skib gennemføres.

- ”Engine with integrated EGR” er et designstudie af motorintegreret EGR system på totakt marine dieselmotorer på to forskellige motorstørrelser. Herunder design strategi og krav til EGR komponenter.

- ”Combined EGR and EGC scrubber” er et case studie på kombineret EGR og EGC med henblik på et studie i synergieffekter og installationsbehov. Det undersøges hvordan systemerne kan kombineres inklusiv hjælpesystemer og der laves økonomisk vurdering af besparelse ved kombinationen.

I ”Retrofit of EGC scrubber”, er det potentielle marked for EGC scrubber retrofit i det nuværende europæiske ECA undersøgt. Formålet med en EGC scrubber er at reducere udledningen af $SO_x$. Det anslås, at være relevant for ca. 3000 skibe at installere EGC scrubber. Disse er en blanding af tankskibe, tørlastskibe, containerskibe, Ro-Ro skibe, færger, krydstogtskibe, og andre. Motorstørrelserne vil typisk variere fra få MW og op til 40 MW. Et beregningsprogram til design af EGC scrubbere er blevet udviklet. Dette beregningsværktøj er essentielt for udlægning af nye EGC scrubbere og til at vurdere indflydelsen af forskellige parametre, som kan variere betragteligt fra case til case. Som et case studie er mulighederne for at retrofitte EGC scrubbere på Scandlines færge M/V Prins Richard undersøgt nærmere. Tegningsmateriale for installation af en scrubber efter en af skibets 3.5 MW motorer er blevet udarbejdet. Baseret på disse er der indhentet tilbud på værftsarbejdet mv. EGC scrubber systemet og installationen vil kunne betales tilbage efter ca. 15.000 driftstimer. For en anden case, vil tilbagebetalingstiden alt andet lige reduceres hvis motorstørrelsen øges.

I ”Engine with integrated EGR”, er der arbejdet intenst med udvikling af motorintegreret EGR design. Formålet med EGR er at reducere udledningen af $NO_x$. En stor motor 6S80ME-C9.2 på 27

MW og en mindre 6G50ME-C9.2 på 10 MW er blevet designet med integreret EGR. Designstrategien har været at motorernes outline ikke måtte blive påvirket nævneværdigt, så værfterne ikke skal ændre deres normale indretning af maskinrum. Dette er lykkedes og motorernes "footprint" er bibeholdt. Kun gallerier er rykket lidt og herudover er det tilslutningerne til EGR systemet der skal tages hensyn til.

Fremadrettet vil der blive arbejdet videre med at mindske størrelsen på EGR enheden da studiet har vist at det er vanskeligt at få plads til EGR enheden på mindre motorer.

I del-projekt C, "Combined EGR and EGC scrubber", er der udført en række undersøgelser af hvorledes EGR og EGC kan kombineres og hvilken betydning det har for driftsbetingelserne, kompleksitet af hjælpesystemer samt for økonomien. Der er gennemført et case studie af et 4.900 teu (20 fod container ækvivalent) containerskib med en 6S80ME-C9.2 motor i samarbejde med det kinesiske skibsværft Hudong Zhongua. Studiet viste at det er muligt at kombinere EGR og EGC scrubber på en fordelagtig måde med positive synergieffekter på såvel installation som på økonomi.

Beregningerne i case studiet viser at det er muligt at reducere investeringen med 5 - 20%.

Ved at kombinere EGR og EGC scrubber kan rederen fortsat benytte billig heavy fuel olie og samtidig overholde krav til $NO_x$, $SO_x$ og PM i ECA områder. Besparelsen på driftsudgiften ved at benytte en kombination af EGC scrubber og EGR anlæg er 17% til 30% i forhold til sejlads på dyrere marine gas- og dieselolie, hvilket giver en tilbagebetalingstid på under 2 år.

Udover at opfylde $NO_x$ og $SO_x$ kravene vil mængden af udledte partikler være reduceret markant, idet såvel EGR systemet som EGC scrubber systemet fjerner en stor mængde af partiklerne. Tilsammen estimeres PM reduktionen ved Tier III drift til at være op til 80%, sammenlignet med en standard Tier II motor. Ved Tier II drift med EGC scrubberen i drift og stoppet EGR system vil reduktionen i PM være op til 70%.

# 1. EGC scrubber

ALA has made scrubbers for several decades as part of Inert Gas Systems, which basically is a fuel oil combustion unit burning high sulphur fuel oil followed by a scrubber that cleans the flue gas for $SO_2$ and soot particles in order to create a clean inert (low oxygen content) gas that can be used to prevent explosions in oil or chemical tankers. These scrubbers have been developed and optimised for operation in the exhaust gas funnel after an diesel engine. The first tests were made in cooperation with MDT at their test center in Holeby-DK in 2009 and subsequently full-scale EGC scrubbers (PureSOx) were installed on M/V Ficaria Seaways in 2010 and on M/V Spliethoff Plyca in 2012. Additional PureSOx EGC scrubber systems are planned to be installed during the second half of 2013.

The scrubber on Ficaria has now exceeded 10.000 operating hours and both on Ficaria and Plyca, $SO_x$ emissions well below that corresponding to 0.1% sulphur in the fuel are measured continuously after the scrubber (Ref. 3). In Holeby-DK, PM removal efficiencies between 45-79% were measured by MDT according to ISO 8178 (Ref. 4). A PM removal efficiency of 94% was recently measured by Force Technology (ISO 8178) on a full-scale PureSOx system in operation. These reduced PM levels are significantly lower than what can be expected if operating an engine on MGO instead of HFO (~60%).

## 1.1 Objectives and deliveries in sub-project A

The objectives of this sub-project are:

- Clarification of design parameters for EGC scrubber systems.
- Clarification of standard solutions and acceptable variability.
- Development of design tools.
- Screening of different ship types covering the majority of the market.
- Establishment of contact to ship owners.
- Inclusion of a ship design bureau.
- Specification of the selected ships.
- Feasibility study on economy and environment.
- Mapping of sailing pattern for the selected ships.
- Production of engineering material for retrofit of EGS system.

The deliverables of this sub-project are:

- Note covering design parameters and design tool.
- Note covering specification and drawings of the selected ship.
- Input to the final project report.

## 1.2 Conditions influencing on the design of an EGC scrubber system

An EGC scrubber design program has been made based on the data and experiences from the first full-scale scrubber in operation. As an EGC scrubber system, in principle, can be fitted on any type of ship sailing in any ocean in the world, it is important to understand how factors like sea water temperature, sea water alkalinity, fuel oil quality, and engine or boiler type influence on the dimensions and efficiency of the scrubber. Such a design program validated with as much real data as possible is essential for lowering the capital investment as well as the long-term operational costs of the EGC scrubber system.

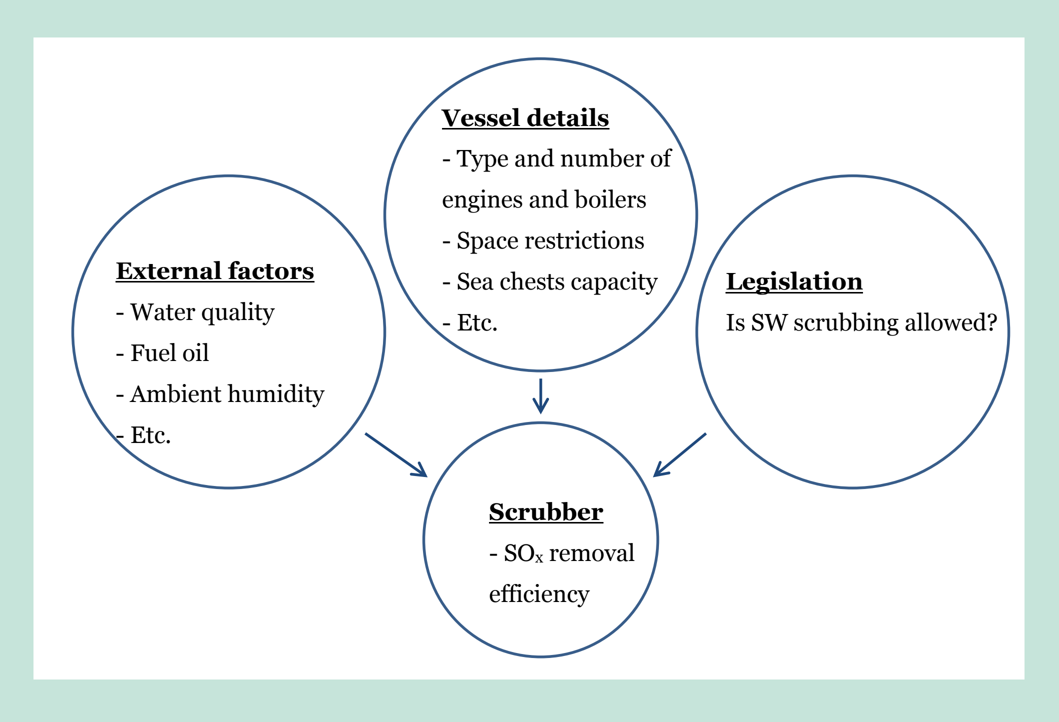

Figure 1: Main groups of design factors for an EGC scrubber system.

## External factors

- Fuel oil type and quality: The sulphur content determines the $SO_2$ emission level and the hydrogen content influences on the water consumption in FW mode. The fuel oil quality also has an influence on the soot emission and hence on the size of the water treatment system as well as on the amount of sludge that is collected by the EGC scrubber system.
- Water quality: The water alkalinity has an influence on the amount of sea water required for a SW scrubber and hence on the size of pumps, etc. For an FW mode scrubber, the water quality is important to avoid the risk of scaling and corrosion.
- Air temperature and relative humidity are important to calculate the water content in the exhaust gas and hence the overall water consumption for the EGC scrubber system.
- Sea water temperature influences on the $SO_x$ removal efficiency in SW mode and on the cooling and hence overall FW consumption in FW mode.

Common for this group is that the EGC scrubber system has to be designed for a worst case scenario. However, it is very important to consider this scenario carefully as it will have a significant influence on the size of the EGC scrubber system as well as on the long-term operating costs. It is also important to have other back-up possibilities in mind, e.g. that the scrubber can switch from SW to FW mode or to low sulphur fuel in some extremes (e.g. very low alkalinity, maximum engine load on all main and auxiliary engines, and max. allowable fuel-S content). In practice, it is unlikely that a vessel will experience all these extremes simultaneously.

## Vessel details

- Engine type and size determine the amount of exhaust gas to the scrubber and have a significant influence on the scrubber dimensions. Two-stroke engines use more excess air for the combustion which results in a lower $SO_2$ concentration and hence a larger scrubber size. It also has to be ensured that the pressure drop through the entire exhaust line, which typically also includes an exhaust gas boiler and silencer will not exceed the engines maximum allowable back pressure.

- An exhaust gas boiler or a waste heat recovery boiler will lower the exhaust gas temperature whereby the size of the plate heat exchanger in an FW EGC scrubber system can be reduced.
- Space restrictions: For retrofit projects, there are typically restrictions to the diameter and height of the scrubber as well as there may be limitations on tank capacity for storage of fresh water, caustic soda and sludge. Though a high speed separator for water cleaning requires much less space than other water cleaning solutions due to the high g-forces exposed to the soot particles, it is still necessary to find approximately 2.5 x 2.5 meters of space for this equipment.
- Limitations on electrical power. In most cases, auxiliary engines will have excess power available for the EGC scrubber system but this has to be checked in an early stage of the project.

**Legislation**
Scrubbers are designed to comply with the guidelines as provided by MEPC under IMO, which are being implemented in EU, US and national legislations.

- Sulphur limit: In the EU and US ECA, the scrubber has to reduce the $SO_2$ emission to an equivalent of 0.1% (w/w) sulphur in the fuel. Globally, this limit will be 0.5% from 2020 or 2025 (depending on the availability of low sulphur fuel in 2018).
- Discharge water. It is still being discussed within IMO/MEPC whether SW scrubbing will be allowed or not due to the slightly acid discharge. If SW scrubbing for some reasons is prohibited, it will be necessary to operate the scrubbers in FW mode whereby there will be an additional consumption of caustic soda.

## 1.3 Design program

A design program has been developed in order to process the input data as described above. The parameters (mass and heat transfer coefficients, chemical equilibrium constants, flooding factors, etc.) have been estimated by using literature data as well as by fitting so the calculations agree with real data from our current scrubbers in operation. With this program, it is possible to avoid over-dimensioning the scrubbers and, at the same time, to guarantee that the EGC scrubber system can comply with the 0.1% fuel-S equivalent under all specified conditions.

This design program has been used to select and dimension the EGC scrubbers considered in this project.

**Output**: The output from the design program is e.g.:

- Size and weight of the scrubber.
- Consumption of FW, caustic, and electricity
- Pressure drop through the scrubber
- Dimensions of water pipes, pumps, etc.

The output can be further processed to calculate a price for the EGC scrubber system as well as to generate production drawings.

## 1.4 Identification of ships for this case study

The market for exhaust gas cleaning scrubber (EGC scrubber) systems can be divided into a retrofit market and a new building market. Retrofitting EGC scrubbers on existing ships that are already built and sailing in the current European ECA (Baltic, North Sea, English Channel) will be the greatest challenge during the years from now (2013) and until 2020. This market will then start to decline but is expected to be followed by a global retrofit market because the global sulphur cap will go down to 0.5% from 2020[1]. A statistic of the number of ships that are sailing within the European ECA is shown in Figure 2. A total of 3,002 ships are sailing more than 50% of their time in ECA while the remaining 8,362 of these ships are sailing less than 50% of their time in ECA. In general, the payback time will be shortest for the ships sailing all their time in ECA, though it will also be attractive to retrofit EGC scrubber on some of the other ships sailing less time in ECA.

For shipowners, it is interesting to calculate the total amount of fuel that is actually burned within ECA. An owner can find his fuel consumption as well as he can estimate his expected remaining life time for each of his ships. He can then rank all his ships and those burning most fuel in ECA and those that are expected to have a long remaining lifetime are – at a first sight – those that are most relevant to evaluate further for retrofitting of EGC scrubber.

Unfortunately, it is very difficult to generalise about the type of ships that are relevant for retrofitting of EGC scrubber. Figure 3 shows a general division of ships into different types. Most of these are fishing boats but these are usually not relevant as they are already sailing on low sulphur fuel oil due to their limited sizes and hence also limited engine capacities. Excluding the fishing boats and yacht vessels, the remaining retrofit market for EGC scrubbers will be a mixture of oil tankers, chemical tankers, bulk carriers, container vessels, Ro-Ro ships, ferries, cruise ships and others. Further to this, the engine sizes on these different ships will typically range from few MW and up to about 40 MW. The biggest container vessels with up to 100 MW engine power will only sail a limited time in ECA. Passenger ships including cruise vessels are normally using four-stroke engines because these engines are less noisy and create fewer vibrations. Ro-Ro vessels typically also use four-stroke engines due to their lower stroke length and hence lower height, which makes it easier to construct the ship because there will be better access for truck trailers to be rolled on and rolled off[2]. However, two-stroke engines have a slightly better fuel economy and also lower maintenance costs and are therefore used in many of the tankers, container ships and other ship types. Due to the above, the retrofit market for EGC scrubbers must be expected to be difficult to generalise about – both with respect to ship types, engine types and engine sizes.

One criterion that is interesting to investigate is the lower limit engine size for which it will no longer be attractive to retrofit EGC scrubbers. As an EGC scrubber system contains a lot of fixed cost equipment, like gas analysers, water analysers, PLC control system, that are independent on the size of the engine and hence scrubber, there is a minimum engine size (or rather fuel consumption) below which it will no longer be attractive to retrofit EGC scrubber. This is studied further in the below case study.

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[1] The global sulphur cap on max 0.5% (w/w) from 2020 is subject for revision by IMO in 2018. If there is insufficient availability of low sulphur fuel, this cap might be delayed until 2025. However, the EU commission has stated that the 0.5% sulphur cap will prevail from 2020 within EU.

[2] The Ro-Ro vessel Ficaria Seaways, which was the first ship with a two-stroke engine (21 MW from MAN Diesel & Turbo) subject to EGC retrofit, is an exemption to this.

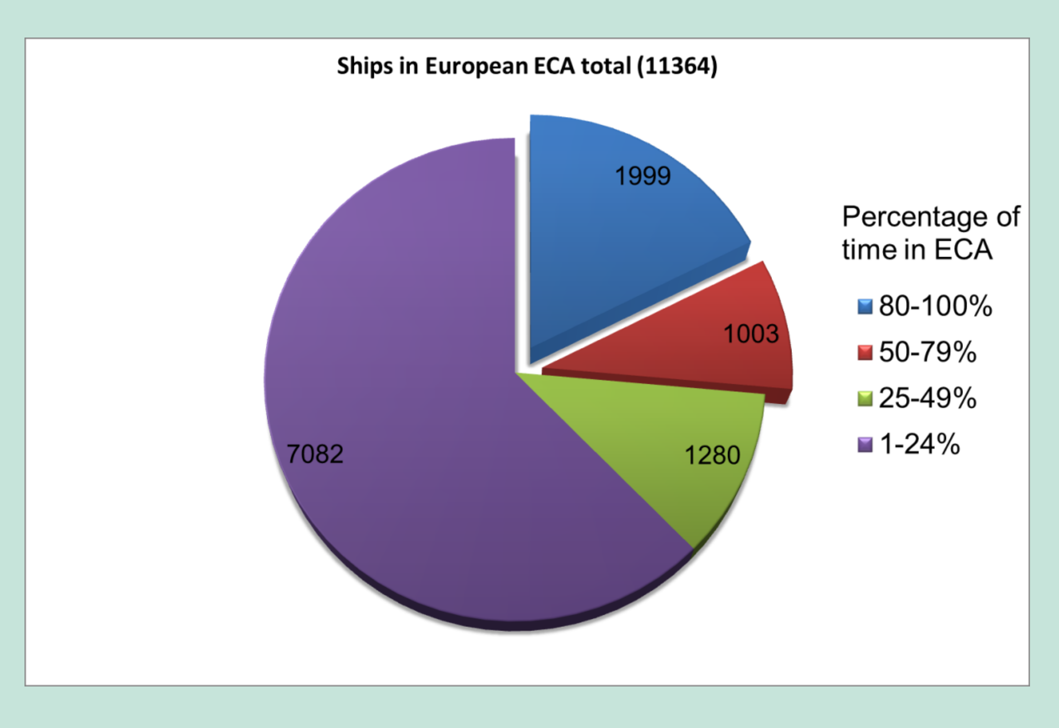

Figure 2: Statistic of ships sailing in the European ECA

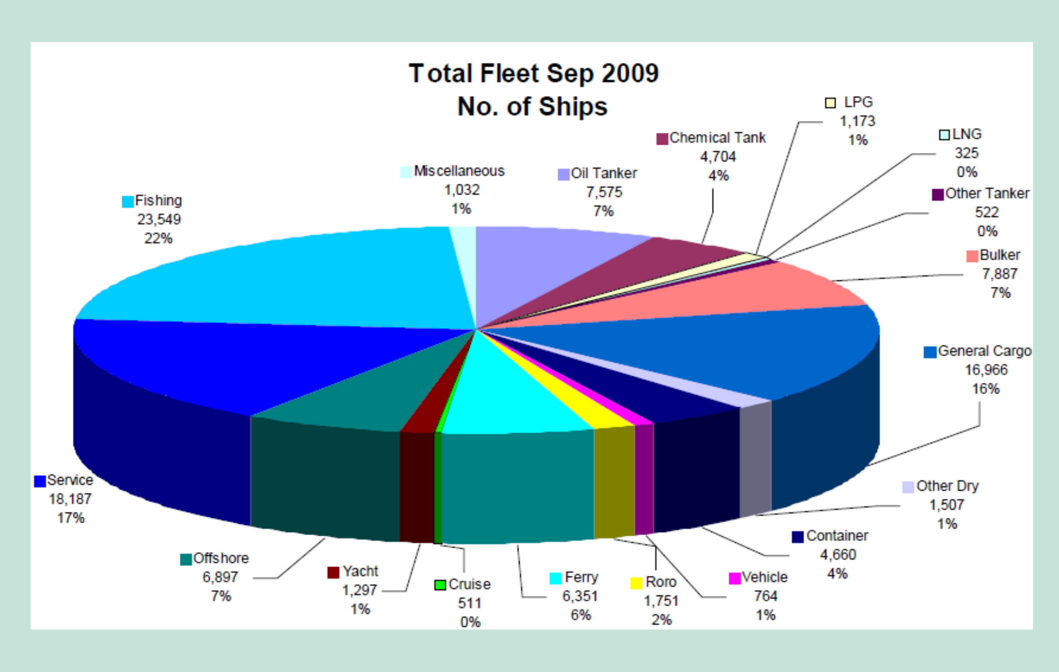

Figure 3: Division of major ships into different types – worldwide.

Two different vessels were initially selected to study further in this part of the project: An 1,800 teu container vessel with a 17 MW two-stroke engine and a passenger ferry with five four-stroke engines of 3.5 MW each. These vessels can be considered as examples of a medium “scale” and “small” scale project. Unfortunately, it has not been possible to finalise the case study with the container vessel because all the electronic drawing material of this vessel belongs to a Chinese yard. Easy access to the original ship drawings (preferably in an electronic format) is therefore also an important parameter when considering which ships to select to study further.

## 1.5 Passenger ferry

Scandlines operates four almost identical ferries between Rødby (Denmark) and Putgaarden (Germany) and has volunteered to study the possibility of retrofitting scrubbers on one of these ferries. Two of the four ferries are Danish flagged and built at Ørskov Steel Shipyard. One of these two, MF Prince Richard, was selected for this study. The vessel is shown in Figure 4 and the route is shown in Figure 5. Some basic details about the vessel are listed in Table 1 below.

Figure 4: MV Prince Richard selected for the case study.

Figure 5: The route (red dotted line) of MV Prince Richard between Rødby (DK) and Putgaarden (DE).

Table 1: Data for MV Prince Richard (source: www.ferry-site.dk)

| **Route** | **Rødbyhavn - Puttgarden** |
|---|---|
| IMO | 9144419 |
| Building year | 1997 / 2004 |
| Building yard | Ørskov Staalskibsværft A/S, Frederikshavn, Denmark (#193) |
| Owner | Scandlines A/S |
| Operator | Scandlines GmbH |
| Length | 142.0 m |
| Breadth | 25.4 m |
| Draft | 5.8 m |
| GT | 14,621 |
| Machinery | 5 * MaK 8M32 |
| Speed | 18.5 kn |
| Number of passengers | 900 |
| Number of beds | 0 |
| Number of cars | 286 / 355 |
| Lane metres | 580 |
| Number of railway tracks | 1 |
| Length of railway tracks | 118 m |
| Port of registry | Rødbyhavn |
| Flag | Denmark |

The most important factors when considering the possibilities and costs of retrofitting exhaust gas scrubbers on board a ship are: engine sizes, the allowable extra pressure drop in the exhaust gas system, the actual engine load profiles, the space restrictions on board, the capacity of the existing sea water system, the requirements for reliability and redundancy, as well as the “worst possible” ambient conditions which the ship might be exposed to.

MV Prince Richard has five four-stroke MaK engines, each rated 3,520 kW (17,600 kW in total). These are all equipped with generators for producing electricity to the propulsion system. Normally on board most vessels, the engines are connected mechanically to the propeller, but with this diesel-electric system, electrically driven propellers are installed at both ends of the ship. The obvious advantage of this is that they save both time and fuel because they avoid manoeuvring the ship around each time they are in harbour. A trip usually takes about 40 minutes of which the first 10 minutes are with low engine load out of harbour, the next 20 minutes are with high engine load at open sea, and the last 10 minutes are with low engine load again into harbour. In harbour, only a single engine is running at low load in order to produce electricity for on board usage only. Scandlines has now equipped their ferry with a battery whereby it will be possible to reduce the maximum engine load and hence the size of the scrubbers. Scandlines judges that it will be sufficient to operate only two of the five engines if the battery can supply some additional power during the 20 minutes journey where they need most propulsion power. The battery can then be recharged in harbour when less propulsion power is required. As can be seen from Figure 4, Prince Richard has a funnel on each side of the ship. The exhaust pipes from two of the five engines are in the port side funnel and the remaining three are in starboard side funnel together with a flue gas stack from the oil fired boiler. The width of the existing funnel casing is approximately 2.0 meters. During a visit on board the ship, it was discussed that this casing could be extended in the length direction and upwards in order to get space for the scrubbers.

The exhaust gas scrubbers from Alfa Laval Aalborg are categorised as sea water (SW), fresh water (FW) or hybrid scrubbers. The most simple to explain are the SW scrubbers. In these, the water from the sea is simply pumped through to the scrubber and discharged to the sea again. The gaseous sulphur dioxide ($SO_2$) gets in contact with the sea water in the scrubber whereby it absorbs and reacts to sulphate, which already exists in much larger quantities in the sea water. FW scrubbers are slightly more complicated because the water is circulated and continuously neutralised by addition of caustic soda. A small part of this circulated water must be cleaned and discharged to the sea to avoid build-up and precipitation of sodium sulphate salt in the water system. A hybrid scrubber is basically a combination of the FW and SW scrubbers so it is possible to switch between the two scrubbing modes. Details of these systems are described in Sub-project C – Combined EGR and EGC scrubber.

For the one hour journey between Rødby and Puttgarden, a hybrid scrubber with a sudden switch-over from FW to SW outside harbour is considered inappropriate because the operation time in SW mode will be very limited. Process simulations have been made for both FW and SW scrubbers (not hybrid); key data from the technical specifications are listed in Table 2 below. A FW scrubber will be 30 cm smaller in diameter but, on the other hand, require the following additional equipment: plate heat exchanger for cooling the fresh water, a caustic soda storage and dosing system for neutralising of the fresh water, a circulation tank and a centrifuge separator for cleaning the fresh water.

Table 2: Data for Alfa Laval PureSOx SW scrubber and FW scrubber. Designed for one of the MaK 8M32 engines running on high sulphur heavy fuel oil.

| | **SW scrubber** | **FW scrubber** |
|---|---|---|
| Scrubber dimensions | | |
| Diameter | 2.0 m | 1.7 m |
| Height | 6.1 m | 6.0 m |
| Weight (operational) | 6 tonne | 6 tonne |
| Pressure drop | 100 mmWC | 100 mmWC |
| Sea water flow to scrubber (max) | 266 $m^3/h$ | - |
| NaOH consumption (50% solution) | - | 49.7 L/h |

Drawings of a new funnel casing with a scrubber retrofitted have been made by Hauschildt Marine. Before the battery was actually installed, it was considered to install one scrubber on each side of the ship and then – by aid of sealing air valves – it will be possible to clean the exhaust from any two of the five engines at time. As an alternative, several engines could operate at part load as long as the total amount of exhaust gas to the scrubber will not exceed the maximum capacity of the scrubber. As shown in Appendix A.1, it will be possible to keep the current width of the existing funnel casing, but it will be necessary to extend the casing in the length direction of the ship. Water pipes (blue) can be drawn from the pump room, through the inlet filters, through the engine room and up to the scrubber. The dimensions of this pipe will be DN200 for an SW scrubber or DN150 for an FW scrubber. However, due to the costs of five individual scrubbers and to avoid this significant modification of both funnel casings, it was agreed to investigate the possibilities of reducing the number of engines subject to EGC scrubber retrofit.

As already mentioned, a new Li-Ion battery was installed on the vessel after this project was initiated. By aid of this battery, it will be possible to operate only one of the five engines at almost full load and almost constantly instead of operating two engines. A single scrubber will then be sufficient to clean the exhaust gas from this engine. New drawings of this setup are shown in Figure 6.

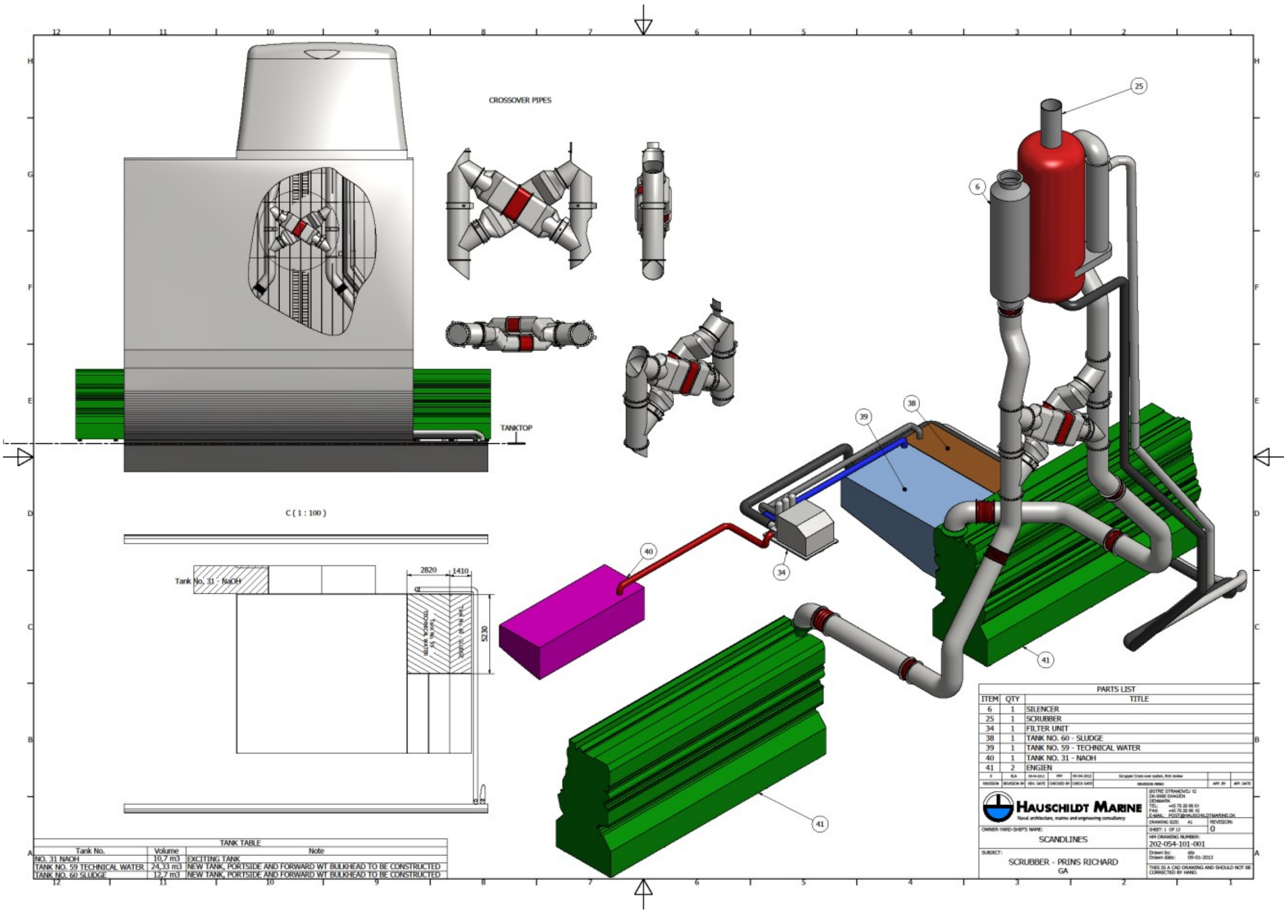

Figure 6: MV Prince Richard funnel casing with only one scrubber. The exhaust gas can be cleaned from one of the two engines at a time by changing the valve positions in the "Kolstra cross" in the exhaust gas ducting. One of the silencers has been removed in order to make space for the scrubber. An expensive modification of the existing funnel casing is thereby avoided as well as there will be no significant additional pressure drop (the pressure drop through the scrubber is compensated by removing the pressure drop through the silencer). One of the two silencers is still left, so one of the engines can still operate on low sulphur MGO if necessary and as redundancy.

Downstream of the scrubber, a cross-over ducting system has been drawn. With this cross-over, it is possible to switch between the two engines operating on high sulphur fuel oil. The scrubber is only designed for cleaning the gas from one of the engines at a time, but with this cross-over it will be possible to wear both of the engines equally and one of the engines can always be repaired.

The current exhaust gas pressure after the exhaust turbocharger was measured to 195 mm WC at full engine load. According to the engine data sheet, the engines can stand a back pressure of 300 mm WC, i.e. 105 mm WC is left for the pressure drop through the new exhaust pipe, sealing air valves and scrubber. The new expected exhaust gas back pressure should be calculated (e.g. by aid of CFD) according to the detailed drawings of the exhaust gas system and it should be confirmed by the engine supplier that this new back pressure is acceptable.

### 1.5.1 CAPEX

Budget costs for the installation as drawn in Figure 6 are summarised in Table 3.

Table 3: Budget costs for the scrubber and installation

| | Supplier / contractor | Cost in USD |
|---|---|---|
| PureSOx EGC scrubber system<br>- Exhaust gas cleaning unit<br>- Valves and sensors required for regulation<br>- Control and data logging system<br>- Water cleaning system<br>- Caustic soda dosing system<br>- Commissioning and support | Alfa Laval<br>(www.alfalaval.com) | 1,575,000 |
| Modification of funnel<br>- Cutting app. 3x3 meter hole in casing hull, movement of existing installations, enforcements, foundations, installation of scrubber, closing of casing, painting of casing according to yard standard, incl. scaffolding<br>- Fabrication and mounting of necessary exhaust pipe pieces, expansion joints, and exhaust gas dampers<br>- Fabrication and mounting of steel pipes for caustic soda (NaOH) | Orskov yard<br>(www.orskov.dk) | 750,000 |
| Electrical cabling and connection | Estimated<br>(www.elektromarine.dk) | 177,000 |
| Exhaust gas dampers and entire cross-over (with sealing air) | Kolster Hesa-tek A/S<br>(www.ksm-hema.dk) | 29,000 |
| Drawing work | Hauschildt Marine<br>(www.hauschildtmarine.dk) | 27,000 |
| Not included / Unforeseen | +25% | 640,000 |
| **Total investment costs** | | 3,199,000 |

### 1.5.2 OPEX and payback period

The savings in OPEX are strongly related to the fuel oil prices, i.e. the difference between high sulphur HFO and low sulphur MGO. The average price (Rotterdam) of a 380ct HFO (high sulphur) for the last 6 months (Dec 2012 – May 2013) has been 624 USD/ton and that for MGO (low sulphur) has been 952 USD/ton.

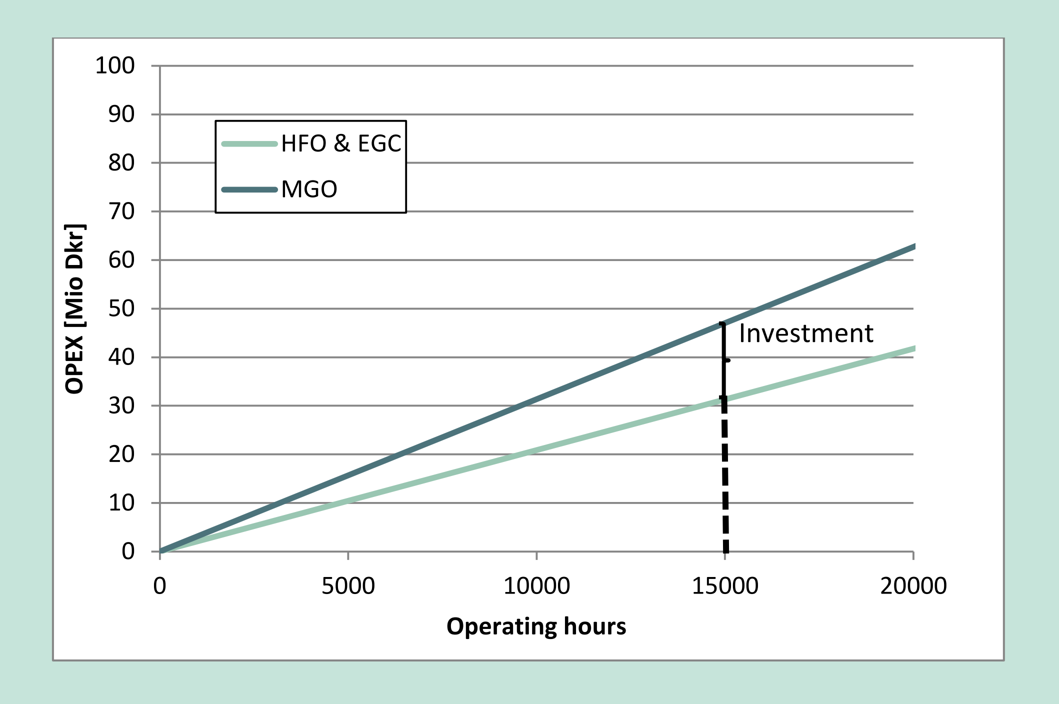

Figure 7: Costs of operating one of the 3.52 MW engines on low sulphur MGO and high sulphur HFO.

As indicated in Figure 7, the total investment (CAPEX) will be paid back after approximately 15,000 hours of operation. Assumptions: 90% engine load (MCR), specific fuel oil consumption = 184 kg/MWh, 1.5% increase in fuel consumption due to running the scrubber pump and increased back pressure on the engine.

## 1.6 Conclusion

Approximately 3,000 ships are sailing more than 50% of their time in the European ECA and are therefore interesting to study further regarding the possibilities of retrofitting EGC scrubbers. These ships are a mixture of oil tankers, chemical tankers, bulk carriers, container vessels, Ro-Ro ships, ferries, cruise ships and others. The engine sizes for these different ships are typically ranging from few MW and up to about 40 MW. The biggest container vessels with up to 100 MW engine power will normally sail on routes to Asia and are therefore less interesting.

A reliable design program is essential in order to avoid over-dimensioning of an EGC scrubber and hence to avoid excessive installation costs. A design program is also important in order to reduce the risk of installing a scrubber that later on might be found unable to comply with the 0.1% sulphur limit on a day where the vessel e.g. will bunker a fuel with unusual high sulphur content and, at the same time, will operate all engines at maximum load simultaneously.

Scandlines ferry MV Prins Richard sailing between Rødby (Denmark) and Puttgarden (Germany) has been studied in more detail. This ferry has five 3.52 MW engines. Drawings of an EGC scrubber installed to clean the exhaust gas from one of these engines have been made. Based on these drawings, the total costs of retrofitting an EGC scrubber has been estimated to 3.2 mio USD. The EGC scrubber account for 1.6 mio USD, i.e. the total retrofitting costs is approximately twice the costs of the EGC scrubber system itself. This can be used as a rule of thumb in other projects as well. With a current price difference between MGO and HFO, it will require approximately 15,000 operating hours to pay back this investment. As an EGC scrubber system contains a lot of fixed costs, the payback time will go down for larger engines. The small 3.5 MW engine is on the limit of what is attractive, while installation on larger engines hence will be more attractive.

# 2. Sub-project B – Engine with Integrated EGR

## 2.1 Objectives and deliveries in sub-project B

The objectives of this sub-project are:

- Engine performance calculations for the selected engine types.
- Production of requirement specification for EGR system.
- Selection of design strategy.
- Design of EGR system and engine modifications.

The deliverables of this sub-project are:

- EGR engine specification for a small and large engine.
- 3D design models of the two different EGR engines.
- Input to the final project report.

## 2.2 Description of EGR

EGR is a well-known technology used for $NO_x$ reduction in the automotive sector for decades. The regulation for emissions in the marine sector during the latest years has brought up the need for high impact $NO_x$ reducing means such as SCR or EGR. Adjustment of combustion parameters is not enough for these high reduction ratios, hence EGR is implemented on two-stroke diesel engines for the marine sector.

### 2.2.1 The EGR process

Exhaust gas recirculation (EGR) is a method to significantly reduce the formation of $NO_x$ in marine diesel engines. In the EGR system, after a cooling and cleaning process, part of the exhaust gas is recirculated to the scavenge air receiver. In this way, part of the oxygen in the scavenge air is replaced by $CO_2$ from the combustion process. This replacement slightly increases the heat capacity of the scavenge air, thus reducing the temperature peak of the combustion and the formation of $NO_x$. The $NO_x$ reduction is almost linear to the ratio of recirculated exhaust gas. The principle of EGR is illustrated in Figure 8.

Two different layouts are available for the EGR systems: a layout based on T/C cut-out and a layout based on EGR bypass. In Figure 9, a schematic of the bypass layout is shown. The bypass layout can be used either for engines equipped with one or multiple turbochargers. In Figure 10, shows a schematic of the T/C cut-out layout. The T/C cut-out layout can be used for engines with multiple turbochargers only.

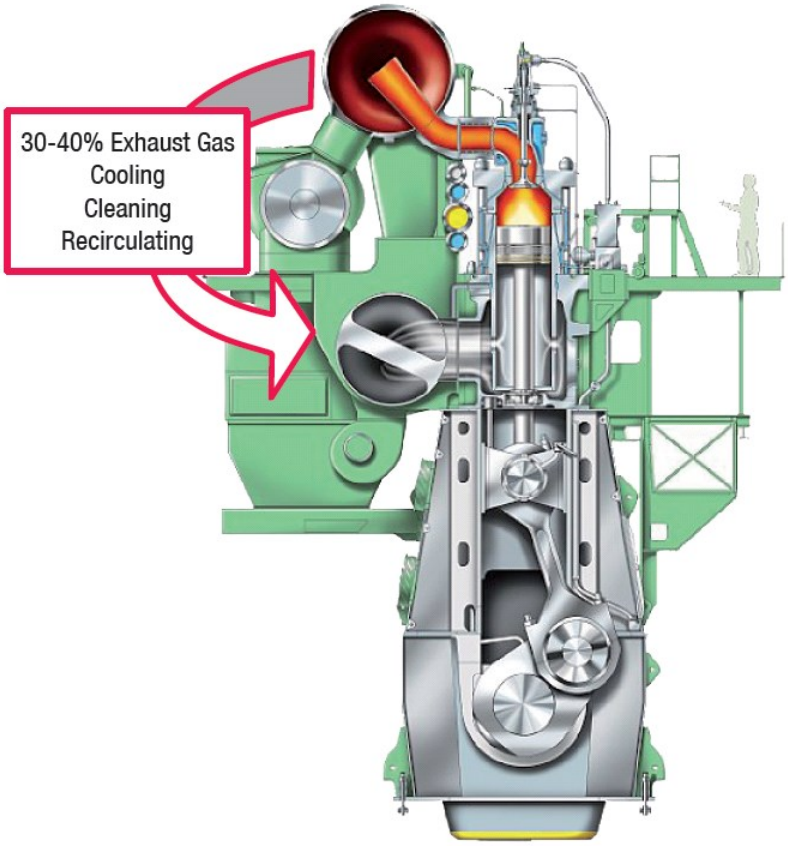

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Figure 8: Basic EGR principle.

