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Final Regulatory Support Document: Control of Emissions from New Marine Compression-Ignition Engines at or Above 30 Liters per Cylinder

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Final Regulatory Support Document: Control of Emissions from New Marine Compression-Ignition Engines at or Above 30 Liters per Cylinder

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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List of Acronyms

$\mu g/m^3$	micrograms per cubic meter
ASTM	American Society for Testing and Materials
BSFC	brake-specific fuel consumption
CIMAC	Conseil International Des Machines A Combustion (International Council on Combustion Engines)
CO	carbon monoxide
COHb	carboxyhemoglobin
cSt	centistokes
DI	direct injection
DWT	dead-weight tonnage
EF	emission factor
EGR	exhaust gas recirculation
EIAPP	Engine International Air Pollution Prevention
EPA	U.S. Environmental Protection Agency
g/kW-hr	grams per kilowatt-hour
GmbH	Gesellschaft mit beschränkter Haftung
HC	hydrocarbon
IAPP	International Air Pollution Prevention
IMO	International Maritime Organization
kPa	kilopascals
m/s	meters per second
MARAD	Maritime Administration
MARPOL	the International Convention on the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto
MEPC	Marine Environment Protection Committee
NAAQS	National Ambient Air Quality Standards
NIST	National Institute of Standards and Technology
NO_2	nitrogen dioxide
NOx	oxides of nitrogen
NPV	net present value
NTC	NOx Technical Code
OAQPS	Office of Air Quality Planning and Standards
OMB	Office of Management and Budget
OPA 90	Oil Pollution Act of 1990
PM	particulate matter

ppm	parts per million
ppmS	parts per million sulfur
R&D	research and development
RPE	retail-price equivalent
RSZ	Reduced-speed zones
SAE	Society of Automotive Engineers
SCR	selective catalytic reduction
SECA	SOx Emission Control Area
SIC	Standard Industrial Classification
SIP	State Implementation Plan
SO_2	sulfur dioxide
SOx	oxides of sulfur
VOC	volatile organic compound
wt%	weight percent

CHAPTER 1: Introduction

At the Environmental Protection Agency (EPA), we are adopting national emission standards for the first time for new marine diesel engines with per-cylinder displacement of 30 liters or more that are installed on vessels flagged or registered in the United States.[a] These engines, also known as Category 3 marine diesel engines, are very large engines used primarily for propulsion power on ocean-going marine vessels such as container ships, tankers, bulk carriers, and cruise ships. Category 3 marine diesel engines have not previously been regulated under our nonroad engine programs. This Final Regulatory Support Document provides technical, economic, and environmental analyses for this emission-control program.

We are also adopting standards for new marine diesel engines with per-cylinder displacement of 2.5 to 30 liters installed on vessels flagged or registered in the United States. These engines, also known as Category 1 and Category 2 marine diesel engines, are already subject to more stringent Tier 2 standards beginning in 2007, pursuant to a rule we finalized in 1999 (64 FR 73300, December 29, 1999; 40 CFR part 94). The standards we are finalizing, which are currently voluntary for these engines, will be mandatory for new engines manufactured from 2004 through 2006. Our technical, economic, and environmental analysis for the standards for these engines can be found in the Final Regulatory Impact Analysis for our 1999 rule and is not repeated in this document.[1]

1.1 Executive Summary

1.1.1 Standards Adopted

The near-term Tier 1 standards we are adopting are equivalent to the internationally negotiated NOx standards established by the International Maritime Organization (IMO) in Annex VI to the International Convention on the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto (more commonly referred to as MARPOL or MARPOL 73/78; the standards are referred to as the Annex VI NOx standards).[2] The standards are set out in Table 1.1-1. These standards are achievable almost immediately, with less than one year of lead time, because manufacturers are already achieving and certifying to these standards under our Voluntary Statement of Compliance program for Annex VI. These near-term standards are being achieved through the application of currently available technology, including optimized turbocharging, higher compression ratios, and optimized fuel injection.

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[a] Today's rule applies to "new" marine diesel engines and to "new" marine vessels that include marine diesel engines. In general, a "new" marine diesel engine or a "new" marine vessel is one that is produced for sale in the United States or that is imported into the United States. The emission standards established in today's rule, therefore, will typically apply to marine diesel engines that are installed on vessels flagged or registered in the United States.

The near-term standards in this final rule will be enforceable under U.S. law for new engines built on or after January 1, 2004. These standards will apply until we adopt a second tier of standards in a future rulemaking. In developing that future rulemaking, which will be completed no later than April 27, 2007, we will consider both the state of technology that may permit deeper emission reductions and the status of international action for more stringent standards. We will also consider whether to apply such a second tier of standards to engines on foreign vessels that enter U.S. ports.

Table 1.1-1
NOx Emission Standards (g/kW-hr)

Engine Speed (n)		
$n \geq 2000$ rpm	$2000 > n \geq 130$ rpm	$n < 130$ rpm
9.8	$45.0 \times n^{-0.2}$	17.0

We are not adopting emission standards for particulate matter (PM) from Category 3 engines in this final rule. The majority of PM emissions from large marine diesel engines comes directly from the high concentration of sulfur in the residual fuel they use, so the simplest way to reduce these emissions is by removing sulfur from the fuel. Annex VI provides a mechanism to control the sulfur content of fuels used by vessels that operate in specially designated SOx Emission Control Areas (SECAs). After the Annex goes into force, ships operating in these designated areas must use marine fuel with a sulfur content below 15,000 ppm or aftertreatment technology to achieve equivalent emission reductions (for comparison, sulfur levels in marine residual fuels may be as high as 45,000 ppm). We intend to investigate this special designation for one or more areas in the United States. We will also reconsider this issue in our future rulemaking.

To implement these standards in an effective way, we are adopting a certification and compliance program for Category 3 marine diesel engines that is similar but not identical to the internationally negotiated program contained in the Technical Code on the Control of Emissions of Nitrogen Oxides from Marine Diesel Engines (also known as the NOx Technical Code).[3] The differences between the two programs are intended to ensure that test data be representative of actual in-use conditions and that manufacturers demonstrate that the emission controls will be durable for the full useful life of the engine. We specify that this useful life for Category 3 engines is three years, based on the time that engines operate before being rebuilt for the first time. To allow manufacturers time to incorporate these changes in their testing and certification procedures, we are adopting a provision that will allow manufacturers to certify their engines with EPA by using the international procedures on an interim basis, after which they must use the procedures in this final rule.

For Category 1 and Category 2 engines, we specify certification and testing requirements based on the requirements we adopted for these engines when we set the Tier 2 standards in 1999. Similar to the provisions for Category 3 engines, we allow manufacturers to certify their engines using the international procedures until the Tier 2 standards apply.

We are also adopting voluntary low-emission standards, consistent with the approach we have taken in several other programs, to encourage the introduction and more widespread use of low-emission technologies. To be designated as a Blue Sky engine, an engine must have emissions at least 80 percent below Annex VI NOx levels (excluding a nitrogen adjustment). The specific voluntary low-emission NOx standard is expressed as $9.0 \times n^{-0.2}$ (in g/kW-hr), with a cap of 3.4 g/kW-hr for engines with rated speed over 130 rpm (no specific standard applies to engines over 2000 rpm, because Category 3 engines all have engine speeds well below 2000 rpm). The engine must also have hydrocarbon (HC) and carbon monoxide (CO) emissions below a cap of 0.4 g/kW-hr and 3.0 g/kW-hr, respectively.

1.1.2 Projected Impacts and Costs

This Final Regulatory Support Document contains our analysis of the projected impacts and costs of applying these standards to Category 3 marine diesel engines. Similar information about the impacts and costs of applying these standards to Category 1 and Category 2 marine diesel engines are contained in the Final Regulatory Impact Analysis for our 1999 rule.

We expect the costs of compliance to be negligible. We do not anticipate any engineering or design costs associated with the near-term standards because manufacturers should already be certifying engines to the Annex VI standards to comply with the internationally negotiated program and new Category 3 marine diesel engines installed on ships since January 1, 2000 are widely understood to already comply with the standards set forth in both Annex VI and this rule. While there will be certification and compliance costs, these costs will be negligible, because manufacturers will be able to use the same test data for both programs. The emission reductions will reflect only reductions from engines that are currently in noncompliance with the Annex VI NOx limits. For these reasons, the projected impacts of this rule are expected to be negligible. Accordingly, we have not calculated values to quantify the cost-effectiveness of the final rule. Table 1.1-2 shows the estimated emission inventory from Category 3 marine diesel engines.

Table 1.1-2
Category 3 Marine Vessel NOx National Emission Inventories
(Emissions from Engines on U.S. and Foreign Vessels)

		1996	2010	2020	2030
No control baseline (thousand short tons)		190	303	439	659
EPA/MARPOL Annex VI	(thousand short tons)	190	274	367	531
	Percent reduction (relative to no control)	—	9.6%	16.2%	19.5%

1.1.3 Future Rulemaking

We are committing to a future rulemaking to promulgate additional engine controls that EPA determines are appropriate under Clean Air Act section 213(a)(3). This future rulemaking will reassess the standards in place at the time using information about the feasibility of optimizing in-cylinder controls and applying advanced NOx and PM control technologies described in Chapter 5 to Category 3 marine diesel engines. These advanced technologies would also lead us to consider the need for several additional provisions, such as an enhanced compliance program and new standards to address HC, CO, and particulate-matter emissions. We intend to consider the application of these standards to engines on foreign vessels that enter U.S. ports. We will also include in our evaluation an assessment of the status of international action to set more stringent standards. The standards in this final rule will remain in effect unless modified by a future rulemaking. We are committing to take final action on appropriate standards for marine diesel engines by April 27, 2007, and to issue a proposal no later than approximately one year before. EPA considers this time as necessary and appropriate to properly take into consideration additional information expected to become available about emerging technologies, as well as any developments in the international negotiations for more stringent emission limits.

Chapter 5 of this Final Regulatory Support Document contains a description of some of the advanced technologies we will consider in our future rulemaking. Table 1.1-3 provides a summary of our current understanding of the potential per-engine costs for several emission control scenarios, as detailed in Chapter 6. Table 1.1-4 summarizes the projected emission inventories under various scenarios of adopting more stringent standards based on advanced technologies.

We intend to use the future rulemaking as an opportunity also to reconsider Tier 3 emission standards for Category 1 and Category 2 standards. We proposed Tier 3 standards for these engines on December 11, 1998 (63 FR 68508), but chose not to finalize the Tier 3 standards in that rulemaking. Given the current and expected advances in emission-control technologies for land-based diesel engines and the need to coordinate standards for all categories of marine engines, we believe this may be the appropriate context and timing to reopen the proposed Tier 3 standards.

Table 1.1-3
Summary of Projected Costs per Engine for Advanced Technology[a]

Technology Package	Scope of Standards	Cost Parameter	Medium-speed Engines			Slow-speed Engines			Composite
			6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.	
Direct Water Injection	U.S. vessels only	Total cost per engine (yr. 1)	$119,105	$139,153	$159,201	$156,579	$239,391	$319,582	$188,617
		Total cost per engine (yr. 6 and later)	$26,486	$39,317	$52,148	$50,470	$103,469	$154,792	$70,974
		Operating costs (NPV)	$55,912	$84,029	$111,824	$111,824	$223,971	$335,794	$153,887
	U.S. and foreign vessels	Total cost per engine (yr. 1)	$49,157	$69,205	$89,253	$86,631	$169,443	$249,634	$118,669
		Total cost per engine (yr. 6 and later)	$26,486	$39,317	$52,148	$50,470	$103,469	$154,792	$70,974
		Operating costs (NPV)	$9,749	$14,651	$19,497	$19,497	$39,051	$58,549	$26,832
SCR	U.S. vessels only	Total cost per engine (yr. 1)	$241,160	$335,899	$433,863	$435,153	$821,847	$1,208,542	$579,647
		Total cost per engine (yr. 6 and later)	$124,155	$184,788	$247,485	$248,310	$495,795	$743,279	$340,787
		Operating costs (NPV)	$435,240	$642,579	$852,782	$861,574	$1,668,952	$2,504,036	$1,161,373
	U.S.- and foreign vessels	Total cost per engine (yr. 1)	$198,709	$293,448	$391,412	$392,702	$779,396	$1,166,091	$537,196
		Total cost per engine (yr. 6 and later)	$124,155	$184,788	$247,485	$248,310	$495,795	$743,279	$340,787
		Operating costs (NPV)	$90,500	$126,651	$163,302	$172,094	$312,868	$458,472	$221,463

[a] These estimated costs reflect our understanding of the current state of technology development for these emission-control strategies. We will revisit these estimates before proposing emission standards based on these technologies.

Table 1.1-4
Estimated 2030 Emission Inventories
under Scenarios of Applying Long-Term Emission Standards

Scenario	NOx (1000 tons)	percent reduction
Baseline (Annex VI)	531	--
50% Reduction—U.S. vessels only	519	2.3%
50% Reduction—All vessels	301	43%
80% Reduction—U.S. vessels only	511	3.7%
80% Reduction—All vessels	160	70%

1.2 Organization of This Document

The remainder of this Chapter 1 contains the definitions of the categories of marine diesel engines and a brief description of the International Maritime Organization and MARPOL Annex VI.

As noted above, the analysis in this Final Regulatory Support Document focuses on Category 3 marine diesel engines. Chapter 2 reviews information related to the health and welfare effects of the pollutants of concern and presents the estimated contribution of Category 3 marine diesel engines to the nationwide inventory of these pollutants. Chapter 3 contains an overview of Category 3 marine diesel engine manufacturers and ship builders and a broad description of the range of engines involved and their place in the market. Chapter 4 summarizes the available information describing the technologies that manufacturers are applying to meet the internationally negotiated standards and the expected environmental benefits from those standards. Chapter 5 presents the available information about advanced technologies that could be used to achieve greater emission reductions from these engines. These technologies hold out the potential for emission improvements in the future, after constraints on their application to marine engines are resolved. Chapter 6 provides estimated costs of applying these technologies to Category 3 marine diesel engines and Chapter 7 provides estimated inventory impacts of applying them. These costs and benefits are tentative, and will be revisited in our future rulemaking. Finally, Chapter 8 discusses issues related to new test procedures for these engines.

1.3 Categories of Marine Diesel Engines

In our 1999 final rule for commercial marine diesel engines, we defined a marine engine as one that is installed or intended to be installed on a marine vessel. We also differentiated between three types of marine diesel engines. As explained in the 1999 rule, this approach is necessary because marine diesel engines are typically derivatives of land-based diesel engines that are subject to different emission standards, testing procedures, and effective dates. The definitions for the different categories of marine diesel engines are contained in 40 CFR 94.2 and are summarized in Table 1.3-1.

Table 1.3-1
Marine Engine Category Definitions

Category	Displacement per cylinder	power range (kW)	rpm range
1	disp. < 5 liters (and power $\geq$ 37 kW)	37 - 2,300	1,800 - 3,000
2	5 $\leq$ disp. < 30 liters	1,500 - 8,000	750 - 1,500
3	disp $\geq$ 30 liters	2,500 - 80,000	60 - 900

1.4 The International Maritime Organization and MARPOL

1.4.1 International Maritime Organization

The International Maritime Organization (IMO) is an international organization created by the United Nations in 1948. According to the convention that established it, the IMO's purpose is "to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships." The Organization also provides administrative and legal support for the committees of Member States that develop the international marine programs.[4]

One of the important conventions adopted by the Member States of the IMO is the International Convention on the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto (more commonly referred to as MARPOL or MARPOL 73/78).[5] This Treaty addresses several types of pollution associated with ships. The requirements for each of these are contained in Annexes to the Treaty. They are:

- Annex I – discharge of oil
- Annex II – noxious liquid substances
- Annex III – packaged goods
- Annex IV – sewage (the U.S. has not ratified this Annex)
- Annex V – garbage
- Annex VI – air emissions

1.4.2 MARPOL Annex VI

In response to growing international concern about air pollution and in recognition of the highly international nature of maritime transportation, the International Maritime Organization initiated development of international standards for NOX, SOx, and a variety of other air emissions arising from marine vessel operations. As a result of these discussions Annex VI was drafted between 1992 and 1997 and was adopted by the Parties to MARPOL at a Diplomatic Conference on September 26, 1997. Annex VI covers several kinds of air pollutants from ships, including NOX, SOx, volatile organic compound (VOC) emissions from tanker-loading operations, ozone-depleting chemicals (i.e., halons), and emissions from shipboard incinerators. As part of that conference, the Parties also passed a resolution adopting the Technical Code on the Control of Emissions of Nitrogen Oxides from Marine Diesel Engines (also known as the NOX Technical Code). Through Annex VI and the NOX Technical Code, the IMO created a legal framework to control emissions from marine diesel engines and a procedure to test engines and demonstrate compliance with the engine standards.

The Annex VI requirements are not enforceable until the Annex enters into force. As specified in Article 6 of the Annex, it will enter into force twelve months after the date on which not less than fifteen member states, the combined merchant fleets of which constitute not less than 50 percent of the gross tonnage of the world's merchant shipping, have ratified the agreement. To date, more than four years after it was adopted, the Annex has been ratified by only 6 countries representing about 26 percent of the world's merchant shipping. The countries that have ratified Annex VI are Sweden, Norway, Bahamas, Singapore, Marshall Islands, and Liberia.[6]

1.4.3 The MARPOL Annex VI NOX Limits

The MARPOL Annex VI NOX limits are set out in Table 1.1-1, above. These standards cover only NOX emissions; there are currently no international restrictions on particulate matter (PM), HC, or CO emissions. The standards are based on engine speed and apply to engines above 130 kW. These standards were expected to reduce NOX emissions by 30 percent when fully phased in. More recent analysis by EPA, based on newly estimated emission factors for these engines, indicates an expected reduction on the order of about 20 percent by 2030 when the standards are fully phased-in, when compared with uncontrolled emissions.

The Annex VI NOX limits apply to each diesel engine with a power output of more than 130 kW installed on a ship constructed on or after January 1, 2000, or that undergoes a major conversion on or after January 1, 2000. The Annex does not distinguish between marine diesel engines installed on recreational or commercial vessels and applies to engines on vessels engaged only in domestic service as well as to engines on vessels engaged in international voyages. All marine diesel engines above 130 kW would be subject to the standards regardless of their use. The test procedures for demonstrating compliance are set out in the NOX Technical Code[7]. They are based on ISO 8178 and are performed using distillate fuel. Engines can be pre-certified or certified after they are installed onboard. After demonstrating compliance, pre-certified engines would receive an Engine International Air Pollution Prevention (EIAPP) certificate. This document, to be issued by the Administration of the flag country, is needed by the ship owner as part of the process of demonstrating compliance with all the provisions of Annex VI and obtaining an International Air Pollution Prevention (IAPP) certificate for the vessel once the

Annex goes into force. The Annex also contains engine compliance provisions based on a survey approach according to which engines must be periodically inspected. These survey requirements would apply after the Annex goes into force. An engine is surveyed right after it is installed, every five years after installation, and at least once between 5-year surveys. Engines are not required to be tested as part of a survey, however. The surveys can be done by a parameter check, which can be as simple as reviewing the Record Book of Engine Parameters that must be maintained for each engine and verifying that current engine settings are within allowable limits.

The Annex requires that engines installed on a ship constructed on or after January 1, 2000 must comply with the specifications set forth in Regulation 13 of the Annex and the NOX Technical Code. In addition, a ship owner must bring an existing engine into compliance if the engine undergoes a major conversion on or after that date.[8] Although the Annex has not yet entered into force and is not yet legally binding, it is widely recognized that the vast majority of marine diesel engines manufactured and installed after January 1, 2000 meet the requirements of the Annex. To facilitate implementation while the Annex is not yet in force and to allow engine manufacturers to certify their engines before the Annex goes into force, we have set up a process for manufacturers to obtain a Statement of Voluntary Compliance.[9] After Annex VI goes into effect for the United States, we will develop a process by which an EPA-issued Statement of Voluntary Compliance can be exchanged for an EIAPP. It should be noted that an engine certificate (EIAPP) or Statement of Voluntary Compliance for an engine installed on a U.S. vessel must be issued by the U.S. EPA. Marine classification or survey societies are not authorized to issue such certificates on behalf of the U.S. government for U.S. vessels.

1.4.4 MARPOL SOx Limits

MARPOL Annex VI contains requirements for fuels used onboard marine vessels. These requirements, which will take effect when the Annex goes into force, consist of two parts. First, Annex VI specifies that the sulfur content of fuel used onboard ships may not exceed 45,000 ppm (4.5 percent). Information gathered in an international monitoring program indicates refiners are currently complying with this requirement and that the current sulfur level of marine bunker fuels ranges between 5,000 and 45,000 ppm, with an average sulfur content of about 27,000 ppm. Second, the Annex provides a mechanism to designate SOx Emission Control Areas, within which ships must either use fuel with a sulfur content not to exceed 15,000 ppm or an exhaust gas cleaning system to reduce SOx emissions. To date, two SOx Emission Control Areas have been designated: the North East Atlantic (North Sea, Irish Sea and English Channel) and the Baltic Sea.

1.4.5 Continuing Action at the IMO

At the time the Annex VI NOX limits were adopted, in September 1997, several Member States expressed concern that the NOX limits were not stringent enough and would not result in the emission reductions they were intended to achieve. Due to the efforts of these Member States, the Conference of the Parties adopted a resolution that provides for review of the emission limits with the aim of adopting more stringent limits taking into account the adverse effects of such emissions on the environment and any technological developments in marine engines. The Marine Environment Protection Committee (MEPC) is to review the standards at a minimum of five-year intervals after entry into force of the Annex and, if appropriate, amend the NOX limits to reflect more stringent controls.

In March 2000, the United States requested the Marine Environment Protection Committee (MEPC) to begin consideration of more stringent emission limits for marine diesel engines.[10] EPA's analysis of emission-control technology for our 1999 rulemaking indicated that more stringent standards were feasible for all Category 1 and Category 2 marine diesel engines. Engine manufacturers were also beginning to investigate applying these emission-control strategies to Category 3 marine diesel engines, as well as more advanced strategies such as water emulsification and selective catalytic reduction. Reflecting the potential emission reductions that could be obtained from applying these strategies to all marine diesel engines, the U.S. recommended Annex VI Tier 2 NOX limits be set at 25 to 30 percent below the existing Annex VI NOX limits for all engines subject to the regulation (engines above 130 kW), to go into effect in 2007. This recommendation was discussed at the 44th session of the MEPC (London, March 2000), but the committee took no action.

The United States will continue to promote more stringent standards at IMO and encourage MEPC to adopt a second tier of emission limits that will reflect available technology and reduce the impact of marine diesel engines on air quality around the world. Technology has continued to advance since we made our request for review in 2000. We now believe that the Member States of the IMO should consider further reductions of 50 percent or more from the NOX limits currently stipulated under Regulation 13 of the Annex, to be applicable to engines installed on vessels constructed on or after a date to be determined.

Chapter 1 References

1.Final Regulatory Impact Analysis: Control of Emissions from Marine Diesel Engines, November, 1999. EPA420-R-99-026. A copy of this document can be found in Docket A-97-50, Document No. V-B-01.

2.Annex VI was adopted by a Conference of the Parties to MARPOL on September 26, 1997, but has not yet entered into force. Copies of the conference versions of the Annex and the NOx Technical Code on the Control of Emissions of Nitrogen Oxides from Marine Diesel Engines (also known as the NOx Technical Code, which contains certification and compliance procedures) can be found in Docket A-97-50, Document II-B-01. Copies of updated versions can be obtained from the International Maritime Organization (www.imo.org)

3.See Endnote 2.

4.More information about the IMO can be found on its website, http://www.imo.org on the "About IMO" tab.

5.More information about the MARPOL convention can be found on the IMO website, http://www.imo.org ; go to the "About IMO" tab and click on "Conventions," then "MARPOL 73/78."

6. Information about Annex VI ratification can be found at www.imo.org (look under Conventions, Status of Conventions - Complete List).

7.To obtain copies of this document, see Endnote 2, above.

8.As defined in Regulation 13 of Annex VI, a major conversion means the engine is replaced by a new engine, it is substantially modified, or its maximum continuous rating is increased by more than 10 percent.

9.For more information about our voluntary certification program, see "Guidance for Certifying to MARPOL Annex VI," VPCD-99-02. This letter is available on our website: http://www.epa.gov/otaq/regs/nonroad/marine/ci/imolettr.pdf and in Docket A-2001-11, Document No. II-B-01.

10.MEPC 44/11/7, Prevention of Pollution from Ships, Revision of the NOx Technical Code, Tier 2 Emission Limits for Marine Diesel Engines at or Above 130 kW, submitted by the United States. This document is available at Docket A-2001-11, Document No. II-A-16.

CHAPTER 2: Health and Welfare Concerns

The engines that are subject to the standards in this final rule generate NOX, PM, CO, and HC emissions that contribute to ozone and CO nonattainment as well as adverse health effects associated with ambient concentrations of PM. They also contribute to visibility impairment and regional haze. This chapter presents our estimates of the contribution these engines make to our national air inventory. We include in this chapter estimates of pre- and post-control inventory contributions. These estimates are described in greater detail in Chapter 7.

This chapter also describes the health and environmental effects related to these emissions. These pollutants cause a range of adverse health and welfare effects, especially in terms of respiratory impairment and related illnesses and visibility impairment. Air quality modeling and monitoring data presented in this chapter indicate that a large number of our citizens continue to be affected by these emissions.

2.1 Inventory Contributions

2.1.1 National Inventory - Category 3 Marine Diesel Engines

We developed baseline Category 3 vessel emission inventories under contract with E. H. Pechan & Associates, Inc.[1] Inventory estimates were developed separately for vessel traffic within 25 nautical miles of port areas (called "in-port" emissions) and vessel traffic outside of port areas but within 175 nautical miles of the coastline (called "non-port" emissions). This two-part method allows us to take advantage of both the detailed port-specific information maintained by commercial port administrations rather than relying simply on cargo movement data maintained by the U.S. Army Corps of Engineers and the Maritime Administration. More detailed information regarding the development of the baseline emission inventories can be found in Chapter 7.

The in-port inventories are based on detailed emission estimates for nine specific ports for a baseline year of 1996. The inventories were estimated using activity data for that port (number of port calls, vessel types and typical times in different operating modes) and an emission factor for each mode. Emission estimates for all other commercial ports (120 ports) were developed by matching each of the other commercial ports to one of the nine specific ports. Matching was based on characteristics of port activity, such as predominant vessel types, harbor draft and region of the country. The detailed port emissions were then scaled for the other commercial ports based on relative port activity. This inventory accounts for emissions that occur within a radius of 25 miles of the port.

Because we do not have detailed information about the nature of non-port vessel traffic, we developed the non-port emission inventories using information about cargo movements and waterways data for 1996. In this case, the estimates are based on vessel speeds, average dead weight tonnage per ship, assumed cargo capacity factors and an emission factors (in grams per nautical mile) developed using cruise mode emission factors and total freight tonnage from the nine specific ports discussed above. This inventory accounts for emissions that occur in the area beginning at 25 nautical miles from the coasts and extending to sea 175 nautical miles.

The impact on coastal areas of emissions from marine diesel engines on vessels operating at sea depends on the extent to which those emissions actually reach land. Pollutant transport is a very complicated subject, and the transport distance can vary dramatically depending on a variety of factors, including the pollutant under consideration; prevailing wind speed and direction and other atmospheric conditions; and how far away from shore a ship is operating. There has been little study of the transport of marine vessel NOX emissions off U.S. coasts.

In our inventory estimates work for the proposal we included all Category 3 vessel emissions within 175 nautical miles of the U.S. coastline on the assumption that emission transport would bring these emissions on to shore and affect U.S. ambient air quality. We requested comment on the transport issue, including whether 175 nautical miles was the appropriate distance from shore to consider or whether we should consider a range different from 175 nautical miles as our primary scenario, and whether we should consider different distances from the coast for different areas of the country. We also asked if there was additional information available to help us assess the emission transport issue. In general, the comments received were supportive of including all emissions within 175 nautical miles of the coast in the national emission inventory. While some commenters questioned this distance, we received no substantial new data or information suggesting that a different distance would be more appropriate or that would help us determine what distance from shore we should use in our inventory analysis.

For the purpose of this final rule, we are including all Category 3 vessel emissions within 175 nautical miles of the U.S. coast in our emission inventory estimates. However, we acknowledge that this emission transport issue is complex and requires further investigation. For example, as we noted in the proposal for this rule, the U.S. Department of Defense (DoD) has presented some information to us that suggests a different, shorter (offshore distance) limit be established rather than the proposed 175 nautical miles as the appropriate location where emissions from marine vessels would affect on-shore air quality. DoD's modeling work on the marine vessels issue in Southern California led them to conclude that emissions within 60 nautical miles of shore could make it back to the coast due to eddies and the nature of the sea-breeze effects. They note that this distance seems to be confirmed by satellite data showing a distinct tendency for a curved line of demarcation separating the offshore (unobstructed) or parallel ocean wind flow from a region of more turbulent, recirculated air that would impact on-shore areas. That curved line of demarcation was close to San Nicolas Island, which is about 60 nautical miles offshore. Studies and published information on other coastal areas in California indicates that they experience somewhat a narrower (perhaps 30 nautical miles) region of "coastal influence." Nevertheless, commenters from California support a 175 nautical-mile boundary.

