IACCSEA White Paper

The Technological and Economic Viability of

Selective Catalytic Reduction for Ships

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1. Regulatory outlook

The Marine Environment Protection Committee of the International Maritime Organisation (IMO) agreed a three-tier structure for new engines in 2008, which would set progressively tighter nitrogen oxide (NOx) emission standards depending on their date of installation. NOx emission limits are set for diesel engines depending on the engine maximum operating speed - n, rpm (see the table below and Figure 1).

Tier	Date	NOx Limit - g/kWH		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17	$45 . N^{-0.2}$	9.8
Tier II	2011	14.4	$44 . N^{-0.23}$	7.7
Tier III	2016	3.4	$9 . N^{-0.2}$	1.96

Tier III (an 80% reduction from Tier I) applies to a diesel engine installed on a ship constructed on or after 1 January 2016, when the ship is operating in a designated Emission Control Area (ECA). Outside a designated ECA, Tier II limits apply. The economic and technological viability of Tier III is under review in 2012. During this IMO review, exhaust gas aftertreatment technology has been described as the most well developed option for meeting Tier III. During the last 3-4 years, all major engine manufacturers have developed and tested engines or announced their intention to do so in order to meet market demand for Tier III compliance. This is the case for both 2-stroke and 4-stroke engine manufacturers.

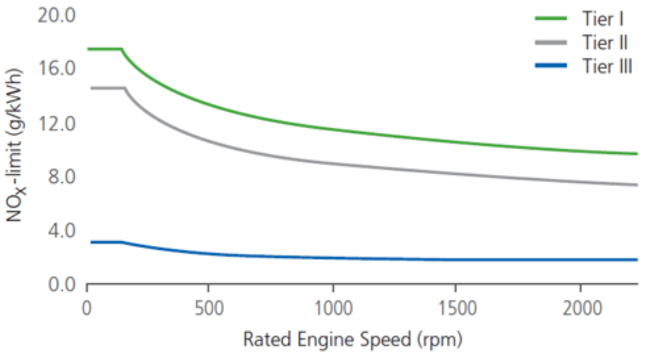

Figure 1: NOx regulations for new engines (source DNVhttp://www.dnv.com/industry/maritime/servicessolutions/maritime_environment/nox/)

On 1 August 2012 a North American ECA entered into force 200nm around the United States and Canada. This was the first designated ECA to incorporate NOx. The key arguments contained within the US Environmental Protection Agencies successful ECA application focussed upon the economic competitiveness of marine emission abatement technology, the low cost of compliance for ship operators and the benefits to public health[1]. A second EPA proposal for an ECA around Puerto Rico and the US Virgin Islands has also been accepted and will be effective as of Jan 2014.

Since 2010, the coastal countries of the Baltic Sea have been involved in a decision-making process over an application to the IMO to designate the Baltic Sea as a NOx ECA. In March 2011, the coastal countries of the North Sea commissioned an environmental impact assessment and an economic impact assessment to support a possible application to the IMO to designate the North Sea (including the English Channel) as a NOx ECA. Other regions such as the Mediterranean, Japan, Hong Kong, Singapore, Mexico and Australia are also considering the benefits of implementing ECAs.

Prior to the implementation of ECAs, the Norwegian NOx tax and associated fund, a 2 € per kg tax (or 0,5-1,5 € per kg to the fund) on NOx emitted within Norwegian waters, has driven the market for NOx aftertreatment technology (engines exceeding 750 kW and boilers over 10 MW).

Also, the Swedish environmental differentiated fairway dues have been an important driver for early implementation of SCR on ships.