Introducing EGR on two-stroke diesel engines, results in more engine running modes in order to switch between operation of the EGR system and operation of the engine as normal.
The engine modes further depend on the EGR layout, T/C cut-out or bypass.

Table 4 shows an overview of the engine running modes.

Table 4: Engine running modes with EGR.

| Mode | T/C cut-out layout | Bypass layout | Tier II/III |
|---|---|---|---|
| Economy (basis) | Yes | Yes | II |
| T/C cut-out | Yes | No | II |
| ECA-EGR | Yes | Yes | III |

The different engine running modes are described below.

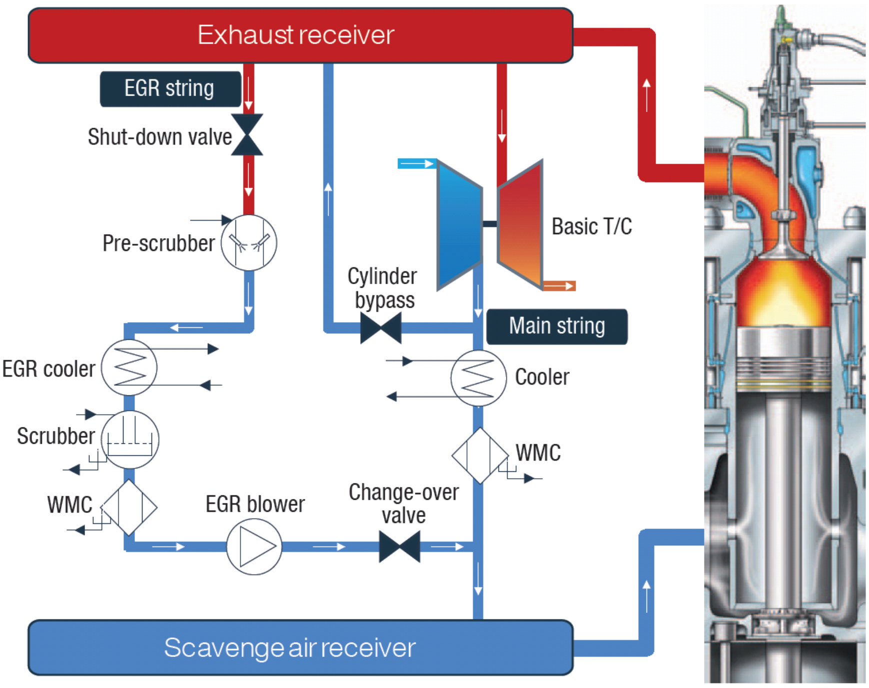


Figure 9: EGR system with bypass layout.

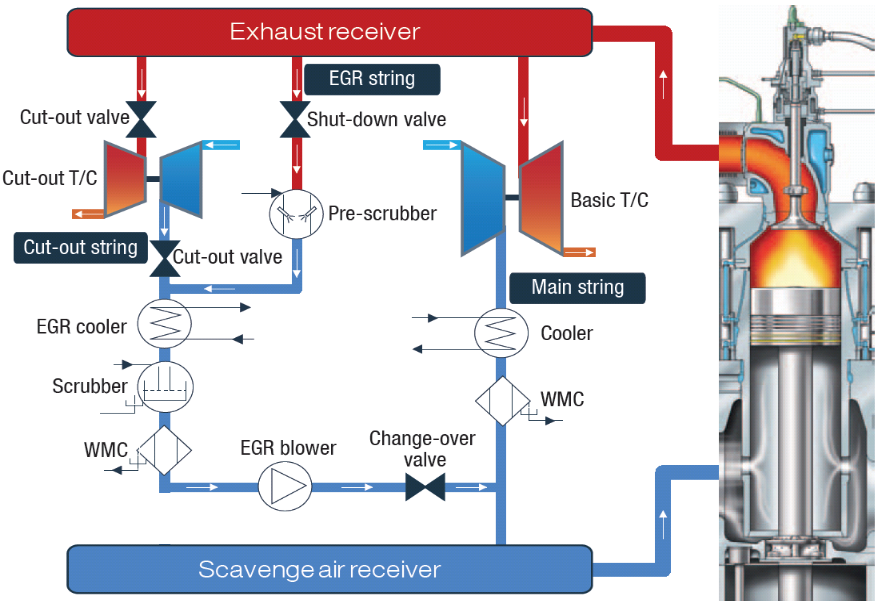


Figure 10: EGR system with TC cut-out layout.

**Economy mode** is a basic mode with engine running as a standard engine. All EGR components are inactive and the shutdown valve is closed. The small turbocharger, as well as the large turbocharger, is in operation due to opened T/C cut-out valves. The mode is IMO $NO_x$ Tier II compliant for use in non-ECA areas in the full load range.

**T/C cut-out mode** is an engine running mode in which one or two turbochargers is/are cut out by a valve arrangement reducing the turbocharger capacity to approx. 60% in order to fit the turbocharger map to operation with EGR gas. The engine load is limited to 50% in this mode. All EGR components are inactive, as no gas or air passes through the EGR module. However, the engine is now ready to start up the EGR system. The mode is IMO $NO_x$ Tier II compliant with a load restriction to avoid over-speed of the large turbocharger. The mode is only considered an intermediate mode for changing over from T/C cut-out mode to ECA-EGR mode. Further, the mode is the fallback mode in case of EGR system shutdown.

**ECA-EGR mode** is the IMO Tier III compliant mode for ECA operation. The EGR system is active and all EGR components are matched for this mode in order to ensure an IMO cycle value of maximum 3.4 g/kWh. The EGR flow is adjusted to reduce $NO_x$ emissions to the Tier III level with an EGR blower in operation throughout the load range.
EGR is affecting the combustion process by exchanging oxygen with carbon dioxide in the combustion chamber, resulting in a fuel penalty as seen from below. Table 5 shows the auxiliary consumptions when running the EGR system in ECA areas.

Table 5: Consumptions for EGR engine operating in ECA-EGR mode. NaOH and sludge amounts are dependent on fuel quality.

| **Engine load,% MCR** | **25%** | **50%** | **75%** | **100%** | |
|---|---|---|---|---|---|
| Delta SFOC Tier III | 0.0 | 2.0 | 3.0 | 4.0 | g/kWh |
| Power, WTS | 2.4 | 2.9 | 3.5 | 4.0 | kW/MW MCR |
| Power, EGR blower | 2.0 | 6.5 | 9.0 | 6.2 | kW/MW MCR |
| NaOH | 0.07 | 0.11 | 0.15 | 0.17 | l/h/MW MCR |
| Sludge | 0.5 | 0.9 | 1.3 | 1.5 | l/h/MW MCR |
| WTSEGR freshwater | 2.0 | 2.0 | 2.0 | 2.0 | l/h/MW MCR |

### 2.2.2 EGR emissions

When a part of the $O_2$ content in the combustion chamber is exchanged with $CO_2$ by EGR the emissions are affected. At a small EGR amount almost only $NO_x$ is affected in a positive way meaning that it is reduced. SFOC and other emissions are almost not affected at small EGR amounts, e.g. below 10%. At higher EGR amounts, e.g. 30-40%, the SFOC and other emissions are affected. Typically, the SFOC increases by 0-4 g/kWh and CO increases significantly. By adjustment of the engine parameters it is possible to maintain an acceptable CO level, but an SFOC increase seems impossible to eliminate.

Figure 11 shows measured values of $NO_x$ values from shop test of the 6S80ME-C9.2 EGR engine at the different engine running modes. Economy mode is the basis Tier II running mode outside ECA areas. In ECA areas the engine is switched on to the ECA-EGR running mode in order to comply with the Tier III criteria. As can be seen from the graph, the NTE (Not To Exceed) level of 5.1 g/kWh (for marine engines with a speed below 130 rpm) is obtained at the four engine loads; 25, 50, 75 and 100%, in the test cycle E3 (MARPOL Annex VI). The total weighted cycle value of the E3 cycle fulfils 3.4 g/kWh of $NO_x$ which is the Tier III criteria for marine engines with a speed below 130 rpm.

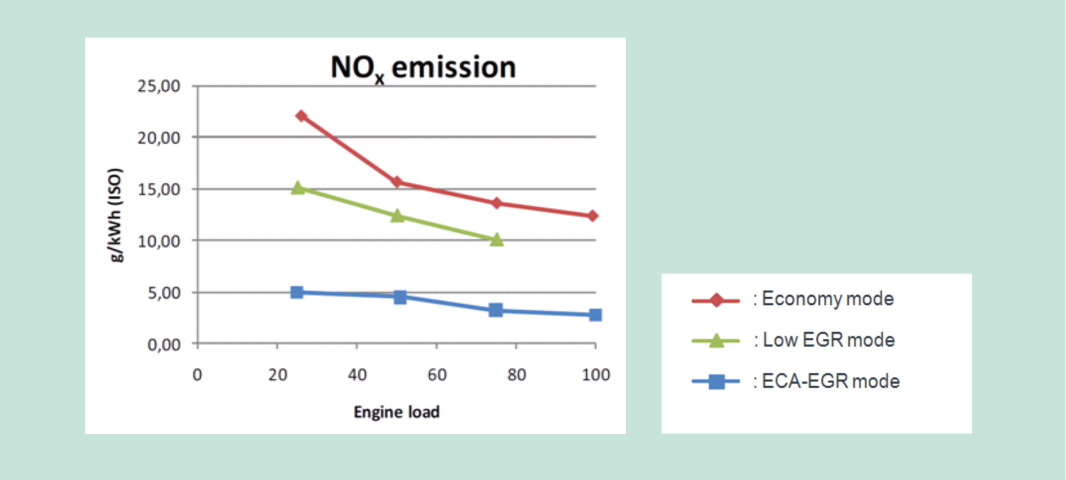


Figure 11: NO$_x$ emissions at the three different modes.

As shown in the graph, a “Low EGR mode” is also tested in order to examine the options for utilising EGR for SFOC saving in Tier II. In this case the combustion is fuel optimised with the consequence of high NO$_x$. The EGR system is used for bringing down the NO$_x$ to the Tier II level. The low EGR mode test showed potentials of significant SFOC saving, but further investigation is necessary before the full potential can be clarified.

### $SO_2$ and PM trapping

Tests accomplished on the 7 MW MDT test engine in Copenhagen have shown that the EGR scrubber system is very efficient with regard to removal of sulphur ($SO_2$) and particulate mass (PM). As shown in Figure 12, the removal of $SO_2$ is above 95% and removal of PM is above 85% which is very good compared to what is normally observed in after-treatment scrubbers. It should be noted that this reduction applies only to the gas recirculated to the combustion chamber.

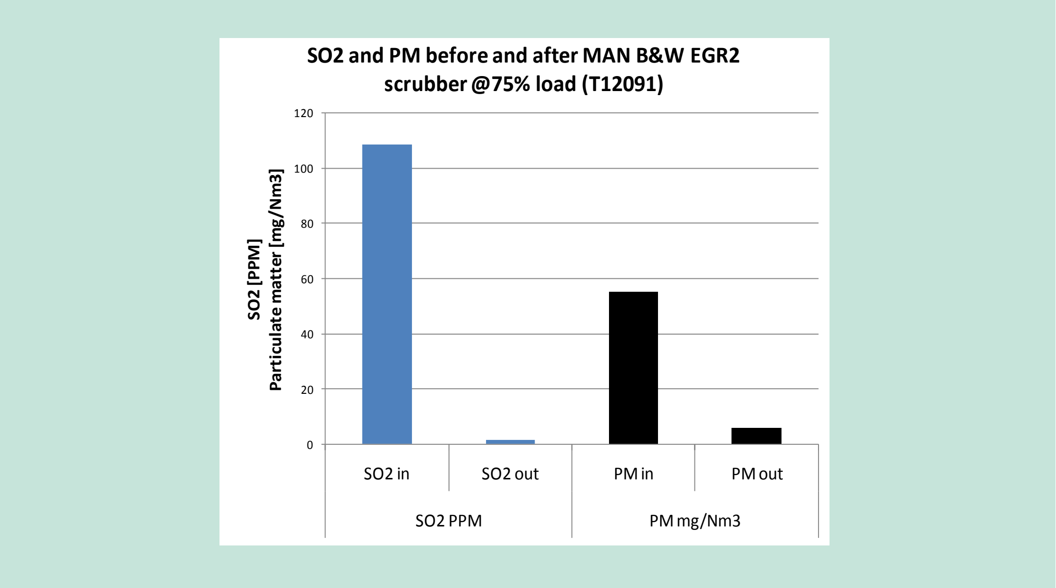


Figure 12: SO2 and PM trapping in the EGR scrubber.

One thing is how much PM is reduced in the EGR scrubber, another thing is how the PM in the exhaust gas out of the funnel is affected by EGR. Normally, it would be expected that the PM amount produced during combustion will increase when EGR is applied. On the other hand, the high PM trapping efficiency (ISO 8178) in the EGR scrubber, treating 30-40% of the exhaust gas, seems to have a significant positive impact as shown in Figure 13. Reduction of PM in the funnel is more or less corresponding to the amount of PM trapped in the EGR scrubber.

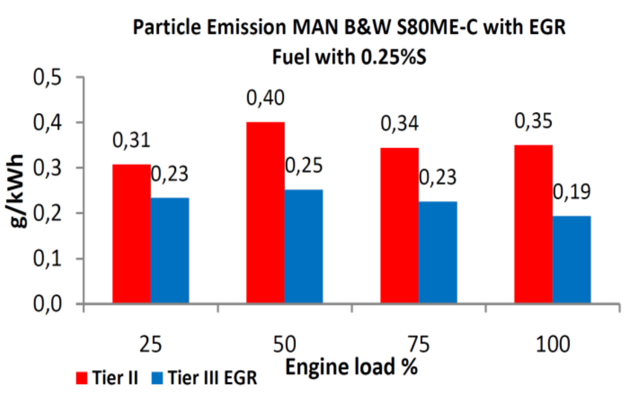


Figure 13: Tier II and Tier III PM measurements in the exhaust gas funnel by ISO 8178.

## 2.3 Design of integrated EGR

A basic consideration before the design process began was to consider where to put the EGR unit – on the engine or in the ship away from the engine.
If the EGR unit is placed in the ship away from the engine it should be connected to the unit by two major gas pipes and the unit itself should be supplied with scrubber water in/out, cooling water in/out and power for the EGR blower. The shipyard should find space for the unit in the engine room and connect the unit to the engine and to the Water Treatment System (WTS).
When the unit is integrated on the engine, the only additional connections for the shipyard, is scrubber water in/out and power for EGR blower. The EGR engine will be slightly wider compared to a standard engine.

An additional advantage of the integration is that the engine can be tested and matched in the assembly shop and performance confirmed on a test bench because all EGR components are available during shop test.

The first EGR layout (EGR1) had the following component sequence; pre-scrubber – scrubber – EGR cooler – water mist catcher and EGR blower. This was the foundation for the design suggestion for the 5S60ME-C8 which was used in the early stages of this project. The new EGR2 concept has changed the sequence of the gas flow components to pre-scrubber – EGR cooler – scrubber – water mist catcher and EGR blower. The EGR2 design is similar to the existing design of turbocharger units and is easier to integrate into the engine design. Furthermore, with the EGR cooler positioned between the pre-scrubber and the scrubber the contact between water and gas is improved which leads to better sulphur reduction and particle trapping than EGR1.

Part of the EGR2 concept was tested at a test rig together with Vestas Aircoil in order to reduce the amount of water removed from the scrubber, and the trapping efficiencies were confirmed by a test on the MDT test engine in Copenhagen.

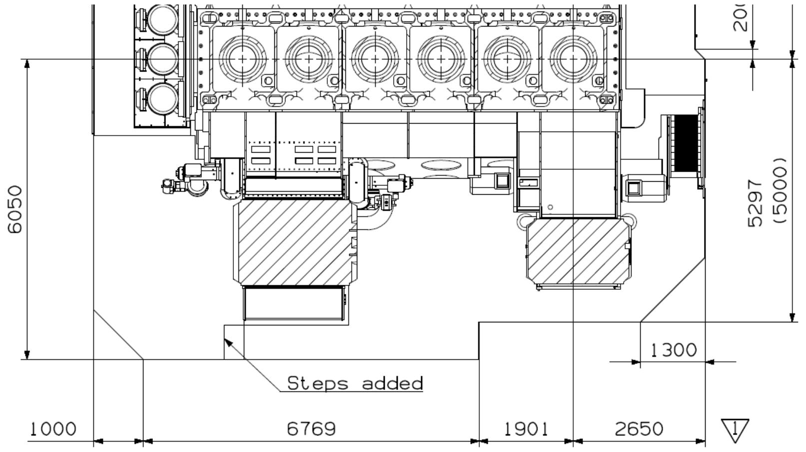


Figure 14: Outline drawing of the centre exhaust side.

The integrated EGR design features an EGR unit which replaces an existing charge air unit. This ensures that the engine layout remains similar to what we know from existing engines. However, due to the increased heat dissipation of the EGR cooler and the addition of scrubber trays, the outline dimensions of the exhaust side is changed compared to a standard engine. The width of the engine is increased by approximately 1,050 mm (6050 – 5000 mm) compared to a standard engine, see Figure 14.

The 6S80ME-C9 engine used for this project has the EGR unit positioned on the aft-side, see Figure 15, which suited a specific container vessel with this engine type studied in the beginning of the project. Later investigations and the experiences from sub-project C have revealed that, in general, the preferred position of the EGR unit is in the fore-end due to ship hull designs.

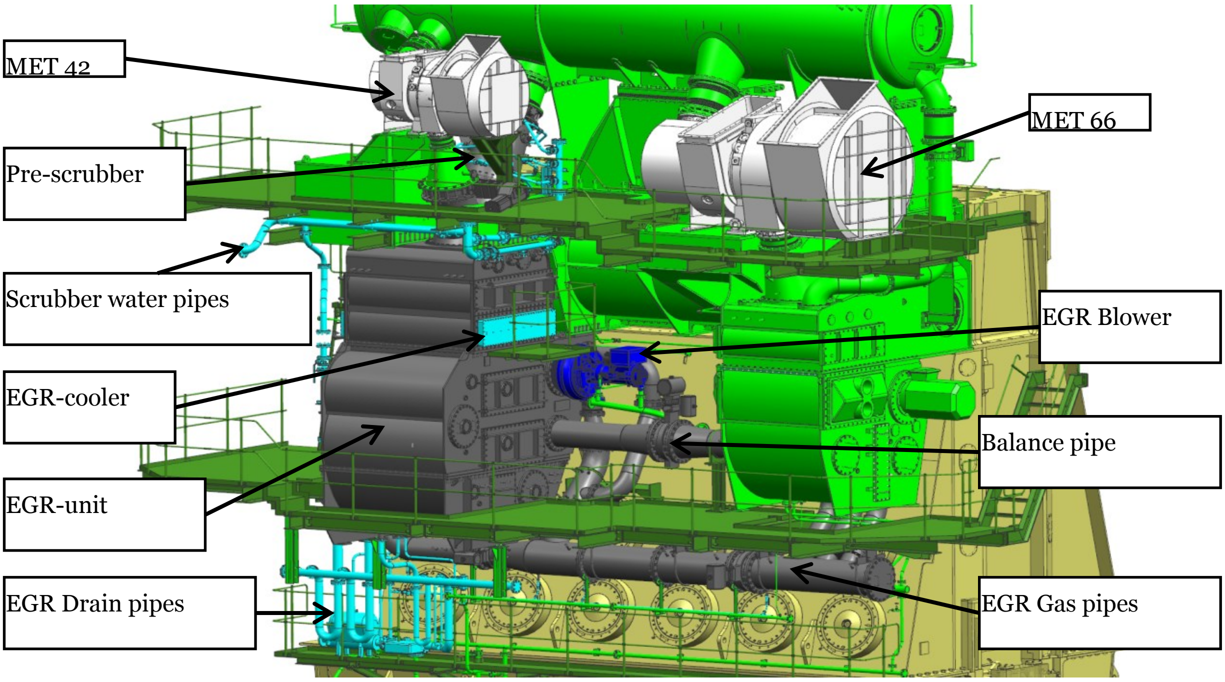


Figure 15: View of the exhaust side of 6S80ME-C9 and material selection for the stainless steel parts.

The intention is to have a scalable design, meaning that the basic idea with dual functionality of the EGR unit and turbocharger cut-out could be applied up to the largest engine in the programme. The limitation for this design is how small the small turbocharger can be without compromising the turbo charging efficiency. For smaller engines, the turbocharger can be replaced by a cylinder bypass at the expense of a higher capacity of the main turbocharger string, see Figure 16.

The cross-section of the EGR unit will change from the smaller engines to the larger, but the design concept remains the same for the cut-out and the bypass solutions.

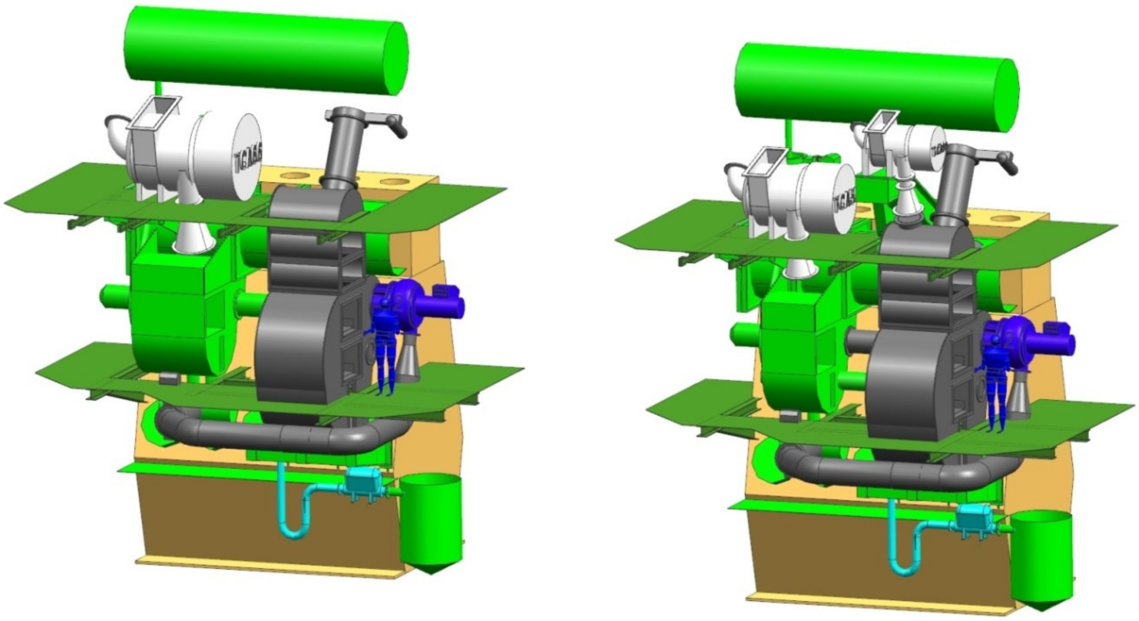


Figure 16: Design mock-up of 5S60ME-C8. Bypass solution to the left, T/C cut-out solution to the right.

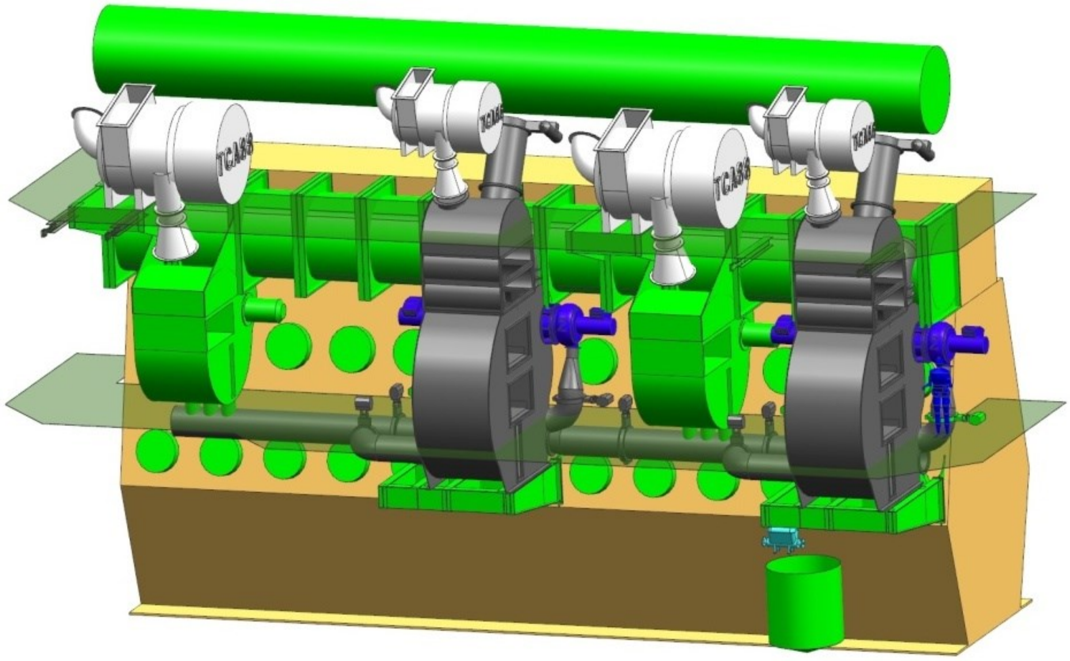


Figure 17: Design mock-up of 12S90ME-C9 with two EGR units and two main turbochargers.

Figure 17 shows an example of the EGR design for a 12S90ME-C9, one of the biggest MAN B&W engines.

The engine structure is only subjected to minor changes due to the EGR application. The bedplate and frame box have additional support faces for supporting EGR components and gallery brackets. The cylinder frame and combustion chamber remain largely unchanged.
The scavenge air receiver, see Figure 18, is modified due to the fact that the EGR-unit replaces one of the air cooler housings and the turbocharger is smaller.

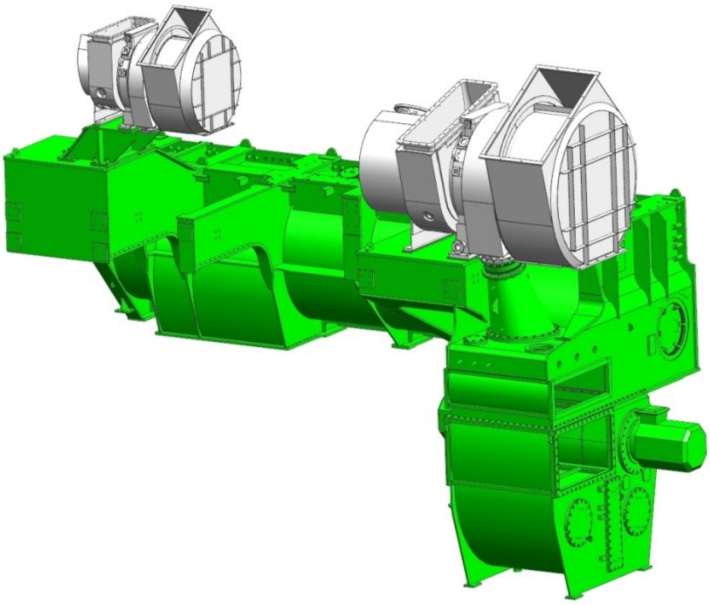


Figure 18: Scavenge air receiver with interfaces towards the EGR unit on the aft side.

The choice of material for a given component depends on the composition, pressure and temperature of the gas or liquid which it comes into contact with as well as manufacturing considerations and how severe consequences of failures are. In general, the structural components of the EGR unit are designed in Duplex stainless steel, due to the resistance against crevice corrosion and stress corrosion. The internal components that are easy to replace are made from AISI 316L.

An overview of the EGR string is shown in Figure 19. The main components are:

- Shut-down valve; gas-tight valve that seals off the EGR string from the exhaust receiver.
- Pre-scrubber; scrubber water is injected into the hot exhaust gas. The water is distributed across the flow section in order to maximise the water-gas contact and making sure that no gas passes through the pre-scrubber without a temperature drop due to evaporation. The gas temperature of 450°C and the sulphuric acid not fully neutralised define a highly corrosive environment and the pre-scrubber is made from high grade stainless steel AISI 904L.
- Cooler housing and coolers; support the cooler elements and distribute gas and water over the cooler surface. Additional scrubber water is sprayed over the cooler top face in order to prevent any build-up of salt. The cooler can be either the tubular or tubular-fin type. During Tier II running, the T/C cut-out valve is open and the coolers work as charge air coolers.
- Scrubber; consists of two parallel levels of trays. Inside the tray a bubble bath maximises the water-gas contact for maximum cleaning efficiency. Scrubber water is drained from the

scrubber and sent back to WTS for cleaning. During Tier II operation the scrubber trays are emptied for water and the air passes through the empty scrubber.

- Reversing chamber and Water Mist Catcher (WMC); the reversing chamber catches the major part of the scrubber water dragged from the scrubber and the Water Mist Catcher (WMC) removes the remaining droplets.
- EGR blower and EGR gas pipe; the EGR gas pipe connects the blower outlet to the air unit on the fore-end. A change-over valve is mounted in the pipe and, together with the EGR blower, regulates the EGR rate.
- Mixing point; the mixing of the cleaned EGR gas and the fresh air from the MET66 takes place inside the reversing chamber of the air unit. The mixed air/gas enters the scavenge air receiver, where the resulting oxygen level is measured.
- Drain system; when EGR is running the three-way valve directs the flow towards the drainer, which separates the water from the gas. The dirty scrubber water is sent to the WTS. When EGR is not running the three-way valve directs the clean condensate water to the clean bilge tank in the ship.

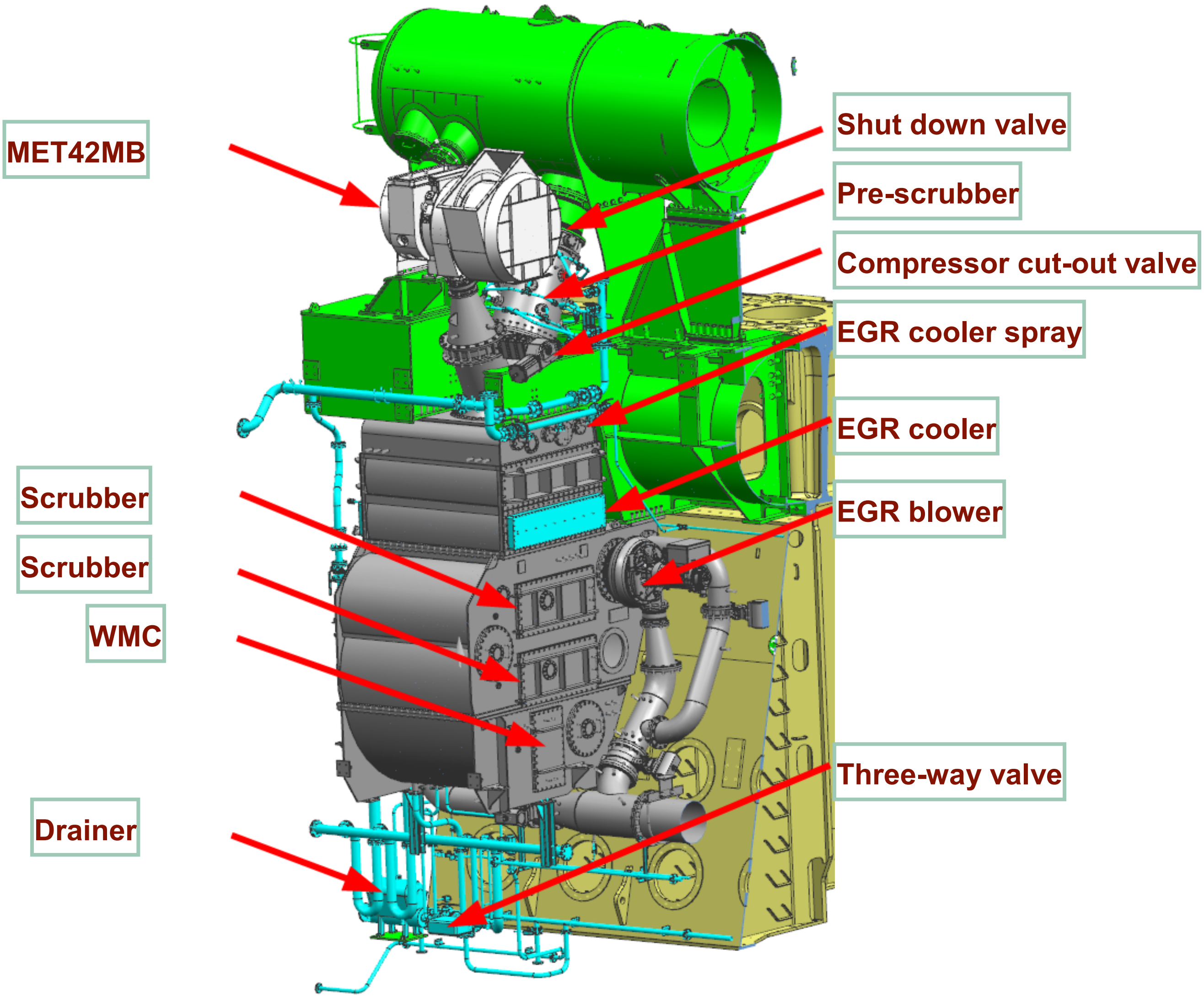


Figure 19: Overview of the EGR components.

Appendix B.4 shows a specification of a small engine, 6G50ME-B9.3 with a bypass solution, including 3D drawing, and Appendix B.5 shows a specification of a large engine with cut-out solution, including 3D drawings of the 6S80ME-C9.2 engine with EGR.

## 2.4 Requirements for engine-integrated EGR

The different requirements for an engine with EGR are described in the following. Requirements cover dimensioning parameters for the process, i.e. EGR gas amount, cooling capacities, scrubber size, etc.

### 2.4.1 Process calculation

The engine process calculations processed in this project is focused on the 6S80ME-C9.2 EGR engine with T/C cut-out, used for the combined project described in sub-project C "Combined EGR and EGC scrubber".

The process calculation is done with an MDT made Matlab software program which is used for dimensioning/specification of the following EGR-related components:

- EGR cooler
- EGR blower
- Impact on exhaust/scavenge air data: Temperature, flow, composition
- Turbocharger matching
- Cylinder bypass valve
- Exhaust gas bypass valve
- WTS

A schematic of the process parameters used in the MDT software tool for calculation of the EGR process is shown in Figure 20.

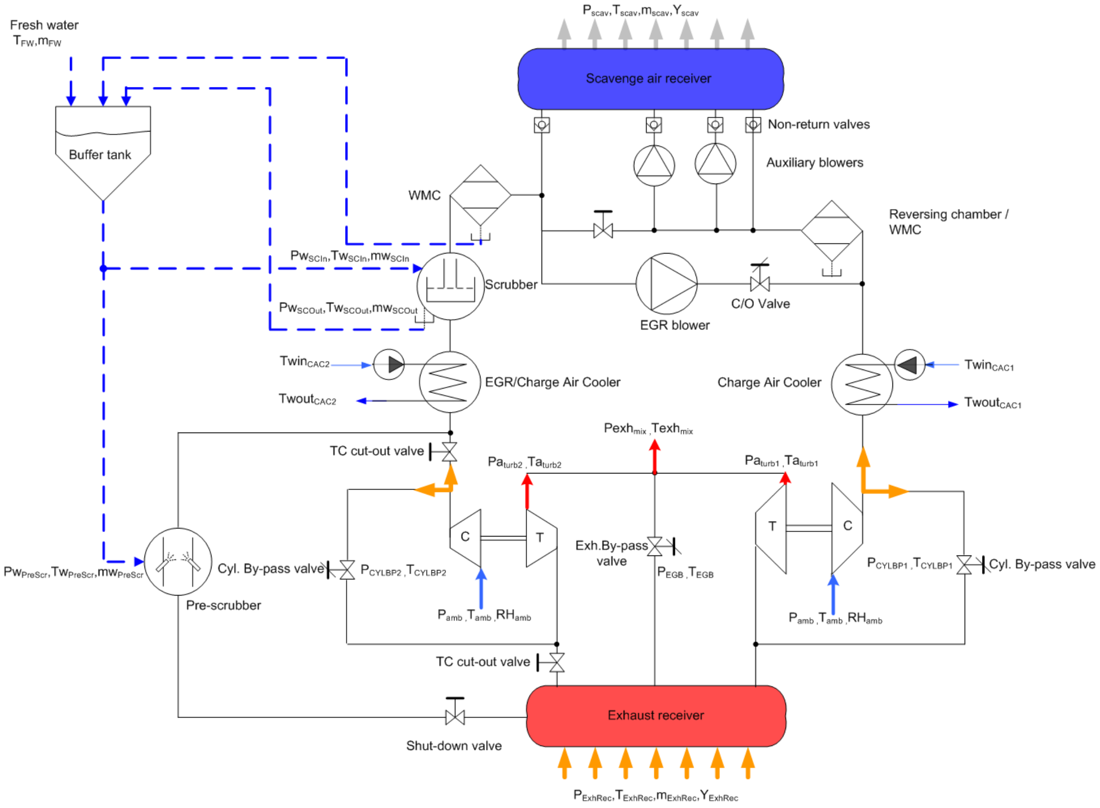


Figure 20: Schematic of the process and parameters used in the MDT tool for calculation of EGR process.

Appendix B.1 shows the EGR specification calculated by the MDT software tool. In Appendix B.2, the specification for EGR blower can be seen.

The MDT EGR software program will, in the future, be used for producing data to the official CEAS calculation tool used by the MDT customers for engine room installation and engine performance guide.

### 2.4.2 Design requirements for 6S80ME-C9.2

A standard 6S80ME-C9.2 engine is equipped with two identical turbocharger units working in parallel. The purpose of these units is to compress the scavenge air to about 4 bara, lower the temperature of the compressed air to 37°C and to remove condensed water from the cooling process.

For the 6S80ME-C9.2 with EGR, there are also two turbocharger units but with different purposes:

The main turbocharger unit is positioned in the fore end of the engine. The requirement for this system is very similar to standard engines, except the point where EGR gas is combined with the fresh air. The main turbocharger (MET66MB) delivers similar pressure as for a standard engine, the charge air cooler lowers the temperature to 37°C and the water mist catcher is also identical to standard engines. At the mixing point between EGR gas and air, the coating inside the cooler housing is improved and the design of the mixing ensures that the gas and air is sufficiently mixed before entering the oily scavenge air receiver. This unit is symbolised by the blue line in Figure 21 and is always active during all engine modes.

The smaller turbocharger unit in the aft-end consists of the small turbocharger (MET42MB) that can be cut in or taken out of operation and the EGR unit.
During Tier II running, the purpose of the EGR unit is to act as charge air cooler and water mist catcher for the small turbocharger. The EGR unit is sealed from the exhaust receiver with the EGR shutdown valve. This process is symbolised by the pink line in Figure 21.
During EGR running, the purpose of the EGR unit can be divided into four parts (green line in Figure 21):

- A cooling process of the EGR gas.
- A cleaning/neutralisation process of the EGR gas.
- A water separation process removing water from the cleaning process.
- Increase pressure of the EGR gas to scavenge air pressure.

The EGR cooler lowers the EGR gas temperature to scavenge air temperature, condensates the evaporated water from the pre-scrubber and cools the excess water from the pre-scrubber. This process requires significantly higher heat dissipation compared to a standard charge air cooler.

The cleaning/neutralisation process starts with the pre-scrubber, continues through the EGR cooler and ends with the scrubber trays. The gas should be cleaned sufficiently of particles in order to avoid build-up of combustion particles inside the EGR system and in the scavenge air system. When scrubber water is injected into the exhaust gas, sulphuric acid is formed, and this acid is neutralised with NaOH in order to protect the engine components from corrosion and impact to the cylinder condition.

During the neutralisation process $Na_2SO_4$ salt is diluted into the scrubber water. An effective water separation process ensures that no $Na_2SO_4$ is carried by scrubber water through the EGR blower with the risk of salt deposits building up in the system.

The EGR blower compensates for the pressure difference between exhaust pressure and scavenge air pressure and the pressure drop across the EGR string. As the blower is continuously running during EGR operation, the efficiency is essential in order to reduce running cost. The blower is comparable to a turbocharger compressor but is directly driven by an electric motor.

All EGR components are subjected to a highly corrosive environment due to the temperatures in the system and presence of water and sulphuric acid in the scrubber water. Consequently, different types of stainless steel are applied throughout the EGR system.