Because of the continued data and modeling uncertainties surrounding this issue, we intend to investigate this issue as part of our future rule. As part of this investigation, we will consider the special characteristics of emission transport in separate parts of the country. For example, we expect that the Gulf Coast and East Coast areas of the United States would have their own unique meteorological conditions that might call for different lines of demarcation between on-shore and off-shore effects due to different prevailing winds in those parts of the country.

The 1996 NOX and PM emission inventories for the in-port and non-port areas are shown in Table 2.1-1. We used 1996 as the starting point for this analysis because that is the most recent year that we have detailed information available for the nine specific port areas.

Table 2.1-1
Category 3 Marine Diesel Engine 1996 Baseline Emission Inventories (thousand short tons)

Scenario	NOX	PM
In-port (within 25 nautical miles of coast)	101	9.3
Non-port (between 25 and 175 nautical miles of coast)	89	7.7
Total (within 175 nautical miles of coast)	**190**	**17**

To estimate inventories for years after 1996, we developed inventory projections based on expected increases in vessel freight movement and expected changes in vessel characteristics, as well as fleet turnover based on 25 years as the average age of the world fleet at time of scrappage. We also take the internationally negotiated NOX limits into account because, although these international NOX standards are not yet effective, most, if not all shipbuilders and shipping companies around the world are currently complying with them, and this is a trend we expect to continue. Our estimated emission inventories are based on the assumption that all vessels built after 1999 (both U.S. and foreign) will comply with the MARPOL NOX limits. Table 2.1-2 shows the future year Category 3 marine diesel engine NOX and PM inventories for selected years out to 2030, accounting for the implementation of Tier 1/ MARPOL Annex VI NOX limits. The ports inventories refer to the areas within 25 nautical miles of ports areas, while the non-ports inventories refer to the areas outside of 25 nautical miles, but within 175 nautical miles of the coast. More detailed information regarding the development of the future year emission inventories can be found in Chapter 7.

Table 2.1-2
Future Year NOX and PM Inventories for
Category 3 Marine Diesel Engines (thousand short tons)

Year	NOX			PM		
	Ports	Non-ports	All areas	Ports	Non-ports	All areas
1996	101	89	190	9	8	17
2010	146	128	274	14	12	26
2020	196	172	367	20	16	37
2030	288	243	531	30	24	54

Baseline emission inventory estimates (total port and non-port) for the year 2000 for Category 3 marine diesel engines are reported in Table 2.1-3. This table shows the relative contributions of the different mobile-source categories to the overall national mobile-source inventory. Of the total emissions from mobile sources, all Category 3 marine diesel engines contribute about 1.5 percent of NOX and 2.6 percent of PM emissions in the year 2000.

Our draft emission projections for 2030 for Category 3 marine diesel engines show how emissions from these engines are expected to increase over time after implementation of Tier 1/ MARPOL Annex VI NOX limits. The projections for 2030 are reported in Table 2.1-4 and indicate that Category 3 marine diesel engines are expected to contribute 8.9 percent NOX and 7.3 percent of PM emissions in the year 2030. Population growth and the effects of other regulatory control programs are factored into these projections. The relative importance of uncontrolled nonroad engines in 2030 is higher than in the projections for 2000 because there are already emission-control programs in place for the other categories of mobile sources which are expected to reduce their emission levels. The effectiveness of all control programs is offset by the anticipated growth in engine populations.

Table 2.1-3
Modeled Annual Emission Levels for
Mobile-Source Categories in 2000 (thousand short tons)

Category	NOX		HC		CO		PM	
	tons	percent of mobile source	tons	percent of mobile source	tons	percent of mobile source	tons	percent of mobile source
Total for engines subject to new standards (Category 3 engines on U.S. vessels)	**28**	**0.2%**	**1**	**0.0%**	**2**	**0.0%**	**2.5**	**0.4%**
Commercial Marine Diesel - Category 3	214	1.6%	9	0.1%	19	0.02%	19.7	2.8%.
Commercial Marine Diesel - Categories 1 and 2	703	5.2%	22	0.3%	103	0.1%	20	2.9%
Highway Motorcycles	8	0.1%	84	1.1%	331	0.4%	0.4	0.1%
Nonroad Industrial SI > 19 kW	308	2.3%	226	3.1%	1,734	2.3%	1.6	0.2%
Recreational SI	5	0.0%	418	5.7%	1,120	1.5%	12.0	1.7%
Recreation Marine Diesel	38	0.3%	1	0.0%	6	0.0%	1	0.1%
Marine SI Evap	0	0.0%	100	1.4%	0	0.0%	0	0.0%
Marine SI Exhaust	32	0.2%	708	9.6%	2,144	2.8%	38	5.4%
Nonroad SI < 19 kW	106	0.8%	1,460	19.8%	18,359	24.2%	50	7.1%
Nonroad Diesel	2,625	19.6%	316	4.3%	1,217	1.6%	253	35.9%
Locomotive	1,192	8.9%	47	0.6%	119	0.2%	30	4.3%
Total Nonroad	5,231	39%	3,391	46%	25,152	33%	426	60%
Total Highway	7,981	60%	3,811	52%	49,813	66%	240	34%
Aircraft	178	1%	183	3%	1,017	1%	39	6%
Total Mobile Sources	13,389	100%	7,385	100%	75,982	100%	705	100%
Total Man-Made Sources	24,532	--	18,246	--	97,735	--	3,102	--
Mobile Source percent of Total Man-Made Sources	55%	--	40%	--	78%	--	23%	–

Table 2.1-4
Modeled Annual Emission Levels for
Mobile-Source Categories in 2030 (thousand short tons)

Category	NOX		HC		CO		PM	
	tons	percent of mobile source	tons	percent of mobile source	tons	percent of mobile source	tons	percent of mobile source
Total for engines subject to new standards (Category 3 engines on U.S. vessels)[a]	**28**	**0.5%**	**1**	**0.0%**	**2**	**0.0%**	**2.5**	**0.3%**
Commercial Marine Diesel - Category 3	531	8.9%	26	0.5%	57	0.05%	54.0	7.3%
Commercial Marine Diesel - Categories 1 and 2	680	11.4%	26	0.5%	137	0.1%	20.0	2.7%
Highway Motorcycles	17	0.3%	172	3.4%	693	0.7%	1.0	0.1%
Nonroad Industrial SI > 19 kW	44	0.7%	17	0.3%	265	0.3%	2.0	0.3%
Recreational SI	20	0.3%	294	5.8%	1,843	1.9%	10.5	1.4%
Recreation Marine Diesel	52	0.9%	2	0.0%	11	0.0%	1.4	0.2%
Marine SI Evap	0	0.0%	122	2.4%	0	0.0%	0	0.0%
Marine SI Exhaust	64	1.1%	269	5.3%	2,083	2.1%	29	3.9%
Nonroad SI < 19 kW	126	2.1%	1,200	23.7%	32,310	33.3%	93	12.6%
Nonroad Diesel	1,994	33.4%	158	3.1%	1,727	1.8%	306	41.6%
Locomotive	531	8.9%	30	0.6%	119	0.1%	18	2.4%
Total Nonroad	4,059	68%	2,316	46%	39,245	40%	535	73%
Total Highway	1,648	28%	2,496	49%	56,303	58%	158	22%
Aircraft	262	4%	262	5%	1,502	2%	43	6%
Total Mobile Sources	5,969	100%	5,074	100%	97,050	100%	736	100%
Total Man-Made Sources	16,177	--	16,094	--	121,428	--	3,297	--
Mobile Source percent of Total Man-Made Sources	37%	--	32%	--	80%	--	22%	--

[a] These inventories are the same as for 2000 because, based on comments received, we assumed no future increase in U.S. domestic trade.

2.1.2 Category 3 Inventories for Specific Ports

In the previous section we presented estimates of Category 3 marine diesel engine emissions as percentages of the national mobile source inventory. However, marine vessel activity tends to be concentrated in port areas, and thus we would expect that Category 3 marine diesel engines would have a proportionately bigger impact on the mobile source pollution inventories of certain port areas, particularly those with large commercial ports or those where the commercial port activity is a large share of the economic activity of the area. Using the port-specific Category 3 inventories developed for use in our national inventory and the inventories for specific areas developed in support of the heavy-duty on-highway 2007 rule, we developed estimates of the contribution of Category 3 marine diesel engines to both the mobile source and total man made NOX and PM inventories for several selected port areas, including several located in ozone nonattainment areas. The NOX results are shown in Table 2.1-5 and the PM results are shown in Table 2.1-6. As can be seen from these tables, the relative contribution of Category 3 marine diesel engine pollution to mobile source and total man made pollution for these areas is expected to increase in the future, even in the presence of the Tier 1/MARPOL Annex VI NOX limits. This is due both to the expected growth of shipping traffic in the future and the effect of emissions control programs already in place for other mobile sources. Consequently, we expect Category 3 marine diesel engines to continue to be significant contributors to ozone and PM inventories in these areas in 2020.

Table 2.1-5
Category 3 Marine Diesel Engines NOX Inventories
as a Percentage of Total Man Made and Mobile Source NOX in Selected Port Areas

Ozone Nonattainment Area?	Port Area	% of Total Man-Made NOX from C3 Engines		% of Mobile-Source NOX from C3 Engines	
		1996	2020	1996	2020[a]
Y	Baton Rouge and New Orleans, LA	4.0	6.7	7.4	15.8
Y	Los Angeles/Long Beach, CA	1.7	6.4	2.0	8.6
Y	Beaumont/Port Arthur, TX	0.9	1.6	1.4	3.1
Y	Houston/Galveston/Brazoria, TX	0.9	2.3	1.5	4.9
Y	Baltimore/Washington DC	1.3	5.2	2.1	11.4
Y	Philadelphia/Wilmington/Atlantic City	1.1	3.0	1.8	6.9
Y	New York/New Jersey	0.7	3.2	1.0	6.2
N	Seattle/Tacoma/Bremerton/ Bellingham, WA	3.7	17.3	4.3	26.3
N	Miami/Ft. Lauderdale, FL	4.4	19.5	5.4	28.1
N	Portland/Salem, OR	1.7	9.3	1.9	11.9
N	Wilmington, NC	2.4	6.9	6.9	26.8
N	Corpus Christi, TX	2.2	3.8	4.8	12.2
N	Brownsville/Harlington/San Benito, TX	1.7	6.0	1.8	6.6

[a] For reference, the nationwide contribution of Category 3 marine diesel engines to mobile source NOX in 2020 is projected to be 5.7 percent.

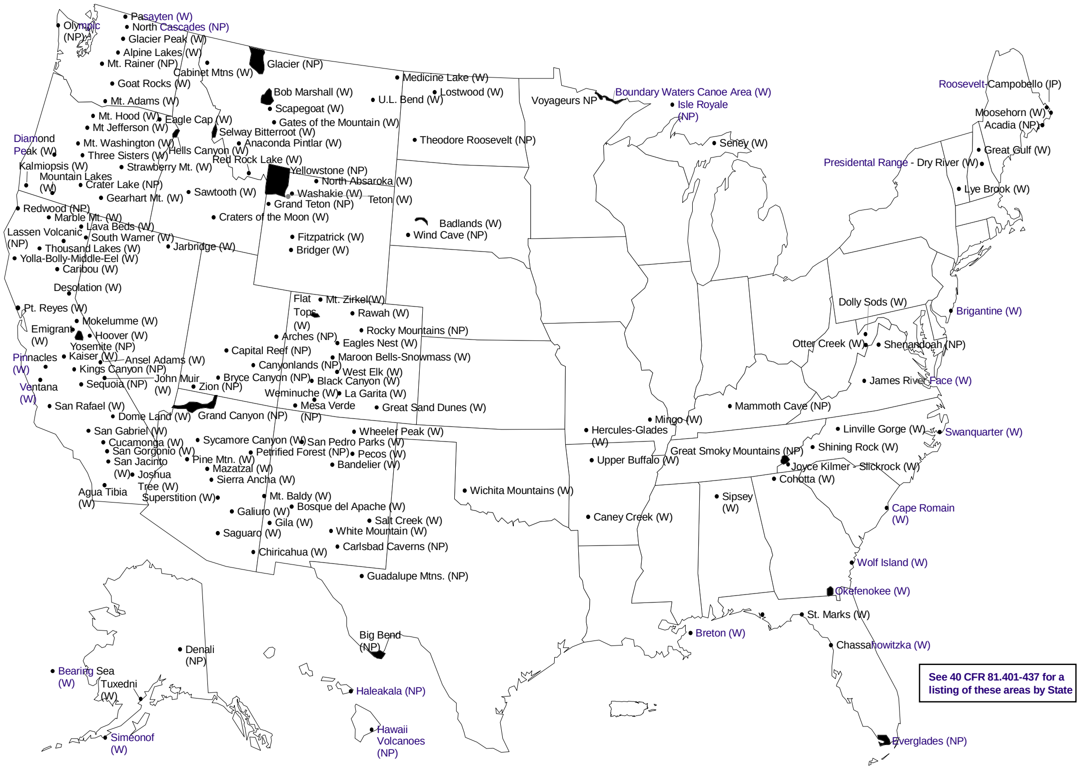
Table 2.1-6
Modeled PM Inventories as a Percentage of
Total Man Made and Mobile Source PM in Selected Port Areas

Port Area	% of Total Man-Made PM from C3 Engines		% of Mobile-Source PM from C3 Engines	
	1996	2020	1996	2020[a]
Baton Rouge and New Orleans, LA	4.0	5.9	12.1	22.6
Los Angeles/Long Beach, CA[b]	1.8	4.4	3.9	10.8
Beaumont/Port Arthur, TX	2.3	4.1	7.4	18.3
Houston/Galveston/Brazoria, TX	2.0	3.8	3.3	8.5
Baltimore/Washington DC	1.0	3.0	3.2	9.6
Philadelphia/Wilmington/Atlantic City	0.7	1.2	2.8	6.3
New York/New Jersey	0.5	1.9	1.6	5.7
Seattle/Tacoma/Bremerton/Bellingham, WA	3.4	10.6	8.5	25.5
Miami/Ft. Lauderdale, FL	7.5	19.9	10.6	28.7
Portland/Salem, OR	1.4	4.4	3.9	12.1
Wilmington, NC	2.1	3.3	8.1	22.4
Corpus Christi, TX	3.3	3.6	6.0	9.6
Brownsville/Harlington/San Benito, TX	2.0	4.6	3.1	14.9

[a] For reference, the nationwide contribution of Category 3 marine diesel engines to mobile source PM in 2020 is projected to be 5.8 percent.
[b] PM nonattainment area.

Note that many of these ports, and other commercial ports, are in or near Class I Areas, as shown in Figure 2.1-1. Category 3 marine diesel engines on vessels that use these ports or the sea lanes near them contribute to visibility degradation in these areas, particularly through their PM emissions. The importance of Class I Areas is described in Section 2.5, below.

Figure 2.1-1



See 40 CFR 81.401-437 for a listing of these areas by State

Map of 156 Mandatory Class I Federal Areas

2.1.3 Category 3 Emissions in Nonport Areas

Emissions from Category 3 marine diesel engines can also have a significant impact on inventories in areas without large commercial ports. For example, Santa Barbara estimates that engines on ocean-going marine vessels contribute about 37 percent of total NOx in their area (see Table 2.1-7). These emissions are from ships that transit the area, and "are comparable to (even slightly larger than) the amount of NOx produced onshore by cars and truck.[2] By 2015 these emissions are expected to increase 67 percent, contributing 61 percent of Santa Barbara's total NOx emissions. While Santa Barbara's exact conditions may be unique due to the relative close proximity of heavily used shipping channels to shore and the meteorological conditions in their area, other coastal areas may also have relatively high inventory impacts from ocean-going vessels.

Table 2.1-7
NOx Emissions, Santa Barbara County, California

Source	1999		2015	
	Tons/Day	percent of total	Tons/day	percent of total
Onshore				
Motor vehicles	25.95	33	9.96	13
Other mobile sources	17.27	22	14.19	18
Stationary sources	5.3	7	4.42	6
Area-wide sources	0.76	1	1.24	1
Offshore				
Ships, boats	28.38	36	47.29	61
Oil and gas production	0.7	1	0.66	1
TOTAL	78.36	—	77.76	—

2.1.4 Category 3 Contribution by flag

It is important to determine how much of the Category 3 marine diesel engine pollution inventory is contributed by U.S. flagged vessels, given that we are applying emission standards only to U.S. flagged vessels. We estimated the relative contribution of U.S. and foreign flagged vessels separately for port areas and nonport areas due to the fact the we had different data sets available for each.

We estimated the proportion of total Category 3 emissions in-port attributable to U.S. flagged vessels for the ports areas using port call data obtained from the U.S. Maritime Administration (MARAD). These data contained all port calls in 1999 to U.S. ports by vessels of greater than

1000 gross registered tons engaged in foreign trade, including the country in which they are flagged and the number of port calls each vessel made, but did not include port calls of vessels engaged in U.S. domestic trade. We estimated the number of port calls made by U.S. flagged vessels engaged in domestic trade and added those to those taken from the MARAD database. An analysis of the port call data shows that U.S. flagged vessels only account about 10 percent of port calls to U.S. ports. For the lack of more detailed information regarding the breakout of U.S. and foreign flagged vessel emissions we applied the percentage of port calls from U.S. and foreign flagged vessels to the national ports inventories to determine the relative contributions of each to the national ports inventories.

As just described, we estimated that 10 percent of Category 3 vessel calls to U.S. ports are made by U.S. flagged vessels. However, we note that this estimate is a national average, and that the percentage of port calls made by U.S. flagged vessels in any given port may well be different than this. Such factors as the size of the port and the nature of the commodities being shipped in and out of a given port would affect the percentage of calls made by U.S. versus foreign flagged vessels. For example, in 1997 U.S. flagged vessels made up less than 10 percent of port calls by ocean going vessels in the Houston-Galveston area but around 15 percent of port calls in the South Coast of California.[3,4]

To estimate the proportion of total Category 3 non-port emissions attributable to U.S. vessels, we used new port call information provided by MARAD.[5] This data showed not only whether a vessel was U.S. or foreign flagged, but whether the vessels came from other U.S. ports or from foreign ports. The data provided by MARAD was summary data and did not include any detailed background information. However, given the small number of Category 3 vessels engaged in U.S. domestic trade and the large number of port calls listed in this data as being from vessels engaged in U.S. domestic trade, we believe the data contained a significant number of Category 2 vessels in the U.S. domestic trade category. Nonetheless, this data gives us a much better picture of the nature of vessel traffic between ports than we had for the proposal, and we used it to estimate that roughly 20 percent of non-port emissions come from U.S. flagged vessels.

We intend to continue researching the issue of U.S. versus foreign flagged vessel emissions and plan to further refine our analysis in any future rulemaking efforts aimed at Category 3 vessels.

2.1.5 Category 1 and Category 2 Inventory Estimates

Inventory estimates for Category 1 and Category 2 marine diesel engines were developed for our 1999 rulemaking and can be found in the Final Regulatory Impact Analysis for that rule.[6] The standards we are adopting for engines with in-cylinder displacement of 2.5 to 30 liters are equivalent to the internationally-negotiated NOx standards and are currently voluntary for those engines. To comply with Annex VI, engines installed on ships since January 1, 2000 are widely understood to already comply with those standards. Therefore, we are not adjusting our previous emission inventory estimates for those engines.

2.2 Ozone

2.2.1 General Background

Ground-level ozone, the main ingredient in smog, is formed by complex chemical reactions of volatile organic compounds (VOC) and NOx in the presence of heat and sunlight. Ozone forms readily in the lower atmosphere, usually during hot summer weather. Volatile organic compounds are emitted from a variety of sources, including motor vehicles, chemical plants, refineries, factories, consumer and commercial products, and other industrial sources. Volatile organic compounds also are emitted by natural sources such as vegetation. Oxides of nitrogen are emitted largely from motor vehicles, off-highway equipment, power plants, and other sources of combustion. Hydrocarbons (HC) are a large subset of VOC, and to reduce mobile source VOC levels we set maximum emission standards for hydrocarbons. VOCs can also be part of the secondary formation of PM.

The science of ozone formation, transport, and accumulation is complex. Ground-level ozone is produced and destroyed in a cyclical set of chemical reactions involving NOx, VOC, heat, and sunlight.[7] As a result, differences in weather patterns, as well as NOx and VOC levels, contribute to daily, seasonal, and yearly differences in ozone concentrations and differences from city to city. Many of the chemical reactions that are part of the ozone-forming cycle are sensitive to temperature and sunlight. When ambient temperatures and sunlight levels remain high for several days and the air is relatively stagnant, ozone and its precursors can build up, resulting in higher ambient ozone levels than typically would occur on a single high temperature day. Further complicating matters, ozone also can be transported into an area from pollution sources found hundreds of miles upwind, resulting in elevated ozone levels even in areas with low local NOx or VOC emissions.

On the chemical level, NOx and VOC are the principal precursors to ozone formation. The highest levels of ozone are produced when both VOC and NOx emissions are present in significant quantities on clear summer days. Relatively small amounts of NOx enable ozone to form rapidly when VOC levels are relatively high, but ozone production is quickly limited by removal of the NOx. Under these conditions, NOx reductions are highly effective in reducing ozone while VOC reductions have little effect. Such conditions are called “NOx limited.” Because the contribution of VOC emissions from biogenic (natural) sources to local ambient ozone concentrations can be significant, even some areas where man-made VOC emissions are relatively low can be NOx limited.

When NOx levels are relatively high and VOC levels relatively low, NOx forms inorganic nitrates but relatively little ozone. Such conditions are called “VOC limited.” Under these conditions, VOC reductions are effective in reducing ozone, but NOx reductions can actually increase local ozone under certain circumstances. Even in VOC limited urban areas, NOx reductions are not expected to increase ozone levels if the NOx reductions are sufficiently large.

Rural areas are almost always NOx limited, due to the relatively large amounts of biogenic VOC emissions in such areas. Urban areas can be either VOC or NOx limited, or a mixture of both.

Ozone concentrations in an area also can be lowered by the reaction of nitric oxide with ozone, forming nitrogen dioxide (NO_2); as the air moves downwind and the cycle continues, the NO_2 forms additional ozone. The importance of this reaction depends, in part, on the relative concentrations of NOx, VOC, and ozone, all of which change with time and location.

As described in Section 2.1, Category 3 engines currently account for about 1.6 and 0.1 percent of the national mobile source NOx and HC inventories, respectively. This is expected to increase to 8.9 and 0.5 percent, respectively, by 2030 even when considering the presence of the internationally negotiated NOx limits.

2.2.2 Health and Welfare Effects of Ozone and Its Precursors

Based on a large number of studies, EPA has identified several key health effects caused when people are exposed to levels of ozone found today in many areas of the country.[8, 9] Short-term exposures (1 to 3 hours) to high ambient ozone concentrations have been linked to increased hospital admissions and emergency room visits for respiratory problems. For example, studies conducted in the northeastern U.S. and Canada show that ozone air pollution is associated with 10-20 percent of all of the summertime respiratory-related hospital admissions. Repeated exposure to ozone can make people more susceptible to respiratory infection and lung inflammation and can aggravate preexisting respiratory diseases, such as asthma. Prolonged (6 to 8 hours), repeated exposure to ozone can cause inflammation of the lung, impairment of lung defense mechanisms, and possibly irreversible changes in lung structure, which over time could lead to premature aging of the lungs and/or chronic respiratory illnesses such as emphysema and chronic bronchitis.

Children and outdoor workers are most at risk from ozone exposure because they typically are active outside during the summer when ozone levels are highest. For example, summer camp studies in the eastern U.S. and southeastern Canada have reported significant reductions in lung function in children who are active outdoors. Further, children are more at risk than adults from ozone exposure because their respiratory systems are still developing. Adults who are outdoors and are moderately active during the summer months, such as construction workers and other outdoor workers, also are among those most at risk. These individuals, as well as people with respiratory illnesses such as asthma, especially asthmatic children, can experience reduced lung function and increased respiratory symptoms, such as chest pain and cough, when exposed to relatively low ozone levels during prolonged periods of moderate exertion.

Ozone can aggravate asthma and can cause coughs and chest pain, lung inflammation and cell damage, decreases in lung function, and increased susceptibility to respiratory infection. Ozone has been associated with increased hospitalizations and emergency room visits for respiratory causes. Repeated exposure over time may permanently damage lung tissue.

The 8-hour standard, issued by EPA in 1997, is based on well-documented science demonstrating that more people are experiencing adverse health effects at lower levels of exertion, over longer periods, and at lower ozone concentrations than addressed by the one-hour ozone standard. The 8-hour standard greatly limits ozone exposures of concern for the general population and populations most at risk, including children active outdoors, outdoor workers, and individuals with pre-existing respiratory disease, such as asthma.

Since the ozone national ambient air quality standards (NAAQS) were promulgated in 1997, over fifteen hundred new health and welfare studies have been published. Many of these studies have investigated the impact of ozone exposure on such health effects as changes in lung structure and biochemistry, inflammation of the lungs, exacerbation and causation of asthma, respiratory illness-related school absence, hospital and emergency room visits for asthma and other respiratory causes, and premature mortality. Although these studies have been published in peer reviewed journals, they have not yet been incorporated into a revised Air Quality Criteria Document for Ozone and Other Photochemical Oxidants. Key new health information falls into four general areas: development of new-onset asthma, hospital admissions for young children, school absence rate, and premature mortality.

Aggravation of existing asthma resulting from ambient ozone exposure was reported prior to the 1997 decision and has been observed in studies published since (Thurston et al., 1997; Ostro et al., 2001). Although preliminary, an important new finding is evidence suggesting that air pollution and outdoor exercise could contribute to the development of new-onset asthma. In particular, a relationship between long-term ambient ozone concentrations and the incidence of asthma in adults was reported by McDonnell et al. (1999). Subsequently, McConnell et al. (2002) suggested that incidence of new diagnoses of asthma in children is associated with heavy exercise in communities with high concentrations of ozone.

Previous studies have shown relationships between ozone and hospital admissions in the general population. A new study in Toronto found a significant relationship between 1-hour maximum ozone concentrations and respiratory hospital admissions in children under two (Burnett et al. 2001). Given the relative vulnerability of children in this age category, this is an important addition to the literature on ozone and hospital admissions.

Increased school absence rate caused by respiratory illness has been associated with 1-hour daily maximum and 8-hour average ozone concentrations in studies conducted in Nevada (Chen et al., 2000) in grades K-6 and in Southern California (Gilliland et al., 2001) in grades 4-6. These studies suggest that higher ambient ozone levels may result in increased school absenteeism.

The air pollutant most clearly associated with premature mortality is particulate matter, with dozens of studies reporting such an association. Repeated ozone exposure is a likely contributing factor for premature mortality, causing an inflammatory response in the lungs which may predispose elderly and other sensitive individuals to become more susceptible. The findings of three recent analyses provide consistent data suggesting that ozone exposure is associated with increased mortality. Although the National Morbidity, Mortality, and Air Pollution Study did not find an effect of ozone on total mortality across the full year, Samet et al. (2000), who conducted the study, did observe an effect after limiting the analysis to summer when ozone levels are highest. Similarly, Thurston and Ito (1999) have shown associations between ozone and mortality. Toulomi et al. (1997) found that 1-hour maximum ozone levels were associated with daily numbers of deaths in 4 cities (London, Athens, Barcelona, and Paris), and a quantitatively similar effect was found in a group of 4 additional cities (Amsterdam, Basel, Geneva, and Zurich).

In addition to the health effects described above, there exists a large body of scientific literature that shows that harmful effects can occur from sustained levels of ozone exposure at low levels. Studies of prolonged exposures, those lasting about 7 hours, showed health effects from exposures to ozone concentrations as low as 0.08 ppm. Prolonged and repeated exposures to ozone at these levels are common in areas that do not attain the 1-hour NAAQS, and also occur in areas where ambient concentrations of ozone are in compliance with the 1-hour NAAQS.

