CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 034

Operational insights into marine selective catalytic reactors (SCRs)

Exhaust Gas Aftertreatment Solutions & CCS

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ABSTRACT

The International Maritime Organization (IMO) regulates the control of NOx emissions from diesel engines in international shipping. This is achieved through the survey and certification requirements of MARPOL Annex VI and NOx Technical Code 2008, culminating in the issuance of an Engine International Air Pollution Prevention (EIAPP) Certificate. The certification of the NOx emissions of marine diesel engines and selective catalytic reactors is stipulated in the NOx Technical Code 2008 and MEPC.291(71) Guidelines. These guidelines provide additional details related to marine diesel engines equipped with selective catalytic reduction (SCR) systems, including specific requirements for SCR catalyst blocks. Various technological approaches are permissible for demonstrating the deterioration rate of SCR performance, such as evaluating exchange conditions and recommended replacement intervals for SCR catalyst blocks.

Despite these regulatory efforts, there is growing concern among stakeholders that the NOx emission control program outlined in Regulation 13 is falling short of achieving the expected emission reductions and associated air quality improvements. This concern has been documented in various reports and studies, highlighting instances where ships fail to meet the Regulation 13 NOx limits, particularly during low-load operation.

To comprehensively understand the technologies and methodologies employed by engine designers and SCR manufacturers for assessing SCR performance degradation, a structured summary of applied control mechanisms becomes essential. Within this context, this paper provides a consolidated overview of ships equipped with SCR systems, including their operational areas. Additionally, the paper summarizes, the results of a survey conducted among ship owners and managers with a specific focus on practical experiences related to verifying the deterioration rate of SCR catalyst blocks in real-world conditions.

1 INTRODUCTION

The International Maritime Organization (IMO) regulates NOx emissions from diesel engines in international shipping through the survey and certification requirements stipulated in MARPOL Annex VI and the NOx Technical Code 2008, culminating in the issuance of an Engine International Air Pollution Prevention (EIAPP) Certificate. The certification process for NOx emissions from Marine Diesel Engines and Selective Catalytic Reduction (SCR) systems is detailed in the NOx Technical Code 2008 and the MEPC.291(71) Guidelines, [1], which address additional aspects of the NOx Technical Code with regard to specific requirements for Marine Diesel Engines equipped with SCR systems. These guidelines provide comprehensive details related to SCR-equipped Marine Diesel Engines, including specific requirements for SCR catalyst blocks.

Various technological approaches are permissible for demonstrating the deterioration rate of SCR performance, such as evaluating exchange conditions and recommended replacement intervals for SCR catalyst blocks. Despite these regulatory efforts, some stakeholders express growing concern that the NOx emission control program outlined in Regulation 13 is not achieving the expected emission reductions and associated air quality improvements. This concern is documented in various reports and studies, which highlight instances where ships fail to meet the Regulation 13 NOx limits, particularly during low-load operations, [2], [3].

To comprehensively understand the technologies and methodologies utilized by engine designers and SCR manufacturers in evaluating SCR performance degradation, it is imperative to provide a structured summary of the applied control mechanisms. Within this framework, the paper offers a consolidated analysis of vessels equipped with SCR systems, considering factors such as the age, size, and types of ships. Furthermore, the paper synthesizes the results of a survey conducted among surveyors of a classification society, emphasizing their practical experiences of operational aspects and on how deterioration rates of SCR catalyst blocks are verified under real-world conditions.

2 REGULATIONS

The International Maritime Organization (IMO) MARPOL Annex VI, first adopted in 1997, regulates the main air pollutants contained in ships' exhaust gases, including sulphur oxides (SOx) and nitrogen oxides (NOx), and prohibits the deliberate emission of ozone-depleting substances. The 2008 revision of MARPOL Annex VI introduced stricter limits on NOx emissions. The second stage (Tier II) mandates a reduction in NOx emissions by approximately 20% compared to previous levels. A further reduction of around 80% (Tier III) applies to certain keel laying dates and operational areas.

The revised MARPOL Annex VI introduces progressive reductions in NOx emissions from marine diesel engines, establishing a stringent "Tier III" emission limit for engines installed on ships constructed (keel laying date) on or after January 1, 2016, and operating in the North American and/or U.S. Caribbean Sea Emission Control Areas (ECAs). The North Sea and Baltic Sea followed for ships keel-laid after January 1, 2021.

In October 2024 MEPC 82 adopted amendments to MARPOL Annex VI and introduced new ECAs: The Norwegian Sea and the Canadian Arctic. The amendments will enter into force on 1 March 2026. For the Canadian Arctic, the requirements take effect as follows: The Tier III NOx requirements will apply to ships constructed (keel-laid) on or after 1 January 2025, although the requirements will enter into force on 1 March 2026. For the Norwegian Sea, the requirements take effect as follows: The Tier III NOx requirements will apply to ships contracted on or after 1 March 2026; or in the absence of a contract, keel-laid on or after 1 September 2026; or delivered on or after 1 March 2030. As a consequence of introducing contract and delivery dates as application dates for the Norwegian Sea ECA, the format of the supplement to the IAPP certificate was updated to include contract and delivery dates in addition to the keel-laid date.

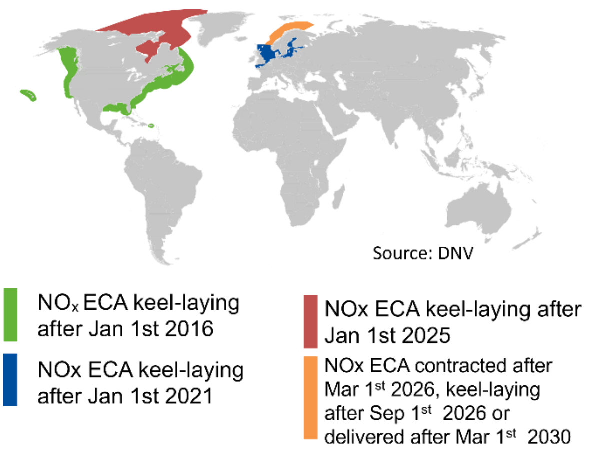

Figure 1. IMO NOx ECAs

The special ECAs for NOx are also often referred to as “NOx ECAs” or “NECAs”, even though the official terminology is “ECAs for the adoption of special mandatory measures for emissions from ships is required to prevent, reduce and control air pollution from NOx or SOx and particulate matter". The short term "NOx ECA" will be used in this document to address ECAs for NOx. The NOx ECAs are illustrated in Figure 1. Ships which are keel-laid after these dates and not operating in these NOx ECAs are not subject to Tier III requirements, but have to comply with the "Tier II" emission limits which have been in place since 2011.