2. Description of SCR technology

Selective Catalytic Reduction (SCR) has the capabilities of reducing the concentration of NOx in the exhaust gases of marine engines to below the emission limits set by IMO Tier III. It is an emission reduction method that reduces NOx through catalytic aftertreatment technology (SCR is the only technology that controls NOx emissions in the exhaust gas after they have been generated in a marine engine running on diesel). In the presence of high-temperature exhaust gas (greater than 250°C), an SCR system uses a catalyst to chemically reduce NOx to N2 and water by using ammonia (NH3) as the reducing agent (aqueous urea solution is most frequently chosen as the reagent):

NO + NO2 + 2NH3 -> 2N2 + 3H2O

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[1] **Key EPA Arguments**

- The cost to reduce a tonne of NOx from ship emissions is estimated at $2,400 ($2,300 tonne NOx for trucks)
- Operating costs for a ship in a route that includes 1,700 nm of operation in the proposed ECA would increase by approximately 3% (an $18 increase for the transport of a 20 foot container)
- 14,000 lives will be saved and nearly five million people will experience relief from acute respiratory symptoms each year

It is theoretically possible to achieve 100% NOx conversion if the NH3-to-NOx ratio is 1:1 and the space velocity within the catalyst is sufficient to allow time for the reactions to occur. The urea dosing strategy and the desired NH3-to-NOx ratio is dependent on the conditions present in the exhaust; namely gas temperature and the quantity of NOx. Typically, SCR as designed to remove 80-95% of NOx in the exhaust gas of a marine engine.

3. Installed base of marine SCR

Selective catalytic reduction of NOx using ammonia as the reducing agent was patented in the United States by the Englehard Corporation in 1957. Since this time thousands of systems have been installed on terrestrial applications, from power plants to locomotives to automobiles.

SCR is also a proven technology in marine applications. Systems have been installed on over 500 marine vessels over the last 30 years. Some have been in operation for well over 10 years and have accumulated >80,000 hours of experience. Engine manufacturers apply SCR to a wide range of ship types (including ferries, supply ships, RoRos, tankers, container ships, icebreakers, cargo ships, workboats, cruise ships, and foreign navy vessels for both propulsion and auxiliary engines), engine sizes, utilizing different fuels (of differing sulphur content) and operating over a range of engine conditions.

The vast majority of the installed SCR base has been applied to 4-stroke engines. However, some of the earliest experience was with large, 2-stroke engines and more recently, there has been a revised interest in developing this further. It is anticipated by the industry that this engine subset will be fully served with commercially available SCR solutions by 2014.

Even taking into consideration the significant number of SCR systems that are being successfully utilized on marine vessels, a series of concerns are consistently raised about the applicability of the technology. The remainder of this paper seeks to address the most frequently asked questions related to marine SCR.

4. The application of marine SCR – frequently asked questions

4.1. Does SCR work efficiently when using high sulphur fuels?

Yes. Maritime vessels are typically using fuels with sulphur content of 0.1% (Marine Gas Oil - MGO) to 3% (Heavy Fuel Oil - HFO). The global average sulphur content of HFO is currently around 2.4%.

Although sulphur is not a poison to conventional SCR catalysts, the high sulphur content of marine fuels presents a challenge to the efficacy of SCR. This is because, at low temperatures, ammonia and sulphuric acid condense as liquid ammonium bisulfate, NH_4HSO_4, (ABS) in the catalyst pore structure, which inhibits the catalysts performance. ABS may also adversely affect engine operation by increasing exhaust backpressure. The condensation reaction for ammonium bisulphate formation is written as:

$$NH3_{(g)} + SO3_{(g)} + H2O_{(g)} \rightarrow NH4HSO4_{(l)}$$

For more detail see footnote [2]

If vessels use low sulphur fuels in ECAs with fuel sulphur content of 0.1%, this should be sufficiently low to reduce the sensitivity of systems to ammonium sulphate deposition. At higher fuel sulphur content, where sulphur oxides are present in significant amounts in exhaust gas, care must be taken to design system operating temperatures which are high enough to prevent ammonium sulphate masking the catalyst and introducing backpressure. The optimal temperature for the DeNOx technology is between 350°C and 420°C. When operating on marine distillate fuel with 0.1% sulphur, the minimum exhaust temperature would be on the order of 270°C. For typical heavy fuel oils, the exhaust temperature would need to be over 300°C to prevent ABS as the condensation point in the SCR reactor inlet is typically around 290°C (see Figure 2).