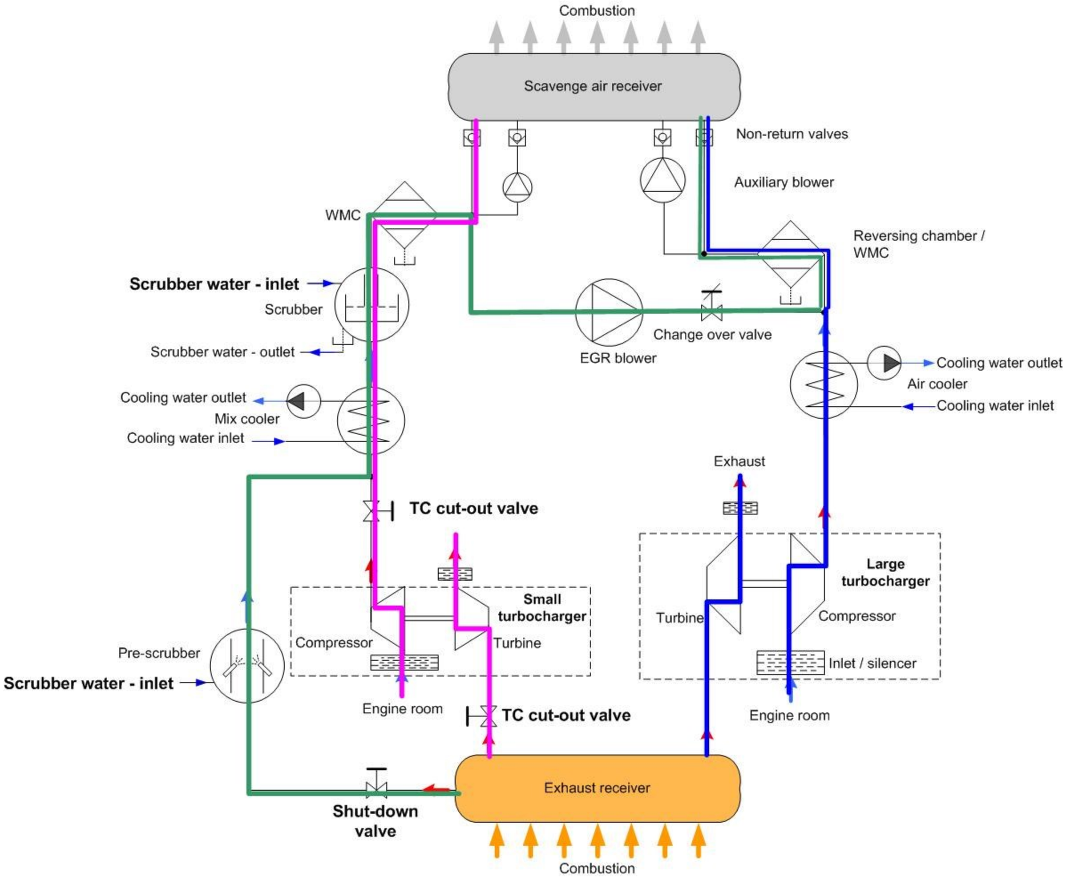


Figure 21: Schematic view of an EGR engine with two turbochargers.

### 2.4.3 EGR auxiliary equipment

To prevent sulphur and particles from damaging the engine, cleaning of the recirculated exhaust gas is required. The cleaning is done by a scrubbing process in the EGR unit using recirculated fresh water (FW). In order to maintain the ability to clean the exhaust gas, a water treatment system (WTS) is needed. The system must ensure the removal of accumulated particles and neutralisation of sulphuric acid in the scrubber water and ensure the delivery of water at a sufficient supply rate and pressure to the EGR unit. In addition, the WTS must also handle the surplus of water accumulated in the system from the combustion process. If discharged overboard, the water quality must meet the international requirements for scrubber water outlet as stated in *2009 Guidelines for Exhaust Gas Cleaning Systems*, MEPC 184 (59). A water treatment system approved for the EGR Tier III process is available from Alfa Laval. The system consists of a collecting tank unit (CTU) placed below the EGR unit, which receives and redirects the untreated scrubber water, and a water treatment unit (WTU) that cleans the scrubber water and delivers it to the EGR unit. To supply the WTS with additive for sulphur neutralisation and to store the sludge generated from the cleaning process, an NaOH tank and an EGR sludge tank are required. The principle of the water treatment system including tanks is illustrated in Figure 22.

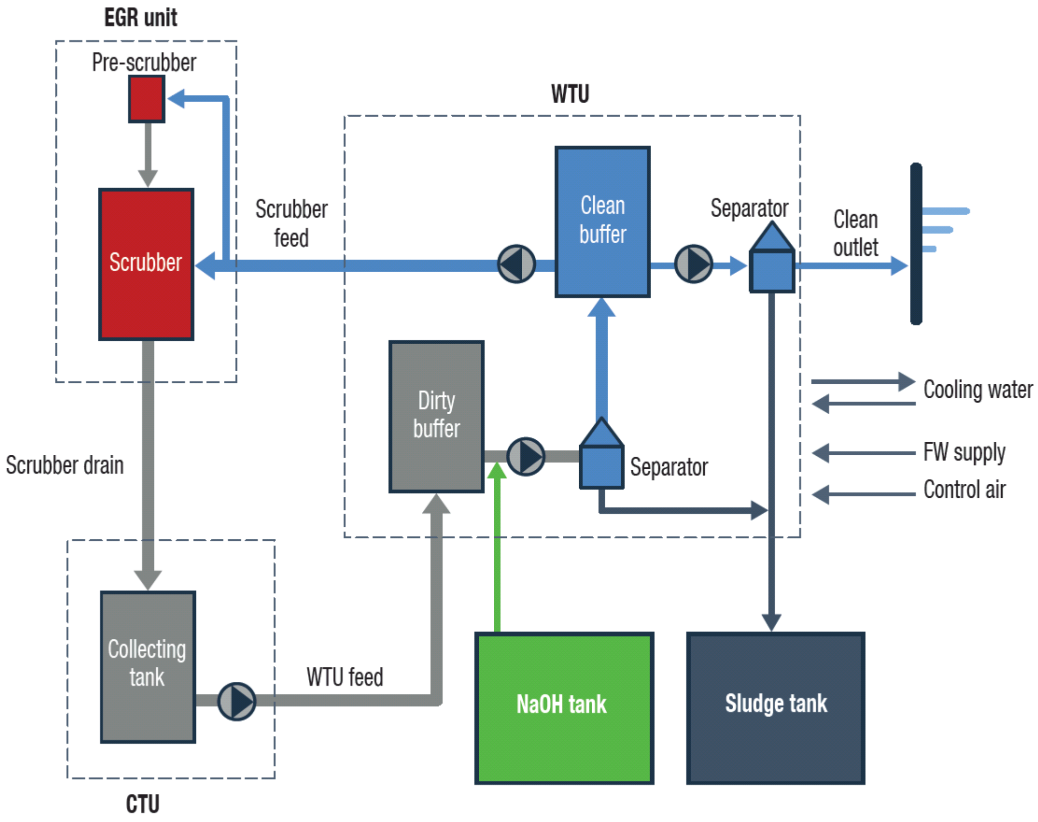


Figure 22: Schematic of the WTS layout for EGR engines.

The principle used in the WTS is independent of the different EGR layouts of the engine. However, the capacity must be designed to handle the maximum scrubber water flow required for the EGR process, which depends on the engine size. Having this requirement in mind, the layouts of the CTU and the WTU described below are basically not affected, but the size and number of the elements in the system must be designed for the actual engine size. The NaOH tank, the sludge tank and the pipe connections are yard deliveries.

The CTU, which includes a buffer tank and a feed pump, must be placed at a level below the EGR unit to enable correct drainage of the scrubber. The purpose of the unit is to allow a freedom in the arrangement of the WTU. Other solutions for redirecting the scrubber water to the WTU are possible. The CTU is shown in Figure 23.

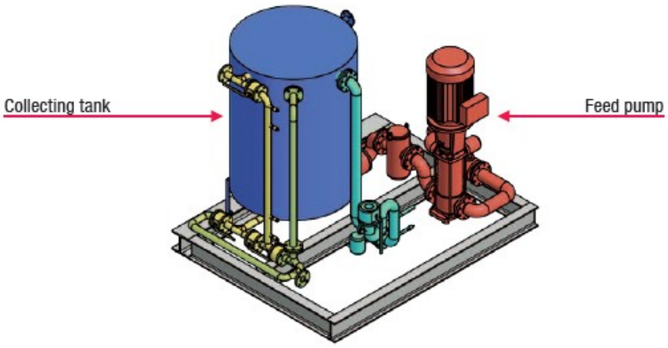


Figure 23: 3D example of CTU.

The WTU shown in Figure 24 has two functions. The primary function, which cleans and neutralises the scrubber water, includes a dirty buffer tank, one or more full flow separators, a clean buffer tank and a scrubber water pump. The secondary function, which enables discharge of the excess water generated in the EGR system from the combustion process while meeting the IMO discharge criteria, includes a pump, a bleed-off separator and a water quality test unit. The WTU furthermore includes one or more NaOH pumps and an electric control cabinet.

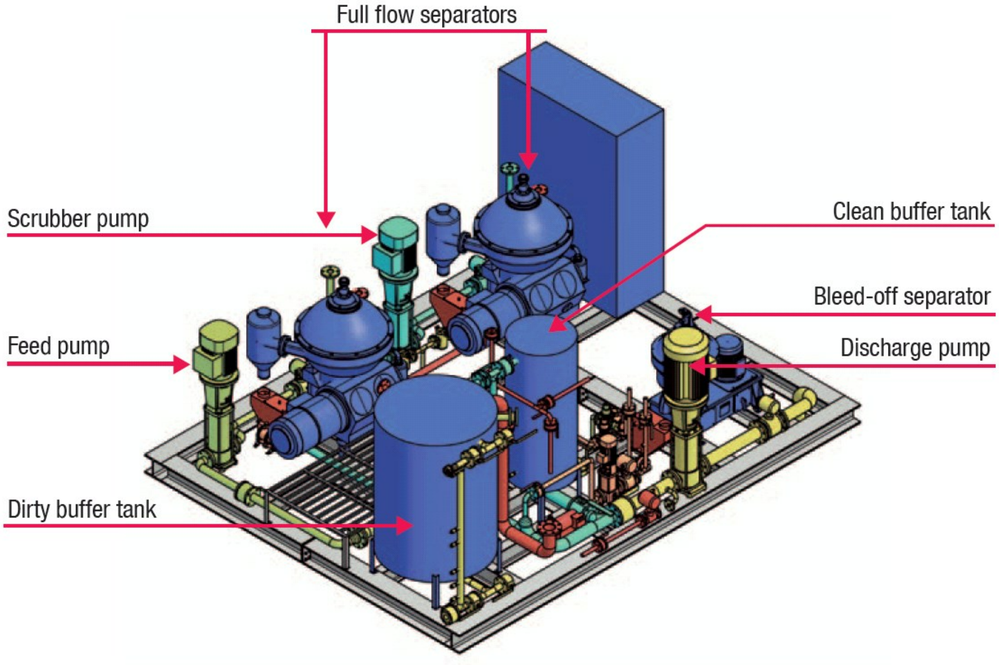


Figure 24: 3D example of WTU.

Besides the WTS system, there is a need for installation of tanks for NaOH and sludge. Finally, connections, i.e. pipes and electrical cabling between engine, WTS and tanks, are also a part of installation of the EGR engine. Below is a description of tanks and pipes related to installation of the system.

The NaOH tank should be suitable for the media, normally a 50% NaOH solution. Such a solution will start to crystallise below 12°C, and the tank should therefore keep a minimum temperature of

16°C. Accordingly, the tank should therefore be installed in a room with a controlled temperature or be insulated and fitted with means for heating. Furthermore, the temperature in the tank should be kept below 45°C to prevent other negative impacts from the solution. The material of the tank must be suitable for the NaOH solution, such as stainless steel, coated steel, polymer or other materials fulfilling the relevant requirements.

When estimating the capacity of the NaOH tank, the ECA sailing time, the sailing pattern, the fuel sulphur content, the NaOH solution and the planned bunker period must be considered. Furthermore, the capacity could include an additional volume to receive a full standard bunker volume when refilling. An example of dimensioning the NaOH tank is found in Appendix B.3.

The sludge outlet from the WTU is an aqueous solution of combustion particles, sulphur compounds and other material separated from the scrubber water. The pH value would normally vary between 6 and 9. The water content in the sludge is more than 90%, which makes it easy to discharge by a pump. The sludge tank could be a separate tank or part of another tank, i.e. the dirty bilge tank, which holds similar sludge from the engine room to be discharged to reception facilities.

The sludge tank can be made of stainless steel or coated steel taking the variation of pH value into consideration. When estimating the capacity of the sludge tank, it is important to take into account the ECA sailing time, the sailing pattern, the fuel sulphur content, the water content and the planned discharged period. Furthermore, an additional volume should be included to allow for overflow from the CTU and WTU. An example of dimensioning the sludge tank is found in Appendix B.3.

## 2.5 Conclusion

The design work with integration of the EGR unit on the engine has been successful, providing a compact design with a minimum impact on the shipyards' installation work. Basically, only pipe connections between the EGR unit and the WTS system and the electrical connection to the EGR blowers have to be made by the shipyard. However, shipyards should still install WTS, a sludge tank and a NaOH tank. It is concluded that integration of the EGR unit on the engine is the right way to go in order to satisfy installation requirements from shipyards.

The future work with integrated EGR includes working with our sub-suppliers in order to identify limits in capacity and sizes for the different components. The minimum size of turbochargers will define the split between the cut-out solution and the bypass solution. The capacity of EGR coolers and EGR blowers will limit the maximum size of EGR units.
Options for downsizing and simplification of the engine-mounted EGR unit will be carried out due to the fact that on small engines it is challenging to find the necessary space for the EGR unit on the engine.

# 3. Sub-project C – Combined EGR and EGC scrubber

## 3.1 Objectives and deliveries in sub-project C

The objectives of this sub-project are:

- Establishment of contact to relevant ship owners and ship yards.
- Selection of ship owner or ship yard.
- Selection of ship type and engine type for a case study.
- Performance calculations on combined operation of EGR and EGS system for the selected. engine and ship.
- 3D design of the combined EGR and EGC scrubber.
- Evaluation of synergy options including auxiliary system such as the water treatment system.
- Economical calculation of first cost and operating cost by combination of EGR and EGC scrubber.

The deliverables of this sub-project are:

- Note including specification and drawings of the selected ship.
- 3D model of the combined EGR and EGC scrubber.
- Economical calculation including CAPEX and OPEX.
- Input to the final project report.

## 3.2 Description of combined processes

The basis for this part of the project is a new vessel to be built after 2016 and which therefore has to comply with Tier III $NO_x$ limits in NECA. The fuel is anticipated to be HFO with max 3.5% sulphur both inside and outside $NO_x$ and $SO_x$ ECAs. This means that a $SO_x$ scrubber is needed with sufficient efficiency to reduce the $SO_2$ to a level corresponding to max 0.1% sulphur in the fuel in SECA and – after 2020 - 0.5% outside SECA. In this part of the project, an exhaust gas cleaning scrubber (EGC scrubber) system placed on the low pressure side of the turbocharger is combined with an EGR scrubber system working on the high pressure side of the turbocharger.

The main advantage of combining EGR and EGC scrubber is that the size of the EGC scrubber can be reduced if the EGR scrubber is used for partial removal of $SO_2$ when operating at higher engine loads. The EGC scrubber can operate on either FW or SW but the EGR scrubber is in this project limited to only operation on FW. Principally, the EGR scrubber could also operate on SW but this solution would compromise reliability and size of the EGR system components for which reason it is left out.

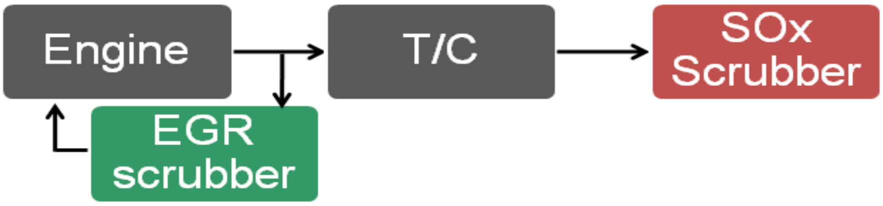


Figure 25: Simplified layout of combined EGR and EGC scrubber

As shown in Figure 25, the EGR system includes an EGR scrubber placed on the high pressure side of the turbocharger. The EGR scrubber removes $SO_2$ and particulate matter in order to protect the engine components from corrosion and scaling by soot particles. The EGR scrubber cleans the exhaust gas which is then re-circulated to the combustion chamber. Approximately 30-40% of the exhaust gas from the engine is re-circulated.

Figure 26 shows the combined EGR and EGC scrubber system including the most important components, but without the auxiliary system. The EGR system is the engine integrated bypass version which can be combined with the T/C cut-out EGR system.

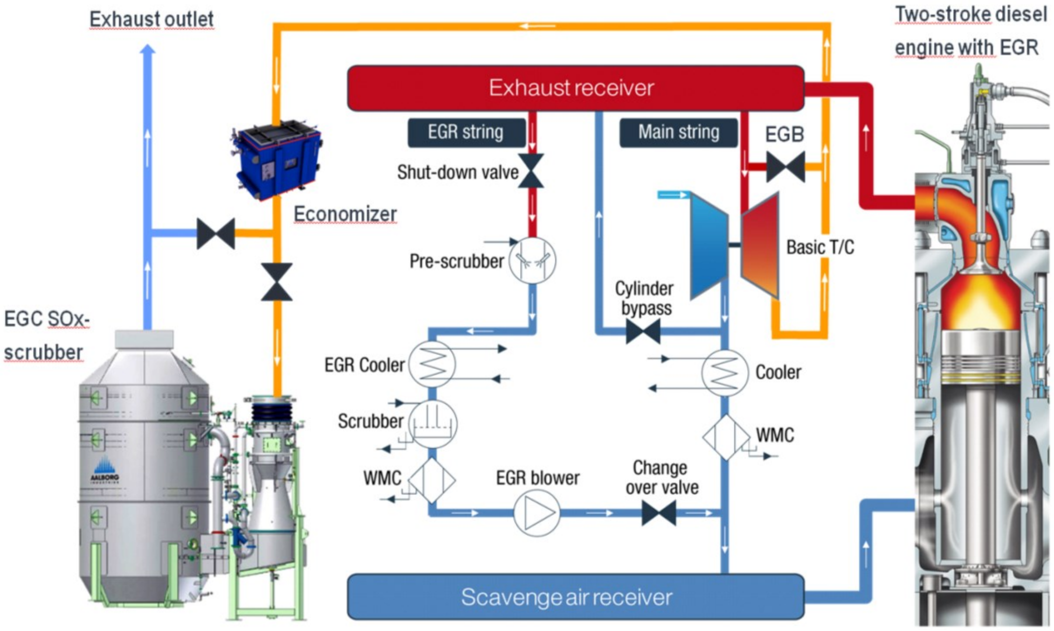


Figure 26: Layout of combined EGR and EGC scrubber without auxiliary systems.

As the EGR system circulates 30-40% of the exhaust gas in the “internal loop”, the exhaust gas flow through the EGC scrubber is reduced by 30-40% compared to a similar sized engine without EGR. This means that the EGC scrubber can be designed to handle only 60-70% of the exhaust gas if the EGR system is activated at engine loads above 60-70%. Other possibilities, e.g. bypass combined with low sulphur fuel are discussed in chapter 3.2.1.

The water treatment systems (WTS) for the EGR system and the EGC scrubber system can be combined. The following configurations are considered and sketched below:

A. Both the EGR and EGC scrubber units are operating on FW. The discharge water must be cleaned to comply with the requirements for Wash Water Discharge.
B. The EGR system operates on FW while the EGC scrubber unit operates on SW.
C. As configuration A, but the scrubber system can operate on SW when it is acceptable to discharge the seawater, e.g. outside coastal areas.

Principally, the EGR scrubber could also operate on SW, but this solution is left out because it will compromise reliability and the size of the EGR system components.

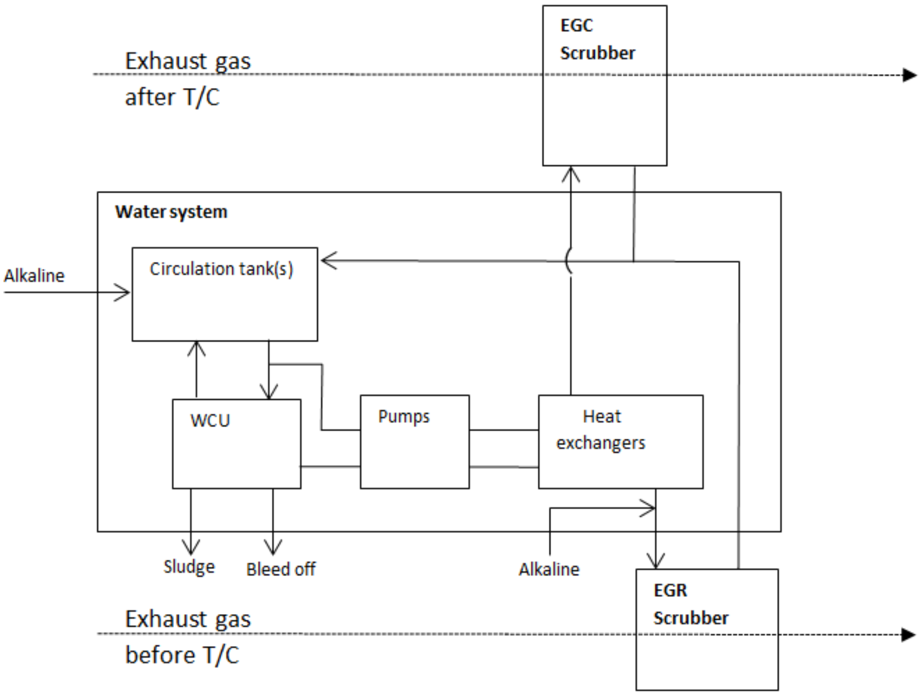


Figure 27: Configuration A with FW to both the EGR and EGC scrubber units.

Figure 27 shows configuration A with FW to both the EGR and EGC scrubber units. The EGR and EGC scrubber share the same water system. The water flow from one or more circulation tanks will flow to the EGR scrubber via either:

- a water cleaning unit (WCU), one or more pumps, one or more plate heat exchangers, or
- directly to the EGC scrubber via a pump and a plate heat exchanger. If the scrubbers are not in operation (e.g. in harbour), the WCU can continue to clean the water in the circulation tank(s). SW cooling lines to the heat exchangers and the EGR scrubber cooler are not shown.

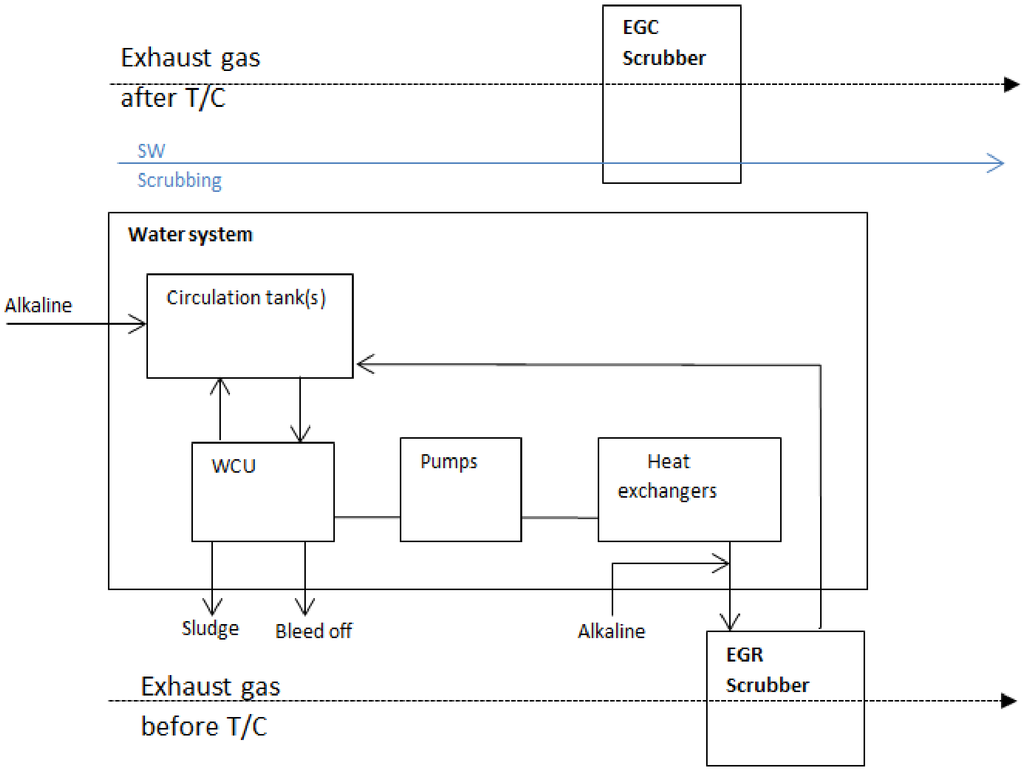


Figure 28: Configuration B with FW to the EGR scrubber and SW to the EGC scrubber.

Figure 28 shows configuration B with FW to the EGR scrubber and SW to the EGC scrubber. SW cooling line to the EGR scrubber cooler is not shown.

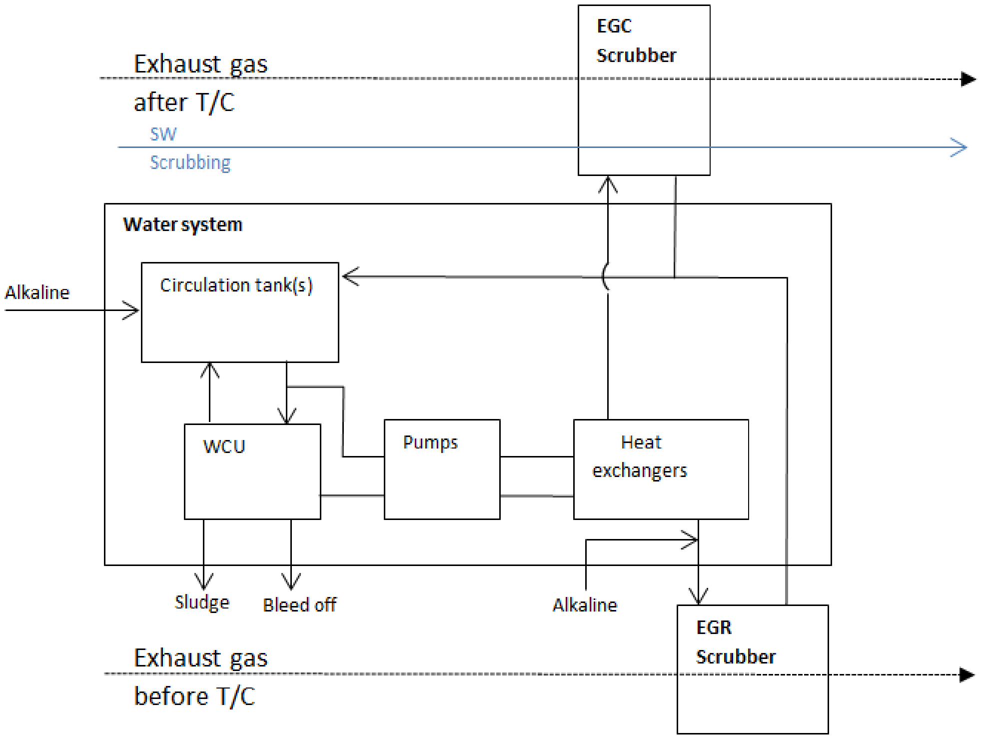


Figure 29: Configuration C with FW to EGR scrubber and a “hybrid” solution for the EGC scrubber.

Figure 29 shows configuration C with FW to the EGR scrubber and a “hybrid” solution for the EGC scrubber. With this configuration, the EGC scrubber can e.g. operate on SW at open sea and then switch to FW in port. Operating valves for switching between SW and FW to the EGC scrubber unit as well as SW cooling lines to the heat exchangers and the EGR scrubber cooler are not shown.

A calculation program for the combined process has been made by ALA and MDT. Some basic assumptions were made in order to compare the different possibilities.

**Assumptions**

- It is assumed that the ship will operate 6,000 hours a year, 20% of the year in an area with both $NO_X$ and $SO_X$ limits (an ECA) – the remaining 80% will be outside ECA.
- The power of the main engine will follow the standard IMO E3 profile in ECA and outside ECA:
    - 20% of the time at 100% load
    - 50% at 75% load
    - 15% at 50% load
    - 15% at 25% load
- Tank volumes for NaOH consumption and sludge production will be dimensioned for two months of operation.

## 3.3 Evaluation and selection of combined processes

The different combinations of the EGR and EGC scrubber systems are evaluated in order to decide which solution to continue with in the case study subsequently.

### 3.3.1 The exhaust gas system

A main dimensioning parameter for the size of the EGC scrubber system is the exhaust gas flow while the fuel sulphur content only has a minor influence. In the combined system, the EGC scrubber unit can be reduced as the EGR consumes approx. 30% of the exhaust gas at maximum engine load. This requires a solution when the 70% engine load is exceeded:

1. Outside an NECA where the EGR is not required, the EGR has to be started when the engine load exceeds 70%.

2. Another possibility outside an SECA and NECA could be to bypass a fraction of the exhaust gas around the EGC scrubber unit. The final gas mixture should of course stay below the demanded sulphur level (0.5% in 2020). As the EGC scrubber system can reduce sulphur from 3.5% down to below 0.1% $S_{eq}$, it is possible to bypass up to 11% of the gas and still stay below the 0.5% $S_{eq}$ allowed outside ECA. For loads above 81%, other means have to take over as for example:
    - use the EGR above 81% load to reduce the $SO_X$ emission and the exhaust gas flow.
    - use fuel with lower sulphur fuel at loads above 81%.
    - Figure 30 shows the max. allowed fuel sulphur content as a function of the engine load.

The proposal can reduce the diameter of the scrubber from 5.8 m to 5.1 m and the weight of the EGC scrubber unit (incl. water) with 30%. The power required for pumping water is also reduced by 30%. Using the EGR for $SO_X$ reduction will increase the NaOH consumption as this will only operate on FW.

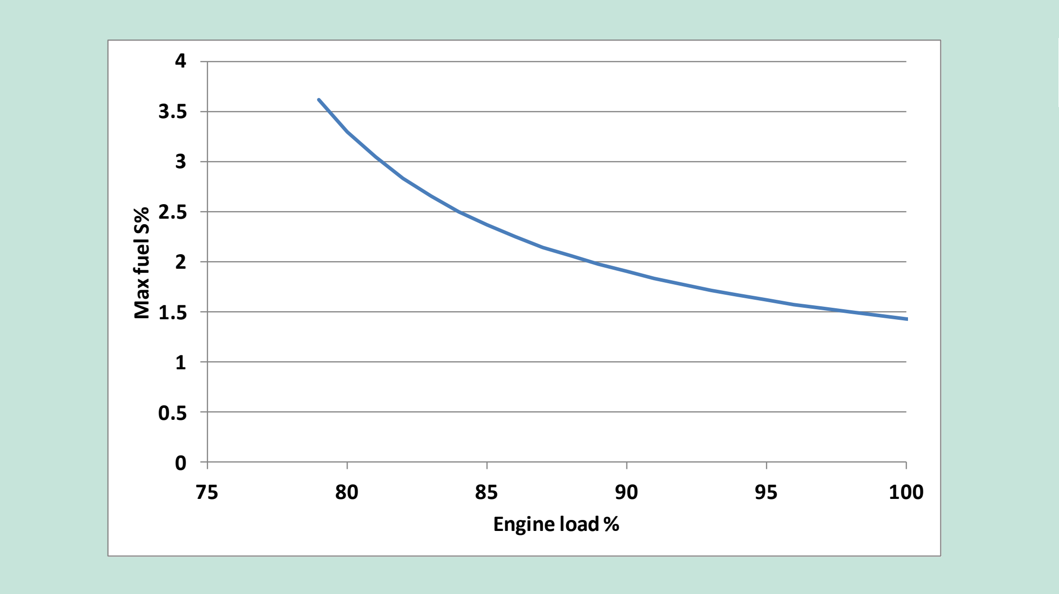


Figure 30: Max. allowed fuel sulphur content if the EGC scrubber is designed to 70% of the exhaust gas flow and the surplus gas is bypassed in order to reduce the final sulphur content to correspond to a 0.5% sulphur fuel.

### 3.3.2 The scrubber water system

Configuration A is capturing soot in the water cleaning unit; it is attached to both the EGR and the EGC scrubbers. However, the consumption of NaOH is high as it handles the total gas flow at all times.

Configuration B has the lowest NaOH consumption as only the EGR system uses NaOH. The pumping power is increased as the SW flow is higher than the FW. In addition, the height above sea level of the EGC scrubber has a lager influence.

Configuration C combines A and B – it is more complex than the two other systems. It is able to function on FW in close loop near the coast and on SW and therefore without NaOH when that is possible. This is a copy of the EGC scrubber layout on Ficaria Seaways (see ref. 4).

For the three configurations sketched above. Calculations are included in Appendix C.3.

- It is assumed that the ship is 20% of the time in ECA and that the load profile is the same as used by ISO for emission test – in ECA and outside ECA. This is the same as assumed in the project unless something else is stated.

- The requirements are to reduce the sulphur to 0.1% $S_{eq}$ inside ECA from 2015 and to 0.5% $S_{eq}$ from 2020 globally outside ECA.

In order to select the optimal configuration between option A, B or C, Table 6 is created.

The different points:
CAPEX is the capital investment
OPEX is operational costs
Complexity – is the handling and the system complexity
Flexibility – is the capability to cope with different local water discharge criteria
Installation requirements – plant and tank volumes.

Values:
1 best
2 good
3 average
4 poor
5 worst

The different points do not have the same weight for a shipowner – therefore weighing factors for each point have been introduced – and final values have been calculated.

It must be stressed that is a very uncertain way to evaluate the three systems and the numbers are subjectively evaluated.

Table 6 Evaluation of possibilities A, B and C.

| **Configuration** | **A** | **B** | **C** | **Weight factors** | **A** | **B** | **C** |
|---|---|---|---|---|---|---|---|
| CAPEX | 3 | 3 | 4 | 20 | 0.6 | 0.6 | 0.8 |
| OPEX | 5 | 2 | 3 | 30 | 1.5 | 0.6 | 0.9 |
| Complexity | 3 | 2 | 4 | 10 | 0.3 | 0.2 | 0.4 |
| Flexibility | 1 | 5 | 1 | 30 | 0.3 | 1.5 | 0.3 |
| Installation requirements | 3 | 3 | 4 | 10 | 0.3 | 0.3 | 0.4 |
| | | | | | | | |
| Sum | | | | 100 | 3 | 3.2 | 2.8 |

*Based on this, it was decided to continue this part of the project with a hybrid EGC scrubber system (configuration C).*

## 3.4 Vessel selection and shipyard background

In April 2011, MAN Diesel & Turbo held a meeting with Hudong Zhonghua shipyard in China, with the intention of establishing cooperation between the two companies. ALA was subsequently included in this cooperation.

Hudong Zhonghua (HZ) shipyard had received approaches from shipowners for vessels equipped with Tier III and $SO_x$ emission reduction technology.

During this meeting, an 8,500 teu container vessel with a 9S90ME-C8.2 main engine was discussed as the basis for the project. During further discussions with HZ shipyard, it emerged that a 4,900 teu vessel with a 6S80ME-C8.2 main engine was preferred, primarily as this was the vessel size requested by a specific shipowner looking for the new emission reduction technologies.

**4,900 teu Vessel**

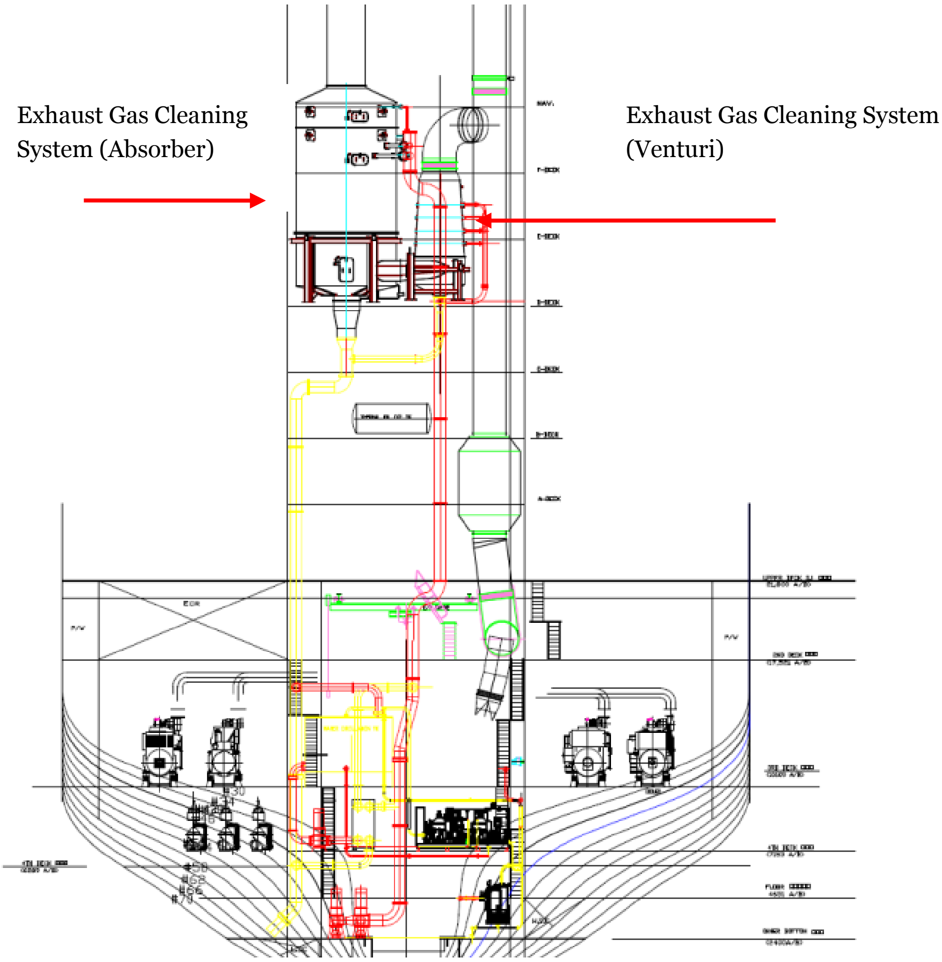
The vessel chosen for the project was a 4,900 teu container vessel, see Figure 31, with an MAN B&W 6S80ME-C9.2 main engine which was to be Tier III, and SECA compliant. The vessel design is similar to the 4,500 teu design for Hudong, which was delivered to CSC and OOCL previously with an 8K90MC-C main engine, with a design speed of 24.2 knots.

Figure 31: Picture of the ship type chosen for the combined EGR and EGC scrubber.

The reduction in propeller rpm with an S80 type engine gives a significant gain in propulsion efficiency. Tier III compliance is achieved with the application of EGR, whilst the EGC scrubber system allows the vessel to operate in SECA areas on standard HFO, without the need for reduced sulphur content in the fuel.

## 3.5 Ship arrangement of EGR engine and EGC scrubber

HZ was provided with the drawings of the main engine (M/E), EGC scrubber system and some of the auxiliary equipment that is required for the combined installation. The design of an M/E equipped with integrated EGR is quite similar to a standard M/E, however whilst the outline of the main engine is almost the same as a standard Tier II engine, there are some small changes in installation space requirement and piping connections which must be considered by the shipyard. It was not necessary for HZ to make any changes in the engine room (E/R) for installation of an M/E with integrated EGR, compared to the standard Tier II M/E without EGR. Auxiliary equipment for operation of the EGR system also has to be considered and is covered in section 3.6.



Exhaust Gas Cleaning System (Absorber)

Exhaust Gas Cleaning System (Venturi)

Figure 32: EGC scrubber arrangement shown in cross section seen from aft side.

However, for the EGC scrubber installation, substantial design changes of the funnel casing are required. The main problem is the size of the unit, and in order to find sufficient space, the only suitable location is in the existing exhaust gas stack. There are several undesirable issues with this installation which MDT has discussed with HZ. Firstly, there was some concern regarding the stability of the vessel, as quite some mass is introduced high up in the vessel. The wet weight of the scrubber is approximately 37 tons. However, given this weight, HZ informed that the impact on the vessel stability was insignificant. Secondly, the additional energy required to pump the high flow of water required for open loop scrubbing increases as the installation height increases. Various options were discussed, including installation of the EGC scrubber in the engine room itself, but HZ was not able to find sufficient space.

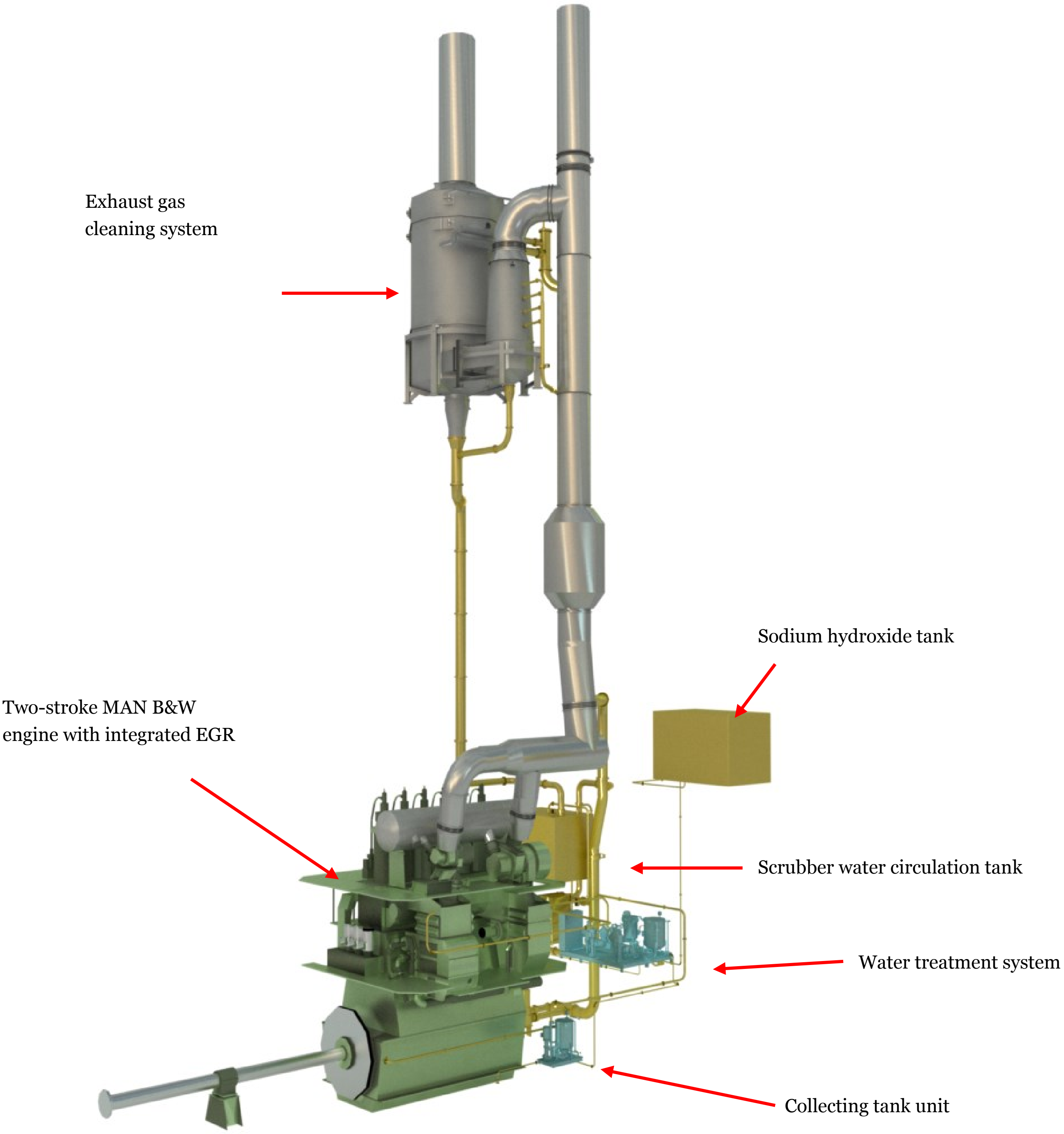


Figure 33: 3D arrangement of EGR engine, EGC scrubber, WTS and tanks.