This third stage presents significant technical and operational challenges for engine manufacturers, ship operators, and certifiers, as Tier III emission limits for NOx cannot be met without specific exhaust gas treatment, advanced technologies or the usage of alternative fuels. The Maritime Environmental Protection Committee (MEPC) at the IMO has issued a guideline for the certification of Selective Catalytic Reduction (SCR) systems, referred to as the "SCR guideline" (IMO Resolution MEPC.291(71)). The guideline is under revision at the 12th IMO's sub-committee on pollution prevention and response (PPR 12). The outcome of these revisions was not available at the time of completing this paper.

3 COMPLIANCE OPTIONS

To adhere to the stringent NOx Tier III emission limits, ship operators have several compliance options at their disposal. The selection of an appropriate compliance method is influenced by variables such as the vessel's trading pattern, engine size, speed, and other operational considerations. This paper will concentrate exclusively on the technical aspects, compliance requirements, and operational experiences related to Selective Catalytic Reduction (SCR). Other potential methods, which are not the focus of this paper, include Exhaust Gas Recirculation (EGR), the use of alternative fuels, internal engine modifications, Direct Water Injection (DWI), fuel-water emulsion (FWE), and intake air humidification.

3.1 Selective Catalytic Reduction (SCR)

Selective Catalytic Reduction (SCR) is an advanced exhaust gas after-treatment technology designed to achieve NOx reduction efficiencies exceeding 80%, thus fulfilling the NOx Tier III levels. The SCR process involves the injection of a urea-water solution into the exhaust gas stream, where it reacts with a catalyst unit located in the exhaust channel (refer to Figure 2). As an "add-on" exhaust treatment system, SCR does not interfere with the fundamental engine design, thus permitting operators to choose any engine manufacturer freely.

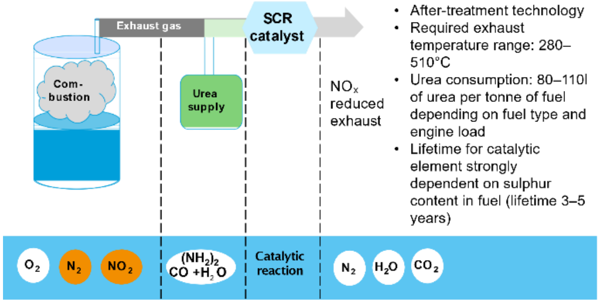

Figure 2. Selective Catalytic Reduction (SCR)

Selective Catalytic Reduction (SCR) requires a minimum engine exhaust gas temperature level (280°C-510°C), posing challenges under low engine load conditions. Consequently, for two-stroke engines, the SCR unit is optimally positioned before the turbine part of the turbocharger to expand the operational range of the SCR system. An alternative approach is a low-pressure SCR system, which employs a preheater to raise the exhaust gas temperatures to the necessary levels, with the SCR unit placed downstream of all engine components.

Regardless of the configuration, the replacement frequency of catalyst elements is influenced by factors such as operational time, fuel quality, type of catalyst, and other variables. Properly designed and maintained SCR systems can be used with high-sulphur fuels. The lifespan of the catalyst depends on the quality of fuel oil, urea, and adherence to the manufacturer's maintenance guidelines. Due to their sound attenuation capabilities, SCR units can partially or entirely replace the exhaust gas silencers in four-stroke engines, reducing the space required for installation. Currently, combined SCR and silencer packages are available to optimize space usage. However, in single main engine applications, a bypass is necessary to ensure engine operation in the event of SCR system collapse or clogging.

3.2 Challenges with instationary or transitional engine loads

Selective Catalytic Reduction (SCR) applications face no limitations for continuously operating four-stroke engines coupled to a controllable-pitch propeller or diesel-electric generator. In these scenarios, the engine load can consistently exceed 20%, maintaining the required exhaust temperature (280°C–510°C) across all operational modes, including maneuvering.

However, challenges persist with two-stroke engines, which are directly coupled to a fixed-pitch propeller and must operate at extremely low loads, even stopping completely for reversing during maneuvering operations. Under conditions characterized by low exhaust gas temperatures, the Selective Catalytic Reduction (SCR) unit for two-stroke engines may be deactivated to inhibit the formation of ammonium bisulphate, a compound that poses a risk of system damage. This deactivation, aimed at preventing potential harm, adheres to established rules and regulations when classified as an Auxiliary Control Device (ACD). Consequently, there remains potential for further improvements in SCR technology for low engine load conditions, such as those encountered during maneuvering.

It is important to note that transient engine loads are outside the scope of the regulations controlling NOx emissions from marine diesel engines. This implies that short periods of engine operation, including engine starts and brief maneuvering activities requiring engine reversal, are not covered by MARPOL Annex VI Regulation 13. Nonetheless, the use of defeat devices and irrational control strategies that undermine the regulation's intent is strictly prohibited. A forthcoming revision of the NOx Technical Code, up for adoption at MEPC 83, will implement more stringent regulations to deter irrational control strategies. This will be achieved by requiring extensive zones beyond the conventional load points, which are necessary to comply with emission limits.

Nevertheless, the challenges of low-load performance of SCR systems have been addressed in recent studies, for example in [2] and [3], which investigates the issue of actual emission levels at low loads to understand the effect of low-load propulsion operations on the performance of IMO NOx Tier III technologies. Based on the findings of these studies, recommendations on the process to engage IMO to consider modifications to the certification test cycle are discussed as well as potential modifications to the certification process. Among other studies these papers initiated the request for a new output to revise the certification requirements at IMO.

3.3 Undersized SCRs and derating of engine in NOx ECA

To reduce initial investment costs and minimize the space required for the SCR system, it may be advantageous to design the SCR system for less than the full maximum continuous rating, as engines are unlikely to operate at full power within the NOx Emission Control Area (ECA). Although undersized SCR systems and dual-rated engines are not explicitly addressed in current NOx regulations, if the engine manufacturer provides sufficient evidence that all regulatory requirements are met, such approaches can be approved.

