

# **Emission Project Guide** MAN B&W Two-stroke Marine Engines

Engineering the Future – since 1758. **MAN Diesel & Turbo** 



# **Emission Project Guide**

# for Marpol Annex VI Regulations

The intention of the Emission Project Guide is to give sufficient information to decide and design solutions for emission reductions at the initial stage of a project involving MAN B&W two-stroke marine engines.

The information is to be considered as **preliminary**. It is intended for the project stage only and subject to modification in the interest of technical progress. The Emission Project Guide provides the general technical data available at the date of issue.

It should be noted that all figures, values, measurements or information about performance stated in this project guide are **for guidance only** and should not be used for detailed design purposes or as a substitute for specific drawings and instructions prepared for such purposes.

The latest, most current version of the Emission Project Guide is available on the Internet at: www.marine.man.eu  $\rightarrow$  'Two-Stroke'  $\rightarrow$  'Project Guides'  $\rightarrow$  'Other Guides'.

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**Emission Project Guide** 

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## **Emission Project Guide**

Scope

The intention of the Emission Project Guide is to give sufficient information to decide and design solutions for emission reductions at the initial stage of a project involving MAN B&W two-stroke marine engines. The information provides technical data needed for the preliminary design, including data for performance, layout, consumables, control and installation of the equipment.

The Emission Project Guide is divided in two parts:

Part 1 NO<sub>x</sub> reduction – IMO Tier III solutions

Part 2 SO<sub>x</sub> reduction – exhaust gas cleaning system

The latest, most current version of this Project Guide is available on the Internet at: www.marine.man.eu  $\rightarrow$  'Two-Stroke'  $\rightarrow$  'Project Guides'  $\rightarrow$  'Other Guides'.







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ABS	Ammonium Bisulphate
AIG	Ammonia Injection Grid
RTU	Buffer Tank Linit
	Computarised Engine Application System
	Culinder Bypage Value
DCU	
ECA	Emission Control Area
EGB	Exhaust Gas Bypass
EGCSA	Exhaust Gas Cleaning Systems Association
EGR	Exhaust Gas Recirculation
EMC	Electro Magnetic Compatibility
ERCS	Emission Reduction Control System
FW	Freshwater
HFO	Heavy Fuel Oil
HP	High Pressure
HS	High Sulphur
IMO	International Maritime Organisation
ISO	International Standard Organisation
LL	Low Load
LNG	Liquified Natural Gas
LP	Low Pressure
LS	Low Sulphur
MARPOL	International Convention for the Prevention of Pollution from Ships
ME-ECS	Engine Control System
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MOP	Main Operating Panel
MPC	Multi Purpose Controller
NECA	NO Emission Control Area
NO	Nitrogen Oxides
PAH	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
20	Quality Control
RH	Relative Humidity
RBV	Reactor Bypass Valve
RSV	Reactor Sealing Valve
RTU	Receiving Tank Linit
RTV	Reactor Throttle Valve
S%	Sulphur content percentage in fuel oil
SCB	Selective Catalytic Reduction
SECA	SO Emission Control Area
SEOC	Specific Fuel Oil Consumption
SMCB	Specified Maximum Continuous Bating
SO	Sulphur Oxides
SU	Supply Unit
SW	Seawater
T/C or TC	Turbocharger
WC	Water Column
WCU	Water Cleaning Unit
WHS	Water Handling System
WMC	Water Mist Catcher
W/TS	Water Treatment System
W/TU	Water Treatment Linit
WRII	Waste Reduction Unit

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## NO<sub>x</sub> and SO<sub>x</sub> rules

The international requirements on emissions of NO<sub>x</sub> (nitrogen oxides), SO<sub>y</sub> (sulphur oxides) and PM (particulate matter) are determined by the MARPOL convention Annex VI – Regulations for the Prevention of Air Pollution from Ships.

NO<sub>x</sub>

According to the rules, the NO<sub>x</sub> emission of any marine diesel engine installed in a ship constructed on or after 1st January 2016 shall meet the so-called Tier III level when operating inside a NO<sub>x</sub> emission control area (NO<sub>x</sub> ECA). In case a NO<sub>x</sub> ECA is designated at a later date, the requirements only apply to ships constructed on or after this date. The ECA in North America is applicable for NO, from January 2016 and the ECA in Northern Europe is applicable for NO, from January 2021.

Any abatement technology reducing the NO<sub>x</sub> emission to the required level can be accepted. However, guidelines developed for this purpose must be followed.

SO, and PM

Emissions of SO, and PM are regulated by the sulphur content of any fuel used on board ships. The rules of SO, and PM apply to all ships, no matter the date of ship construction.

When sailing inside SO<sub>x</sub> emission control areas (SO<sub>x</sub> ECA), the sulphur content must not exceed 0.1%. The ECA in North America and Northern Europe are now applied for SO<sub>x</sub>. Outside SO<sub>x</sub> ECA, the sulphur content must not exceed 3.5% until 1 January 2020 where a new limit of 0.5% sulphur is introduced.

Any abatement technology reducing the emission of SO<sub>x</sub> to a level equivalent to the emission level when using compliant fuels will be accepted, provided the relevant guidelines are followed.

The existing ECA's are shown in Fig. 1.01.



Fig. 1.01: Existing ECA - Emission Control Area - in North America and Northern Europe

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## 1 NO<sub>x</sub> reduction – Tier III solutions 1.1.1 Introduction

#### NO<sub>x</sub> limits

Tier II Tier III The international  $NO_x$  emission limits on marine diesel engines as determined by MARPOL Annex VI are shown in Fig.1.01 as a function of the rated engine speed, rpm.



Fig. 1.01: NO<sub>x</sub> emission limits according to MARPOL Annex VI

The Tier II limits must be met globally by all ships constructed January  $1^{\rm st}$  2011 or later.

Tier III limits are local requirements to be met in designated NO<sub>x</sub> Emission Control Area by ship constructed on or after the ECA designation date. The present NO<sub>x</sub> ECA and dates are listed in Table 1.01.

NOx Emission Cont	NO <sub>x</sub> ECA date	
North America	US/Canada - 200 naut. mile	January 1 <sup>st</sup> 2016
Northern Europe	Baltic sea, North sea & English channel	January 1st 2021

Table 1.01



NO<sub>x</sub> reduction

Two-way approach to MAN Diesel & Turbo offers two alternative methods to meet the Tier III NO, requirement on two-stroke engines. The first method, exhaust gas recirculation (EGR), is an internal engine process to prevent the formation of NO, by controlling the combustion process. The second method, selective catalytic reduction (SCR), is an after-treatment method using a catalyst and an additive to reduce the NO<sub>x</sub> generated in the combustion process. The SCR system is available in a high pressure system, HP SCR, and a low pressure system, LP SCR. Fig. 1.02 shows the layout of an EGR and HP SCR engine.



Influence of sulphur in fuel

Fig. 1.02: Two-way approach for Tier III engine – EGR and SCR solutions

In addition to meet the Tier III NOx requirement, ships sailing in a combined NOx and SOx ECA must either run on low-sulphur fuel or run an exhaust gas cleaning process, i.e. a SOx scrubber system. The EGR system and the HP SCR system will be able to run on high sulphur fuel, but in this case the exhaust gas system must be equipped with a SOx scrubber system. A LP SCR can normally not be used for high sulphur fuel on two-stroke engines. When planning the Tier Ill installation, these conditions must be taken into account.

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#### 1.1.2 NO<sub>x</sub> compliance in service

A Tier III engine has two emission cycle operating modes: Tier II for operation outside  $NO_x$  Emission Control Areas and Tier III for operation inside  $NO_x$  Emission Areas.

Similar to the existing fleet of Tier I and Tier II engines, emission compliance needs to be verified in service. Annual surveys are required, but also ensuring day to day emission regulation compliance is an issue that must be covered. For this purpose MAN B&W engines offer two different systems specifically developed for Tier III engines:

- Two specialized Onboard Survey Methods for demonstration compliance for each of the operating modes for Tier II and Tier III
- Engine control system output signals allowing monitoring of when Tier III mode is engaged

Onboard Survey<br/>MethodThe specialized Onboard Survey Methods included in the engine NOx<br/>File for Tier II and Tier III modes offers a tool to verify that the engine fulfills the<br/>relevant NOx<br/>levels.

The Onboard Survey Method is similar to the well-known Unified Survey Method developed and delivered with numerous MAN B&W engines through the last 15 years. The Onboard Survey Method utilized the performance parameter method as described in MARPOL Annex VI and the  $NO_x$  Technical Code. By reading or measuring certain performance parameters and comparing to limit values, the compliance is verified. The Onboard Survey Method for Tier II mode on a Tier III engine is similar to the Onboard Survey Method delivered with standard Tier II engines. For the Tier III mode a few additional parameters are included.

Regarding EGR, NO<sub>x</sub> reduction is closely correlated to the O<sub>2</sub> content of the mixed fresh intake air and cleaned recirculated exhaust gas. The parameter is also used for control of the EGR ratio. Due to this, O<sub>2</sub> is included as an Onboard Survey parameter for EGR.

Regarding SCR, the consumption of reducing agent and an exhaust emission concentration sensor is used to verify that the system is fully functional as intended and certified. The consumption of reducing agent is included as an onboard Survey parameter for SCR. The concentration sensor is used in the control system to catch two different phenomenon's indicating a system problem:

- Lower NO<sub>x</sub> concentration than expected, indicating an overdose of reducing agent and thus a potential risk of Ammonia slip
- Higher than expected NO<sub>x</sub> concentration, indicating a potential failure in the NO<sub>x</sub> reduction system

The two indications should be followed up by a system diagnostics in order to find the potential problem. If a problem is found, possible solutions will be suggested.



Monitoring of NO<sub>x</sub> compliance The requirement for operating the engine in Tier III mode is triggered when the ship is sailing inside a NO<sub>x</sub> Emission Control Area. The operator must assure that the engine is operated in accordance with the requirements. Tier III compliance could be documented using a logging system but this is not part of the engine control system. To facilitate this, MAN B&W engines are equipped with an engine control system which delivers signal output documenting the emission mode status of the engine.

Two Tier III compliance status signals are available:

- 'Tier III system started'. This signal is activated when 1) a Tier III mode command has been issued to the engine control system, and 2) the Tier III system is working (no failures, auto mode)
- 'NO, reduction active'. This signal is activated when NO, reduction begins

The first signal allows for logging when a Tier III mode command is issued by the ship crew, the second allows for logging when the engine is actually operating at reduced  $NO_x$  emission level. The difference between the two signals is caused by startup time or by specific operating conditions.

Certain cases will result in non-error situations where the operator has issued a command and the system is not reducing  $NO_x$ . This could happen in the following situations:

- Engine load change is faster than the guidance load change curve
- Rough sea conditions resulting in oscillating engine load
- Time during engaging and dis-engaging of control valves
- Engine load or ambient conditions outside the operating window of the emission control system as specified in the NO<sub>x</sub> Technical File

Tier III systems are designed to minimize these cases as far as possible. As the engine is Tier III certified, and these are transient situations not covered by the certification cycle, the engine is still considered to be in Tier III mode although  $NO_x$  reduction is not occurring.

In case of system failures, the engine control system will issue an alarm code and text, allowing for the situation to be corrected. In addition, both Tier III compliance signals are removed.

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#### 1.2 EGR – Exhaust Gas Recirculation

#### 1.2.1 EGR principle

Exhaust gas recirculation (EGR) is a method to significantly reduce the formation of NO<sub>x</sub> in marine diesel engines. By using this method, the Tier III requirements in NO<sub>x</sub> ECA can be met.

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 decrease the  $O_2$  content and 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 Fig. 1.03.





#### 1.2.2 EGR system

Two different matching methods are used for the EGR systems:

- EGR with bypass, configured with only one turbocharger and used for engines of bore 70 or less.
- EGR with TC cut-out matching, configured with two or more turbochargers and used for engines of bore 80 or greater.
- Bypass matching An EGR system configured with bypass matching is shown in Fig. 1.04. Two strings, a main string and an EGR string, are available to direct the scavenge air into the scavenge air receiver:
  - the main string, with the capacity to lead all the scavenge air through the turbocharger compressor and the scavenge air cooler.
  - the EGR string, with the capacity to lead up to 40% of the exhaust gas through the pre-spray and the EGR unit (EGR cooler and WMC) to a mixing point in the main string.



Fig. 1.04: EGR process diagram. Bypass matching



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Two modes are available for bypass matching:

Tier II mode

In Tier II mode only the main string is in operation. The valves in the EGR string (SOV/BTV) and the cylinder bypass (CBV) is kept closed. In this mode, the exhaust gas bypass (EGB) is fully open at high loads and partly open at low loads to balance the turbocharger. However, on engines with a bore of 40 or less, the exhaust gas bypass will be closed at high loads and the EGR string open, to obtain sufficient scavenge air pressure while meeting restrictions on the turbocharger speed.

Tier III mode

In Tier III mode, the EGR string is activated by opening the EGR shut-off valve and the blower throttle valve (SOV/BTV). The exhaust gas is led through the pre-spray and the EGR unit to the mixing point and scavenge air receiver, forced by the EGR blower. The EGR ratio is controlled by changing the flow of the EGR blower. The cylinder bypass (CBV) is active in this mode to increase the scavenge air pressure and thereby reduce the SFOC. The exhaust gas bypass (EGB) is closed.

In Table 1.02 an overview of the valve control is given.