The arrangement for EGC scrubber system installation can be seen in Figure 32. In addition to the space taken up by the EGC scrubber system unit itself, considerable space is taken up with the piping for the seawater supply as the inlet pipes are up to 600 mm in diameter, and the outlet pipes 1,000 mm in diameter from the absorber. Based on practical experience, pipes in non-corrosive material like Glas fiber Reinforced Epoxy (GRE) is advised.

HZ has provided the 3D arrangement shown in Figure 33 showing the main engine with an integrated EGR system, the EGC scrubber in the vessels chimney and all the auxiliary equipment. This visualises the additional requirements of the full EGR and EGC scrubber system installation compared to a normal engine. More 3D views can be seen in Appendix C.6.

## 3.6 Arrangement of auxiliary components

Installation aspects covering dimensions and arrangement of system components are described in the following. The more detailed auxiliary equipment for the EGR system is described in Chapter 2.3.3.

**Collecting Tank Unit (CTU)**
The CTU, described in Chapter 2.3.3, which includes a buffer tank and a feed pump, must be placed at a level below the drainers close to the main engine in order to enable correct drainage of the scrubber. The purpose of the unit is to allow a freedom of degree in the arrangement of the WTU. The size of the CTU is based on the amount of scrubber water in the internal compartment of the scrubber and in the drain pipes. A CTU tank capacity of approx. 1.5 $m^3$ is adequate.

**Water Treatment Unit (WTU)**
The Water Treatment Unit (WTU) is designed to meet the requirements given in Chapter 3.4. The capacity and configuration of the cleaning unit is independent of the EGR layout as the scrubber water flow relates to the specified engine power and required EGR%.
The necessary water flow to the EGR scrubber is 2.5 $m^3$/MWh resulting in a max required flow to be treated in the WTU of approx. 70 $m^3$/h.

**Sodium Hydroxide tank**
The Sodium Hydroxide (NaOH) tank is designed on the basis of 40 days of service at NCR for 3.5% Sulphur HFO. The capacity of the tank for this vessel was calculated to 20 $m^3$. The tank is bunkered from a bunker station with a truck.

**Scrubber circulation tank**
In the combined EGR and EGC scrubber system a common water circulation tank is employed. Based on the flow to the EGC scrubber and to the EGR system, the capacity is calculated to 15 $m^3$.

**EGC scrubber cleaning tank**
Due to the possibility of switching the EGC scrubber system between operating on SW and FW, it is necessary to flush the EGC scrubber and related pipes in order to avoid mixing of SW and FW during switching and hence pollution of the EGR scrubber with SW.

The capacity is dependent on the residual SW volume in the EGC scrubber unit and the water pipes. In this case the tank size is estimated to 3 $m^3$.

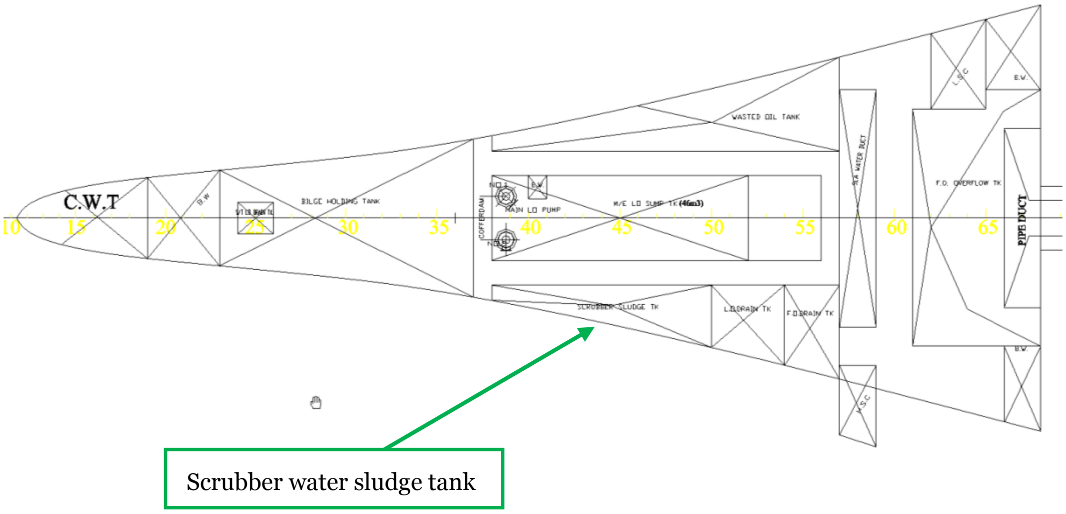


Figure 34: The aft-side viewed from above showing the scrubber sludge tank.

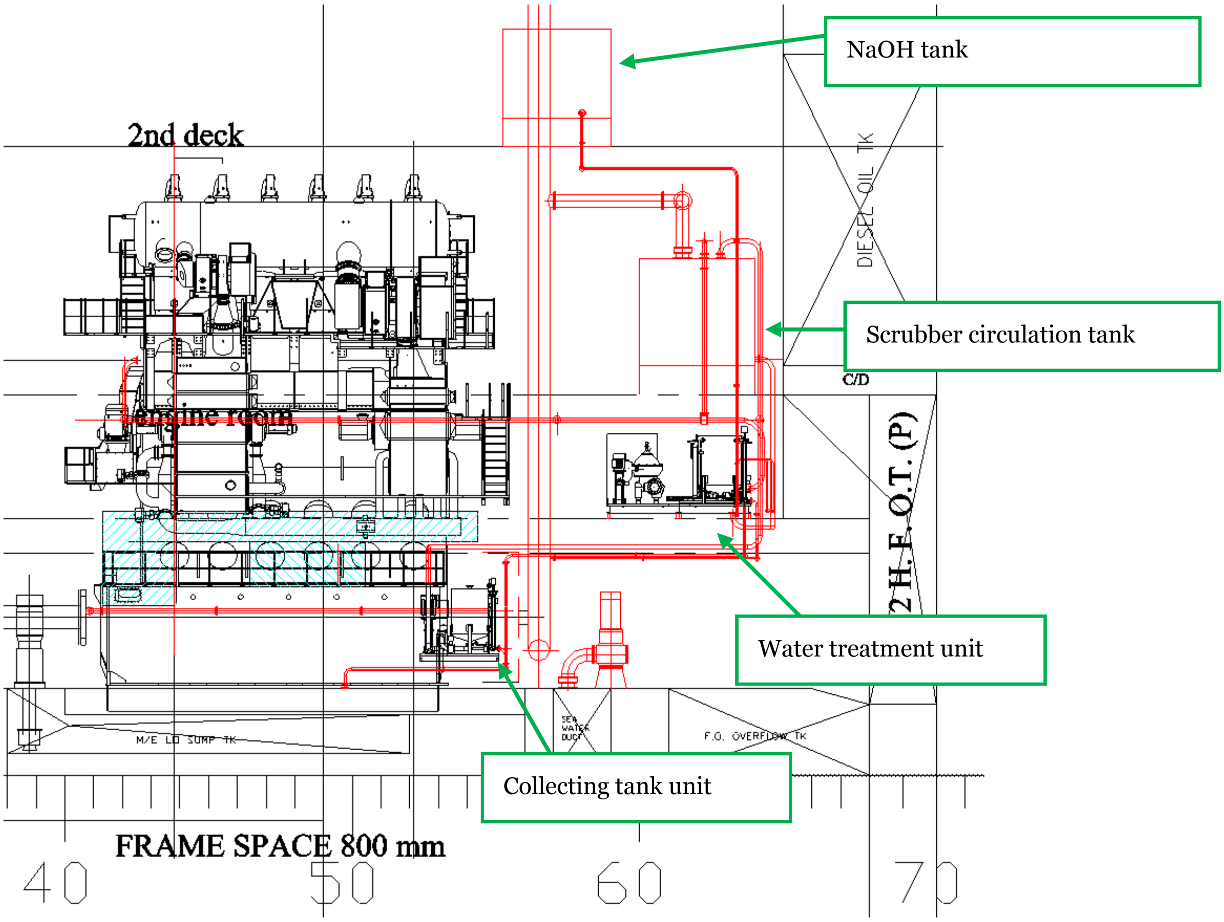


Figure 35: Arrangement of auxiliary equipment seen from star board side.

### Sludge tank

The capacity of the sludge tank has been calculated to be 20 $m^3$ on the basis of 40 days of constant service at NCR. The tank itself is located after the main engine integrated into the vessel at tank top level.

The sludge tank is designed with a discharge pump that can discharge to shore when required. The full arrangement can be seen in Appendix C.4: EGR and EGC scrubber Combined Diagrams.

### Pump capacities

The capacities of the pumps required for the combined water treatment systems of the EGR and EGC scrubber systems have been estimated, and are shown in Table 7.

Table 7: Pump capacities for combined EGR and EGC scrubber system.

| Pump description | Capacity |
|---|---|
| EGC scrubber sea water pumps | 1954 $m^3/h$ |
| EGC scrubber fresh water pumps | 652 $m^3/h$ |
| Water cleaning unit pump | 83 $m^3/h$ |
| Bleed off pump | 8 $m^3/h$ |
| Clean bleed off pump | 8 $m^3/h$ |
| Clean buffer pump | 83 $m^3/h$ |
| EGR return pump | 81 $m^3/h$ |
| EGC scrubber NaOH dosing pump | 0.5 $m^3/h$ |
| WTS NaOH dosing pump | 0.5 $m^3/h$ |

### Piping arrangement

There is a considerable amount of extra piping required for the installation of the EGC scrubber system, and the large diameter of some of the seawater piping makes it difficult to find a good routing through the vessel. There are very few opportunities to use common piping for the EGR and EGC scrubber systems, as their locations are different. Only the piping to and from the tanks can be shared.

Table 8 shows the different pipe sizes in the combined EGR and EGC scrubber system.

Table 8: List of pipe size for the combined EGR and EGC scrubber system.

| Piping table | | | |
|---|---|---|---|
| Flange | Unit | Description | DN |
| 210 | WTS Module 2 | EGR scrubber drain inlet | 100 |
| 201C | WTS Module 2 | EGR scrubber water outlet | 80 |
| 219 | WTS Module 1a | EGR scrubber water outlet | 80 |
| 201C | WTS Module 1a | EGR scrubber water inlet | 100 |
| 499 | WTS Module 1a | NaOH supply | 15 |
| 222A | WTS Module 1a | Common sludge outlet | 25 |
| 310 | WTS Module 1b | Water inlet | 25 |
| L12 | EGC scrubber | SW Overboard | 700 |
| L20/L3 | EGC scrubber | SW/FW inlet | 600 |
| L20/L3 | EGC scrubber | SW/FW inlet | 600 |
| L11/L9 | EGC scrubber | SW/FW discharge from absorber | 1000 |

## 3.7 Economic evaluation of combined system

When evaluating the economics of the combined EGR and scrubber system, then consideration has been on both the operating costs and the first costs. Furthermore, as the focus is on the synergies between the two systems, the economic benefits of integrating the two systems are of primary concern. In order to consider all the costs involved, Hudong Zhonghua shipyard has also contributed with the installation costs for the EGR and EGC scrubber systems, including tanks, piping, flanges, valves, supports, foundations and labour costs.

### 3.7.1 First Cost (CAPEX)

Table 9: First cost for EGR and EGC scrubber of a 27 MW engine installation

| | **Separate** | **Combined** | **Reduced** Combined/Reduced size scrubber |
|---|---|---|---|
| **Total** | **6.5 mio $** | **6.2 mio $** | **5.3 mio $** |
| Savings | - | 0.3 mio $ | 1.2 mio $ |
| Savings% | - | 4.6% | 18.5% |

| | | | |
|---|---|---|---|
| EGR | 1.0 mio $ | 1.0 mio $ | 1.0 mio $ |
| EGC scrubber | 3.4 mio $ | 3.4 mio $ | 2.5 mio $ |
| WTS (EGR/EGC)* | 1.3 mio $ | 1.1 mio $ | 1.1 mio $ |
| Installation | 0.8 mio $ | 0.7 mio $ | 0.7 mio $ |

*) Estimated by MDT as the combined WTS is not tested and released for sale.

Taking into account all the possible synergies of the two systems, there is approximately 5% saving to be made in combining the EGR and EGC scrubber system whilst maintaining a full size scrubber. If the owner, in addition, wishes to select a reduced sized scrubber – explained in the following part – then the saving increases to around 20%, but a penalty on the operating cost must be expected. The majority of the saving in both cases comes from reduced cost of the water treatment system and the EGC scrubber system. A graphical illustration is found in Figure 36.

For the actual ship the EGR/EGC scrubber system addition is approx 10-13% of the vessel price.

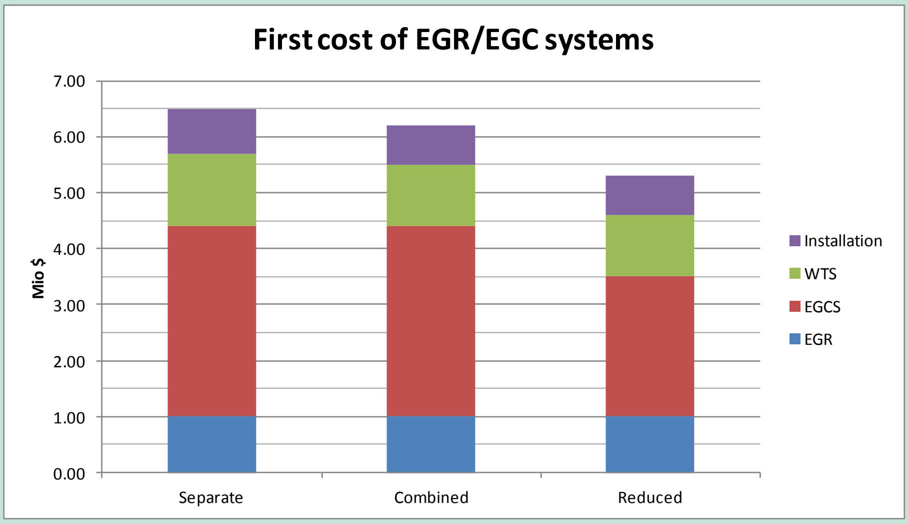


Figure 36: First cost of combined EGR/EGC scrubber system of a 27 MW engine at different scenarios

**Operating Costs (OPEX)**

The operating cost of the combined system is calculated for the two different situations of emission control, an ECA and a Non ECA situation. In this context "ECA" means Emission Control Area with $NO_x$ Tier III requirements and low sulphur (0.1% S) requirements; "Non ECA" means outside these areas, where global emission control restrictions must be met, i.e. $NO_x$ Tier II and global sulphur limit (0.5% S, as required from 2020). Furthermore, the calculations are made for both FW and SW scrubbing in the EGC scrubber. The EGR scrubber uses only FW.

The consumption parameters and prices used to calculate the operating cost of the combined system are listed[3] in Table 10.

Table 10: Consumables and operating cost of the combined EGR/EGC scrubber system, EGC is using SW.

| **Consumables** | | |
|---|---|---|
| SFOC ME - Tier II engine | 171 | g/kWh |
| SFOC penalty Scrubber | 0.22 | % of ME power |
| Power WTS | 6.50 | kW/MW |
| Power EGR blower | 0.28 | kW/MW/EGR% |
| Power Scrubber - FW | 0.25 | % of engine SMCR power |
| Power Scrubber - SW | 0.80 | % of engine SMCR power |
| NaOH consumption (SFOC 171 g/kWh) | 0.0428 | kg/MWh/ΔS%/EGR% |
| SFOC AE, MDO | 200 | g/kWh |
| Generator efficiency | 0.95 | |

| **Price, June 2013** | **S%** | | |
|---|---|---|---|
| Fuel price, S% | 0.1% | 865 | $/ton |
| Fuel price, S% | 0.5% | 714 | $/ton |
| Fuel price, S% | 3.0% | 580 | $/ton |
| NaOH price | Solid | 400 | $/ton |
| Electric power price | | 0.220 | $/kW |
| Maintenance EGR - variable | | 0.090 | $/MWh (40%EGR) |
| Maintenance EGR - fixed | | 0.115 | $/MWh |
| Maintenance scrubber - variable | | 0.225 | $/MWh (100% massflow) |
| Maintenance scrubber - fixed | | 0.290 | $/MWh |

The operating cost of the combined system using the above parameters are calculated and listed in Appendix C.5. The cost includes the fuel cost, which is highly dependent on the sulphur content in the fuel.

A graphical illustration of the operating cost of the combined system at different scenarios is found in Figure 37. The effect of replacing the expensive low sulphur fuel (0.1% S) in ECA with high sulphur fuel (3.0% S) using an EGC scrubber is clearly demonstrated. The same effect is found in Non ECA, although the gain is smaller due to a lower cost of fuel allowed in this area (0.5% S).

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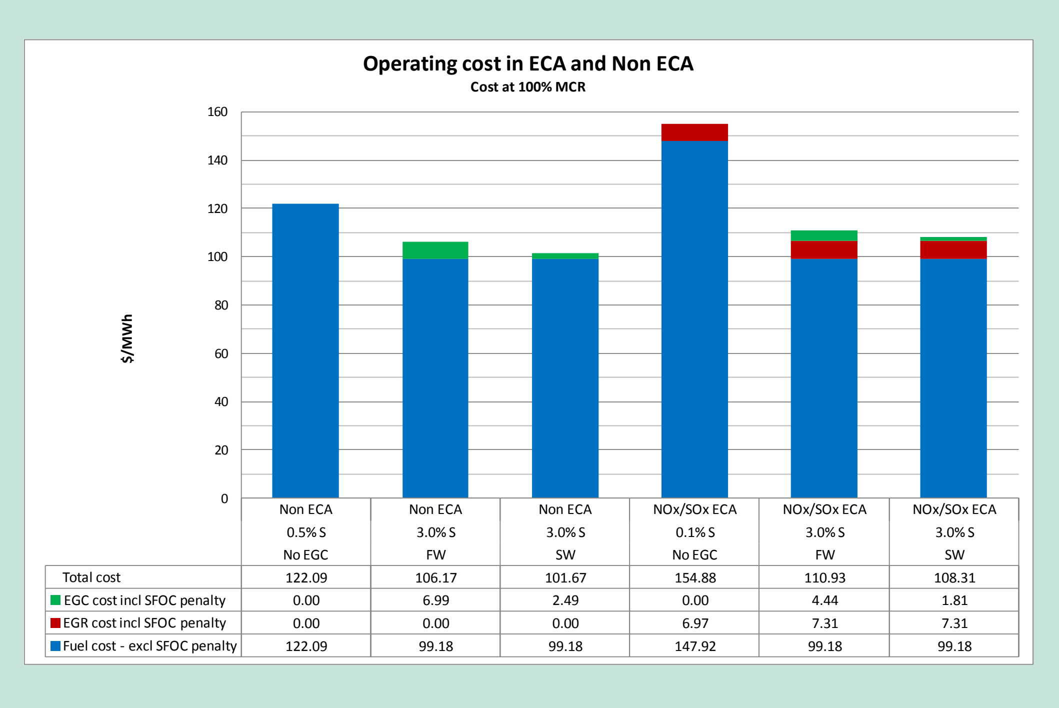
[3] Cost of sludge disposal is unknown and not included in the calculations



| | Non ECA<br>0.5% S<br>No EGC | Non ECA<br>3.0% S<br>FW | Non ECA<br>3.0% S<br>SW | NOx/SOx ECA<br>0.1% S<br>No EGC | NOx/SOx ECA<br>3.0% S<br>FW | NOx/SOx ECA<br>3.0% S<br>SW |
|---|---|---|---|---|---|---|
| Total cost | 122.09 | 106.17 | 101.67 | 154.88 | 110.93 | 108.31 |
| 🟩 EGC cost incl SFOC penalty | 0.00 | 6.99 | 2.49 | 0.00 | 4.44 | 1.81 |
| 🟥 EGR cost incl SFOC penalty | 0.00 | 0.00 | 0.00 | 6.97 | 7.31 | 7.31 |
| 🟦 Fuel cost - excl SFOC penalty | 122.09 | 99.18 | 99.18 | 147.92 | 99.18 | 99.18 |

Figure 37: Total operating cost of combined EGR/EGC scrubber system at different scenarios

Reduced cost combining EGR and EGC scrubber

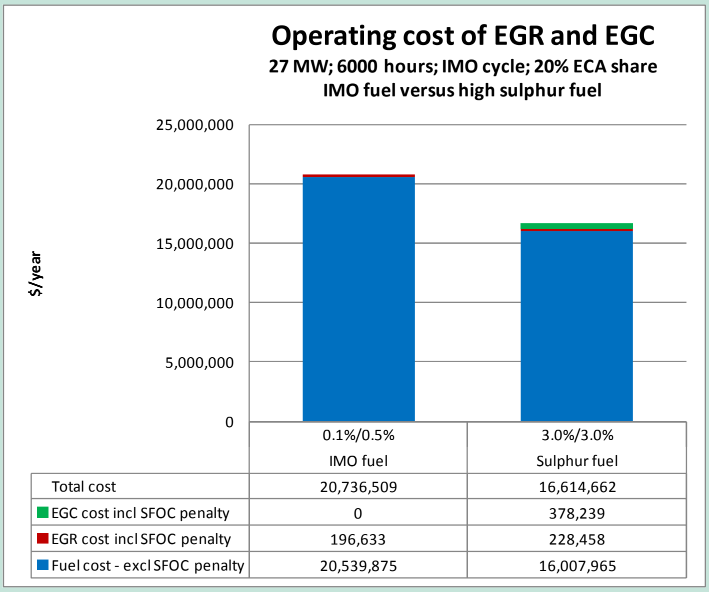
As the EGR system takes a significant part (30% - 40%) of the scrubbing process, the operating cost of EGC scrubber is reduced when an EGR system is engaged. The cost reduction depends on the scrubbing medium, SW or FW. The effects at 100% MCR are listed in Table 11. The cost of EGC scrubber in SOx –ECA, where no EGR will be needed, is compared with the cost of EGC scrubber in NOx & SOx -ECA, where the EGR must be engaged to comply with Tier III requirements and thereby reduces the operating cost of EGC scrubber.

Table 11: Operating cost of EGC scrubber will be reduced when EGR is engaged.

| ECA | | SO$_x$ only | NO$_x$ and SO$_x$ | SO$_x$ only | NO$_x$ and SO$_x$ |
|---|---|---|---|---|---|
| Combination | | No combi | Combi | No combi | Combi |
| Fuel S% used | | 3.0% | 3.0% | 3.0% | 3.0% |
| scrubber media | | FW | FW | SW | SW |
| SFOC penalty scrubber | $/MWh | 0.22 | 0.15 | 0.22 | 0.15 |
| NaOH Scrubber | $/MWh | 4.96 | 3.47 | 0.00 | 0.00 |
| Power Scrubber | $/MWh | 1.98 | 0.39 | 1.76 | 1.23 |
| Maintenance scrubber | $/MWh | 0.52 | 0.43 | 0.52 | 0.43 |
| Total EGC scrubber operating cost | $/MWh | 7.68 | 4.44 | 2.50 | 1.81 |
| Operating cost reduction | $/MWh | | 3.23 | | 0.68 |

Combined ECA and Non ECA trade

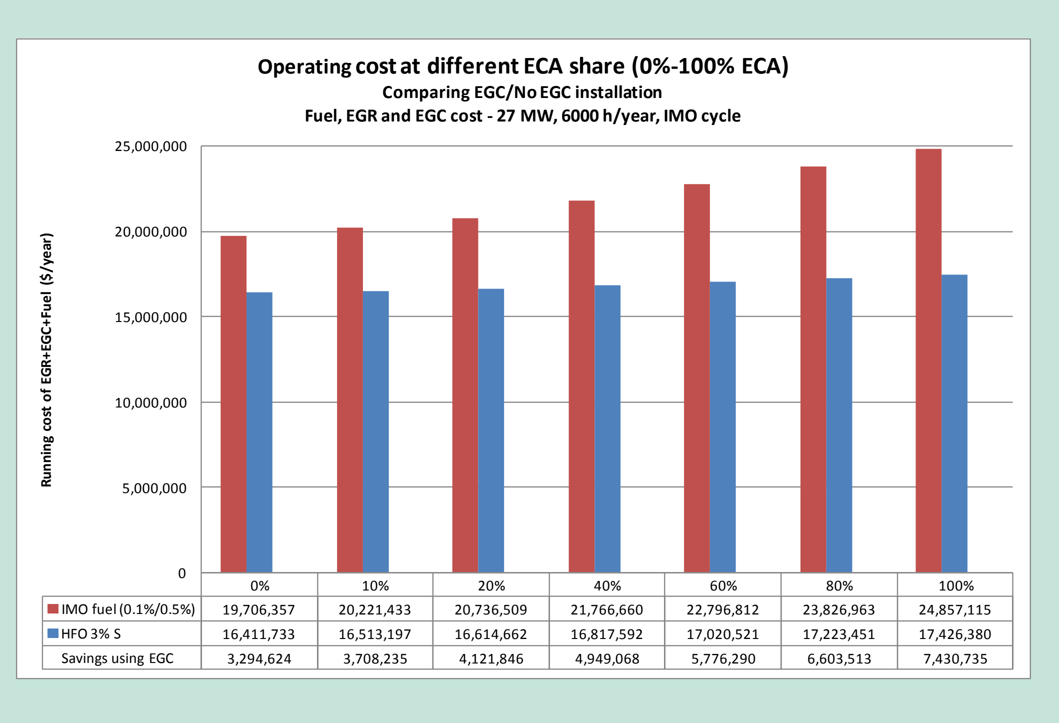
An example of operating cost connected to a specific sailing profile is shown in Figure 38. The scenario is 6,000 sailing hours, of which 20% is in ECA and 80% outside ECA (Non ECA). The load profile is chosen as an IMO test cycle, E3. The cost relates to a 27 MW engine and the EGC scrubber is using SW scrubbing.



| | 0.1%/0.5% IMO fuel | 3.0%/3.0% Sulphur fuel |
|---|---|---|
| Total cost | 20,736,509 | 16,614,662 |
| 🟩 EGC cost incl SFOC penalty | 0 | 378,239 |
| 🟥 EGR cost incl SFOC penalty | 196,633 | 228,458 |
| 🟦 Fuel cost - excl SFOC penalty | 20,539,875 | 16,007,965 |

Figure 38: Operating cost of a 27 MW engine in combined 20% ECA and 80% Non ECA trade

The total operating cost of fuel, EGC scrubber and EGR depends on the time spent in ECA. Figure 39 shows the cost at different percentages of sailing time in ECA. The effect of the EGC scrubber system on the cost is significant in all situations when compared to the use of IMO fuel, showing a reduction of the total operating cost of 17% sailing full time outside ECA (ECA share = 0%) and 30% reduction sailing full time in ECA (ECA share = 100%).



| | 0% | 10% | 20% | 40% | 60% | 80% | 100% |
|---|---|---|---|---|---|---|---|
| 🟥 IMO fuel (0.1%/0.5%) | 19,706,357 | 20,221,433 | 20,736,509 | 21,766,660 | 22,796,812 | 23,826,963 | 24,857,115 |
| 🟦 HFO 3% S | 16,411,733 | 16,513,197 | 16,614,662 | 16,817,592 | 17,020,521 | 17,223,451 | 17,426,380 |
| Savings using EGC | 3,294,624 | 3,708,235 | 4,121,846 | 4,949,068 | 5,776,290 | 6,603,513 | 7,430,735 |

Figure 39: Operating cost reduction of 17% – 30% in combined EGR/EGC scrubber systems

A way to reduce the size and cost of the EGC scrubber system is to use the capacity of the EGR system. As the EGR system reduces the gas flow through the exhaust gas system according to the EGR%, the reduction can be used to install a cheaper and smaller EGC scrubber system. The drawback is the need for partly operating the EGR system when sailing outside ECA – at low loads the EGC scrubber needs no support from the EGR system, but at high loads the EGR system must be engaged to compensate the flow in accordance with the engine load. The principle, named Reduced Exhaust Mode (REM)[4] is illustrated in Figure 40 and Figure 41.

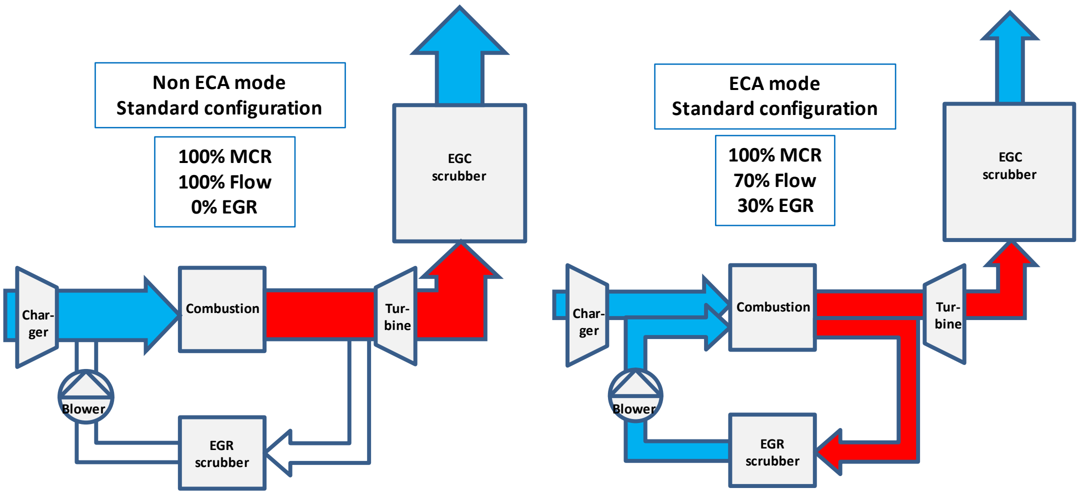


Figure 40: Full size EGC scrubber at 100% MCR in Non ECA mode and ECA mode

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[4] Patent pending

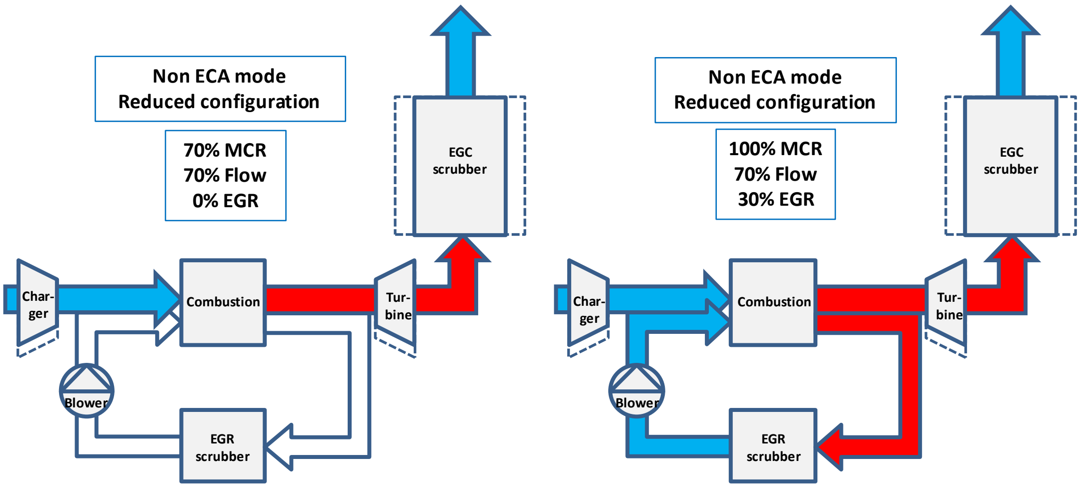
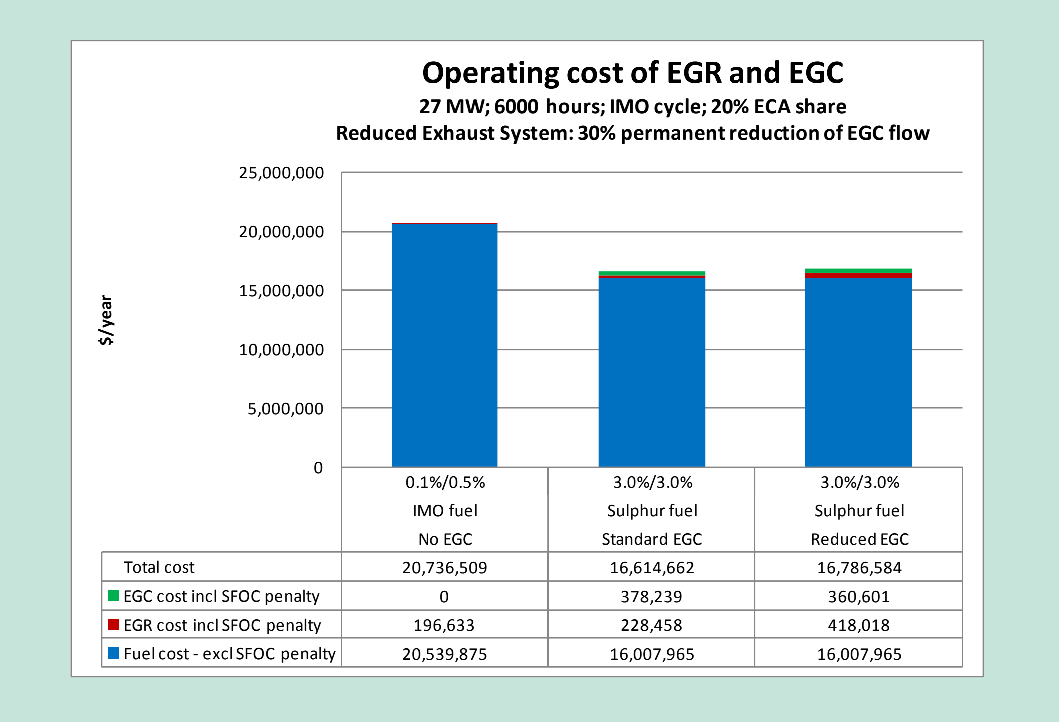


Figure 41: Reduced EGC scrubber in Non ECA mode at 70% MCR and Non ECA mode at 100% MCR

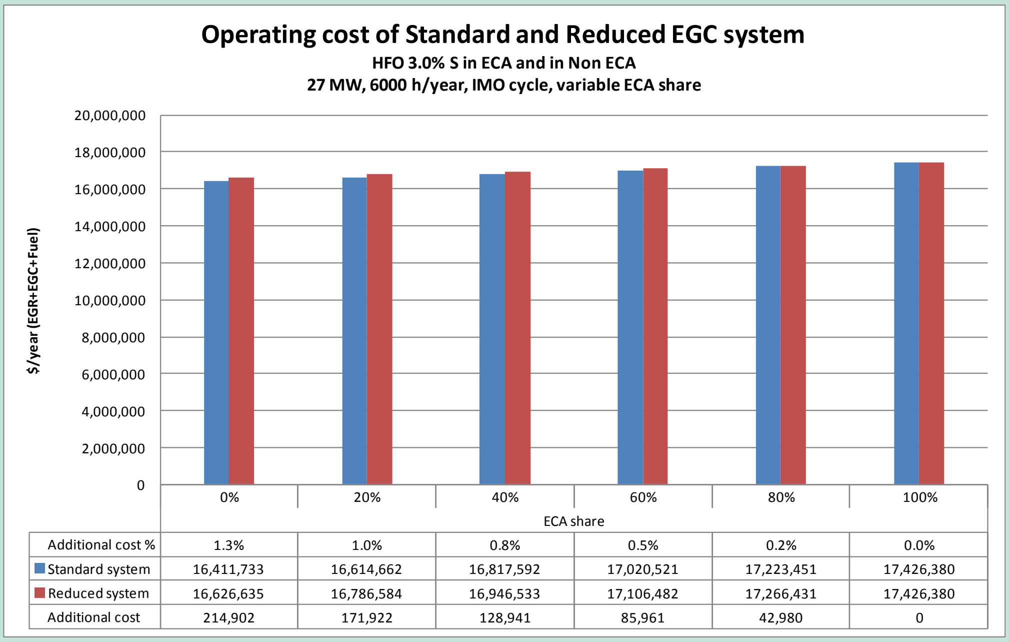
The total operating cost using this principle is shown in Figure 42. The EGC scrubber system is reduced 30% which reflects the capacity of the EGR scrubber. The scenario is the same as the previous example: 27 MW engine, 8,000 hours, ECA share of 20% and IMO load profile. The example shows a slight increase of the total operating cost. If the ECA share is higher than 20%, the price gap will be even smaller.



| | 0.1%/0.5%<br>IMO fuel<br>No EGC | 3.0%/3.0%<br>Sulphur fuel<br>Standard EGC | 3.0%/3.0%<br>Sulphur fuel<br>Reduced EGC |
|---|---|---|---|
| Total cost | 20,736,509 | 16,614,662 | 16,786,584 |
| 🟩 EGC cost incl SFOC penalty | 0 | 378,239 | 360,601 |
| 🟥 EGR cost incl SFOC penalty | 196,633 | 228,458 | 418,018 |
| 🟦 Fuel cost - excl SFOC penalty | 20,539,875 | 16,007,965 | 16,007,965 |

Figure 42: Operating cost using EGR to reduce the EGC scrubber system.

The operating cost using REM at different ECA shares is illustrated in Figure 43. If the ship never enters an ECA where the Tier III requirement must be met, the increased operating cost of the reduced EGC scrubber system will be 286,537 $/year, i.e. 1.3% of the total operating cost. If, on the other hand, the ship will always be in ECA, there will be no additional operating cost of a reduced EGC scrubber system.



| | 0% | 20% | 40% | 60% | 80% | 100% |
|---|---|---|---|---|---|---|
| Additional cost % | 1.3% | 1.0% | 0.8% | 0.5% | 0.2% | 0.0% |
| 🟦 Standard system | 16,411,733 | 16,614,662 | 16,817,592 | 17,020,521 | 17,223,451 | 17,426,380 |
| 🟥 Reduced system | 16,626,635 | 16,786,584 | 16,946,533 | 17,106,482 | 17,266,431 | 17,426,380 |
| Additional cost | 214,902 | 171,922 | 128,941 | 85,961 | 42,980 | 0 |

Figure 43: Total operating cost (fuel, EGC scrubber and EGR) at different ECA shares

### 3.7.2 Payback time

Depending on the ECA share and operating time of the ship, the effect of installing a combined EGR and EGC scrubber system can be evaluated. Some assumptions are made in Table 12 and based on these, the payback time of the combined and the reduced system can be calculated to between 0.7 and 1.9 years. In case of 20% time in ECA, the payback of a combined system will be 1.5 years or 1.3 years if a reduced EGC scrubber solution is selected. Increasing the ECA share to 100%, the payback time will be even lower, 0.8 year for the combined system and 0.7 year for the reduced system. Even if the ship will only be engaged outside ECA there will be a short payback time, i.e. 1.9 years.

Table 12: Payback time of combined EGR/EGC scrubber system

| **Engine size** | **Operating time** | **CAPEX EGC scrubber and EGR** | **OPEX per year Fuel, EGR and EGC scrubber (SW)** | | | **Payback time** |
|---|---|---|---|---|---|---|
| 27 MW | 6000 h/year | | Reference No EGC | OPEX (3% S) | Saving per year | |
| **System** | **ECA share** | Mio $ | Mio $ | Mio $ | Mio $ | Years |
| Combined | 0% ECA | 6.20 | 19.71 | 16.41 | 3.29 | 1.9 |
| | 20% ECA | 6.20 | 20.74 | 16.61 | 4.12 | 1.5 |
| | 100% ECA | 6.20 | 24.86 | 17.43 | 7.43 | 0.8 |
| Reduced | 0% ECA | 5.30 | 19.71 | 16.63 | 3.08 | 1.7 |
| | 20% ECA | 5.30 | 20.74 | 16.79 | 3.95 | 1.3 |
| | 100% ECA | 5.30 | 24.86 | 17.43 | 7.43 | 0.7 |

Although the payback time of the reduced system is shorter, the operating cost per MWh is still higher compared to the combined WTS. Comparing the accumulated savings of the two systems, shown in Figure 44, the long-term benefit can be evaluated. If the ship has an expected ECA share of 20%, the accumulated savings of a reduced system will be caught up after passing 4.5 years. An ECA share of 80% will keep the time of benefit for more than 20 years. A ship with an ECA share close to 100% will always benefit of a reduced system – in addition to the reduced size of the system.

