WORKING PAPER 2014-4

MARCH 2014

Feasibility of IMO Annex VI Tier III implementation using Selective Catalytic Reduction

Author: Alyson Azzara, Dan Rutherford, Haifeng Wang

Date: March 2014

Keywords: Selective Catalytic Reduction (SCR), Nitrogen Oxides (NO_x), International Maritime Organization (IMO), Tier III Requirements, and Emission Control Areas (ECA)

Summary

In 2008 the Marine Environmental Protection Committee (MEPC) of the International Maritime Organization (IMO) agreed upon progressively stricter limitations for nitrogen oxide (NO_x) emissions from vessels based on their date of engine installation, with the strictest Tier III requirements to take effect in designated Emission Control Areas (ECA) beginning in 2016. At MEPC-66 in April 2014, an amendment that would delay the introduction of the Tier III standards to 2021 will be considered based on concerns arising from perceived equipment, supply chain, and cost barriers raised at MEPC-65. This paper investigates the current status of selective catalytic reduction (SCR), a key technology to meet Tier III requirements. Challenges and costs of the technology, including applicability to various engine and vessel types, potential environmental side effects, urea and catalyst availability and disposal, and anticipated system costs, are discussed. Based on this evaluation of technological capabilities and history of successful application of SCR technology to maritime vessels, we find no substantial equipment, supply chain, or cost barriers to necessitate the delay of IMO's Tier III requirements.

Background

Nitrogen oxides (NO_x) are an important air pollutant created as a by-product of combustion. Air contains primarily nitrogen (N_2) and oxygen (O_2). The heat generated during combustion causes these to react to form NO_x in direct proportion to peak combustion temperature and pressure. International shipping is a major source of oxides of nitrogen (NO_x) globally.[1] Oceangoing vessels emitted about 25 million metric tons (MMt) of NO_x in 2007 [2] representing about 15% of anthropogenic NO_x emissions.[2] NO_x, including nitrogen monoxide (NO) and nitrogen dioxide (NO_2), are major contributors to local and regional air quality issues such as acidic nitrate deposition and health impacts such as lung irritation. NO_x emissions can be mitigated with engine controls that decrease combustion temperature and/or aftertreatment, including in-cylinder approaches such as combustion improvements, exhaust gas recirculation (EGR), and SCR.

Annex VI of the International Convention for the Prevention of Pollution From Ships (MARPOL 73/78), the major international convention that regulates air pollutants from ships, introduces a stepwise approach to the reduction of emissions of NO_x from new marine vessels. The original emission limit from Annex VI is now referred to as "Tier

AUTHORS Alyson Azzara is a researcher and Haifeng Wang a senior researcher with the ICCT marine team. Dan Rutherford is ICCT's program director for marine and aviation.

---

[1] Wang, H., D. Liu, and G. Dai, *Review of maritime transportation air emission pollution and policy analysis* Journal of Ocean University of China, 2009. **8**(3): p. 283-290; Buhaug, Ø., et al., *Second IMO GHG Study 2009 Update of the 2000 GHG Study: Final Report covering Phrase 1 and Prase 2*, 2009, IMO: London; Eyring, V., et al., *Transport impacts on atomosphere and climate: Shipping.* Atmospheric Environment, 2010. **44**(37): p. 4735-4771.

[2] Corbett, J.J. and P.S. Fischbeck, *Emissions From Ships.* Science, 1997. **278**(5339): p. 823-824; Endresen, O., et al., *Emission from international sea transportation and environmental impact.* Journal of Geophysical Research.D.Atmospheres, 2003. **108**(D17).

I", while future emission limits are called "Tier II" and "Tier III". The NO_x emission limits in MARPOL Annex VI are summarized in Table 1. The original Tier I limit on NO_x emissions applies to engines built on or after January 1, 2000, or to engines built before January 1, 2010 but subject to a major conversion[3]. In addition, the Revised Annex VI, which entered into force in July 2010, requires marine diesel engines installed on a ship constructed between January 1, 1990 and January 1, 2000 with a power output of more than 5000 kW and a per cylinder displacement at or above 90 liters to install an approved engine upgrade kit where commercially available. The effect of the upgrade is to ensure NO_x emissions meet Tier I requirements.

Table 1: NO_x limits in MARPOL Annex VI

Tier	Effective Date	NO_x 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	$44*n^{-0.2}$	7.7
Tier III***	2016	3.4	$9*n^{-0.2}$	1.96

"n" refers to rated engine speed (rpm)
* Excluding ships with marine diesel engines less than 130 kW or ships solely for emergency purposes
** Annex VI entered into force in 2004, but it applies retroactively to new engines larger than 300 kW installed on ships on or after January 1, 2000
*** Tier III applies only in emission control areas

Tier II applies to marine diesel engines installed on ships constructed on or after January 1, 2011, or to engines subject to a major conversion on or after January 1, 2011. Increasing engine combustion efficiency and reducing emissions can meet the Tier II standard. Tier III applies to marine diesel engines installed on ships constructed on or after January 1, 2016, or to engines subject to a major conversion on or after January 1, 2016. Tier III will only apply to ships sailing in North American Emission Control Areas (ECA). By achieving Tier III standards using SCR, EPA estimates a reduction of 130,000 school absence days, 360,000 minor restricted activity days and up to 360 premature mortalities by 2020 through reducing ozone alone.