Prolonged exposure to levels of ozone below the NAAQS have been reported to cause or be statistically associated with transient pulmonary function responses, transient respiratory symptoms, effects on exercise performance, increased airway responsiveness, increased susceptibility to respiratory infection, increased hospital and emergency room visits, and transient pulmonary respiratory inflamation. Such acute health effects have been observed following prolonged exposures at moderate levels of exertion at concentrations of ozone as low as 0.08 ppm, the lowest concentration tested. The effects are more pronounced as concentrations increase, affecting more subjects or having a greater effect on a given subject in terms of functional changes or symptoms. A detailed summary and discussion of the large body of ozone health effects research may be found in Chapters 6 through 9 (Volume 3) of the 1996 Criteria Document for ozone.[10] Monitoring data indicates that 291 counties have design values that exceed these levels based on 1999-2001 data in 1997-99.[11]

Ozone can have other welfare effects, with damage to plants and ecosystems being of most concern. Ozone adversely affects crop yield, vegetation and forest growth, and the durability of materials. Because ground-level ozone interferes with the ability of a plant to produce and store food, plants become more susceptible to disease, insect attack, harsh weather and other environmental stresses. Ozone causes noticeable foliage damage in many crops, trees, and ornamental plants (i.e., grass, flowers, shrubs) and causes reduced growth in plants. Studies indicate that current ambient levels of ozone are responsible for damage to forests and ecosystems (including habitat for native animal species). The adverse effect of ozone on forests and other natural vegetation can in turn cause damage to associated ecosystems, with additional resulting economic losses. Prolonged ozone concentrations of 0.10 ppm can be phytotoxic to a large number of plant species, and can produce acute injury and reduced crop yield and biomass production. Ozone concentrations within the range of 0.05 to 0.10 ppm have the potential over a longer duration of creating chronic stress on vegetation that can result in reduced plant growth and yield, shifts in competitive advantages in mixed populations, decreased vigor, and injury.

Ozone effects on vegetation are discussed in Section 2.2.4 below and presented in more detail in Chapter 5, Volume II of the 1996 Criteria Document. In addition, ozone chemically attacks elastomers (natural rubber and certain synthetic polymers), textile fibers and dyes, and, to a lesser extent, paints. For example, elastomers become brittle and crack, and dyes fade after exposure to ozone.

2.2.3 Ozone Nonattainment and Contribution to Ozone Nonattainment

The current primary and secondary ozone National Ambient Air Quality Standard (NAAQS) is 0.12 ppm daily maximum 1-hour concentration, not to be exceeded more than once per year on average. The determination that an area is at risk of exceeding the ozone standard in the future was made for all areas with current design values greater than or equal to 0.125 ppm (or within a 10 percent margin) and with modeling evidence that exceedances will persist into the future.

EPA is replacing the previous 1-hour ozone standard with a new 8-hour standard. The new standard is set at a concentration of 0.08 parts per million (ppm). The measurement period is 8 hours. Areas are allowed to disregard their three worst measurements every year and average performance over three years to determine if they meet the standard. That is, the standard is set by the 4th highest maximum 8-hour concentration.

Ground level ozone today remains a pervasive pollution problem in the United States. About 51 million people live in areas with design values above the level of the 1-hour ozone standard based on three years of data (1999-2001). In addition, about 111 million people live in areas with design values above the 8-hour ozone standard based on those three years of data. Approximately 61 million of these people live in areas with design values above the 8-hour standard but are below the design standard for the 1-hour ozone standard (i.e., they are attaining the 1-hour standard). The remainder of these people live in areas with design values above the 8-hour ozone standards but are above the design value for the 1-hour ozone standard (i.e., they are not attaining the 1-hour standard).[12] This represents 222 counties with design values above the level of the 8-hour standard.

Over the last decade, declines in ozone levels were found mostly in urban areas, where emissions are heavily influenced by controls on mobile sources and their fuels. Twenty-three metropolitan areas have realized a decline in ozone levels since 1989, but at the same time ozone levels in 11 metropolitan areas with 7 million people have increased.[13] Regionally, California and the Northeast have recorded significant reductions in peak ozone levels, while four other regions (the Mid-Atlantic, the Southeast, the Central and Pacific Northwest) have seen ozone levels increase. The highest ambient concentrations are currently found in suburban areas, consistent with downwind transport of emissions from urban centers. Concentrations in rural areas have risen to the levels previously found only in cities.

2.2.4 Additional Health and Welfare Effects of NOx Emissions

In addition to their role as an ozone precursor, NOx emissions are associated with a wide variety of other health and welfare effects.[14, 15] Nitrogen dioxide can irritate the lungs and reduce resistance to respiratory infection (such as influenza). Nitrogen dioxide and airborne nitrate also contribute to pollutant haze, which impairs visibility and can reduce residential property values and the value placed on scenic views. Elevated levels of nitrates in drinking water pose significant health risks, especially to infants. NOx emissions are an important precursor to acid rain that may affect both terrestrial and aquatic ecosystems. Atmospheric deposition of nitrogen leads to excess nutrient enrichment problems ("eutrophication"). Deposition of nitrogen-containing compounds also affects terrestrial ecosystems.

2.2.4.1 Acid Deposition

Acid deposition, or acid rain as it is commonly known, occurs when SO_2 and NOx react in the atmosphere with water, oxygen, and oxidants to form various acidic compounds that later fall to earth in the form of precipitation or dry deposition of acidic particles.[16] It contributes to damage of trees at high elevations and in extreme cases may cause lakes and streams to become so acidic that they cannot support aquatic life. In addition, acid deposition accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are part of our nation's cultural heritage. To reduce damage to automotive paint caused by acid rain and acidic dry deposition, some manufacturers use acid-resistant paints, at an average cost of $5 per vehicle--a total of $61 million per year if applied to all new cars and trucks sold in the U.S.

Acid deposition primarily affects bodies of water that rest atop soil with a limited ability to neutralize acidic compounds. The National Surface Water Survey investigated the effects of acidic deposition in over 1,000 lakes larger than 10 acres and in thousands of miles of streams. It found that acid deposition was the primary cause of acidity in 75 percent of the acidic lakes and about 50 percent of the acidic streams, and that the areas most sensitive to acid rain were the Adirondacks, the mid-Appalachian highlands, the upper Midwest and the high elevation West. The National Surface Water Survey found that approximately 580 streams in the Mid-Atlantic Coastal Plain are acidic primarily due to acidic deposition. Hundreds of the lakes in the Adirondacks surveyed have acidity levels incompatible with the survival of sensitive fish species. Many of the over 1,350 acidic streams in the Mid-Atlantic Highlands (mid-Appalachia) region have already experienced trout losses due to increased stream acidity. Emissions from U.S. sources contribute to acidic deposition in eastern Canada, where the Canadian government has estimated that 14,000 lakes are acidic. Acid deposition also has been implicated in contributing to degradation of high-elevation spruce forests that populate the ridges of the Appalachian Mountains from Maine to Georgia.

2.2.4.2 Eutrophication and Nitrification

Nitrogen deposition into bodies of water can cause problems beyond those associated with acid rain. The Ecological Society of America has included discussion of the contribution of air emissions to increasing nitrogen levels in surface waters in a recent major review of causes and consequences of human alteration of the global nitrogen cycle in its Issues in Ecology series.[17] Long-term monitoring in the United States, Europe, and other developed regions of the world shows a substantial rise of nitrogen levels in surface waters, which are highly correlated with human-generated inputs of nitrogen to their watersheds. These nitrogen inputs are dominated by fertilizers and atmospheric deposition.

Human activity can increase the flow of nutrients into those waters and result in excess algae and plant growth. This increased growth can cause numerous adverse ecological effects and economic impacts, including nuisance algal blooms, dieback of underwater plants due to reduced light penetration, and toxic plankton blooms. Algal and plankton blooms can also reduce the level of dissolved oxygen, which can also adversely affect fish and shellfish populations. This problem is of particular concern in coastal areas with poor or stratified circulation patterns, such as the Chesapeake Bay, Long Island Sound, or the Gulf of Mexico. In such areas, the "overproduced" algae tends to sink to the bottom and decay, using all or most of the available oxygen and thereby reducing or eliminating populations of bottom-feeder fish and shellfish, distorting the normal population balance between different aquatic organisms, and in extreme cases causing dramatic fish kills.

Collectively, these effects are referred to as eutrophication, which the National Research Council recently identified as the most serious pollution problem facing the estuarine waters of the United States.[18] Nitrogen is the primary cause of eutrophication in most coastal waters and estuaries.[19] On the New England coast, for example, the number of red and brown tides and shellfish problems from nuisance and toxic plankton blooms have increased over the past two decades, a development thought to be linked to increased nitrogen loadings in coastal waters. We believe that airborne NOx contributes from 12 to 44 percent of the total nitrogen loadings to United States coastal water bodies. For example, some estimates assert that approximately one-quarter of the nitrogen in the Chesapeake Bay comes from atmospheric deposition.

Excessive fertilization with nitrogen-containing compounds can also affect terrestrial ecosystems.[20] Research suggests that nitrogen fertilization can alter growth patterns and change the balance of species in an ecosystem, providing beneficial nutrients to plant growth in areas that do not suffer from nitrogen over-saturation. In extreme cases, this process can result in nitrogen saturation when additions of nitrogen to soil over time exceed the capacity of the plants and microorganisms to utilize and retain the nitrogen. This phenomenon has already occurred in some areas of the U.S.

2.3 Particulate Matter

2.3.1 General Background

Particulate pollution is a problem affecting urban and non-urban localities in all regions of the United States. Particulate matter (PM) represents a broad class of chemically and physically diverse substances. It can be principally characterized as discrete particles that exist in the condensed (liquid or solid) phase spanning several orders of magnitude in size. All particles equal to and less than 10 microns are called PM_{10}. Fine particles can be generally defined as those particles with an aerodynamic diameter of 2.5 microns or less (also known as $PM_{2.5}$), and coarse fraction particles are those particles with an aerodynamic diameter greater than 2.5 microns, but equal to or less than a nominal 10 microns.

Manmade emissions that contribute to airborne particulate matter result principally from combustion sources (stationary and mobile sources) and fugitive emissions from industrial processes and non-industrial processes (such as roadway dust from paved and unpaved roads, wind erosion from crop land, construction, etc.). Human-generated sources of particles include a variety of stationary sources (including power generating plants, industrial operations, manufacturing plants, waste disposal) and mobile sources (light- and heavy-duty on-road vehicles, and off-highway vehicles such as construction, farming, industrial, locomotives, marine vessels and other sources). Natural sources also contribute to particulate matter in the atmosphere and include sources such as wind erosion of geological material, sea spray, volcanic emissions, biogenic emanation (e.g., pollen from plants, fungal spores), and wild fires.

The chemical and physical properties of PM vary greatly with time, region, meteorology, and source category. Particles may be emitted directly to the atmosphere (primary particles) or may be formed by transformations of gaseous emissions of sulfur dioxide, oxides of nitrogen or volatile organic compounds (secondary particles). The vast majority (>90 percent) of the direct mobile-source PM emissions and their secondary formation products are in the fine PM size range. Mobile sources can reasonably be estimated to contribute to ambient secondary nitrate and sulfate PM in proportion to their contribution to total NOx and SOx emissions.

As described in Section 2.1, Category 3 engines currently account for about 2.8 percent of the national mobile source PM inventory; this is expected to increase to 7.3 percent by 2030 if left uncontrolled.

2.3.2 Health and Welfare Effects of PM

Particulate matter can adversely affect human health and welfare. Discussions of the health and welfare effects associated with ambient PM can be found in the Air Quality Criteria for Particulate Matter.[21]

Key EPA findings regarding the health risks posed by ambient PM are summarized as follows:

a. Health risks posed by inhaled particles are affected both by the penetration and deposition of particles in the various regions of the respiratory tract, and by the biological responses to these deposited materials.

b. The risks of adverse effects associated with deposition of ambient particles in the thorax (tracheobronchial and alveolar regions of the respiratory tract) are markedly greater than for deposition in the extrathoracic (head) region. Maximum particle penetration to the thoracic regions occurs during oronasal or mouth breathing.

c. Published peer-reviewed studies have reported statistical associations between PM and several key health effects, including premature death; aggravation of respiratory and cardiovascular disease, as indicated by increased hospital admissions and emergency room visits, school absences, work loss days, and restricted activity days; changes in lung function and increased respiratory symptoms; changes to lung tissues and structure; and altered respiratory defense mechanisms. Most of these effects have been consistently associated with ambient PM concentrations, which have been used as a measure of population exposure, in a large number of community epidemiological studies. Additional information and insights on these effects are provided by studies of animal toxicology and controlled human exposures to various constituents of PM conducted at higher than ambient concentrations. Although mechanisms by which particles cause effects are not well known, there is general agreement that the cardio-respiratory system is the major target of PM effects.

d. Based on a qualitative assessment of the epidemiological evidence of effects associated with PM for populations that appear to be at greatest risk with respect to particular health endpoints, we have concluded the following with respect to sensitive populations:

   1. Individuals with respiratory disease (e.g., chronic obstructive pulmonary disease, acute bronchitis) and cardiovascular disease (e.g., ischemic heart disease) are at greater risk of premature mortality and hospitalization due to exposure to ambient PM.

   2. Individuals with infectious respiratory disease (e.g., pneumonia) are at greater risk of premature mortality and morbidity (e.g., hospitalization, aggravation of respiratory symptoms) due to exposure to ambient PM. Also, exposure to PM may increase individuals' susceptibility to respiratory infections.

   3. Elderly individuals are also at greater risk of premature mortality and hospitalization for cardiopulmonary problems due to exposure to ambient PM.

   4. Children are at greater risk of increased respiratory symptoms and decreased lung function due to exposure to ambient PM.

   5. Asthmatic individuals are at risk of exacerbation of symptoms associated with asthma, and increased need for medical attention, due to exposure to PM.

e. There are fundamental physical and chemical differences between fine and coarse fraction particles. The fine fraction contains acid aerosols, sulfates, nitrates, transition metals, diesel exhaust particles, and ultra fine particles; the coarse fraction typically contains high mineral concentrations, silica and resuspended dust. It is reasonable to expect that differences may exist in both the nature of potential effects elicited by coarse and fine PM and the relative concentrations required to produce such effects. Both fine and coarse particles can accumulate in the respiratory system. Exposure to coarse fraction particles is primarily associated with the aggravation of respiratory conditions such as asthma. Fine particles are closely associated with health effects such as premature death or hospital admissions, and for cardiopulmonary diseases.

With respect to welfare or secondary effects, fine particles have been clearly associated with the impairment of visibility over urban areas and large multi-State regions. Particles also contribute to soiling and materials damage. Components of particulate matter (e.g., sulfuric or nitric acid) also contribute to acid deposition, nitrification of surface soils and water eutrophication of surface water.

2.3.3 PM Nonattainment

There are two indicators related to PM NAAQS. The first indicator is PM_{10}, and the second is $PM_{2.5}$. Concentrations above the $PM_{2.5}$ standard are much more widespread than are violations of the PM_{10} standard, and emission reductions needed to attain the $PM_{2.5}$ standards will also lead to attainment of the PM_{10} standards.

2.3.3.1 PM_{10} Concentrations and Nonattainment

The NAAQS for PM_{10} was established in 1987. According to these standards, the short term (24-hour) standard of 150 $\mu g/m^3$ is not to be exceeded more than once per year on average over three years. The long-term standard specifies an expected annual arithmetic mean not to exceed 50 $\mu g/m^3$ over three years. Recent PM_{10} monitoring data indicates that there are 8 serious and 58 moderate PM_{10} nonattainment areas with about 30 million people in 63 mainly western counties.

2.3.3.2 $PM_{2.5}$ Concentrations

The NAAQS for $PM_{2.5}$ indicator was established in 1997. According to these standards, the short term (24-hour) standard is set at 65 $\mu g/m^3$ based on the 98th percentile averaged over three years. The long-term standard specifies an expected annual arithmetic mean not to exceed 15 $\mu g/m^3$ over three years.

Fine particle concentrations contribute to both health effects and visibility impairment. We have monitored air quality data that establishes a present widespread nonattainment problem, and modeling results that indicate a continuing problem plus visibility needs. Current PM2.5 monitored values for 1999-2001, which cover about a quarter of the nation's counties, indicate that at least 65 million people in 129 counties live in areas where design values of ambient fine particulate matter levels are at or above the PM2.5 NAAQS. Three years of complete data are required to make regulatory determinations of attainment or nonattainment but, based on more limited available data, there are an additional 9 million people in 20 counties where levels exceeding the NAAQS are being measured, but there are insufficient data at this time to make an official estimate of the design value. In total, this represents 39 percent of the population in the areas with monitors.[22] To estimate the current number of people who live in areas where long-term ambient fine particulate matter levels are at or above 16 µg/m^3 but for which there are no monitors, we can use modeling performed for the Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control rule (also called the "HD07" rule) described elsewhere.[23] At that time, we conducted 1996 base year modeling to reproduce the atmospheric processes resulting in formation and dispersion of $PM_{2.5}$ across the U.S. This 1996 modeling included emissions subject to this final rule. According to our national model predictions, there were a total of 76 million people (1996 population) living in areas with modeled annual average $PM_{2.5}$ concentrations at or above 16 µg/m^3 (29 percent of the population).[24]

While the final implementation process for bringing the Nation's air into attainment with the $PM_{2.5}$ NAAQS is still being completed, the basic framework is well defined. EPA's current plans call for designating $PM_{2.5}$ nonattainment areas in late-2004. Following designation, Section 172(b) of the Clean Air Act allows states up to three years to submit a revision to their state implementation plan (SIP) that provides for the attainment of the $PM_{2.5}$ standards. We expect states to submit these SIPs in late-2007. Section 172(a)(2) of the Clean Air Act requires that these SIP revisions demonstrate that the nonattainment areas will attain the $PM_{2.5}$ standards as expeditiously as practicable but no later than five years from the date that the area was designated nonattainment. However, based on the severity of the air quality problem and the availability and feasibility of control measures, the Administrator may extend the attainment date "for a period of no greater than 10 years from the date of designation as nonattainment." Therefore, we expect that areas will be ultimately be required to attain the $PM_{2.5}$ air quality standard in the 2009 to 2014 time frame.

2.3.4 Diesel Exhaust

In addition to its contribution to ambient PM inventories, diesel exhaust PM is of special concern because it has been implicated in an increased risk of lung cancer and respiratory disease in human studies, and an increased risk of noncancer health effects as well.

EPA recently released its final "Health Assessment Document for Diesel Engine Exhaust" (the Diesel HAD).[25] There, we concluded that diesel exhaust is likely to be carcinogenic to humans by inhalation and environmental exposures in accordance with the revised draft 1996/1999 EPA cancer guidelines. A number of other agencies (e.g., National Institute for Occupational Safety and Health, the International Agency for Research on Cancer, the World Health Organization, California EPA, and the US Department of Health and Human Services) have made similar determinations.

The EPA Diesel HAD states that the conclusions of the document apply to diesel exhaust as a whole including both on-road and non-road engines as well as older and newer engines.

EPA generally derives cancer unit risk estimates to more precisely estimate risk from exposure to carcinogens. The cancer unit risk is that increased risk associated with average lifetime exposure of 1 µg/m^3. EPA concluded in the Diesel HAD that it is not possible to currently calculate a cancer unit risk for diesel particles due to a variety of factors that limit the current studies such as lack of adequate dose-response relations between exposure versus cancer incidence. However, in the absence of a cancer unit risk, the Diesel HAD made estimates about the possible magnitude of risk from exposure to diesel exhaust by comparing the environmental exposure levels to the occupational exposure levels. This analysis suggests a range for environmental risk between 10^{-3} and 10^{-5}. While these risk estimates are exploratory and not intended to provide a definitive characterization of cancer risk, they are useful in gauging the possible range of risk based on reasonable judgement. It is important to note that the possible risks could also be lower and a zero risk cannot be ruled out. Some individuals in the population may have a high tolerance to exposure from diesel exhaust and low cancer susceptibility. Also, there could be a threshold of exposure below which there is no cancer risk although evidence has not been seen or substantiated on this point.

Even though EPA does not have a carcinogenic potency with which to accurately estimate the carcinogenic impact of diesel exhaust, the likely hazard to humans together with the potential for significant environmental risks leads us to conclude that diesel exhaust emissions should be reduced from nonroad engines in order to protect public health. The following factors lead to our determination:

- EPA has officially designated diesel exhaust has been designed a likely human carcinogen. Other organizations have made similar determinations.
- The entire population is exposed to various levels of diesel exhaust.
- The possible range of risk for the general US population due to exposure to diesel exhaust is 10^{-3} to 10^{-5} although the risk could be lower and a zero risk cannot be ruled out.

Thus, the concern for a carcinogenicity hazard resulting from diesel exhaust exposures is longstanding and widespread.

2.4 Carbon Monoxide

2.4.1 General Background

Unlike many gases, CO is odorless, colorless, tasteless, and nonirritating. Carbon monoxide results from incomplete combustion of fuel and is emitted directly from vehicle tailpipes. Incomplete combustion is most likely to occur at low air-to-fuel ratios in the engine. These conditions are common during vehicle starting when air supply is restricted (“choked”), when vehicles are not tuned properly, and at high altitude, where “thin” air effectively reduces the amount of oxygen available for combustion (except in engines that are designed or adjusted to compensate for altitude). Carbon monoxide emissions increase dramatically in cold weather. This is because engines need more fuel to start at cold temperatures and because some emission control devices (such as oxygen sensors and catalytic converters) operate less efficiently when they are cold. Also, nighttime inversion conditions are more frequent in the colder months of the year. This is due to the enhanced stability in the atmospheric boundary layer, which inhibits vertical mixing of emissions from the surface.

As described in Section 2.1, Category 3 engines currently account for about 0.02 percent of the national mobile source CO inventory; this is expected to increase to 0.05 percent by 2030 if left uncontrolled.

2.4.2 Health Effects of CO

Carbon monoxide enters the bloodstream through the lungs and forms carboxyhemoglobin (COHb), a compound that inhibits the blood's capacity to carry oxygen to organs and tissues.[26] Carbon monoxide has long been known to have substantial adverse effects on human health, including toxic effects on blood and tissues, and effects on organ functions. Although there are effective compensatory increases in blood flow to the brain, at some concentrations of COHb, somewhere above 20 percent, these compensations fail to maintain sufficient oxygen delivery, and metabolism declines.[27] The subsequent hypoxia in brain tissue then produces behavioral effects, including decrements in continuous performance and reaction time.[28]

Carbon monoxide has been linked to increased risk for people with heart disease, reduced visual perception, cognitive functions and aerobic capacity, and possible fetal effects. Persons with heart disease are especially sensitive to carbon monoxide poisoning and may experience chest pain if they breathe the gas while exercising. Infants, elderly persons, and individuals with respiratory diseases are also particularly sensitive. Carbon monoxide can affect healthy individuals, impairing exercise capacity, visual perception, manual dexterity, learning functions, and ability to perform complex tasks.

Several recent epidemiological studies have shown a link between CO and premature morbidity (including angina, congestive heart failure, and other cardiovascular diseases. Several studies in the United States and Canada have also reported an association of ambient CO exposures with frequency of cardiovascular hospital admissions, especially for congestive heart failure (CHF). An association of ambient CO exposure with mortality has also been reported in epidemiological studies, though not as consistently or specifically as with CHF admissions. EPA reviewed these studies as part of the Criteria Document review process.[29] There is emerging evidence suggesting that CO is linked with asthma exacerbations.

2.4.3 CO Nonattainment

The current primary NAAQS for CO are 35 parts per million for the one-hour average and 9 parts per million for the eight-hour average. These values are not to be exceeded more than once per year. Air quality carbon monoxide value is estimated using EPA guidance for calculating design values. In 1999, 30.5 million people (1990 census) lived in 17 areas designated nonattainment under the CO NAAQS.[30]

Nationally, significant progress has been made over the last decade to reduce CO emissions and ambient CO concentrations. Total CO emissions from all sources have decreased 16 percent from 1989 to 1998, and ambient CO concentrations decreased by 39 percent. During that time, while the mobile source CO contribution of the inventory remained steady at about 77 percent, the highway portion decreased from 62 percent of total CO emissions to 56 percent while the nonroad portion increased from 17 percent to 22 percent.[31] Over the next decade, we would expect there to be a minor decreasing trend from the highway segment due primarily to the more stringent standards for certain light-duty trucks.[32] CO standards for passenger cars and other light-duty trucks and heavy-duty vehicles did not change as a result of other recent rulemakings.

2.5 Visibility Degradation

2.5.1 General Background

Visibility can be defined as the degree to which the atmosphere is transparent to visible light.[33] Visibility impairment has been considered the "best understood and most easily measured effect of air pollution."[34] Visibility degradation is often directly proportional to decreases in light transmittal in the atmosphere. Scattering and absorption by both gases and particles decrease light transmittance. It is an easily noticeable effect of fine PM present in the atmosphere, and fine PM is the major cause of reduced visibility in parts of the United States, including many of our national parks and in places where people live, work, and recreate. Fine particles with significant light-extinction efficiencies include organic matter, sulfates, nitrates, elemental carbon (soot), and soil. The engines subject to this rule contribute to visibility degradation through their contribution to the national PM inventory.

Visibility is an important effect because it has direct significance to people's enjoyment of daily activities in all parts of the country. Individuals value good visibility for the well-being it provides them directly, both where they live and work and in places where they enjoy recreational opportunities. Visibility is highly valued in significant natural areas such as national parks and wilderness areas because of the special emphasis given to protecting these lands now and for future generations. Visibility can be described in terms of visual range, light extinction or deciview.[b]

In addition to limiting the distance that one can see, the scattering and absorption of light caused by air pollution can also degrade the color, clarity, and contrast of scenes. Visibility impairment also has a temporal dimension in that impairment might relate to a short-term excursion or to longer periods (e.g., worst 20 percent of days or annual average levels). More detailed discussions of visibility effects are contained in the EPA Criteria Document for PM.

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[b] Visual range can be defined as the maximum distance at which one can identify a black object against the horizon sky. It is typically described in miles or kilometers. Light extinction is the sum of light scattering and absorption by particles and gases in the atmosphere. It is typically expressed in terms of inverse megameters (Mm^{-1}), with larger values representing worse visibility. The deciview metric describes perceived visual changes in a linear fashion over its entire range, analogous to the decibel scale for sound. A deciview of 0 represents pristine conditions. Under many scenic conditions, a change of 1 deciview is considered perceptible by the average person.

Visibility effects are manifest in two principal ways: (1) as local impairment (e.g., localized hazes and plumes) and (2) as regional haze. The emissions from engines covered by this rule contribute to both types of visibility impairment.

Local-scale visibility degradation is commonly in the form of either a plume resulting from the emissions of a specific source or small group of sources, or it is in the form of a localized haze such as an urban “brown cloud.” Plumes are comprised of smoke, dust, or colored gas that obscure the sky or horizon relatively near sources. Impairment caused by a specific source or small group of sources has been generally termed as “reasonably attributable.”

The second type of impairment, regional haze, results from pollutant emissions from a multitude of sources located across a broad geographic region. It impairs visibility in every direction over a large area, in some cases over multi-state regions. Regional haze masks objects on the horizon and reduces the contrast of nearby objects. The formation, extent, and intensity of regional haze is a function of meteorological and chemical processes, which sometimes cause fine particulate loadings to remain suspended in the atmosphere for several days and to be transported hundreds of kilometers from their sources.[35]

On an annual average basis, the concentrations of non-anthropogenic fine PM are generally small when compared with concentrations of fine particles from anthropogenic sources.[36] Anthropogenic contributions account for about one-third of the average extinction coefficient in the rural West and more than 80 percent in the rural East.[37] Because of significant differences related to visibility conditions in the eastern and western U.S., we present information about visibility by region. Furthermore, it is important to note that even in those areas with relatively low concentrations of anthropogenic fine particles, such as the Colorado plateau, small increases in anthropogenic fine particle concentrations can lead to significant decreases in visual range. This is one of the reasons Class I areas have been given special consideration under the Clean Air Act.

2.5.2 Visibility Impairment Where People Live, Work and Recreate

Visibility impairment occurs in many areas throughout the country, where people live, work, and recreate, including Class I Areas. As described in Section 2.12 above, the engines covered by this rule contribute to PM2.5 levels in areas across the country with unacceptable visibility conditions.

The secondary PM NAAQS is designed to protect against adverse welfare effects such as visibility impairment. In 1997, the secondary PM NAAQS was set as equal to the primary (health-based) PM NAAQS (62 Federal Register No. 138, July 18, 1997). EPA concluded that PM can and does produce adverse effects on visibility in various locations, depending on PM concentrations and factors such as chemical composition and average relative humidity. In 1997, EPA demonstrated that visibility impairment is an important effect on public welfare and that visibility impairment is experienced throughout the U.S., in multi-state regions, urban areas, and remote Federal Class I areas.

EPA recently finalized a finding that nonroad engines contribute significantly to adverse visibility effects (67 FR 68251, November 8, 2002). Category 3 engines contribute to these effects. They are estimated to emit 54 tons of direct PM in 2030, which is 7.3 percent of total mobile source anthropogenic PM emissions. They also contribute to visibility degradation through their NOx and HC emissions.

References for Chapter 2

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5.Letter from Bruce J. Carlton, Acting Deputy Maritime Administrator, U.S. Department of Transportation, Maritime Administration to Jeffrey R. Holmstead, U.S. EPA, August 29, 2002. Air Docket A-2001-11, item IV-G-04.