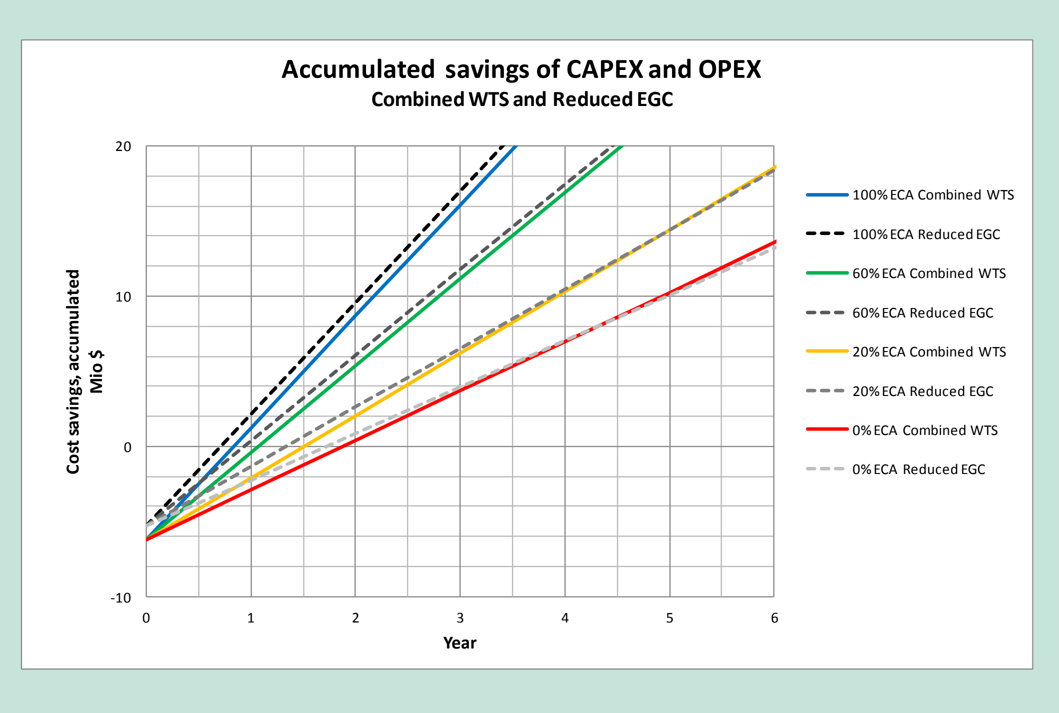


Figure 44: Accumulated savings at different ECA shares

It should be kept in mind that the above calculations use the global sulphur fuel limit of 0.5% outside ECA, which will enter into force in 2020. In the period 2016-2020, the global sulphur fuel limit is 3.5% and the fuel cost savings will only be obtained in ECA, having a sulphur limit of 0.1%. In this period the contribution to a fuel cost saving will come from the time spent in ECA. An engagement of 100% ECA will keep the short payback time.

The accumulated savings when installing a combined system in 2016 is shown in Figure 45. From the figure it can be seen that a combined system at 20% ECA share will be paid back in about 4 years – at the time when further benefits will be achieved due to the change in the global sulphur limit of 0.5%.

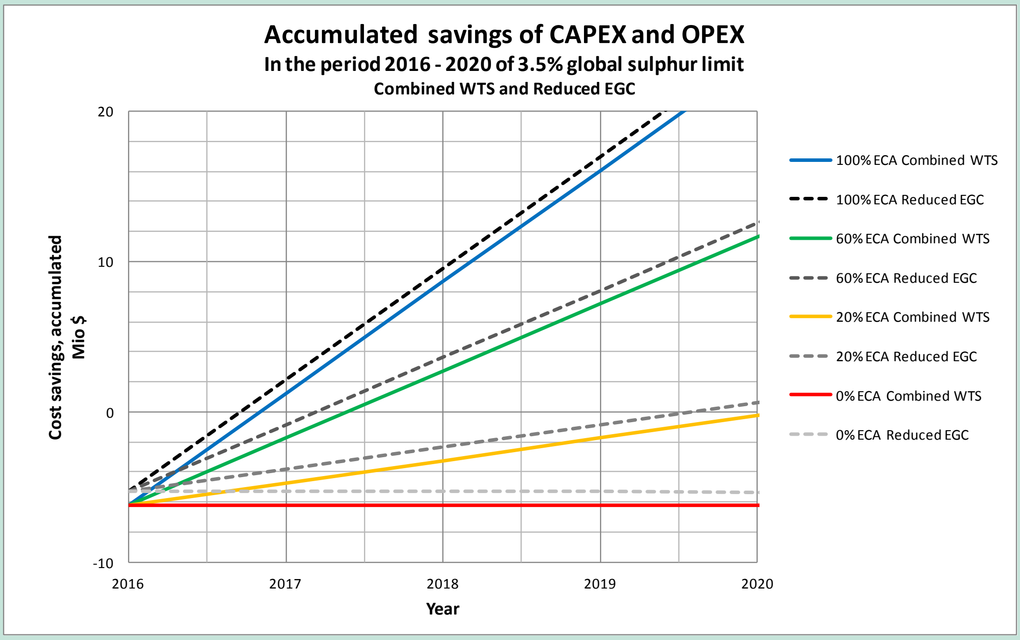


Figure 45: Accumulated savings at different ECA shares in the period of a global sulphur limit of 3.5%

## 3.8 Process calculations

A flow sheet for the combined WTS is sketched in Figure 46.
Normally, only a smaller part of the water circulating to the EGC scrubber is cleaned in the WTS while all the water to the EGR scrubber is cleaned. As it is impossible to make a demister that catches 100% of the water after a scrubbing process, it is important that relatively clean water is circulated – especially to the EGR scrubber as the engine must be protected towards impurities of soot and water droplets that unavoidable will escape the demister. In the combined plant, all water to the EGR scrubber is therefore cleaned – this is approximately 20-40% of the total water flow to the EGR and EGC scrubber. In this way, the cleanest water will be used in the EGR scrubber after which it will be used in the EGC scrubber. This will make the conditions for the EGR and the engine similar to how it is for separate EGR and EGC scrubbers today.

At low ambient air temperature, low hydrogen content in the fuel and a warm sea water temperature, it will be difficult to cool and condense water in the EGC scrubber system. However, as the water evaporated in the EGR scrubber will pass the EGC scrubber cooler, the combined system will have reduced water consumption relative to a stand-alone EGC scrubber.

The NaOH is dosed before the centrifuge in order to ensure the correct pH level of the water entering the EGR. NaOH is also added upstream the EGC scrubber unit.

The fuel sulphur and NaOH reacts to sodium sulphate, which is very soluble in water. However if the salt concentration in the water increases too much, free salt will settle on the surrounding materials and the centrifuges are unable to separate the “dirt” from the heavier salt water. The salt concentration is reduced by bleeding off a small amount of water with a high content of sodium sulphate and replacing this water with clean fresh water. Preferably, cooling and condensation in the EGC scrubber, as mentioned above, will support the dilution and only topping up with on board generated fresh water if necessary.

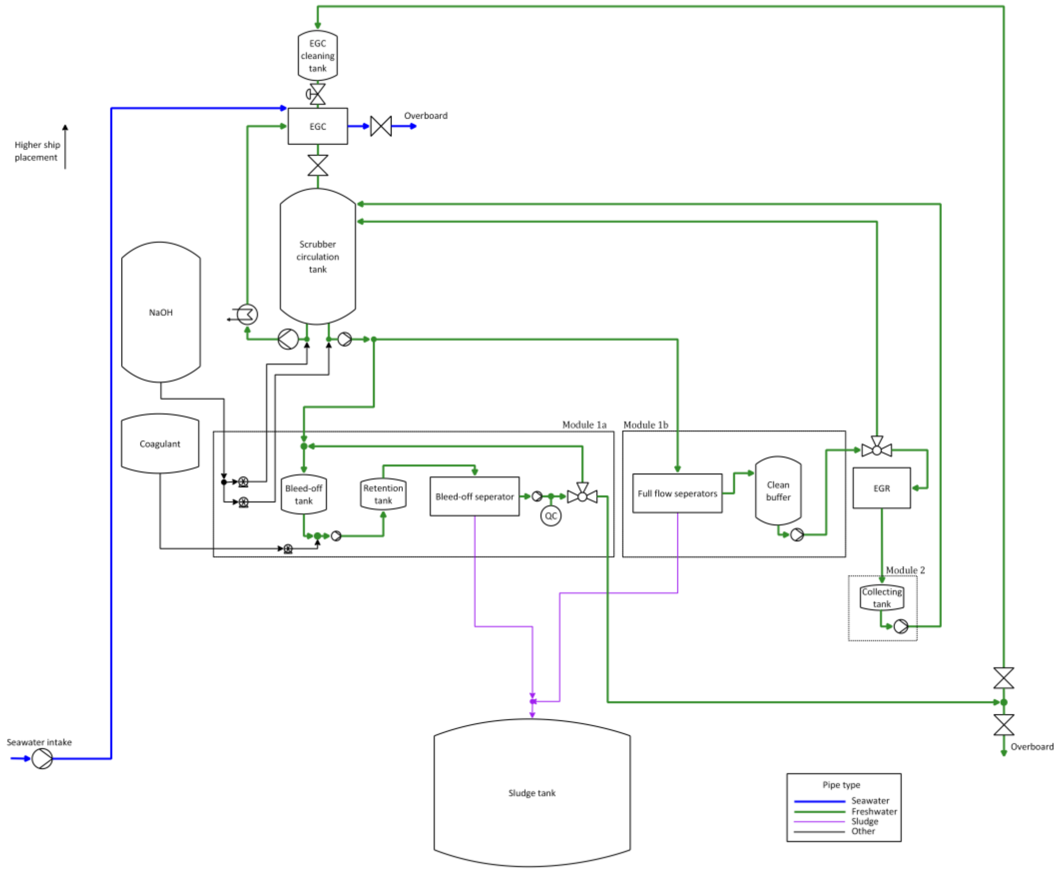


Figure 46: Sketch of the combined EGR and EGC scrubber system.

In the EGR system, SW can result in corrosion problems for the engine. When the two systems are combined, it will therefore be necessary to flush the EGC scrubber with FW when changing from SW to FW in order to avoid mixing of the two liquids. Tank capacity for sufficient flush water has to be established. It is possible to use the cleaned FW indended for discharge for this flushing. This means that the bleed-off centrifuge should fill a "flush water tank".

The system is designed to function in the following operating modes:

- Combined EGC scrubber and EGR – both on FW
- Combined EGC scrubber and EGR – EGC scrubber on SW and EGR on FW
- Switch-over from SW to FW
- EGR only
- EGC scrubber only – FW mode
- EGC scrubber only – SW mode.

Diagrams showing the water flows are shown in Appendix C.4.

A design calculation program has been jointly programmed by MDT and Alfa Laval to calculate the volumes of the tanks shown on the flow sheets in Appendix C.4 as well as other important results taking into account all the parameters affecting this. It is important to mention that this excel sheet program is based on many assumptions and rough simplifications. It must therefore be re-programmed and checked further for full commercial usage. However, it is for now an excellent tool to highlight some important parameters as below – see Appendix C.1 for a description and Appendix C.2 for examples of print out.

A comprehensive parameter analysis is included in Appendix C.3. One important result to note is that if the altitude of the EGC scrubber unit is increased by 35 m the added pumping energy corresponds to an increased fuel consumption of 1.3% for the engine, i.e. significant energy savings can be gained if the EGC scrubber unit is mounted at sea level rather than up in the highest position of the chimney.

By aid of the program, the influence of some parameters has been calculated. Some main results are summarised in Table 13 in which the columns or cases are explained as follows:

1. Reference calculation assuming that the vessel is operating 20% in SECA and NECA and according to an IMO load profile.
2. Case where the ship is not in SECA and NECA. The EGR scrubber is never used and the EGC scrubber is always operating in SW mode. This is the situation with the lowest total $CO_2$ impact.
3. Case where the ship is always in SECA and NECA. FW is used in the EGR scrubber while the EGC scrubber switches between SW and FW. The $CO_2$ emission as well as the generation of sludge is higher than in case 2 where only SW scrubbing was applied.
4. Case where the ship is always in SECA and never in NECA. The EGR scrubber is off while the EGC scrubber switches between SW and FW.
5. Case where the ship is always in SECA and never in NECA. The EGR scrubber is off and the EGC scrubber is always operated on FW. Compared with case 4, the emission reduction is the same, but the $CO_2$ emission is increased due to the water cleaning and the NaOH consumption. This is the solution that collects most of the soot as sludge but also the case with the greatest $CO_2$ impact (but still lower $CO_2$ impact than switching to low sulphur distillate fuel).
6. Case where the ship is always in SECA and in NECA. FW is always used in both the EGR and the EGC scrubbers. This is the sea water “friendly” way to reduce both $NO_X$ and $SO_X$, but it also increases the $CO_2$ emission by 1.6% point relative to case 5.
7. Case where the ship is not in SECA and NECA– as case 2; but the level of the EGC scrubber is increased by 35 m simulating that the position is in the chimney. The additional height increases the $CO_2$ emission by 1.3%.

Table 13: Influence of operating profile on fuel consumption, NaOH consumption and gaseous emissions. The amounts are calculated for a journey on 263 hours during which the main engine consumes 732 tonne of high sulphur HFO.

| | | 1. Standard profile 20% in SECA/NECA IMO profile | 2. Never in SECA / NECA always SW | 3. Always in SECA / NECA | 4. Always in SECA never in NECA, standard SW/ FW | 5. Always in SECA Never in NECA, always FW | 6. Always in SECA and NECA always FW | 7. Never in SECA / NECA altid SW – EGC high above sea water |
|---|---|---|---|---|---|---|---|---|
| Pumping height | m | 5 | 5 | 5 | 5 | 5 | 5 | 40 |
| **Additional consumptions:** | | | | | | | | |
| ME - fuel consumption: | t/trip | 3.2 | 1.3 | 16.3 | 1.3 | 1.3 | 16.3 | 1.3 |
| AE - fuel consumption: | t/trip | 3.0 | 1.4 | 5.7 | 2.6 | 6.7 | 6.7 | 11.4 |
| In percent of "without EGR+EGS": | % | 0.8 | 0.4 | 2.9 | 0.5 | 1.1 | 3.0 | 1.7 |
| | | | | | | | | |
| Total NaOH consumption (50%) | t /trip | 7.3 | 0.0 | 43.0 | 3.6 | 107.4 | 109.6 | 0.0 |
| Sludge | t /trip | 8.6 | 0.0 | 50.2 | 2.9 | 61.9 | 106.5 | 0.0 |
| | | | | | | | | |
| **Emissions:** | | | | | | | | |
| $CO_2$ due to additional power: | t /trip | 19.4 | 8.6 | 69.4 | 12.2 | 25.3 | 72.7 | 40.2 |
| $CO_2$ due to NaOH | t /trip | 8.0 | 0.0 | 47.3 | 4.0 | 118.2 | 120.6 | 0.0 |
| Total additional $CO_2$ caused by emission reduction: | t /trip | 27.4 | 8.6 | 116.6 | 16.2 | 143.5 | 193.3 | 40.2 |
| $CO_2$ increase incl $CO_2$ for NaOH production | % | 1.1 | 0.4 | 4.9 | 0.7 | 6.0 | 8.0 | 1.7 |
| $CO_2$ increase /S removed | t/t | 1.4 | 0.5 | 5.0 | 0.7 | 6.3 | 8.2 | 2.2 |
| | | | | | | | | |
| $SO_x$ reduction: | % | 82.3 | 80.0 | 98.0 | 98.0 | 98.0 | 98.0 | 80.0 |
| $NO_x$ reduction: | % | 10.1 | 0.0 | 76.4 | 0.0 | 0.0 | 76.4 | 0.0 |

## 3.9 Conclusion

Significant synergies can be gained by combining an EGR system for $NO_x$ removal with an EGC scrubber system for $SO_x$ removal. The purpose of the EGR scrubber is to remove sulphur and PM from the engine exhaust gas so this gas can be re-introduced to the engine without damaging the cylinder liners or other engine components. The sulphur and PM removed in this process does not have to be removed again in the EGC scrubber as well as the total exhaust gas flow is reduced. In this way, the EGC scrubber can be made smaller compared to the size it would have had for a similar sized engine without EGR scrubber. The reduced scrubber size though requires operation of the EGR system or fuel switch to a low sulphur fuel at engine loads above approx. 80% outside NECA.

Also, the water treatment system can be combined and reduced in size. The WTS is primarily to be dimensioned for cleaning the full water flow to the EGR scrubber. This full flow cleaning is anticipated also to be able to keep the water to the EGC scrubber sufficiently clean.

If a vessel is not operated in NECA or SECA, fuel is saved by switching off the EGR scrubber and the 0.5% $S_{eq}$ can be met by operating the EGC scrubber with a reduced flow of SW which also reduces the electrical power consumption.

Within NECA and SECA, both the EGR and the EGC scrubbers can be operated resulting in 74% reduction in $NO_X$, 98% reduction in $SO_2$ and around 80% reduction of the PM emission.

The $CO_2$ footprint is affected by the EGC scrubber and the EGR process, but it is significantly lower than the alternative by removal of sulphur at the refinery. Even an increase of $CO_2$ in the magnitude of 6.8%, as calculated for FW operation, of the EGC scrubber combined with EGR, is significantly lower than Low Sulphur Fuel (LSO) $CO_2$ footprint (Appendix C.2). The $CO_2$ footprint is higher when the EGC scrubber system is operated on FW with addition of NaOH compared to SW operation, due to the energy consumption in the production process of NaOH. A benefit from the FW operation of the EGS system is that the scrubber water is cleaned in a water treatment system hence reducing the impact on the water environment.

The case study showed that EGR and EGC scrubber can be combined in a beneficial way with positive synergy effects on ship installation and economy. The case study shows that the benefit of installing EGR and EGC scrubber as a combined system is a potential reduction in CAPEX around 20% if the EGC scrubber is reduced according to the reduced exhaust gas flow when operating with EGR. If the full EGC scrubber size is kept the saving in CAPEX is around 5%. The OPEX savings by operating on HFO with EGR and EGC scrubber systems compared to operation on MGO is around 20% giving a payback time below 2 years.

By combining EGR and EGC scrubber, the shipowner can maintain the use of low cost HFO containing sulphur and meanwhile comply with the future IMO requirements for $NO_x$ and $SO_x$ in the ECA areas. The OPEX savings by operating on HFO with EGC scrubber and EGR systems compared to operation on MGO/MDO (0.1%/0.5% S) is 17% to 30%, giving a payback time below two years.

# 4. References

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4) Hansen, J.P. "Udvikling og demonstration af et modulopbygget varmegenvindings- og skrubberanlæg til reduktion af SOx, PM, CO2 og NOx", Danish EPA, ISBN No.: 978-87-92903-29-7.
5) "Tier III Two-Stroke Technology" MAN Diesel & Turbo technical paper, August 2012.
6) "Emission Project Guide" – 7020-0145-00, MAN B&W Two-stroke Engines - , MAN Diesel & Turbo, Copenhagen, December 2012.
7) Preem, M., Kaltoft, J. "Development of integrated EGR system for two-stroke diesel engines", CIMAC paper No. 219, Shanghai 2013.
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9) Kaltoft, J. "Tier III EGR for large two-Stroke MAN B&W Diesel engines", ISME586, Kobe, Japan, October 2011.
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11) Revised MARPOL Annex VI, Regulations for the Prevention of Air Pollution from Ships and $NO_x$ Technical Code 2008, International Maritime Organization, London, 2009.
12) Andreasen, A., Mayer, ―Use of Seawater Scrubbing for SO2 Removal from Marine Engine Exhaust Gas‖, Energy & Fuels 21(6), 2007 pp. 3274–3279.
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# Appendix A.1

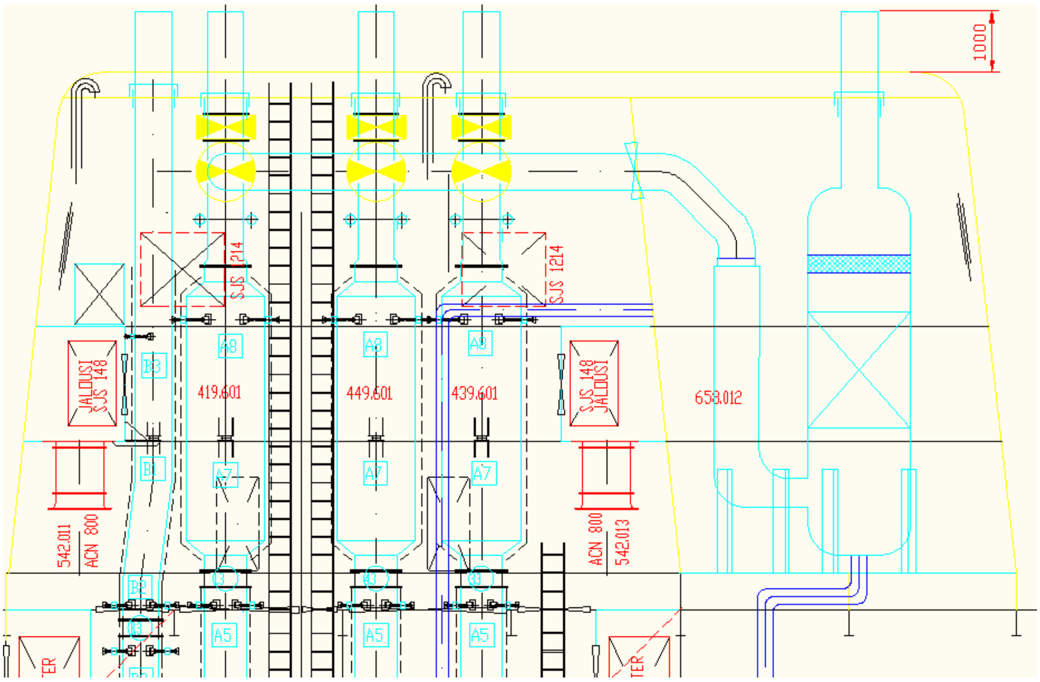


Figure A.1.1: MV Prince Richard funnel casing with scrubber seen from centre line towards port.

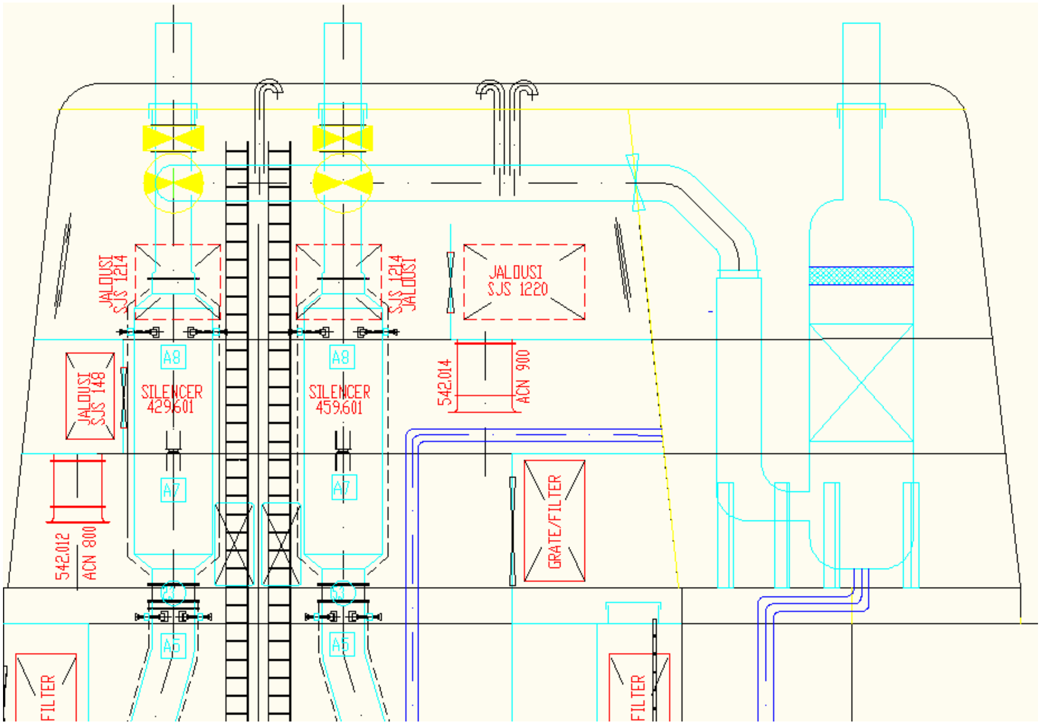


Figure A.1.2: MV Prince Richard funnel casing with scrubber seen from west towards centre line.

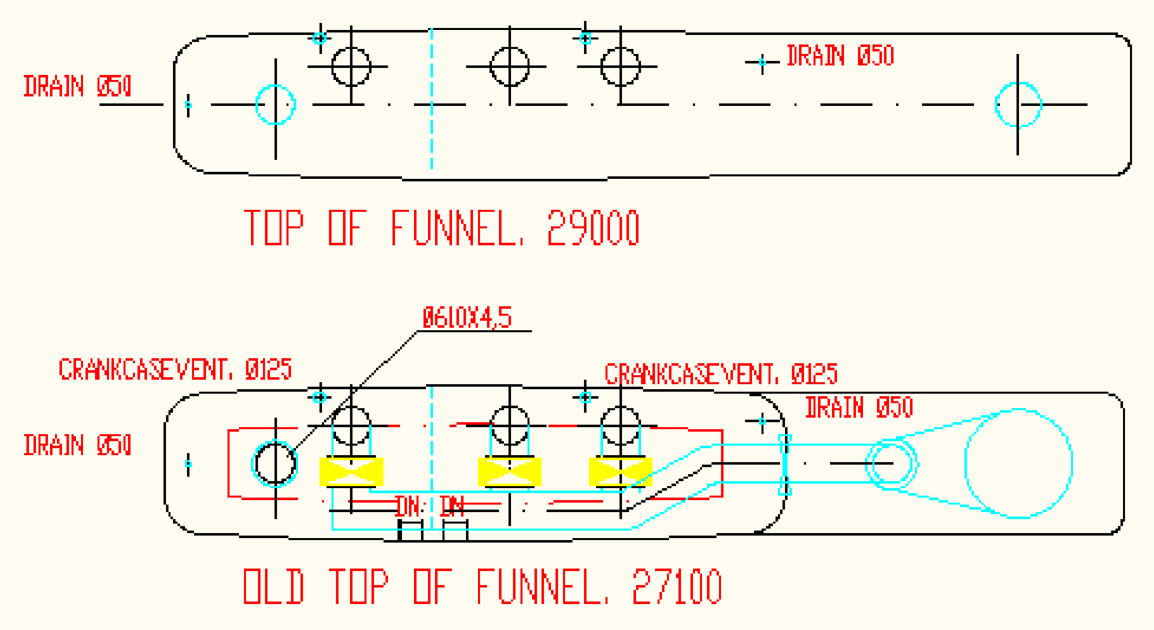
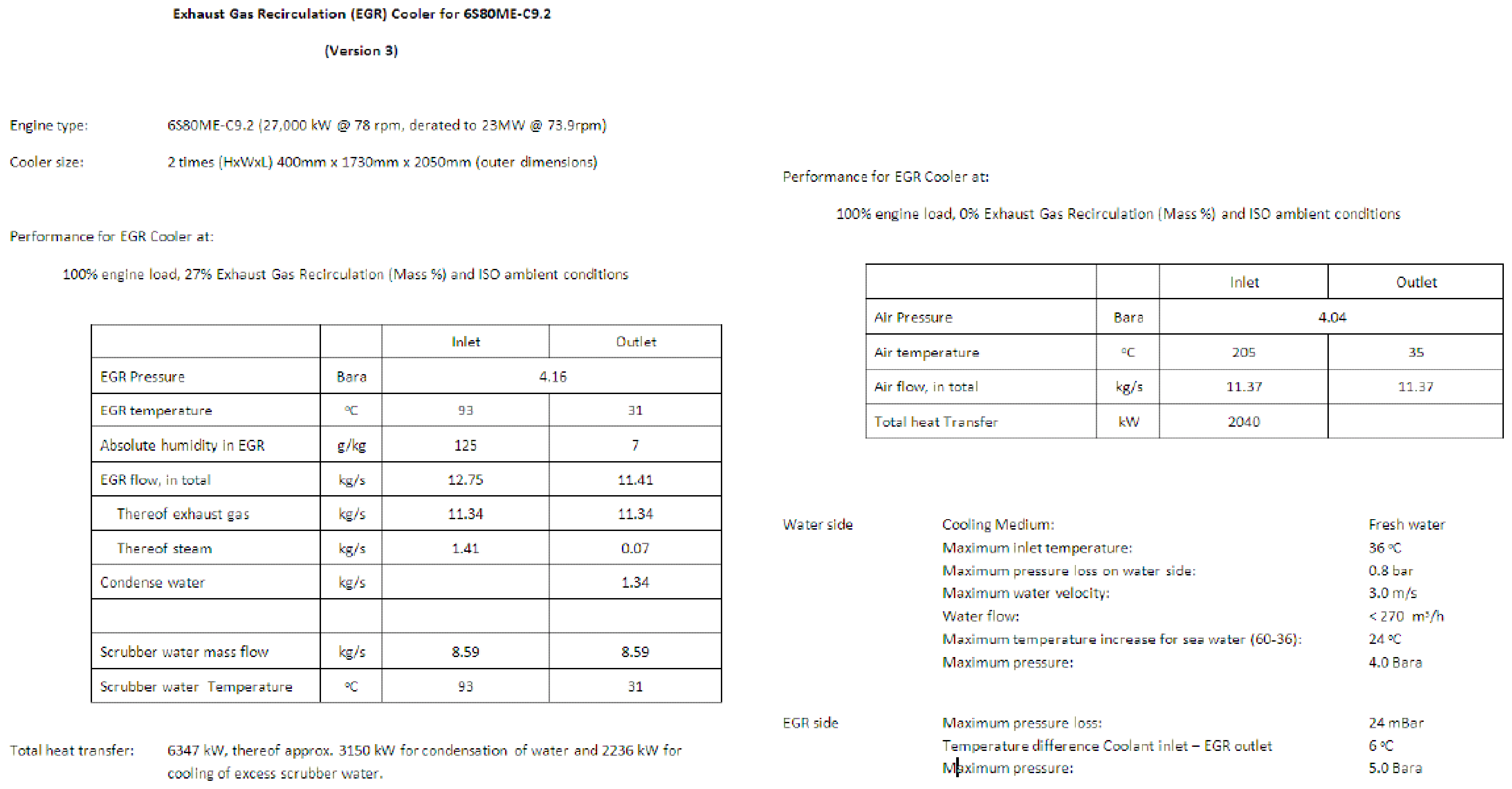


Figure A.1.3: MV Prince Richard funnel casing with scrubber seen from top (starboard side).

# Appendix B.1



**Exhaust Gas Recirculation (EGR) Cooler for 6S80ME-C9.2**

**(Version 3)**

| | |
|---|---|
| Engine type: | 6S80ME-C9.2 (27,000 kW @ 78 rpm, derated to 23MW @ 73.9rpm) |
| Cooler size: | 2 times (HxWxL) 400mm x 1730mm x 2050mm (outer dimensions) |

Performance for EGR Cooler at:

100% engine load, 27% Exhaust Gas Recirculation (Mass %) and ISO ambient conditions

| | | Inlet | Outlet |
|---|---|---|---|
| EGR Pressure | Bara | 4.16 | |
| EGR temperature | °C | 93 | 31 |
| Absolute humidity in EGR | g/kg | 125 | 7 |
| EGR flow, in total | kg/s | 12.75 | 11.41 |
| Thereof exhaust gas | kg/s | 11.34 | 11.34 |
| Thereof steam | kg/s | 1.41 | 0.07 |
| Condense water | kg/s | | 1.34 |
| | | | |
| Scrubber water mass flow | kg/s | 8.59 | 8.59 |
| Scrubber water Temperature | °C | 93 | 31 |

| | |
|---|---|
| Total heat transfer: | 6347 kW, thereof approx. 3150 kW for condensation of water and 2236 kW for cooling of excess scrubber water. |

Performance for EGR Cooler at:

100% engine load, 0% Exhaust Gas Recirculation (Mass %) and ISO ambient conditions

| | | Inlet | Outlet |
|---|---|---|---|
| Air Pressure | Bara | 4.04 | |
| Air temperature | °C | 205 | 35 |
| Air flow, in total | kg/s | 11.37 | 11.37 |
| Total heat Transfer | kW | 2040 | |

| | | |
|---|---|---|
| Water side | Cooling Medium: | Fresh water |
| | Maximum inlet temperature: | 36 °C |
| | Maximum pressure loss on water side: | 0.8 bar |
| | Maximum water velocity: | 3.0 m/s |
| | Water flow: | < 270 m³/h |
| | Maximum temperature increase for sea water (60-36): | 24 °C |
| | Maximum pressure: | 4.0 Bara |
| EGR side | Maximum pressure loss: | 24 mBar |
| | Temperature difference Coolant inlet – EGR outlet | 6 °C |
| | Maximum pressure: | 5.0 Bara |

# Appendix B.2

## Specification of compressor wheel performance

The characteristic of the blower performance sall at minimum fulfill the requirement of point A and B with regard to volume flow and static pressure rise.

Engine operation data:

| | |
|---|---|
| - Engine load: | 100% SMCR |
| - EGR ratio: | up to 40% |

Design data for compressor wheel at an air inlet density of 1.225 kg/m³

| | Volume flow ($m^3/s$) | Static Pressure rise (Pa) |
|---|---|---|
| Point A | 4.3 | 15000 |
| Point B | 4.7 | 12000 |

The isentropic efficiency of the compressor wheel between point A and B shall exceed 80%. The electrical motor shall be designed for operation up to an air density of 4.6 kg/m³.

Operation conditions for compressor wheel

| | |
|---|---|
| - Compressor inlet temperature: | 10 - 50°C |
| - Compressor inlet pressure: | 1.0 - 4.00 bara |
| - Compressor outlet pressure: | 1.0 - 4.35 bara |
| - Compressor volume flow: | 0.0 - 4.5 m³/s |
| - Humidity: | up to 100% |
| - Max. Presssure pulsations: | +/- 0.15 bar (1hz - max. 20hz) |

Operation conditions for electrical motor

| | |
|---|---|
| - Room temperature: | up to 55°C |
| - Humidity: | up to 100% |

Maximum operation conditions for compresssor wheel at an air inlet density of 4.6 kg/m³

| | Volume flow ($m^3/s$) | Mass flow (kg/s) | Inlet air pressure (bara) | Inlet air temperature (°C) | Outlet air pressure (bara) | Static pressure rise (Pa) |
|---|---|---|---|---|---|---|
| Point A | 4.3 | 19.8 | 4.00 | 31 | 4.56 | 56000 |
| Point B | 4.7 | 21.6 | 4.00 | 31 | 4.45 | 45000 |

# Appendix B.3

An example of EGR data for a 27 MW MAN B&W engine is calculated below for two different sailing patterns using the information of consumption and capacities given in the diagrams. The calculation assumes that no $SO_x$ abatement techniques are available, which implies that the fuel sulphur content is not to exceed 0.1% as required for $SO_x$ ECA. A higher sulphur content will significantly increase the NaOH and sludge amount.

**Assumptions:**
Ship construction date ≥ 2016
$NO_x$ reduction EGR Tier III
Engine 6S80ME-9.2
Power 27,060 kW MCR
T/C configuration Multiple T/C
ECA fuel S% 0.1% S
NaOH solution 50%
ECA sailing time 2,000 h/year
ECA sailing profile 25% MCR 15% time
ECA sailing profile 50% MCR 15% time
ECA sailing profile 75% MCR 50% time
ECA sailing profile 100% MCR 20% time

Specific ECA consumptions – as specified in the consumption data

| Engine load, % MCR | 25% | 50% | 75% | 100% | |
|---|---|---|---|---|---|
| Delta SFOC Tier III | 0.0 | 2.0 | 3.0 | 4.0 | g/kWh |
| Power, WTS | 2.4 | 2.9 | 3.5 | 4.0 | kW/MW MCR |
| Power, EGR blower | 2.0 | 6.5 | 9.0 | 6.2 | kW/MW MCR |
| NaOH | 0.07 | 0.11 | 0.15 | 0.17 | l/h/MW MCR |
| Sludge | 0.5 | 0.9 | 1.3 | 1.5 | l/h/MW MCR |
| WTSEGR freshwater | 2.0 | 2.0 | 2.0 | 2.0 | l/h/MW MCR |

Absolute ECA consumptions – according to specified engine

| Engine load, % MCR | 25% | 50% | 75% | 100% | |
|---|---|---|---|---|---|
| Delta SFOC Tier III | 0.0 | 27.1 | 60.9 | 108.2 | kg/h |
| Power WTS | 64.9 | 78.5 | 94.7 | 108.2 | kWh/h |
| Power EGR blower | 54.1 | 175.9 | 243.5 | 167.8 | kWh/h |
| NaOH | 1.9 | 3.0 | 4.1 | 4.6 | l/h |
| Sludge | 13.5 | 24.4 | 35.2 | 40.6 | l/h |
| EGR freshwater | 54.1 | 54.1 | 54.1 | 54.1 | l/h |

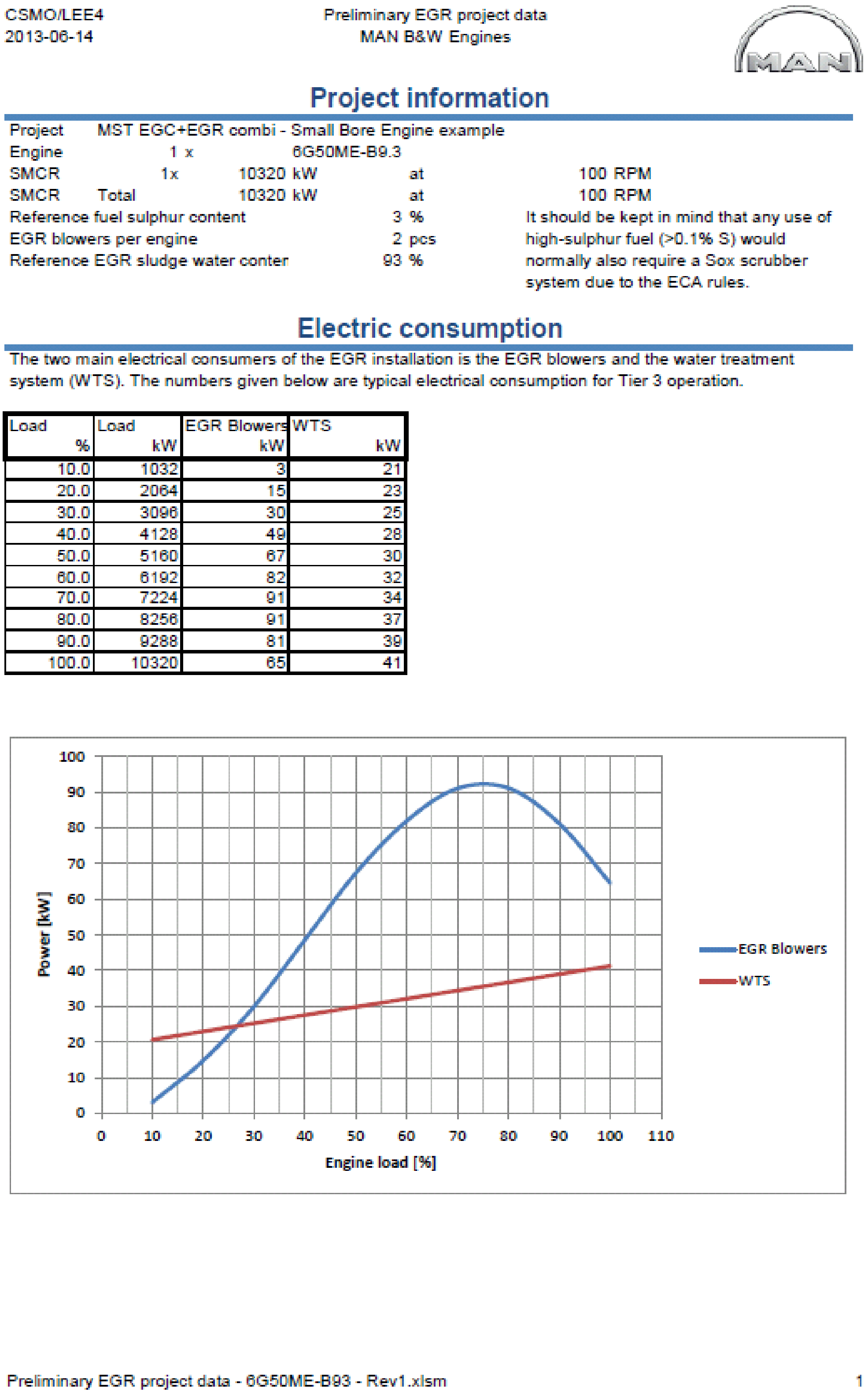
## Total ECA consumptions – according to specified load profile and ECA sailing time

| Engine load, % MCR | 25% | 50% | 75% | 100% | Total | | Total | |
|---|---|---|---|---|---|---|---|---|
| ECA load profile Time | 15% | 15% | 50% | 20% | per hour | | per year | |
| Additional fuel | 0.0 | 4.1 | 30.4 | 21.6 | 56.1 | kg/h | 112.3 | ton/year |
| Power WTS | 9.7 | 11.8 | 47.4 | 21.6 | 90.5 | kWh/h | 181.0 | MWh/year |
| Power EGR blower | 8.1 | 26.4 | 121.8 | 33.6 | 189.8 | kWh/h | 379.7 | MWh/year |
| NaOH | 0.3 | 0.4 | 2.0 | 0.9 | 3.7 | l/h | 7.4 | $m^3$/year |
| Sludge | 2.0 | 3.7 | 17.6 | 8.1 | 31.4 | l/h | 62.8 | $m^3$/year |
| EGR freshwater | 8.1 | 8.1 | 27.1 | 10.8 | 54.1 | l/h | 108.2 | $m^3$/year |

## Tank capacities

| | Consumption /discharge | Bunker frequency | Average bunker volume | Tank capacity |
|---|---|---|---|---|
| NaOH tank | 7.4 $m^3$/year | 2 times/year | 3.7 $m^3$ | 5.0 $m^3$ |
| Sludge tank | 62.8 $m^3$/year | 12 imes/year | 5.2 $m^3$ | 7.0 $m^3$ |

# Appendix B.4



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Preliminary EGR project data
MAN B&W Engines

## Project information

| | | | | | | |
|---|---|---|---|---|---|---|
| Project | MST EGC+EGR combi - Small Bore Engine example | | | | | |
| Engine | 1 x | 6G50ME-B9.3 | | | | |
| SMCR | 1x | 10320 kW | at | 100 RPM | | |
| SMCR | Total | 10320 kW | at | 100 RPM | | |
| Reference fuel sulphur content | | | 3 % | | | |
| EGR blowers per engine | | | 2 pcs | | | |
| Reference EGR sludge water conter | | | 93 % | | | |

It should be kept in mind that any use of high-sulphur fuel (>0.1% S) would normally also require a Sox scrubber system due to the ECA rules.