At MEPC-65 in May 2013, the Russian Federation, citing technical barriers to the adoption of control strategies such as SCR, recommended that the IMO prepare an amendment to delay the implementation of Tier III requirements to 2021. Barriers cited by the Russian submission included a lack of proof of SCR reliability, potential increase in CO_2 emissions, urea supply and infrastructure, as well as capital costs.[4] MEPC agreed to prepare an amendment for consideration at MEPC-66 in April 2014 over the objections of several countries, including Canada, Denmark, Germany, Japan and the United States, who subsequently submitted a paper recommending that the amendment be rejected.[5] This paper analyzes the technological status of SCR application to the marine sector as a means of investigating the feasibility of Tier III implementation in 2016.

Overview of SCR in marine applications

Selective catalytic reduction, using ammonia as the reducing agent, was patented in the United States by the Engelhard Corporation in 1957. Since that time thousands of systems have been installed on terrestrial applications, from power plants to locomotives to automobiles. SCR functions by combining ammonia (NH_3), typically derived from an aqueous solution of urea, with a catalyst mounted on a ceramic monolith, to reduce NO_x, forming nitrogen (N_2) and water (H_2O). While SCR was originally developed to control NO_x emissions from stationary sources, SCR systems have subsequently proven effective in reducing diesel emissions in a variety of mobile applications, including heavy-duty trucks and buses, diesel passenger vehicles, and offroad applications. Today, SCR is in use in millions of vehicles and power plants with a cumulative capacity of a half million megawatts (MW) worldwide.

SCR is the only technology currently available to achieve compliance with the Tier III NO_x standards for all applicable engines (Figure 1). Other technologies can either achieve Tier II standard or achieve Tier III standard for only a subset of applicable engines. SCR has been recognized as one of the most promising means of controlling NO_x by a variety of countries and regulatory authorities.[6] State-of-the-art SCR systems are capable of reducing NO_x emissions by more than 90% under certain conditions. Furthermore, SCR has proven popular with equipment manufacturers because it allows NO_x control with little or no fuel efficiency penalty, and sometimes a net benefit. This occurs because manufacturers can tune their engines for maximum fuel efficiency and use SCR to clean up the resulting "engine out" NO_x.[7]

---

[3] Major conversion is defined by the IMO as a modification that "substantially alters the dimensions, carrying capacity or engine power of the ship", "changes the type of the ship", or that the intent of the modification "in the opinion of the Administration, is to substantially prolong the life of the ship"

[4] MEPC 65/4/27

[5] MEPC 66/6/6

[6] MEPC 65/4/7

[7] Walsh, M.; Kodjak, D.; Rutherford, D. A Model Regulatory Program For Reducing Exhaust and Evaporative Emissions From Heavy-Duty Vehicles and Engines. International Council on Clean Transportation. November 2007.

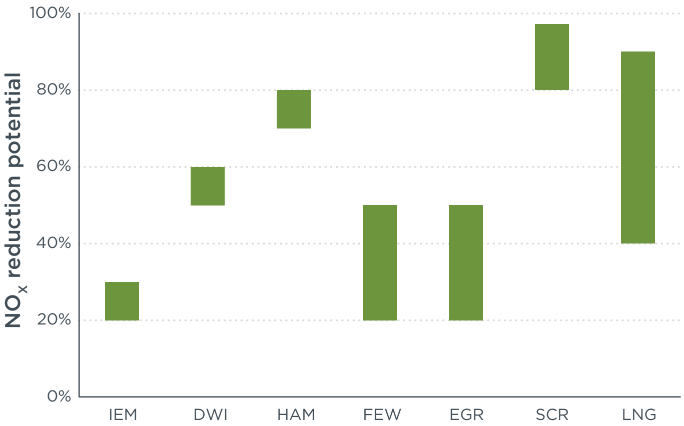

Figure 1: Shipping NO_x Reduction potential[8]

IEM: Internal Engine Modification; DWI: Direct Water Injection; HAM: Humid Air Motors; FEW: Fuel-Water Emulsion; EGR: Exhaust Gas Recirculation; SCR: Selective Catalytic Reduction; LNG: Liquefied Natural Gas

The maritime sector has had more than two decades of experience with SCR. Early implementation included efforts by MAN B&W and Wärtsilä. Between 1989 and 1992 MAN B&W tested the viability of SCR systems aboard four vessels in the San Francisco Bay Area and received acceptance and classification from the Bay Area Air Quality Management District (BAAQMD) for the reduction of NO_x emissions.[9] Furthermore, between 1999 and 2000, Wärtsilä equipped three two-stroke Roll on-Roll off vessels with SCR systems attaining emissions of 2 g/kWh (below Tier III standards) over 10 years of continuous operation[10], with SCR subsequently expanded to two LPG carriers in 2000 and 2001.[11]

Today, SCR is a well-proven technology with over 500 applications in the marine sector in 2013 (Figure 2). A 2012 survey of marine vessel operators yielded data on number of vessels, engines, fuel types, and equipment manufacturers currently using or developing SCR technology[12]. Overall, approximately 1250 SCR systems have been installed on marine vessels in the past decade. Those vessels with the longest track records have accumulated upwards of 80,000 hours of operation over the past two decades.