The catalyst activity is directly related to the extent of pore condensation which means that ABS inhibition increases gradually as the temperature is lowered towards the bulk dew point (it is important to note that some SCR catalyst types are designed with the ability of performing with a high weight % of ABS accumulated in the pores).

Due to the fact that exhaust gas temperatures are correlated with the operating load placed on the engine, it is a challenge to maintain sufficiently high temperatures

[2] The condensation point in the SCR reactor inlet is typically around 290°C. ABS first condenses in the smallest catalyst pores and as the temperature approaches the bulk dew point the entire catalyst is filled with ABS. The bulk dew point is calculated according to Matsuda et al.[2]:

$$\ln\left(P_{NH_3} \cdot P_{H_2SO_4}\right)_{eq,bulk} = 27.97 - \frac{26671}{T_{dew}[K]}$$

The catalyst activity is directly related to the extent of pore condensation, which means that ABS inhibition increases gradually as the temperature is lowered towards the bulk dew point. Operation below the bulk dew point is not an option except for very low SO3 concentrations in low dust SCR installations since ABS will condense not only inside the catalyst pores, but also on the catalyst surface, creating a sticky surface which could over time lead to pluggage of the catalyst. It is important to notice that some SCR catalyst types are designed with the ability of performing with a high weight % of ABS accumulated in the pores.

The vanadium based SCR catalyst is not sensitive to sulphur except for ABS condensation.

when engines are operating at low engine loads (<25%) for extended periods of time.

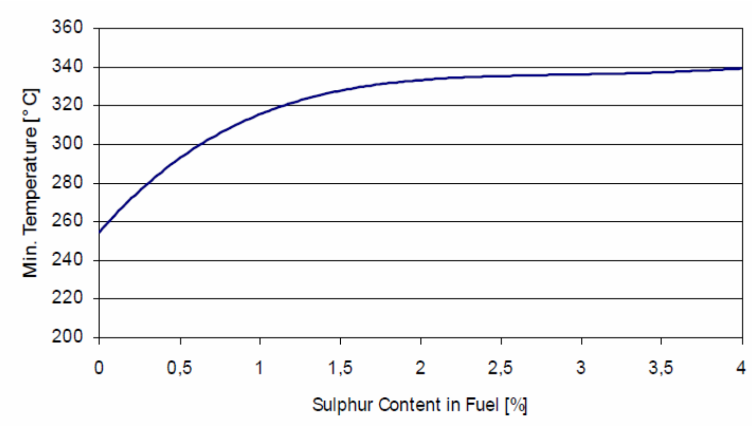

Figure 2: Minimum temperature for long-term SCR operation (SCR operates well above the blue line, below the line we see ABS formation).

Adequate exhaust gas temperatures can be achieved through a number of methods. One approach is to properly position the SCR catalyst relative to the turbocharger (the exhaust gas temperature is always higher at the inlet - before the turbine stage - than at the outlet due to the fact that when exhaust gases pass through the turbocharger, heat energy from the exhaust is converted into shaft work, where it is used to compress the intake air). For 4-stroke engines the SCR catalyst can be mounted downstream of the turbocharger with a by-pass (or wastegate) installed in the exhaust before the turbocharger to divert hotter exhaust to the catalyst as the need arises. Other mechanisms include reducing the level of charge air or modifying the injection timing; elevating exhaust temperatures by using burner systems during low power operations; cylinder bypass or some other method; or, on a ship with multiple propulsion engines, shutting down one or more engines such that the remaining engine or engines will operate at higher power.

4.2. Will HFO poison the catalyst and lead to ammonia slip?

Catalyst providers generally guarantee the operation of their product for a standard operating time such as 16,000 hours or 2-3 years. Catalyst performance will deteriorate over time due to the build up of soot, ash, and poisons from the fuel and lubricants.