## Electric consumption

The two main electrical consumers of the EGR installation is the EGR blowers and the water treatment system (WTS). The numbers given below are typical electrical consumption for Tier 3 operation.

| Load<br>% | Load<br>kW | EGR Blowers<br>kW | WTS<br>kW |
|---|---|---|---|
| 10.0 | 1032 | 3 | 21 |
| 20.0 | 2064 | 15 | 23 |
| 30.0 | 3096 | 30 | 25 |
| 40.0 | 4128 | 49 | 28 |
| 50.0 | 5160 | 67 | 30 |
| 60.0 | 6192 | 82 | 32 |
| 70.0 | 7224 | 91 | 34 |
| 80.0 | 8256 | 91 | 37 |
| 90.0 | 9288 | 81 | 39 |
| 100.0 | 10320 | 65 | 41 |

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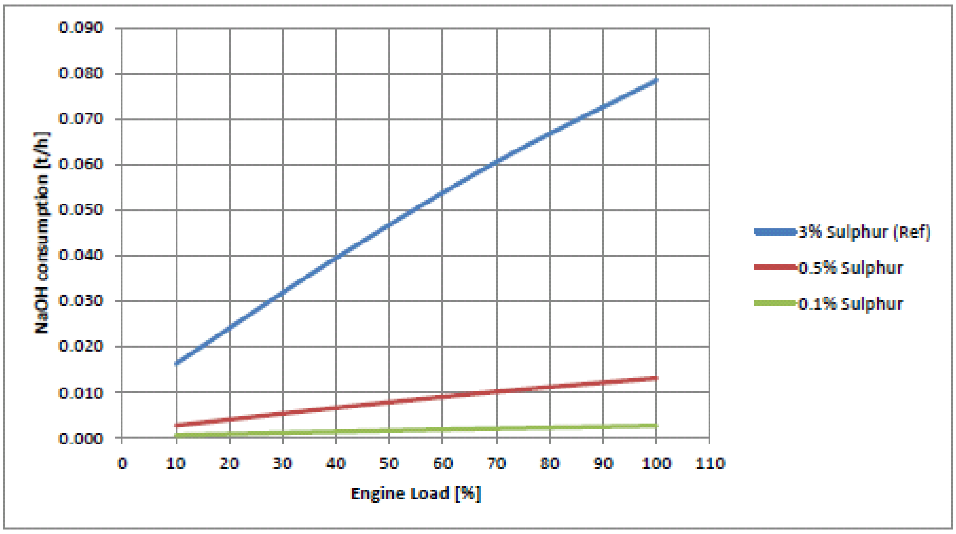
## NaOH consumption

The NaOH consumption is dependent on the Sulphur content of the fuel. The consumption shown below is valid for a 50% NaOH solution with the reference fuel Sulphur content. As a further reference the consumption for 0.1 % and 0.5 % Sulphur are also shown.

| Load<br>% | Load<br>kW | 3% Sulphur (Ref)<br>t NaOH/t fuel | 3% Sulphur (Ref)<br>t/h | 0.5% Sulphur<br>t NaOH/t fuel | 0.5% Sulphur<br>t/h | 0.1% Sulphur<br>t NaOH/t fuel | 0.1% Sulphur<br>t/h |
|---|---|---|---|---|---|---|---|
| 10.0 | 1032 | 0.15 | 0.016 | 0.025 | 0.003 | 0.005 | 0.001 |
| 20.0 | 2064 | 0.15 | 0.025 | 0.025 | 0.004 | 0.005 | 0.001 |
| 30.0 | 3096 | 0.15 | 0.036 | 0.025 | 0.006 | 0.005 | 0.001 |
| 40.0 | 4128 | 0.15 | 0.040 | 0.025 | 0.007 | 0.005 | 0.001 |
| 50.0 | 5160 | 0.15 | 0.045 | 0.025 | 0.007 | 0.005 | 0.001 |
| 60.0 | 6192 | 0.15 | 0.053 | 0.025 | 0.009 | 0.005 | 0.002 |
| 70.0 | 7224 | 0.15 | 0.061 | 0.025 | 0.010 | 0.005 | 0.002 |
| 80.0 | 8256 | 0.15 | 0.068 | 0.025 | 0.011 | 0.005 | 0.002 |
| 90.0 | 9288 | 0.15 | 0.074 | 0.025 | 0.012 | 0.005 | 0.002 |
| 100.0 | 10320 | 0.15 | 0.079 | 0.025 | 0.013 | 0.005 | 0.003 |



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MAN B&W Engines

## Water consumption

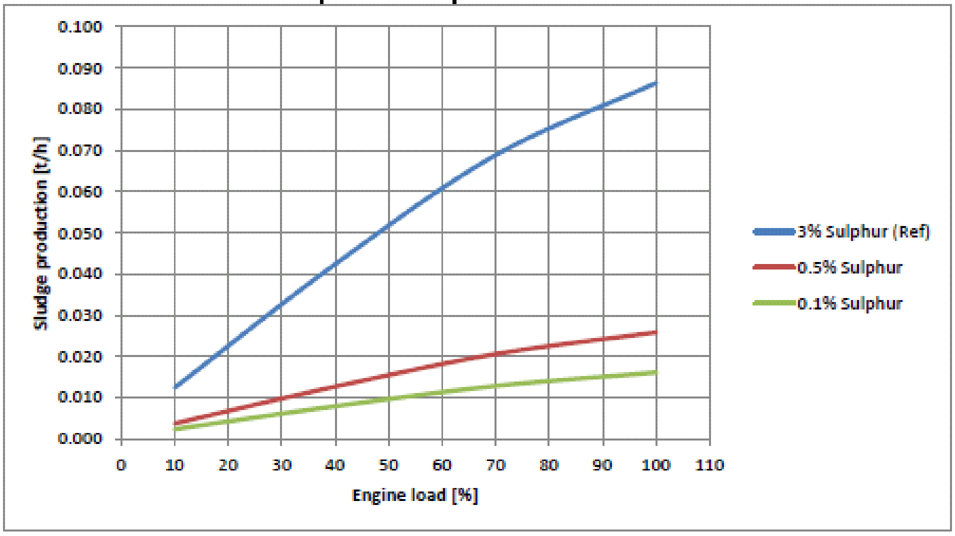
The water consumption depends on the fuel Sulphur content and the amount of water condensated in the coolers. For a more thorough explanation please refer to the Emission Project Guide for MAN B&W engines.

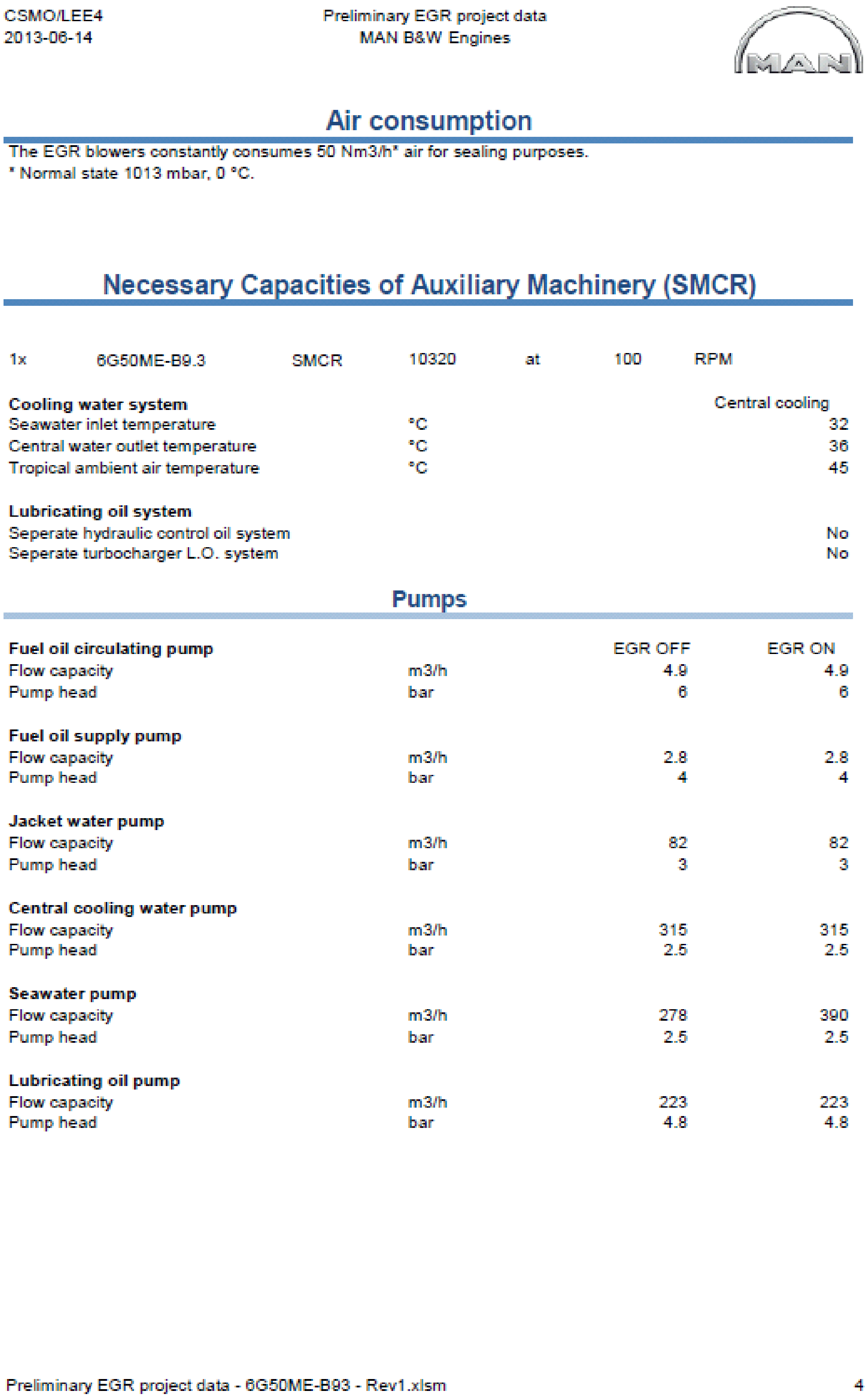
Estimated maximum freshwater consumption 104 l/h

## Sludge production

The sludge production is dependent on the Sulphur content of the fuel. The production shown below is for the reference fuel Sulphur content. As a further reference the consumption for 0.1 % and 0.5 % Sulphur are also shown. Reference sludge water content.

| Load % | Load kW | 3% Sulphur (Ref) t/h | 0.5% Sulphur t/h | 0.1% Sulphur t/h |
|---|---|---|---|---|
| 10.0 | 1032 | 0.012 | 0.004 | 0.0024 |
| 20.0 | 2064 | 0.025 | 0.008 | 0.0047 |
| 30.0 | 3096 | 0.037 | 0.011 | 0.0069 |
| 40.0 | 4128 | 0.042 | 0.013 | 0.0079 |
| 50.0 | 5160 | 0.050 | 0.015 | 0.0093 |
| 60.0 | 6192 | 0.060 | 0.018 | 0.0111 |
| 70.0 | 7224 | 0.069 | 0.021 | 0.0129 |
| 80.0 | 8256 | 0.077 | 0.023 | 0.0143 |
| 90.0 | 9288 | 0.083 | 0.025 | 0.0155 |
| 100.0 | 10320 | 0.086 | 0.026 | 0.0161 |





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Preliminary EGR project data
MAN B&W Engines

## Air consumption

The EGR blowers constantly consumes 50 Nm3/h* air for sealing purposes.
* Normal state 1013 mbar, 0 °C.

## Necessary Capacities of Auxiliary Machinery (SMCR)

1x 6G50ME-B9.3 SMCR 10320 at 100 RPM

| | | |
|---|---|---|
| **Cooling water system** | | Central cooling |
| Seawater inlet temperature | °C | 32 |
| Central water outlet temperature | °C | 36 |
| Tropical ambient air temperature | °C | 45 |
| | | |
| **Lubricating oil system** | | |
| Seperate hydraulic control oil system | | No |
| Seperate turbocharger L.O. system | | No |

### Pumps

| | | EGR OFF | EGR ON |
|---|---|---|---|
| **Fuel oil circulating pump** | | | |
| Flow capacity | m3/h | 4.9 | 4.9 |
| Pump head | bar | 6 | 6 |
| **Fuel oil supply pump** | | | |
| Flow capacity | m3/h | 2.8 | 2.8 |
| Pump head | bar | 4 | 4 |
| **Jacket water pump** | | | |
| Flow capacity | m3/h | 82 | 82 |
| Pump head | bar | 3 | 3 |
| **Central cooling water pump** | | | |
| Flow capacity | m3/h | 315 | 315 |
| Pump head | bar | 2.5 | 2.5 |
| **Seawater pump** | | | |
| Flow capacity | m3/h | 278 | 390 |
| Pump head | bar | 2.5 | 2.5 |
| **Lubricating oil pump** | | | |
| Flow capacity | m3/h | 223 | 223 |
| Pump head | bar | 4.8 | 4.8 |

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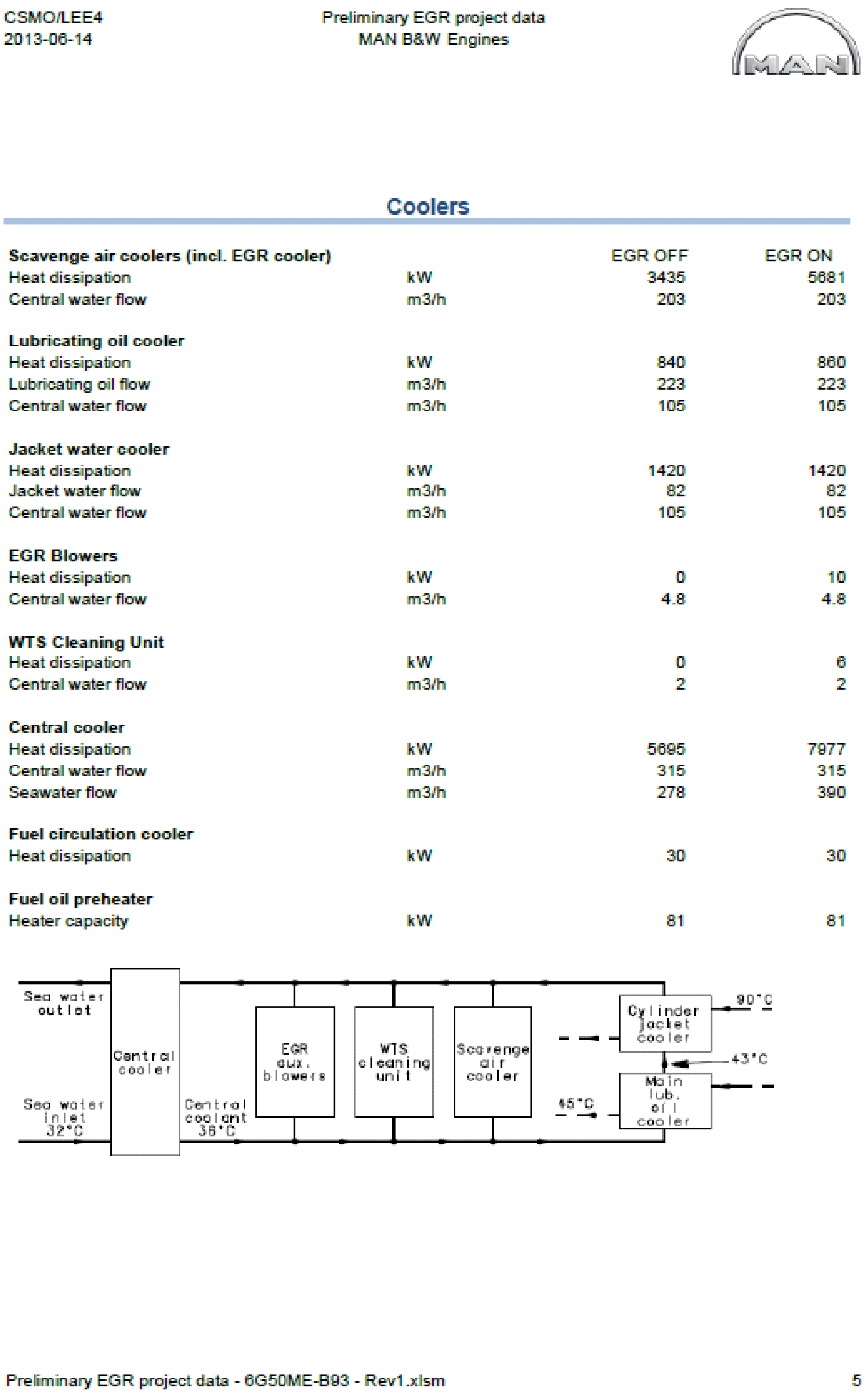

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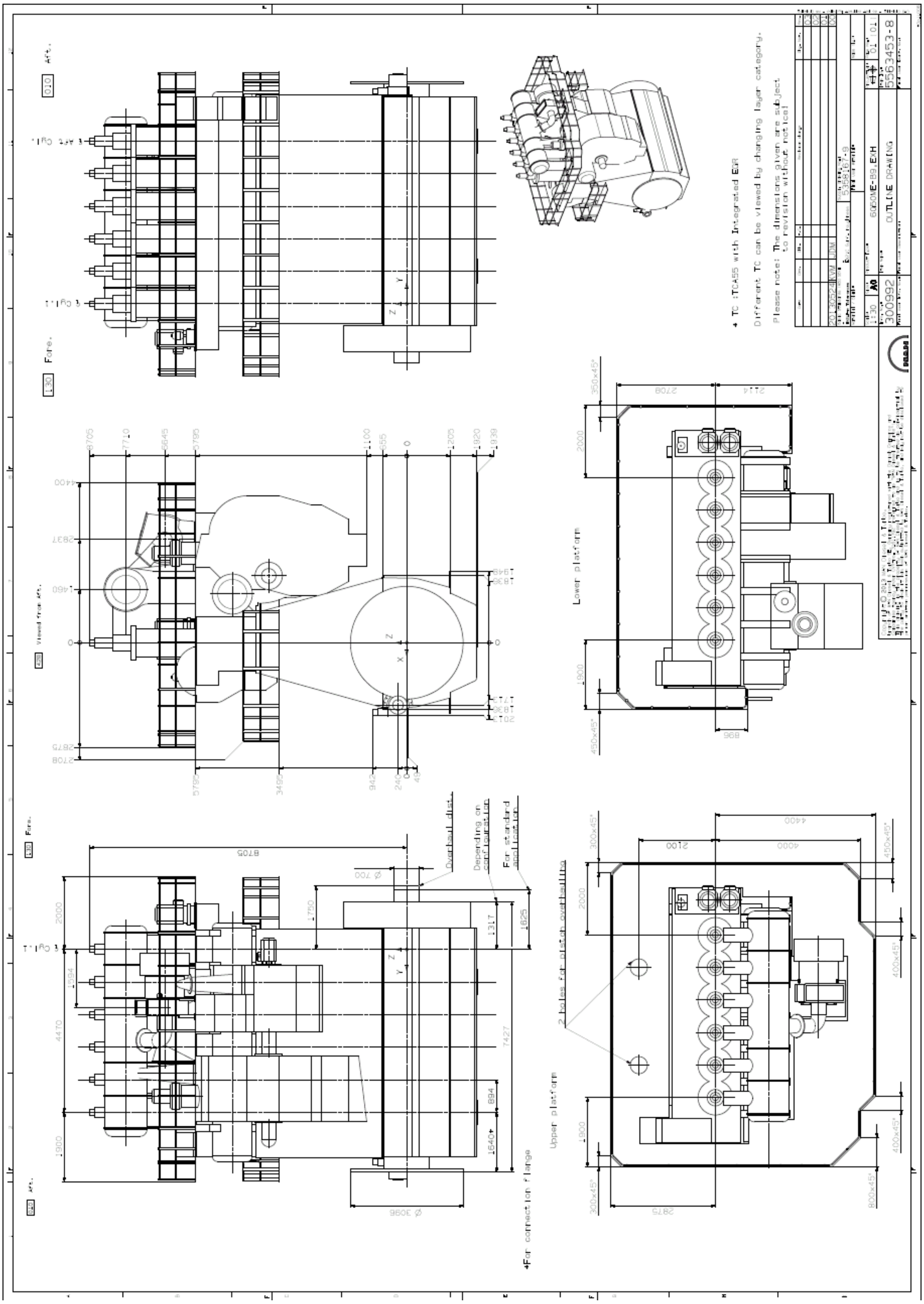
Preliminary EGR project data
MAN B&W Engines

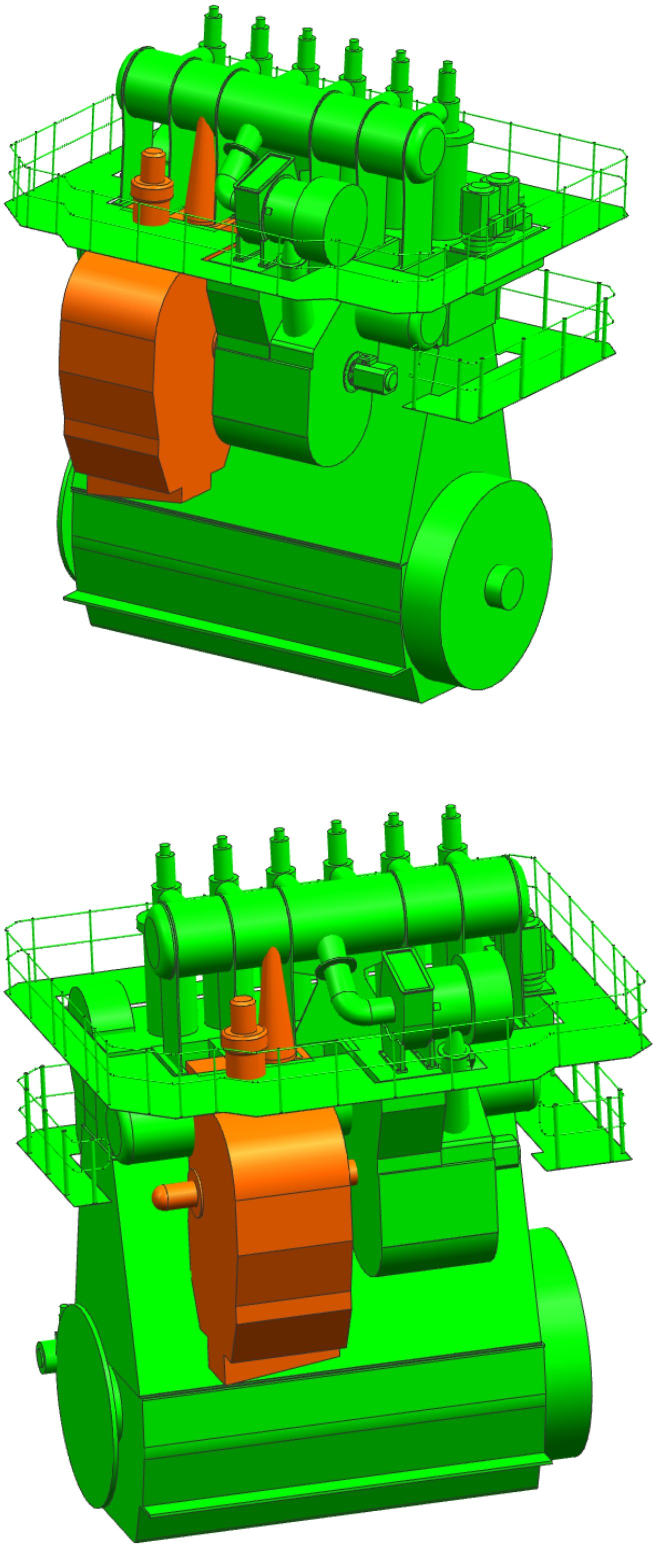
## Coolers

| **Scavenge air coolers (incl. EGR cooler)** | | EGR OFF | EGR ON |
|---|---|---|---|
| Heat dissipation | kW | 3435 | 5681 |
| Central water flow | m3/h | 203 | 203 |
| **Lubricating oil cooler** | | | |
| Heat dissipation | kW | 840 | 860 |
| Lubricating oil flow | m3/h | 223 | 223 |
| Central water flow | m3/h | 105 | 105 |
| **Jacket water cooler** | | | |
| Heat dissipation | kW | 1420 | 1420 |
| Jacket water flow | m3/h | 82 | 82 |
| Central water flow | m3/h | 105 | 105 |
| **EGR Blowers** | | | |
| Heat dissipation | kW | 0 | 10 |
| Central water flow | m3/h | 4.8 | 4.8 |
| **WTS Cleaning Unit** | | | |
| Heat dissipation | kW | 0 | 6 |
| Central water flow | m3/h | 2 | 2 |
| **Central cooler** | | | |
| Heat dissipation | kW | 5695 | 7977 |
| Central water flow | m3/h | 315 | 315 |
| Seawater flow | m3/h | 278 | 390 |
| **Fuel circulation cooler** | | | |
| Heat dissipation | kW | 30 | 30 |
| **Fuel oil preheater** | | | |
| Heater capacity | kW | 81 | 81 |

Preliminary EGR project data - 6G50ME-B93 - Rev1.xlsm 5



Outline of MAN B&W 6G50ME-B9.3 with EGR.



Design mock up of 6G50ME-B9.3. Upper: seen from starboard front – lower: seen from starboard aft.

# Appendix B.5

CSMO/LEE4
2013-06-19

Preliminary EGR project data
MAN B&W Engines

## Project information

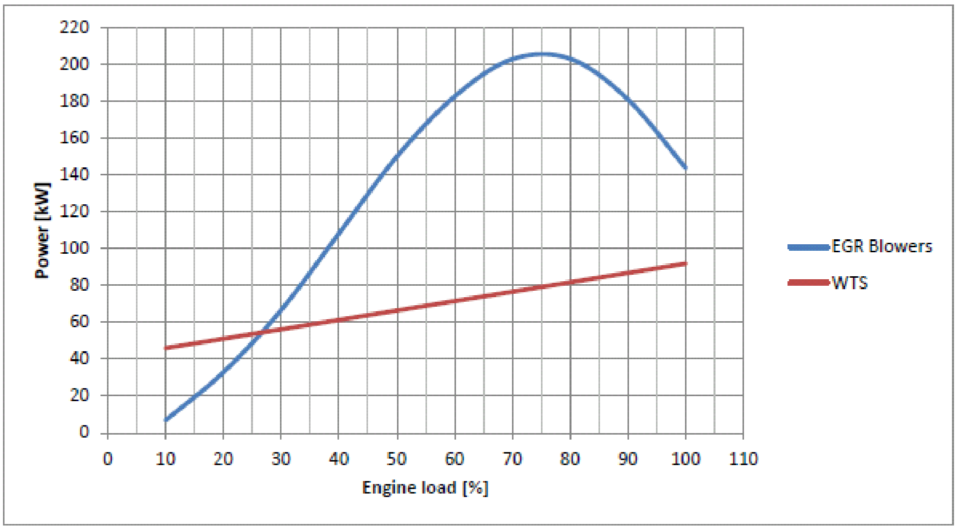
Project MST EGC+EGR combi - Large Bore Engine example
Engine 1 x 6S80ME-C9.4
SMCR 1x 23000 kW at 73.9 RPM
SMCR Total 23000 kW at 73.9 RPM
Reference fuel sulphur content 3 %
EGR blowers per engine 2 pcs
Reference EGR sludge water conter 93 %

It should be kept in mind that any use of high-sulphur fuel (>0.1% S) would normally also require a Sox scrubber system due to the ECA rules.

## Electric consumption

The two main electrical consumers of the EGR installation is the EGR blowers and the water treatment system (WTS). The numbers given below are typical electrical consumption for Tier 3 operation.

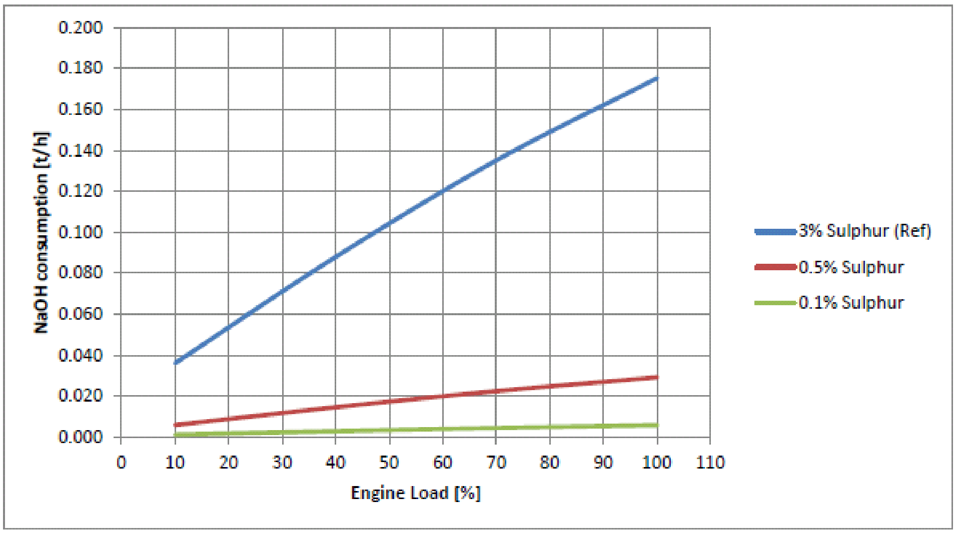
| Load | Load | EGR Blowers | WTS |
|---|---|---|---|
| % | kW | kW | kW |
| 10.0 | 2300 | 7 | 46 |
| 20.0 | 4600 | 33 | 51 |
| 30.0 | 6900 | 67 | 56 |
| 40.0 | 9200 | 108 | 61 |
| 50.0 | 11500 | 150 | 66 |
| 60.0 | 13800 | 183 | 72 |
| 70.0 | 16100 | 203 | 77 |
| 80.0 | 18400 | 203 | 82 |
| 90.0 | 20700 | 181 | 87 |
| 100.0 | 23000 | 144 | 92 |



# NaOH consumption

The NaOH consumption is dependent on the Sulphur content of the fuel. The consumption shown below is valid for a 50% NaOH solution with the reference fuel Sulphur content. As a further reference the consumption for 0.1 % and 0.5 % Sulphur are also shown.

| Load | Load | 3% Sulphur (Ref) | 3% Sulphur (Ref) | 0.5% Sulphur | 0.5% Sulphur | 0.1% Sulphur | 0.1% Sulphur |
|---|---|---|---|---|---|---|---|
| % | kW | t NaOH/t fuel | t/h | t NaOH/t fuel | t/h | t NaOH/t fuel | t/h |
| 10.0 | 2300 | 0.15 | 0.036 | 0.025 | 0.006 | 0.005 | 0.001 |
| 20.0 | 4600 | 0.15 | 0.056 | 0.025 | 0.009 | 0.005 | 0.002 |
| 30.0 | 6900 | 0.15 | 0.079 | 0.025 | 0.013 | 0.005 | 0.003 |
| 40.0 | 9200 | 0.15 | 0.088 | 0.025 | 0.015 | 0.005 | 0.003 |
| 50.0 | 11500 | 0.15 | 0.100 | 0.025 | 0.017 | 0.005 | 0.003 |
| 60.0 | 13800 | 0.15 | 0.118 | 0.025 | 0.020 | 0.005 | 0.004 |
| 70.0 | 16100 | 0.15 | 0.135 | 0.025 | 0.023 | 0.005 | 0.005 |
| 80.0 | 18400 | 0.15 | 0.151 | 0.025 | 0.025 | 0.005 | 0.005 |
| 90.0 | 20700 | 0.15 | 0.165 | 0.025 | 0.027 | 0.005 | 0.005 |
| 100.0 | 23000 | 0.15 | 0.175 | 0.025 | 0.029 | 0.005 | 0.006 |



## Water consumption

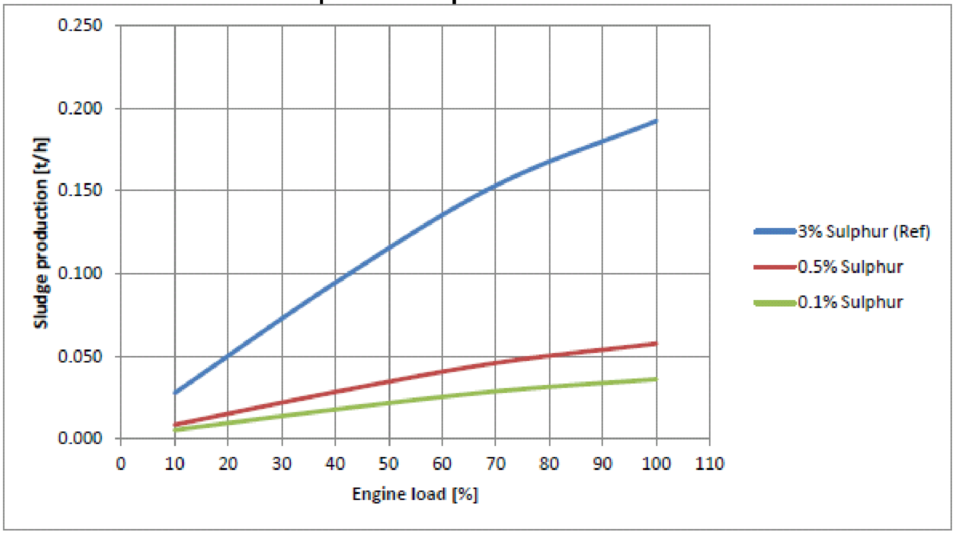
The water consumption depends on the fuel Sulphur content and the amount of water condensated in the coolers. For a more thorough explanation please refer to the Emission Project Guide for MAN B&W engines.

| | |
|---|---|
| Estimated maximum freshwater consumption | 231 l/h |

## Sludge production

The sludge production is dependent on the Sulphur content of the fuel. The production shown below is for the reference fuel Sulphur content. As a further reference the consumption for 0.1 % and 0.5 % Sulphur are also shown. Reference sludge water content.

| Load % | Load kW | 3% Sulphur (Ref) t/h | 0.5% Sulphur t/h | 0.1% Sulphur t/h |
|---|---|---|---|---|
| 10.0 | 2300 | 0.028 | 0.008 | 0.0053 |
| 20.0 | 4600 | 0.056 | 0.017 | 0.0106 |
| 30.0 | 6900 | 0.082 | 0.025 | 0.0154 |
| 40.0 | 9200 | 0.095 | 0.028 | 0.0177 |
| 50.0 | 11500 | 0.110 | 0.033 | 0.0206 |
| 60.0 | 13800 | 0.133 | 0.040 | 0.0248 |
| 70.0 | 16100 | 0.153 | 0.046 | 0.0286 |
| 80.0 | 18400 | 0.171 | 0.051 | 0.0320 |
| 90.0 | 20700 | 0.185 | 0.055 | 0.0345 |
| 100.0 | 23000 | 0.192 | 0.058 | 0.0360 |



## Air consumption

The EGR blowers constantly consumes 50 Nm3/h* air for sealing purposes.
* Normal state 1013 mbar, 0 °C.

## Necessary Capacities of Auxiliary Machinery (SMCR)

| | | | | | | |
|---|---|---|---|---|---|---|
| 1x | 6S80ME-C9.4 | SMCR | 23000 | at | 73.9 | RPM |

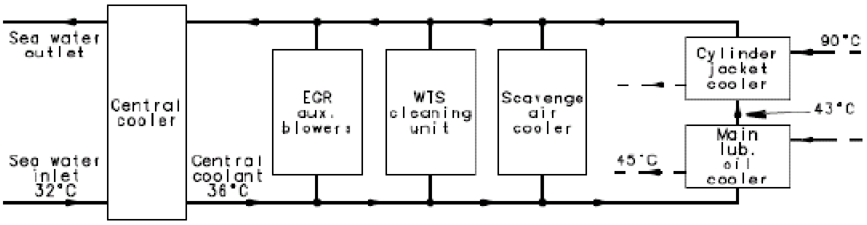
| | | |
|---|---|---|
| **Cooling water system** | | Central cooling |
| Seawater inlet temperature | °C | 32 |
| Central water outlet temperature | °C | 36 |
| Tropical ambient air temperature | °C | 45 |
| | | |
| **Lubricating oil system** | | |
| Seperate hydraulic control oil system | | No |
| Seperate turbocharger L.O. system | | No |

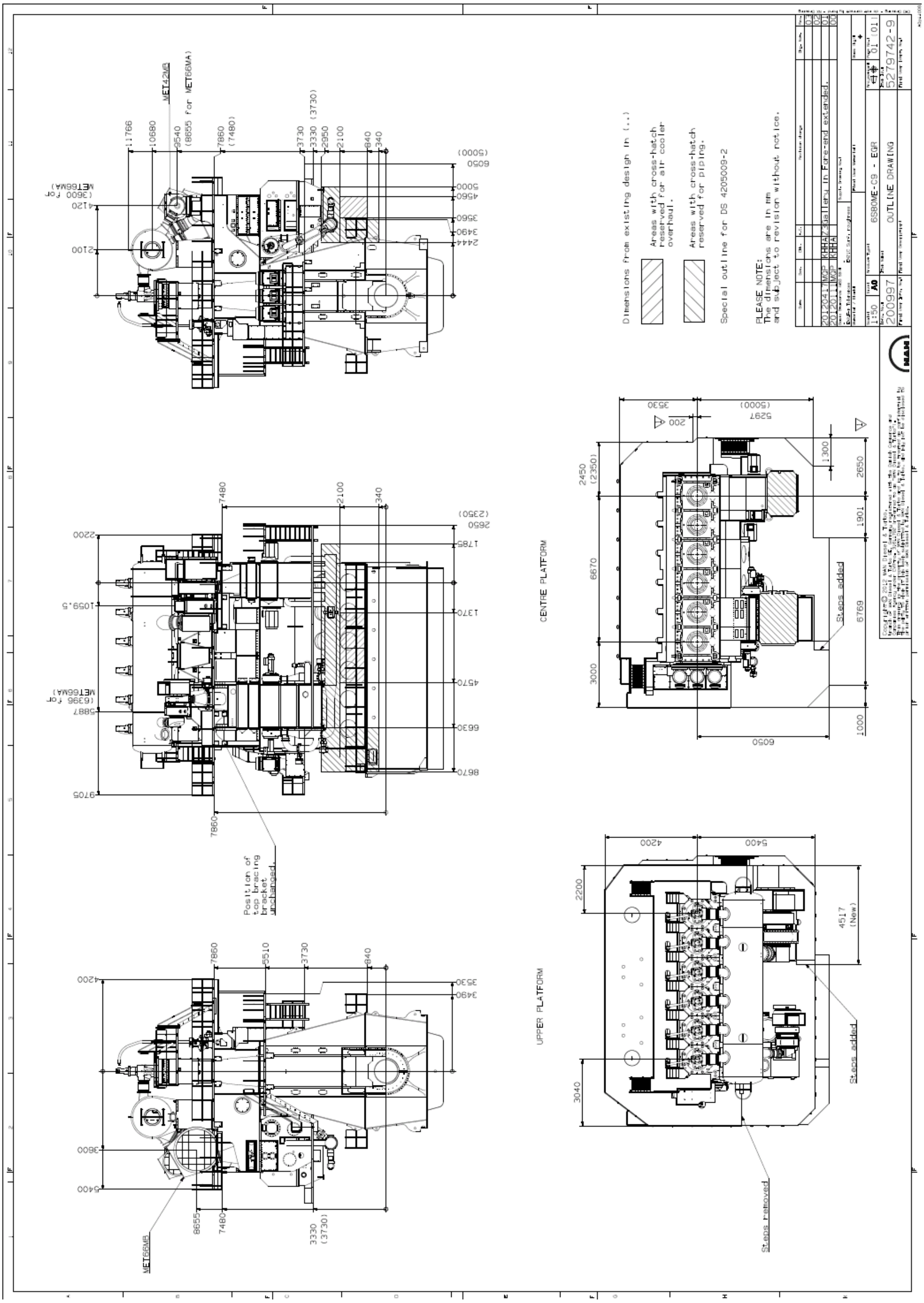
### Pumps

| | | | |
|---|---|---|---|
| **Fuel oil circulating pump** | | EGR OFF | EGR ON |
| Flow capacity | m3/h | 12.4 | 12.4 |
| Pump head | bar | 6 | 6 |
| | | | |
| **Fuel oil supply pump** | | | |
| Flow capacity | m3/h | 6 | 6 |
| Pump head | bar | 4 | 4 |
| | | | |
| **Jacket water pump** | | | |
| Flow capacity | m3/h | 207 | 207 |
| Pump head | bar | 3 | 3 |
| | | | |
| **Central cooling water pump** | | | |
| Flow capacity | m3/h | 734 | 734 |
| Pump head | bar | 2.5 | 2.5 |
| | | | |
| **Seawater pump** | | | |
| Flow capacity | m3/h | 742 | 912 |
| Pump head | bar | 2.5 | 2.5 |
| | | | |
| **Lubricating oil pump** | | | |
| Flow capacity | m3/h | 533 | 533 |
| Pump head | bar | 4.8 | 4.8 |

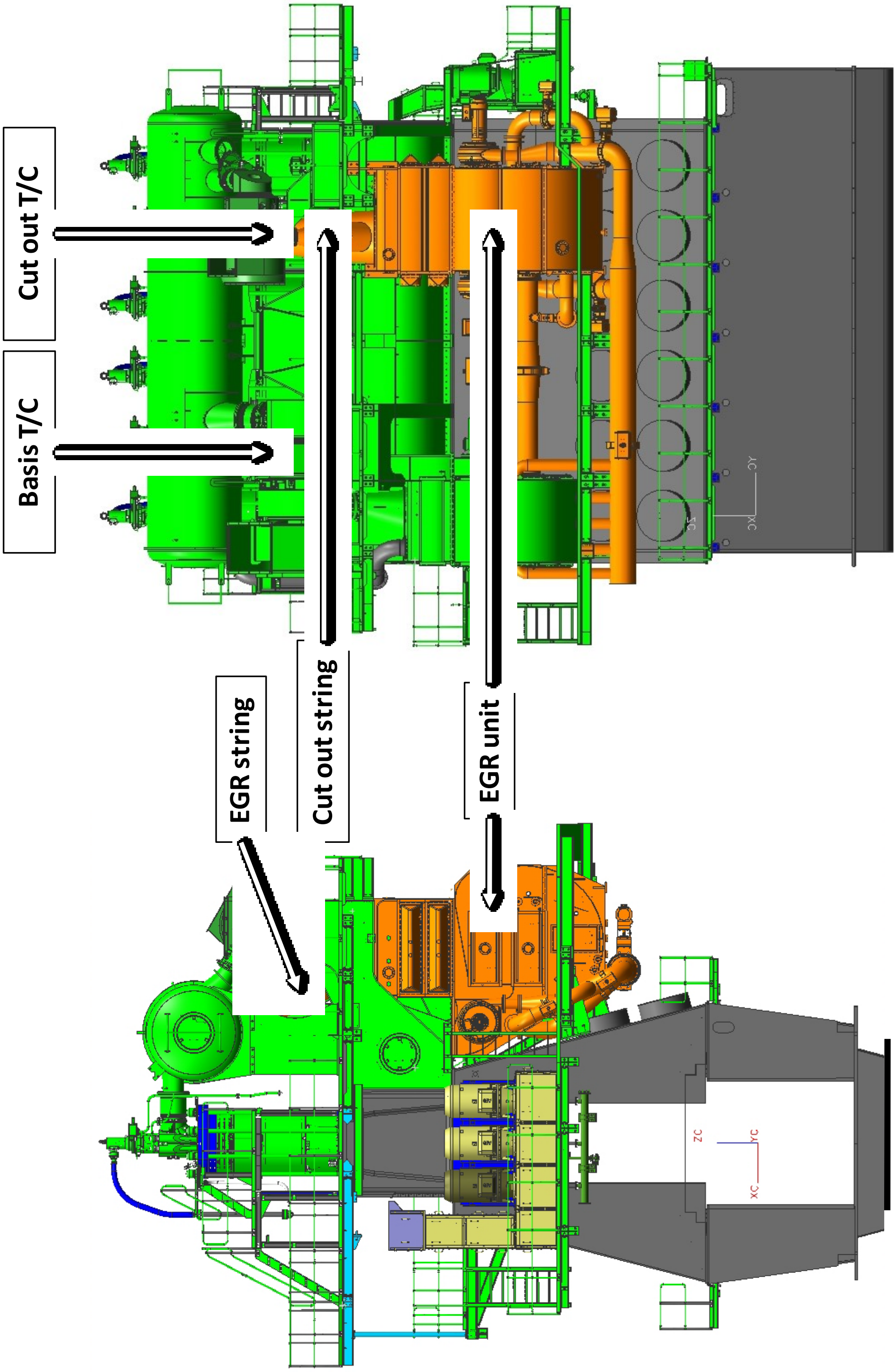
## Coolers

| **Scavenge air coolers (incl. EGR cooler)** | | EGR OFF | EGR ON |
|---|---|---|---|
| Heat dissipation | kW | 10012 | 13461 |
| Central water flow | m3/h | 480 | 480 |
| **Lubricating oil cooler** | | | |
| Heat dissipation | kW | 2000 | 2020 |
| Lubricating oil flow | m3/h | 533 | 533 |
| Central water flow | m3/h | 247 | 247 |
| **Jacket water cooler** | | | |
| Heat dissipation | kW | 3170 | 3170 |
| Jacket water flow | m3/h | 207 | 207 |
| Central water flow | m3/h | 247 | 247 |
| **EGR Blowers** | | | |
| Heat dissipation | kW | 0 | 10 |
| Central water flow | m3/h | 4.8 | 4.8 |
| **WTS Cleaning Unit** | | | |
| Heat dissipation | kW | 0 | 6 |
| Central water flow | m3/h | 2 | 2 |
| **Central cooler** | | | |
| Heat dissipation | kW | 15182 | 18667 |
| Central water flow | m3/h | 734 | 734 |
| Seawater flow | m3/h | 742 | 912 |
| **Fuel circulation cooler** | | | |
| Heat dissipation | kW | 73 | 73 |
| **Fuel oil preheater** | | | |
| Heater capacity | kW | 181 | 181 |





Outline of MAN B&W 6S80ME-C9.2 (values shown in brackets are values for a standard engine).