	Tier II mode			Tier III mode			
	SOV BTV	CBV	EGB	SOV BTV	CBV	EGB	
100			Open				
75					0		
65	Closed	Closed	Partly	Open	Open	Closed	
50			Open				
25					Closed		

Bypass matching -  $45 \le Bore \le 70$ 

#### Bypass Matching - Bore $\leq 40$

	Tier II mode			Tier III mode			
	SOV BTV	CBV	EGB	SOB BTV	CBV	EGB	
100	Open		Closed				
90							
75		Closed	Partly	Open	Open	Closed	
65	Closed		Open				
50							
25					Closed		

Table 1.02: Control valve operation



**TC cut-out matching** An EGR system with TC cut-out matching is shown in the diagram in Fig. 1.05. Three strings, a main string, a cut-out string and an EGR string, are available in the system to direct the scavenge air into the scavenge air receiver:

- the main string, leads up to 70% of the scavenge air through the basic turbocharger and the scavenge air cooler.
- the cut-out string, leads up to 40% of the scavenge air through the cut-out turbocharger and through the EGR unit (EGR cooler and WMC) before entering the scavenge air receiver through the balance pipe.
- the EGR string, leads up to 40% of the exhaust gas through a pre-spray and EGR unit to a mixing point in the main string, forced by one or more EGR blowers. In this case the cut-out string is closed.

On some larger engines, a configuration with more than two turbochargers will be needed. The principle is unchanged although the number of turbochargers and EGR units are increased.



Fig. 1.05: EGR process diagram. TC cut-out matching

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Three modes are available for TC cut-out matching:

• Tier II mode

In Tier II mode the main string and the cut-out string are in operation. The TC cut-out valves (TCV/CCV) and the blower by-pass valves (BBV) are open, while the EGR string is kept closed by the EGR shut-off valve and the blower throttle valve (SOV/BTV). In this mode the EGR cooler works as a normal scavenge air cooler. About 40% of the scavenge air is passed through the cut-out string, the remaining 60% through the main string. The cylinder bypass (CBV) is kept close in this mode.

Tier II mode – TC cut-out

The cut out string gives an opportunity to run the engine in Tier II mode at low loads with a TC cut-out and the SFOC could thereby be reduced. In this case only the main string will be open, while the cylinder bypass (CBV) is kept closed.

Tier III mode

In Tier III mode the cut-out string is closed (TCV/CCV). The EGR string is open by the EGR shut-off valve and the blower throttle valve (SOV/BTV). The exhaust gas is led through the pre-spray and the EGR unit to the mixing point and the scavenge air receiver, forced by the EGR blowers. The EGR ratio is controlled by changing the flow of the EGR blower. The cylinder bypass (CBV) is partly active in this mode to increase the scavenge air pressure and thereby reduce the SFOC.

In Table 1.03 an overview of the valve control is given.

	Tier II mo	II mode Tier II mode – TC cut-out Tier III mode			Tier II mode – TC cut-out				
	SOV BTV	CBV	TCV CCV BBV	SOV BTV	CBV	TCV CCV BBV	SOV BTV	CBV	TCV CCV BBV
100				Not appli	cable			Closed	
75							Open		
65	Closed	Closed	Open					Partly	Closed
50				Closed	Closed	Closed		Open	
25								Closed	

Table 1.03: Control valve operation

TC cut-out matching - Bore  $\ge 80$ 



#### 1.2.3 EGR layout

The EGR cooler and water mist catcher are installed in the EGR unit. The unit, shown in Fig. 1.06, includes a cooler spray with a function to increase the cooling efficiency and to keep the cooler clean. A pre-spray used to prepare the EGR gas for cooling and cleaning is installed in the gas pipe upstream of the EGR unit.

The EGR unit used for a low sulphur EGR system (LS EGR) is designed for a fuel sulphur limit of 0.5% S, covering not only the ECA sulphur limit of 0.1% S but also the 2020 global limit of 0.5% S. The EGR unit used for high sulphur system (HS EGR) is designed for a maximum of 3.5% S and will be larger and more complex than the LS EGR unit. The EGR unit is integrated on the engine, similar to a scavenge air receiver. The layout of the EGR engines is shown in Figs. 1.07 and 1.08

The presence of sulphur in the EGR gas requires that different grades of stainless steel are used for the EGR unit and the EGR cooler. These steel grades cannot be used in connection with seawater, as chlorides in the water will lead to corrosion, and accordingly a central cooling system using freshwater as cooling media is specified for the EGR cooler.



#### Fig. 1.06: Model of EGR unit

The supply of water to the pre-spray and EGR cooler spray, and the removal of water from the EGR unit is part of the EGR water handling system, which will clean and recirculate the water. The system – which also includes discharge of excess water generated in the combustion process - is described and illustrated in Chapter 1.2.6 Water Handling System (WHS). Part of the water handling system, i.e. the Receiving Tank Unit (RTU) which includes a small tank and a circulation pump, is integrated on the engine.



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Fig. 1.07: Integrated EGR layout for bypass matching – 5G70ME-C



Fig. 1.08: Integrated EGR layout for cut-out matching – 7G80ME-C



#### **1.2.4 EGR configuration**

Bypass matching

On an EGR system with bypass matching, the turbocharger is mounted either on the exhaust side or aft. In both cases, the EGR unit is mounted on the exhaust side. The two configurations are shown in Figs. 1.09 and 1.10.



Fig. 1.09: Side-mounted turbocharger and side-mounted EGR unit



Fig. 1.10: Aft-mounted turbocharger and side-mounted EGR unit (RTU is not shown)

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TC cut-out matching The configurations of EGR systems with TC cut-out matching are shown in Figs. 1.11, 1.12 and 1.13. The MAN B&W marine engine programme is covered by combining one or more EGR units including cut-out turbochargers with one or more basic turbochargers.



Fig. 1.11: One basic T/C, one cut-out T/C, and one EGR unit



Fig. 1.12: Two basic T/Cs, one cut-out T/C, and one EGR unit





Fig. 1.13: Two basic T/Cs, two cut-out T/Cs, and two EGR units



#### 1.2.5 Engine outline

Bypass matching

The outline of an EGR system with bypass matching is shown in Fig. 1.14. The engine is shown with side-mounted turbocharger but engines with aft-mounted turbocharger will also be available.







Fig. 1.14: EGR engine with bypass matching, 6G70ME-C9

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NO<sub>x</sub> reduction – Tier III solutions

EGR – Exhaust Gas Recirculation

TC cut-out matching

ch- The outline of an EGR system with TC cut-out matching is shown in Fig. 1.15.





Upper platform

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Lower platform

Fig. 1.15: Outline of a 7S90ME-C9 Tier III engine with one basic T/C, one cut-out T/C and one EGR unit

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#### 1.2.6 Water Handling System (WHS)

WHS principle

To prevent sulphur and particles from damaging the engine, cleaning of the recirculated exhaust gas is required. This is performed in a combined cooling and cleaning process by a pre-spray and an EGR cooler spray in the EGR string, using recirculated freshwater (FW).

In order to maintain the ability of the FW to clean, cool and neutralizing the exhaust gas, a water handling system (WHS) is needed. The system must ensure the removal of accumulated particles and neutralisation of sulphuric acid in the water and ensure the delivery of water at a sufficient pressure and supply rate to the EGR unit. In addition, the WHS must also handle the bleed-off water, which is the surplus of water from the combustion process accumulated in the system. If discharged overboard, the water quality must meet the international requirements for bleed-off water as stated in 2015 Guidelines for Exhaust Gas Cleaning Systems, MEPC 259 (68) <sup>1</sup>.

The principle of the WHS is shown in Fig. 1.16. The water from the EGR unit is drained to the receiving tank unit (RTU) and recirculated to the EGR unit by the circulation pump. Part of the recirculated water is led to the water treatment system (WTS) to be cleaned and returned to the EGR unit by the supply pump. The circulated water is neutralised by NaOH delivered by the NaOH pump to prevent an accumulation of sulphuric acid in the system, which originates from sulphur in the fuel. The supply pump and the NaOH pump is installed in the supply unit (SU). The surplus of water originating from the combustion process is drained from the WTS as bleed-off water and discharged to the sea. The residuals from the cleaning process are discharged to the sludge tank.

When discharge of bleed-off water is not possible due to insufficient water quality or local discharge restrictions, the bleed-off water should be led to the sludge tank. The tank should be designed with a sufficient volume to hold the accumulated bleed-off water.

An alternative solution, which would give the opportunity to reduce the sludge tannk volume, is to lead the retained bleed-off water to a dedicated drain tank. In this case the bleed-off water could be discharged to the sea at a later stage, provided the drain is returned to the WTS and handled by the bleed-off system.

In order to avoid the overboard discharge system and thereby to simplify the WTS, the drain tank could be dimensioned to hold the total amount of bleed-off water accumulated in a voyage. The accumulated bleed-off water should in this case be delivered at port. As the amount of bleed-off water is high this would require a tank of a significant size.

Engines configured with two EGR units will need a supply unit for each unit. In case of twin-engine EGR installations, the WTS could facilitate both engines, provided a supply unit is installed for each EGR unit. The WHS for a twin engine installation is illustrated in Fig. 1.17, which also illustrates the WHS for engines with two EGR units although a common pipe from the EGR units might be used.



<sup>1</sup> A new guideline, "Guideline for the discharge of bleed-off water from exhaust gas recirculation systems", will replace this reference when adopted (expected in October 2018)









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**Fuel sulfur impact** on WHS The EGR system is designed in a low sulphur version (LS EGR) and a high sulphur version (HS EGR) limiting the maximum allowable fuel sulphur content at 0.1% S and 3.5% S respectively. The principle of the WHS is unchanged but the capacities in the system, i.e. water flow, cleaning capacity and dimensions of equipment, are increased in the HS EGR version.

> In case a high sulphur fuel is used on board an exhaust gas cleaning system must be installed to comply with the required SOx emission limits. Depending on the exhaust gas cleaning system some synergy effect could be obtained by the WHS, i.e. common NaOH tank and sludge tank or some common water treatment functions, provided that no negative effects are introduced on the systems this way.

**Receiving Tank Unit** The receiving tank unit (RTU) includes a pressurised tank, a circulation pump and a control valve. The unit is part of the engine and normally placed on the engine but in certain cases, where space is limited, the pump and related equipment could be arranged differently.

The water level in the receiving tank is regulated by the RTU control valve. The level is controlled in combination with the supply pump, which delivers a constant water flow to the RTU circuit. The pH value in the RTU circuit is controlled by addition of NaOH, supplied in the return pipe from the WTS circuit by the NaOH pump.

Supply Unit The supply pump and the NaOH pump are yard supply and not part of the RTU or WTS. The pumps might be installed in a supply unit (SU) on a common frame as shown in fig 1.18. Other arrangements are possible too.



Fig 1.18: Supply unit, designed by PipeCon



Water Treatment System

The water treatment system (WTS) includes a buffer tank, a WTS pump, a water treatment unit (WTU) and quality control (QC). The WTS might be placed on one or more frames to facilitate a convenient engine room installation.

The WTS has two functions:

- Cleaning of the recirculated EGR process water
- Control, cleaning and discharge of excess water, generated in the EGR proces

The discharge of bleed-off water is regulated by keeping the water level in the buffer tank below a certain level. In case the bleed-off water does not meet the discharge criteria, it will be led to the sludge tank or, if available, a drain tank.

An example of a WTS from Alfa Laval and the outlines of the system, covering different power ranges and sulphur limits, are shown in Fig. 1.19 and Table 1.04. The buffer tank and pumps are arranged in a buffer tank unit (BTU) while the water cleaning is arranged in one or more water treatments units (WTU).

An optional system to reduce the amount of water accumulated in the sludge tank is also available. The dimensions of this system, which is arranged in a Waste Reduction Unit (WRU), are included in the table.



Fig. 1.19: WTS installed on two frames, BTU and WTU, both by Alpha Laval





Fig. 1.20: WTS installed on two frames, BTU and WTU, both by Alpha Laval

ME power range					
3.5% S fuel	0.1% S fuel	Unit	L	В	Н
Max 17 MW	Max 52 MW	BTU WTU	1700 2900	1800 1800	2250 2250
17 - 35 MW	52 - 82 MW	BTU WTU	1850 2900	1950 3600	2550 2250
35 - 52 MW	-	BTU WTU	1850 2900	2050 5400	2750 2250
52 - 69 MW	-	BTU WTU	2000 2900	2200 7200	2950 2250
69 - 86 MW	-	BTU WTU	2000 2900	2200 9000	3150 2250
All power ranges		WRU	800	800	1900

Table 1.04: Estimated WTS dimensions for 0.1% sulphur fuel, by Alfa Laval. The ME power range for 3.5% fuel are estimates.

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#### 1.2.7 EGR Control System

The EGR control is handled by the emission reduction control system (ERCS), which is mandatory on all MAN B&W two-stroke Tier III engines. The ERCS is delivered by the engine builder.

On engines with EGR, the ERCS controls the EGR valves, the EGR blowers and part of the water handling system, i.e. the receiving tank unit (RTU), the supply unit (SU) and the interface to the water treatment system (WTS). The ERCS has a close integration with the engine control system (ME-ECS) and communicates to the ME-ECS via a bus connection. On engines with EGR the ERCS consists of 2-4 MPCs, depending of the number of EGR blowers, and 1 ERCS MOP.

The  $O_2$  amount in the scavenge air receiver is controlled by the EGR controller in the ERCS by adjusting the speed of the EGR blowers and thus the amount of recirculated exhaust gas.

# **EGR blower control** The EGR blower control system consists of a frequency converter with a local operating panel which supplies the EGR blower with power. An EGR system can have up to 4 EGR blowers, each one with a frequency converter.

The blower control system monitors and controls the blowers and adjusts the exhaust gas flow in the EGR line, in accordance with input from the EGR control system.

Special requirements apply for the power cabling between the frequency converter and the blower to ensure compliance with EMC regulations. The interface between the EGR blower control and ERCS is hardwired.

# **WTS control** The WTS control system controls all pumps and valves in the WTS. The main control is found on the WTS frame. The WTS control has a local control panel as well as a control panel in the engine control room. The interface between the WTS and ERCS is hardwired.

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#### 1.2.8 Installation

Engine room arrangement A schematic arrangement of the EGR installation is shown in Fig. 1.21. The receiving tank unit (RTU) is integrated on the engine. The system allows a flexible arrangement of the water treatment system (WTS) and the supply unit (SU) in the engine room, giving a possibility to place the units at levels above or below the position shown in Fig. 1.21. The NaOH tank should be located at the same level or above the SU to ensure a natural flow to the pump. The sludge tank should be placed at an adequate level below the WTS to avoid any special arrangement for draining of sludge to the tank. The optional drain tank may be located close to the sludge tank but could also be placed at same level as the WTS.