All non-distillate fuels contain an ash fraction which is emitted through the exhaust gas system. The ash in the fuel consists primarily of vanadium and nickel together with small amounts of sodium and phosphorous. The lubrication oils also typically contain phosphorous, calcium and zinc. Plugging due to these components has to be mitigated by an effective soot blower. A small part of the ash components do accumulate on the SCR catalyst over time, which means that the amount of especially vanadium and nickel increases. The net effect is that the SCR activity is kept at a high level throughout the catalyst lifetime.

Based on experience catalyst suppliers can estimate the accumulation rate of poisons on the catalyst during its lifetime. Catalyst manufacturers factor deactivating mechanisms into their sizing programmes, which means that deterioration can be considered at the design phase. Other mechanisms that can be used to prolong catalyst life and prevent ammonia slip include: operating in catalyst by-pass mode to save the catalyst when operating outside ECAs; using SCR only in ECAs; using low-sulphur fuel; capturing ammonia at the back of the SCR system; and turning off the system at pre-determined low exhaust temperatures. Alternatively, deterioration can be addressed by establishing a management program that includes catalyst replacement.

As long as the SCR catalyst is properly sized for the application, there should be no initial issue with overdosing of urea and subsequent ammonia slip (>10 ppm).

There is a growing consensus that continuous monitoring of exhaust emissions and the active management of the injection rate of the reductant represents the best means to guard against ammonia slip. There are two potential approaches using feedback electronic control units. The first approach is to monitor ammonia slip (>10 ppm) either continuously or at frequent intervals on ships with SCR systems. The second approach is to continuously monitor the NOx emissions from the SCR catalyst outlet. Technologies are readily available today to measure NOx on-board a ship for comparison to measurements made during the certification of the engine or combined engine/SCR system.

4.3. Does SCR work on 2-stroke engines?

Concerns are sometimes raised as to whether temperatures are sufficient within 2-stroke engines to support the efficient operation of SCR. This is because the exhaust gas temperature at full load is typically 390°C-490°C upstream of the turbocharger, but only 250°C-290°C downstream of the turbocharger. The reality is that 2-stroke vessels have been operating SCR successfully for several years.

There are two potential locations for the SCR system, one is located upstream of the turbocharger (Pre-T/C SCR), the other is downstream of turbo charger (Post-T/C SCR). Both approaches are evaluated in the table below:

Issue	*Pre - T/C SCR*	*Post - T/C SCR*	*Comments*
CAPEX	√	X	Post - T/C SCR must be considered in conjunction with: a large catalyst, temp rise oil burner, longer exhaust gas duct
OPEX	√	X	Post - T/C SCR will require additional costs for: gas temperature rise burner, oil fired steam boiler
Impact on fuel efficiency	√	X	Due to the T/C back pressure limitation, the series flow arrangement of SCR and EGE is difficult and parallel flow is inevitable. Thus the steam boiler will be wastefully oil powered in the case of post - T/C SCR operation
Size	√	X	Due to high temperature and pressure, pre - T/C SCR will be more compact
Design flexibility in engine room	X	~	Pre - T/C SCR must be arranged near the main engine. Post - T/C SCR is freely arranged after the T/C - the strength of the hull construction and backward visibility from the bridge must be considered
Maintena-nce in engine room	X	~	
Tech' hurdles	√	X	In the case of post T/C SCR, low temperature catalysts are expected, which are not available at this juncture
ABS	√	X	Due to high temperatures, catalyst deterioration and ABS issues are diminished for pre-T/C SCR
√: Good ~: Medium X: Not Good			

As demonstrated in the table, Pre-T/C SCR is the better approach on a vessel with a 2-stroke engine.