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9.U.S. EPA, 1996, Air Quality Criteria for Ozone and Related Photochemical Oxidants, EPA/600/P-93/004aF. The document is available on the internet at http://www.epa.gov/ncea/ozone.htm. A copy can also be obtained from Air Docket No. A-99-06, Document Nos. II-A-15, II-A-16, II-A-17.

10.Air Quality Criteria Document for Ozone and Related Photochemical Oxidants, EPA National Center for Environmental Assessment, July 1996, Report No. EPA/600/P-93/004cF. The document is available on the internet at http://www.epa.gov/ncea/ozone.htm. A copy can also be obtained from Air Docket No. A-99-06, Documents Nos. II-A-15, II-A-16, II-A-17.

11.Memorandum to Docket A-2001-11 from Fred Dimmick, Group Leader, Air Trends Group, “Summary of Currently Available Air Quality Data and Ambient Concentrations for Ozone and Particulate Matter,” January 7, 2003, Air Docket A-2001-11, Document No. IV-B-05.

12.Memorandum to Docket A-2001-11 from Fred Dimmick, Group Leader, Air Trends Group, "Summary of Currently Available Air Quality Data and Ambient Concentrations for Ozone and Particulate Matter," January 7, 2003, Air Docket A-2001-11, Document No. IV-B-05.

13.National Air Quality and Emissions Trends Report, 1998, March, 2000, at 28. This document is available at http://www.epa.gov/oar/aqtrnd98/. Relevant pages of this report can be found in Memorandum to Air Docket A-2000-01 from Jean Marie Revelt, September 5, 2001, Document No. II-A-63.

14.U.S. EPA, 1995, Review of National Ambient Air Quality Standards for Nitrogen Dioxide, Assessment of Scientific and Technical Information, OAQPS Staff Paper, EPA-452/R-95-005.

15.U.S.EPA, 1993, Air Quality Criteria for Oxides of Nitrogen, EPA/600/8-91/049aF.

16.Much of the information in this subsection was excerpted from the EPA document, *Human Health Benefits from Sulfate Reduction*, written under Title IV of the 1990 Clean Air Act Amendments, U.S. EPA, Office of Air and Radiation, Acid Rain Division, Washington, DC 20460, November 1995. Air Docket A-2000-01, Document No. II-A-32.

17.Vitousek, Peter M., John Aber, Robert W. Howarth, Gene E. Likens, et al. 1997. Human Alteration of the Global Nitrogen Cycle: Causes and Consequences. *Issues in Ecology*. Published by Ecological Society of America, Number 1, Spring 1997.

18. National Research Council, 1993. Protecting Visibility in National Parks and Wilderness Areas. National Academy of Sciences Committee on Haze in National Parks and Wilderness Areas. National Academy Press, Washington, DC. This document is available on the internet at http://www.nap.edu/books/0309048443/html/.

19.Much of this information was taken from the following EPA document: *Deposition of Air Pollutants to the Great Waters-Second Report to Congress*, Office of Air Quality Planning and Standards, June 1997, EPA453-R-97-011.

20.Terrestrial nitrogen deposition can act as a fertilizer. In some agricultural areas, this effect can be beneficial.

21.EPA (1996) Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information OAQPS Staff Paper. EPA452-R-96-013. Docket Number A-2001-11, Document No. II-A-52. The particulate matter air quality criteria documents are also available at http://www.epa.gov/ncea/partmatt.htm.

22.Memorandum to Docket A-2001-11 from Fred Dimmick, Group Leader, Air Trends Group, "Summary of Currently Available Air Quality Data and Ambient Concentrations for Ozone and Particulate Matter," January 7, 2003, Air Docket A-2001-11, Document No. IV-B-05.

23.See the Final Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements, Document EPA420-R-00-026, December 2000. Docket A-2000-01, Document No. II-A-13. This document is also available at http://www.epa.gov/otaq/diesel.htm#documents.

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32.The more stringent standards refer to light light-duty trucks greater than 3750 pounds loaded vehicle weight, up through 6000 pounds gross vehicle weight rating (also known as LDT2).

33.Old endnote 36.

34.Old endnote 37.

35. National Research Council, 1993 (Ibid).

36.National Research Council, 1993 (Ibid).

37. National Acid Precipitation Assessment Program (NAPAP), 1991. Office of the Director. Acid Deposition: State of Science and Technology. Report 24, Visibility: Existing and Historical Conditions - Causes and Effects. Washington, DC. Cited in US EPA, Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information. OAQPS Staff Paper. EPA452-R-96-013. This document is available in Docket A-99-06, Document II-A-23. Also, US EPA. Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information, OAQPS Staff Paper. Preliminary Draft. June 2001. Docket A-2000-01, Document IV-A-199.

CHAPTER 3: Industry Characterization

To help assess the potential impact of this emission-control program, it is important to understand the nature of affected industries. This chapter describes the Category 3 marine diesel engine and vessel industries. The picture that emerges is one of a fairly concentrated market, with only four companies producing over 75 percent of all Category 3 marine diesel engines worldwide and shipyards in only three countries producing over 60 percent of all vessels that use these engines. Through Caterpillar's acquisition of MaK, the United States now has a presence in the C3 marine diesel engine market, although no engines are currently produced in the United States. The U.S. share of the world market of vessel construction, however, is very small. This is mainly due to the shipyard subsidy policies of other governments. Because the United States does not provide similar subsidies most, if not all, of U.S. ship production is vessels required under the Jones Act to be built in the United States.

This chapter concludes with a brief profile of the vessels that enter U.S. ports. Analysis of national port entrance data indicates that the vast majority of Category 3 vessels that enter U.S. ports are flagged or registered in other countries. We do not attempt to perform this analysis on a port-specific basis. However, given the small number of U.S. vessels in comparison with the world fleet, it is likely that the contribution of U.S. vessels with Category 3 engines to local air pollution in any given port is likely to be small compared with that of foreign vessels.

It should be noted from the outset that it is difficult to obtain reliable data on engine construction, vessel construction, fleet size, and port activity levels. While there are several sources available through various government agencies (e.g., Coast Guard, the Maritime Administration) and industry groups, the data they provide are often inconsistent or incomplete. There are also differences in what these groups count and how they count it. Therefore, the numbers contained in this chapter should be interpreted as approximations and not as definitive counts. However, because of the differences in magnitude between U.S. and foreign manufacture of engines, vessels, and fleet sizes, the observations we make about these sectors remain valid.

We provided an industry characterization for Category 1 and Category 2 marine diesel engines in the Final Regulatory Impact Analysis document for our 1999 rule.[1]

3.1 Description of Category 3 Marine Engines

For large ocean-going vessels, it is common for the ship to have multiple engines. The primary purpose of the engines is to provide propulsive power to propel the vessel. Engines are also required to generate electrical power to be used for auxiliary purposes such as navigation equipment, maneuvering equipment, and crew services. Marine engines have traditionally been diesel- or steam-powered engines. Since 1980, virtually all large marine engines built have been diesel.

EPA defines Category 3 marine engines as compression-ignition (i.e., diesel) engines with a displacement greater than or equal to 30 liters per cylinder. Steam engines are not considered Category 3 engines. Category 3 engines can be incredibly large. These engines are equipped with anywhere between four to 14 cylinders with displacement ranging from 30 liters per cylinder up to 2000 liters per cylinder and output between 2,000 kW to over 100,000 kW. There are two common types of Category 3 engines: "low-speed" (e.g., engine speed of 150 rpm or less) and "medium-speed" (e.g., engine speed of approximately 300 rpm). Low-speed engines are two-stroke models which are connected to a direct drive propulsion system. The medium-speed engines are typically four-stroke engines (a very small percentage are two-cycle). These engines are commonly connected to an electric drive propulsion system. The electric drive system is actually a large electrical generator that can also be used to generate auxiliary power as well drive the propulsion system.

Another important characteristic of Category 3 diesel engines is that they generally operate on a very low-grade petroleum-based fuel called "bunker" or "residual" fuel. This fuel is the remnant fuel left over from the refinery process of making gasoline, diesel, and other petroleum fuels. It is inexpensive and contains high levels of sulfur and nitrogen. Because of its high level of paraffins, bunker fuel is solid at ambient temperature. Therefore, the fuel has to be heated in order for it to become a liquid which can be combusted in the engine. As a result, vessels using Category 3 engines are equipped with elaborate fuel storage and handling systems. This is described in greater detail in Section 8.1.2 of Chapter 8.

There is usually a distinction between the engines used for propulsion and the engines used to generate electrical power for navigation equipment (radar, gyrocompass, telecommunications), maneuvering equipment (steering gear, bow thrusters) and crew services (lighting & cooking). The engines used to generate electrical power are typically Category 2 diesel engines (5-30 liters per cylinder). Some vessels, such as refrigerated cargo vessels ("reefers") may require Category 3 engines to meet electric power requirements. Examples of this are the Dole Columbia and Dole Chile which are equipped with MaK M32 engines (39 liters per cylinder) as generators.[2] Cruise ships often employ diesel-electric engines, discussed above, that provide both propulsion and power generation. In addition to propulsion and electric power engines, an auxiliary engine is typically installed for emergency use.

Category 3 marine diesel engines are unique among engines in the sense that they are very large and are not typically mass-produced. They also come in a broad configuration of models: varying number of cylinders, engine displacement, power output, and engine speed. Because there are so many different vessel applications and such a large selection of available engine configurations, the engine selection is a major design consideration in the overall design of a vessel. As a result, the engine selected for a specific vessel is often a unique design or configuration that is built specifically for that vessel.

Once a vessel manufacturer has determined the size and output of the engine necessary for a particular vessel design, the engine manufacturer develops the engine on a test bed. After engine development is completed, the engine is assembled and tested. The tests consists of making sure the engine starts and operates properly. Certification testing to demonstrate compliance with the MARPOL Annex VI NOx limits may also occur at this time. The engine is disassembled and shipped to the shipyard where the vessel is to be built. The shipyard or an approved licensed assembler reassembles the engine and fits it into the vessel and connects it the propulsion system. This is typically done with engine manufacturer supervision.

Once the vessel is complete, the shipyard will typically perform a series of three more engine tests. The first is referred to as "light-off," which is when the engine is started for the first time in the vessel. The second engine test is dock testing, where the engine is operated in dock to make sure that all systems are operational. The third test is sea testing, where the vessel is taken out on it's "maiden voyage."

3.2 Category 3 Marine Engine Manufacturers

3.2.1 Companies That Make Category 3 Marine Engines

Category 3 engine manufacturers are generally large, multi-national, diversified companies which also produce smaller marine engines, marine propulsion and marine electric generation equipment. In addition, these companies produce engines for other uses such as locomotives and power plants. Many have divisions which manufacture vessels and operate shipyards.

We have identified 16 companies that manufacture Category 3 marine diesel engines. Four large companies (MAN B&W Diesel, Wartsila/New Sulzer, Catepillar/MaK, and Mitsubishi) dominate the sales of Category 3 engines. These four companies account for nearly 75 percent of medium-speed engine sales and 100 percent of low- speed engine sales. The remaining 25 percent of medium-speed engine sales are distributed among the other 12 engine manufacturers.

Category 3 diesel engine manufacturers are located primarily in Europe and Japan. Only one engine company (Caterpillar) which manufactures Category 3 diesel engines is headquartered in the United States. Caterpillar recently purchased MaK located in Kiel, Germany. However, Caterpillar does not manufacture any Category 3 diesel engines in the United States. Therefore, there are no Category 3 engines manufactured in the United States.

Table 3.2-1 is a list of engine manufacturers which produce Category 3 engines. This list was compiled from the *Directory of Marine Diesel Engines*.[3]

Table 3.2-1 Current Worldwide Manufacturers of Category 3 Marine Diesel Engines

Akasaka Diesels	Mitsubishi Heavy Industries Ltd
Caterpillar Motoren GmbH & Co., KG	Mitsui Engineering & Shipbuilding Co. Ltd
Daihatsu Diesel Mfg. Co., Ltd.	Niigata Engineering Co Ltd, Japan
Fincantieri Diesel	Rolls-Royce
Hanshin Diesel Works Ltd	SEMT Pielstick
Makita Corp	SKL Motoren-und Systemtechnik GmbH
MAN B&W Diesel	Wärtsilä/New Sulzer
Matsui Iron Works Co.,Ltd.	Yanmar Diesel Engine Co., Ltd

3.2.2 Production of Category 3 Marine Engines

Shipbuilding is a multi-year process, therefore the number of engines produced per year is not generally tracked by the shipping industry. The number of engines "produced" in a given year is reported as the number of engine installations on vessels which are delivered in that year. This number reflects the number of engines installed for propulsion power, not electric generating or auxiliary power.

Due to the size and complexity of the engine manufacturing companies, it is difficult to obtain sales and production data for individual engine models or classes. Most companies which were researched only report annual income at the division level. It is not appropriate to compare these sales data since the types of activities and structure of a given division vary greatly between companies. In addition, many of the engines provided by these manufacturing companies are used for other applications other than marine propulsion and power, such as locomotive and land-based electric power generation.

We estimated the number of propulsion engines installed annually by each manufacturer based on information in Motorship's *Annual Analysis* publication for 1998.[4] The *Annual Analysis* data are based on a survey of ships with dead weight tonnage (DWT) greater than 2,000 that were delivered in that year. These data are presented in Table 3.2-2. The analysis gives the number of engines installed on all vessels by manufacturer. Note that several of the companies are now owned or controlled by other manufactures including Sulzer (Wärtsilä), Bergen (Rolls Royce), MaK (Caterpillar), Rushton (MAN B&W). Table 3.2-3 indicates that for 1998, approximately 765 low-speed engines and 497 medium-speed engines were produced for a total of 1,262 Category 3 engines worldwide.

Table 3.2-2
Summary of Worldwide Category 3 Engine Manufacturer Production for Vessels of >2,000 DWT in 1998

LOW-SPEED ENGINES			MEDIUM-SPEED ENGINES		
Manufacturer	**Engines**	**Percent of Total**	**Manufacturer**	**Engines**	**Percent of Total**
MAN B&W	515	67.3%	Wärtsilä	135	27.2%
Sulzer	150	19.6%	MAN B&W	92	18.5%
Mitsubishi	100	13.1%	MaK	75	15.1%
			Caterpillar	32	6.4%
			Sulzer	24	4.8%
			Bergen	21	4.2%
			Deutz MWM	20	4.0%
			GMT	19	3.8%
			Ruston	15	3.0%
			Hanshin	13	2.6%
			MTU	9	1.8%
			Niigata	9	1.8%
			Yanmar	7	1.4%
			Pielstick	6	1.2%
			Akasaka	6	1.2%
			Unknown	5	1.0%
			SKL	4	0.8%
			Daihatsu	3	0.6%
			Russki	2	0.4%
Total	765		Total	497	0.4%

Source: Motorship, *Annual Analysis*

Table 3.2-3
Top 10 Licensees of Category 3 Engines for Years 1999 and 2000

Yard Nationality	**Licensee**	**Manufacturer**	**No of Engines**
	1999		
JAPAN	Mitsui Engineering & Shipbuilding Co Ltd	MAN B&W DIESEL A/S	117
S. KOREA	Hyundai Heavy Industries Co	MAN B&W DIESEL A/S	93
JAPAN	Kawasaki Heavy Industries Ltd	MAN B&W DIESEL A/S	45
JAPAN	DIESEL UNITED	SULZER	45
JAPAN	Hitachi Zosen Corp	MAN B&W DIESEL A/S	31
S. KOREA	Sasung Heavy Industries Co	MAN B&W DIESEL A/S	28
NORWAY	WÄRTSILÄ FINLAND	WÄRTSILÄ	26
S. KOREA	Korea Heavy Industries & Construction Co	MAN B&W DIESEL A/S	25
FINLAND	WÄRTSILÄ FINLAND	WÄRTSILÄ	23
CHINA	Hudong Heavy Machinery Co	MAN B&W DIESEL A/S	19
	2000		
JAPAN	Mitsui Engineering & Shipbuilding Co Ltd	MAN B&W DIESEL A/S	107
S. KOREA	Hyundai Heavy Industries Co	MAN B&W DIESEL A/S	101
JAPAN	Kawasaki Heavy Industries Ltd	MAN B&W DIESEL A/S	48
JAPAN	DIESEL UNITED	SULZER	43
JAPAN	Hitachi Zosen Corp	MAN B&W DIESEL A/S	42
ITALY	WÄRTSILÄ FINLAND	WÄRTSILÄ	33
S. KOREA	Hyundai Heavy Industries Co	SULZER	28
CHINA	WÄRTSILÄ FINLAND	WÄRTSILÄ	26
JAPAN	HANSHIN	HANSHIN	24
GERMANY	MaK	MaK	22

Source: Motorship, *Annual Analysis*

3.2.3 Relationship Among Worldwide Engine Manufacturers

Engine manufacturing companies are often involved with financial and design agreements with other engine manufacturers. The types of associations included component manufacturing licensing agreements, engine licensing agreements, controlling stock ownership of other companies, and acquisitions. The following acquisitions occurred in recent years: Rolls Royce acquired Bergen, Wärtsilä acquired Sulzer, Caterpillar acquired MaK, MAN B&W acquired Alstom (Mirrlees Blackstone and Ruston).

Licensing agreements also exist between the manufacturers and the shipyards. These licensing agreements generally are for a model design. Engines are vessel-specific and are field erected during installation on a vessel. The shipyard typically assembles the engine within the vessel at the shipyard per the engine manufacturers instructions.

Licensee information was also reported in the Motorship database. We compiled a list of the licensees based on the manufacturer, the location and the number of engines installed for years 1999 and 2000. This information is presented in Table 3.2-3 for the top 10 licensees. Notice that the top five licensees are the same for both years.

3.3 Vessel Manufacturers

This section gives a general characterization of the large-vessel manufacturing segment of the marine industry that may be impacted by this final rule. This industry characterization was developed in part under contract with ICF Consulting[5] as well as independent analyses conducted by EPA through interaction with the industry and other sources.

3.3.1 United States Vessel Manufacturers

3.3.1.1 Description of Vessels

This section characterizes U.S. manufacturers of large commercial vessels equipped with Category 3 engines. These vessels engage in waterborne trade and/or passenger transport and typically exceed 400 feet in length and/or weigh more than 2,000 gross tons. The U.S. Department of Transportation Maritime Administration (MARAD) identifies a major shipbuilder as one that is capable of producing a ship of 400 feet in length or greater. Commercial vessels operate in the Great Lakes, coastwise, intercoastal, and/or transoceanic routes. The principal commercial vessel types are auto carriers, bulk carriers, container ships, general cargo ships, refrigerator ships, roll-on/roll-off (ro ro), tankers, and passenger ships. Passenger ships include cruise ships and large ferries.

3.3.1.2 Production of Large Vessels Equipped with Category 3 Marine Diesel Engines

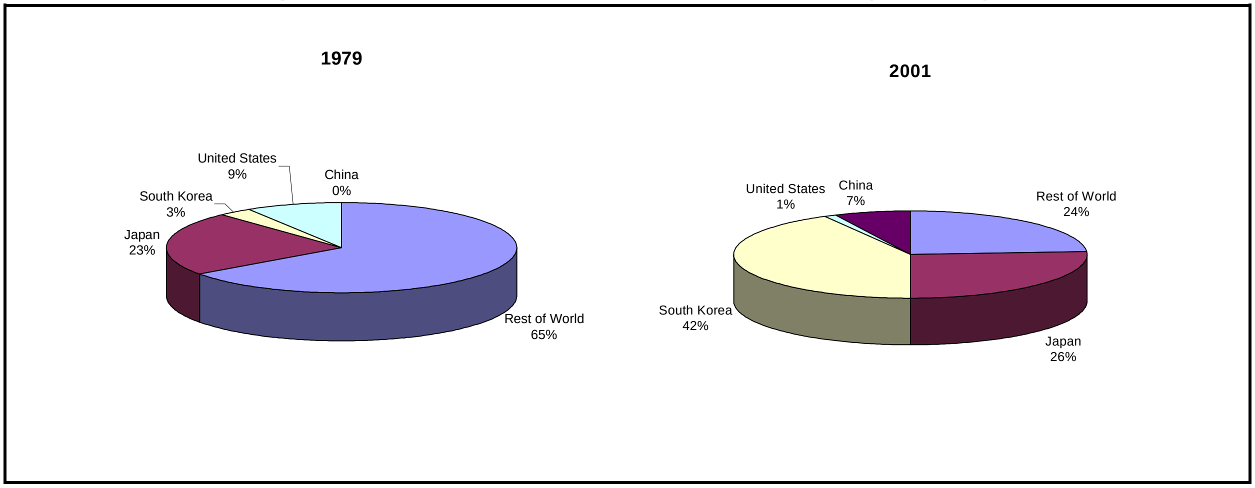
The process of designing and building a large vessel is long and complicated. The whole process takes approximately 32 to 36 months. Once a fleet owner decides to build a new ship, they work with a shipyard and engine manufacturer to design the ship. The design process is the most time consuming part of the shipbuilding process and can take up to 18 months. In the early stages of the design process, the owner works with ship architects and classification societies that ensure that the design and materials to be used for the vessel meet appropriate performance and safety specifications. An example of a U.S. classification society is the American Bureau of Shipbuilding (ABS). It is also during the design process that the owner and architects decide what engines to use. In determining the appropriate propulsion engine for the specific vessel design, they consider engine type (e.g., medium- or slow-speed), engine size, and power output to name a few. Once a design has been approved and completed, the actual construction of the vessel begins. This process takes place at a shipyard and can take between 12 and 14 months.

3.3.1.3 Background of the U.S. Shipbuilding Industry and Global Competition

Shipbuilding has historically been an important industry in the United States. However, according to the American Shipbuilding Association (ASA), the U.S. shipbuilding industry has been contracting since 1980. In 1981, there were 22 shipyards holding ship construction contracts for the government, commercial customers, or both. By 2001, the number of active new construction shipyards building large oceangoing vessels fell to three.

The vast majority of commercial ships used throughout the world are built in other countries. A major shift in shipbuilding market share began in the 1960s with Japan's entry into the market. South Korea entered the market in the1970s, and China entered in 1980. Few ships have been built in the U.S. since the boom years in the mid 1970's through the mid 1980's. Between 1987 to 1989, no commercial ships were built at U.S. shipyards. Since 1990, approximately 19 large commercial ships that use Category 3 engines have been built in the U.S., for an average of 1.9 ships per year. The ASA believes that the collapse of commercial shipbuilding in the United States was largely due to the elimination of the Construction Differential Subsidy Program (CDS) in 1981. The CDS program, established in 1936 and administered by MARAD, provided for a subsidy of up to 50 percent of the construction cost of a commercial vessel built in the United States to offset the lower foreign construction costs. The subsidy was only available for those ships built in the United States that were to be registered under the laws of the United States, and operated in the international trades. The United States was the only shipbuilding country in the world to eliminate its subsidies as Asia and Europe dramatically increased subsidies to their industries. As a result, the U.S. lost its international commercial market share, which was at nine percent. U.S. commercial business is today comprised of construction of ships to serve our domestic coastwise trade. This market accounts for about one percent of the worldwide commercial market. Figure 3.3-1 illustrates the change in the distribution of the world's commercial shipbuilding tonnage.

Figure 3.3-1: World Commercial Shipbuilding Tonnage



A moderate resurgence in U.S. commercial orders began in 1995 as a result of demand for replacement tonnage for the U.S. domestic coastwise trade, known as Jones Act Vessels (which requires ships transporting cargo between two U.S. points to be U.S. built, owned and crewed; see below) and the revitalization of the Title XI Ship Loan Guarantee Program (a government ship loan guarantee program administered by MARAD).

Both commercial and naval shipbuilding are cyclical. This mix of commercial and military shipbuilding orders has been the cornerstone of the shipbuilding industrial base in the United States. Between 1955 and 1985, U.S. shipbuilders delivered an average of 20 commercial ships per year for both domestic and international trades. Between the same period, the U.S. Navy ordered an average of 19 ships per year.

Table 3.3-1 presents the delivery of merchant and military vessels from U.S. shipyards over the ten year period between 1990 and 2000 according to the Colton company.[6]

Table 3.3-1
Deliveries from U.S. Shipyards, 1990 to 2000
(Merchant ships over 1000 Gross Tons and Naval ships over 1000 LT)

	Merchant (No. of ships)	Merchant (1000GT)	Naval (No. of ships)	Naval (1000LT)
1990	0	0	14	102
1991	0	0	14	100
1992	3	45	18	218
1993	0	0	18	129
1994	1	17	15	158
1995	1	2	17	221
1996	1	28	11	92
1997	4	107	11	186
1998	2	24	11	251
1999	6	161	5	90
2000	1	7	8	134

Source: The Colton Company

3.3.1.4 Cabotage Laws in the United States: The Jones Act and the Passenger Vessel Services Act

The term “cabotage,” (derived from the French “caboter,” meaning to sail coast-wise, or literally, “by the capes”) refers to a body of maritime law dealing with the right to conduct trade or transport goods in coastal waters or between two points within a country. These laws, common in some form in more than 40 nations with significant ocean-going fleets, are designed to ensure a strong national merchant marine fleet for defense, employment, and general economic purposes by reserving a country’s domestic maritime transportation for its own citizens. Cabotage laws are designed to guarantee the participation of a country’s citizens in its own domestic trade. These laws foster the development of a merchant marine and give preference to local labor and industry. They also support national security and protect the domestic economy.

Cabotage laws in the U.S. date back to 1789, when Congress first restricted participation in coastal trades and fisheries to U.S.-built and U.S.-owned vessels and gave these vessels preferential treatment regarding taxes and import duties. Currently, U.S. maritime cabotage laws include a number of different statutes that govern the transportation of cargo and passengers between two points in the U.S. (including its territories and possessions), as well as all dredging, towing, salvage, and other marine operations and fishing. Two major enactments, The Merchant Marine Act of 1920 (46 U.S.C. 861) and the Passenger Vessel Services Act of 1886 (46 U.S.C. 289), in combination provide the majority of U.S. cabotage provisions related to the transport of cargo or passengers. Variations of these laws exist today in the U.S. transportation, communications, and utility industries.

Section 27 of the Merchant Marine Act of 1920 (46 U.S.C. 883; 19 CFR 4.80 and 4.80b), popularly known as the “Jones Act,” essentially requires that domestic waterborne commerce between two points within the U.S. and subject to coastwise laws must be transported in vessels built in the U.S., documented under the laws of the U.S. (i.e., registered under the American flag), and crewed and owned by U.S. citizens. The Passenger Vessel Services Act sets essentially the same standards for passenger vessels as the Merchant Marine Act sets for cargo vessels. Specifically, the primary requirements of the Jones Act state that:

- No merchandise may be transported by water between points in the U.S., either directly or via a foreign port, unless the transporting vessel is built in the U.S., documented under the laws of the U.S., and owned by U.S. citizens.
- A foreign vessel can pick up or deliver cargo at a U.S. port, but it can’t pick up cargo in one U.S. port and deliver the same cargo to another U.S. port, even if the vessel stops at a foreign port in the mean time.
- Vessels over 200 gross tons with domestic U.S. trading privileges that are sold to foreign owners or registered under a foreign flag may return to being U.S.-flagged, but the vessel’s domestic U.S. trading privileges are forever forfeited.
- Vessels with domestic U.S. trading privileges which are rebuilt may only retain those privileges if the entire rebuilding is performed within the U.S.

In addition, Congress included some exceptions to the requirements of the Jones Act to deal with special circumstances. These provisions include service on the Yukon River, established ferry services owned by railroad companies, transport of empty cargo accessory equipment, transfers of cargo between barges of the same owner, and transport of fish processing supplies. The provisions of the U.S. cabotage laws may be waived administratively by the Treasury Department only in the interest of national defense. The only other way in which the provisions may be waived and a non-qualifying vessel granted domestic trading privileges is via Congressional action.

The Jones Act fleet, or those vessels engaged in or otherwise authorized to be engaged in U.S. domestic commerce, is a subset of the fleet of U.S. vessels. In other words, all Jones Act vessels are U.S.-flagged, but not all U.S.-flagged vessels are necessarily endorsed to engage in domestic commerce. For example, as noted above, a formerly U.S.-flagged vessel could, after a period of being registered under a foreign flag, return to being U.S.-flagged, but that vessel will never be able to engage in U.S. domestic shipping.

There are tens of thousands of Jones Act vessels that operate in three major sectors of U.S. domestic shipping: the Great Lakes, the inland waterways, and the domestic ocean trades (along the coasts or non-contiguous trade between the U.S. mainland and Puerto Rico, Alaska, Hawaii, and other U.S. Pacific islands). The vast majority of these, however, are non-self-propelled dry cargo barges and tanker barges that ply the U.S. internal waterways. As of July 1998 there were about 61 self-propelled merchant vessels of 1,000 gross registered tons with unrestricted domestic trading privileges (i.e., Jones Act vessels).[7]

3.3.1.5 U.S. Vessel Manufacturers

MARAD uses the Major Shipbuilding Base (MSB) to track the U.S. shipbuilding industry. The MSB is defined as those privately owned shipyards that are open and have at least one shipbuilding position capable of accommodating a vessel 122 meters (400 feet) in length or over (vessels of this size are generally considered by the shipbuilding industry to be very large deep-sea vessels; many of these would use Category 3 engines). The shipyard must also have in place a long-term lease on the shipbuilding facility and there must be no dimensional obstructions (i.e., locks, bridges) in the waterway leading to open water. As of January 1, 1998, utilizing this definition, there were 18 major shipbuilding facilities in the United States. However, the majority of these shipyards produce military vessels or smaller commercial vessels that do not use category 3 engines.