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EGR c	cooling	system
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The EGR engines are specified with central cooling system using freshwater as cooling media to prevent material damage to the EGR cooler and unit. In certain cases, if special precautions are taken, a combined cooling system can be used, using central cooling for the EGR cooler and seawater cooling for the scavenge air cooler.

An optimised cooling system for EGR could be installed to reduce the pump power consumption, when the EGR system is not operating. In this case the vessel cooling water pumps must be prepared for variable flow regulation in way of either variable frequency drives or a well-defined two speed operation. The ad-on functionality at the engine comprises of a valve arrangement, which automatically shut off the water supply to the EGR cooler when the engine runs in Tier II mode.

**Pipes for Water Handling System Handling System The pipes installed for the WHS should be designed for a pH range of 3 – 9 and** a maximum pressure of 10 bar. The material should be stainless steel but other material, such as glass-fibre reinforced plastic suitable for the medium, could be used. The pipe dimensions must be adequate for the water flow which is related to the engine power. The estimated water flow is found in Section 1.2.9 Consumptions and capacities.

NaOH tank NaOH is a corrosive and harmful product with a tendency to crystallise at low temperatures, and the NaOH tank installation must therefore be designed with this in mind. The material could be stainless steel, specially coated steel, polymer or other materials suitable for the product. <sup>2</sup> If a 50% NaOH solution is used, the liquid will start to crystallise below 12 °C, and the tank should therefore keep a minimum temperature of 16 °C. Accordingly, the tank should be installed in a room with a controlled temperature or be insulated and fitted with means for heating. However, if a 30% NaOH solution is chosen, the crystallising temperature is 4 °C and the temperature demand does not call for special requirements, but the required volume of the tank will be larger due to the lower NaOH concentration. The installation of the tank should include precautions to prevent any leakage from the tank and tank connections.

When estimating the required capacity of the NaOH tank, several parameters must be considered: the Tier III sailing time and sailing pattern, the fuel sulphur content, the NaOH concentration and the planned bunker frequency. An example of estimating the NaOH tank capacity is given in Section 1.2.10 Calculation of EGR data

Sludge tank

The sludge outlet from the WTU is an aqueous solution of combustion particles, sulphur compounds and other material separated from the recirculated water. The pH value normally varies 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, which holds similar sludge to be discharged to reception facilities.

The capacity of the sludge tank depends on the Tier III sailing time and sailing pattern, the fuel sulphur content and the planned discharge period. An example of estimating the sludge tank capacity is found in Section 1.2.10 Calculation of EGR data.

2 See also The Chlorine Institute, Pamflet 94 regarding storage and piping





In case the sludge tank is designed as a settling tank, further removal of water from the sludge could be obtained, thereby minimising the amount of sludge to be delivered ashore. An optional function in the WTU using the capacity of the separators for this purpose is available as referred in section 1.2.6 Water Hand-ling System.

Drain tank As explained in the previous section, a drain tank might be installed to retain bleed-off water, which by any reason could not be discharged into the sea. The tank should be designed with a sufficient volume to hold the amount of bleed-off water generated in the period where discharge is not possible. The accumulated bleed-off water may be discharged to the sea at a later stage, using the WTS to control the discharge.

The design of the drain tank could be based on an estimate of the expected time and sailing distance in which a discharge could not take place or an unforeseen overhaul of the WTS is required. An example of estimating the drain tank capacity is found in Section 1.2.10 Calculation of EGR data.

Example of engine room arrangements On the following pages in Fig. 1.22 an example of EGR installation in a 182,000 DWT bulk carrier is shown. Consumption and capacity data for the EGR system, including capacities of the NaOH tank, drain tank and sludge tanks, are given as an example in Section 1.2.10 Calculation of EGR data.



Ship: Engine: EGR system: Fuel sulphur: 182,000 DWT Bulk carrier 6G70ME-C9.5, 16.4 MW By-pass matching 0.1% S

Fig. 1.22: Example of EGR System on a 182,000 DWT Bulk carrier, arrangement by Odense Maritime Technology (OMT)

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# 1.2.9 EGR Spare parts and maintenance

Spare parts that support the operation of the EGR system are given below.

Required spare for unrestricted engine operation (MDT):

- 1 pcs. Blindflange for Exh. Gas Reciever.
- 1 pcs. Blindflange for EGR mixing chamber

Recommended spares for unrestricted EGR operation:

- 2 pcs. Pre-spray nozzles.
- 1 pcs. O-ring for EGR cooler.
- 1 pcs. Complete Siemens Sipart controller incl. NCS and magnet.
- 2 pcs. pH-sensor probes.
- 1 pcs. Level sensor for RTU (can be used in var. EGR applications).
- 1 bottle gas for SUC 2-point calibration.
- 2 pcs. Seals for EGR sludge trap.

Spare parts for Water Treatment System and Supply Unit should be in accordance with the supplier's recommendation.



# 1.2.10 EGR retrofit

If a ship is not intended during its lifetime to enter a NOx ECA, in which it would be required to meet Tier III regulation, there would be no reason to include a comprehensive Tier III installation.<sup>3</sup> However, any doubt on whether the ship in the future would enter the area could lead to a decision to install the equipment anyway or at least prepare the ship for a retrofit installation.

Two methods to prepare for EGR retrofit installation are available:

- EGR Tier III DS (Design Specification)
- EGR prepared Tier II DS (Design Specification)
- EGR Tier III DS is the solution for ships where an EGR solution most likely will be needed in a later period of the ship. This gives the opportunity to postpone the purchasing and installation of several sub-components and thereby delay the related first cost expenses, installation cost and aging of components in the system. However, it should be kept in mind that installation on a ship in service, even when planned for docking period in connection with a renewal survey, is more complicated and time consuming than installation during new building. Accordingly, the extent of preparation for the EGR retrofit installation should be carefully considered.

The EGR Tier III DS solution would include the parent engine of a certain series of vessels to be tested and certified as a Tier III engine. If installed on board, including required auxiliary systems, the ship owner is provided with a Tier III compliant ship. However, if the date for Tier III compliance on this ship is uncertain, some Tier III components already produced and tested for this engine needs not be installed, and the additional Tier III auxiliary systems required for the system needs not be purchased before it is actually required.

The subsequent member engines for the ships in the series could be configured more or less prepared for EGR retrofit or as fully EGR Tier III compliant engines if convenient. It must be noted that in case some ships in the series are planned for alternative fuel sulphur compliance (HS versus LS) for Tier III mode, the engines for these ships need another parent engine certification for compliance even in case the engine rating is unchanged.

The extent of EGR preparation and retrofit installation can be organised in 4 categories:

- Required: Preparations and installations required for retrofit installation
- Recommended: Installations recommended for the EGR prepared engine
- Convenient: Installations convenient for inclusion in the EGR prepared engine
- Postponed: Sub components recommended for postponement for final Tier III installation



<sup>3</sup> Tier III requirements will apply to ships constructed after January 1st 2016 for ships sailing in North American ECA, and to ships constructed after January 1st 2021 for ships sailing in Northern Europe ECA. Requirements for future ECA's will relate to the date of the ECA designation.

In Table 1.05 and Fig 1.23 a suggestion of components and preparations for Tier III DS retrofit based on the 4 categories are given.

EGR Tier III DS retrofit preparation

Phase	EGR TC by-pass	EGR TC cut-out
Required	Tier III certified parent engine	Tier III certified parent engine
	- EGR unit holding brackets Reinforcement for RTU Scavenge air mixing chamber - EGR gas pipe connections Exhaust gas by-pass valve EGR engine platforms and galleries Relevant blind flanges and dummies Sufficient auxiliary power Sufficient central cooling capacities Reservation of space WTS, tanks etc.	EGR TC configuration TC cut-out valves EGR unit holding brackets Reinforcement for RTU Scavenge air mixing chamber EGR unit EGR/scav. air cooler EGR gas pipe connections Cylinder by-pass valve EGR engine platforms and galleries Relevant blind flanges and dummies Sufficient auxiliary power Sufficient central cooling capacities Reservation of space WTS, tanks etc.
Recommended <sup>5</sup>	EGR unit RTU Platform Integrated tanks (i.e. sludge/drain tanks)	- RTU Platform Integrated tanks (i.e. sludge/drain tanks)
Convenient	EGR Gas pipes Water pipes/valves on engine EGR power cabling Access for retrofit installation	EGR Gas pipes Water pipes/valves on engine EGR power cabling Access for retrofit installation
Postponed	EGR control system Receiving tank unit, RTU Cabling EGR blower EGR cooler EGR shut down valve EGR closing valve Cylinder by-pass valve Water treatment system, WTS Supply unit, SU Independent tanks (i.e. NaOH tank) Water pipes NaOH pipes Bunker pipes Venting pipes	EGR control system Receiving tank unit, RTU Cabling EGR blower - EGR shut down valve EGR balance valve - Water treatment system, WTS Supply unit, SU Independent tanks (i.e. NaOH tank) Water pipes NaOH pipes Bunker pipes Venting pipes

Table 1.05. Components and preparations for EGR Tier III DS retrofit installation

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- 4 Strongly recommended if retrofit planned at first renewal survey
- 5 Recommended if retrofit is planned at first renewal survey







Fig. 1.12: Retrofit preparations for EGR Tier III DS installation

EGR prepared Tier II DS EGR prepared Tier II DS is the solution for ships where the Tier III compliance will not be needed during the planned lifetime of the ship. However, the uncertainty of the future trade of the ship could be met by a minimum preparation of a later EGR retrofit installation. This gives the opportunity to avoid the cost of the EGR system and still keeping a door open for a later installation.

In case a retrofit is later decided, a major retrofit job would be required. In addition to the cost of the Tier III equipment and its installation, expenses for modification of the engine and T/C components should be included. The engine will need re-certification for both Tier II and Tier III modes, which calls for a new sea trial, on-board survey and class approval.

The extent of EGR preparation is given as example in Table 1.06 and Fig. 1.24.

EGR prepared Tier II DS

Phase	EGR TC by-pass	EGR TC cut-out
Required	-	TC configuration according to EGR spec.
	-	TC cut-out valves
	EGR unit holding brackets	EGR unit holding brackets
	Reinforcement for RTU	Reinforcement for RTU
	Scavenge air mixing chamber	Scavenge air mixing chamber
	-	EGR unit
	-	EGR cooler
	-	Cylinder by-pass valve
	EGR gas pipe connections	EGR gas pipe connections
	Relevant blind flanges	Relevant blind flanges
	Sufficient auxiliary power	Sufficient auxiliary power
	Sufficient central cooling capacities	Sufficient central cooling capacities
	Reservation of space for WTS, tanks etc.	Reservation of space for WTS, tanks etc.

Table 1.06: EGR prepared Tier II DS





Fig. 1.24 EGR prepared Tier II DS installation



#### **1.2.11 Consumptions and capacities**

The following estimated performance and consumption data are based on ISO conditions, except where otherwise stated. <sup>6</sup> EGR data for a specific engine is available by the engine calculation programme, CEAS. <sup>7</sup>

Specific fuel oil consumption The EGR concept affects the performance data of the engine. The exhaust gas amount is reduced due to the recirculation of exhaust gas, and the specific fuel oil consumption (SFOC) therefore normally increases due to the changes in the combustion process.

In Tier III mode, the SFOC increases to a maximum of 5.0 g/kWh at 100% MCR compared to the standard Tier II engine. The change of SFOC relative to a Tier II standard high load tuned engine is shown in Tables 1.07, 1.08 and 1.09 below. Reference regarding matching methods is made to paragraph 1.2.2, EGR systems.

|--|

SFOC g/kWh – relative to Tier II standard engine				
% SMCR	Tier II mode		Tier III mode	
100		+1.0		+4.0
75		-0.5		+3.0
65		-5.0		+2.5
50		-5.0		+2.0
25		-5.0		0.0

Table 1.07: Change of SFOC on EGR engines with cut-out matching

#### $45 \leq \text{Bore} \leq 70$ - By pass matching

SFOC g/kWh – relative to Tier II standard engine			
% SMCR	Tier II mode		Tier III mode
100		+2.0	+5.0
75		0.0	+4.0
65		-5.0	+3.5
50		-5.0	+3.0
25		-5.0	0.0

Table 1.08: Change of SFOC on EGR engines of bore 45-70 with by-pass matching

6 All data presented are approximate values and subject to change without further notice

7 CEAS is found at http://www.mandieselturbo.com/ceas/index.html.

Bore  $\leq$  40 – By pass Matching

SFOC g/kWh – relative to Tier II standard engine			
% SMCR	Tier II mode	Tier III mode	
100*	+5.0	+5.0	
90*	+2.0	+4.5	
75	+1.0	+4.0	
65	-4.0	+3.5	
50	-4.0	+3.0	
25	-4.0	0.0	

\*EGR required

Table 1.09: Change of SFOC on engines of bore 40 or less with by-pass matching

# **Power consumption** The electrical power required for the EGR system is mainly related to the WHS and the EGR blower.

The electrical power required for the WHS is dependent on the engine size and the fuel Sulphur limit for the EGR system. In Table 1.10 the power for WTS, RTU pump and SU pump, which represent the WHS, is shown.

#### El power - kW/MW SMCR

0.1% S	3.5% S
1.2	2.4
0.2	0.6
0.2	0.3
1.6	3.3
	0.1% S 1.2 0.2 0.2 1.6

Table 1.10: Estimated power consumption for WHS

The electrical power required for the EGR unit relates to the EGR blower, which raises the pressure of exhaust gas for recirculation. The power is relative to the engine size, the engine load and the EGR rate. The power needed for the blower depending on the engine load is shown in Table 1.11.