To assess compliance with the regulations, the engine manufacturer must submit comprehensive documentation, including the NOx Technical File, which must detail the switching and recording of the Tier modes. At present, all dual-rating and undersized SCR approaches are evaluated on a case-by-case basis.

It is important to note that dual-rated engines may influence other disciplines and regulations, necessitating careful consideration (e.g., energy efficiency design index (EEDI), energy efficiency existing ship index (EEXI), minimum required propulsion power, class rules, etc.). Both Tier II and Tier III modes must be tested on a test bed for emission compliance, and both ratings must be specified on the engine's nameplate.

3.4 Reductant control strategy

Selective Catalytic Reduction (SCR) systems, utilized in international shipping, permit both controlled and uncontrolled strategies for the injection of reductants. The most commonly used reductant in the maritime industry is a urea solution.

The volume flow rate of the reductant can be managed either through a pre-defined map, which provides data on the required flow based on engine load, engine speed, exhaust gas temperatures, and other parameters without a NOx-sensor, as illustrated in Figure 3. This strategy's advantage is that it eliminates the need for installing and maintaining NOx sensors. However, it has the drawback of potentially not detecting the deterioration of the catalyst material effectively or, even worse, not meeting the requirements under real operation conditions, leading to excessive reductant slip. Consequently, initial and periodic spot-checks are necessary to validate the correct reduction rate of the catalysts, see also 4.1.3 and 5.2.

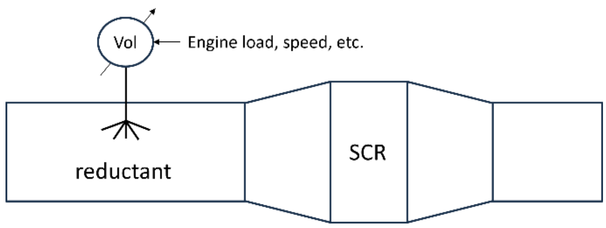

Figure 3. Feed forward reductant control strategy without NOx-sensor.

An advanced control strategy involves a feedback mechanism that utilizes a NOx sensor positioned downstream of the SCR chamber, see Figure 4. The commonly used NOx sensors are zirconium oxide-based sensors, which, despite their relatively low cost, offer a reasonable lifespan even under the harsh conditions of the marine environment. Utilizing NOx sensors in combination with a feed back control strategy, initial spot-checks after installation in the shipyard become unnecessary. Moreover, NOx sensors can be effectively employed to verify the deterioration of the catalyst material.

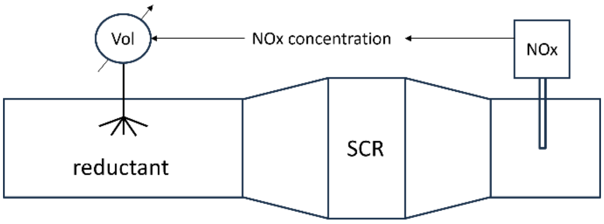

Figure 4. Feed back reductant control strategy with NOx-sensor.

4 INITIAL CERTIFICATION OF ENGINES WITH SCR

The certification of marine diesel engines equipped with Selective Catalytic Reduction (SCR) systems is governed by guideline MEPC.291(71), [1], which was adopted by the International Maritime Organization (IMO) on July 7, 2017, and subsequently amended by MEPC.313(74), [4]. According to these guidelines, when a NOx-reducing device (SCR) is included within the Engine International Air Pollution Prevention (EIAPP) certification, it must be recognized as an integral component of the engine and documented in the engine's Technical File.

The SCR guideline by IMO is under revision at the 12th IMO's sub-committee on pollution prevention and response (PPR 12). The outcome of these revisions was not available at the time of completing this paper.

The referred SCR guideline provides two equivalent procedures for certifying engines fitted with SCR systems, referred to as Scheme A and Scheme B. It is important to note that certification under Scheme B does not imply that the catalyst can be certified independently; it remains an integral part of the engine, as illustrated in Figure 5.

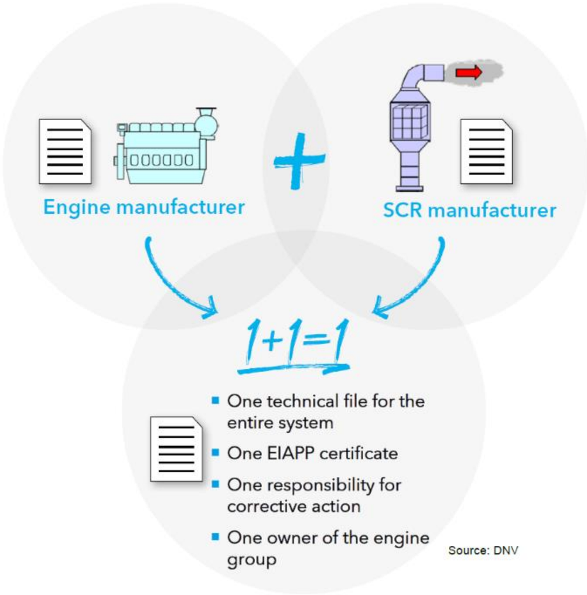

Figure 5. Certification of SCR systems according to IMO guideline MEPC.291(71) as amended by MEPC.313(74).

4.1.1 SCR certification: Scheme A

The statutory certification under Scheme A is considered the traditional procedure as per the specifications of the NOx Technical Code 2008 (NTC 2008) established by the International Maritime Organization (IMO). In this scheme, the engine, along with the Selective Catalytic Reduction (SCR) system, undergoes testing at the engine manufacturer's test bed (pre-certification test). Following installation on board, a successful on-board verification procedure, as outlined in the NOx Technical File of the engine and SCR, is required. Upon completion, the International Air Pollution Prevention (IAPP) certificate for the vessel can be issued, as depicted in Figure 6. It has to be noted that depending on the urea injection strategy, additional initial spot-checks might be required, see 4.1.3.