According to the ASA, there are eight shipyards that have built large category 3 engine-powered commercial vessels over the last several years. Only three of these shipyards are currently building vessels. Table 3.3-2 lists the eight shipyards that have most recently been involved in building large commercial vessels.

Table 3.3-2
U.S. Shipyards Building Large Commercial Vessels

Shipyard	Location
National Steel & Shipbuilding Co.	San Diego, CA
Avondale Industries, Inc.	Avondale, LA
Ingalls Shipyard	Pascagoula, MS
Newport News Shipyard	Newport news, VA
Kvaerner Philadelphia Shipyard, Inc.	Philadelphia, PA
Friede Goldman Halter	Pascagoula, MS
Alabama Shipyard, Inc.	Mobile, AL
Todd Shipyards	Seattle, WA

The three shipyards currently building large commercial vessels are National Steel & Shipbuilding Co., Avondale Industries, Inc., and Ingalls Shipyard. A fourth shipyard, Kvaerner Philadelphia Shipyard, Inc. had a long history of producing large oceangoing vessels, primarily for the Navy, but was closed in 1996. In 1997, Kvaerner signed an agreement with the city of Philadelphia and the state of Pennsylvania to re-open the shipyard. While the shipyard is still sorting out who the owner will be, they have stated that they plan to focus primarily on the domestic oceangoing cargo ship market. Thus, they may soon be building large ships equipped with Category 3 engines.

The 18 major shipbuilding facilities tracked by the MSB employ about 65 percent of the workforce engaged in shipbuilding and/or boatbuilding (SIC 3731). About 43 percent of the workforce at MSB yards is engaged in military ship construction and repair work. The largest six shipyards (known as the “big six”) account for over 90 percent of commercial shipbuilding dollars in the United States and over 98 percent of the U.S. Navy’s shipbuilding budget.[8] Table 3.3-3 presents the employment and sales for the largest U.S. shipyards still active (or with capacity) to build large commercial vessels by yard. Table 3.3-4 presents similar information related to the parent companies.

Table 3.3-3 Employment and Sales for the Largest U.S. Shipyards Active (or With Capacity) in Building Large Commercial Vessels

Shipyard	Shipyard Total Employment	Shipyard Total Sales (millions $)	Comments
National Steel & Shipbuilding Co.	5,000	$500	currently engaged in commercial shipbuilding; about half of employment and sales is commercial shipbuilding and repair
Avondale Industries, Inc.	5,000	$625	currently engaged in commercial shipbuilding
Ingalls Shipyard	10,000	$1,300	currently engaged in commercial shipbuilding
Newport News Shipyard	18,000	$1,800	In 2000 ended its commercial shipbuilding practice, but has capacity
Kvaerner Philadelphia Shipyard, Inc.	n/a	n/a	Employment available for parent company only
Friede Goldman Halter	n/a	n/a	Filed for bankruptcy April 2001
Alabama Shipyard, Inc.	n/a	n/a	Has commercial capability, but focuses on military construction
Todd Shipyards, Seattle	500-1,000	n/a	Has commercial capability, but focuses on ferry construction

Table 3.3-4 Employment and Sales for the Parent Companies of Largest U.S. Shipyards Active (or With Capacity) in Building Large Commercial Vessels

Parent Company	Shipyard(s)	Parent Company Total Employment	Parent Company Total Sales (millions $)
General Dynamics	National Steel & Shipbuilding Co., Bath Iron Works, and Electric Boat	33,000	$12,000
Northrop Grumman	Avondale Industries, Inc., Ingalls Shipyard, and Newport News Shipbuilding	100,000	$18,000
Kvaerner-Aker	Kvaerner Philadelphia Shipyard, Inc.	40,000	$6,000
Friede Goldman Halter	Halter Marine	n/a*	n/a*
Atlantic Marine	Alabama Shipyard, Inc.	n/a	n/a
Todd Shipyards	Todd Shipyards, Seattle	500 - 1,000	n/a

*Filed for bankruptcy April 2001

3.3.1.6 Shipping Outlook

According to the ASA, two factors creating near-term commercial markets for U.S. shipbuilding are the Jones Act, which requires ships transporting cargo between two U.S. points to be U.S. built, owned and crewed, and the Oil Pollution Act of 1990 (OPA 90), which requires all oil tankers calling in U.S. waters by the year 2015 to be equipped with double hulls.[2]

According to MARAD, shipbuilding analysts expect a significant rise in new orders for commercial ships. This increase in new orders emanates from projections of high growth in the seaborne trade for oil and dry bulk cargoes, as well as the continued demand for replacement ships due to the aging of the world fleet. The average age of the world fleet was 19 years at the end of 2000. Projected total new worldwide demand for new tonnage between 1998-2010 will be approximately 339.0 million DWT.[7] Another estimate is that worldwide new construction demand over the 10 year period 2001-2010 may be 230 million DWT, according to Drewery Shipping.[9] Prior to September 2001, ASA believed that another commercial market opportunity for U.S. shipbuilders was construction of large oceangoing cruise ships for U.S. domestic trade as the demand for U.S. coastal cruises grows.[2] In addition, the ASA projected demand over the next 10 years for 30 dry cargo ships.[10]

Worldwide shipyards are seeing and will continue to see an influx of orders for double hulled tankers, as a result of the requirements of enactment OPA-90. OPA-90 requires that by the year 2015 all tankers entering U.S. ports must be double-hull. According to ASA, since enactment of OPA-90, U.S. shipyards have built 10 double-hulled tankers with options for two more. United

States shipbuilders anticipate orders for over 40 double hulled tankers over the next 10 years. Recently, ASA projected demand over the next 10 years for 25 40,000-DWT double-hulled tankers.[11] Other analysts are less optimistic, estimating that the commercial shipbuilding industry overall is over capacity by as much as 30 percent due to distortions from foreign subsidies.[12]

3.3.2 International Vessel Manufacturers

There are just over 22 countries that build large Category 3 engine-powered commercial vessels. In 1998, 1,080 commercial ships with a dead weight tonnage (DWT) of over 2,000 were built worldwide, including U.S. production. Over 60 percent of those ships were built by three countries: Japan, South Korea, and China. Germany and Poland round out the five leading shipbuilding countries. These five countries produced over 70 percent of the large commercial vessels built in 1998.

3.4 U.S. Fleet Characterization

3.4.1 Background

There are a number of data sources that have information on the U.S. fleet. Of these sources, the MARAD's "Vessel Inventory Report" dated July, 2001 was the most reliable and comprehensive. It contains data for ocean-going, self-propelled merchant vessels of 1,000 gross tons and over that are flagged or registered in the U.S. The vessel name, ship type, engine type, the year and country in which the operator (government or private) vessel was built, gross tonnage, and DWT and whether the vessel is classified a Jones Act vessel by the U.S. are all identified in the MARAD data.

3.4.2 U.S. Fleet

Despite the cabotage laws which protect the U.S. shipping industry, the U.S. fleet has been declining in numbers of vessels and DWT since the end of World War II. The United States now ranks 17th in number of oceangoing vessels, having fallen from a top-ten ranking just a few years ago. The U.S. merchant fleet ranks 11th on a deadweight tonnage basis.[13] Today, the U.S. fleet's share of oceanborne commercial foreign trade, by weight, continues to be less than five percent.

The current estimate for the size of the U.S. fleet for vessels using Category 3 diesel engines is approximately 200 vessels. Table 3.4-1 presents the estimated number of vessels in the U.S. Fleet with Category 3 diesel engines based on the MARAD data. The table presents data for the number of privately-owned (commercial) vessels, government-owned vessels, and Jones Act vessels. There are over 25 different types of U.S. vessels that visited U.S. ports in 1999. The average age for these vessels was 22.7 years, with the oldest vessel being 95 years old.

Table 3.4-1 MARAD Summary of U.S. Fleet Vessels for Vessels ≥2,000 DWT

Total	Commercial	Government	Jones Act
200	163	37	67

3.4.3 Foreign Vessels that Enter U.S. Ports

The current estimate that 7,600 foreign vessels with Category 3 engines enter U.S. ports. There are over 25 different types of foreign vessels that visited U.S. ports in 1999. The average age for these vessels was 14 years, with the oldest vessel being 96 years old.

3.4.4 Cruise Vessels

Cruise ships are very unique vessels. They are passenger vessels designed for extended trips ranging from several days to weeks. They are quite literally floating towns. They are equipped not only with overnight rooms, similar to hotel rooms, but they can also have pools, recreational facilities, exercise clubs, restaurants, night clubs, and even casinos. The largest cruise ships can exceed 1,000 feet in length, hold up to 5,000 passengers and crew, contain over 1,600 cabins, and have up to 14 decks. There are twelve companies that account for the majority of cruise ship activity in U.S. waters. Table 3.4-2 lists these twelve companies.

Table 3.4-2 Major Cruise Ship Companies

Carnival Cruises	Princess Cruises
Celebrity Cruises	Royal Carribean International
Cunard	Europa Cruises Corporation
Holland American Line	Tropicana Cruises
International Shipping Partners	La Cruise
Norwegian Cruises	Palm Beach Casino Line

According to an EPA published Cruise Ship White Paper, the worldwide cruise ship fleet included more than 223 ships that carried an estimated 9.5 million passengers in 1998. There are no cruise ships flagged or registered in the United States. The vast majority of cruise ships that visit U.S. ports are flagged under Liberia, Panama, the Bahamas, and Norway. This EPA White Paper also stated that by 2003, cruise ship companies plan to add 33 new and/or bigger cruise ships to the market, which would increase passenger capacity by 35 percent.

According to ASA, the downturn of the U.S. economy which began in late 2000 started to take it’s toll on the U.S. tourism industry, and the September 11th attacks on the U.S. sent the cruise market into a tailspin with decreased bookings, increased cancellations, and many companies offering huge fare discounts. As a result, two smaller cruise lines, Renaissance

Cruises and American Classic Voyages have filed for Chapter 11 bankruptcy reorganization, and the financial viability of other cruise lines are threatened by the free fall in bookings and stock prices. U.S. shipbuilders began to feel the aftermath of the September 11th attacks on October 25, 2001, when Ingalls Shipbuilding announced that it had stopped work on Project America, a cruise ship program to build two 1,900-passenger cruise ships.

3.5 U.S. Port Activity

3.5.1 Background

3.5.1.1 Major U.S. Ports

According to MARAD, the top five major U.S. commercial ports, based on the total number of calls made to each port, are Los Angeles, Houston, New Orleans, New York, and San Fransico. Table 3.5-1 lists the total number of calls for each of these five ports, their world ranking, and the number of calls for the four most common ship types. This table indicates that the majority of dry goods and products entered and left the U.S. through Los Angeles, New York and San Fransico, while the majority of oil and other tanker-carried products entered and left the U.S. primarily through Houston and New Orleans.

Table 3.5-1 Top Five U.S. Commercial Ports in 2000 - Based on Calls

Port	Total Calls	World Ranking	Tankers	Dry Bulk	Containership	Other General Cargo
Los Angeles	5,326	10	911	783	2,955	677
Houston	5,129	12	2,988	748	614	779
New Orleans	5,090	13	1,371	2,676	388	655
New York	4,605	15	1,271	301	2,172	861
San Fransico	3,575	18	787	626	1,936	226

3.5.1.2 Number of Vessels Visiting U.S. Ports Each Year

According to MARAD, about 7,600 foreign vessels with Category 3 engines visited U.S. ports in 1999. When the U.S. fleet of 200 vessels is added, this means that about 97 percent of the total number of Category 3-powered vessels that made calls to U.S. ports were by foreign vessels. U.S. vessels accounted for only about three percent of the total number of vessels visiting U.S. ports. Table 3.5-2 lists U.S. vessel types for 1999 and the number of each type.

Table 3.5-2 MARAD Summary of U.S. Vessels Visiting U.S. Ports

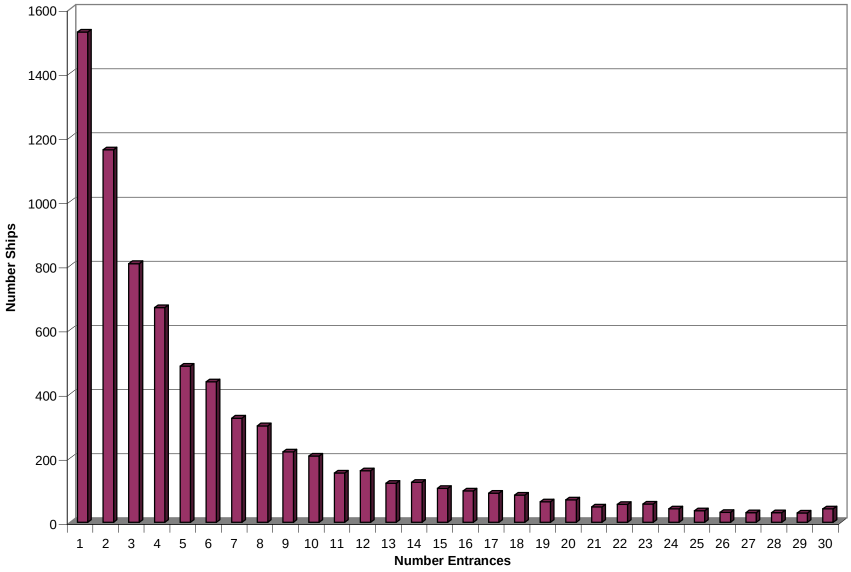
Vessel Type	Number of Vessels
Containership	59
RO/RO	41
Tanker	39
Tug Barge	15
Freighter	14
Bulk Carrier	12
Chemical Tanker	10
Combo Pass & Cargo	5
Heavy-Lift Carrier	4
Car Carrier	2
Total	200

3.5.1.3 Number of Entrances to U.S. Ports

The term “entrance” and “call” are often used interchangeably within the marine industry. An “entrance” is often defined as a vessel entering a port/waterway area. A “call” is defined as one entrance and one clearance by a vessel. Because the MARAD data set is the most comprehensive and since they list the number of entrances and not calls, we looked at entrances as a measure of how many visits were made by individual vessels. The number of entrances made into U.S. ports is overwhelmingly dominated by foreign vessels. As stated above, 7,800 vessels visited U.S. ports in 1999. These vessels made a total of 75,700 entrances to U.S. ports. Of these entrances, 67,500 or 89 percent, were made by foreign vessels. Only 8,200 entrances or 11 percent were made by U.S. vessels.

EPA analysis of MARAD data for vessel entrances into U.S. ports, indicates that a large percentage of visits made to U.S. ports are made by a relatively small percentage vessels that make many visits. For example, when looking at those vessels that made at least three entrances into U.S. ports in 1999, 50 percent of the total entrances made into U.S. ports were made by only 12 percent of the total vessels making visits. Seventy five percent of all the entrances were made by only 29 percent of the total vessels. This trend was apparent for both U.S. and foreign vessels. This indicates that the majority of the vessels visiting U.S. ports only make a couple of visits per year, while a relatively small population of vessels are making numerous visits each year. Figure 3.5-1 is a graph of the number of entrances versus the number of vessels (U.S. and foreign) for 1999.

Figure 3.5-1: Vessel Entrances for 1999 - All Vessels



3.5.2 Cruise Ship Activity

As stated earlier, in 2000 the worldwide cruise ship fleet included more than 223 ships that carried an estimated 9.5 million passengers in 1998. In 2000, 8 million embarkations occurred from ports worldwide. Embarkations from U.S. ports accounted for about 67 percent of total worldwide embarkations. The port of Miami, Florida alone accounted for 21 percent of worldwide embarkations. In fact, the port of Miami had more cruise ship embarkations than the rest of the world combined. Of the top five U.S. ports, three are located in Florida: Miami, Port Canaveral, and Port Everglades. The other two top U.S. ports are Los Angeles and New York. These fives ports alone account for 54 percent of worldwide embarkations. Approximately 600,000 or 7.5 percent of worldwide embarkations occur from other U.S. ports located in Alaska, Louisiana, Massachusetts, Puerto Rico, and Texas.

The cruise industry has seen a large increase in popularity over the last decade and the number of U.S. embarkations has doubled since 1990. In early 2000, industry analysts were projecting that the number of embarkations would continue to grow. However, as discussed above, the recent downturn of the U.S. economy had an adverse impact on the U.S. tourism industry. The September 11th attacks exacerbated this impact, and 2001 was the first year in a decade in which embarkations actually decreased. According to the Cruise Lines International Association, the cruise industry has rebounded dramatically since the tragic events of September 2001, and the number of embarkations in 2002 have increased over 2001. The cruise industry is responding to consumer confidence by continuing to expand its fleet. More than 20 ships are slated to enter the cruise fleet between fall of 2002 and the end of 2003.[14]

3.6 Conclusion

The Category 3 marine diesel engine and vessels industry is relatively concentrated. In 1998 there were approximately 1,300 Category 3 marine diesel engines produced worldwide. Seventy-five percent of those engines were manufactured by four companies. None of these engines are built in the United States. The overwhelming majority of the vessels that use these engines are built in South Korea, China, and Japan. U.S. shipyards build about one percent of these vessels. This is mainly due to the shipyard subsidy programs of other countries. Because the U.S. does not provide similar subsidies most, if not all, of U.S. ships produced are vessels required under the Jones Act to be built in the United States.

The vast majority of Category 3 vessels that enter U.S. ports are flagged or registered outside the United States. Approximately 200 U.S. vessels with Category 3 engines used U.S. ports in 1999. That represents about three percent of the total number of vessels entering U.S. ports for that year. Given that the number of U.S. vessels is small in comparison with the world fleet, it is likely that the contribution of U.S. vessels with Category 3 engines to local air pollution in any given port is small compared with that of foreign vessels.

Chapter 3 References

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CHAPTER 4: Tier 1 Standards

This chapter describes the current state of technology for marine diesel engines greater than 2.5 liters per cylinder. This includes a discussion of the feasibility of meeting the Tier 1 standards. The combustion process and potential technologies are basically the same for all the marine engine types in this rule including slow-speed, two-stroke engines and medium-speed four-stroke engines, and will be differentiated only where significant differences exist.

4.1 Marine Engine Technology

4.1.1 Diesel Engine Emission Formation

Marine diesel engines, like their land-based counterparts, operate by compressing and cooling the charge air before it fills the cylinder where fuel is injected, which auto-ignites under pressure. In marine engines, the charge air is compressed using a turbocharger under cruising and high loads and possibly a supercharger driven by the crankshaft at low loads. The charge air is typically cooled in two stages, first with jacket water and then with a second-stage aftercooler that relies on a seawater heat exchanger. Fuel is injected with the use of fuel injection pumps on each cylinder. Individual injection pumps are used so that each cylinder may be independently optimized for peak performance. The amount of fuel to be injected and fuel injection timing are typically set at cruising speed with mechanical fuel injection systems.

Many cylinder and injection parameters determine how the fuel and air mix to prepare for ignition and combustion, including piston head geometry, injection timing and duration, droplet sizes, and fuel jet momentum. NOx and PM are the emission components of most concern from diesel engines. High temperatures and excess oxygen are necessary for the formation of NOx. These conditions are found in a diesel engine as the fuel is injected into an oxygen rich environment, auto-ignites under pressure and multiple flame fronts spread through the combustion chamber. Typical diesel engine operation includes very high peak temperatures shortly after the onset of combustion and the nitrogen in the air combines with available oxygen to form NOx (the relatively high nitrogen content of fuels for Category 3 engines also contributes directly to NOx emissions during combustion). Because of the presence of excess oxygen, hydrocarbons evaporating in the combustion chamber tend to be completely burned and HC emission levels remain low. Similarly, CO emissions, which result from incomplete oxidation of hydrocarbons from the fuel are kept low by the ample supply of oxygen in the cylinder.

The majority of PM emissions from these engines comes from running on heavy fuel oil (residual fuel) and the high level of sulfur in the fuel. The highest portion of PM (by weight) is from ash, metal, oxides, and sulfates (see Table 4.1-1). Carbon soot makes up about a quarter of the overall PM content. It forms as a result of localized areas where there is not enough oxygen for complete combustion of fuel droplets while cylinder temperatures are high enough to maintain combustion. A small amount of PM is also from incomplete evaporation and burning of the fine fuel droplets or vapor and from small amounts of lubricating oil that escape into the combustion chamber. Engines that operate on distillate fuel generally have a much lower percentage sulfur and corresponding lower contribution of sulfates, as shown in Table 4.1-1. Note that the total amounts of PM in each chart are not the same for the different fuel types.

Table 4.1-1
Comparison of Particulate Emission Composition[1]

Parameter	Truck Diesel Engine Operating on Diesel Oil*	Medium-Speed Diesel Engine Operating on Heavy Fuel Oil*
Carbon soot	35%	25%
Hydrocarbons (fuel oil, lubrication oil)	50%	10%
Ash metal (oxides, sulfates)	15%	65%
Typical value	0.15 g/kW-hr	0.4 g/kW-hr
Measurement method	ISO 8178	ISO 9096

*Values are approximate.

In general, controlling both NOx and PM emissions requires different, sometimes opposing strategies. The key to controlling NOx emissions is reducing peak combustion temperatures, since NOx forms at high temperatures. In contrast, the key to controlling PM is higher temperatures in the combustion chamber or faster burning. This reduces PM by decreasing the formation of particulates and by oxidizing those particulates that have formed. To control both NOx and PM, manufacturers need to combine approaches using many different design variables to achieve optimum performance. However, in Category 3 marine engines, whose fuel injection timing and fuel pressure is often set at cruising speeds, and not optimized at lower loads, there may be a possibility of reducing emissions of both pollutants through the use of common rail and electronic controls.

4.1.2 Category 3 Marine Engine Design and Use

Category 3 marine engines generally fall into one of two distinct types, as shown in Table 4.1-2. They are either slow-speed, two-stroke engines or medium-speed four-stroke engines. The slow-speed engines are usually coupled to the ship's propeller shaft without reduction gears. In contrast, medium-speed engines are used with reduction gears or are used to generate electricity for both ship propulsion and auxiliary power. Category 3 marine engines are generally designed for commercial shipping vessels larger than 2,000 dead-weight tons (dwt). Dead-weight tons is a measure of the weight of a ship at maximum cargo load. One unique feature of slow-speed, two-stroke engines is that they generally use a crosshead piston design. An additional linkage is used in the piston-crank assembly to allow for longer stroke.

Table 4.1-2: General Characteristics of Category 3 Marine Diesel Engines

Engine Type	Fuel Type	Size Range, Liters/cyl	Rated Speed Range, rpm	Stroke/Bore Ratio	Number of Cylinders	Power Range, Total kW
slow speed 2-stroke	residual	57-2006	54 to 250	2.38 to 4.17	4 to14	1,100 to 103,000
medium speed 4-stroke	residual, distillate	30 to 290	327 to 750	1.15 to 1l71	5 to 20	1,000 to 18,100

Source: Diesel & Gas Turbine Catalog 2001[2]

Category 3 marine diesel engines are designed for continuous operation, with total annual operation often exceeding 5,000 hours. These engines are designed to maximize durability and fuel efficiency, which results in low operating costs. Typical applications for C3 marine engines include tankers, roll-on roll-off vessels, container vessels, and cruise ships. The majority of ocean-going vessels use Category 3 engines for propulsion. Great Lakes and Mississippi River vessels most often use Category 2 propulsion engines, though some of these vessels continue to use Category 3 propulsion engines. Vessels with Category 3 engines are also used to a lesser extent in coast-wise service.

The majority of Category 3 marine diesel engines burn heavy fuel oil, also known as residual fuel. Residual fuel is make up of the heavier components of crude oil, including contaminants such as sulfur, that remain after the crude oil has been processed to obtain gasoline, number 2 diesel, kerosene, and other lighter fuels. Vessels with these engines have fuel heaters to raise fuel temperatures to 100° or 200° C so that the fuel can flow through the fuel system for eventual combustion in the engine. Prior to entering the combustion chamber, the heated fuel passes through a filtration system. Filtration systems may be uniquely designed for each vessel, but generally include a centrifuge to remove excess water and undesirable solids. In addition, vessel operators must verify proper engine operation through adjustment of engine injection timing each time they refuel with heavy fuel oil due to the wide range of fuel qualities in the marketplace.

Category 3 engines are significantly different from Category 1 and Category 2 commercial marine engines in important ways that affect emissions and emission-control technologies. Category 3 engine operation is typically characterized by extended operation under cruising conditions. This high usage rate, combined with the very high power of Category 3 marine engines, makes fuel costs such a significant factor for these vessels. Category 3 engines therefore have the lowest brake-specific fuel consumption rates (BSFC) of any internal-combustion engine (as low as 176 g/kW-hr).[3,4] Manufacturers achieve this with very high brake mean-effective pressures (up to 2,200 kPa) and low mean piston speeds (7 to 9 m/s). These engine parameters maximize mechanical and propeller efficiencies.[5] Compared with Category 1 or Category 2 engines, these designs for optimum efficiency result in lower power density (power output for a given engine weight or cylinder displacement).

This operating profile also has an effect on the tradeoff between NOx and PM emissions. Maximum engine efficiency typically depends on managing engine and fuel injection parameters to achieve very high combustion temperatures and pressures, which correspond to maximum formation of NOx emissions, as described above. These same conditions provide for good oxidation of any carbonaceous particulate matter remaining in the cylinder after combustion. Over the past ten or twenty years, NOx emissions from uncontrolled Category 3 marine engines have tended to increase with BSFC improvements as engine manufacturers worked to address ship owners' desire to reduce operating costs. In response to MARPOL, manufacturers have reduced NOx emissions and have found they are able to keep the same BSFC whereas they may have improved BSFC if not designing for NOx control.

4.1.3 Anticipated Technology to Meet Emission Standards

Engine manufacturers are meeting the Tier 1 standards today using a variety of emission-control technologies. Table 4.1-3 summarizes technology being used by manufacturers to meet these levels. No individual engine relies on all the listed technologies, but manufacturers have shown that each of the technologies can be used effectively. The most common approach has been to focus on increased compression ratio, adapted fuel injection, valve timing and different fuel nozzles to trim NOx emissions. Manufacturers have generally been able to do this with little or no increase in fuel consumption.

Table 4.1-3: Summary of NOx Reduction Techniques Used to Meet IMO Standards

Manufacturer	In-Engine changes
Wartsila[6]	Retard injection Miller cycle valve timing Higher compression ratio Increased turbo efficiency Higher max cyl pressure Common rail injection
Caterpillar[7] (MaK)	Higher compression ratio Higher cylinder pressure Higher charge pressure Flexible injection system
FMC[8]	Two stage injection Miller cycle valve timing Greater stroke/bore ratio Adjustable compression Two stage turbocharger Low intake temperature
Yanmar[9]	Retard injection Shorter combustion time Higher compression ratio Higher boost pressure Reduced nozzle hole size Increased number of holes

4.1.4 Description of Technology

4.1.4.1 Combustion Optimization

Several parameters in the combustion chamber of a heavy-duty diesel engine affect its efficiency and emissions. These engine parameters include fuel injection timing, combustion chamber geometry, compression ratio, valve timing, turbulence, injection pressure, fuel spray geometry and rate, peak cylinder temperature and pressure, and charge air temperature and pressure. Some strategies are not directly related to improving control of NOx emissions, but are included in this discussion because of their potential to prevent increases in fuel consumption or HC or PM emissions resulting from NOx-related emission controls

4.1.4.1.1 Fuel Injection Timing and Electronic Control

Advanced timing is typically used for optimum fuel consumption. In advanced timing the fuel is injected early and mixes substantially before ignition, resulting in very rapid initial combustion and a sharp spike in cylinder temperatures and correspondingly high NOx emissions. Once combustion begins, fuel injection continues while combustion changes to diffusion burning, in which a relatively constant heat release results in significantly lower burn temperatures. Retarded timing reduces NOx emissions because the premixed burning phase is shortened and because cylinder temperature and pressure are lowered. Timing retard, however, increases HC, PM, and fuel consumption, because the end of injection comes later in the combustion stroke where the time for extracting energy from fuel combustion is shortened and the cylinder temperature and pressure are too low for effective oxidation of PM. Timing retard in combination with other fuel injection upgrades can delay the start of injection without changing the end of the combustion event.[10] This can be accomplished by using increased injection pressure, optimized nozzle geometry, or rate shaping. Combining technologies in this way allows for substantial NOx reductions while minimizing the negative impacts on fuel consumption or HC and PM emissions.