El power - kW/MW SMCR			
% SMCR	EGR blower		
100		5.5	
75		4.2	
50		4.3	
25	_	2.8	

Table 1.11: Estimated power consumption for EGR blower





NaOH consumption The additive applied to neutralise the accumulated sulphur in the EGR water is normally a 50% NaOH solution, but a 30% solution could be chosen to prevent heating requirements, see Section 1.2.8 Installation. The amount of NaOH applied depends on the engine size, the engine load, the SFOC, the EGR ratio, the NaOH % and on the sulphur content in the fuel.

> The estimated NaOH consumptions for low and high sulphur fuels are shown in Table 1.12. The figures represent a standard SFOC for EGR Tier III engines.

NaOH (50% solution) - I/h/MW SMCR	50% So	olution	30% So	olution
% SMCR	0.1% S	3.5% S	0.1% S	3.5% S
100	0.17	6.0	0.28	10.0
75	0.15	5.3	0.25	8.8
50	0.11	3.9	0.18	6.5
25	0.07	2.5	0.11	4.1

Table 1.12: NaOH consumption for Low sulphur and High sulphur fuels

Sludge production The contamination of the water recirculated in the EGR system is removed by the separators in the WTS and discharged in the sludge tank. The fuel sulphur % and the water content in the sludge will have a significant impact on the sludge amount. A solution of 93% water and 7% sludge could normally be expected.

> Means of reducing the sludge amount delivered ashore could be obtained by using the capacity of the separators in the WTS, as described in 1.2.8 Installation.

In table 1.13 the estimated sludge production for low and high sulphur fuels relative to the engine load and engine size are shown.

% SMCR	0.1% S	3.5% S
100	0.60	2.5
75	0.51	2.1
50	0.30	1.3
25	0.17	0.7

Table 1.13: Sludge production for Low sulphur and High sulphur fuels

# Sludge (93% water) - I/h/MW SMCR

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## Bleed-off water

The surplus of water accumulated in the WTS is discharged as bleed-off water. The volume relates to the EGR ratio, engine size, load and the ambient conditions. An estimate of the discharge is given in table 1.14.

The size of a drain tank, which is installed to temporarily hold a bleed-off volume as explained in the previous section, should be based on the estimated volume accumulated during the period of WTS overhauling or the period where discharge is not allowed due to local restrictions. Alternatively, if no drain tank is installed, the estimated volume should be included in the sludge tank for delivery at port reception facilities.

Bleed-off -	I/h/MW	SMCR
Dioou on	1/ 11/ 101 00	0111011

% SMCR	0.1%S	3.5%S
100	60	70
75	48	41
50	30	35
25	16	18

Table 1.14: Estimated discharge of bleed-off water



# MAN Diesel & Turbo

Freshwater consumption	Besides of the initial filling of the Water treatment system freshwater is mainly used as process water for the sludge discharge in the separator process. Al- though various parameters will influence the required amount, the freshwater consumption could be calculated from the sludge volume including a surplus of 20%, i.e. sludge × 120%.
EGR cooling water capacity	The capacity of cooling water for the EGR Tier III engine is increased due to the need for cooling the recirculated exhaust gas, which has a significantly higher temperature than the scavenge air it is replacing. The cooling water amount for scavenge air cooling in Tier III mode is increased by about 45% compared to the standard Tier II.
Lube oil capacity	The lubricating oil flow is only slightly increased on an EGR Tier III engine. The lubricating oil flow for the EGR blowers, which are the only additional consumers, will be around 0.3 m <sup>3</sup> /h/MW SMCR with a minimum of 3.6 m <sup>3</sup> /h.
Compressed air capacity	Compressed air is needed for sealing of the EGR blower and for control pur- poses throughout the EGR system. The required sealing air for the EGR blower will be around 2.5 kg/h/MW SMCR with a minimum of 30 kg/h.

# 1.2.12 Calculation of EGR data

An example of EGR data for a 16.4 MW engine is calculated below for a specific NECA sailing pattern. The example is given for fuels of 0.1% S and a 3.5% S. The consumption and capacities are found by the engine calculation programme, CEAS, as noted in the previous section. An engine room arrangement for this installation is given as an example in section 1.2.8 Installation. A NaOH solution of 30% is used for low sulphur fuel to avoid heating of the small NaOH tank.

#### **Assumptions:**

Ship	Bulk carrier
Size	182,000 DWT
Engine	6G70ME-C9.5
Power, SMCR	16,440 kW
Engine speed	83.0 rpm
EGR system	By-pass matching
Fuel Sulphur content - LS	0.1% S
Fuel Sulphur content – HS	3.5% S
NaOH solution – LS	30%
NaOH solution – HS	50%
NaOH tank margin	10%
Sludge tank margin	33%
Drain tank margin	33%
NaOH bunker frequency	300 operating hours in NECA
Sludge discharge frequency	50 operating hours in NECA
Bleed-off period of no discharge	6 operating hours in NECA
NECA sailing time	600 h/year
NECA sailing profile 25% MCR	30% time/180h
NECA sailing profile 50% MCR	30% time/180 h
NECA sailing profile 75% MCR	30% time/180 h
NECA sailing profile 100% MCR	10% time/60 h

### Step 1

Based on the input from the specified engine, CEAS provides the data for SFOC in Tier II and Tier III mode, and the electric power consumption, NaOH consumption, sludge amount and bleed-off discharge in Tier III mode. The additional fuel consumptions in Tier III mode are shown in Table 1.15, and Table 1.16.

### Step 2

The total consumption in NECA i.e. when the EGR system is operating, will depend on the sailing profile and the sailing time in the area. When multiplying the values found in step 1 with the sailing profile values, the consumption for one hour could be found. The yearly consumption is found when the NECA sailing time is known. The result is shown in Table 1.17.

### Step 3

The NaOH and the sludge tank capacity can be calculated when the bunker frequency of reducing agent and the frequency of the sludge discharge is known. A margin should be included to compensate for variations in the sailing profile and sailing hours. The size of drain tank, if installed, could be based on a specific time sailing in an area with discharge restrictions or an expected overhaul time for an unforeseen breakdown of the WTS. If drain tank is not installed, the size of the sludge tank should be increased to include an unforeseen accumulation of bleed-off water. The result of the calculation, is shown in Table 1.18.



Engine load, % MCR	25%	50%	75%	100%	
SFOC Tier III	169.0	164,5	161.0	165.0	g/kWh
SFOC Tier II	164.0	156.5	156.5	162.0	g/kWh
Additional SFOC	5.0	8.0	4.5	3.0	g/kWh
Additional fuel Tier III	20.6	65.8	55.5	49.3	kg/h

Table 1.15: EGR fuel consumptions

Engine load, % MCR		25%	50%	75%	100%	
Power, EGR blower		49.0	67.0	64.0	84.0	kW
Power, WTS	0.1%S	27.3	27.3	27.3	27.3	kW
NaOH 30%	0.1%S	1.7	2.5	3.5	4.1	l/h
Sludge	0.1%S	6.0	12.0	19.0	22.0	l/h
Bleed-off water	<u>0.1%S</u>	156	331	526	655	<u>l/h</u>
Power, WTS	3.5%S	54.6	54.6	54.6	54.6	kW
NaOH 50%	3.5%S	35.0	52.5	73.5	87.5	l/h
Sludge	3.5%S	11.0	21.0	32.0	40.0	l/h
Bleed-off water	3.5%S	341	501	706	853	l/h

Table 1.16: EGR operating values

Engine load, % M	CR	25%	50%	75%	100%	Total per hour		Total per year	
NECA load profile	Time	30%	30%	30%	10%				
Additional fuel		6.2	19.7	16.6	4.9	47.5	kg/h	28.5	ton/year
Power, EGR blow	er	14.7	20.1	19.2	8.4	62.4	kWh/h	37.4	MWh/year
Power, WTS	0.1%S	8.2	8.2	8.2	2.7	27.3	kWh/h	16.4	MWh/year
NaOH 30%	0.1%S	0.5	0.8	1.0	0.5	2.7	l/h	1.7	m³/year
Sludge	0.1%S	1.8	3.6	5.7	2.2	13.3	l/h	8.0	m³/year
Bleed-off water	0.1%S	46.8	99.3	157.8	65.5	369.4	l/h	221.6	m³/year
Power, WTS	3.5%S	16.4	16.4	16.4	5.5	54.6	kWh/h	32.8	MWh/year
NaOH 50%	3.5%S	10.5	15.8	22.1	8.8	57.1	l/h	34.2	m³/year
Sludge	3.5%S	7.4	14.8	23.4	9.1	54.7	l/h	32.8	m³/year
Bleed-off water	3.5%S	80	150	227	94	552	l/h	331	m³/year

Table 1.17: Accumulated EGR operating values

Item		Frequency		Volume		Margin	Tank size	
NaOH tank (30%)	0.1%S	300	hours	0.8	m <sup>3</sup>	10%	0.9	m <sup>3</sup>
Sludge tank	0.1%S	50	hours	0.7	m <sup>3</sup>	33%	0,9	m <sup>3</sup>
Drain tank	0.1%S	6	hours	2.8	<u>m<sup>3</sup></u>	33%	3.8	<u>m<sup>3</sup></u>
NaOH tank (50%)	3.5%S	300	hours	17.1	<u>m<sup>3</sup></u>	10%	18.8	<u>m<sup>3</sup></u>
Sludge tank	3.5%S	50	hours	2.7	m <sup>3</sup>	33%	3.6	m <sup>3</sup>
Drain tank	3.5%S	6	hours	3.3	т³	33%	4.4	т³

Table 1.18: EGR tank capacities

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# 1.3 SCR – Selective Catalytic Reduction

Unless stated otherwise the SCR solutions in this chapter assume low sulphur fuels ( $\leq$  0.1% S) for Tier III running modes.

# 1.3.1 SCR principle

Selective Catalytic Reduction (SCR) is an exhaust gas treatment method by which the  $NO_x$  generated in a marine diesel engine can be reduced to a level in compliance with the  $NO_x$  Tier III requirements.

The NO<sub>x</sub> reduction is obtained by a catalytic process in an SCR reactor installed in the exhaust gas line after the combustion process. In the SCR reactor, the NO<sub>x</sub> is reduced catalytically to nitrogen and water by adding ammonia as a reducing agent. The catalyst in the reactor consists of blocks with a large number of channels, providing a large surface area, in which the catalytic process takes place, see Fig. 1.32.



Fig. 1.32: The SCR system

 $\mathrm{NO}_{\mathrm{x}}$  is reduced according to the following overall reaction scheme:

For reasons of safety, the ammonia is normally added to the system in the form of aqueous urea. This decomposes to ammonia and carbon dioxide when it is injected into the vaporiser:

$(NH_2)_2CO_{(aq)}$	$\rightarrow$ (NH <sub>2</sub> ) <sub>2</sub> CO <sub>(s)</sub> + × H <sub>2</sub> O <sub>(g)</sub>
$(NH_2)_2 CO_{(s)}$	$\rightarrow NH_{3(q)} + HNCO_{(q)}$
$HNCO_{(q)} + H_2O_{(q)}$	$\rightarrow NH_{3(q)} + CO_{2(q)}$

NO<sub>x</sub> reduction – Tier III solutions SCR – Selective Catalytic Reduction



# 1.3.2 SCR system

**SCR operation** An essential parameter of the SCR process is the inlet gas temperature. A lower temperature limit is dictated by the sulphur content in the fuel and the subsequent formation of sulphuric acid in the gas. At low temperatures, the sulphuric acid is neutralised by ammonia. <sup>8</sup> This forms a sticky product, ABS (ammonium bisulphate,  $NH_4HSO_4$ ), which may accumulate in the SCR elements. However, this reaction can be suppressed by keeping a high temperature of the exhaust gas. When the sulphur content in the fuel is equal or less than 0.1%, a temperature of approximately 310 °C would be sufficient. At low exhaust gas pressures, the required minimum temperature will be lower.

The minimum temperatures required to avoid the formation of ammonia bisulphate are found in Fig. 1.33, which shows the relation between the fuel sulphur content and the exhaust gas pressure. Fig. 1.33 shows a high pressure curve (4.0 bara) and a low pressure curve (1.5 bara), which is the approximate pressure at high engine load and at low engine load respectively.



4.0 Bara1.5 Bara

Fig. 1.33: Required temperatures for SCR related to sulphur content and exhaust gas pressure

On the other hand, the temperature must not be too high as this will result in an increased  $SO_3$  formation in the catalyst.  $SO_3$  subsequently reacts with water creating sulphuric acid, which appears as an undesired white aerosol plume. Another undesired reaction which also limits the upper temperature for SCR operation is the oxidation of NH<sub>3</sub> as the exhaust gas temperature approaches 500 °C, i.e. more NH<sub>3</sub> is needed. Additionally, the catalyst material starts to sinter at temperatures above 500-550 °C.

In other words, to ensure a robust SCR operation it is crucial to maintain exhaust gas temperatures within a certain temperature window.

The low sulphur SCR systems could be chosen as high pressure low sulphur (HP LS SCR) or low pressure low sulphur (LP LS SCR) installation, explained in the following paragraphs.

8 The temperature limit may vary depending on the catalyst type.

pressure

SCR process - High The HP LS SCR process, illustrated in Fig. 1.34, takes place in the SCR line, which consists of two major components: the combined vaporiser/mixer unit and the SCR reactor. In the vaporiser, the catalytic process is prepared by injecting the reducing agent which will vaporise and mix with the exhaust gas. The prepared gas is led to the SCR reactor where the NO, reduction takes place.

> Due to the demand for a relatively high temperature of the SCR process, it is convenient to place the SCR line on two stroke marine diesel engines on the high pressure side, i.e. before the turbocharger. Depending on the engine load, the exhaust gas temperature on this side is 50-175 °C higher than on the low pressure side.



Fig. 1.34: HP LS SCR system

When operating in Tier II mode, the SCR system is cut off by the reactor sealing valve (RSV) and the reactor throttle valve (RTV). The reactor bypass valve (RBV), is open and exhaust gas passes directly to the turbocharger. The system also includes an exhaust gas by-pass valve (EGB) to provide the engine with low load EGB tuning in Tier II. When operating in Tier III mode the SCR system will be engaged. The SCR line is opened by the valves, RSV and RTV, while the valve RBV will be closed.