SCR has been deployed on a variety of vessel and engine types using various fuels. Figure 3 shows the various vessel types currently using SCR, including ferries,

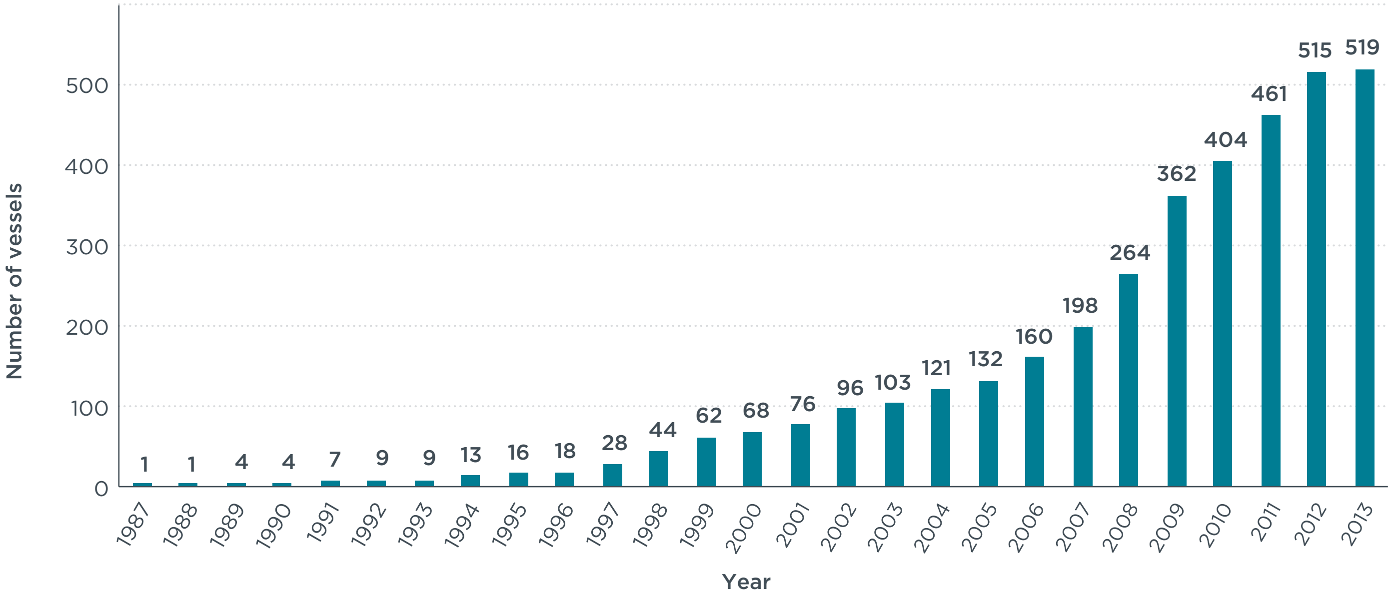

Figure 2. Total number of vessels with SCR systems installed by year

---

[8] Data for Figure 1. was compiled from the following sources: Fleetway, NO_x emission study: an investigation of water-based emission control technologies, 2005: Canada.; Landet, R., PM emissions and NO_x-reduction due to water in fuel emulsions in marine diesel engines, 2010, Norwegian University of Science and Technology.; EPA, Proposal to Designate an Emission Control Area for Nitrogen Oxides, Sulfur Oxides and Particulate Matter Technical Support Document, 2009, United States Environmental Protection Agency: Washington, DC.; ICCT, Air Pollution and Greenhouse Gas Emissions from Ocean-going Ships: Impacts, Mitigation Options and Opportunities for Managing Growth, 2007, International Council on Clean Transportation: Washington DC.; IMO, Compliance and testing issues for Tier III engines submitted by the United States, 2009, BLG: London.

[9] Emission Control Two-Stroke Low-Speed Diesel Engines, MAN B&W 1996.

[10] Wärtsilä, IMO Tier III Solutions for Wärtsilä 2-Stroke, Engines—Selective Catalytic Reduction (SCR), 2011.

[11] MAN, SCR – Selective Catalytic Reduction - http://www.mandiesel-turbo.com/1000874/Press/Press-Releases/Trade-Press-Releases/Marine-Power/Low-Speed/Two-Stroke-Archive-2001/Selective-Catalytic-Reduction.html

[12] IACCSEA, *Field Experience of Marine Selective Catalytic Reduction*, CIMAC Congress, Shanghai 2013 paper 220

tankers, container ships, icebreakers, cargo ships, work boats, cruise ships, and naval vessels. Approximately half of SCR equipped vessels were categorized as carriers (incorporating RoPax/RoRo/cargo/ferry/high speed catamaran/container vessel/RoRo cargo/cruise ferry/tanker/LPG tanker/chemical tanker), with patrol (15%) and supply vessels (14%) being the second and third most prevalent type.