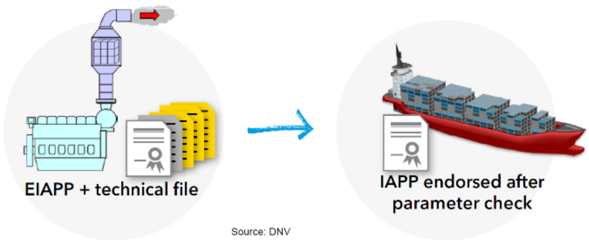

Figure 6. Scheme A according to MEPC.291(71)

4.1.2 SCR certification: Scheme B

Since the amendment of the IMO Resolution MEPC.313(74), [4], in 2019, Scheme B is considered as an equivalent process to Scheme A.

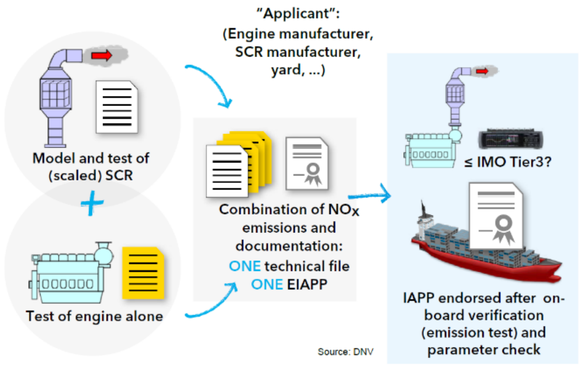

Figure 7. Scheme B according to MEPC.291(71)

A detailed description of the Scheme B approach is illustrated in Figure 7. According to the guideline, the engine can be tested independently of the SCR system on a test bed. Additionally, a scaled SCR chamber can be evaluated using either exhaust gas from a diesel engine or simulated gas. However, the SCR chamber must demonstrate the NOx reduction as expected from the diesel engine exhaust gas alone. Therefore, the NOx reduction rate of the SCR chamber should be determined for each individual mode point.

If the reduction rate test is conducted on a scaled version of the SCR chamber, the scaling process and modelling must be validated to the satisfaction of the administration. The validated modelling can then be applied to other engine groups operating within the same defined boundary conditions.

After the combined system is installed on board the ship, a confirmation test is required for the parent engine, comprising the diesel engine and the SCR system. If the parent engine system of the group is not the first to complete the onboard confirmation test, then the onboard confirmation test must be performed for all installed engine systems within the engine group, unless it is an identical NOx specification member engine. The confirmation test should be conducted as close as possible to 25%, 50%, and 75% of rated power, regardless of the test cycle. At each mode point of the confirmation test, the operating values specified in the NOx Technical File must be verified. The analysers used for the onboard confirmation test should comply with the requirements of a test conducted on an engine manufacturer's test bed, as outlined in Chapter 5 of NTC 2008. The NOx emission concentrations should be measured at both the inlet and outlet of the SCR chamber, and the NOx reduction rate should be calculated. Both values should be either dry or wet. The obtained NOx reduction rate should be compared to the initial confirmation test value required at each mode point as specified in the Technical File. The reduction efficiency values at each test point should not be less than the corresponding values in the Technical File by more than 5%.

The objective of the confirmation test is to demonstrate that the predicted NOx reduction rate of the scaled SCR system and the model calculations can be achieved in the full-scale application. Following the successful confirmation test and a successful on-board verification procedure as described in the NOx Technical File for the engine and SCR system, the International Air Pollution Prevention (IAPP) certificate for the ship can be issued. An engine group (engine and SCR system) can be established, requiring no further confirmation tests for identical installations on subsequent ships.

It is important to distinguish between the initial confirmation test and initial spot checks. The initial spot check is mandated independently of the certification scheme and is contingent upon the urea control strategy implemented, as detailed in the following paragraphs.

4.1.3 Initial spot-checks

Depending on the applied reductant control strategy, after installation on board the vessel, the combined engine and SCR system may necessitate an initial check to ensure compliance with certified specifications. Only if the system employs a feed-forward reductant control strategy without a NOx-sensor (as detailed in section 3.4), it must undergo an initial spot-check on board the vessel. It is crucial to recognize that this requirement extends not only to the parent engine but also to each member of the engine family/group. Only after a successful spot-check the International Air Pollution Prevention (IAPP) certificate for the vessel can be issued.

The initial-spot check is waived in case a feed back reductant control strategy with NOx sensor is applied.

5 PERIODICAL VERIFICATION OF ENGINES WITH SCR

5.1 Deterioration rate and lifetime

The deterioration rate of Selective Catalytic Reduction (SCR) systems is influenced by several critical factors that impact the efficiency of catalyst blocks over time. One primary factor is catalyst clogging, caused by the accumulation of solid particles such as soot and ash within the catalyst. This accumulation can obstruct the flow of exhaust gases, reducing system efficiency. Clogging can be mitigated through the effective design of catalyst geometry. Nevertheless, regular inspections and manual cleaning are recommended to mitigate this issue and maintain optimal performance.

Another significant factor is thermal deterioration. Elevated exhaust temperatures 550°C and above adversely affect catalyst materials, leading to the collapse of their pores and a reduction in catalytic surface area available for reactions. Over time, this degradation can result in a noticeable decline in SCR system efficiency.

Chemical poisoning is also a crucial issue, involving the contamination of the catalyst by substances such as sulphur compounds, heavy metals, and trace elements present in exhaust gases. Elements such as arsenic (As), nickel (Ni), phosphorus (P), zinc (Zn), and calcium (Ca) can originate from the fuel and lubricating oil used in the engine. These contaminants bind to the catalyst, reducing the number of active sites available for the NOx reduction reaction. The use of high-quality fuel, preferably marine gas oil and matching lubricants meeting the SCR designer's specification are essential to minimize chemical poisoning.

Finally, urea crystallization presents a challenge to SCR system performance. Incorrect urea dosing can lead to crystal formation, which can clog injectors and other components within the system, thereby reducing the efficiency of the NOx reduction process. Accurate dosing control is crucial to preventing this issue and ensuring the continued effectiveness of the SCR system.

Guidance on assessing catalyst NOx reduction efficiency and the deterioration rate should be based on periodic spot checks or monitoring and should be specified by the designer of the system. Records must be maintained for inspection during annual, intermediate, and renewal surveys. The frequency of periodic spot checks is to be determined by the designer, considering the expected deterioration of the catalyst. Spot-check frequency should be at least once after installation and subsequently every 12 months. The regulation mandates adherence to spot check intervals regardless of whether the Selective Catalytic Reduction (SCR) system has been operational during the specified period. Failure to conduct spot checks within the required intervals results in non-compliance with the survey guidelines under the harmonized system of survey and certification [7]. This non-compliance would lead to a condition of authority and the withholding of the International Air Pollution Prevention (IAPP) certificate for the vessel.