Even though the reactor is placed before the turbine, the exhaust gas temperature will normally still be too low at low loads. To increase the temperature, a cylinder bypass from the scavenge air receiver to the turbine inlet is installed. The bypass is controlled by the cylinder bypass valve, CBV. When opening the bypass, the mass of air through the cylinders will be reduced without loosing the scavenge air pressure and, accordingly, the exhaust gas temperature will increase. This system makes it possible to keep the temperatures above the reguired level. However, the cylinder bypass will increase the SFOC depending on the required temperature increase.



Fig. 1.35 illustrates the load range, when using low sulphur fuels, in which the cylinder bypass must be open to keep a sufficient temperature for the SCR process. The required cylinder by-pass range will be wider on an engine with a relative low turbine inlet temperature compared to one with a higher temperature.



Fig. 1.35: Cylinder by-pass range to meet minimum turbine inlet temperatures

At low loads, below approximately 15% MCR depending on the engine and sulphur content, the urea injection will be suspended in order to prevent deposits in the SCR system caused by insufficient temperatures.

The HP SCR reactor and vaporiser introduce a significant heat capacity and thermal delay between the exhaust receiver and the turbocharger. During Tier III operation this could lead to thermal instability of the engine and turbocharger at any engine load depending on the size and heat capacity of the installed SCR system. To counteract this instability, the auxiliary blowers will deliver additional charge air to stabilise the system. The auxiliary blowers are furthermore used to improve the heating time of SCR at all loads and during engine accelerations.

The auxiliary blowers should be able to support operation until 65% SMCR and for this reason the capacity of the electrical motor for the auxiliary blowers must be increased approximately 1.5 times the standard motor rating.

# SCR process – Low pressure

When restricting the sulphur content in the fuel during the SCR operation to 0.1% S or less, it is possible to install a low pressure SCR system. In this system, the SCR line is placed after the turbo charger which provides flexibility for arranging the SCR installation.

The LP LS SCR system, illustrated in figure 1.36, consist of three major components: an SCR reactor, a mixer (AIG - ammonia injection grid) and a Decomposition Unit (DCU). The DCU, which is placed in a gas line between the reactor outlet and mixer inlet, consists of a blower, a heater (burner) and a vaporiser. The reducing agent is injected in the vaporiser forming a mixture of ammonia vapour, which is let to the mixer and finally to the SCR reactor, forced by the blower. Even when using low sulphur fuel the exhaust gas temperature is still too low for the SCR process, especially at low engine loads or cold ambient conditions. To increase the exhaust gas temperature to the required level, part of the exhaust gas from the high pressure side of the turbine is bypassed, controlled by an Exhaust Gas Bypass valve (EGB), and directed to the low pressure side. As a consequence of the bypass the SFOC will increase depending on the required temperature.

Although the fuel sulphur content is very low, ABS formation can not be entirely avoided. One method to dissolve the ABS is to use the DCU to heat and circulate an appropriate amount of gas through the reactor to remove the ABS.



Fig. 1.36: LP LS SCR system



# Tuning methods

High Pressure SCR SCR systems, designed for high pressure and low sulphur operation, use "HP LS SCR" tuning. In Tier II mode the SFOC and the exhaust gas properties are the same as for a standard Tier II engine with "Low Load EGB" tuning. In Tier III mode the SFOC values are increased between 0.5 and 2.0 g/kWh compared to a low load tuned Tier II engine. An overview of the valve control on HP LS SCR is shown in Table 1.37. As the opening range of CBV is dependent on the specific engine rating an undefined range between 25% and 75% MCR is shown for this valve.

	Tier II r	er II mode Tier III mode								
MCR	RBV	RSV	RTV	CBV	EGB	RBV	RSV	RTV	CBV	EGB
100 85					Open				Closed	Open
75	Open	Closed	Closed	Closed		Closed	Open	Open		
50					Closed				Open	Closed
25									opon	

Table 1.37: Valve control of HP LS SCR system

Low Pressure SCR SCR systems, designed for low pressure and low sulphur operation, use "LP LS SCR" tuning. In Tier II mode the SFOC and the exhaust gas properties are the same as for a standard Tier II engine with "Low Load EGB" tuning. In Tier III mode the SFOC values are increased between 1.0 and 2.0 g/kWh compared to a low load tuned Tier II engine. An overview of the valve control on LP LS SCR is shown in Table 1.38.

	Tier II mo	de			Tier III mode			
MCR	RBV	RSV	RTV	EGB	RBV	RSV	RTV	EGB
100				0000				
85				Open				
75	Open	Closed	Closed		Closed	Open	Open	Open
50				Closed				
25								

Table 1.38: Valve control of LP LS SCR system

The SFOC is further specified in chapter 1.3.8 Consumption and capacities.

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SCR influence on boiler	The slip of ammonia from the SCR system combined with sulfur originating from the fuel can lead to deposits of ABS (Ammonium bisulfate) on the low tempera- ture surfaces of the exhaust gas boiler. The amount of ABS deposits is depend- ent on the type of fuel used during SCR operation and on the amount of ammo- nia slip from the SCR reactor.
Low sulfur fuel opera- tion (≤0.1%)	For SCR systems designed for low sulfur fuels the formation of ABS in the boiler is limited due to the low amount of sulfur in the exhaust gas. Even if the ammo- nia slip from the SCR system is increased, the formation of ABS will be limited due to the low sulfur content. Furthermore, the deposits formed in the boiler during low sulfur operation are easily removed by standard cleaning methods
High sulfur fuel opera- tion (>0.1%)	SCR systems designed for high sulfur fuels can lead to significant ABS deposits when the sulfur content and ammonia slip is high. Furthermore, the deposits formed in the boiler under SCR operation with high sulfur fuel tend to be sticky and hard to remove by standard cleaning methods. It is the experience that well designed high sulfur SCR system will have low ammonia slip and the ABS de- posits will be limited. However, to secure unrestricted passage of exhaust gas from the main engine in the exhaust gas line, it is recommended to install a by- pass of the exhaust gas boiler for use during SCR high sulfur fuel operation.



# 1.3.3 SCR layout

Although the SCR system is closely related to the engine, the SCR line is not part of the engine delivery. The system, however, must be based on specifications from MAN Diesel & Turbo.

The size of the SCR components is determined by the gas flow and depends on the specified engine power, but other factors will influence the size too. Among these factors are:

- the specified lifetime of the catalyst elements if an increased lifetime of the catalyst elements is required, the volume of catalyst and accordingly the size of the reactor will increase
- the choice of reducing agent if ammonia is chosen as the reducing agent, the process time for vaporising is reduced and only a small mixer is needed. However, the storage and handling of ammonia will be more complex compared to urea.
- High Pressure SCR An example of a high-pressure SCR system, supplied by Hitachi Zosen Corporation, is shown in Fig. 1.39. As the exhaust gas is led from the SCR reactor to the turbocharger, the system is arranged close to the engine. The arrangement, which also includes a turbine bypass, could be chosen differently according to engine room restrictions.



Fig. 1.39: Layout of a high-pressure SCR system, as supplied by Hitachi Zosen

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Low Pressure SCR

An example of a low-pressure SCR system, supplied by Doosan Engine Corporation, is shown in Fig. 1.40. The system is connected to the exhaust gas pipe after the turbine outlet, providing flexibility to arrange the SCR away from the engine.



Fig. 1.40: Layout of a low-pressure SCR system, as supplied by Doosan



# 1.3.4 Outline

High Pressure SCR

An example of a high-pressure SCR outline is shown in Fig. 1.41. The SCR line can be arranged in different ways to meet the engine room restrictions.



Fig. 1.41: SCR installation on an 8 MW engine (6S46ME-B) using Hitachi Zosen HP SCR system

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Low Pressure SCR

An example of a low-pressure SCR engine is shown in Fig. 1.42. The SCR line is placed in the exhaust gas line away from the engine, providing high flexibility for the arrangement.



Fig. 1.42: SCR installation on a 14 MW engine (6S60ME-C) using Doosan LP SCR system

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# 1.3.5 SCR auxiliary systems

Supply system of reducing agent The reducing agent used for the SCR process is either anhydrous ammonia  $(NH_3)$ , aqueous ammonia (25%  $NH_3$ ) or aqueous urea (32.5% or 40% solution).

As anhydrous ammonia (NH<sub>3</sub>) is classified as a toxic and dangerous substance, it is convenient for marine purposes to use urea, which has no significant hazards. In addition, the urea supply system is less complex than the supply system for anhydrous ammonia, but the consumption and storage volume of urea is larger. In addition, urea requires a more complex vaporising and mixing process which influences the layout of the SCR system. Aqueous ammonia (25% NH<sub>3</sub>), although corrosive and harmful for the health and environment, could with some precautions be handled like urea. Independent of the selected reducing agent, the injection is performed in combination with compressed air.

It is essential that both the injection and the mixing of the reducing agent are performed effectively. Any unused ammonia, defined as the ammonia slip, is likely to react with the exhaust gas to become ammonium bisulphate ( $NH_4HSO_4$ ) when the temperature decreases, and involves the risk of deposits in the exhaust gas system, e.g. in the exhaust gas boiler.

Urea

An example of a urea supply system is shown in Fig. 1.43. From the storage tank, urea is pumped to the vaporiser/mixer by a urea pump in the supply unit. The supply unit also has a wash water tank and a pump for purging the urea injection nozzles. A control unit controls the injection of urea and compressed air into the vaporiser. When the SCR process is shut down, the urea injection nozzles are purged with wash water to prevent clogging of the nozzles. As an alternative, urea could be stored as solids and mixed on board

Ammonia (NH<sub>3</sub> anhydrous)

Ammonia supplied as anhydrous  $NH_3$  is classified as a toxic substance and harmful for the health and environment and is not used for marine purpose.

Ammonia (aqueous solution)

Ammonia supplied as an aqueous solution of  $NH_3$  (25% solution) is classified as corrosive and harmful for the environment. The storage tank and the part of the supply system that includes an evaporator must be situated in a separate room away from the machinery room and the accommodation, see Fig. 1.44. The consumption and storage volume for this solution is largely the same as for urea.

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Soot blower system	To prevent contamination of the reactor elements, a soot blower system using compressed air to keep the SCR reactor clean is installed. The soot blower process is performed periodically during the SCR process and the soot is led out with the exhaust gas after being blown loose from the elements inside the reactor.

SCR heating system The SCR reactor and the vaporiser have significant heat capacities due to the size and mass of the components. The system should normally be engaged in due time before entering a NO<sub>x</sub> ECA to obtain the right operating temperature of the SCR reactor and vaporiser. However, when in harbour, i.e. at engine standstill, the temperature will slowly decrease and means to keep the temperature at the required level or to heat up the system must be available. To meet this demand, the system needs to be equipped with heat tracing or other appropriate means.

1.3.6 SCR control s	ystem
	The SCR control is handled by the Emission Reduction Control System (ERCS), which is mandatory on all MDT 2-stroke Tier III engines. The ERCS is delivered by the engine builder.
High Pressure SCR control system	On engines with High Pressure SCR the ERCS controls the reductant dosing amount and the SCR valves. It further handles the interfaces to a number of subsystems. These subsystems comprise a reductant dosing system, a soot blowing system, a standby heating system and a venting system. The subsystems mentioned may be implemented as one or more systems. The ERCS has a close integration with ME-ECS and communicates to ME-ECS via a bus connection. The ERCS on High Pressure SCR consists of 2-3 MPCs, depending on the configuration, and 1 SCR MOP.
Low Pressure SCR control system	On engines with Low Pressure SCR the ERCS controls the reductant dosing amount and handles interfaces to a number of subsystems. These subsystems comprise a reductant dosing system, a valve control system and a regenera- tion system. The subsystems mentioned may be implemented as one or more systems. The ERCS has a close integration with ME-ECS and communicates to ME-ECS via a bus connection. The ERCS on Low Pressure SCR consists of 1 MPC and 1 SCR MOP.



# 1.3.7 Installation

Engine room arrangement A schematic arrangement of an SCR installation using urea as the reducing agent is shown in Fig. 1.45. The arrangement includes a compressor unit supplying compressed air to the injection process and to the soot blower system. The compressor can be part of the general supply of compressed air for the engine room or, alternatively, be dedicated to the SCR system.





Storage of reducing agent Due to different hazards and different specific consumption figures, the arrangement, material and volume of the storage tank for the reducing agent will depend on the actual choice of reducing agent.

The required volume of the tank depends on the consumption of the specific reducing agent, the estimated ECA sailing time, the sailing pattern, and the planned bunker period. Furthermore, the lot size of the reducing agent when bunkering should be taken into consideration. An example of dimensioning the storage tank is found in the following chapter, 'Consumption and capacities'.

All material used for storage, transportation and handling of the reducing agent including tanks, tubes, valves and fittings must be compatible with the specific reducing agent to avoid any contamination of the substance and corrosion of devices used. Furthermore, the storage temperature of the reducing agent should be in accordance with the supplier's reccomendations.

Urea tank

The urea tank could be an independent tank suitable for the solution or an integrated tank properly coated. The tank must be ventilated to open air.

Ammonia tank (aqueous solution)

With aqueous ammonia as the reducing agent, it must be stored in an independent tank suitable for the solution. The tank and the supply system should be placed in a separate room ventilated to open air and the supply pipes in the engine room must be laid in ventilated ducts or double-walled pipes. The bunkering system must include a vapour return pipe to the bunker delivery.

SCR circuit installation The arrangement and installation of SCR reactor, vaporizer/mixer and gas pipes must be carefully considered, taking the high pressure and temperatures in the SCR system and the forces on the ship and engine into account. A guideline for installation and calculation of back pressure is available on request.