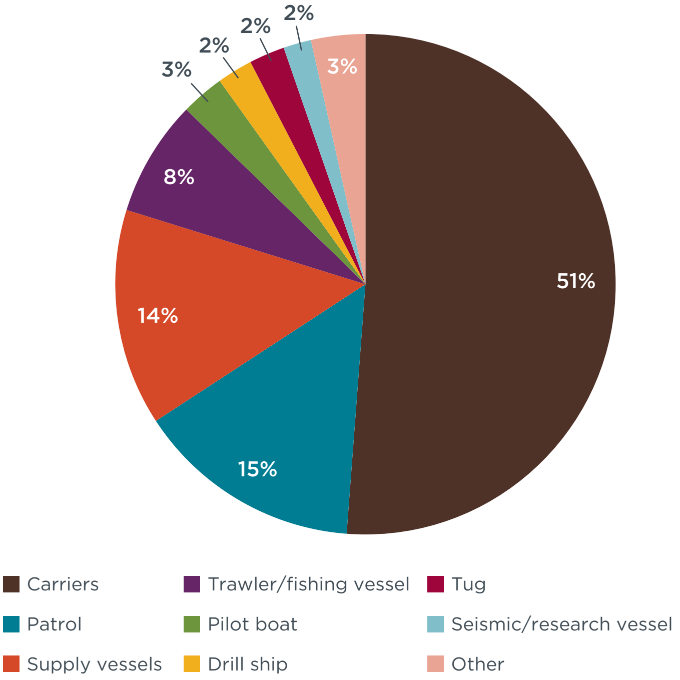

Figure 3. Breakdown of SCR systems by vessel type

While SCR technology was initially tested on main engines, it has since been applied to auxiliary engines and boilers. According to the same 2012 survey, 67% of vessels surveyed had SCR systems on the main engine, 23% had been installed on auxiliary engines, and 9% on combined boilers and auxiliary boilers.[13] Additionally, SCR has been successfully operated on engines and boilers run on a variety of fuels, including low sulfur distillate fuel and high sulfur residual fuel: approximately half of vessels used marine gas oil (MGO) or heavy fuel oil (HFO) in equal measure, while 22% operated on diesel and 14% on marine diesel oil (MDO). Smaller numbers of engines operated on combinations of these fuels (e.g. HFO/MDO, LNG/MDO, etc.). Based on these data, in addition to other reports of successful application, SCR technology is applicable for a diverse vessel fleet under variable fueling requirements, which should not be considered limiting factors for this technology.

A number of manufacturing companies have invested in SCR in the 25 years since it was first applied to marine vessels. A significant number of companies based in Europe, the US, and Asia are delivering marine SCR technologies capable of meeting current and future NO_x reduction requirements. Table 2 presents a non-exhaustive list of companies pursuing engine, SCR, and catalyst technologies. These companies supply full SCR systems, components, reagent, or some combination of the three. The collaborations between engine designer, builder and catalyst designer facilitate the development and delivery of a complete emissions reduction system. [14]

Table 2. Companies developing engine, SCR, and catalyst technologies.

Engine Technologies	SCR and Catalyst Technologies
Wärtsilä	Haldor Topsoe
MAN	Johnson Matthey
MTU	Hitachi Zosen
ABC	Panasia
Bergen Engines	Tenneco
Yanmar	Cormetech
Hitachi Zosen	Ceram (Ibiden Group)
Mitsubishi Heavy Industry	Nano
Mitsui	Dansk Teknologi
Himsen	Mecmar
Daihatsu	HUG Engineering

Many current SCR applications are retrofits, where the aftertreatment system has been retroactively applied to an existing engine. Those vessels are powered by engines manufactured by a variety of original engine manufacturers (OEMs), as shown in Figure 4.

---

[13] IACCSEA, *Field Experience of Marine Selective Catalytic Reduction*, CIMAC Congress, Shanghai 2013 paper 220.