Most Category 3 engines currently use mechanical systems to adjust injection timing. Timing is set based on optimal performance and engine durability at the vessel’s cruising speed, where the ship operates most frequently and combustion pressure and temperature are the highest. Optimizing fuel injection timing for NOx emissions at points other than cruising speed is generally impractical unless the engine is electronically controlled or has a simplified mechanical system which can be adjusted while the engine is in operation. Electronic controls are being developed and have been implemented on at least one vessel.

4.1.4.1.2 Combustion Chamber Geometry

Parameters within the combustion chamber geometry that yield reduced emissions include the shape of the chamber and reduced crevice volumes. One manufacturer states, “Cylinder heads with flat bottoms were found to avoid the danger of deposition of the fuel with its negative effects on soot emission at low load. Combustion chambers with small dead volumes have a favorable effect on the possible utilization of the air during operation under conditions with low excess air ratios."[11]

Others state that in comparison with a wide, open bowl, the smaller inner diameter bowls are designed to generate jet/piston interaction that retards the combustion process.[12] The slower burning rate leads to lower NOx. At the end of combustion the piston bowls with smaller diameter generate a faster burning rate due to a higher turbulence level generated during the jet/piston interaction and therefore to more efficient soot oxidation. One researcher found also found that a piston with a wide bowl and raised central hump, along with increased compression ratio, represents the best compromise with regard to low-load smoke emission, full-load fuel consumption and NOx emissions.[13]

4.1.4.1.3 Compression Ratio

Increasing the compression ratio can lower NOx levels by increasing the density of the intake air in the combustion chamber. Redesigning the piston crown or increasing the length of the connecting rod or piston pin-to-crown length could raise the compression ratio.[14] There is a limit to the benefit of higher compression ratios because of increased combustion pressure and the limits on engine cylinder safety. One manufacturer demonstrated a 35-percent reduction in NOx emissions without increasing fuel consumption by increasing peak cylinder pressure 10 percent.[15] This increase in pressure was achieved with a compression ratio of 17. The authors reported that a long-stroke engine has the ideal conditions for a compact combustion space—smooth surfaces and no corners with difficult access for the fuel jet. Such high compression ratios also demand reduced valve overlap to avoid valve pockets in the piston crown. Reducing valve overlap increases the residual gas proportion in the combustion space due to the lower scavenging efficiency. This further reduces NOx emissions by incorporating a degree of internal exhaust gas recirculation, as described later in this chapter. The boost pressure and therefore the firing pressure of the engine must be increased to maintain the low exhaust gas temperatures necessary for reliable operation with heavy oil.

4.1.4.1.4 Valve Timing

Medium-speed four-stroke engines employ valves in their design whereas two-stroke generally operate with ports. This technology is only relevant for designs with valves. The efficiency of a diesel engine generally increases with its expansion ratio because more work is generated by the engine for a given stroke.[16] If the intake and exhaust valves are closed during the compression stroke, the compression ratio is equal to the expansion ratio. Although a high expansion ratio is desirable, the corresponding compression ratio is limited by material strength and NOx formation at high pressures and temperatures.

In an engine-design strategy known as the Miller (or Atkinson) cycle, valve timing is planned to increase the expansion ratio without increasing the compression ratio. In a standard diesel engine design, the intake valve opens shortly before the piston reaches top dead center and stays open until the piston is near bottom dead center. This allows the most time to force air into the cylinder, which helps maximize volumetric efficiency. In a Miller cycle engine, the intake valve is kept open well beyond bottom dead center. This reduces the amount of pressure generated during the compression stroke, thereby allowing a greater expansion ratio. Enhanced turbocharging or supercharging is required to offset the resulting loss in volumetric efficiency,

Several engine manufacturers are using a "semi-Miller cycle" to reduce fuel consumption and emissions from Category 2 and Category 3 propulsion engines by slowing the intake valve seating and increasing the boost pressure. Coupled with timing retard, one manufacturer reduced NOx by more than 10 percent while simultaneously reducing fuel consumption by 3 percent.[17] This manufacturer reported that slowing the valve seating extended the life of the valve seat. Another manufacturer uses intake and exhaust valve timing to reduce pumping losses, which reduces fuel consumption without increasing NOx emissions in Category 1 and 2 auxiliary engines.[18] A third manufacturer retarded the intake valve closing by 20 degrees and increased the boost pressure by 7 percent, resulting in a 10-percent reduction in NOx emissions and unchanged fuel consumption rates.[19]

4.1.4.1.5 Swirl

Increasing the turbulence of the intake air entering the combustion chamber (i.e., inducing swirl) can improve the mixing of air and fuel in the combustion chamber. Swirl can be induced by routing the intake air to achieve a circular motion in the cylinder or by designing piston geometry for increased turbulence during the compression stroke. Swirl generally has advantages for reducing PM emissions and improving fuel consumption, but can be used in combination with other fuel injection strategies for controlling NOx emissions. For example, combining timing retard or rate shaping strategies to delay the onset of combustion can be done with minimal negative effects by using swirl to increase the burn rate.[20]

4.1.4.2 Improving Charge Air Characteristics

Category 3 engines rely on turbochargers, sometimes in combination with superchargers, to compress the charge air, improving the power capability of the engine. Cooling the compressed charge air (aftercooling) increases its density, allowing further improvements in power and fuel consumption. Aftercooling also lowers NOx emissions by reducing combustion temperatures. Manufacturers have already incorporated extensive use of turbocharging and aftercooling. To the extent that manufacturers can improve aftercooling technologies, this would serve to further reduce NOx emissions.

An additional factor related to aftercooling is the water that condenses out of the charge air. Depending on the humidity of the ambient air and the amount of aftercooling, this can involve very large quantities of water. Manufacturers have found ways to divert the water from the engine for disposal, though this same water may be available for separate use for other emission-control technologies (see section 5.1.2).

4.1.4.3 Fuel Injection

Control of the many variables involved in fuel injection is central to any strategy to reduce diesel engine emissions. The principal variables being investigated are injection pressure, nozzle geometry (e.g., number of holes, hole size and shape, and fuel spray angle), the timing of the start of injection, and the rate of injection throughout the combustion process (e.g., rate shaping). Common rail, with a control system that allows for electronic change of injection timing, is also a useful technology that is currently being used to decrease NOx.

4.1.4.3.1 Fuel Injection Pressure

Particle emissions and fuel consumption generally go down with increasing injection pressure.[21] Increasing the injection intensity, combined with a NOx-neutral increase of compression ratio and peak pressure, may best balance competing demands for controlling low-load smoke emissions, fuel consumption, and NOx emissions.[22]

Manufacturers continue to investigate new injector configurations for nozzle geometry and higher injection pressure (in excess of 2300 bar (34,000 psi)).[23,24] Increasing injection pressure achieves better atomization of the fuel droplets and enhances mixing of the fuel with the intake air to achieve more complete combustion. Though HC and PM are reduced, higher cylinder pressures can lead to increased NOx formation.[25] However, in conjunction with retarding the start of fuel injection, higher fuel injection pressures can lead to reduced NOx because of lower combustion temperatures. HC, PM, or fuel economy penalties from this strategy can be avoided because the termination of fuel injection need not be delayed. Nozzle geometry is used to optimize the fuel spray pattern for a given combustion chamber design to improve mixing with the intake air and to minimize fuel condensation on the combustion chamber surfaces.[26]

4.1.4.3.2 Nozzle Geometry

Nozzle geometry is a very important parameter for combustion development.[27] Injection duration, droplet sizes and fuel jet momentum are responsible for the quality of the mixture formation. The nozzle-hole intake is hydro-grinded to optimize the flow. Graphs can be made of specific fuel consumption (number of holes and effective nozzle flow area) and particle emission as a function of effective nozzle-flow area. This determines the fuel mass flow rate and therefore the burning rate and mixture formation. Particle emission and fuel consumption show distinct minima for slightly different nozzle flow areas. If mixture formation is supported by jet/piston interaction, nozzle protrusion and spray-elevation angle have to be optimized in relation to the piston bowl used. This technology, in combination with engine tuning, was used by one engine manufacturer to achieve IMO levels. The fuel injection nozzles were designed to optimize spray distribution in the combustion chamber but without compromising on component temperatures and thereby engine reliability. A graph supplied in the reference paper shows a maximum reduction of approximately 18% NOx.[28]

The same manufacturer states their experience with testing of mini-sac nozzles that they had developed. "Tests have shown that the main source of smoke and soot deposits is the fuel trapped into the fuel injector sac hole which enters the combustion chamber in an uncontrolled way during the expansion stroke." One manufacturer has developed a new "mini-sac hole" fuel nozzle concept. Test-bed results have shown, as expected, a remarkable reduction of smoke and hydrocarbon (HC) emissions, slightly better fuel consumption and only a marginal influence on NOx emissions."[29] Results were 50-70% reduction in HC, 30-50% reduction in smoke with fuel consumption slightly better (~0.5 g/kWh) and combustion chamber temperatures on the same level as before. At the time of the paper (CIMAC Congress 2001), such fuel injectors were in field tests to confirm their reliability.

4.1.4.3.3 Controlling the Timing and Rate of Injection

The most recent advances in fuel injection technology are the systems that use rate shaping or multiple injections to vary the delivery of fuel over the course of a single injection. Igniting a small quantity of fuel initially limits the characteristic rapid increase in pressure and temperature that leads to high levels of NOx formation. Injecting most of the fuel into an established flame then allows for a steady burn that limits NOx emissions without increasing PM emissions. Rate shaping may be done either mechanically or electronically. Rate shaping has been shown to reduce NOx emissions by up to 20 percent.[30]

For electronically controlled engines, multiple injections may be used to shape the rate of fuel injection into the combustion chamber. Recent advances in fuel system technology allow high-pressure multiple injections to be used to reduce NOx by 50 percent with no significant penalty in PM. Two or three bursts of fuel can come from a single injector during the injection event. The most important variables for achieving maximum emission reductions with optimal fuel economy using multiple injections are the delay preceding the final pulse and the duration of the final pulse.[31] This strategy is most effective in conjunction with retarded timing, which leads to reduced NOx emissions without the attendant increase in PM.

4.1.4.3.4 Common Rail

The main advantages of common rail injection systems and corresponding engine control system are the flexible injection timing and the high variable injection pressure within the whole performance map.[32] Common rail systems for Category 3 medium speed and low speed engines are being designed and implemented by at least one of the engine manufacturers for this category.

MEDIUM SPEED: A common rail system for medium speed engines basically consists of four components: the pump, the common rail, the injector and the control unit. The pump is used to fill the common rail with fuel and maintain the pressure at the level requested by the control unit can vary between 900-1500 bar depending on the optimum for a specific operating point. The pump can be either a single pump consisting of several pumping elements driven by the crankshaft through a gear, or camshaft-driven jerk pumps similar to the conventional injection pumps. The pumps can be speeded up by employing two or more cam lobes per pump and this way the size and number of pumps can be reduced significantly. The accumulator stores the pressurized fuel.

A design by one manufacturer has some unique features.[33] The common rail pipe is split into several smaller volumes interconnected with parts with a relatively small flow area rather than one pipe. The advantages of this include 1) the accumulator volume can be concentrated close to the injectors, 2) the accumulators can be standardized and easy to manufacture, the accumulator and one pump serve two cylinders and, 3) the system can be easily shielded and any fuel leakages collected in a separate drain system. The injector employs servo oil actuation for fuel injection control rather than direct fuel oil actuation. This is done to lengthen the life of the solenoid armature which can be affected by high temperatures such as the temperature of heavy fuel oils (150°C+) This also ensures that the injection will not be affected by erosion wear and clogging of the small drillings. The design does not have the rail (accumulator) pressure prevailing at the nozzle seat in between the injection events, mainly to avoid leaking nozzles. Otherwise, a large amount of fuel could leak into the cylinder since the non-injection period represents more than 95% of the total. The injector also has a "rail pressure aided needle closing" which ensures fast opening of the needle when the pressure in the nozzle is high enough and equally fast closure of the needle at the end of injection. This ensures combustion control and smokeless operation. The control unit controls the timing and the quantity of the injected fuel and controls the refilling and pressure in the accumulators. It also takes care of major safety functions like pre-circulation, over-pressure protection, pressure evacuation at emergency stop, etc. Software goes through several iterations in parallel with testing and optimization on the engine to assure stable software that is easy to configure for various application needs.

LOW SPEED: One common rail system for low speed engines has recently come into the marketplace and is currently powering a low speed bulk carrier that completed its sea trials in September 2001. As stated by the manufacturer in the reference material:

> The common rail is a manifold running the length of the engine at just below the cylinder cover level. It provides a certain storage volume for the fuel oil, and has provision for damping pressure waves. The common-rail injection system is fed by heated fuel oil at the usual high pressure (nominally 1000 bar) ready for injection. The supply unit has a number of high pressure pumps running on multi-lobe cams. The pump design is based on the proven injection pumps used in the manufacturer's four-stroke engines. Fuel is delivered from the common rail through a separate injection control unit for each engine cylinder to the standard fuel injection valves, which are hydraulically operated in the usual way by the high pressure fuel oil. The control units, using quick acting rail valves by the engine manufacturer, regulate the timing of fuel injection, control the volume of fuel injected, and set the shape of the injection pattern. The three fuel injection valves in each cylinder cover are separately controlled so that they may be programmed to operate separately or in unison as necessary. The common rail system is built for operation on the grades of heavy fuel oil available today. The key features of the common rail system are thus: precise volumetric control of fuel injection, with integrated flow-out security, variable injection rate shaping and free selection of injection pressure, ideally suited for heavy fuel oil, well proven, high efficiency supply pumps, lower levels of vibration and internal forces and moments, steady operation at very low running speeds with precise speed regulation and no visible smoke at any operating speed.[34]

In addition to fuel injection, the system incorporates exhaust valve actuation and starting air control. The exhaust valves are operated with hydraulic pushrod, but with the actuating energy combing from a servo oil rail at 200 bar pressure. "The servo oil is supplied by high pressure hydraulic pumps incorporated in the supply unit with the fuel supply pumps. The electronically controlled actuating unit for each cylinder gives full flexibility for valve opening and closing patterns."[35]

The system is controlled and monitored through the electronic control system developed by the manufacturer. The modular system has separate microprocessor control units for each cylinder and overall control and supervision by duplicated microprocessor control units. This provides the interface for the electronic governor, the shipboard remote control, and the alarm system. The common rail system replaces some parts such as mechanical injection pumps (setting the engine is simplified).

The manufacturer claims that this system may provide selective injection patterns to give shipowners the option of 20% lower NOx emissions when NOx control is required (fuel consumption increases) and may be set for fuel economy in areas where NOx control is not required.

4.1.4.3.5 Electronic-Hydraulic Control of Fuel Injection and Exhaust Valve Actuation

One manufacturer has installed an electronically controlled cam-less engine using an in-house developed electronic-hydraulic platform on a 37,500 dwt deep sea chemical carrier.[36] The system allows for electronically controlled fuel injection and exhaust valve actuation which permit individual and continuous adjustment of the timing for each cylinder. Parts that are removed from the mechanical system include the chain drive for camshaft, camshaft with fuel cams, exhaust cams and indicator cams, fuel pump actuating gear, including roller guides and reversing mechanism, conventional fuel injection pumps, exhaust valve actuating gear and roller guides, engine driven starting air distributor, electronic governor with actuator, regulating shaft, mechanical, engine driven cylinder lubricators, and engine side control console. The items added to the engine include a hydraulic power supply, hydraulic cylinder unit with electronic fuel injection and electronic exhaust valve activation, electronic alpha cylinder lubricator, electronically controlled starting valve, local control panel, control system with governor, and condition monitoring system. Two electronic control units are used to control the system with one being a backup for the first. The manufacturer claims that the electronic version of the engine was very easy to adjust to the prescribed setting values and was able to keep the very satisfactory setting values without further adjustments since the vessel's sea trials in November 2000.

A second manufacturer has further developed their mechanically actuated, electronically controlled unit injectors and hydraulically actuated, electronically controlled unit injectors to provide the flexible fuel injection characteristics needed to optimize engine performance and emissions.[37] The manufacturer states that the design approach in both injector concepts is to utilize a Direct Operated Check (DOC) to precisely control the pressure, timing and delivery of fuel. The DOC is applicable to electronic unit injector or unit pump configurations with either mechanical or hydraulic actuation of the pressurizing units. The manufacturer has claimed the technology eliminates spray distortion and minimizes parasitic losses that may be seen in common rail fuel systems. The manufacturer includes a discussion on closed loop NOx control, stating that ultra-fast NOx sensors are a key part to closed-loop control of NOx emissions. The sensors provide the benefits of minimized engine to engine variations, minimized cylinder-to-cylinder variations and improved transient response with reduced emission and reduced operational costs.

4.1.4.4 Lube Oil Consumption

Many of the Category 3 marine diesel engine manufacturers are working to reduce the consumption of lubricating oil from their engines, to address customer's demand for reduced operating costs. Highway diesel engines have greatly reduced HC and PM emissions by decreasing oil consumption. This is especially relevant for highway engines, because half or more of uncontrolled PM emissions can be attributed to lubricating oil.

For Category 3 marine engines operating on residual fuel, the high concentration of ash in residual fuel dominates PM emissions. Therefore, a much smaller percentage of the PM mass comes from the oil (see Table 4.1-1). Reducing oil consumption in Category 3 marine engines will decrease PM emissions by a lesser percentage than the same kind of improved oil control in highway diesel engines.

4.1.4.5 Emission-Controls and System Approaches

Table 4.1-4 identifies several technologies that individual manufacturers have already incorporated to reduce emissions and may likely be used to meet the near-term standards. All these different approaches together would reduce emissions at least 10 or 15 percent below the near-term standards. The table also identifies several technologies that are beginning to gain field experience on engines in-use and may be available as the basis for the eventual long-term standards.

Table 4.1-4: "In-Engine" Combustion Process Changes Currently In-Use or Being Investigated by Marine Diesel Engine Design and Manufacturing Companies[38]

Component or Operation Changed	Change	Parameter Affected	Slow-Speed 2-Stroke	Medium Speed 4-Stroke
turbocharger	improved efficiency, variable flow	BSFC, intake pressure	Yes	Yes
intercooler	improved efficiency	air inlet temperature	Yes	Yes
air inlet port	redesign shape	swirl	Maybe	Yes
cylinder head	redesign shape	swirl, compression ratio	Maybe	Yes
piston crown	redesign piston crown shape	swirl, compression ratio	No	Yes
injection pressure	increase	atomization	Yes	Yes
injectors	redesign	low sac, injection rate shaping	Yes	Yes
nozzle	hole geometry & number	spray pattern changes	Possibly	Yes
exhaust valve timing	"Miller cycle" timing	peak cylinder temperature	Yes	Yes
electronic control	replaces mechanical control	engine operation, BSFC	Yes	Yes
common rail injection	replace unit injection	higher fuel pressure (all loads)	Yes	Yes
injection timing	retard and/or vary with load	peak cylinder temperature	Yes	Yes

4.2 Technology Costs

The standards in this rule align with these internationally negotiated standards, so we expect manufacturers to incur only negligible costs to meet the EPA requirements. These costs will likely be limited to administrative expenses, such as applying for certification, updating training manuals, and revising engine labels.

4.3 Emission Reductions

The standards in this rule align with the internationally negotiated MARPOL Annex VI NOx standards. Engine manufacturers have been manufacturing engines in compliance with these internationally negotiated NOx standards for the last few years, and we expect that they will continue to do so. Thus, we do not expect that there will be any emission reductions associated with this rule. Table 4.3-1 shows the national Category 3 NOx inventories, with and without the internationally negotiated NOx standards. The no control scenario was developed by taking the baseline emissions case (compliance with the internationally negotiated NOx limits, as described in Chapter 7) and applying to all new vessels the ratio of pre-control emission factors to emission factors under the internationally negotiated NOx limits.

Table 4.3-1
Category 3 Marine Vessel NOx National Emission Inventories

		1996	2010	2020	2030
No control baseline (thousand short tons)		190	303	439	659
EPA / MARPOL Annex VI	(thousand short tons)	190	274	367	531
	Percent reduction (relative to no control)	—	9.6%	16.2%	19.5%

4.4 Impact on Noise, Energy, and Safety

The Clean Air Act requires that we consider potential impacts on noise, energy, and safety when establishing the feasibility of emission standards. One important source of noise in diesel combustion is the sound associated with the combustion event itself. When a premixed charge of fuel and air ignites, the very rapid combustion leads to a sharp increase in pressure, which is easily heard and recognized as the characteristic sound of a diesel engine. The conditions that lead to high noise levels also cause high levels of NOx formation. Fuel injection changes and other NOx control strategies therefore typically reduce engine noise, sometimes dramatically.

The impact of the new emission standards on energy is measured by the effect on fuel consumption from complying engines. Many of the marine engine manufacturers are expected to retard engine timing which, by itself, increases fuel consumption somewhat. Most manufacturers control NOx emissions by incorporating a combination of engine technologies. Some of these changes in isolation may increase fuel consumption, but these are generally offset by other changes that decrease fuel consumption. Moreover, given the fact that we do not expect the standards in this final rule to change engine technologies, we expect no change in fuel efficiency to result from the near-term standards.

There are no apparent safety issues associated with the new emission standards. Marine engine manufacturers have or are currently proving the technologies in the field.

4.5 Category 1 and 2 Marine Engines Greater Than 2.5 Liters/Cylinder

As with Category 3 marine engines, manufacturers are designing their Category 1 and 2 marine engines greater than 130 kW to meet the MARPOL Annex VI NOx limits. Manufacturers have met these limits through in-cylinder combustion optimization. In our final rule for Tier 2 standards for Category 1 and 2 marine engines, we only attributed costs and for NOx reductions beyond the negotiated international NOx limit (64 FR 73300, December 29, 1999). In the Final Regulatory Impact Analysis for that rule, we discussed in-cylinder emission-control strategies such as those used by manufacturers today to meet the negotiated international NOx limit.[39]

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CHAPTER 5: Advanced Emission-Control Technologies

This chapter focuses on technologies under development which could be used to achieve further emission reductions beyond current standards for Category 3 marine engines. These technologies will be considered as we develop standards for our future rule. Section 5.1 discusses the introduction of water into the combustion process to reduce emissions. Sections 5.2 and 5.3 discuss selective catalytic reduction and fuel cells. Section 5.4 discusses other engine technologies that could be used in conjunction with water strategies or SCR.

The discussion in this chapter focuses on Category 3 marine diesel engines. Similar information about the technology associated with applying these standards to Category 1 and Category 2 marine diesel engines are contained in the Final Regulatory Impact Analysis for our 1999 rule.[1] Section 5.5 briefly discusses those technologies.

Section 5.6 discusses PM emission control from Category 3 marine diesel engines.

5.1 Water Introduction into the Combustion Process

Water can be used in the combustion process to lower maximum combustion temperature, and therefore lower NOx formation, without increasing in fuel consumption. Water has a high heat capacity, which allows it to absorb enough of the energy in the cylinder to reduce peak combustion temperatures. Water may be introduced into the combustion process through emulsification with the fuel, direct injection into the combustion chamber, or saturating the intake air. Data on water-based emission-control technologies suggest that this technology has the potential to reduce NOx emissions by more than 50 percent from the standards we are finalizing. However, there are several problems with this technology that must be resolved before it can be applied generally. These issues are discussed below.

5.1.1 Description of the Technology

Water emulsification refers to mixing water with the fuel as a stable suspension. Testing on a high speed diesel engine has shown a 40 percent reduction in NOx with a water-to-fuel ratio of 50 percent[c] with only a slight increase in smoke.[2] Two power plants with slow-speed diesel engines are using water emulsification today to reduce NOx.[3] In the referenced case, they are achieving a 44 percent NOx reduction with 35 percent water emulsification. However, the fuel consumption was increased by 1 to 2 percent. Although, these were not marine engines, it is reasonable to expect that similar results would be seen on marine engines that are similar in design and operation. Water emulsification requires changes to the engine and fuel system.

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[c] For the purposes of this discussion, the water-to-fuel ratio is expressed in percent. For example, an engine using 50 percent water would use 50 gallons of water for every 100 gallons of fuel oil consumed.

Larger volume fuel injectors and pumps are needed to handle the additional fuel/water volume. According to a marine engine manufacturer who investigated this technology on its engines, combining water with fuel in the tank may introduce combustion problems due to unstable emulsion if more than a 30 percent NOx reduction is targeted.[4] Also, this technique requires a significantly redesigned fuel handling system to overcome the potential risk of corrosion and to maintain power output. However, these problems may be overcome in the future as the strategy is refined.

As an alternative to storing emulsified fuel in the tank, water and fuel can be injected into the combustion chamber using a common injector. The fuel and water can be mixed just prior to injection or stratified in the injector. An example of the first strategy was developed for a medium speed diesel engine, used in a power plant, in which the water is emulsified in the fuel just prior to injection.[5] The fuel/water is injected using solenoid controlled single injection units. Through this system, the fuel/water mix can be changed under different conditions. At low power (below 30 percent of rated), no water is added, from 30-40 percent of rated power, 20 percent water is added, above 40 percent of rated power, about 35 percent water is added. This water dosage strategy suggests that the engine may be less tolerant of water in the combustion chamber at lower loads. Also, the water is shut off for about a minute when the engine load is increased and the water dosage is significantly decreased prior to shutting off the engine. Using this strategy, NOx was reduced by 52 percent at intermediate speed and 57 percent at rated speed. This report stated that more work would be necessary to construct a durable injection pump that was eroded by cavitation and water wear after 900 hours. An example of stratified injection was developed for a slow-speed diesel engine.[6] In this case the injector alternates between fuel and water. In this application, NOx was reduced 50 percent with about 70 percent water added. By creating a multi-water layer in the fuel charge, this reduction was achieved without a significant increase in fuel oil consumption.

More effective control of the water injection process can be achieved through the use of an independent nozzle for water. Using a separate injector nozzle for the water allows larger amounts of water to be added to the combustion process because the water is injected simultaneously with the fuel, and larger injection pumps and nozzles can be used for the water injection. In addition, the injection timing can be better optimized. On one slow-speed diesel engine, a 45 percent NOx reduction was achieved with 60 percent water (9 g/kW-hr).[7] Further work on another engine achieved a NOx reduction of 70 percent with 90 percent water (6 g/kW-hr).[8] With only 50 percent water, a 40 percent reduction in NOx from this engine was observed. Wartsila has installed direct water injection systems on engines in 14 vessels. These are primarily ferries and ro-ro vessels operating in European waters where there are economic incentives for reducing NOx emissions. In addition, Wartsila plans to install direct water injection on engines in another 8 vessels by the end of 2003.[9] A list of these applications is contained in the appendix following this chapter.

Wartsila is also evaluating two other methods introducing water into the combustion process.[10] These methods are combustion air humidification and steam injection. With combustion air humidification, a water nozzle is placed in the engine intake and an air heater is used to offset condensation. The result is saturated air at 70-90°C. Initial testing shows that an 80 percent NOx reduction can be achieved with a water-to-fuel ratio of two (4 g/kW-hr). Corrosion at this high water-to-fuel ratio is not an issue due to the anti-polishing ring used on newer engines. With steam injection, waste heat is used to vaporize water which is then injected into the combustion chamber during the compression stroke. Initial tests have shown an 85 percent NOx reduction with a 3.0-3.5 water-to-fuel ratio (2.4-3.0 g/kW-hr). Fuel consumption was improved by 2 g/kW-hr (roughly 1 percent). Although higher NOx reductions are seen with combustion air humidification and steam injection than with direct water injection, more water is needed for a given NOx reduction, possibly due to the heating of the water prior to introduction into the cylinder.

5.1.2 Issues to Resolve

Fresh water is necessary for this NOx reduction strategy. Introducing salt water into the engine could result in serious deterioration due to corrosion and fouling. For this reason, a ship using water strategies would need to either produce fresh water through the use of a desalination or distillation system or store fresh water on board. Cruise ships may already have a source of fresh water that could be used to enable this technology. This water source is the “gray” water, such as drainage from showers, which could be filtered for use in the engine. For other ocean-going vessels, water storage tanks would likely displace either fuel storage which would limit the range of the vessel or cargo space which would affect revenues. The alternative of using a desalination or a distillation unit would include costs for the unit and would also require space for the unit and for some water storage. Also, when and where a ship operates can have an effect on the available water. A ship operating in cold weather uses all of the available steam heated by the exhaust just to heat the fuel. Also, a ship operating in an area with low humidity would not be able to condense water out of the air using the jacket water aftercooler.

Another concern with the use of water in the combustion process is the effect on PM emissions. The water in the cylinder reduces NOx, which is formed at high temperatures, by reducing the temperature in the cylinder during combustion. However, PM oxidation is most efficient at high temperatures. At this time, we do not have sufficient information on the effect of water emulsification and injection strategies on PM emissions to quantify this effect.