**Example of an SCR** arrangement The example presented in the following pages (Fig. 1.46) shows an SCR arrangement on a 6G70ME-C9.5 engine in a 182,000 DWT bulk carrier. Consumption and capacity data for this system, including capacity of the Urea tank, is given as an example in Section 1.3.9 Calculation of SCR data.

<u> NO reduction – Tier III solutions</u>

SCR – Selective Catalytic Reduction





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#### 1.3.8 Consumptions and capacities

The following estimated performance and consumption data are based on ISO conditions, except where otherwise stated. <sup>9</sup> SCR data for a specific engine is available by the engine calculation programme, CEAS. <sup>10</sup>

Specific fuel oil consumption The SCR concept affects the performance data of the engine. The influence on the specific fuel oil consumption (SFOC) for low sulphur SCR systems is depending on the choice of system, be it a high pressure (HP LS SCR) or a low pressure system (LP LS SCR). Furthermore, the engine type will have an influence, as SFOC of low pressure SCR system will be higher at low loads on ME-B engines compared to ME-C engines. An estimate of the SFOC penalty relative to Low Load EGB tuning (LL EGB) is found in Tables 1.47, 1.48 and 1.49.

SFOC g/KWh - relative to Tier II standard engine (LL EGB)

Fuel	≤3.5% S	≤0.1% S
MCR	Tier II mode	Tier III mode
100	_	+0.5
75	SFOC as	+1.0
50	LL EGB	+1.5
25		+2.0

Table 1.47: Influence on SFOC of High Pressure Low Sulphur SCR

Fuel	≤3.5% S	≤0.1% S
MCR	Tier II mode	Tier III mode
100		+1.0
75	SFOC as	+1.0
50	LL EGB	+1.0
25		+1.5

SFOC g/KWh – relative to Tier II standard engine (LL EGB)

Table 1.48: Influence on SFOC of Low Pressure Low Sulphur SCR, ME-C engines

SFOC g/KWh -	relative to	Tier II standard	engine	(LL EGB)
--------------	-------------	------------------	--------	----------

0		<b>o</b> ( <i>'</i>	
Fuel	≤3.5% S	≤0.1% S	
MCR	Tier II mode	Tier III mode	_
100		+1.0	_
75	SFOC as	+1.0	
50	LL EGB	+3.0	
25		+6.5	

Table 1.49: Influence on SFOC of Low Pressure Low Sulphur SCR, ME-B engines

9 All data presented are approximate values and subject to change without further notice
10 CEAS is found at http://www.mandieselturbo.com/ceas/index.html.

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Electrical power consumption

The power required for the SCR system is related to the auxiliary systems for the SCR system. The power consumption includes power to supply the reducing agent and the compressed air, additional power for the auxiliary blowers and for the heating of SCR reactor. The electrical power consumption is roughly regarded independent on the engine load and estimated to 5 kW/MW SMCR.

Consumption of reducing agent

The consumption of reducing agent depends on the agent type, the engine load and the NO<sub>x</sub> reduction rate. The estimated specific consumption required to reduce the NO<sub>x</sub> level from Tier II to Tier III is shown in Table 1.50. Urea consumption for a specific engine could alternatively be found by the engine calculation programme, CEAS.

Reducing agent	g/kWh	I/MWh	
Urea – 40%	17.9	16.1	
Ammonia - 24.5%	16.6	18.4	

Table 1.50: Consumption of reducing agent

Catalyst replacement Depending on the load of the SCR reactor, the catalyst elements will slowly lose the ability to facilitate the  $NO_x$  reduction process. To keep the required efficiency of the reactor, the elements should be replaced periodically according to the catalyst supplier. Therefore, the catalyst elements are regarded as consumables and should be included in the running costs of the SCR system, depending on sailing pattern and time in Tier III mode.

The catalyst lifetime depends on the need for  $NO_x$  reduction. The engine load, the  $NO_x$  reduction rate and the time, during which the reactor is engaged, will directly influence the lifetime of the catalyst. The type and relative volume of the catalyst compared to the engine size will also influence the lifetime. The lifetime of the catalyst should be specified by the supplier.



Compressed air capacity	The capacity of compressed air used for soot blowing and for the injection process relates to the reactor size, the type of reducing agent and the sulphur content in the fuel. As an alternative to a dedicated SCR compressor, it could be part of the general supply of compressed air for the engine room. The capacity of compressed air for the injection and soot blowing should be considered in the ship design process according to the supplier's standard.
SCR heating	The need for heating of the SCR components before leaving a port inside an ECA can be met by a number of different methods, but the capacity for the system chosen must be according to the SCR supplier's standard and be included in the capacity for ship.
Auxiliary blower capacity	The auxiliary blower must be able to support operation until 65% SMCR, and the capacity of the auxiliary blower is approximately 1.5 times the capacity of a standard blower configuration.



# **1.3.9 Calculation of SCR Data**

An example of SCR data for a 16.4 MW MAN B&W engine is calculated below for a specific NECA sailing pattern. The consumption and capacities are found by the engine calculation programme, CEAS, as noted in the previous section. An engine room arrangement for this SCR installation is given as an example in section 1.3.7 Installation.

#### Assumptions

	Ship Size Engine Power, SMCR Engine speed SCR system NECA Fuel Sulphur content% Reducing agent Tank margin Bunker frequency <sup>11</sup> NECA sailing time NECA sailing profile 25% MCR NECA sailing profile 50% MCR NECA sailing profile 75% MCR NECA sailing profile 100% MCR	Bulk carrier 182,000 DWT 6G70ME-C9.5 16,440 kW 83.0 rpm HP LS SCR 0.1% S Urea 40% 10% 300 operating hours in NECA 600 h/year 30% time/180 h 30% time/180 h 30% time/180 h 30% time/180 h	
Step 1	Based on the input from the specified engine CEAS provides the data used in the example for SFOC in Tier II and Tier III mode and for the urea supply in Tier III mode. The additional fuel consumptions in Tier III mode are calculated and shown in Table 1.51a. The electric power and the urea consumptions are shown in Table 1.51b. The electric power consumption are based on the data given in the previous chapter.		
Step 2	The total consumption in an NECA area, i.e. when the SCR system is operating, depends on the sailing profile and the sailing time in the NECA. When multiply- ing the values found in step 1 with the profile values, the consumption for one hour could be found. The yearly consumption is found when the NECA sailing time is known. The result is shown in Table 1.51c.		
Step 3	The Urea tank capacity is calculated agent. A margin should be included profile and sailing hours. The result of	I based on the bunker frequency of reducing to compensate for variations in the sailing of the calculation is shown in Table 1.51d.	

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<sup>11</sup> Please note, that the bunker frequency of 300 operating hours is an example of an adequate time between bunkering of urea for a return trip in the Northern European ECA ( $NO_x$ ECA from Jan. 2021)
Engine load, % MCR	25%	50%	75%	100%	
SFOC Tier III	166.8	158.0	157.5	162.0	g/kWh
SFOC Tier II	164.0	156.5	156.5	161.5	g/kWh
Additional SFOC	2.8	1.5	1.0	0.5	g/kWh
Additional fuel Tier III	11.5	12.3	12.3	8.2	kg/h

Table 1.51a: Fuel consumptions in Tier II and Tier III mode

Engine load, % MCR	25%	50%	75%	100%	
El. power	82.2	82.2	82.2	82.2	kW
Urea	85	150	180	230	l/h

Table 1.51b: Additional SCR operating values

Engine load, % MCR	25%	50%	75%	100%	Total		Total	
NECA load profile Time	30%	30%	30%	10%	per ho	ur	per year	
Additional fuel	3.5	3.7	3.7	0.8	11.7	kg/h	7.0	ton/year
El. power	24.7	24.7	24.7	8.2	82.2	l/h	49.3	MWh/year
Urea	25.5	45.0	54.0	23.0	147.5	l/h	88.5	m³/year

Table 1.51c: Accumulated SCR operating values <sup>12</sup>

Item	Parameter	Volume	Margin	Tank size
Urea tank	300 hours	44 m <sup>3</sup>	10 %	48 m <sup>3</sup>

Table 1.51d: Tank capacity of reducing agent

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12 In addition to the above consumption, the replacement of catalyst elements, which is also regarded as consumables, should be included in the evaluation

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# 2 SO<sub>x</sub> reduction 2.1 Introduction

Sulphur limits

The international requirements on emissions of SO<sub>x</sub> (sulphur oxides) and PM (particulate matter) are determined by the MARPOL convention Annex VI, which specifies a global limit and a local (SO<sub>x</sub> ECA) limit on the sulphur content in marine fuel. The specified sulphur limits will change according to the illustration in Fig. 2.01, showing a reduction in SO<sub>x</sub> ECA from 1.0% to 0.1% sulphur in 2015, and a reduction in the global limit from 3.5% to 0.5% sulphur in 2020.



Fig. 2.01: Fuel sulphur limits according to MARPOL Annex VI

Equivalents

1

Although the SO<sub>x</sub> requirements can be met by using a low-sulphur fuel, the regulation allows alternative methods to reduce the emissions of SO<sub>x</sub> to an equivalent level. The techniques used for this purpose must follow additional guidelines specified by IMO to prove equivalence with the fuel sulphur limits. <sup>1</sup>

MEPC.184(59) 2009 Guidelines for Exhaust Gas Cleaning Systems

# 2.2 Low-sulphur fuels

Diesel fuel	The SO <sub>x</sub> ECA limit can be met using a low-sulphur fuel, e.g. marine gas oil (MGO) with a sulphur below 0.1%. The limit outside SO <sub>x</sub> ECA (non-ECA) can be met using e.g. marine diesel oil (MDO) with a sulphur content below 0.5%, which will be required from 2020. Certain precautions must be taken when using these fuel types.
	Further information can be found in the paper 'Low-sulphur fuel operation', pub- lished by MAN Diesel & Turbo.
Gas fuel	As liquified natural gas (LNG) contains no sulphur, the SO <sub>x</sub> limits can be met by installing an MAN B&W ME-GI dual fuel engine, provided also the pilot oil meets the sulphur limits. Furthermore, when running in fuel oil mode, the SO <sub>x</sub> limit must be met by using low-sulphur fuels, if no alternative method for SO <sub>x</sub> reduction is available.
	Further information on ME-GI dual fuel engines can be found in the paper 'ME-GI Dual Fuel MAN B&W Engines', published by MAN Diesel & Turbo. The paper is available for download at: www.marine.man.eu $\rightarrow$ 'Two-Stroke' $\rightarrow$ 'Technical Papers'.

## 2.3 SO<sub>x</sub> scrubber

The cost of low-sulphur fuels such as MDO and MGO is high compared to heavy fuel oil (HFO). Therefore, alternative low-cost methods to reduce the emissions of  $SO_x$  by exhaust gas cleaning have been developed.

The process of exhaust gas cleaning is performed in a scrubber unit using a dry or wet agent to remove  $SO_x$  and PM. Marine engines are normally fitted with wet scrubbers using either seawater (SW), which is easily available, or recirculated freshwater (FW) with chemical addition.

This project guide describes the  $SO_x$  scrubber systems from Alfa Laval, which are based on the wet scrubber principle, but other scrubber systems are available. <sup>2</sup>



Fig. 2.02: SO<sub>x</sub> scrubber from Alfa Laval

2.3.1 Principle

In a wet scrubber, the exhaust gas is cleaned by water on its way to the funnel. The water is injected into the exhaust gas stream and is discharged from the bottom of the scrubber. The sulphur oxides generated in the combustion process due to the sulphurous fuel are dissolved and removed by the scrubber water following a simple chemical reaction:

 $SO_2 + H_2O \rightarrow H_2SO_3$  (sulphurous acid)  $SO_3 + H_2O \rightarrow H_2SO_4$  (sulphuric acid)

The water used in the process could be either seawater (SW) or freshwater (FW), which calls for different solutions for both the installation and the operation.

2 Further information on available EGC systems can be found in 'EGCSA Handbook 2012' published by the Exhaust Gas Cleaning Systems Association (EGCSA), www.egcsa. com.



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# 2.3.2 System

Basically,  $SO_x$  scrubber systems are divided into open loop systems using SW, and closed loop systems using FW as medium. Both systems could be chosen for an installation. Furthermore, when a high degree of flexibility is required, a hybrid solution could be installed, combining open and closed loop systems with the ability to switch between SW and FW scrubbing.

#### Open loop system

When SW is used for scrubbing, an open loop system is chosen as illustrated in Fig. 2.03. The natural chemical composition of seawater neutralizes the impact of  $SO_x$  in the scrubber water. The water is taken directly from the sea and fed to the scrubber. Leaving the scrubber, the water is discharged into the sea without any further treatment. The discharge criteria set by the IMO guidelines is met by the high water flow through the scrubber.



Fig. 2.03: Open loop system

The open loop system is typically used in open waters where the alkalinity of the seawater is sufficiently high for effective scrubbing. The system is simple and the cheapest solution in regards to installation and operating cost. However, an open loop system lacks flexibility when local regulations prevent or limit the use of the system due to low alkalinity or restricted discharge criteria. Open loop operation requires a SW amount of approximately 45m<sup>3</sup>/MWh when a 2.7% sulphur HFO is used.

#### Closed loop system

When FW is used for scrubbing, a closed loop system is chosen, as illustrated in Fig. 2.04. To neutralise the sulphuric acid in the scrubber water, an addition of chemicals is needed. This could be sodium hydroxide (NaOH) forming a sulphate in the following process:

$H_2SO_3 + 2NaOH + \frac{1}{2}O_2$	$\rightarrow$	$Na_2SO_4 + H_2O$
$H_2SO_4 + 2NaOH$	$\rightarrow$	$Na_2SO_4 + H_2O$



However, the sulphate and the particulate matter (PM) from the combustion process accumulates in the scrubber water. To avoid an increase in salinity and contamination of the system, the sulphate and PM must be removed continuously. This is done by bleeding off scrubber water from the system and adding FW to replace the lost volume. Most of the FW is regained in the scrubbing process by condensed water from the combustion process. To minimise the loss of FW escaping with the exhaust gas, the scrubber water is led through a cooler before it is injected into the scrubber. A demister is installed to prevent droplets escaping through the funnel. Any loss of water is supplied by the FW supply on board. Before discharging the bleed-off water, a cleaning process is required to meet the IMO guidelines criteria. The cleaning process is performed in a water cleaning unit (WCU) and the sludge is led to a sludge tank.