Figure 3 shows a pre-T/C SCR arrangement in the engine room for a 38,000 MT type bulk carrier (main engine: 7000 kW class). The key points are that: a) the vaporizer and reactor are located near to the main engine; b) stuck-out decks are added to the 2nd/3rd deck level in the engine room, but the engine room length and engine casing size remain the same.

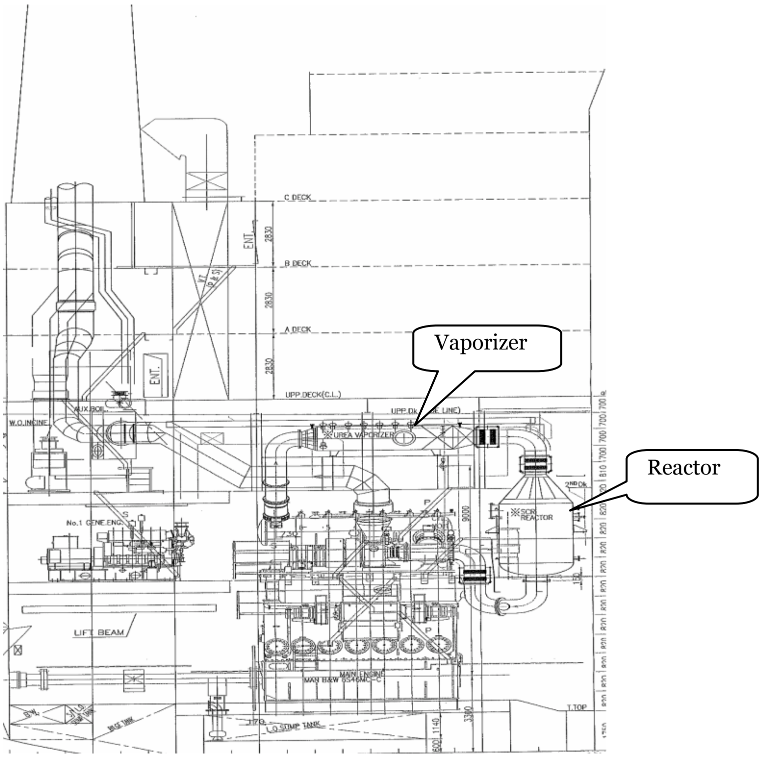

Figure 3: Pre-T/C SCR arrangement in engine room

4.4. *Can SCR be used in conjunction with SOx scrubbers?*

It is anticipated that sulphur regulations coming into force in 2015 will drive the uptake of SOx scrubbers and questions are being asked in relation to the compatibility of this technology with SCR.

The reality is that SCR can be used in conjunction with a scrubber. However, given the temperature range within which SCR operates efficiently (see Figure 2), the common view is that the SCR system should be positioned upstream of the scrubber. If the SCR is located downstream of the scrubber, it is necessary to reheat the gas to approximately 200°C (due to the low sulphur content) which carries an inherent carbon cost associated with reheating. However, some dry SOx scrubbers do not lower the temperature, meaning that in these instances the SCR system could be placed downstream of the scrubber.

4.5. *In 2016, will there be issues with the availability of urea?*

Land-based SCR applications currently require 20 million tonnes of urea solution per year. The total demand for urea solution in marine applications today is approximately 30 thousand tonnes, or less than 1% of the total land-based use (yearly consumptions of urea for a vessel are typically be between 30 - 1000 tonnes, 30 tonnes for smaller fishing vessels and 1000 tonnes for large ferries, cruise ships and big deep sea vessels).

When the Tier III NOx standards become effective in 2016, the maritime demand for urea will continue to be relatively small and sufficient quantities of urea will be available for marine applications. Urea will only be required by vessels built or that undergo a major conversion beginning in 2016 that are equipped with SCR technology and that are operating in ECA areas. Marine demand is expected to grow slowly over time as more new vessels and major conversions become subject to the requirements.