[14] http://www.marinelink.com/news/tieriii-diesel-turbo359279.aspx

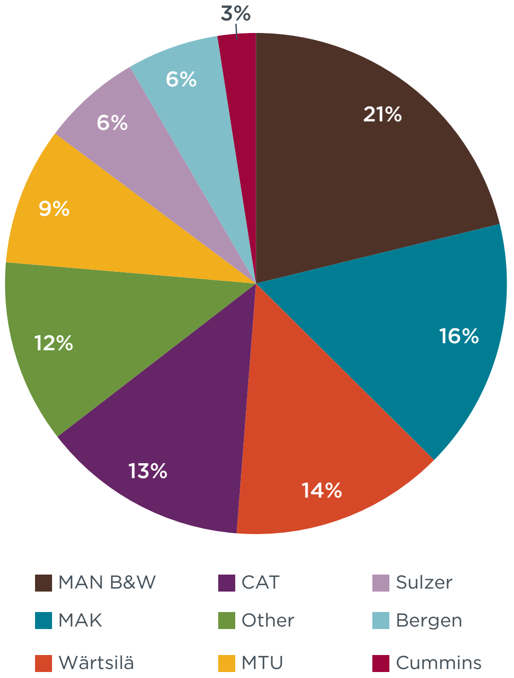

Figure 4. Breakdown of SCR system by engine manufacturer

Challenges to the use of SCR in marine applications

Like all aftertreatment strategies, the effectiveness of SCR systems will vary depending upon a variety of factors, including the nature of the catalyst used, fuel quality (especially sulfur content), and engine exhaust temperature. Furthermore, SCR requires the use of a consumable reagent, so production and delivery infrastructure must be put in place to make sure that SCR-equipped vessels have adequate access to urea. Finally, some concerns have been raised about potential environmental side effects from SCR, notably excess CO_2 emissions and ammonia slip. This section explores these issues in light of the demonstrated reliability of the marine SCR systems that have evolved over the past two decades.

A variety of catalysts are used in SCR applications. Marine SCR systems are already being used with marine fuels of varying sulfur content. For marine applications, vanadium-based catalysts are expected to be favored due to their lower cost and relative insensitivity to fuel sulfur content.[15,16] Because of implementation for new ships and engine rebuilds, the initial demand for marine SCR catalysts will be small when compared with that for industrial power plants and on-road vehicles. Catalysts must be periodically replaced in order to maintain system function. SCR systems will require intermediate inspection every 2.5 years and full inspection every 5 years. Because of the heavy metals that can deposit over time, their disposal must be treated with care, so an industry has evolved to regenerate spent catalysts and reintroduce them into the supply chain. The useful life of a marine SCR catalyst can be on the order of 5 to 6 years, with manufacturers typically guaranteeing catalysts for up to 16,000 hours of service. For vessels operating only part of the time within ECAs this lifetime may be extended, in particular where 0.1% sulfur fuel is available.[17]

Like many pollution control systems, the operation of SCR can be sensitive to engine exhaust temperature. Although common practices of slow steaming could potentially contribute to issues with low-load operation, a survey of vessel operators demonstrated that 80%–90% of vessels surveyed operated above 20% with 55%–80% operating above 30% load. Additionally, 80% of respondents combined slow steaming with full-load steaming either some of the time or all of the time.[18] Traditionally, urea dosing for SCR systems is discontinued at low exhaust temperatures in order to safeguard system function and avoid ammonia slip associated with poor catalyst performance. Research on on-road heavy-duty vehicles in Europe[19] and Japan[20] has raised concerns that SCR-equipped vehicles emit relatively high levels of NO_x when operated at low-load, urban driving conditions due to lower exhaust temperatures. Since this problem was identified, a variety of measures—improved and/or supplemental certification procedures, advanced catalysts with better low temperature performance, improved thermal management strategies, etc.—have been developed. SCR remains the cornerstone technology to meet near-zero NO_x emission standards for on-road vehicles worldwide.[21]

Marine SCR applications have been designed to operate over a range of exhaust temperatures depending on fuel type, engine and catalyst design, and operating conditions. General minimum operation temperature ranges are between 260°–340°C, although systems can operate at lower temperatures for limited periods of time. Since Tier III requirements will go into effect in areas where 0.1% sulfur fuel is available, minimum temperature

---

[15] Wärtsilä, IMO Tier III Solutions for Wärtsilä 2-Stroke, Engines—Selective Catalytic Reduction (SCR), 2011.

[16] http://ect.jmcatalysts.com/pdfs-library/Focus%20on%20SCR%20Technology.pdf

[17] Wärtsilä, IMO Tier III Solutions for Wärtsilä 2-Stroke, Engines—Selective Catalytic Reduction (SCR), 2011.

[18] http://www.swedishclub.com/upload/Loss_Prev_Docs/Machinery/MAN%20PrimeServ%20-%20Slow%20Steaming%20Rapport%20 2012[1].pdf

[19] Ligterink, N.; de Lange, R.; Vermeulen, R; and Dekker, H. 2009. “On-road NO_x emissions of Euro-V trucks.” TNO. December 2.

[20] Suzuki, H.; Ishii, H.; Sakai, K.; Fujimori, K. 2008. “Regulated and Unregulated Emission Components Characteristics of Urea SCR Vehicles.” JSAE Proceedings, Vol. 39 No. 6. November (Japanese).

[21] http://www.meca.org/galleries/files/MECA_Diesel_White_Paper_12-07-07_final.pdf

ranges of around 260°C are expected, corresponding to effective operation over a extended range of conditions.