5.2 Selective Catalytic Reduction

SCR is one of the most effective means of reducing NOx from large diesel engines. This technology is already being developed for land-based diesel engines and has been used in some marine demonstration projects. Data suggests that SCR has the potential to reduce NOx emissions by more than 80 percent from the standards we are finalizing. However, there are still several problems with this technology that must be resolved before it can be applied generally. These issues are discussed below.

5.2.1 Description of the Technology

In SCR systems, a reducing agent, such urea ($(NH_2)C_2O$) is injected into the exhaust. This urea is mixed into a water solution and injected into the exhaust where the heat decomposes the urea to produce ammonia and carbon dioxide which is channeled through a reactor where NOx emissions are reduced. In a system known as "compact SCR", oxidation catalysts are used in conjunction with the SCR reactor to increase the effectiveness of the system. An oxidation catalyst upstream of the SCR reactor can be used to convert NO to NO_2. Because the reduction of NOx can be rate-limited by NO reductions, converting some NO to NO_2 allows manufacturers to use a smaller reactor and/or operate at lower temperatures.[11] In addition, oxidation catalysts can be used downstream of the reactor to oxidize any ammonia that "slips" through the SCR unit. SCR systems are being successfully used for many stationary applications, which generally operate under constant, high-load conditions. In fact, emission reductions in excess of 90 percent can be achieved using SCR.

Manufacturers are demonstrating similar NOx reduction using SCR technology for marine applications. The Royal Navy has developed a demonstration system that was tested on a replica exhaust system for a Type 23 Frigate.[12] One vessel with a MaK 8M32 engine (medium-speed Category 3) has shown reduced NOx emissions by over 90 percent with no fuel consumption penalty with the SCR system operating.[13]

Wartsila has demonstrated a standard SCR system on 8 vessels and a compact SCR system, which uses an oxidation catalyst upstream of the SCR reactor to reduce reactor size, on four vessels.[14,15] Combined, these twelve vessels are equipped with a total of 40 medium-speed Category 3 marine engines. Also, one manufacturer of SCR systems under the trade name SINOx, had systems on 56 Category 2 or Category 3 marine engines operating on both residual and distillate fuel oil at the end of 2000.[16] Lists of the systems are contained in the appendix following this chapter. The majority of these engines were in ferries and ro-ro vessels operating in European waters where there are economic incentives to use SCR. In addition, these engines are four-stroke medium-speed engines which have higher exhaust temperatures than two-stroke low-speed engines which better enables the use of SCR. To prevent sulfur poisoning of the catalysts, the fuel used by these vessels ranges from 0.1 to 1 percent sulfur.

In one case, SCR was equipped on vessels with two-stroke low-speed engines. More than ten years ago, MAN B&W worked with California Agencies and Hyundai Heavy Industries to produce four vessels equipped with SCR.[17] The goal of this program was to reduce the emissions emitted during the transportation of steel to a facility in Pittsburg, California. The first ship was completed in 1989 and the fourth ship was completed in 1992. Because the vessels were equipped with low-speed engines (6S50MC, 10,680 hp), the exhaust temperatures were low. In addition, the vessels operate at low load near the coast; therefore, certain modifications to the system were necessary. Primarily, the exhaust system was reconfigured to provide the maximum heat to the reactor which had negative impacts on transient response and efficiency. Also, the catalyst was formulated to be effective at temperatures as low as 270°C. Because such a reactive catalyst is vulnerable to sulfur poisoning, the vessels only operate on 0.05 percent sulfur fuel when the SCR unit is active. MAN B&W estimates that these vessels only make about 6 calls to California per year and that the SCR unit is only active for about 12 hours per call.

Generally, SCR systems available today are effective only above 300°C. To date, these systems have been applied to four-stroke medium speed engines which have exhaust temperatures above 300°C at high load. Two-stroke slow speed engines have lower exhaust temperatures and are discussed later in this section. The effectiveness of the SCR system is decreased during engine operation at partial loads due to decreased exhaust temperatures. Most of the engine operation in and near commercial ports and waterways close to shore is likely to be at these partial loads. In fact, reduced speed zones can be as large as 100 miles for some ports. Because of the cubic relationship between ship speed and engine power, engines may operate at less than 25 percent power in a reduced speed zone. During this low-load operation, little or no NOx reduction would be expected; SCR would therefore be less effective during low-load operation near ports. Some additional heat to the SCR unit can be gained by placing the reactor upstream of the turbocharger; however, this temperature increase would not be large at low loads and the volume of the reactor would diminish turbocharger response when the engine changes load. The engine could be calibrated to have higher exhaust temperatures; however, this could affect durability (depending on the fuel used) if this calibration also increased temperatures at high loads. For an engine operating on residual fuel, vanadium in the fuel can react with the valves at higher temperatures and damage the valves.

5.2.2 Issues to Resolve

Low sulfur fuel is necessary to assure the durability of the SCR system because sulfur can become trapped in the active catalyst sites and reduce the effectiveness of the catalyst. This is known as sulfur poisoning which can require additional maintenance of the system. SCR units in service today are operating of fuel ranging from 500 to 10,000 ppmS. Even if these systems can be made to operate on 15,000 ppmS fuel, an infrastructure would be necessary to ensure that ships could refuel with 15,000 ppmS fuel at ports they visit. Low sulfur residual fuel is available in areas which provide incentives for using such fuel, including the Baltic Sea, however such fuel is not yet available at ports throughout the United States.

Slow-speed marine engines generally have lower exhaust temperatures than medium speed engines due to their two-stroke design. However, we are aware of four slow-speed Category 3 marine engines that have been successfully equipped with SCR units. Because of the low exhaust temperatures, the SCR unit is placed upstream of the turbocharger to expose the catalyst to the maximum exhaust heat. Also, the catalyst design required to operate at low temperatures is very sensitive to sulfur. Especially at the lower loads, the catalyst is easily poisoned by ammonium sulfate that forms due to the sulfur in the fuel. To minimize this poisoning, these four in-service engines use highway diesel fuel (0.05 percent S). In addition, these ships only operate with the exhaust routed through the SCR unit when they enter port areas in the U.S., which is about 12 hours of operation every 2 months. Therefore, the sulfur loading on the catalyst is much lower than it would be for a vessel that continuously used the SCR system. To prevent damage to the catalyst due to water condensation, this system needs to be warmed up and cooled down gradually using external heating. Another issue associated with the larger slow-speed engines and lower exhaust temperatures is that a much larger SCR system would be necessary than for a vessel using a smaller medium-speed engine. Size is an issue because of the limited space on most ships.

Sulfur in the fuel is also a concern for systems using an oxidation catalyst because, under the right conditions, sulfur can also be oxidized to form direct sulfate PM. At higher temperatures, up to 20 percent of the sulfur could be converted to direct sulfate PM in an oxidation catalyst. For a typical diesel engine without aftertreatment, the conversion rate is about 2 percent.[18] Depending on the precious metals used in the SCR unit, it may convert some sulfur to direct sulfate PM in the reactor as well. Manufacturers would have to design their exhaust system (and engine calibration) such that temperatures would be high enough to have good conversion of NO, but low enough to minimize conversion of sulfur to direct sulfate PM. Direct sulfate PM emissions could be reduced by using lower sulfur fuel.

SCR systems traditionally have required a significant amount of space on a vessel; in some cases the SCR unit is as large as the engine itself. However, at least one manufacturer is developing a compact system with an oxidation catalyst upstream of the reactor to convert some NO to $NO_{2,}$ thus reducing the reactor size necessary. The reactor size is reduced because the NO_2 can be reduced without slowing the reduction of NO. Therefore, the catalytic reaction is faster because NOx is being reduced through two mechanisms. This compact SCR unit is designed to fit into the space already used by the silencer in the exhaust system. If designed correctly, this could also be used to allow the SCR unit to operate effectively at somewhat lower exhaust temperatures. The oxidation catalyst and engine calibration would need to be optimized to convert NO to NO_2 without significant conversion of sulfur to direct sulfate PM. NOx reductions of 85 to 95 percent have been demonstrated with an extraordinary sound attenuation of 25 to 35 dB(A).[19]

A vessel using a SCR system would also require an additional tank to store ammonia (or urea to form ammonia). The urea consumption results in increased operating costs. If lower sulfur diesel fuel were required to ensure the durability of the SCR system or to minimize direct sulfate PM emissions, this lower sulfur fuel would also increase operating costs. The operation characteristics of ocean going vessels may interfere with correct maintenance of the SCR system. Ferries that use SCR today do not run continuously and therefore any maintenance necessary can be performed during regular down times. The availability of time for repair can be an issue for ocean going vessels which often do not have regular down time.

If the combustion is not carefully controlled, some of the ammonia can pass through the combustion process and be emitted as a pollutant. This is less of an issue for Category 3 marine engines, which generally operate under steady-state conditions, than for other mobile-source applications. In addition, in ships where banks of engines are used to drive power generators, such as cruise ships, the engines generally operate under steady-state conditions near full load. If ammonia slip still occurred, an oxidation catalyst downstream of the reactor could burn off the excess ammonia.

SCR reactors need constant cleaning using either ultrasound or compressed air. Ultrasound is performed by the use of an acoustic horn installed in the reactor. The horn automatically sounds for a period of time periodically during the operation of the engine. The air pulsation from the horn prevents dirt from building up on the catalyst without requiring engine shut down for maintenance. The horn may be driven by air from the normal air system installed on the vessel. Compressed air cleaning requires a period of engine shut down, during which a soot blowing probe is inserted into the catalyst unit to remove soot. Inspection holes are opened to allow the insertion of the probe. It is envisioned that the reactor will be cleaned during each port call, taking 4 person-hours for medium-speed engines and 6 person-hours for low-speed engines. SCR reactors can operate for about 20,000 hours before needing replacement.

5.3 Fuel Cells

Another approach to achieve large reductions in emissions would be to use fuel cells to power the vessel in place of an internal combustion engine. A fuel cell is like a battery, except a fuel cell generates electricity instead of storing it. The electro-chemical reaction taking place between hydrogen and oxygen gases generate the electricity from the fuel cell. The key to the energy generated in a fuel cell is that the hydrogen-oxygen reaction can be intercepted to capture small amounts of electricity. The by-product of this reaction is the formation of water. Current challenges include the storage or formation of hydrogen for use in the fuel cell and cost of the catalyst used within the fuel cell.

Over the past 5 years, several efforts to apply fuel cells to marine applications have been conducted. These include grants from the Office of Naval Research and the U.S. Navy. The Office of Naval Research initiated a three-phase advanced development program to evaluate fuel cell technology for ship service power requirements for surface combatants in 1997.[20] The U.S. Navy in early 2000 sponsored an effort to continue the development of the molten carbonate fuel cell for marine use.[21] The Society of Naval Architects and Marine Engineers released the technical report “An Evaluation of Fuel Cells for Commercial Ship Applications.”[22] This report examines fuel cells for application in commercial ships of all types for electricity generation for ship services and for propulsion.

The concept of fuel cells is currently supported by several sources, including the U.S. Maritime Administration (MARAD) and the state of California’s Fuel Cell Partnership. MARAD’s Division of Advanced Technology has included the topic of fuel cells as a low-emission technology that should be demonstrated. California’s Fuel Cell Partnership seeks to achieve four main goals which include 1) demonstrate vehicle technology by operating and testing the vehicles under real-world conditions in California; 2) demonstrate the viability of alternative fuel infrastructure technology, including hydrogen and methanol stations; 3) explore the path to commercialization, from identifying potential problems to developing solutions; and 4) increase public awareness and enhance opinion about fuel cell electric vehicles, preparing the market for commercialization.

5.4 Other Engine Technologies

Chapter 4 discusses several in-cylinder technologies that are being used to meet levels the internationally negotiated NOx standards. These technologies can be used in conjunction with water introduction strategies or selective catalytic reduction to optimize the engine/exhaust systems for further reductions. This section describes two other in-cylinder control strategies that could be used in conjunction with advanced technology for further emission reduction: exhaust gas recirculation and electronic control.

5.4.1 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is a recent development in diesel engine control technology for obtaining significant NOx reductions. EGR reduces peak combustion chamber temperatures by slowing reaction rates and absorbing some of the heat generated from combustion. While NOx emissions are reduced, PM and fuel consumption can be increased, especially at high loads, because of the reduced oxygen available and longer burn times during combustion.[23,24]

There are several methods of controlling any increase in PM emissions attributed to EGR. One method of minimizing PM increases is to reduce the flow of recirculated gases during high-load operation, which would also prevent a loss in total power output from the engine. Recent experimental work on a four-stroke high-speed diesel engine showed NOx reductions of about 50 percent, with little impact on PM emissions, using just six percent EGR in conjunction with a strategy of multiple injections.[25] Another method is to cool the exhaust gas recirculated to the intake manifold. By cooling the recirculated gas, it takes up less volume allowing more room for fresh intake air. With EGR cooling, a much higher amount of exhaust gas can be added to the intake charge. At light loads, there can be a small NOx penalty due to increased ignition delay, but at high loads, some additional NOx reduction may result from EGR cooling.[26] A third method to offset the negative impacts of EGR on PM is through the use of high intake air boost pressures. By turbocharging the intake air, exhaust gas can be added to the charge without reducing the supply of fresh air into the cylinder.[27]

Exhaust gas recirculation has also been shown on a slow-speed two-stroke engine, in conjunction with direct water injection, to achieve a 70 percent reduction in NOx.[28] Without EGR, only a 50 percent reduction in NOx was achieved. In a separate engine, six percent EGR dilution with a slow-speed two-stroke engine reduced NOx emissions by 22 percent.[29] In these cases, internal EGR was used by decreasing the efficiency of the scavenging process and trapping additional exhaust gas in the cylinder. The use of internal EGR has two primary advantages. First, the benefits of EGR can be achieved without any additional hardware such as lines and valves, thereby reducing the costs and complexity of the system. Second, internal EGR avoids some problems associated with external EGR. For example, routing the exhaust gas into the intake stream could cause soot to form deposits in the intake system, leading to wear on the turbocharger or a decrease in the efficiency of the aftercooler. As the amount of soot in the cylinder increases, so does the amount of soot that works its way past the piston rings into the lubricating oil, which can lead to increased engine wear. Another concern with routing the exhaust into the intake stream, especially for engines operating on residual fuel, would be corrosion in the intake system if the sulfur in the exhaust gas were to condense and form sulfuric acid. Using internal EGR avoids these problems.

5.4.2 Electronic Control

Various electronic control systems are in use or under development for nonroad, locomotive, highway, and marine diesel engines. Use of electronic controls enables designers to implement much more precise control of the fuel injection system and is especially beneficial for advanced concepts such as rate shaping. Through this precise control, trade-offs between various control strategies can be better balanced to minimize any negative effects. In addition, electronic controls can be used to sense ambient conditions and engine operation to maximize performance and minimize emissions over a wide range of conditions, such as transient operation of the engine. It can also be used with a feedback loop to optimize the exhaust conditions for effective selective catalytic reduction of NOx. Electronic control is already used in limited marine applications.

5.5 Category 1 and Category 2 Marine Diesel Engines

We also intend to reconsider Tier 3 emission standards for Category 1 and Category 2 standards in a future rulemaking. We proposed Tier 3 standards for these engines on December 11, 1998 (63 FR 68508), but chose not to finalize the Tier 3 standards at that time. Further analysis of potential Tier 3 standards for Category 1 and Category 2 marine diesel engines may be found in the draft Regulatory Impact Analysis prepared for the proposal for our 1999 rule.[30] Those standards relied on the types of in-cylinder controls described in 5.1 above.

In determining the proposed Tier 3 standards for Category 1 and Category 2 marine engines, we considered the application of technology being used for land-based nonroad and locomotive engines to marinized engines. We recently published a report on technology that we believe can be used by nonroad engines to meet Tier 3 standards.[31,32] We will consider the application of this technology to marinized engines as well. We will also consider the feasibility of using more advanced technologies than in-cylinder control for Category 1 and Category 2 marine engines. For instance, water-injection and SCR may also be applied to these engines.

5.6 PM Emission Control from Category 3 Marine Diesel Engines

For typical diesel engines operating on distillate fuel, particulate matter formation is primarily the result of incomplete combustion of the fuel (and lube oil). The traditional in-cylinder technologies discussed in section 4.1.4 can be used to reduce this type of PM formation while simultaneously reducing NOx emissions. If aftertreatment, such as SCR, is used to control NOx, then the in-cylinder technologies can be used primarily for PM reductions. However, because Category 3 marine engines generally use high-sulfur residual fuel, two issues arise.

The first issue is that the majority of PM emissions in engines burning residual fuel comes directly from the high concentration of sulfur in the fuel. As discussed in Chapter 4, metal oxides and sulfur in the fuel can make up 65 percent of the PM in the exhaust compared with only 15 percent in highway diesel engines. The emission-control technology discussed above would only have an impact on the non-sulfur PM exhaust emissions. A more effective control strategy would be to reduce the amount of sulfur in the fuel used by Category 3 marine engines. In addition, engines calibrated and tested for PM on distillate fuel would not necessarily see the same reduction in PM when operated on residual fuel due to the differences in the fuel characteristics. This leads to the second issue.

The second issue is that no acceptable procedure exists for measuring PM from engines operating on fuels with a sulfur level greater than 0.8 percent, as specified by ISO 8178. This is supported by correlation testing performed on a Category 3 engine at four laboratories.[33] Residual fuels typically have sulfur levels on the order of 2-4 percent and even distillate fuels used by Category 3 marine diesel engines generally have sulfur levels over 1 percent. Established PM test methods collect PM on a filter with a specification for maximum temperature. This maximum temperature is intended to ensure that the soluble organic fraction of the PM will condense and be collected on the filter. While non-sulfate PM is made up of hydrocarbons from the fuel and lube oil, the direct sulfate portion of the PM is made up of sulfate ions bonded with water. As a result, the measured mass of the sulfate portion of the PM is sensitive to test conditions such as temperature and humidity. This causes unacceptable variability in PM test results from engines operating on high sulfur fuels. In addition, when testing on residual fuel, the particulate concentration can ten times higher than when testing on distillate fuel. At these high PM levels, the PM in the exhaust can unpredictably deposit on the walls of the dilution tunnel and re-entrain into the exhaust stream. This adds some further uncertainty to the measured results.

Appendix to Chapter 5: Current DWI and SCR Installations

Wartsila DWI Reference List 2001 [34]

Ship	Owner	Engine	In Service
Ro ro	Goby Shipping AB	12V46C	Jan 1999
Ro ro	Goby Shipping AB	12V46C	Feb 1999
Ro ro	Ernst Russ GmbH & Co	12V46C	Mar 1999
Ro ro	Ernst Russ GmbH & Co	12V46C	Apr 1999
Ro ro	Bror Husell Chartering AB Ltd	16V46B	May 1999
Ro ro	Ernst Russ GmbH & Co	16V46B	Jun 1999
Ro ro	Ernst Russ GmbH & Co	16V46B	Dec 1999
Silja Symphony	Silja Line	4x9L46A	Jun 1999
Silja Serenade	Silja Line	4x9L46A	Jun 1999
Finnmarken	OVDS, Norway	2xW6L32, 2xW9L32	Nov 2001
Trolfjord	TFDF, Norway	2xW9L32	End 2001
Superfast XI	Superfast Ferries	4x12V46	End 2001
Superfast XII	Superfast Ferries	4x12V46	Spring 2002
Coral Princess	P&O Princess Cruises	2x16V46	Sep 2002
Island Princess	P&O Princess Cruises	2x16V46	Sep 2002
Diamond Princess	P&O Princess Cruises	2xW846, 2xW9L46	Jul 2003
Saphire Princess	P&O Princess Cruises	2xW846, 2xW9L46	End 2003
Chrystal Serenity	NYK Line	6x12V38B	Apr 2002
Chemical Tanker	Fortum Oil and Gas Oy	9L46C	May 2003
Chemical Tanker	Fortum Oil and Gas Oy	9L46C	July 2003
Car Ferry	TFDF, Norway	2xW9L32	End 2003
Chemical Tanker	Fortum Oil and Gas Oy	8L46	Jan 2003
Chemical Tanker	Fortum Oil and Gas Oy	8L46	July 2003

Wartsila SCR Reference List 2001 [35]

Vessel	Application	Engines	Fuel	Reduction Agent	Delivery Date	Notes
Aurora af Helsingborg	Double ended ferry	1 x WV6R32	MDO 0.1%S	40% urea water	1992	
Silja Serenade	Cruise ferry	1 x WV8R32	HFO 0.5%S	40% urea water	1995	
Silja Symphony	Cruise ferry	1 x WV8R32	HFO 0.5%S	40% urea water	1995	
Gabriella	Cruise ferry	1 x WV6R32	HFO 0.5%S	40% urea water	1997	Retrofit
Thjelvar	Ferry	2 x WV4R32 4 x WV12R32	HFO 0.5%S	40% urea water	1997	Compact SCR, retrofit
Birka Princess	Cruise ferry	4 x WV12R32 2 x WV6R32 1 x WV4R32	HFO 0.5%S	40% urea water	1999	Compact SCR, retrofit
M/V Spaarneborg	Ro-Ro	1 x 7RTA52U 2 x W6L20	HFO MDO	40% urea water	1999	
M/V Schieborg	Ro-Ro	1 x 7RTA52U 2 x W6L20	HFO MDO	40% urea water	1999	
M/V Slingeborg	Ro-Ro	1 x 7RTA52U 2 x W6L20	HFO MDO	40% urea water	2000	
Gotland Rederi	RoPax	4 x 12V46 3 x 9L20	HFO <1%S	40% urea water	2000	Compact SCR
Gotland Rederi	RoPax	4 x 12V46 3 x 9L20	HFO <1%S	40% urea water	2000	Compact SCR
M/V Granö	Ro-Ro	1 x WV1632	HFO	40% urea water	2000	Compact SCR, retrofit
Newbuilding	Special	2 x W6L32 2 x W12V32	LFO	40% urea water	2002	Compact SCR

SIEMENS SINOx Marine Exhaust Gas Treatment Plants and Systems[36,37]

Customer Operator	Field of Application	Fuel	Capacity in kW	Volume flow in Nm^3/h	Extent of Delivery	Delivery Date
TT-Line(D) Nils Dacke	Ship propulsion	MDO	4,500	27,500	SINOx	1995
Hertug Skule(N) Fosen Trafikklag	Ship propulsion	MDO	920	7,200	SINOx	1997
Gabriella (SF) Viking Line	Ship genset	MDO	2,000	12,000	SINOx	1997
Thielvar (S) Gotland Rederi	Ship propulsion 4 main engines 2 aux engines	MDO	4x3,720 2x1,240	4x18,500 2x6,000	SINOx	1997
Visby(S) Gotland Rederi	Ship propulsion 4 main engines 3 aux engines	MDO	4x5,200 3x1,435	4x37,500 3x7,500	SINOx	1997
Fast Ferry(S) Gotland Rederi	Ship propulsion 4 main engines 3 aux engines	MDO	4x7,000 3x450	4x40,000	SINOx	1998
MS Cellus (S) Roerd Braren	Ship propulsion 1 main engine 1 aux engine	HFO MDO	3,840 540	21,000 3,000	SINOx	1998
Birka Princess Wartsila NSD	Ship propulsion 4 main engines 2 aux engine	HFO MDO	4x4,500 2x2,250	4x26,000 2x14,200	SINOx	1998
MS Ortviken(S) SEA PARTNER	Ship propulsion 2 x main engines 3 x aux engines	HFO MDO	2x4,050 3x610	2x25,500 3x3,200	SINOx	1999
MS Baltic 2	Ship propulsion 1 main engine	HFO	3,360	19,000	SINOx	1999
MS Baltic 3	Ship propulsion 1 main engine	HFO	3,360	19,000	SINOx	1999
MS Baltic 4	Ship propulsion 1 main engine	HFO	3,360	19,000	SINOx	1999
MS Timbus(S) Roerd Braren	Ship propulsion 1 main engine 1 aux engines	HFO MDO	3,840 540	21,000 3,000	SINOx	1999
Customer Operator	Field of Application	Fuel	Capacity in kW	Volume flow in Nm3/h	Extent of Delivery	Delivery Date

Customer Operator	Field of Application	Fuel	Capacity in kW	Volume flow in Nm^3/h	Extent of Delivery	Delivery Date
MS Forester(S) Roerd Braren	Ship propulsion 1 main engine 2 aux engines	HFO MDO	3,840 2x239	21.000 2x1,200	SINOx	1999
Silja Line	Ship propulsion 4 main engines	HFO	4 x 7,950	48,500	SINOx	2000
1600 LM RoPax(S) Gotland Rederi	Ship propulsion 4 main engines 3 auxillary engines	HFO	4x12,600 3x1,530	4 x 63,000 3 x 9,000	SINOx	2000

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CHAPTER 6: Estimated Costs for Advanced Technologies

This chapter presents estimated costs for several of the emission-control technologies described in Chapter 5 for reducing emissions below the levels necessary to meet this first tier of EPA emission standards. While the technologies can be applied generally to marine diesel engines, we analyze the costs of these technologies only for engines over 30 liters per cylinder.

These estimated costs are based on our current understanding of the changes necessary to incorporate the advanced technologies on marine diesel engines. We start with a general description of the approach for estimating costs, then describe the various technologies and assess the projected costs of each approach. We developed the costs for individual technologies in cooperation with ICF, Incorporated and A.D. Little.[1] When we propose emission standards in the future, we will revisit the cost estimates presented in this chapter. We intend to use any information that becomes available in the meantime to update the cost estimates as needed to most accurately project the anticipated economic impacts of the standards we eventually propose.

6.1 Methodology

To simplify the analyses, costs were examined for one medium-speed engine and one slow-speed engine. Each of these base engines is considered in three different cylinder configurations to cover a wider range of power ratings. While these engines are drawn from real product offerings, they are intended to represent a broader group of engines than just these two models. Table 6.1-1 highlights the key operating characteristics of these representative engines.

Costs of control include variable costs (for incremental hardware and assembly) and fixed costs (for tooling and R&D). For technologies sold by a supplier to the engine manufacturers, variable costs are marked up at a rate of 29 percent to account for the supplier's overhead and profit.[2] The analysis also includes consideration of operating costs where that would apply. The result is a total estimated incremental cost for individual engines of various sizes. Costs are presented in 2002 dollars.

The impact of fixed costs on the per-engine costs depends on the number of engines produced using the advanced technologies. We consider two cost scenarios: applying the advanced technologies only to Category 3 engines on U.S. vessels, and applying them to Category 3 engines on all vessels that use U.S. ports.

Table 6.1-1
Power Ranges and Nominal Power for Estimating Costs (kW)

Specific Displacement (L/cyl)	Maximum engine speed (rpm)	Number of Cylinders	Rated Power (kW)
55	600	6	4,000
		9	6,000
		12	8,000
900	80	4	8,000
		8	16,000
		12	24,000

6.2 Technology Costs

Total estimated costs are developed by considering the development time and hardware costs to design and integrate emission-control strategies into a marketable engine. The following paragraphs describe these technologies and their application to marine engines.

6.2.1 Fuel Injection Improvements

Fuel-injection improvements can be made in at least two ways. First, manufacturers might redesign existing systems for higher pressure, better control (including rate shaping), and adjusted injection timing. Other manufacturers may make a design decision to make a step change in technology, switching to common rail systems. Second, common rail technology allows the engine designer to maintain high-pressure injection at all engine speeds and makes it easier to control injection timing, including the ability to manage split injection. Common rail systems depend on incorporating electronic controls to manage fuel delivery.

Table 6.2-1 details the variable costs associated with a common-rail system, including estimated costs for the various controllers, pumps, and other necessary hardware. Total variable costs range from $11,000 to $22,000 for medium-speed engines and from $24,000 to $71,000 for slow-speed engines. These costs would be the same whether the standards apply to engines on U.S. vessels or whether they also apply to engines on foreign vessels. Fixed costs for development and tooling are considered in the next section.

Table 6.2-1
Projected Costs per Engine for Fuel Injection Upgrade

	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
Hardware cost to manufacturer						
electronic control unit	$350	$350	$350	$350	$350	$350
common rail accumulator	$2,000	$3,000	$4,000	$4,000	$8,000	$12,000
low-pressure pump	$1,600	$2,400	$3,200	$3,200	$6,400	$9,600
high-pressure pump	$3,200	$4,800	$6,400	$6,400	$12,800	$19,200
modified injectors	$2,100	$3,150	$4,200	$7,200	$14,400	$21,600
wiring harness	$300	$300	$300	$600	$600	$600
Total component cost	$9,550	$14,000	$18,450	$21,750	$42,550	$63,350
Assembly @ $28/hr	$1,882	$2,822	$3,763	$2,509	$5,018	$7,526
Total Hardware cost	$11,432	$16,822	$22,213	$24,259	$47,568	$70,876

6.2.2 Engine Modifications

Engine modifications may include a wide range of strategies to improve the way an engine handles air intake, fuel injection, or air-fuel mixing in the cylinder. Several different strategies may work together to provide an optimum level of emission control while minimizing any potential negative effects on performance, durability, or fuel consumption.