3D model of MAN B&W 6S80ME-C9.2 with EGR seen from starboard and aft. The main EGR components are marked.

# Appendix C.1

Alfa Laval Aalborg (ALA) and MAN Diesel & Turbo (MDT) have developed a calculation program for a combined EGR and EGC scrubber system. The program is designed for a sailing profile of 100 points and is able to calculate the increase in $CO_2$ emission and the reduction in the emissions of $SO_X$, $NO_X$ and particulates.

The program is "only" made in Excel and this limits the complexity – a "real" program ought to be made based on this "prototype".

As the program contains specific data for ALA and MDT products it cannot be used for other manufactures and this description does not show all details.

The main inputs are:

- System specific information as fuel consumption, EGR rates and additional fuel consumption due to EGR for 9 pre chosen engine loads.
- Fuel sulphur and ash content
- Sulphur and PM removal efficiencies in SECA and in non SECA
- Molar ratio between NaOH and fuel sulphur
- Bleed-off centrifuge capacity
- Water content in the sludge
- Water flow using SW and FW
- Pumping height (incl. nozzles, loss etc.)
-

For each of the 100 points the following is needed:

- Operating time in hours
- Engine load
- In SECA and/or in NECA
- FW or SW to the EGC scrubber
- Relative humidity, sea water and air temperature

The main results are:

1. Consumption of NaOH
2. Needed water supply
3. Energy consumption to water treatment and water pumping.
4. Calculations of need of water bleed-off relative to the centrifuge capacity.
5. Changes of emissions are estimated for $CO_2$, $NO_X$, $SO_X$ and PM.

Calculation procedure.
For each of the 100 steps the inputs for SW temperature, humidity, engine load etc are given and the total fuel consumption, FW or SW flow and need for water supply etc. are calculated. At the end max and sum results are found. Short explanations – with no. reference to the above is given below.

1. The NaOH consumption depends on the fuel consumption and the fuel sulphur content.
2. The needed water supply take the air humidity, the water trapped in the charge air cooler, the water from the added NaOH, the combustion of the fuel (the H/C ratio), discharge as clean water and the water part of the sludge into account.
3. The energy required for pumping of the water is calculated – taking the level above seawater into account.

4. A limit value for the salt concentration is stated – if the bleed-off centrifuge is unable to clean the discharge water flow the surplus is passed on to a *fictive* water tank.
5. The emission calculation includes all energy used on board and energy used for production of NaOH.

# Appendix C.2

The page below shows a printout from the program.

The load profile – see figure C.1 - starts with 20 hours in the harbour. Only the auxiliary (the generators) are running. Then a long sailing period before it reaches a harbour. The load profile is not realistic nowadays as many ships are slow steaming, but it is close to IMO's load profile for emission measurements – see more later.

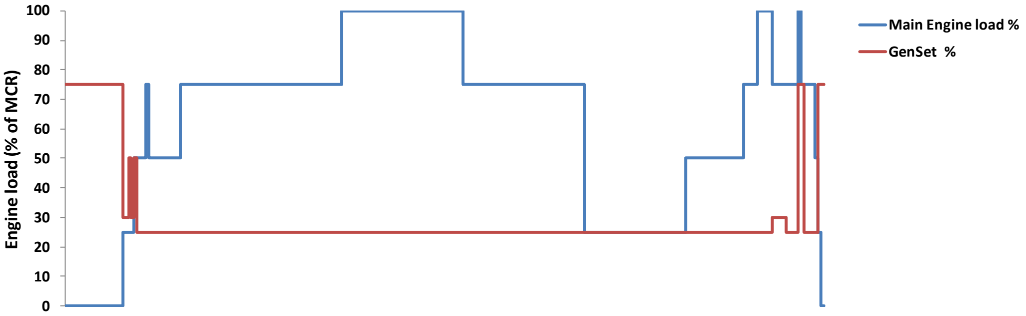


Figure C.1: Engine load profile.

Figure C.2 show the profile for allowed emissions and demand for recirculation of water. This profile is designed in order to be in SECA and NECA 20% of the time. Recirculation is chosen close to the coast.

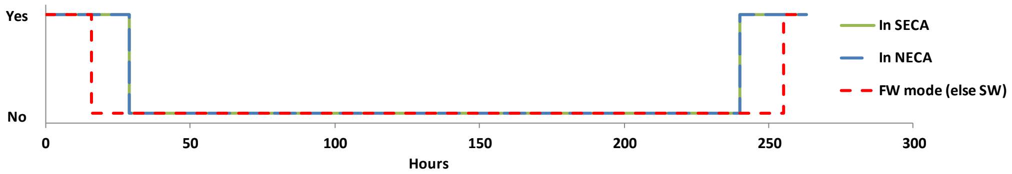


Figure C.2: Emission profile.

The load profile is designed to be close to an IMO load profile both in the SECA/NECA and outside – this can be seen in the below printout.

The basis for the calculation is the situation in 2020 that is Tier III in NECA and max 0.1% sulphur in the fuel in SECA and 0.5% outside SECA. In the below the main engine use a fuel containing 3.5% sulphur.

Some results of the calculation can be seen in Figure C.3 and C.4. Figure C.3 shows the NaOH consumption and the production of sludge.

Figure C.3: Result of the calculation – NaOH consumption and sludge production.

Note that as the sludge water content is uncertain, it is difficult to make a good estimate of the “wet sludge”. The calculation is carried out as an estimate of the trapped “dry sludge”. To this the water is “added” in order to obtain the correct water concentration; but a little uncertainty in the calculation of the dry sludge result in a significant error in the wet sludge calculation.

Figure C.4 show the flow to the dirty water tank.The bleed off centrifuge is chosen to handle 2 $m^3/h$ - this is not enough in all conditions and the bleed off flow exceeding this value must be stored in a tank for treatment in the centrifuge later on. The reason for a high starting value is to start where it ends after the trip.

Figure C.4: Results: flow to dirty water tank and accumulated water.

The centrifuge should have had a capacity of 3.1 $m^3/h$ in order to handle the bleed off flow at all times. Now a tank volume of 8 $m^3$ and a centrifuge with a capacity of 2 $m^3/h$ is able to do the same. Other combinations are possible - what is chosen depends on installation costs and available space.

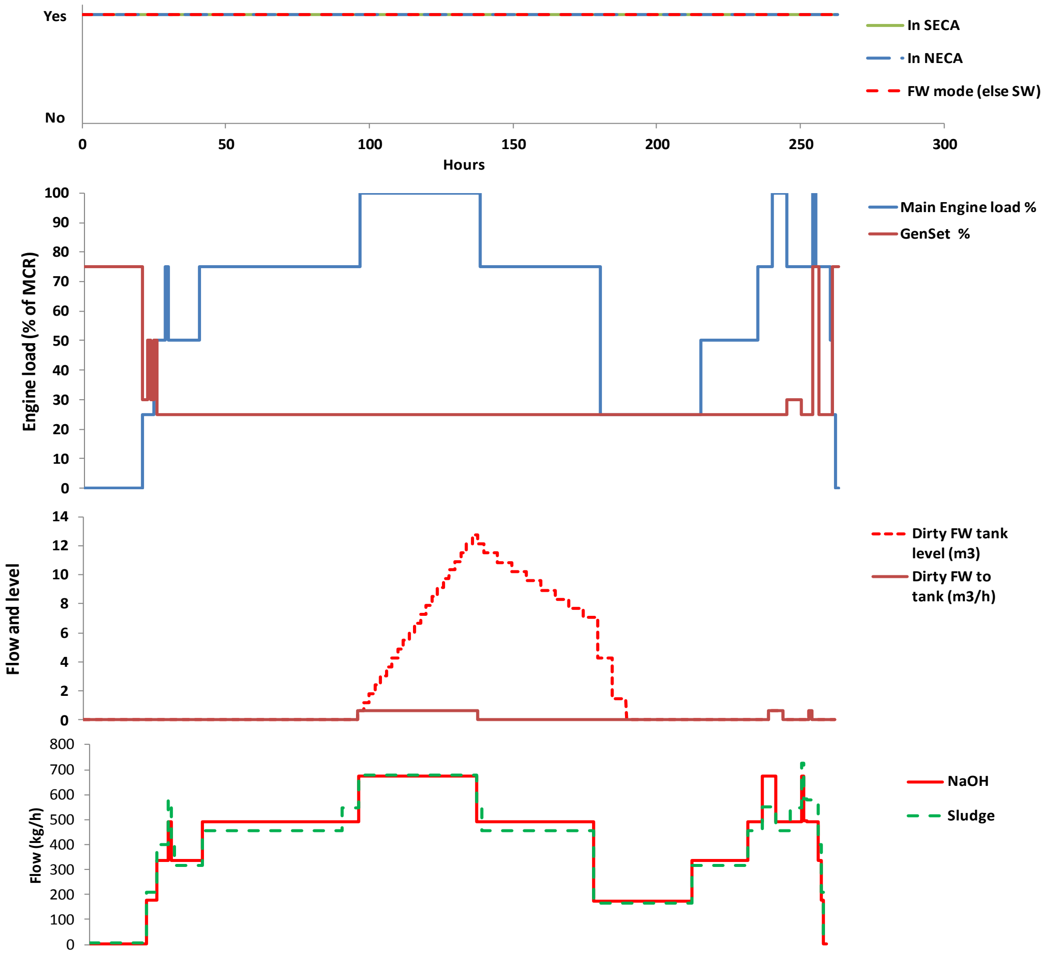
The program estimates a lot of other results – a few are highlighted here and the rest can be seen below:

- the $SO_X$ emission is reduced by 82%
- $NO_X$ is reduced by 10.7%
- $CO_2$ is increased by 1.16% - 0.8% is due to increased fuel consumption – the rest is due to production of NaOH.

Alternatively, if low sulphur fuel is used the desulphurisation of the fuel at the refinery is expected to result in a $CO_2$ increase of around 14% (Ref. 1,2). This value is not shown in the printout as the additional energy consumption most probably depends on the refinery technology and the base crude oil.

Example of results:

| Calculation of a combined EGR and EGS system | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | Percent of main engine running time: | | | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 100.0 | 10% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| Relative period in Non SECA: | 0.0 | 25% | 16.5 | #DIV/0! | 16.5 | #DIV/0! | 16.5 | #DIV/0! | |
| Relative period in NECA: | 100.0 | 30% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| Relative period in Non NECA: | 0.0 | 40% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| Relative period "no water outlet": | 0.0 | 50% | 14.9 | #DIV/0! | 14.9 | #DIV/0! | 14.9 | #DIV/0! | |
| EGC needs FW | 100.0 | 60% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| EGC uses SW | 0.0 | 75% | 48.8 | #DIV/0! | 48.8 | #DIV/0! | 48.8 | #DIV/0! | |
| | | 100% | 19.8 | #DIV/0! | 19.8 | #DIV/0! | 19.8 | #DIV/0! | |
| | | | | | | | | | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 0 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 4 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | | | | | | | | | |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 5 | m | 5 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| | | | | | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| | | | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 744.7 | t /trip | 16990 | t/year | Add due to EGR+EGS: | | | 16.3 | t/trip |
| AE - fuel consumption: | 54.4 | t /trip | 1240 | t/year | Add due to EGR+EGS: | | | 6.7 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 3.0 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 109.6 | t /trip | 2501.1 | t/year | | | | | |
| | | | | | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 355.0 | m3/trip | 1.3 | m3/h in average; but with a max consumption of: | | | | 2.2 | m3/h |
| Dirty water FW tank min: | 12.8 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| | | | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 106.5 | t /trip | 2430 | t/year | | | | | |
| Sludge max production | 726.1 | kg/h | | | | | | | |
| | | | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 179.5 | m3 | | | Tank volume (incl. 20% safty): | | | 220 | m3 |
| Sludge min | 221.9 | m3 | | | | | | 270 | m3 |
| | | | | | | | | | |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 72.7 | t /trip | 1658 | t/year | | | | | |
| CO2 due to NaOH | 120.6 | t /trip | 2751.2 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 193.3 | t /trip | 4409.3 | t /year | This equals a CO2 increase of | | | 8.05 | % |
| SOx reduction: | 98.0 | % | | | | | | | |
| NOx reduction: | 76.4 | % | | | | | | | |
| Reduction of particulates (PM): | 81 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 587 | t /trip | | | corresponding to an increase i CO2 of | | | 24.4 | %) |


Yes
No
0
50
100
150
200
250
300
Hours
In SECA
In NECA
FW mode (else SW)
Engine load (% of MCR)
100
90
80
70
60
50
40
30
20
10
0
Main Engine load %
GenSet %
Flow and level
14
12
10
8
6
4
2
0
Dirty FW tank level (m3)
Dirty FW to tank (m3/h)
Flow (kg/h)
800
700
600
500
400
300
200
100
0
NaOH
Sludge

# Appendix C.3

The process calculation program has been used for the different parameter variation used in the report.

The reduction of sulphur in the fuel and the production of NaOH are energy consuming, both are estimated and included in the calculations. It has been difficult to find good references on the subjects - especially the added power consumption at the refineries are difficult to estimate probably because it will depend on the crude oil quality, refinery type and other products produced on the refinery. A more thorough investigation is requested but is outside the scope of this project.

The assumptions for calculations A, B and C are: the described load profile - the EGR system is excluded from the calculation because it is always operated on FW due to mentioned corrosion issues.

| **Calculation of a combined EGR and EGS system** | | | | | | | | | Case A |
|---|---|---|---|---|---|---|---|---|---|
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | Percent of main engine running time: | | | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 100.0 | 10% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| Relative period in Non SECA: | 0.0 | 25% | 16.5 | #DIV/0! | 16.5 | #DIV/0! | 16.5 | #DIV/0! | |
| Relative period in NECA: | 100.0 | 30% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| Relative period in Non NECA: | 0.0 | 40% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| Relative period "no water outlet": | 0.0 | 50% | 14.9 | #DIV/0! | 14.9 | #DIV/0! | 14.9 | #DIV/0! | |
| EGC needs FW | 100.0 | 60% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| EGC uses SW | 0.0 | 75% | 48.8 | #DIV/0! | 48.8 | #DIV/0! | 48.8 | #DIV/0! | |
| | | 100% | 19.8 | #DIV/0! | 19.8 | #DIV/0! | 19.8 | #DIV/0! | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 0 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 4 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 5 | m | 5 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 744.7 | t /trip | 16990 | t/year | Add due to EGR+EGS: | | | 16.3 | t/trip |
| AE - fuel consumption: | 54.4 | t /trip | 1240 | t/year | Add due to EGR+EGS: | | | 6.7 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 3.0 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 109.6 | t /trip | 2501.1 | t/year | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 355.0 | m3/trip | 1.3 | m3/h in average; but with a max consumption of: | | | | 2.2 | m3/h |
| Dirty water FW tank min: | 12.8 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 106.5 | t /trip | 2430 | t/year | | | | | |
| Sludge max production | 726.1 | kg/h | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 179.5 | m3 | | | Tank volume (incl. 20% safty): | | | 220 | m3 |
| Sludge min | 221.9 | m3 | | | | | | 270 | m3 |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 72.7 | t /trip | 1658 | t/year | | | | | |
| CO2 due to NaOH | 120.6 | t /trip | 2751.2 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 193.3 | t /trip | 4409.3 | t /year | This equals a CO2 increase of | | | 8.05 | % |
| SOx reduction: | 98.0 | % | | | | | | | |
| NOx reduction: | 76.4 | % | | | | | | | |
| Reduction of particulates (PM): | 81 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 587 | t /trip | | | corresponding to an increase i CO2 of | | | 24.4 | %) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Calculation of a combined EGR and EGS system** | | | | | | | | | Case B |
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | Percent of main engine running time: | | | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 100.0 | 10% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | #DIV/0! | 0.0 | |
| Relative period in Non SECA: | 0.0 | 25% | 16.5 | #DIV/0! | 16.5 | #DIV/0! | #DIV/0! | 16.5 | |
| Relative period in NECA: | 100.0 | 30% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | #DIV/0! | 0.0 | |
| Relative period in Non NECA: | 0.0 | 40% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | #DIV/0! | 0.0 | |
| Relative period "no water outlet": | 0.0 | 50% | 14.9 | #DIV/0! | 14.9 | #DIV/0! | #DIV/0! | 14.9 | |
| EGC needs FW | 0.0 | 60% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | #DIV/0! | 0.0 | |
| EGC uses SW | 100.0 | 75% | 48.8 | #DIV/0! | 48.8 | #DIV/0! | #DIV/0! | 48.8 | |
| | | 100% | 19.8 | #DIV/0! | 19.8 | #DIV/0! | #DIV/0! | 19.8 | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 0 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 2 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 5 | m | 5 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 744.7 | t /trip | 16990 | t/year | Add due to EGR+EGS: | | | 16.3 | t/trip |
| AE - fuel consumption: | 52.5 | t /trip | 1197 | t/year | Add due to EGR+EGS: | | | 4.8 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 2.8 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 38.8 | t /trip | 884.4 | t/year | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 110.7 | m3/trip | 0.4 | m3/h in average; but with a max consumption of: | | | | 0.6 | m3/h |
| Dirty water FW tank min: | 0.0 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 45.2 | t /trip | 1030 | t/year | | | | | |
| Sludge max production | 235.9 | kg/h | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 63.5 | m3 | | | Tank volume (incl. 20% safty): | | | 80 | m3 |
| Sludge min | 94.1 | m3 | | | | | | 115 | m3 |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 66.6 | t /trip | 1520 | t/year | | | | | |
| CO2 due to NaOH | 42.6 | t /trip | 972.9 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 109.3 | t /trip | 2493.3 | t /year | This equals a CO2 increase of | | | 4.55 | % |
| SOx reduction: | 98.0 | % | | | | | | | |
| NOx reduction: | 76.4 | % | | | | | | | |
| Reduction of particulates (PM): | 81 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 587 | t /trip | | | corresponding to an increase i CO2 of | | | 24.4 | %) |

| Calculation of a combined EGR and EGS system | | | | | | | | | Case C |
|---|---|---|---|---|---|---|---|---|---|
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | Percent of main engine running time: | | | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 100.0 | 10% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | 0.0 | |
| Relative period in Non SECA: | 0.0 | 25% | 16.5 | #DIV/0! | 16.5 | #DIV/0! | 45.5 | 15.2 | |
| Relative period in NECA: | 100.0 | 30% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | 0.0 | |
| Relative period in Non NECA: | 0.0 | 40% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | 0.0 | |
| Relative period "no water outlet": | 0.0 | 50% | 14.9 | #DIV/0! | 14.9 | #DIV/0! | 9.1 | 15.2 | |
| EGC needs FW | 12.2 | 60% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | 0.0 | |
| EGC uses SW | 87.8 | 75% | 48.8 | #DIV/0! | 48.8 | #DIV/0! | 45.5 | 48.9 | |
| | | 100% | 19.8 | #DIV/0! | 19.8 | #DIV/0! | 0.0 | 20.8 | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 4.3 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 2 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 5 | m | 5 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 744.7 | t /trip | 16990 | t/year | Add due to EGR+EGS: | | | 16.3 | t/trip |
| AE - fuel consumption: | 53.3 | t /trip | 1216 | t/year | Add due to EGR+EGS: | | | 5.6 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 2.9 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 41.1 | t /trip | 936.8 | t/year | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 117.2 | m3/trip | 0.4 | m3/h in average; but with a max consumption of: | | | | 1.7 | m3/h |
| Dirty water FW tank min: | 7.1 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 48.0 | t /trip | 1096 | t/year | | | | | |
| Sludge max production | 583.2 | kg/h | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 67.2 | m3 | | | Tank volume (incl. 20% safty): | | | 85 | m3 |
| Sludge min | 100.1 | m3 | | | | | | 125 | m3 |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 69.3 | t /trip | 1580 | t/year | | | | | |
| CO2 due to NaOH | 45.2 | t /trip | 1030.4 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 114.4 | t /trip | 2610.4 | t /year | This equals a CO2 increase of | | | 4.77 | % |
| SOx reduction: | 98.0 | % | | | | | | | |
| NOx reduction: | 76.4 | % | | | | | | | |
| Reduction of particulates (PM): | 81 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 587 | t /trip | | | corresponding to an increase i CO2 of | | | 24.4 | %) |

| Calculation of a combined EGR and EGS system | | | | | | | | | Case 1 |
|---|---|---|---|---|---|---|---|---|---|
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | | | Percent of main engine running time: | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 19.8 | 10% | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Relative period in Non SECA: | 80.2 | 25% | 16.1 | 16.6 | 16.1 | 16.6 | 45.5 | 15.2 | |
| Relative period in NECA: | 19.8 | 30% | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Relative period in Non NECA: | 80.2 | 40% | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| Relative period "no water outlet": | 0.0 | 50% | 16.1 | 14.7 | 16.1 | 14.7 | 9.1 | 15.2 | |
| EGC needs FW | 12.2 | 60% | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | |
| EGC uses SW | 87.8 | 75% | 48.4 | 48.8 | 48.4 | 48.8 | 45.5 | 48.9 | |
| | | 100% | 19.4 | 19.9 | 19.4 | 19.9 | 0.0 | 20.8 | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 4.3 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 2 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 5 | m | 5 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 731.7 | t /trip | 16692 | t/year | Add due to EGR+EGS: | | | 3.2 | t/trip |
| AE - fuel consumption: | 37.5 | t /trip | 856 | t/year | Add due to EGR+EGS: | | | 3.0 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 0.8 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 7.3 | t /trip | 165.4 | t/year | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 20.6 | m3/trip | 0.1 | m3/h in average; but with a max consumption of: | | | | 1.7 | m3/h |
| Dirty water FW tank min: | 7.1 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 8.6 | t /trip | 195 | t/year | | | | | |
| Sludge max production | 583.2 | kg/h | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 11.9 | m3 | | | Tank volume (incl. 20% safty): | | | 15 | m3 |
| Sludge min | 17.8 | m3 | | | | | | 25 | m3 |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 19.4 | t /trip | 444 | t/year | | | | | |
| CO2 due to NaOH | 8.0 | t /trip | 182.0 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 27.4 | t /trip | 625.5 | t /year | This equals a CO2 increase of | | | 1.14 | % |
| SOx reduction: | 82.3 | % | | | | | | | |
| NOx reduction: | 10.1 | % | | | | | | | |
| Reduction of particulates (PM): | 71 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 339 | t /trip | | | corresponding to an increase i CO2 of | | | 14.1 | %) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Calculation of a combined EGR and EGS system** | | | | | | | | | Case 2 |
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | Percent of main engine running time: | | | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 0.0 | 10% | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | |
| Relative period in Non SECA: | 100.0 | 25% | #DIV/0! | 16.5 | #DIV/0! | 16.5 | #DIV/0! | 16.5 | |
| Relative period in NECA: | 0.0 | 30% | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | |
| Relative period in Non NECA: | 100.0 | 40% | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | |
| Relative period "no water outlet": | 0.0 | 50% | #DIV/0! | 14.9 | #DIV/0! | 14.9 | #DIV/0! | 14.9 | |
| EGC needs FW | 0.0 | 60% | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | |
| EGC uses SW | 100.0 | 75% | #DIV/0! | 48.8 | #DIV/0! | 48.8 | #DIV/0! | 48.8 | |
| | | 100% | #DIV/0! | 19.8 | #DIV/0! | 19.8 | #DIV/0! | 19.8 | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 0 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 2 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 5 | m | 5 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 729.7 | t /trip | 16648 | t/year | Add due to EGR+EGS: | | | 1.3 | t/trip |
| AE - fuel consumption: | 34.1 | t /trip | 778 | t/year | Add due to EGR+EGS: | | | 1.4 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 0.4 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 0.0 | t /trip | 0.0 | t/year | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 0.0 | m3/trip | 0.0 | m3/h in average; but with a max consumption of: | | | | 0.0 | m3/h |
| Dirty water FW tank min: | 0.0 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 0.0 | t /trip | 0 | t/year | | | | | |
| Sludge max production | 0.0 | kg/h | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 0.0 | m3 | | | Tank volume (incl. 20% safty): | | | 5 | m3 |
| Sludge min | 0.0 | m3 | | | | | | 5 | m3 |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 8.6 | t /trip | 196 | t/year | | | | | |
| CO2 due to NaOH | 0.0 | t /trip | 0.0 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 8.6 | t /trip | 195.6 | t /year | This equals a CO2 increase of | | | 0.36 | % |
| SOx reduction: | 80.0 | % | | | | | | | |
| NOx reduction: | 0.0 | % | | | | | | | |
| Reduction of particulates (PM): | 70 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 300 | t /trip | | | corresponding to an increase i CO2 of | | | 12.5 | %) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Calculation of a combined EGR and EGS system** | | | | | | | | | Case 3 |
| | | | | | | | | | |
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | Percent of main engine running time: | | | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 100.0 | 10% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | 0.0 | |
| Relative period in Non SECA: | 0.0 | 25% | 16.5 | #DIV/0! | 16.5 | #DIV/0! | 27.8 | 15.6 | |
| Relative period in NECA: | 100.0 | 30% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | 0.0 | |
| Relative period in Non NECA: | 0.0 | 40% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | 0.0 | |
| Relative period "no water outlet": | 0.0 | 50% | 14.9 | #DIV/0! | 14.9 | #DIV/0! | 27.8 | 13.8 | |
| EGC needs FW | 14.8 | 60% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | 0.0 | |
| EGC uses SW | 85.2 | 75% | 48.8 | #DIV/0! | 48.8 | #DIV/0! | 38.9 | 49.6 | |
| | | 100% | 19.8 | #DIV/0! | 19.8 | #DIV/0! | 5.6 | 21.0 | |
| | | | | | | | | | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 8.3 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 2 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | | | | | | | | | |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 5 | m | 5 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| | | | | | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| | | | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 744.7 | t /trip | 16990 | t/year | Add due to EGR+EGS: | | | 16.3 | t/trip |
| AE - fuel consumption: | 53.3 | t /trip | 1217 | t/year | Add due to EGR+EGS: | | | 5.7 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 2.9 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 43.0 | t /trip | 980.2 | t/year | | | | | |
| | | | | | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 124.1 | m3/trip | 0.5 | m3/h in average; but with a max consumption of: | | | | 2.2 | m3/h |
| Dirty water FW tank min: | 11.1 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| | | | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 50.2 | t /trip | 1146 | t/year | | | | | |
| Sludge max production | 726.1 | kg/h | | | | | | | |
| | | | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 70.3 | m3 | | | Tank volume (incl. 20% safty): | | | 85 | m3 |
| Sludge min | 104.6 | m3 | | | | | | 130 | m3 |
| | | | | | | | | | |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 69.4 | t /trip | 1583 | t/year | | | | | |
| CO2 due to NaOH | 47.3 | t /trip | 1078.2 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 116.6 | t /trip | 2660.9 | t /year | This equals a CO2 increase of | | | 4.86 | % |
| SOx reduction: | 98.0 | % | | | | | | | |
| NOx reduction: | 76.4 | % | | | | | | | |
| Reduction of particulates (PM): | 81 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 587 | t /trip | | | corresponding to an increase i CO2 of | | | 24.4 | %) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Calculation of a combined EGR and EGS system** | | | | | | | | | Case 4 |
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | | | Percent of main engine running time: | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 100.0 | 10% | 0.0 | #DIV/0! | #DIV/0! | 0.0 | 0.0 | 0.0 | |
| Relative period in Non SECA: | 0.0 | 25% | 16.5 | #DIV/0! | #DIV/0! | 16.5 | 45.5 | 15.2 | |
| Relative period in NECA: | 0.0 | 30% | 0.0 | #DIV/0! | #DIV/0! | 0.0 | 0.0 | 0.0 | |
| Relative period in Non NECA: | 100.0 | 40% | 0.0 | #DIV/0! | #DIV/0! | 0.0 | 0.0 | 0.0 | |
| Relative period "no water outlet": | 0.0 | 50% | 14.9 | #DIV/0! | #DIV/0! | 14.9 | 9.1 | 15.2 | |
| EGC needs FW | 12.2 | 60% | 0.0 | #DIV/0! | #DIV/0! | 0.0 | 0.0 | 0.0 | |
| EGC uses SW | 87.8 | 75% | 48.8 | #DIV/0! | #DIV/0! | 48.8 | 45.5 | 48.9 | |
| | | 100% | 19.8 | #DIV/0! | #DIV/0! | 19.8 | 0.0 | 20.8 | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 3.9 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 2 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 5 | m | 5 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 729.7 | t /trip | 16648 | t/year | Add due to EGR+EGS: | | | 1.3 | t/trip |
| AE - fuel consumption: | 35.2 | t /trip | 804 | t/year | Add due to EGR+EGS: | | | 2.6 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 0.5 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 3.6 | t /trip | 82.8 | t/year | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 11.7 | m3/trip | 0.0 | m3/h in average; but with a max consumption of: | | | | 1.6 | m3/h |
| Dirty water FW tank min: | 6.8 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 2.9 | t /trip | 66 | t/year | | | | | |
| Sludge max production | 379.5 | kg/h | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 5.9 | m3 | | | Tank volume (incl. 20% safty): | | | 10 | m3 |
| Sludge min | 6.0 | m3 | | | | | | 10 | m3 |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 12.2 | t /trip | 279 | t/year | | | | | |
| CO2 due to NaOH | 4.0 | t /trip | 91.1 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 16.2 | t /trip | 370.2 | t /year | This equals a CO2 increase of | | | 0.68 | % |
| SOx reduction: | 98.0 | % | | | | | | | |
| NOx reduction: | 0.0 | % | | | | | | | |
| Reduction of particulates (PM): | 70 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 587 | t /trip | | | corresponding to an increase i CO2 of | | | 24.4 | %) |

| **Calculation of a combined EGR and EGS system** | | | | | | | | | Case 5 |
|---|---|---|---|---|---|---|---|---|---|
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | Percent of main engine running time: | | | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 100.0 | 10% | 0.0 | #DIV/0! | #DIV/0! | 0.0 | 0.0 | #DIV/0! | |
| Relative period in Non SECA: | 0.0 | 25% | 16.5 | #DIV/0! | #DIV/0! | 16.5 | 16.5 | #DIV/0! | |
| Relative period in NECA: | 0.0 | 30% | 0.0 | #DIV/0! | #DIV/0! | 0.0 | 0.0 | #DIV/0! | |
| Relative period in Non NECA: | 100.0 | 40% | 0.0 | #DIV/0! | #DIV/0! | 0.0 | 0.0 | #DIV/0! | |
| Relative period "no water outlet": | 0.0 | 50% | 14.9 | #DIV/0! | #DIV/0! | 14.9 | 14.9 | #DIV/0! | |
| EGC needs FW | 100.0 | 60% | 0.0 | #DIV/0! | #DIV/0! | 0.0 | 0.0 | #DIV/0! | |
| EGC uses SW | 0.0 | 75% | 48.8 | #DIV/0! | #DIV/0! | 48.8 | 48.8 | #DIV/0! | |
| | | 100% | 19.8 | #DIV/0! | #DIV/0! | 19.8 | 19.8 | #DIV/0! | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 0 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 4 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 5 | m | 5 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 729.7 | t /trip | 16648 | t/year | Add due to EGR+EGS: | | | 1.3 | t/trip |
| AE - fuel consumption: | 39.4 | t /trip | 898 | t/year | Add due to EGR+EGS: | | | 6.7 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 1.1 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 107.4 | t /trip | 2450.8 | t/year | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 360.5 | m3/trip | 1.4 | m3/h in average; but with a max consumption of: | | | | 2.2 | m3/h |
| Dirty water FW tank min: | 10.8 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 61.9 | t /trip | 1413 | t/year | | | | | |
| Sludge max production | 503.1 | kg/h | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 175.9 | m3 | | | Tank volume (incl. 20% safty): | | | 215 | m3 |
| Sludge min | 129.0 | m3 | | | | | | 155 | m3 |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 25.3 | t /trip | 577 | t/year | | | | | |
| CO2 due to NaOH | 118.2 | t /trip | 2695.9 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 143.5 | t /trip | 3272.7 | t /year | This equals a CO2 increase of | | | 5.97 | % |
| SOx reduction: | 98.0 | % | | | | | | | |
| NOx reduction: | 0.0 | % | | | | | | | |
| Reduction of particulates (PM): | 70 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 587 | t /trip | | | corresponding to an increase i CO2 of | | | 24.4 | %) |