5.2 Verification of NOx limits on board

Annually, the system undergoes an inspection in accordance with the onboard verification procedure detailed in the approved NOx Technical File. Almost all installed systems follow the engine parameter check method as outlined in section 6.2 of the NOx Technical Code, [5]. The alternative approach, which utilizes direct measurement and monitoring, is currently not being implemented in practise.

The designer is required to specify all parameters, settings, and components that influence the NOx emissions of the system. Additionally, the designer must provide comprehensive details on how these elements can be inspected to ensure compliance with regulatory standards.

When a feedback or feed-forward reductant control strategy is implemented with a NOx measurement device, it is considered an acceptable method for monitoring catalyst condition and degradation. The criteria for replacing catalyst blocks based on the NOx measurement device readings must be specified by the designer, along with the maintenance, service, and calibration requirements for the NOx measurement device.

Where a NOx measurement sensor is applied in the system, the following details should be included in the approved NOx Technical file:

- type/model (identification number);
- calibration, zero and span check procedures and the periodicity of such checks, if applicable;
- calibration gases to be carried on board if applicable; and
- maintenance and/or exchange requirements.

In case a feed forward reductant control strategy is adopted is adopted without incorporating a NOx measurement device, the application must provide detailed information regarding the following:

- the expected deterioration curve under expected operating conditions or the life of catalyst under expected operating conditions;
- factors which can influence catalyst NOx reduction efficiency; and
- guidance on how to assess catalyst NOx reduction efficiency based on periodical spot checks or monitoring as specified by the designer.

Records are to be kept for inspection during annual, intermediate and renewal surveys. The frequency of periodical spot checks is to be defined by the designer considering the expected deterioration of the catalyst. The frequency for spot-checks should be at least after installation and once every 12 months.

6 VESSELS WITH SCR: FACTS AND FIGURES

For the analysis of vessels equipped with Selective Catalytic Reduction (SCR) systems, the class register of the classification society DNV serves as the primary basis. Unfortunately, other sources, such as IHS Fairplay, do not provide sufficient information to conduct a comprehensive global analysis of the world fleet. Given that approximately one-fourth of all sea-going vessels are classified by DNV, the analysis provided here serves as a reliable proxy for the global fleet.

Vessels classed with DNV require the mandatory class notation “ER (SCR)” in case an SCR system is installed in one or more exhaust lines, [6]. The analysis focuses solely on ships with a gross tonnage of 400 and above, as only these vessels are subject to the survey and certification requirements stipulated by MARPOL Annex VI and fall under the purview of the Harmonized System of Survey and Certification (HSSC), [7], as per IMO regulations.

6.1 Number vessels with SCR

At the time of this paper's preparation, a total of 8250 ships with a gross tonnage exceeding 400 are classified by the classification society DNV. Additionally, 361 are either contracted or currently under construction. Out of these 8611 ships, 864 can be identified to have at least one SCR installed. This accounts for 10% of the seagoing ships classified by DNV. It must however be taken into account that out of these 864 ships, 283 are still under construction. These numbers are illustrated in Figure 8.

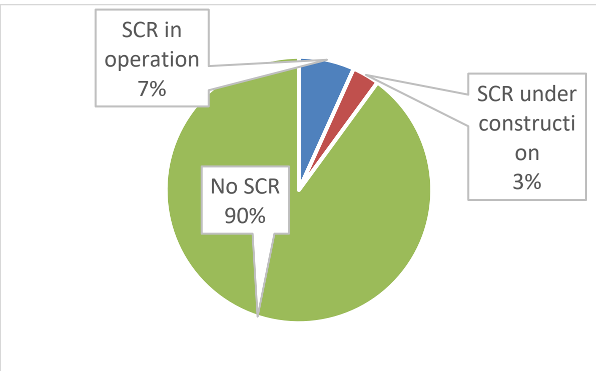

Figure 8. Ships classed by DNV, GT>400 tons, percentage of SCR.

6.2 Vessel age

Further investigating the vessels with SCRs, which are already in operation indicates that more than 80% all vessels with SCR have an age of 3 years or less. A big portion of vessels (38%) have only been delivered one year or less, as illustrated in Figure 9.

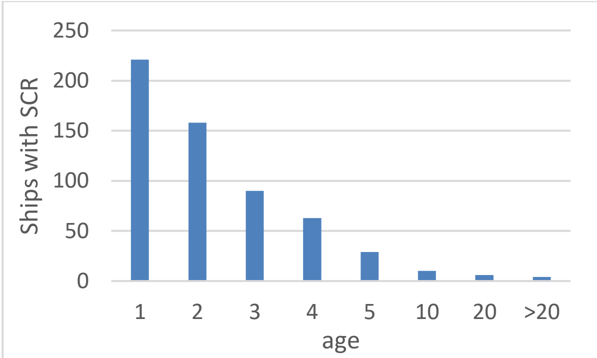

Figure 9. Ships with SCR and age.

These figures demonstrate that although Selective Catalytic Reduction (SCR) systems have been available in the maritime sector for a considerable period, their application in seagoing vessels remains relatively new on a larger scale. The development over time depending on ship type is further illustrated in Figure 14.

6.3 Vessel sizes

Upon examining the dimensions of vessels equipped with Selective Catalytic Reduction (SCR) systems, vessel gross tonnage (GT) serves as a reliable indicator. As depicted in Figure 10, SCR systems are no longer confined to smaller vessels. Their application now spans the entire size range, extending up to vessels exceeding 200,000 GT.

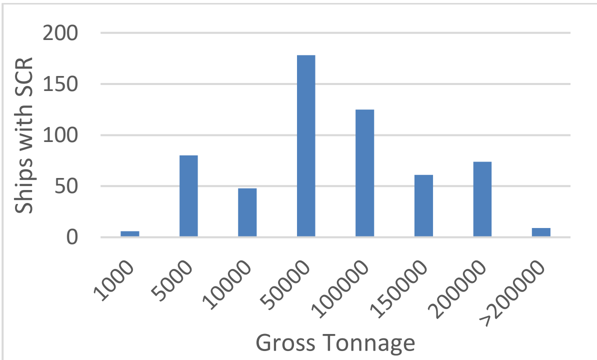

Figure 10. Ships with SCR and gross tonnage.