For marine engines, a variety of strategies are under development to expand the range of operating load conditions under which the SCR system functions normally. Exhaust gas temperatures can be boosted by several means, including reducing the amount of air and using a system to preheat the exhaust before entry into the SCR system;[22] adjusting injection timing; bypassing part of the exhaust through a heated hydrolysis catalyst which allows urea to be injected at exhaust gas temperatures as low as 150°C; heating the urea dosing system prior to injection to maximize efficiency;[23] and, for ships with multiple engines, shutting down one or more engines, and running fewer at higher power. In another approach, at low loads, a portion of the catalyst can be bypassed by condensing the exhaust gas volume and forcing it through a smaller catalyst volume, maintaining turbulent flow and catalyst temperature. Hitachi Zosen and MAN Diesel recently completed a successful sea trial with SCR systems in use to 10% engine load.[24]

Engine architecture may allow specific strategies. For four-stroke engines, the SCR catalyst can be mounted after the turbocharger. Four-stroke engines have been developed on which the SCR system operates down to 10%–15% load. For two-stroke engines, the catalyst is mounted before the turbocharger inlet[25] where the exhaust gas temperatures and pressures are higher. This has the added benefit of allowing the system to be operated using a smaller reactor.[26] For two-stroke engines, the placement of the SCR catalysts upstream of the exhaust turbine can ensure effective NO_x reduction down to at least 25%, load and at times lower.[27] The “preturbocharger” SCR approach has been used successfully for over a decade on vessels equipped with slow-speed engines that required NO_x control when operating at low loads near coastal areas.[28] Recently, Hitachi Zosen certified an engine design utilizing a compact, high pressure, high temperature SCR system that meets Tier III standards while producing minimal additional CO_2 emissions down to 10% engine load.[29]

Another potential challenge to mobile source SCR use is urea distribution. For road transport, it can be challenging to develop a new infrastructure to deliver urea to tens or even hundreds of thousands of small, geographically dispersed cars, trucks, and buses. Producing and distributing urea to marine vessels is less challenging, for several reasons. First, the required volumes will be small. In most countries, urea is already widely produced for use in agricultural and industry applications (although the standard for marine use will differ).[30] Overall, demand for urea for marine SCR applications is expected to be modest compared to other applications. On-road SCR applications are projected to consume 6 million tons of urea in 2015; the marine sector currently requires less than 1% of that for all SCR systems. US EPA estimates that urea use in the North American NO_x ECA will total approximately 454,000 tons in 2020, or less than 10% of 2015 on-road consumption levels and an even smaller fraction of 2020 use.[31] Since road transport is expected to consume no more than 5% of 2020 worldwide urea production, this suggests that marine urea consumption in 2020 will be significantly less than 1% of the worldwide total.

Furthermore, in contrast to road transport, where urea needs to be distributed to a very large number of locations—centralized fleet fueling stations, trucks stops and gasoline stations, and large and small retail outlets, to name a few—for marine applications urea can be distributed to a smaller number of ports. Currently, urea is produced in over 50 countries and several independent distributors service ports in these countries supporting vessels with SCR. The rapid growth in northern European countries due to current environmental regulations has likely resulted in the development of best practices for urea distribution in ports that could be implemented elsewhere. The capacity to deliver urea to 2,200 international ports has already developed and an expert group within AGU, a sector group of the European Chemical Industry Council (CEFIC) including stakeholders from the entire value chain, recently completed and successfully submitted a joint proposal for ISO standardization of urea solution for Marine SCR application. Even during this process, vessels in North and Latin America, Europe, including the Baltic States and Russia, as well as Africa, Oceania, and the Middle East have been successfully serviced. Urea is currently available at every EU port.[32]

In general, the service requirements of the SCR system are not expected to be vastly different from current

---

[22] http://webdh.munters.com/webdh/BrochureUploads/Case%20Study-%20SCR%20Energy%20Recovery.pdf

[23] MAN Diesel & Turbo, Tier III Compliance, Low Speed Engines

[24] http://www.hitachizosen.co.jp/english/news/2011/12/000568.html

[25] Munters, “Selective Catalytic Reduction,” presented at Clean Ships Conference, San Diego, CA, February 7, 2007.

[26] Wärtsilä, IMO Tier III Solutions for Wärtsilä 2-Stroke, Engines—Selective Catalytic Reduction (SCR), 2011.

[27] U.S. EPA Regulatory Impact Analysis: Control of Emissions of Air Pollution from Category 3 Marine Diesel Engines EPA-420-R-09-019 December 2009

[28] “Emission Control Two-Stroke Low-Speed Diesel Engines,” December 1996, Docket ID EPA-HQ-OAR-2007-0121-0020 (http://cleantech.cnss.no/wp-content/uploads/2011/06/unknown-MAN-B-W-Emission-Control-MAN-B-W-Two-stroke-Diesel-Engines.pdf)

[29] http://www.hitachizosen.co.jp/english/news/2011/12/000568.html

[30] Fable, S.; Kamakate, F.; Venkatesh, S. 2002. Selective Catalytic Reduction Urea Infrastructure Study. (NREL/SR-540-32689). Arthur D. Little. July.