Fig. 2.04: Closed loop system

The closed loop system offers a high degree of flexibility for the vessel as the use is not restricted by local regulations. However, the initial costs are higher, compared to the open loop system, due to the additional equipment. In addition, operating costs are higher mainly because of the constant addition of chemicals. The flow rate in a closed loop system is about half that of an open loop, 30m<sup>3</sup>/MWh. Typically, closed loop operation requires a constant discharge at the rate of 0.1 to 0.3 m<sup>3</sup>/MWh, although the system can operate with zero discharge for limited periods.

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### Hybrid system (Open/Closed loop)

The hybrid system, illustrated in Fig. 2.05, combines both an open and a closed loop system and each of their operation modes. Due to the combination, the hybrid system is more complex, but it offers the highest degree of flexibility. The open loop mode is typically used in open waters where the alkalinity is sufficiently high for effective scrubbing. The closed loop system is used in certain enclosed waters, harbours and estuaries or where the alkalinity of the seawater is low. This combination optimises the chemical consumption and ensures that discharges do not affect sensitive areas with little water exchange.



Fig. 2.05: Hybrid system

The initial cost of the hybrid system is higher as it includes equipment for both open and closed systems to gain the flexibility. The hybrid system, however, offers the lowest operating costs as it can switch to the most economic mode in any situation. In each operation mode, the scrubber water flows are similar to the flows specified for open and closed loop systems accordingly.

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# 2.3.3 Layout

Various types of wet scrubbers exist. Fig. 2.06 shows some typical methods used by the manufacturers, including open spray, cyclonic, packed bed, wet bath, bubble plate and venturi scrubbing. Combinations of these methods are also available.



Fig. 2.06: Different methods used for wet scrubbers (courtesy of EGCSA)



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The layout of an Alfa Laval  $SO_x$  scrubber is shown in Fig. 2.07. The scrubber consists of two parts, a jet scrubber and an absorber. The jet scrubber is a pre-scrubber, starting the scrubbing process with a jet spray into the incoming exhaust gas. Placed upstream of the absorber, it increases the scrubbing efficiency, especially on PM. From the jet scrubber, the gas stream is led through the absorber, a packed bed scrubber where the  $SO_x$  is removed to the required level. The jet scrubber could be replaced by a venturi scrubber to increase the PM trapping, but it increases the pressure drop across the unit.



Fig. 2.07: Alfa Laval  $SO_x$  scrubber combining a jet scrubber and an absorber



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# 2.3.4 Dimensions

The different types of  $SO_x$  scrubber systems vary in size and shape of the scrubber. The total volume of a scrubber unit depends on the amount and condition of the exhaust gas and its content of sulphur and particles. Furthermore, restrictions on the maximum acceptable additional backpressure from the exhaust system influence the scrubber size.

Typical dimensions of an Alfa Laval  $\rm SO_x$  scrubber for a range of MAN B&W engine sizes are found in Table 2.08.

Engine power MW	Width m	Length m	Height m	Weight ton (dry)	Weight ton (wet)	Water inlet DN	Water outlet DN
4	2.3	4.0	7.0	6	8	200	250
4 - 8	2.8	4.9	7.8	7	11	250	250
8 - 12	3.5	6.3	9.1	12	18	350	400
12 – 16	4.2	7.4	10.2	18	25	400	450
16 – 20	4.8	8.4	11.2	21	31	450	500
20 - 24	5.5	9.2	12.0	27	39	500	600
24 - 32	6.0	10.5	13.2	35	51	600	600

Table 2.08: Typical dimensions of an Alfa Laval SO<sub>x</sub> scrubber



## 2.3.5 Water cleaning system

When running a closed loop system, it is necessary to bleed off scrubber water to avoid accumulation of salt generated in the process. Before discharging the bleed-off water into the sea, it must be cleaned in a water cleaning unit (WCU). The diagram in Fig. 2.09 illustrates the method used in the Alfa Laval WCU. The bleed-off water from the system is collected in a buffer tank. After addition of a coagulant, the bleed-off is led to a retention tank and forwarded to the high-speed separator for the final cleaning process. A monitoring system (QC) controls the quality of the water with regard to pH value, turbidity and polycyclic aromatic hydrocarbons (PAH) concentration. In case the IMO discharge criteria are not met, the bleed-off is recycled in the unit to increase the quality.



Fig. 2.09: Water cleaning performed in the WCU

An example of the Alfa Laval WCU is shown in Fig. 2.10. The footprint of the frame is approximately 2.5 by 2.5 m.



Fig. 2.10: Alfa Laval Water Cleaning Unit

# 2.3.6 Control system

The scrubber control panel serves the scrubber, the water cleaning unit and the water discharge. A hardwired interface is connected to the ship's general alarm system. If an alarm is triggered, or an emergency button is activated, the  $SO_x$  scrubber system shuts down automatically and the scrubber bypass opens without stopping the engine. After the failure has been eliminated, the alarm disappears from the screen and the system can be restarted.

Alarms and related information is integrated and displayed on the control panel's touch screen. To minimise the energy consumption in the individual operating modes, the pumps in the WCU circuit are controlled by a PLC.



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# 2.3.7 Installation

Engine room arrangement

## Hybrid System





Fig. 2.11: Schematic arrangement of a hybrid  $SO_x$  scrubber system (on SW/FW)

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The exhaust gas cleaning units are normally placed high up in the ship, in or around the funnel area, where more space is available and access is easier. The installation will normally include a bypass to be able to run the engine without the scrubbing process, even though the scrubber in certain designs can run dry without the scrubbing process. In most cases, a  $SO_x$  scrubber is an effective silencer even when running dry, which means that the existing silencer can be replaced by a scrubber. As the exhaust temperature is significantly reduced during the scrubbing process, any waste heat recovery system, such as the exhaust gas boiler, must be positioned upstream of the scrubber.

The scrubber water installation in the hybrid system is a combination of the system used in open loop and closed loop installations, as described in the following.

The hybrid system combines the low running costs of the open loop with the flexibility provided by the closed loop system. The hybrid system provides additional flexibility, as the open loop mode can be used also at low SW alkalinity with the addition of NaOH without the need for switching to closed loop mode.



#### Open loop system

The SW installation in open loop systems, illustrated in Fig. 2.12, is relatively simple as SW is supplied by the ship's SW system directly to the scrubber. From the scrubber outlet, water is led to the SW discharge system after a quality control has verified compliance with the IMO guidelines.



Fig. 2.12: Schematic arrangement of an open loop  $SO_x$  scrubber system (SW)

The system has low running costs as no additional treatment is required. However, to obtain a sufficient scrubbing quality, the SW flow rate is relatively high. Combined with the required pressure for the highly placed scrubber, the power needed for SW scrubbing is a running cost that cannot be ignored.

In certain cases, in areas where the seawater alkalinity is too low or restricted outlet criteria is in force, the system cannot be used and running on low-sulphur fuel is required.

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#### Closed loop

The FW scrubbing used in closed loop systems is illustrated in Fig. 2.13. The installation is more complex compared to open loop because a water treatment system is needed. The equipment includes a circulation tank, sludge tank, NaOH tank, circulating pump, FW cooler and a WCU. An alternative to the WCU could be a holding tank to store the bleed-off water for discharge in port. Compared to open loop systems, the scrubber water flow is significantly reduced as the scrubbing efficiency using FW is high compared to SW. Due to the reduced flow, the dimensions of the inlet and outlet pipes are reduced.



Fig. 2.13: Schematic arrangement of a closed loop  $SO_x$  scrubber system (FW)

The running costs of a closed loop system is higher compared to an open loop system, mainly because of the addition of chemicals in the process. However, the closed system can be used in any area without restrictions thanks to the water treatment system.



NaOH tank	The storage tank for the chemical additives used in the closed loop systems should be suitable for the media, e.g. the chemical solution. Normally, the scrubbing process uses 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 be installed in a room with a controlled temperature or be insulated and fitted with means for heating. The material of the tank must meet the specific requirements for the solution, such as stainless steel, coated steel, polymer or other suitable materials. <sup>3</sup>
	When estimating the necessary 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 taken into account. Furthermore, the capacity could include additional volume to receive a full standard bunker volume when refilling. An example of how to dimension the NaOH tank is given by the tables in Section 2.3.9 Calculation of SO <sub>x</sub> scrubber data.
Sludge tank	The sludge outlet from the WCU in a closed loop systems is an aqueous solu- tion of combustion particles, sulphur compounds and other material separated from the scrubber water. The pH value would normally vary between 6 and 9. The sludge can be stored in a separate sludge tank or in a general tank on board, e.g. the dirty bilge tank, which holds similar sludge from the engine room. The tank could be made of coated steel while taking the variation of pH value into consideration.
	When estimating the capacity of the sludge tank, it is important to take into ac- count the ECA sailing time, the sailing pattern, the fuel sulphur content, the wa- ter content and the planned discharging interval. An example of how to dimen-

scrubber data.

sion the NaOH tank is given by the tables in Section 2.3.9 Calculation of  $SO_x$ 





## Circulation tank

The circulation tank is used as a buffer tank in closed loop and hybrid systems. During start-up in closed loop mode, the tank ensures that there is enough FW for the process. In hybrid systems, it acts as a reservoir for FW during open loop operation and ensures a smooth transition when changing between open and closed loop mode. The tank size defines the time in which the system can operate without bleed-off when operating in closed loop mode. Typical tank volumes are given in Table 2.14.

Engine power MW	Circulation tank m <sup>3</sup>
< 10	10
10-20	20
> 20	30

Table 2.14: Typical volumes of circulation tank



#### 2.3.8 Consumptions and capacities

The following data refers to ISO conditions, except where otherwise stated. The estimated data are based on the principles described in the previous chapters. The data may not fully cover data for a specific  $SO_x$  scrubber system and it is therefore suggested to contact the supplier for further information.<sup>4</sup>

Scrubber efficiency The SO<sub>x</sub> scrubber system is a method equivalent to meeting the low-sulphur fuel requirements. Accordingly, the efficiency of the system must be sufficient to achieve a SO<sub>x</sub> emission level, measured as the fraction SO<sub>2</sub>/CO<sub>2</sub>, that is equal to or lower than the required limit. The efficiency depends on the sulphur content in the fuel related to the sulphur limit. The required efficiencies are listed in Table 2.15 for various fuel sulphur content values in ECA and non-ECA.

Fuel sulphur S%	Scrubber efficiency in ECA, % Sulphur limit: 0.1%	Scrubber efficiency in non-ECA, % Sulphur limit: 0.5%	
3.5	97.1	85.7	
3.0	96.7	83.3	
2.5	96.0	80.0	
2.0	95.0	75.0	
1.5	93.3	66.7	
1.0	90.0	50.0	

Table 2.15: Required SO<sub>x</sub> scrubber efficiency

Although the required scrubber efficiency depends on the area and the fuel used, the data in this chapter is based on an efficiency of 97.1%, which is sufficient to clean the exhaust gas from a 3.5% sulphur fuel to meet the requirements. Information on systems including varying efficiencies should be given by the scrubber supplier.

# Back pressure The use of a SOx scrubber increases the pressure drop (back pressure) in the exhaust gas system. The maximum acceptable back pressures in the exhaust gas system on new engines are found in Table 2.16

Power % MCR	Piping mbar	Scrubber mbar	Max total pressure mbar
100	30.0	30.0	60.0
75	17.9	22.5	40.4
50	8.6	15.0	23.6
25	2.5	7.5	10.0

Table 2.16: Total back pressure acceptable in the exhaust gas system

All data presented is approximate values and subject to change without further notice

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# Engine performance

The increased back pressure will slightly influence the engine's performance. The exhaust gas amount decreases and the turbine outlet temperature increases depending on the additional back pressure. The SFOC increases accordingly. The scavenge air pressure is roughly unchanged. Table 2.17 shows the influence on these parameters in relation to the maximum additional back pressure. In cases where only a fraction of the maximum back pressure is present, the influence on the parameters is reduced accordingly.

Power % MCR		$\Delta$ P (max) mbar	∆SF0C g/kWh	∆ Exhaust gas % mass	∆ TC outlet °C
	100	60.0	+1.0	÷7	+20
	75	50.0	+1.0	÷7	+20
	50	40.0	+1.0	÷10	+20
	25	20.0	+1.0	÷10	+20

Table 2.17: Relation between additional back pressure and engine parameters

The additional back pressure of a  $SO_x$  scrubber depends on the scrubber type. Typically a back pressure of 20 to 40 mm mbar at 100% MCR can be expected. Depending on the performance parameters, the SFOC penalty is 0.3-0.7 g/kWh.

#### Scrubber water flow • Open loop

The necessary scrubber water flow is determined by the exhaust gas amount, which depends on the engine power. An estimate of the open loop SW flow is found by the following formula:

 $Flow_{sw} = 50 \text{ m}^3/\text{h/MW}$ 



Electric power

consumption

#### Closed loop

The required flow of FW for sufficient closed loop scrubbing is significantly smaller than required for SW in open loop. The relation between the engine power and FW flow is estimated as follows:

 $Flow_{FW} = 30 \text{ m}^3/\text{h}/\text{MW}$ 

#### Open loop

The electric power consumption in open loop mode relates to pumping SW into the scrubber. Accordingly, the power relates to the flow and pressure delivered by the scrubber pumps. The required pressure reflects the injection pressure and the lifting height, i.e. the vertical distance between sea level and the scrubber injection point. If the installation details are unknown a rough estimate of the power required for open loop mode can be estimated by:

 $\mathsf{P}=0.70\%\times\mathsf{P}_{\mathsf{ME}}\times\mathsf{MCR}$  %

If the height (H) between the seawater level and scrubber inlet is known, and assuming an injection pressure of 10 m WC and a pump efficiency of  $eff_{Pump}$ , the required power can be calculated as follows:

$$P = P_{Pump} = P_{ME} \times MCR \% \times Flow_{SW}/3,600 \times 1.025 \times 9.81 \times (H+10)/eff_{Pump}$$

Fig. 2.18 shows the required power in open loop mode at different pumping heights.