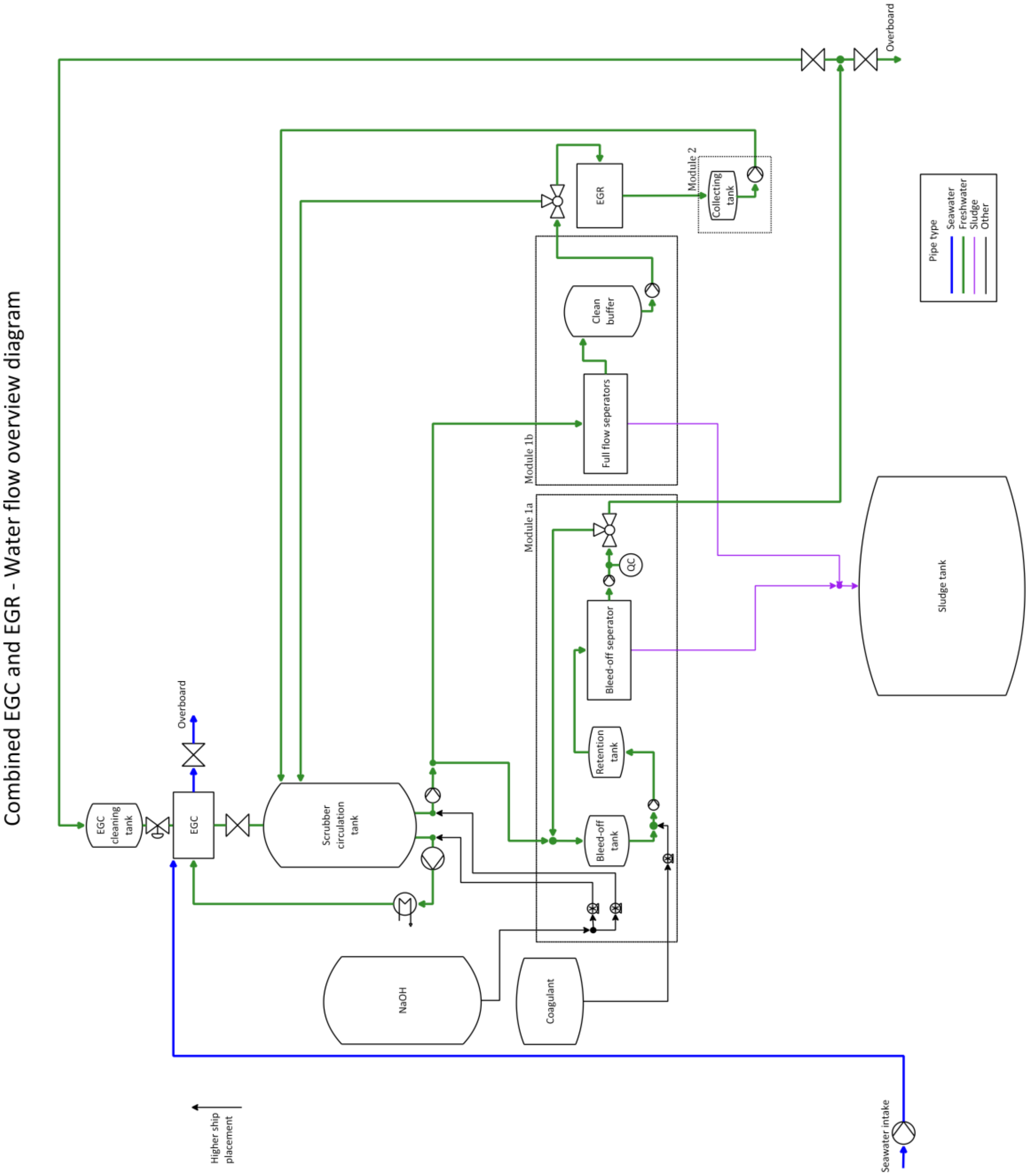
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Calculation of a combined EGR and EGS system** | | | | | | | | | Case 6 |
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | | | Percent of main engine running time: | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 100.0 | 10% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| Relative period in Non SECA: | 0.0 | 25% | 16.5 | #DIV/0! | 16.5 | #DIV/0! | 16.5 | #DIV/0! | |
| Relative period in NECA: | 100.0 | 30% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| Relative period in Non NECA: | 0.0 | 40% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| Relative period "no water outlet": | 0.0 | 50% | 14.9 | #DIV/0! | 14.9 | #DIV/0! | 14.9 | #DIV/0! | |
| EGC needs FW | 100.0 | 60% | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | |
| EGC uses SW | 0.0 | 75% | 48.8 | #DIV/0! | 48.8 | #DIV/0! | 48.8 | #DIV/0! | |
| | | 100% | 19.8 | #DIV/0! | 19.8 | #DIV/0! | 19.8 | #DIV/0! | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 0 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 4 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 5 | m | 5 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 744.7 | t /trip | 16990 | t/year | Add due to EGR+EGS: | | | 16.3 | t/trip |
| AE - fuel consumption: | 54.4 | t /trip | 1240 | t/year | Add due to EGR+EGS: | | | 6.7 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 3.0 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 109.6 | t /trip | 2501.1 | t/year | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 355.0 | m3/trip | 1.3 | m3/h in average; but with a max consumption of: | | | | 2.2 | m3/h |
| Dirty water FW tank min: | 12.8 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 106.5 | t /trip | 2430 | t/year | | | | | |
| Sludge max production | 726.1 | kg/h | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 179.5 | m3 | | | Tank volume (incl. 20% safty): | | | 220 | m3 |
| Sludge min | 221.9 | m3 | | | | | | 270 | m3 |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 72.7 | t /trip | 1658 | t/year | | | | | |
| CO2 due to NaOH | 120.6 | t /trip | 2751.2 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 193.3 | t /trip | 4409.3 | t /year | This equals a CO2 increase of | | | 8.05 | % |
| SOx reduction: | 98.0 | % | | | | | | | |
| NOx reduction: | 76.4 | % | | | | | | | |
| Reduction of particulates (PM): | 81 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 587 | t /trip | | | corresponding to an increase i CO2 of | | | 24.4 | %) |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Calculation of a combined EGR and EGS system** | | | | | | | | | Case 7 |
| **Input** | | | | | | | | | |
| Main Engine (ME) | 6S80ME-C9.2 | | | | | | | | |
| Power | 27000 | kW | | | | | | | |
| In Tier II configuration | | | | | | | | | |
| Fuel sulphur content (>0.5%) | 3 | % | | | | | | | |
| Fuel ash content | 0.02 | % | | | | | | | |
| **Sailing profile:** | | ME | | | Percent of main engine running time: | | | | |
| | % of time | Load (%) | in SECA | in Non SECA | in NECA | in Non NECA | FW | SW | |
| Relative period in SECA: | 0.0 | 10% | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | |
| Relative period in Non SECA: | 100.0 | 25% | #DIV/0! | 16.5 | #DIV/0! | 16.5 | #DIV/0! | 16.5 | |
| Relative period in NECA: | 0.0 | 30% | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | |
| Relative period in Non NECA: | 100.0 | 40% | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | |
| Relative period "no water outlet": | 0.0 | 50% | #DIV/0! | 14.9 | #DIV/0! | 14.9 | #DIV/0! | 14.9 | |
| EGC needs FW | 0.0 | 60% | #DIV/0! | 0.0 | #DIV/0! | 0.0 | #DIV/0! | 0.0 | |
| EGC uses SW | 100.0 | 75% | #DIV/0! | 48.8 | #DIV/0! | 48.8 | #DIV/0! | 48.8 | |
| | | 100% | #DIV/0! | 19.8 | #DIV/0! | 19.8 | #DIV/0! | 19.8 | |
| Sailing hours per year: | 6000 | h | | | Total FW volume | | | 20 | m3 |
| Time between NaOH supply | 40 | days | | | Bleed-off initial water in dirty reservoir | | | 0 | m3 |
| Time between sludge delivery | 40 | days | | | Bleed-off centrifuge capacity | | | 2 | m3/h |
| NaOH concentration: | 50 | % | | | Sludge - water content | | | 93 | % |
| | SW | | FW | | | | | | |
| EGC max vandflow | 1929 | m3/h | 643 | m3/h | | | | | |
| Pumping height (incl nozzles, loss, higher density) | 40 | m | 25 | m | | | | | |
| Pump efficiency (average) | 0.7 | | | | | | | | |
| Electrical power for EGR and EGC WTU | | | 120 | kW | | | | | |
| Electrical power for discharge WTU | | | 30.0 | kW | | | | | |
| **Results:** | | | | | | | | | |
| Hours / trip | 263.0 | h | | | | | | | |
| Number of trips /year | 22.8 | - | | | | | | | |
| **Fuel:** | | | | | | | | | |
| ME - fuel consumption: | 729.7 | t /trip | 16648 | t/year | Add due to EGR+EGS: | | | 1.3 | t/trip |
| AE - fuel consumption: | 44.1 | t /trip | 1006 | t/year | Add due to EGR+EGS: | | | 11.4 | t/trip |
| | | | | | In percent of "without EGR+EGS": | | | 1.7 | % |
| **NaOH** | | | | | | | | | |
| Total NaOH consumption (50 %) | 0.0 | t /trip | 0.0 | t/year | | | | | |
| **Water** | | | | | | | | | |
| Fresh water (FW) consumption: | 0.0 | m3/trip | 0.0 | m3/h in average; but with a max consumption of: | | | | 0.0 | m3/h |
| Dirty water FW tank min: | 0.0 | m3 | | | | | | | |
| Clean water FW tank min: | 0.0 | m3 | | | | | | | |
| **Sludge** | | | | | | | | | |
| Sludge | 0.0 | t /trip | 0 | t/year | | | | | |
| Sludge max production | 0.0 | kg/h | | | | | | | |
| **Tank volumes** | | | | | | | | | |
| NaOH min | 0.0 | m3 | | | Tank volume (incl. 20% safty): | | | 5 | m3 |
| Sludge min | 0.0 | m3 | | | | | | 5 | m3 |
| **Emissions** | | | | | | | | | |
| CO2 due to additional power: | 40.2 | t /trip | 917 | t/year | | | | | |
| CO2 due to NaOH | 0.0 | t /trip | 0.0 | t /year | | | | | |
| Total additional CO2 caused by emission reduction: | 40.2 | t /trip | 916.6 | t /year | This equals a CO2 increase of | | | 1.67 | % |
| SOx reduction: | 80.0 | % | | | | | | | |
| NOx reduction: | 0.0 | % | | | | | | | |
| Reduction of particulates (PM): | 70 | % | this reduces the PM emission to the same level as marine gasoil with 0.1% sulphur | | | | | | |
| (Alternatively - low sulphur fuel - additional CO2 | 300 | t /trip | | | corresponding to an increase i CO2 of | | | 12.5 | %) |

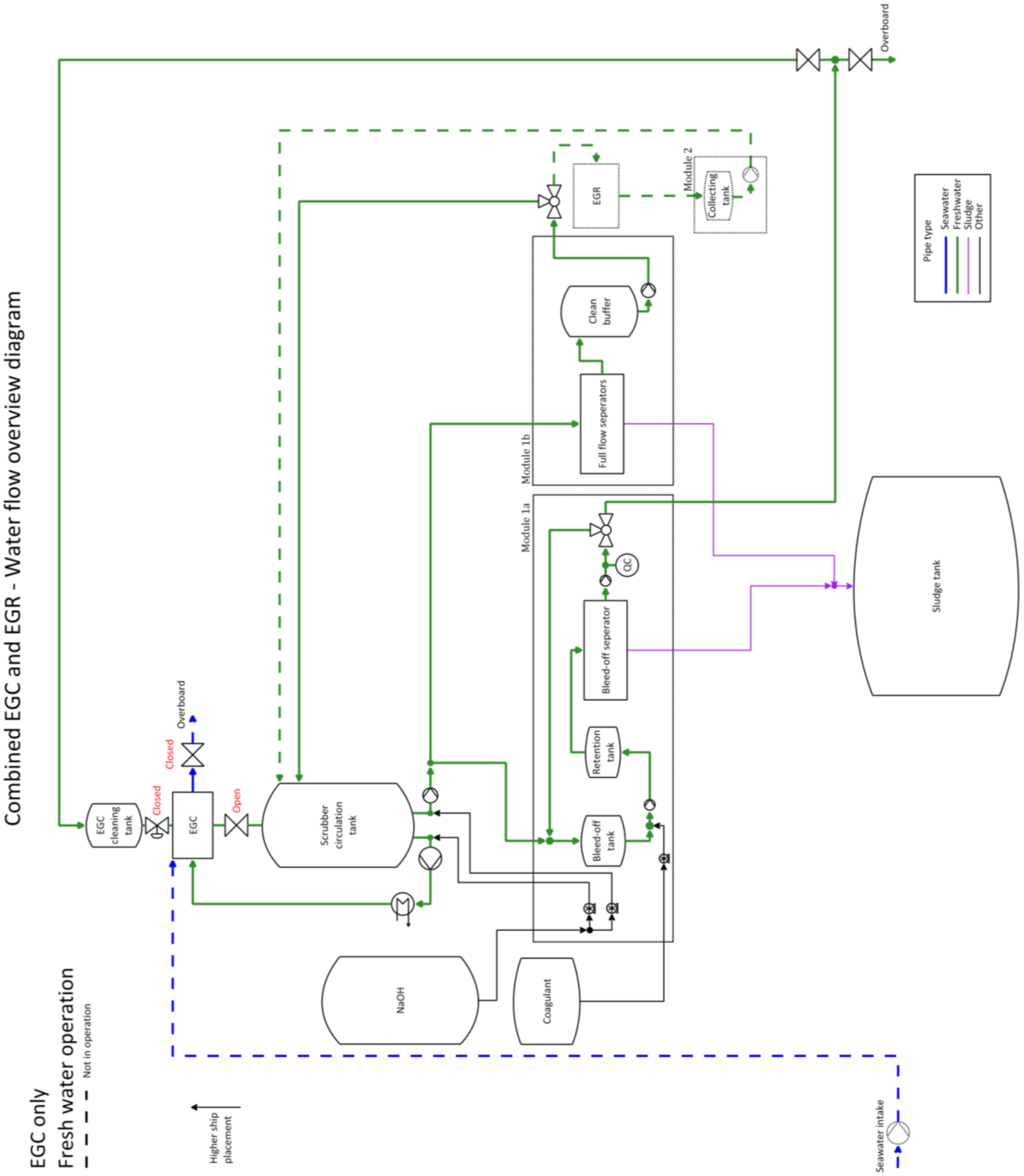
# Appendix C.4

The diagrams below show the following operating modes:

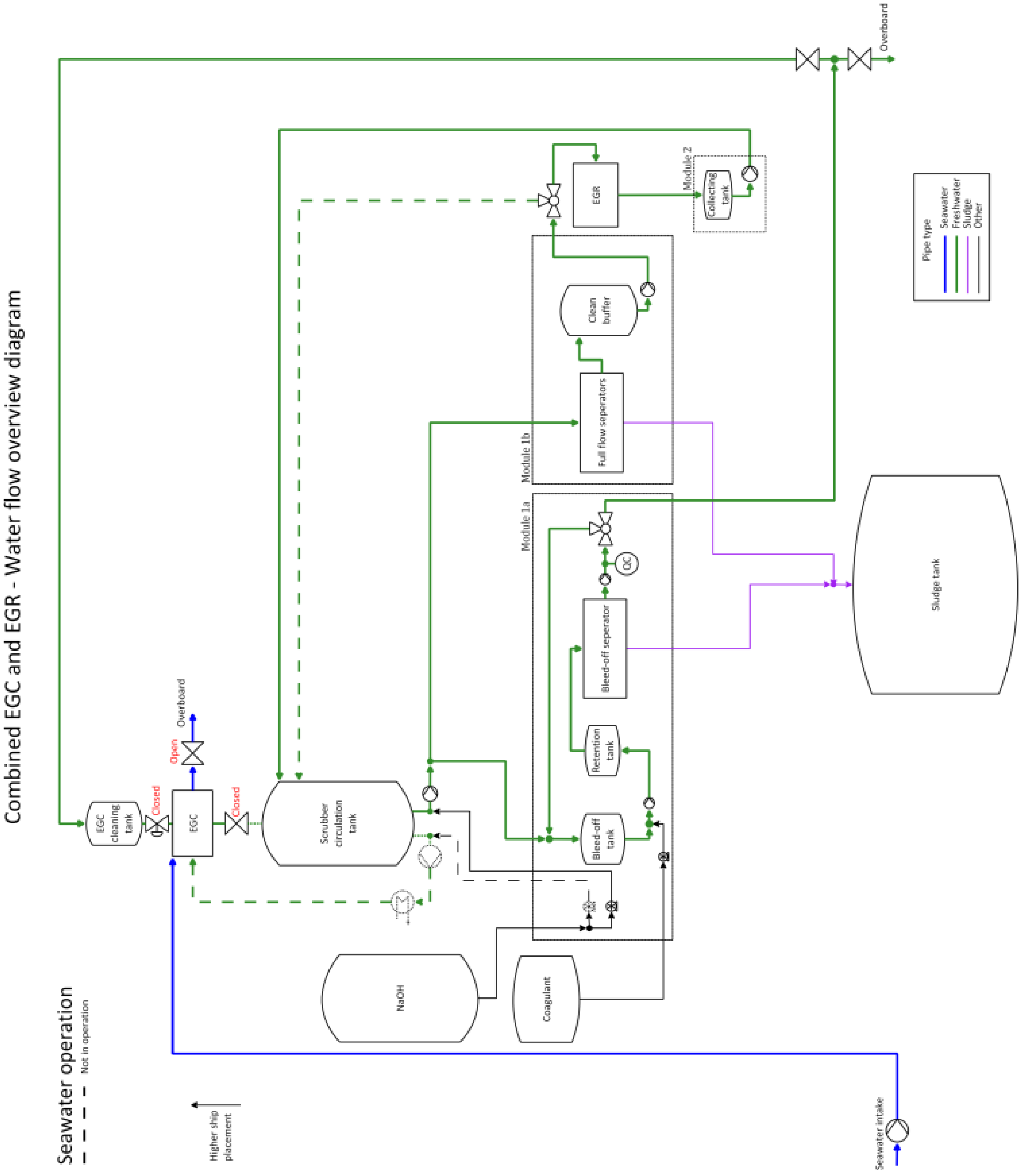
- Overview
- Combined EGC scrubber and EGR – both on FW
- Combined EGC scrubber and EGR – EGC scrubber on SW and EGR on FW
- Switch over from SW to FW
- EGR only
- EGC scrubber only – FW mode
- EGC scrubber only – SW mode.



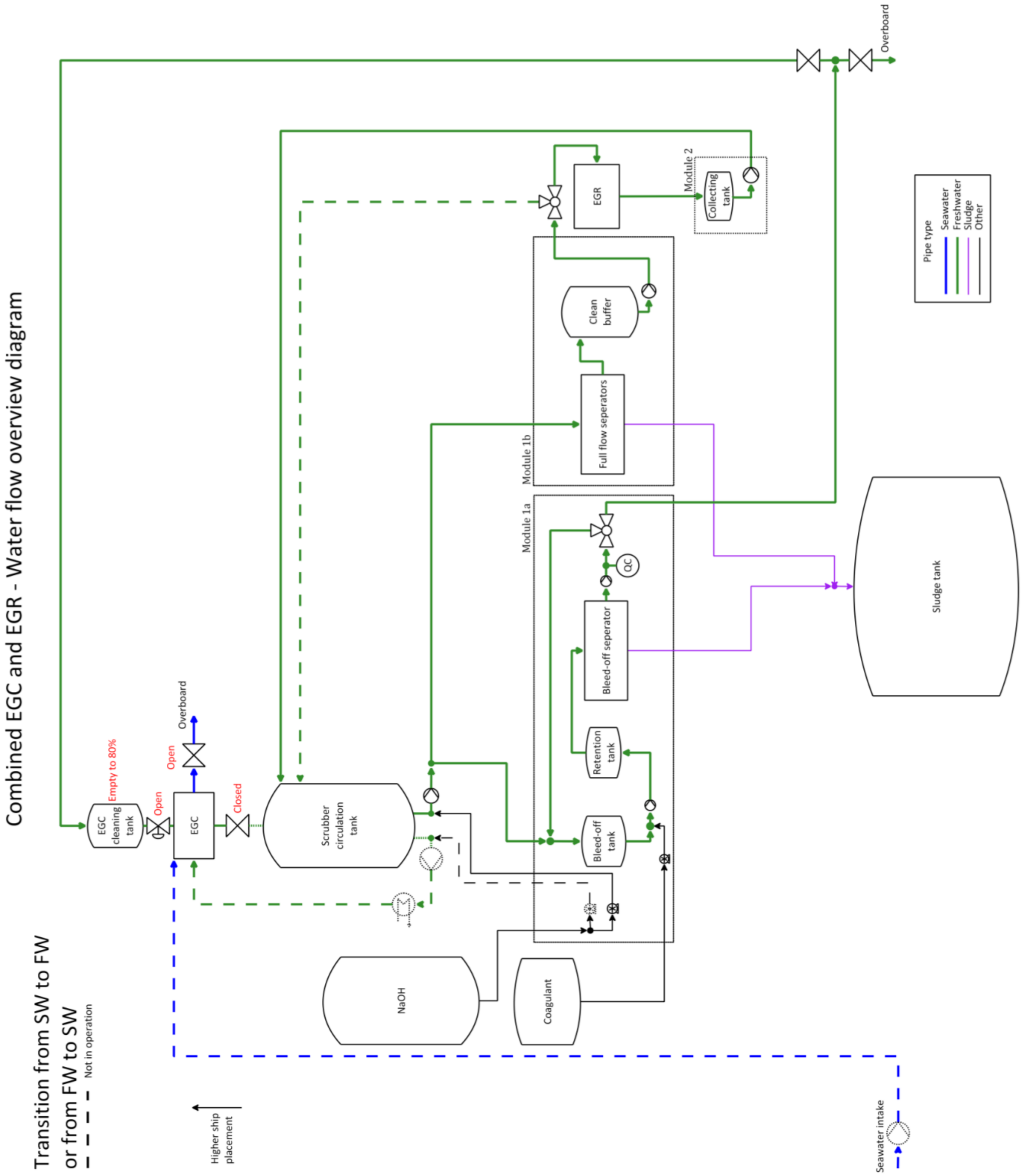
Combined EGC scrubber and EGR scrubber overview.



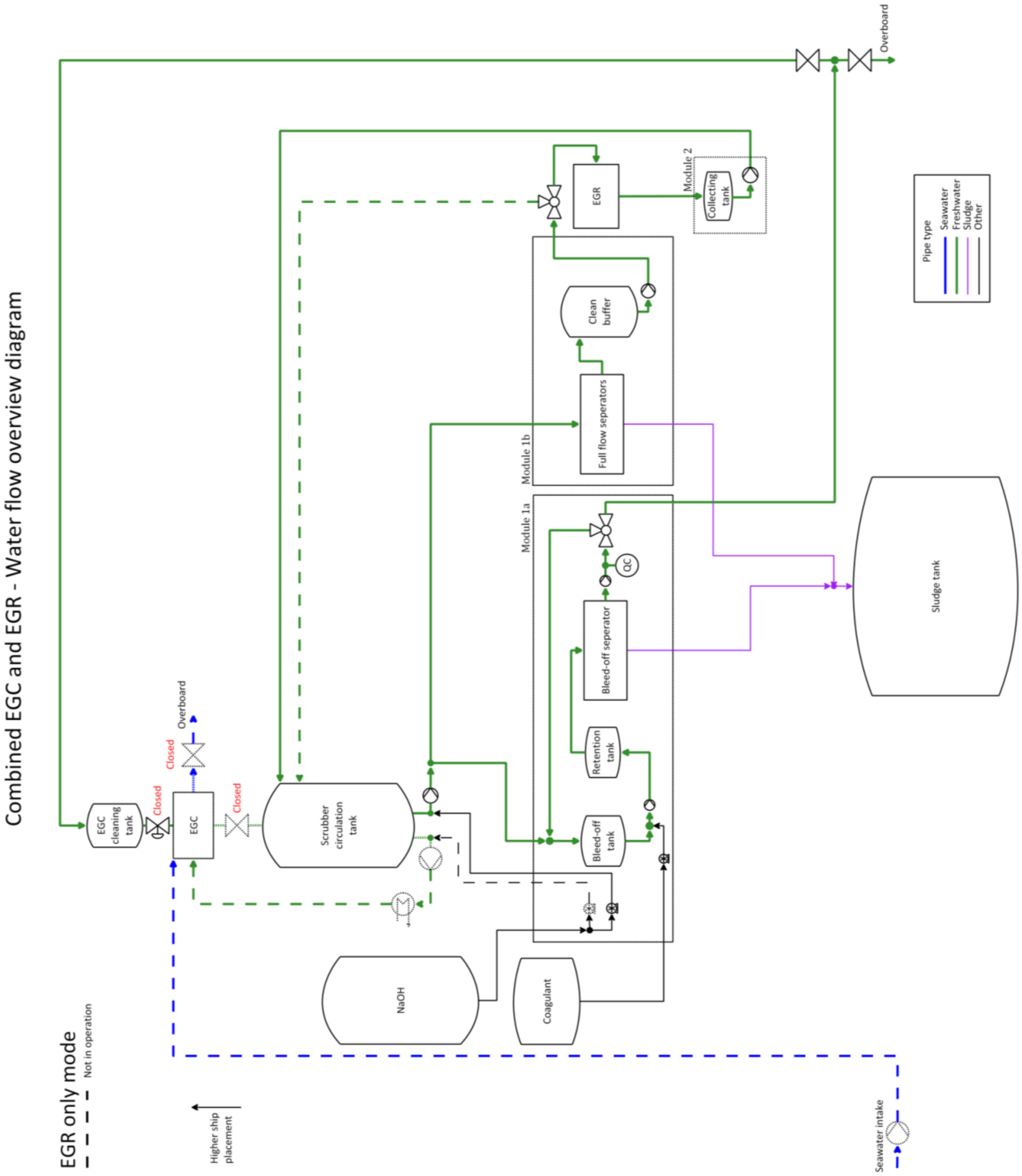
Combined EGC scrubber and EGR scrubber. Both scrubbers operate in FW mode.



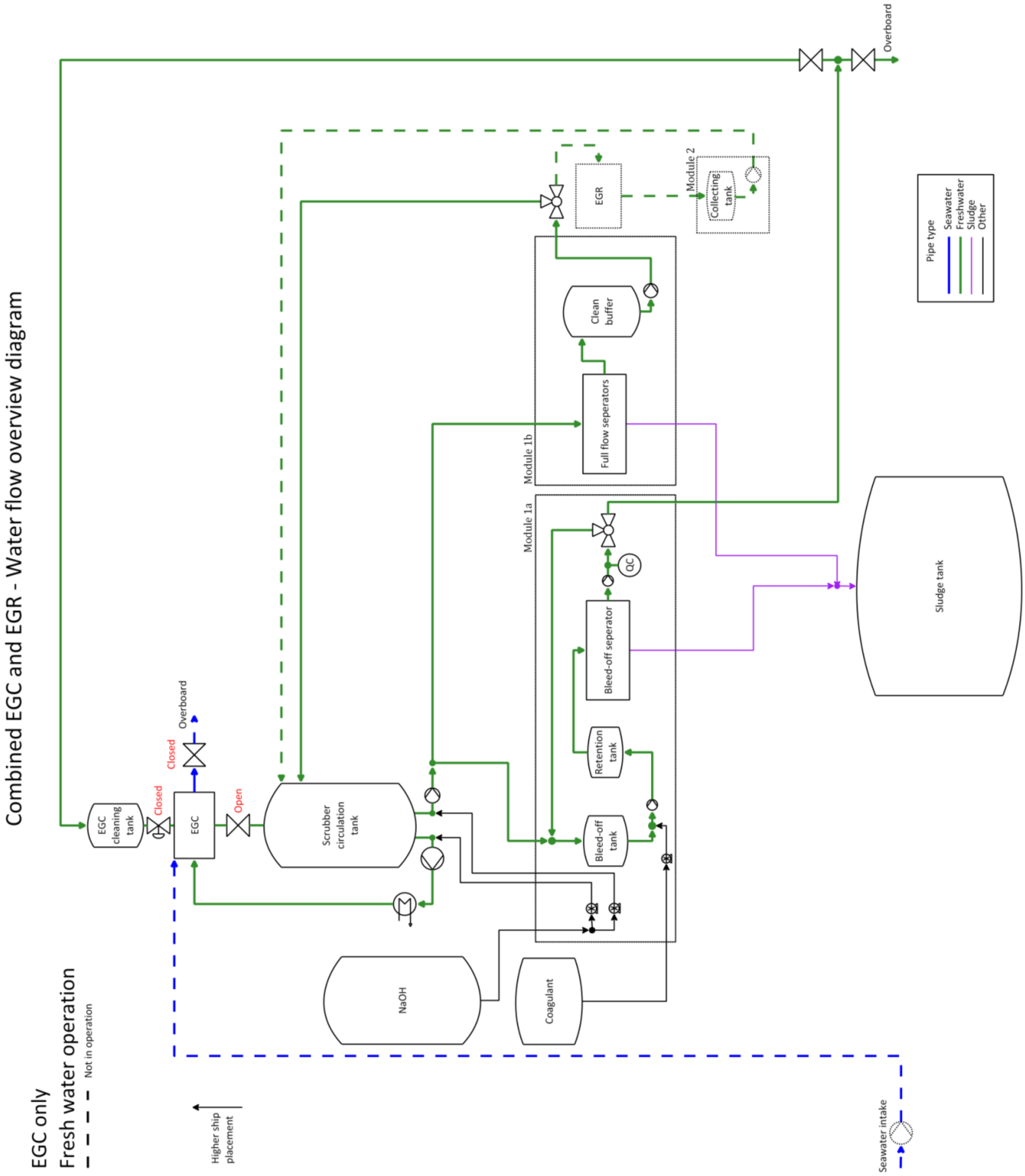
Combined EGC scrubber and EGR scrubber. The EGC scrubber operates in SW mode while the EGR scrubber can be off or operate in FW mode.



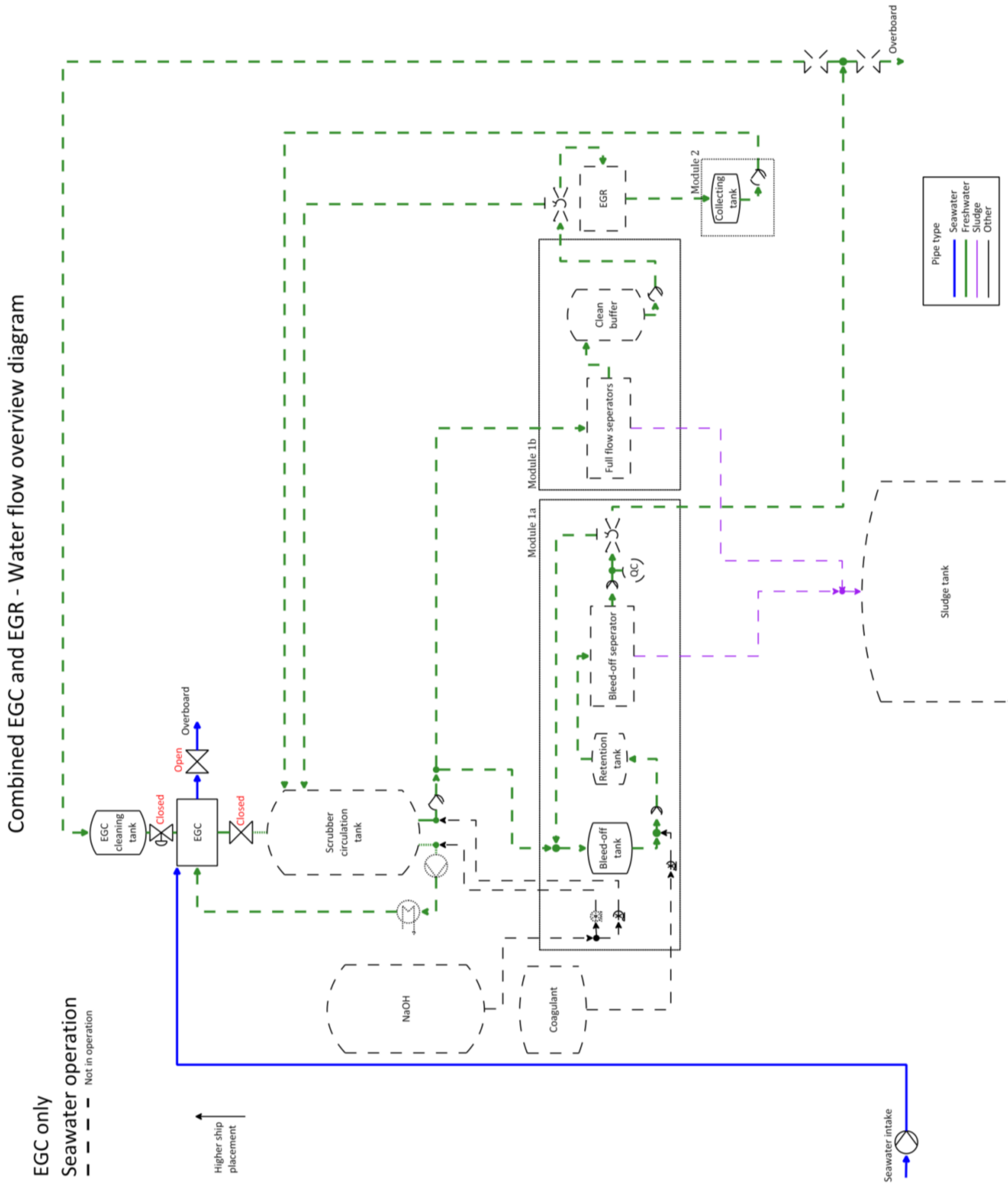
Combined EGC scrubber and EGR scrubber during switch over from SW to FW in the EGC scrubber.



EGR only mode. (The EGR scrubber always operates on FW).



EGC scrubber only mode. The EGC scrubber operates in FW mode.


Combined EGC and EGR - Water flow overview diagram

EGC scrubber only mode. The EGC scrubber operates in SW mode.

# Appendix C.5

| **100% MCR** | **Area:** | **ECA** | **ECA** | **ECA** | **Non ECA** | **Non ECA** | **Non ECA** |
|---|---|---|---|---|---|---|---|
| EGC Scrubber media | | No EGC | FW | SW | No EGC | FW | SW |
| Fuel Sulphur | | 0.1% | 3.0% | 3.0% | 0.5% | 3.0% | 3.0% |
| SFOC penalty EGR | $/MWh | 3.46 | 2.32 | 2.32 | 0.00 | 0.00 | 0.00 |
| NaOH EGR | $/MWh | 0.05 | 1.54 | 1.54 | 0.00 | 0.00 | 0.00 |
| Power EGR | $/MWh | 3.28 | 3.28 | 3.28 | 0.00 | 0.00 | 0.00 |
| Maintenance EGR | $/MWh | 0.18 | 0.18 | 0.18 | 0.00 | 0.00 | 0.00 |
| SFOC penalty Scrubber | $/MWh | 0.00 | 0.15 | 0.15 | 0.00 | 0.22 | 0.22 |
| NaOH Scrubber | $/MWh | 0.00 | 3.47 | 0.00 | 0.00 | 4.28 | 0.00 |
| Power Scrubber | $/MWh | 0.00 | 0.39 | 1.23 | 0.00 | 1.98 | 1.76 |
| Maintenance Scrubber | $/MWh | 0.00 | 0.43 | 0.43 | 0.00 | 0.52 | 0.52 |
| EGR cost incl SFOC penalty | $/MWh | 6.97 | 7.31 | 7.31 | 0.00 | 0.00 | 0.00 |
| EGC cost incl SFOC penalty | $/MWh | 0.00 | 4.44 | 1.81 | 0.00 | 6.99 | 2.49 |
| Fuel cost - excl SFOC pen. | $/MWh | 147.92 | 99.18 | 99.18 | 122.09 | 99.18 | 99.18 |
| Total cost | $/MWh | 154.88 | 110.93 | 108.31 | 122.09 | 106.17 | 101.67 |

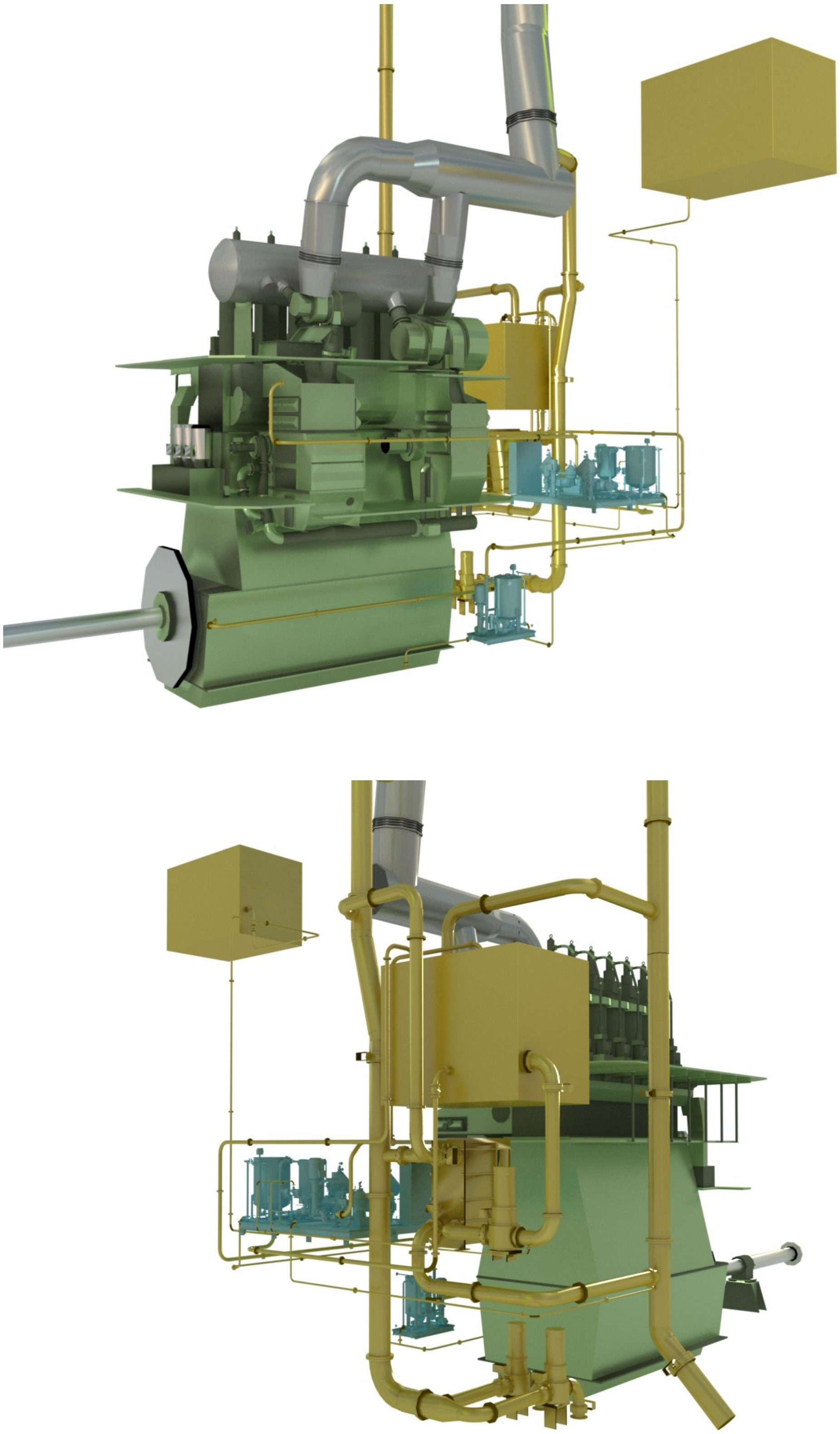
| **75% MCR** | **Area:** | **ECA** | **ECA** | **ECA** | **Non ECA** | **Non ECA** | **Non ECA** |
|---|---|---|---|---|---|---|---|
| EGC Scrubber media | | No EGC | FW | SW | No EGC | FW | SW |
| Fuel Sulphur | | 0.1% | 3.0% | 3.0% | 0.5% | 3.0% | 3.0% |
| EGR cost incl SFOC penalty | $/MWh | 6.43 | 7.31 | 7.31 | 0.00 | 0.00 | 0.00 |
| EGC cost incl SFOC penalty | $/MWh | 0.00 | 4.14 | 1.70 | 0.00 | 6.99 | 2.49 |
| Fuel cost - excl SFOC pen. | $/MWh | 146.88 | 98.48 | 98.48 | 121.24 | 98.48 | 98.48 |
| Total cost | $/MWh | 153.31 | 109.93 | 107.49 | 121.24 | 105.47 | 100.98 |

| **50% MCR** | **Area:** | **ECA** | **ECA** | **ECA** | **Non ECA** | **Non ECA** | **Non ECA** |
|---|---|---|---|---|---|---|---|
| EGC Scrubber media | | No EGC | FW | SW | No EGC | FW | SW |
| Fuel Sulphur | | 0.1% | 3.0% | 3.0% | 0.5% | 3.0% | 3.0% |
| EGR cost incl SFOC penalty | $/MWh | 5.57 | 6.73 | 6.73 | 0.00 | 0.00 | 0.00 |
| EGC cost incl SFOC penalty | $/MWh | 0.00 | 4.14 | 1.70 | 0.00 | 6.99 | 2.49 |
| Fuel cost - excl SFOC pen. | $/MWh | 146.88 | 98.48 | 98.48 | 121.24 | 98.48 | 98.48 |
| Total cost | $/MWh | 152.44 | 109.35 | 106.91 | 121.24 | 105.47 | 100.98 |

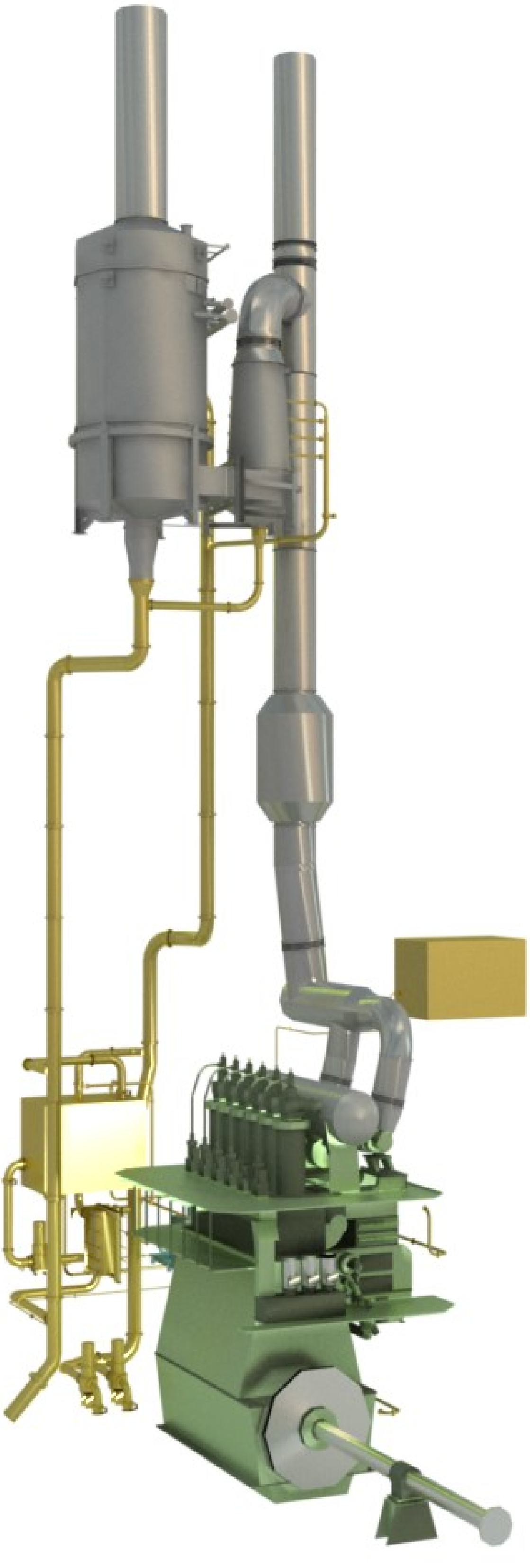
| **25% MCR** | **Area:** | **ECA** | **ECA** | **ECA** | **Non ECA** | **Non ECA** | **Non ECA** |
|---|---|---|---|---|---|---|---|
| EGC Scrubber media | | No EGC | FW | SW | No EGC | FW | SW |
| Fuel Sulphur | | 0.1% | 3.0% | 3.0% | 0.5% | 3.0% | 3.0% |
| EGR cost incl SFOC penalty | $/MWh | 4.17 | 6.15 | 6.15 | 0.00 | 0.00 | 0.00 |
| EGC cost incl SFOC penalty | $/MWh | 0.00 | 3.84 | 1.59 | 0.00 | 6.99 | 2.49 |
| Fuel cost - excl SFOC pen. | $/MWh | 148.78 | 99.76 | 99.76 | 122.81 | 99.76 | 99.76 |
| Total cost | $/MWh | 152.95 | 109.75 | 107.50 | 122.81 | 106.75 | 102.25 |

Table C5: Operating cost at different engine loads. The cost includes the fuel cost, which is highly dependent on the sulphur content in the fuel.

# Appendix C.6



3D drawing of the 6S80ME-C8.2 with both EGR and EGC scrubber. Above seen from the aft starboard and below seen from the front port.



3D drawing of the 6S80ME-C8.2 with both EGR and EGC scrubber – seen from the aft port.

## Reduction of SO2, NOx and Particulate Matter from Ships with Diesel Engines

The objective of this project is to examine competitive, environmentally friendly and practical technologies for reduction of NOx, SO2 and particulate matters from large two-stroke diesel marine engines. The project focuses on EGR and EGC scrubber and how the two technologies can be combined and which synergy effects there are.

Hovedformålet med projektet har været, at undersøge konkurrencedygtige, miljøvenlig og velfungerende teknologier til reduktion af udledning af NOx, SO2 og partikler fra store diesel motorer til skibe. Projektet har fokuseret på EGR og EGC-skrubbere og hvilke synergieffekter, der kan opnås ved at kombinere disse to teknologier.

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