6.4 Main propulsion power

When analyzing the main propulsion power, as depicted in Figure 11, a similar trend is observed. However, it is important to note that the illustrated propulsion power does not necessarily correspond to the design size of the SCR system. The data presented in Figure 11 primarily reflect the power of the main engine installed on board the vessel. Additionally, the main engine may comply with NOx Tier III limits through alternative methods such as exhaust gas recirculation (EGR) or the use of alternative fuels.

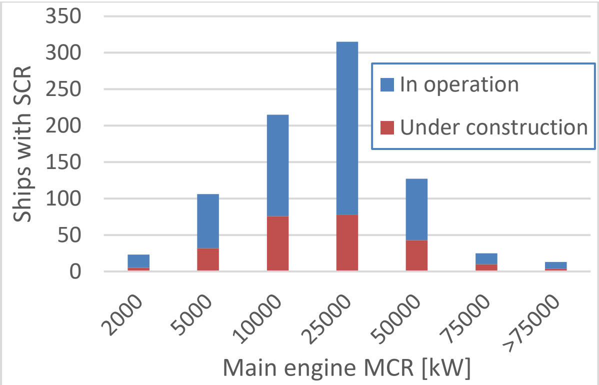

Figure 11. Ships with SCR and main propulsion power.

The data indicate that the propulsion power of vessels equipped with SCR systems spans the entire spectrum, ranging from 2,000 kW to over 75,000 kW. This further demonstrates that SCR systems are no longer limited to niche applications but are now being implemented in the largest sea-going vessels, particularly for auxiliary engines.

6.5 Vessel types

Analyzing the prevalent ship types equipped with SCR systems, either currently installed or under construction, reveals that the container ship segment leads, followed closely by tankers, other types of vessels, and bulk carriers, as illustrated in Figure 12.

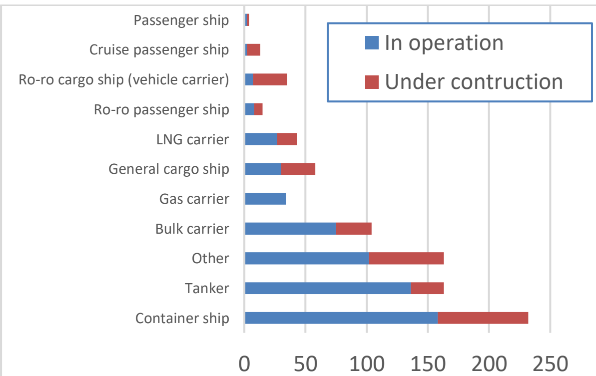

Figure 12. Ships with SCR and ship types.

The predominance of container ships can be attributed to the segment distribution within the classification society DNV, where container ships represent nearly 25% of the fleet, thus making them the leading segment. A more detailed analysis, as depicted in Figure 13, reveals the percentage of SCR systems per segment. Vehicle carriers hold a significant position, with 20% of all vehicle carriers and 25% of all LNG carriers having at least one SCR system installed. This observation may be linked to the operational areas in NOx Emission Control Areas (ECAs), combined with the relatively young age of these fleets. The average age of vehicle carriers is 14 years, while LNG carriers are even younger, with an average age of 10 years (in contrast, general cargo ships have an average age of 18 years). Additionally, the external pressure to meet environmental sustainability goals imposed by owners and charterers may contribute to the adoption of SCR systems in these segments.

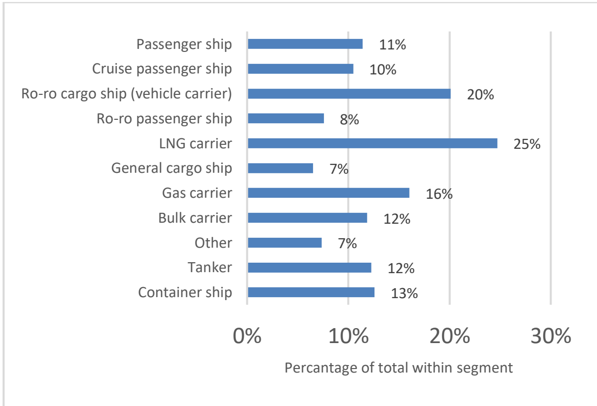

Figure 13. Ships with SCR and percentage within segment.

Given the external pressure to achieve environmental sustainability goals, it is also evident in the cruise passenger segment that all vessels currently under construction are equipped with SCR systems to comply with NOx Tier III requirements.

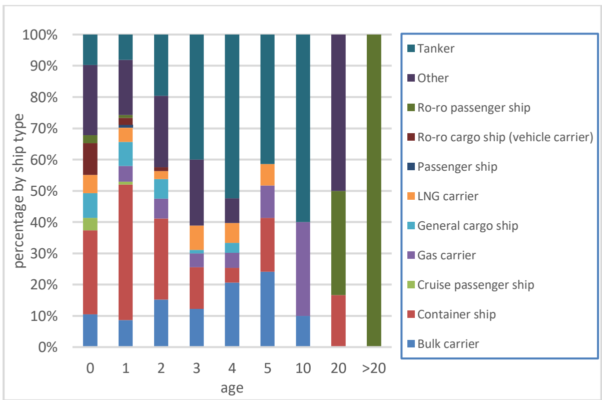

Figure 14. Percentage by ship type over age

Figure 14 demonstrates the widespread adoption of Selective Catalytic Reduction (SCR) systems across various maritime segments. Historically, SCR systems were predominantly installed on Ro-Ro passenger vessels and offshore supply vessels, driven primarily by regional regulations such as Norway's NOx tax and Swedish fairway dues. However, recent trends indicate a broader implementation of SCR systems, influenced by both regional and international regulations, including those imposed by the International Maritime Organization (IMO).