[31] http://www.epa.gov/nonroad/marine/ci/420r09007-chap5.pdf

[32] http://www.yara.us/nox-reduction/urea-scr-marine/seagoing-vessels/availability-secure-global-network/

engine service requirements, so the systems set up in ports to provide needed supplies to vessels at berth will likely be adaptable to SCR applications. Before leaving port, vessels take on fuel, oils, lubricants, and other equipment needed to maintain the engine while at sea. These are provided by any number of companies that vary by port and contract. When the vessel returns to port, they contact the appropriate environmental services company who removes spent oil, used filters, and other lubricants per environmental codes and regulations. Companies that provide this same service for marine SCR systems already exist and are able to support vessels in any number of international ports.

Since the IMO regulation applies to new builds only (and to new engines installed on existing vessels), there should be adequate time for a urea supply chain to develop further in the future as marine SCR application slowly grows in step with the global vessel new-building program. The rapid growth in northern European countries of marine SCR installations coupled with urea supply to international ports in Africa, Oceania, the Americas, and the Baltic states and Russia has resulted in the development of best practices that could be implemented elsewhere.[33] Based on the regulatory impact analysis for the North American ECA, there is no projected issue for urea cost, supply, or infrastructure in the 2016 timeframe for implementation of the Tier III standards.[34]

The final potential issues of concern regarding urea SCR systems relates to the potential creation of environmental byproducts. Two in particular were discussed at MEPC-65 when the Tier III delay was proposed: ammonia slip due to incomplete reduction through the catalyst, and carbon dioxide (CO_2). As a general rule, ammonia slip is of concern under emission standards requiring high NO_x conversion efficiencies (i.e., >90%) where large amounts of urea must be delivered to the SCR system, increasing the risk of ammonia slip should the catalyst not function properly. Relative to other mobile source emission standards, IMO's Tier III standards will require modest NO_x reductions (Figure 5). Compared to Europe's NO_x limits for heavy-duty trucks (Euro VI), IMO's Tier III NO_x standard will allow four times higher emissions for higher speed engines and more than seven times higher emissions for the low speed diesel engines prevalent on large ocean-going vessels. The risk of ammonia slip above 10 ppm thus seems manageable under the Tier III standards.

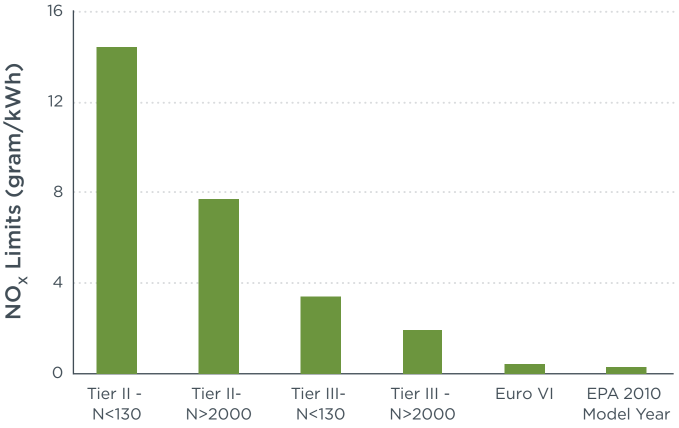

Figure 5. IMO NO_x limits for marine vessels vs. on-road heavy-duty vehicles

Where necessary, methodologies have been developed to address ammonia slip. These include design elements as well as monitoring elements such as continuous exhaust emission monitoring and automatic management of injection rate using feedback electronic controls. Finally, advanced strategies employed in other modes to control ammonia slip, including closed loop urea dosing systems with rapid feedback control coupled with downstream oxidation catalysts, may become viable as fuel quality improves in response to future fuel sulfur requirements. In summary, ammonia slip in maritime SCR applications is not expected to provide a significant barrier to application of the technology.

Typically, engines certified to NO_x emission standards are tuned to reduce emissions by operating at off-optimal combustion conditions, impacting fuel efficiency. Under such conditions, the introduction of the SCR system may allow those engines to be tuned for maximum efficiency, resulting in a potential fuel efficiency benefit and net CO_2 benefit. For example, SCR was estimated to provide a fuel economy benefit of 3%–5% under Europe's Euro V standards for heavy-duty vehicles, with cost savings partially offset by the additional cost of urea.[35] Slightly lower fuel efficiency gains, on the order of 2% to 4%, are expected under Tier III given that engine combustion conditions are currently less constrained under Tier II than equivalent standards for other modes. Thus, it may be possible to reduce both CO_2 and NO_x emissions simultaneously when moving from Tier II to Tier III compliance.

---

[33] http://www.epa.gov/nonroad/marine/ci/420r09019.pdf (pp 4-9)

[34] http://www.epa.gov/nonroad/marine/ci/420r09019.pdf

[35] Majewski, W. 2005. SCR Systems for Mobile Engines. Dieselnet Technology Guide, Revision 2005.05a. http://www.dieselnet.com/tech/cat_scr_mobile.html.

SCR system costs

Growth and development in SCR technology have been seen in areas such as stationary power plants where industrial SCR systems are similar to marine diesel systems. In all applications, over time, production advances in the use of industrial SCR technology has been seen to reduce capital costs. Additionally, stabilization of costs of materials with increased demand suggests an increase in SCR suppliers, which is creating competition in the market, driving technology innovation and overall decreases in capital cost.[36] This results in higher availability of SCR at more reasonable costs.