Urea is produced in over 50 countries and is available across most of the globe including Canada, U.S., Europe, Asia and the Middle East. Distribution systems are expected to expand to major ports in response to urea demand for use on ships. The proposed NOx ECA areas of the North Sea, English Channel and Baltic Sea already have a well established storage and distribution network for urea, as the majority of the ships in these areas are already using SCR technology due to the Norwegian NOx Fond. The U.S. EPA Tier 4 regulations that go into force beginning in 2014 will require urea availability for the US market two years earlier than the North American ECA comes into force.

4.6. How are SCR systems certified?

An SCR system installed to meet the NOx requirements of MARPOL Annex VI must be certified according to the standards set forth in the NOx Technical Code, the associated SCR guidelines (MEPC resolution 198(62)) and the classification societies' rules.

The certification process involves necessary component certification, a certification of the system function and performance (EIAPP certificate) and a certification of the ship with the system(s) (IAPP certificate).

There are two main routes to follow on order to obtain certification, the so called scheme A and scheme B. Scheme A is the "standard" approach used for engines for many years, where the engine + SCR performance are verified on a test bed. Scheme B allows for the certification of the engine which is combined with a certified SCR system. The combined emission performance of the engine + SCR is validated in an onboard test. Scheme B is a new procedure and there are still uncertainties regarding requirements to the certified SCR system.

4.7. Are there certain vessel types upon which SCR cannot be fitted?

Potential issues have been raised with regard to fitting SCR systems on small vessels such as yachts greater than 24 meters in length.[3] Specifically that there is not space in existing designs to incorporate SCR and that, due to large capital investments in the moulds used to manufacture the vessels, vessel designs cannot be modified to incorporate SCR in the 2016 time frame. For small vessels physical constraints cited in opposition to SCR include engine room ventilation issues, lack of infrastructure to support the extra equipment weight, reduced access between engines and increased displacement from extra weight that affects vessel trim and speed.

In reality, for use in such small high speed marine engines, SCR systems can be made more compact and similar to those used in Heavy Duty Diesel applications e.g. trucks. SCR has been installed on several passenger vessels (primarily car/passenger vessels) and SCR systems have also been installed on a small number of recreational craft of less than 24m to comply with emission limits at a comparable level to Tier III (such as NOx tax/Scandinavia and Lake Constance and Austria/Germany/Switzerland regulations). Furthermore, because IMO Tier III applies to new builds, SCR can easily be incorporated into the design phase.

The application of SCR to Mobile Offshore Drilling Units (MODU) has historically been questioned. Specifically, concerns are raised that in nearly all routine operating conditions, the prime movers are not sufficiently loaded to achieve exhaust temperatures necessary for optimal performance of the catalyst. The low operating temperature combined with rapid engine load variations would lead to clogging of the catalyst bed and extensive ammonia slip.

4.8. What are the costs associated with SCR?

CAPEX is a major cost component for SCR technology. For 2-stroke engines CAPEX ranges from 28-55 €/kW. For 4-stroke, costs vary from 25-62 €/kW[4]. The larger the engine, the less expensive the installation costs per kW. OPEX is driven by the cost for the urea solution. Running costs range between 4 and 10 €/MWh for 2-stroke engines and 3 and 7 €/MWh for 4-stroke engines [4]. It is worth noting, however, that the variance in the above figures is due to unknowns related to urea cost and projected time spent by vessels in an ECA.

For all sizes of 4-stroke engine, SCR is the cheapest currently available NOx abatement technology capable of achieving IMO Tier III NOx specifications (costs are on average 83% of the EGR costs) [4].

For 2-stroke, Pre-T/C SCR cost is lower than that of post-T/C SCR due to the temperature rise oil burner, even considering the required modifications for pre-T/C SCR.

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[3] Regulation 13.5.2.2 of MARPOL Annex VI specifically excludes recreational vessels less than 24 metres from the Tier III NOx standards.

[4] Danish Ministry for the Environment - Environment Protection Agency: Economic Impact Assessment of a NOx Emission Control Area in the North Sea