Figure 15 provides a detailed analysis of the expansion of Selective Catalytic Reduction (SCR) systems within the containership segment, highlighting their increasing presence in international waters. Historically, SCR systems were primarily installed on smaller container ships. However, the figure now indicates that Ultra Large Container Vessels (ULCVs) with a carrying capacity exceeding 14,000 TEU are either operational or under construction. Notably, 25% of all ULCVs currently under construction are equipped with SCR systems, underscoring the significant expansion of SCR technology in this segment.

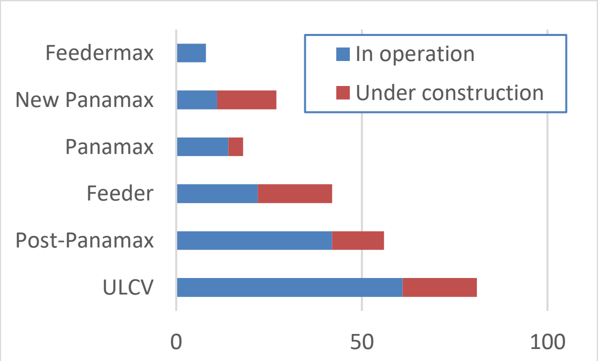

Figure 15. Container ships with SCR and ship size categories.

6.6 Summary of facts and figures

Even though the analysis of vessels equipped with Selective Catalytic Reduction (SCR) systems primarily relies on data from the classification society DNV some trends can be identified and are highlighted as follows:

- 10% of seagoing vessels classed by DNV have at least one SCR system installed;
- vessels with SCR systems are relatively new, with over 80% being three years old or less;
- SCR systems are now installed across a wide range of vessel sizes, from small ships to those exceeding 200,000 GT;
- the adoption of SCR systems has expanded significantly across various maritime segments, driven by both regional and international regulations.

7 OPERATIONAL EXPERIENCE SURVEY

To gather insights on the common challenges associated with Selective Catalytic Reduction (SCR) systems and the practical monitoring of catalyst block deterioration rates, the classification society DNV conducted a comprehensive questionnaire involving over 200 class surveyors globally. The survey questions focused on the practical aspects of conducting surveys, identifying deviations, and the follow-up procedures, as well as determining which components of the SCR system are most prone to failure based on surveyor opinions. The following subsections present a selection the survey results. It is important to note that these results are based on individual experiences and should not be considered an objective analysis. Nevertheless, they provide valuable insights into the operational experience with SCR systems from an independent perspective.

7.1 Scope of SCR survey

The initial notable finding from the survey indicates that although two-thirds of the respondents incorporate visual inspections or request measurements (spot-checks) as part of the survey process, 15% rely exclusively on the review of related documents and records, such as outcomes from spot-checks and maintenance reports, as demonstrated in Figure 16.

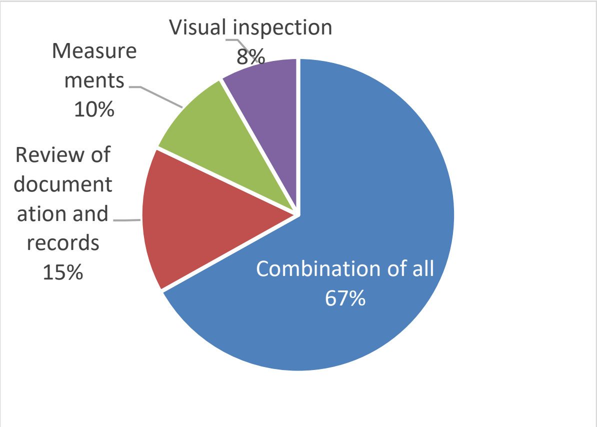

Figure 16. Scope of SCR survey.

In this context, it is important to highlight that according to the International Maritime

Organization (IMO) Resolution A.1186(33) [7], only the following items must be conducted during annual surveys, and it is worth noting that, depending on the installed system, these requirements may be addressed solely through documentation review:

- reviewing engine documentation contained in the NOx technical file and the record book or an electronic record book of engine parameters to check, as far as practicable, engine rating, duty and limitation/restrictions as given in the NOx technical file;
- confirming that the engine has not undergone any modifications or adjustments outside the options and ranges permitted in the technical file since the last survey;
- conducting survey as detailed in the NOx technical file.

7.2 Root causes for malfunctions

Based on the feedback from poll participants, the primary root causes of malfunctions are predominantly associated with the NOx sensor, urea nozzles, and the electronic control unit, as illustrated in Figure 17.

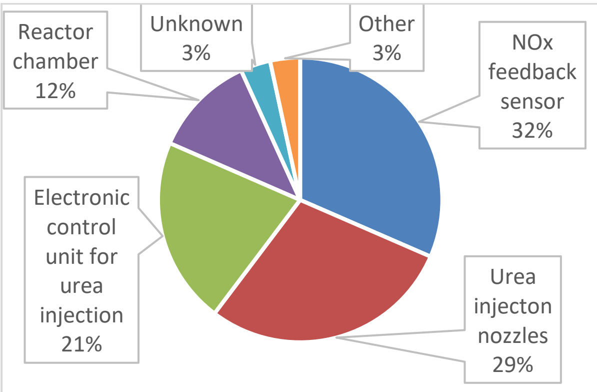

Figure 17. Major findings during annual surveys.

Other findings, including potential failures in the reactor chamber, are considered negligible. Notably, the issues identified with the NOx sensor and urea injection nozzles support the recommendation to enhance continuous maintenance efforts, as detailed in the subsequent subsection.

7.3 Improvement potentials

In order to improve the reliability of SCR systems and in order to reduce the amount of failure cases, majority of the participants of the poll suggested to increase the focus on maintenance, followed up by the recommendation to enhance the crew training, see Figure 18.

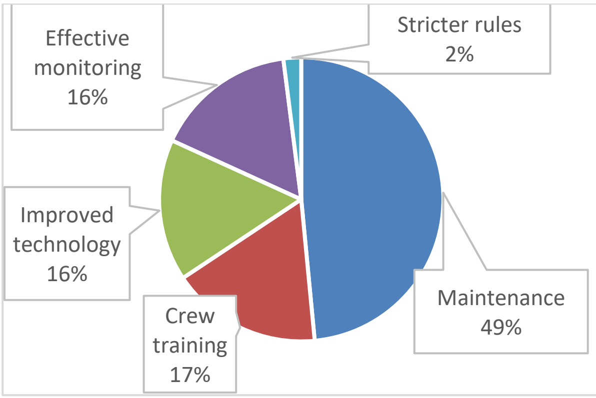

Figure 18. Improvement potentials.