The International Association for Catalytic Control of Ship Emissions to Air (IACCSEA) developed a cost estimation model for SCR installation and operation. Application of the model provides a sample calculation that is indicative of the ranges of costs and benefits anticipated for marine SCR applications. Using the example of a 10 MW engine, powering a vessel of 20,000 DWT using HFO that spends 1500 hours annually in a NO_x ECA, the capital expenditure cost (including system installation) will be of the order of $725,000 US. The major operational costs required to meet IMO Tier III from an IMO Tier I baseline NO_x level would range from $2 to $5 million depending upon urea cost, while catalyst recharge would require on the order of $500,000 US. There will be a fuel penalty associated with increased backpressure associated with the SCR system and a potential fuel efficiency gain when operating a fuel optimized engine/SCR system. After taking into account a backpressure penalty (2%), a 4% fuel-efficiency gain generates fuel saving of $625,000. This equates to a total (undiscounted) operation cost of between $104,000 and $224,000 per year, or approximately $900 to $2000 per tonne of NO_x reduced.

It is expected that the cost of operating marine SCR systems will continue to fall. Evidence for these trends can be found in the cost trends for NO_x emission control technology for stationary sources. With some volatility, the cost for ammonia-based reagents has remained relatively stable over the past 5 years[37] while the cost of catalysts in the United States decreased in unit price by a factor of five between 1980 and 2005 and is projected to remain stable through 2015 for new and decrease slightly for regenerated catalysts.[38] Expected lifespan has increased from one to ten years, contributing to the realized decrease in O&M costs for SCR systems.[39] As the SCR capacity doubled for stationary coal-fired power sources from the mid-1980s to 2000, capital costs decreased to 86% and the operation and management costs to 58% of their original values. Future projections for continued retrofit of SCR estimate an additional 7.4% reduction in capital cost and 15.8% in O&M costs by 2020.

Changes in the cost of SCR technology estimated in these analyses reflect the impact of technological advancement as well as market competition linked to environmental standards as a stimulus for innovation. This phenomenon has been demonstrated for SO_x reduction technologies[40] and again for SCR[41] suggesting that implementation of international regulations and standards will drive further reductions in cost over time.

Conclusions

SCR is a well-proven technology. Those vessels with the longest track records using it have accumulated upwards of 80,000 hours of operation over the past two decades. In the more than two decades in which SCR technology has been fitted to vessels, a number of manufacturing companies have invested in the technology. Today a significant number of companies based in Europe, the US, and Asia are delivering marine SCR technologies to meet current and future NO_x reduction requirements. It is notable that many of the applications to date have been retrofits, which can be more costly and difficult to operate than systems installed on new engines. Since IMO's Tier III requirements will drive OEM applications, even fewer problems may be expected in the future.

This review has identified no systematic barriers to meeting Tier III requirements in 2016 through the use of SCR. Vanadium-based SCR systems, supplemented where necessary with strategies to boost exhaust temperature in low-load operations, will be capable of reducing NO_x over a sufficient range of operational conditions, particularly when paired with the 0.1% sulfur fuel that will be made available in sulfur emission control areas. Production and distribution of urea to marine vessels should be manageable given the relatively small volumes to be delivered, the limited number of

---

[36] http://www.powermag.com/coal/Estimating-SCR-installation-costs_506_p3.html

[37] Historic urea costs can be monitored at http://www.indexmundi.com/commodities/?commodity=urea&months=60

[38] http://www.publicpower.org/files/PDFs/UARGSCR_FGDFinal.pdf

[39] Yeh, S., E.S. Rubin, M.R. Taylor, and D.A. Hounshell. "Technology Innovations and Experience Curves for Nitrogen Oxides Control Technologies." *Journal of the Air & Waste Management Association*, **2005,** *55*, 1827–1838.

[40] Taylor, M.; Rubin, E.S.; Hounshell, D.A. The Effect of Government Actions on Technological Innovation for SO2 Control; *Environ. Sci. Technol*. **2003,** *37,* 4527-4534.

[41] Yeh, S., E.S. Rubin, M.R. Taylor, and D.A. Hounshell. "Technology Innovations and Experience Curves for Nitrogen Oxides Control Technologies." *Journal of the Air & Waste Management Association*, **2005,** *55*, 1827–1838.

ports that need to be served, and the identification of best practices in Europe. Environmental byproducts, notably ammonia slip and excess CO_2 emissions, are not expected to be generated in significant volumes. Finally, the costs of installing and operating SCR are modest and are expected to fall over time as the Tier III requirements generate greater innovation and competition among manufacturers and suppliers.

Based on this evaluation of technological capabilities and history of successful application of SCR technology to maritime vessels, we find no substantial equipment, supply chain, or cost barriers that would significantly inhibit the implementation of MARPOL NO_X Tier III regulations for applicable vessels in 2016 as established by the IMO in 2008.