Fig. 2.18: Required power in open loop mode

Pumping height (m) :



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#### Closed loop

The power consumption in closed loop mode relates to the power to circulate the FW scrubber water and to treat and discharge the bleed-off water. Compared to open loop mode, the required power for closed loop is smaller as the FW flow and the water column height is smaller. The power required for closed loop mode could be estimated as:

 $P = 0.25\% \times P_{ME} \times MCR \%$ 

When the height (h) between the circulation pump and the scrubber inlet is known, the required power P which includes the pumping power P<sub>Pump</sub>, and auxiliary power PAux, could be estimated more specifically. Assuming an injection pressure of 10 m WC and further a 10% additional power for covering the WCU and cooler, the required power is:

 $P = P_{Pump} + P_{Aux} = P_{ME} \times MCR \ \% \times Flow_{FW}/3,600 \times 1.000 \times 9.81 \times (h+10)/eff_{Pump}$ × (100% +10%)

In Fig. 2.19, the required power in closed loop mode at different pumping heights is shown.



Fig. 2.19: Required power in closed loop mode

20.0 15.0

10.0

5.0





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NaOH consumption

In closed loop mode, the required additive applied to neutralise the accumulated sulphur in the scrubber water is normally a 50% NaOH solution. The amount of NaOH depends on the engine size, engine load, SFOC and the sulphur content in the fuel.

Using a solution of 50% NaOH to neutralize the sulphur (S) in the scrubber water, the consumption is:

NaOH (I/h) = P(MW) × MCR% × SFOC (kg/MWh) × S% × 3.27

Fig. 2.20 shows the estimated NaOH consumption relative to the engine load, engine size and sulphur content in the fuel.



Fig. 2.20: NaOH consumption in closed loop mode

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Sludge production

Fuel sulphur content (%):

3.5 3.0

2.0 1.0 The sludge accumulated in closed loop mode in the bleed-off system is removed by the separator in the WCU. The amount of sludge accumulated depends on the engine size, engine load, SFOC and the sulphur content (S) in the fuel. Furthermore, the water content in the sludge has a significant influence on the sludge amount. In this paper, a solution of 93% water and 7% sludge is chosen. A lower fraction of water will increase the viscosity and might give problems in handling the sludge. Furthermore, a higher value will rapidly increase the volume needed to store the sludge.

An estimate of the accumulation of sludge in a 93% water solution could be expressed as:

Sludge (I/h) = P (MW) × MCR% × SFOC (kg/MWh) × (S% × 3.45+0.022)

Based on this formula, the estimated sludge production related to the engine load, engine size and fuel sulphur content is shown in Fig. 2.21.



Fig. 2.21: Sludge production in closed loop mode

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Freshwater

Depending on the fuel sulphur percentage, the closed loop process accumuconsumption lates salt in the scrubber water creating a risk of deposits in the system. However, in several conditions the closed loop system generates a surplus of water due to the condensation of exhaust gas and the salt is diluted and discharged through the bleed-off system. In cases where the condensation is not sufficient, there is a need for adding FW to the system.

> In addition to diluting the salt in the scrubber water, FW is also used as process water in the WCU. The water is used for the discharge of sludge, and the solution of water and sludge is finally dumped to the sludge tank.

> A specific rule for the FW consumption could not be given here as the calculation depends on a wide range of parameters, among these the sulphur percentage and the temperature of air and seawater. But a rough estimate at ISO, Winter and Tropical conditions using high sulphur fuels is given in Table 2.22.

Condition	Air		Sea °C		FW consumption I/MWh
ISO		25 °C		25	100
Winter		10 °C		10	50
Tropical		45 °C		32	0

Table 2.22: Estimated FW consumption in closed loop mode using high sulphur fuels

Cooling water To minimise the FW consumption in closed loop mode, the water circuit includes capacity a scrubber water cooler that reduces the evaporation of the scrubber water through the exhaust gas stream. The capacity of the cooler depends on the engine size and could roughly be estimated to 50% of the main engine power.

# 2.3.9 Calculation of SO<sub>x</sub> scrubber data

An example of calculating data for a hybrid  $SO_x$  scrubber system on a 27 MW MAN B&W marine engine is given in the following. The example takes into account the use of both open and closed loop mode. Furthermore, a comparison is made with the low-sulphur alternative, without a  $SO_x$  scrubber system. It should be kept in mind that the existing sulphur content limit of 3.5% in non-ECA is unchanged until 2020. In this period the  $SO_x$  scrubber system should only be used inside  $SO_x$  ECA.

The scenarios and assumptions used in the calculation are found in Tables 2.23 and 2.24.

Area	Hybrid	SO <sub>x</sub> scrubber s	No scrubber		
	fuel S%	mode	hours/year	fuel S%	hours/year
SO <sub>x</sub> ECA	3.0	open	1,500	0.1	2,000
	3.0	closed	500	0.1	2,000
Non-ECA	3.0	open	3,900	0.5	4,000
	3.0	closed	100	0.5	4,000

Table 2.23: Scenarios for SO<sub>x</sub> scrubber calculations, 6,000 sailing hours a year

Engine	6S80ME-C9.2	
Power, SMCR	27,060 kW	
RPM	78 RPM	
SFOC	25% MCR	171 g/kWh
	50% MCR	165 g/kWh
	75% MCR	162 g/kWh
	100% MCR	166 g/kWh
Increased back pressure at 100% MCR	300 mm WC	
Pumping height SW, open loop	25 m	
Pumping height FW, closed loop	15 m	
Pump efficiency SW, open loop	0.80	
Pump efficiency FW, closed loop	0.80	
NaOH solution	50 %	
NaOH tank margin	33 %	
Sludge tank margin	33 %	
NaOH bunker frequency	12 times/year	
Sludge discharge frequency	12 times/year	
Sailing profile – SO <sub>x</sub> ECA and non-ECA	25% MCR	15% time
	50% MCR	15% time
	75% MCR	50% time
	100% MCR	20% time

Table 2.24: Assumptions for SO<sub>x</sub> scrubber calculations



Step 1

The first step is to find the specific data on SFOC penalty, electric power consumption, NaOH consumption and sludge production as given in Section 2.3.8 Consumptions and capacities.

- The SFOC of the engine is found using the engine calculation program CEAS <sup>5</sup> for the specified engine, see Table 2.25.
- The SFOC penalties at the specified increased back pressure of 300 mm WC is found using Table 2.17. According to this table, the SFOC penalty is 300/600 × 1.0 g/kWh = 0.5 g/kWh at 100% MCR. At lower loads the increased back pressure is lower but the penalty is constant = 0.5 g/kWh.
- The electric power used for the system is divided in open loop consumption and closed loop consumption, which have different water flows, lifting heights and in some cases different pump efficiencies. According to the equations for power consumption in Section 2.3.8, the flow and power is:
- Open loop
  - Flow<sub>sw</sub> = 50 m<sup>3</sup>/h/MW
  - P = P<sub>ME</sub> × MCR % × Flow<sub>SW</sub>/3,600 × 1.025 × 9.81 × (H+10)/eff<sub>Pump</sub> = P<sub>ME</sub> × MCR % × 6.11 kW/MW
- Closed loop
  - Flow<sub>FW</sub> = 30 m<sup>3</sup>/h/MW
  - P = P<sub>ME</sub> × MCR % × Flow<sub>FW</sub>/3,600 × 1.000 × 9.81 × (h+10)/eff<sub>Pump</sub> × 110% = P<sub>ME</sub> × MCR % × 2.81 kW/MW
  - The NaOH amount needed for closed loop operation is calculated as:
    - NaOH =  $P_{ME} \times MCR \% \times SFOC \times S\% \times 3.27$ =  $P_{ME} \times MCR \% \times 16.7 \text{ I/h/MW}$
    - The amount of sludge produced in closed loop operation is calculated as:
    - Sludge =  $P_{ME} \times MCR\% \times SFOC \times (S\% \times 3.45+0.022)$ =  $P_{ME} \times MCR\% \times 21.3$  l/h/MW
  - Finally, the specific FW consumption is estimated for ISO condition as:

-FW = 100 I/MWh

The specific data calculated above are listed in Table 2.25.

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<sup>5</sup> CEAS is found at http://www.mandieselturbo.com/ceas/index.html

Step 2	The second step is to calculate the absolute consumption at each load for a specific engine with an SMCR of 27,060 kW. The calculated data are listed in Table 2.26.
Step 3	The engine's total consumption depends on the sailing profile (engine load and sailing time) in the specific area and on the specific running mode. When multiplying the absolute consumption figures with the profile values, the average consumption for one hour is found by adding these values as shown in Table 2.27.
Step 4	The yearly consumption is found using the scenario in Table 2.22. For compari- son, the scenario where no scrubber system is installed is also calculated. The consumption figures are given in Tables 2.28 and 2.29.
Step 5	Based on the consumption found in Step 4, the operating costs of the two scenarios are calculated. The operating cost of a $SO_x$ scrubber system using high sulphur fuel, shown in Table 2.30, is 10.9 million USD/year. In the scenario in Table 2,31, where no scrubber is installed, the operating cost is 14.0 million USD/ year. The difference, 3.1 million USD/year, is mainly caused by the high cost of low-sulphur fuel.
	Until 2020, the sulphur content limit in non-ECA is 3.5%, and the $SO_x$ scrubber system will therefore only be used in $SO_x$ ECA. When calculating the scenarios in this situation, the price gap is lower, around 1.7 million USD/year. The prices used in the calculation are estimates and based on prices of fuel and NaOH in 2013.
Step 6	The tank capacity can be calculated when the bunker and discharge frequency is known. A margin should be included to compensate for variations in the sail- ing profile and sailing hours, and to leave space to receive a full lot size at de- livery. The tank sizes shown in Table 2.32 are found using the assumed bunker frequency and margin.

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Engine load % MCR	25%	50%	75%	100%	
SFOC engine	171	165	162	166	g/kWh
SFOC penalty	0.5	0.5	0.5	0.5	g/kWh
Power scrubber, open loop	6.1	6.1	6.1	6.1	kW/MW
Power scrubber, closed loop	2.6	2.6	2.6	2.6	kW/MW
NaOH closed loop	16.7	16.7	16.7	16.7	l/MWh
Sludge, closed loop	21.3	21.3	21.3	21.3	l/MWh
FW	100	100	100	100	l/MWh

Table 2.25: Step 1 – Specific consumption figures

Engine load % MCR	25%	50%	75%	100%	
Fuel oil	1,157	2,232	3,288	4,492	kg/h
Fuel oil penalty	3	7	10	14	kg/h
Power scrubber, open loop	41	83	124	165	kWh/h
Power scrubber, closed loop	17	35	52	69	kWh/h
NaOH, closed loop	113	226	338	451	l/h
Sludge, closed loop	144	289	433	577	l/h
FW	677	1,353	2,030	2,706	l/h

Table 2.26: Step 2 – Absolute consumption according to the specified engine

Engine load % MCR Load profile, Time	25% 15%	50% 15%	75% 50%	100% 20%	Total per hour	
Fuel oil	174	335	1,644	898	3,051	kg/h
Fuel oil penalty	1	1	5	3	9	kg/h
Power scrubber, open loop	6	12	62	33	114	kWh/h
Power scrubber, closed loop	3	5	26	14	48	kWh/h
NaOH, closed loop	17	34	169	90	310	l/h
Sludge, closed loop	22	43	216	115	397	l/h
FW	101	203	1,015	541	1,860	l/h

Table 2.27: Step 3 – Absolute consumption according to the load profile

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Area	S0, E	CA	Non-	ECA	SO <sub>x</sub> scrubber – Total
Loop	Open	Closed	Open	Closed	consumption
Hours	1,500	500	3,900	100	6,000 hours
Fuel 3.0% S	4,590	1,530	11,934	306	18,360 ton/year
Electric power	171	24	443	5	642 MWh/year
NaOH	0	155	0	31	186 m³/year
Sludge	0	198	0	40	238 m³/year
FW	0	930	0	186	1,116 m <sup>3</sup> /year

Table 2.28: Step 4 - Consumption figures according to the actual scenario

Area	SO <sub>x</sub> ECA	Non-ECA	No scrubber – Total	
Hours	2,000	4,000	6,000 hours	
Fuel 0.1% S	6,101	0	6,101 ton/year	
Fuel 0.5% S	0	12,203	12,203 ton/year	

Table 2.29: Step 4 – Consumption figures according to the alternative scenario without scrubber

SO <sub>x</sub> scrubber	Consumption	Price	Total cost Million \$/year
Fuel 3.0% S	18,360 ton/year	580 \$/ton	10.65
Electric power, total	642 MWh/year	220 \$/MW	0.14
NaOH	186 m <sup>3</sup> /year	306 \$/m <sup>3</sup>	0.06
Sludge	238 m³/year	0 \$/m³	0.0
FW	670 m <sup>3</sup> /year	0 \$/m <sup>3</sup>	0.0
Total			10.85

Table 2.30: Step 5 – Yearly cost in USD using high sulphur fuel and SO<sub>x</sub> scrubber

No scrubber	Consumption ton/year	Price \$/ton	Total cost Million \$/year
ECA Fuel, 0.1% S	6,101	865	5.28
Non-ECA Fuel 0.5% S	12,203	714	8.71
Total			13.99

Table 2.31: Step 5 – Yearly cost in USD using low-sulphur fuel without scrubber

Substance	Frequency	Volume, m <sup>3</sup>	Margin, %	Tank m <sup>3</sup>
NaOH tank	12	186	33	20.6
Sludge tank	12	238	33	26.4

Table 2.32: Step 6 - Tank capacity of NaOH and sludge



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