7.4 Summary of the survey

To summarize the outcome of the poll, it can be said that clear trends emerged from the survey conducted by the classification society DNV involving over 200 class surveyors globally:

- Trends in SCR Wear and Aging: The survey data reveals clear trends, indicating that increased NOx emissions are the most prevalent indicator of Selective Catalytic Reduction (SCR) system wear and aging. However, violations of NOx emission limits are seldom observed.
- Reliability of Systems with Feedback Control: The survey suggests that systems incorporating feedback control for reductant injection exhibit the highest reliability, particularly when stringent maintenance protocols for NOx sensors are followed.
- Susceptibility to Failure: There is minimal disparity in failure susceptibility between high-pressure and low-pressure SCR systems, although high-pressure systems display a marginally higher propensity for faults.
- Primary Causes of Deterioration: SCR system deterioration and accelerated aging are primarily attributable to suboptimal maintenance. The components most vulnerable to failure are the NOx sensors, followed by urea injection nozzles.
- Root Causes of Component Failures: Failures of NOx sensors are predominantly linked to contamination and deposits of the sensor probes. Mechanical issues and wear are typically responsible for the malfunctioning of the of the urea injection system. This finding indicates a recurring issue with contamination in SCR systems,

which could be ameliorated through more frequent maintenance and cleaning.

- Importance of Regular Maintenance: To address the root causes of these failures, comprehensive and routine maintenance is crucial. The poll's outcomes underscore the necessity of enhancing maintenance efforts to mitigate these issues effectively.

This enhanced approach to maintenance, as indicated by the survey results, supports the recommendation for increased vigilance and regular upkeep to ensure the optimal performance of SCR systems.

8 CONCLUSIONS

The analysis of vessels equipped with Selective Catalytic Reduction (SCR) systems primarily relies on data from the classification society DNV, which classifies about one-fourth of all sea-going vessels. This analysis focuses on ships with a gross tonnage of 400 and above, as these are subject to MARPOL Annex VI regulations.

As of the paper's preparation, 8,250 ships with a gross tonnage exceeding 400 are classified by DNV, with 361 more under construction. Of these, 864 ships (10%) have at least one SCR system installed, though 283 of these are still under construction. Most vessels with SCR systems are relatively new, with over 80% being three years old or less.

SCR systems are now installed across a wide range of vessel sizes, from small ships to those exceeding 200,000 GT. The propulsion power of these vessels also varies widely, from 2,000 kW to over 75,000 kW. Container ships lead in the number of SCR installations, followed by tankers, other vessel types, and bulk carriers. Vehicle carriers and LNG carriers also show significant adoption of SCR systems, likely due to their operation in NOx Emission Control Areas and the pressure to meet environmental sustainability goals.

The cruise passenger segment also shows full adoption of SCR systems for vessels under construction to comply with NOx Tier III requirements. Overall, the adoption of SCR systems has expanded significantly across various maritime segments, driven by both regional and international regulations.

A global poll of over 200 DNV surveyors shows that increased NOx emissions are the most common indicator of SCR system wear and aging, although NOx emission limit violations are rare. Systems with feedback control for reductant injection are the most reliable, especially with strict NOx sensor maintenance. The survey found little difference in failure rates between high-pressure and low-pressure SCR systems, though high-pressure systems are slightly more prone to faults.

The primary cause of SCR system deterioration and accelerated aging is poor maintenance, with NOx sensors and urea injection nozzles being the most failure-prone components. NOx sensor failures are mainly due to contamination and deposits, while mechanical issues and wear typically cause injection problems, indicating frequent contamination issues. The survey underscores the importance of comprehensive and routine maintenance to mitigate these failures, supporting the recommendation for increased vigilance and regular upkeep to ensure optimal SCR system performance.

For future research, it is recommended that subsequent investigations also encompass vessels classified by other classification societies. These analyses should incorporate an examination of the operational regions of vessels equipped with SCR systems, utilizing reliable Automatic Identification System (AIS) data. This approach aims to provide a comprehensive global perspective on the world fleet of vessels with SCR systems.

9 DEFINITIONS, ACRONYMS, ABBREVIATIONS

ACD: Auxiliary Control Device

AIS: Automatic Identification System

ECA: Emission Control Area

EGR: Exhaust Gas Recirculation

EIAPP: Engine International Air Pollution Prevention certificate

GT: Gross Tonnage

IAPP: International Air Pollution Prevention certificate

IMO: International Maritime Organization

MARPOL: International Convention for the Prevention of Marine Pollution from Ships

MEPC: Maritime Environmental Protection Committee

SCR: Selective Catalytic Reduction

SOLAS: International Convention for the Safety of Life at Sea (SOLAS)

ULCV: Ultra Large Container Vessels

10 REFERENCES AND BIBLIOGRAPHY

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[4] IMO Resolution MEPC.313(74). 2019. Amendments to the 2017 Guidelines addressing additional aspects of the NOx Technical Code 2008 with regard to particular requirements related to marine diesel engines fitted with Selective Catalytic Reduction (SCR) Systems (Resolution mepc.291(71)).

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11 CONTACT

Dr. Fabian Kock presently serves as the Head of Environmental Technologies Air at DNV, Hamburg, Germany. He oversees environmental-related certification within the marine sector, encompassing responsibilities such as the certification of marine diesel engines, marine exhaust gas after-treatment systems (including SCR catalysts and scrubbers), and the certification of ships' energy efficiency. His remit also includes the management of a laboratory dedicated to measuring exhaust gas components and particulate matter.

Moreover, Dr. Kock advises the German Ministry of Traffic on technical matters related to air emissions from international shipping at the International Maritime Organization (IMO).

His previous roles include Head of Section for Safety & Systems at the Approval Centre China of DNV. In this capacity, he was responsible for plan approval of statutory, piping, electrical, and bridge systems, as well as propulsion, engines, and machinery within Greater China.

Dr. Kock's extensive background features research in heat transfer and fluid dynamics, along with substantial expertise in the development of internal combustion engines. He commenced his tenure at DNV GL in 2009, following his studies in mechanical engineering in Hamburg, Sydney, and Chennai, coupled with industry experience in engine development.

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