The kind of changes addressed in this section do not necessarily involve variable costs (except for changes to fuel injection, as noted above). Changing valve timing and redesigning the geometry of engine components, for example, would generally not involve cost increases beyond those considered for development time and tooling. Projected costs in this section include the fixed costs associated with the fuel-injection improvements described above. Since fuel-injection variables must be incorporated in the context of other changes to the engine, it is appropriate to consider development time for fuel injection together with the overall R&D effort for each engine model.

The estimated costs include a substantial time allowance for manufacturers to pursue engine improvements. This would allow for further exploration beyond fuel-injection variables into many of the strategies described in Chapter 5. Manufacturers could use this development time to pursue changes in valve timing, compression ratio, location of fuel injectors, piston head geometry, and many other design variables. The cost projections generally contemplate development time (including testing) for two engineers and three technicians to work on each engine family for a full year. This development effort would apply for all the different available cylinder configurations of a given engine family, which is consistent with our provision allowing manufacturers to certify their engine families based on single-cylinder development engines. In practice, manufacturers would likely need more time to redesign the first engine family, while the lessons learned from early development efforts would lead to reduced development time for later engine families.

An important variable in estimating fixed costs on a per-engine basis is identifying the appropriate sales volumes. Sales volumes for U.S. vessels are very small. For this analysis we have estimated that manufacturers will be able to amortize fixed costs related to the emission standards over four engines per year. This is somewhat higher than current sales volumes, for two main reasons. First, even if the standards were to apply only to Category 3 engines on U.S. vessels, manufacturers may be able to market these engines on the global market as a superior product, thereby increasing the sales volume over which they can recover development costs. Second, it is possible that new ship construction for the U.S. market may increase in the future. Currently, new ship construction rates in the U.S. are below the rate necessary for ongoing replacement of vessels, resulting in an overall aging of the U.S. fleet. Requirements related to double-hull tanker designs may also lead ship owners to consider retrofitting or replacing existing ships. Together, these factors may lead to increased rates of ship construction over the next several years. Costs are amortized over five years, consistent with previous cost estimates for emission-control programs.

Amortizing fixed costs would involve a very different set of numbers if the standards apply to engines on foreign vessels. Under this scenario, we would estimate annual sales of 40 engines for each engine family. This comes from dividing the approximately 1200 total engines produced world-wide by half (to exclude those that will never come to the U.S.), and dividing the remaining engines over five companies, each with an average of three separate engine families. Setting international standards that apply globally would roughly double the assumed sales volumes and halve the estimated fixed cost per engine, but this would be a very small effect compared with assigning costs only to engines on U.S. vessels.

These costs are summarized in Table 6.2-2. Estimated costs are about $64,000 per engine. If the standards apply to engines on both U.S. and foreign vessels, the estimated cost per engine drops nearly to $6,000.

Table 6.2-2
Projected Costs per Engine for Engine Modifications

	Amortization parameter	Medium-speed Engine	Low-speed Engine
Total fixed costs	R&D costs	$874,000	$874,000
	Retooling costs	$40,000	$40,000
U.S. vessels only	Engines per year	4	4
	Fixed cost per engine	$64,019	$64,019
Including foreign vessels	Engines per year	40	40
	Fixed cost per engine	$6,402	$6,402

6.2.3 Direct Water Injection

Table 6.2-3 presents estimated costs for injecting water directly into the engine’s cylinders. Variable costs consider the various components and labor required to assemble the system, including the cost of separate injectors for fuel and water. The estimated variable costs include a markup, which reflects the technology development and overhead involved for the company manufacturing the components and assemblies that the engine manufacturer will buy and integrate into the overall engine design. The analysis does not incorporate a cost related to lost cargo space as a result of water storage needs. The engine manufacturer’s fixed costs associated with system integration allow for engineering time to optimize the control technology for effective emission control while maintaining acceptable performance. This includes substantial time for manufacturers to optimize in-cylinder controls in their efforts to produce an overall system solution to incorporating water-injection technology. Total costs range from about $120,000 to $320,000 depending on engine size. If emission standards apply also to engines on foreign vessels, the estimated cost range is $50,000 to $250,000.

In addition, any ship using direct water injection would incur operating costs to keep the system functioning. These operating costs are best quantified on an hourly basis. Total costs depend on how long the systems run. This cost analysis is based on the expectation that ship operators will activate the water-injection systems during the time that the ships are within 175 nautical miles of the U.S. coast. We estimate this annual operating rate to be 975 hours for U.S. vessels and 149 hours for foreign vessels. Considering the population of these types of vessels leads to a composite figure of 170 hours per year for all vessels.

We consider two types of operating costs—water and fuel. At a cost of $0.10 per gallon for distilled water, total estimated costs per year for U.S. vessels range from $4,000 to $23,000. Since foreign vessels spend less of their total operating time near the U.S., their estimated annual water costs range from $600 to $3,600. Calculated as a net present value, with 7 percent discounting to the point of sale, estimated composite costs are $120,000 for U.S. vessels and

$21,000 if we apply the standards to Category 3 engines on all vessels (see Table 6.2-4). Note that these estimated water costs might be significantly reduced if a ship were designed to provide its own supply of fresh water by adding a desalination plant (or increasing the capacity of an existing desalination unit).

We also estimate a 2-percent increase in fuel consumption for engines using direct water injection for operation within 175 miles of the U.S. coast. This involves annual costs of $900 to $5,500 per year for engines on U.S. vessels.[3] Applying standards to Category 3 engines on all vessels would result in estimated average per-engine costs of $200 to $1,000.

As a sensitivity analysis, we consider the effect of operating a water-injection unit at all times that the propulsion engine is running. To quantify this, we calculate revised operating costs for increased fuel consumption and the greater amount of water used to control NOx emissions. The composite calculation of operating costs yields an estimated net present value of $630,000, based on an operating rate of 4,000 hours per year (see Table 6.3-2 to compare with other scenarios). This estimated cost applies equally to all vessels, regardless of their flag state. We would expect no additional fixed or variable costs associated with producing a system designed to operate continuously. On the other hand, a ship owner may substantially reduce operating costs by investing in onboard water-production capability, as described above.

Table 6.2-3
Projected Costs per Engine for Direct Water Injection

	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
Hardware cost to manufacturer						
water tank	$2,600	$3,900	$5,200	$5,200	$10,400	$15,600
low-pressure module	$2,400	$3,600	$4,800	$4,800	$9,600	$14,400
high-pressure module	$4,800	$7,200	$9,600	$9,600	$19,200	$28,800
flow fuses	$3,000	$4,500	$6,000	$6,000	$12,000	$18,000
water injectors	$15,000	$22,500	$30,000	$30,000	$60,000	$90,000
piping	$1,400	$2,100	$2,800	$2,800	$5,600	$8,400
control unit/wiring	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
Total component cost	$30,200	$44,800	$59,400	$59,400	$117,800	$176,200
Assembly @ $28/hr	$1,882	$2,822	$3,763	$3,763	$7,526	$11,290
Total variable cost	$32,082	$47,622	$63,163	$63,163	$125,326	$187,490
Markup @29%	$9,304	$13,810	$18,317	$18,317	$36,345	$54,372
Total Hardware RPE	$41,386	$61,432	$81,480	$81,480	$161,671	$241,862
Fixed costs						
R&D	—	$874,000	—	—	$874,000	—
retooling	—	$250,000	—	—	$250,000	—
marine society approval	—	$5,000	—	—	$5,000	—
engines per year	—	4	—	—	4	—
years to recover	—	5	—	—	5	—
Fixed Cost per Engine	$77,720	$77,720	$77,720	$77,720	$77,720	$77,720
Total Costs per Engine	$119,106	$139,152	$159,200	$159,200	$239,391	$319,582
Including foreign vessels						
Total Hardware RPE	$41,386	$61,432	$81,480	$81,480	$161,671	$241,862
Fixed Cost per Engine	$7,772	$7,772	$7,772	$7,772	$7,772	$7,772
Total Costs per Engine	$49,158	$69,204	$89,252	$89,252	$169,443	$249,634

Table 6.2-4
Water costs for Direct Water Injection

Parameter	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
BSFC (g/kW-hr)	190	190	190	190	190	190
load factor	50%	50%	50%	50%	50%	50%
water/fuel ratio	40%	40%	40%	40%	40%	40%
water use (kg/hr)	152	228	304	304	608	912
water cost per kg	$0.0264	$0.0264	$0.0264	$0.0264	$0.0264	$0.0264
water cost per hour	$4	$6	$8	$8	$16	$24
total cost per year (U.S. vessels only)— @ 975 hours/yr.	$3,900	$5,850	$7,800	$7,800	$15,600	$23,400
Present value (U.S. vessels only)	$43,962	$65,942	$87,923	$87,923	$175,846	$263,769
total cost per year (foreign vessels only)— @ 149 hours/yr.	$596	$894	$1,192	$1,192	$2,384	$3,576
Present value (foreign vessels only)	$6,718	$10,077	$13,436	$13,436	$26,873	$40,309
total cost per year (composite)— @ 170 hours/yr.	$680	$1,020	$1,360	$1,360	$2,720	$4,080
Present value (composite)	$7,665	$11,498	$15,330	$15,330	$30,660	$45,991

6.2.4 Selective Catalytic Reduction

Selective Catalytic Reduction (SCR) can be designed to operate at different levels of NOx-reduction efficiency. Increasing NOx reductions correspond with higher costs. For this analysis, system parameters are based on settings to allow an 80-percent reduction in NOx emissions. Later in this section, we consider the effect on costs of installing and operating a system set for less effective NOx reduction.

Variable costs include the various components and labor required to assemble the system and integrate it into the vessel. The estimated variable costs include a markup, which reflects the technology development and overhead involved for the company manufacturing the components and assemblies that the engine manufacturer will buy and integrate into the overall engine design.

The engine manufacturer's fixed costs associated with system integration allow for engineering time to optimize the control technology for effective emission control while maintaining acceptable performance. This includes substantial time for manufacturers to optimize in-cylinder controls in their efforts to produce an overall system solution to incorporating SCR technology. Total costs range from about $260,000 to $1.23 million, depending on engine size. The expected costs for very high-volume reactors for the largest engines involve oversize components and additional engineering that substantially increase total estimated costs for those units. If emission standards apply also to engines on foreign vessels, the estimated cost range is $220,000 to $1.18 million. Table 6.2-5 summarizes the estimated costs for such an SCR system.

As described in Section 6.2.3, SCR units can be managed so that they operate only within 175 nautical miles of the U.S. coast, which leads us to calculate operating costs on an hourly basis. For SCR, we consider three kinds of operating costs. First, a ship using SCR must provide urea to the engine. At a cost of $1.30 per gallon for aqueous urea, total estimated costs per year for U.S. vessels range from $9,000 to $53,000. Since foreign vessels spend less of their total operating time near the U.S., their estimated annual urea costs range from $1,300 to $8,000. Calculated as a net present value, with 7 percent discounting to the point of sale, estimated composite costs are $270,000 per engine for U.S. vessels and $48,000 per engine if we include foreign vessels (see Table 6.2-5).

Second, SCR operation is more durable when engines operate on fuels with low concentrations of sulfur. This may involve operation with a low-sulfur residual fuel, distillate fuel, or a blend of these two fuel types. Further investigation would help us establish the specific fuel requirements for maintaining SCR systems in the field. This analysis presents the estimated costs associated with operation on distillate fuel within 175 nautical miles of the U.S. coast. We believe that most vessels already have dedicated tanks available for storing distillate fuel. If a vessel would need a new tank or an additional tank devoted to carrying distillate fuel, that would involve an additional cost beyond what we consider in this analysis. Calculating the cost of using a marine distillate fuel depends on an estimated load factor of 50 percent. Current prices for the different fuel types shows an increase of about $75 per ton of fuel for switching to marine distillate. This results in annual costs ranging from $28,000 to $170,000 per engine for U.S. vessels. Including foreign vessels would drop these costs to a range of $5,000 to $29,000 per engine. Fuel costs are discussed in Section 6.2.5.

Third, the analysis considers costs related to system maintenance. The SCR reactor may need routine cleaning for optimum operation. This is performed through the use of either ultrasound or compressed air. Ultrasound is performed by the use of an acoustic horn installed in the reactor. The horn automatically sounds periodically while the engine is operating. The air pulsation from the horn prevents soot from building up in the catalyst. The horn may be driven by air from the normal air system installed on the vessel. This method requires no engine shutdown. Using compressed air to clean the reactor would require a period of engine shut down. In this method, a soot-blowing probe is inserted into the catalyst unit to remove soot. As manufacturers gain experience with these systems, it will become clearer which of these cleaning operations is preferred. For this analysis, we anticipate ten cleaning steps per year, taking 4 person-hours for medium-speed engines and 6 person-hours for low-speed engines. This results in net-present value maintenance costs ranging from \$18,000 to \$26,000, as shown in Table 6.2-7. SCR reactors generally would need to be rebuilt or replaced after about 20,000 hours of operation; however, we do not expect SCR units to operate so long over the life of a Category 3 marine diesel engine.

We consider two sensitivity analyses regarding SCR. First, similar to that described for water injection, we calculate costs based on continuous operation of the SCR unit when the propulsion engine is running. Increasing the annual operating rate to 4,000 hours and increasing to 25 cleaning steps in a year raises the composite operating costs to a net present value of \$4.7 million (see Table 6.3-2 to compare with other scenarios). This estimated cost applies equally to all vessels, regardless of their flag state. We would expect no additional fixed or variable costs associated with producing a system designed to operate continuously.

For the second sensitivity scenario, we consider the cost effect of installing an SCR unit designed to reduce emissions by only 50 percent. The less aggressive NOx reductions translate into lower capital and operating costs based on published estimates for commercially available systems.[4] This leads us to estimate a 10-percent lower level of fixed costs and a 30-percent lower level for variable (or component) costs. This lower costs result mainly from designing and producing a smaller, simpler reactor. The estimated composite cost per engine for an SCR unit achieving a 50-percent NOx reduction is \$415,000 for engines on U.S. vessels and \$375,000 if we include all vessels. Operating costs for urea would decrease approximately in proportion to the NOx reduction. It is unclear whether a 50-percent SCR system would be more tolerant of fuel sulfur or whether it would need the same fuel quality as an 80-percent system. If we make fuel costs also proportional to percent reductions over 975 hours of operation (for U.S. vessels only), we calculate a composite operating cost of \$735,000 (net present value).

Table 6.2-5
Projected Costs per Engine for SCR

	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
Hardware cost to manufacturer						
aqueous urea tank	$2,600	$3,900	$5,200	$5,200	$10,400	$15,600
reactor	$120,000	$180,000	$240,000	$240,000	$480,000	$720,000
dosage pump	$4,400	$6,600	$8,800	$8,800	$17,600	$26,400
urea injectors	$7,500	$10,000	$15,000	$20,000	$40,000	$60,000
piping	$3,000	$4,500	$6,000	$6,000	$12,000	$18,000
exhaust bypass valve	$10,000	$15,000	$20,000	$16,000	$32,000	$48,000
control unit/wiring	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
Total component cost	$148,500	$221,000	$296,000	$297,000	$593,000	$889,000
Assembly @ $28/hr	$1,882	$2,822	$3,763	$3,763	$7,526	$11,290
Total variable cost	$150,382	$223,822	$299,763	$300,763	$600,526	$900,290
Markup @29%	$43,611	$64,908	$86,931	$87,221	$174,153	$261,084
Total Hardware RPE	$193,993	$288,730	$386,694	$387,984	$774,679	$1,161,374
Fixed costs						
R&D	—	$437,000	—	—	$437,000	—
retooling	—	$250,000	—	—	$250,000	—
marine society approval	—	$5,000	—	—	$5,000	—
engines per year	—	4	—	—	4	—
years to recover	—	5	—	—	5	—
Fixed Cost per Engine	$47,168	$47,168	$47,168	$47,168	$47,168	$47,168
Total Costs per Engine	$241,161	$335,898	$433,862	$435,152	$821,847	$1,208,542
Including foreign vessels						
Total Hardware RPE	$193,993	$288,730	$386,694	$387,984	$774,679	$1,161,374
Fixed Cost per Engine	$4,717	$4,717	$4,717	$4,717	$4,717	$4,717
Total Costs per Engine	$198,710	$293,447	$391,411	$392,701	$779,396	$1,166,091

Table 6.2-6
Urea costs for SCR

Parameter	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
BSFC (g/kW-hr)	190	190	190	190	190	190
load factor	50%	50%	50%	50%	50%	50%
aqueous urea rate	7.5%	7.5%	7.5%	7.5%	7.5%	7.5%
aqueous urea use (kg/hr)	29	43	57	57	114	171
aqueous urea cost per kg	$0.3173	$0.3173	$0.3173	$0.3173	$0.3173	$0.3173
total cost per year (U.S. vessels only)— @ 975 hours/yr.	$8,775	$13,650	$17,550	$17,550	$35,100	$52,650
Present value (U.S. vessels only)	$98,913	$153,865	$197,827	$197,827	$395,654	$593,481
total cost per year (foreign vessels only)— @ 149 hours/yr.	$1,341	$2,086	$2,682	$2,682	$5,364	$8,046
Present value (foreign vessels only)	$15,116	$23,514	$30,232	$30,232	$60,464	$90,696
total cost per year (composite)— @ 170 hours/yr.	$1,530	$2,380	$3,060	$3,060	$6,120	$9,180
Present value (composite)	$17,246	$26,828	$34,493	$34,493	$68,986	$103,479

Table 6.2-7
Maintenance costs for SCR

Parameter	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
Cleaning—per event	$157	$157	$157	$235	$235	$235
Cleaning—NPV	$1,570	$1,570	$1,570	$2,350	$2,350	$2,350

6.2.5 Fuel Costs

Table 6.2-8 presents the fuel costs we use in our analyses of various emission-control approaches. These analyses include the costs of reducing fuel sulfur to enable SCR technology and baseline fuel costs for a fuel consumption sensitivity analysis. Prices for residual fuel and marine diesel oil come from Marine Bunker News.[5] Note that these costs represent about a 50% increase compared with the costs from January 2002 that were used in the analysis supporting the proposal.[6] Given the volatility of fuel prices, it is clear that fuel-related cost estimates may change significantly when we reconsider emission standards for Category 3 engines. Table 6.2-9 shows how these prices translate into increased operating costs when switching from the least expensive residual fuel to marine distillate.

Table 6.2-8
Bunker Fuel Costs per Metric Ton (October 23, 2002)

Port	Residual Fuel 380 centistokes	Residual Fuel 180 centistokes	Marine Distillate
Rotterdam	$141-142	$145-146	$212-213
Fujairah	$155-157	$160-161	$255-256
Singapore	$153-154	$157-158	$232-236
Houston	$144-145	$147-148	$218-220

Table 6.2-9
Costs of Switching from Residual Fuel to Marine Distillate Fuel to Enable SCR Technology

Parameter	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
BSFC (g/kW-hr)	190	190	190	190	190	190
load factor	50%	50%	50%	50%	50%	50%
increased fuel cost per hour	$29	$43	$58	$58	$113	$171
total cost per year (U.S. vessels only)— @ 975 hours/yr.	$28,267	$41,786	$56,534	$56,534	$110,609	$167,143
Present value (U.S. vessels only)	$318,629	$471,016	$637,257	$637,257	$1,246,808	$1,884,066
total cost per year (foreign vessels only)— @ 149 hours/yr.	$4,320	$6,386	$8,639	$8,639	$16,903	$25,543
Present value (foreign vessels only)	$48,693	$71,981	$97,386	$97,386	$190,538	$287,924
total cost per year (composite)— @ 170 hours/yr.	$4,929	$7,286	$9,857	$9,857	$19,286	$29,143
Present value (composite)	$55,556	$82,126	$111,112	$111,112	$217,392	$328,504

6.3 Total Engine Costs

6.3.1 Distribution of Category 3 Marine Engines

We can use the cost estimates presented above to develop an estimated composite cost for applying advanced technologies to Category 3 marine diesel engines. This estimate is based on the characteristics of the current fleet. Population data show that 60 percent of these are two-stroke engines.[7] The average power rating for vessels using Category 3 marine engines is 11,000 kW. This average kW is based on data collected on seven U.S. ports that are available to ocean-going vessels.[8] Using these parameters, we estimated the distribution of engines shown in Table 6.3-1. While the actual distribution clearly covers a much wider range of engines and may change before we propose emission standards requiring advanced technologies, this analysis provides an initial estimate to assess the costs of incorporating advanced technologies.

Table 6.3-1
Estimated Distribution of Category 3 Engine Sizes

Medium-speed Engines			Slow-speed Engines		
6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
20%	10%	10%	25%	20%	15%

6.3.2 Projected Composite Costs for Category 3 Engines

We estimated composite costs for two of the technology approaches described in this chapter—direct water injection and selective catalytic reduction. These costs are summarized in Table 6.3-2. For direct water injection, the total estimated composite costs for U.S. vessels is about $190,000. Annual operating costs are estimated at $14,000, with discounted lifetime operating expenses estimated to be just over $150,000. Including foreign vessels would decrease estimated composite engine costs to around $120,000 and lifetime operating expenses to $26,000.

For SCR, the total estimated composite costs for U.S. vessels is about $580,000, based on parameters that would allow for NOx emission reductions of about 80 percent. Annual operating costs are estimated at $103,000, with discounted lifetime operating expenses estimated to be $1.2 million. Including foreign vessels would decrease estimated composite engine costs to $540,000 and lifetime operating expenses to $220,000.

The analysis is based on manufacturers recovering their fixed costs over a five-year period. Once these costs are fully amortized, they are removed from the analysis. Since fixed costs are large and sales volumes are small, removing the fixed costs substantially reduces the estimated long-term costs, as shown in Table 6.3-2. Long-term costs may also decrease as manufacturers learn to produce emission-control technologies at a lower cost. We have not quantified the learning effect in this analysis.

Table 6.3-2
Summary of Projected Costs per Engine for Advanced Technology

Technology Package	Scope of Standards	Cost Parameter	Medium-speed Engines			Slow-speed Engines			Composite
			6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.	
Direct Water Injection	U.S. vessels only	Total cost per engine (yr. 1)	$119,105	$139,153	$159,201	$156,579	$239,391	$319,582	$188,617
		Total cost per engine (yr. 6 and later)	$26,486	$39,317	$52,148	$50,470	$103,469	$154,792	$70,974
		Operating costs (NPV)	$55,912	$84,029	$111,824	$111,824	$223,971	$335,794	$153,887
	U.S. and foreign vessels	Total cost per engine (yr. 1)	$49,157	$69,205	$89,253	$86,631	$169,443	$249,634	$118,669
		Total cost per engine (yr. 6 and later)	$26,486	$39,317	$52,148	$50,470	$103,469	$154,792	$70,974
		Operating costs (NPV)	$9,749	$14,651	$19,497	$19,497	$39,051	$58,549	$26,832
SCR	U.S. vessels only	Total cost per engine (yr. 1)	$241,160	$335,899	$433,863	$435,153	$821,847	$1,208,542	$579,647
		Total cost per engine (yr. 6 and later)	$124,155	$184,788	$247,485	$248,310	$495,795	$743,279	$340,787
		Operating costs (NPV)	$435,240	$642,579	$852,782	$861,574	$1,668,952	$2,504,036	$1,161,373
	U.S. and foreign vessels	Total cost per engine (yr. 1)	$198,709	$293,448	$391,412	$392,702	$779,396	$1,166,091	$537,196
		Total cost per engine (yr. 6 and later)	$124,155	$184,788	$247,485	$248,310	$495,795	$743,279	$340,787
		Operating costs (NPV)	$90,500	$126,651	$163,302	$172,094	$312,868	$458,472	$221,463

Chapter 6 References

1.“Emission Reduction Technology Costs for Category 3 Marine Diesel Engines,” Draft Report from Louis Browning et al, Arthur D. Little–Acurex Environmental, March 2002.

2."Update of EPA's Motor Vehicle Emission Control Equipment Retail Price Equivalent (RPE) Calculation Formula," Jack Faucett Associates, Report No. JACKFAU-85-322-3, September 1985 (Docket A-97-50; document IV-A-5).

3.The methodology for calculating costs (or savings) related to changes in fuel consumption are documented in “Estimated Cost Impacts of Changing Fuel Consumption Rates for Category 3 Marine Diesel Engines,” EPA memorandum from Alan Stout to Docket A-2001-11, November 15, 2002 (Document IV-B-03).

4.“SCR Economics for Diesel Engines,” Ravi Krishnan, Diesel & Gas Turbine Worldwide, July-August 2001 (Docket A-2001-11; document IV-A-04).

5. Bunker News, “Bunker Prices,” www.bunkernews.com, October 23, 2002.

6. Bunker News, “Bunker Prices,” www.bunkernews.com,
January 4, 2002 (Docket A-2001-11, document II-A-31).

7.*Motor Ship*, Annual Analysis, June 1999, pp. 49-50.

8. “Commercial Marine Activity for Deep Sea Ports in the United States: Final Report,” ARCADIS Geraghty & Miller, Inc., prepared for U.S. EPA, June 30, 1999.

CHAPTER 7: Inventory Baseline and Projections for Advanced Technology

This chapter presents our analysis of emissions from Category 3 marine diesel engines. It was developed under contract with E. H. Pechan & Associates, Inc.[1] The first section contains a description of the methodology used to develop the baseline emission inventories for the base year (1996). The second section contains a description of the methodology used to develop inventory projections for future years. The next two sections contain the expected emission reductions that would result from the long-term emission standards that reflect use of the advanced technologies, both in the national inventories and on a per-vessel basis. We investigated two advanced control scenarios: a 50 percent and an 80 percent reduction from the standards we are finalizing.

This chapter is devoted entirely to emissions from Category 3 marine diesel engines. Our analysis of emissions from Category 1 and 2 marine diesel engines was done in support of our 1999 rulemaking and can be found in the Final Regulatory Impact Analysis for that rule.[2]

7.1 Baseline Inventories

7.1.1 Geographic Boundaries

In developing emission inventories for Category 3 marine diesel engines, it is important to consider the geographic area in which they operate. This is important because, unlike other nonroad engines like trucks or locomotives, marine vessels may not operate all of the time within the U.S. air shed. Therefore, we need to determine what portion of their operating time occurs within the U.S., during which they contribute to U.S. air quality problems. For ships that operate on the Great Lakes or inland waterways, our analysis counts all Category 3 marine diesel emissions as occurring within the United States. For ocean-going vessels, we count only emissions that occur while the vessel is operating within 175 nautical miles from the U.S. coasts. This 175-mile area is based on an estimate of the distance NOx molecules could travel in one day (assuming a 10 mile per hour wind traveling toward a coast, NOx molecules emitted 12 miles from the coast could reach the coast in just over one hour. NOx molecules emitted 175 nautical miles, or 200 statute miles, from the coast could reach the coast in less than a day).

As noted in Chapter 2 and described in more detail below, the inventories were estimated in two parts: in-port emissions are based on information for specific ports and are estimated for a radius of 25 miles from port; non-port emissions are based on cargo movement data and cover the area from 25 to 175 miles from the coasts.

In our proposal we requested comment on the issue of pollutant transport and additional data that would help us better understand the issue and thus develop a better estimate of how far off of the coast we should be considering. We received some comments in favor of using the 175 nautical mile limit and no new data that would allow us to develop a better estimate. Thus, for the purposes of this analysis the 175 nautical mile limit will be used. However, in support of future rulemaking efforts we plan to continue researching the pollutant transport issue in an effort to better understand how offshore emissions affect air quality on land.

7.1.2 Ports Inventories

For port areas we developed detailed emission estimates for nine specific port areas using port activity data including port calls, vessel types and typical times in different operating modes. The nine port areas analyzed in detail were the Lower Mississippi (New Orleans and Baton Rouge), New York, Delaware River (Philadelphia area), Puget Sound, Corpus Christi, Tampa, Baltimore, Coos Bay, Cleveland and Burns Harbor. Vessel types considered included bulk carrier, container ship, general cargo, passenger, refrigerated (reefer), roll-on roll-off (ro ro) tanker, vehicle carrier, and other miscellaneous vessels.

Emission estimates for all other ports were developed by matching each of those ports to one of the nine specific ports already analyzed based on characteristics of port activity, such as predominant vessel types, harbor draft and region of the country. The detailed port emissions were then scaled to the other ports based on relative port activity. Ports were looked at separately for four main regions of the country; the Pacific Coast, the Gulf Coast, the Atlantic Coast, and the Great Lakes.

For the port areas analysis three different types of vessel transit operation were considered. Cruising is when the vessel is approaching the port but not yet required to reduce its speed. The reduced speed zone (RSZ) is the portion of the vessel’s approach to the port where it is required to reduce its speed. Maneuvering includes vessel movement while in port (berthing or moving from one berth to another). The relative amounts of these types of transit operation vary from one port to another, depending on geography and traffic patterns. For example, port areas that include some river transit have greater RSZ operation than other port areas. The load factor (fraction of rated power) for cruise mode was assumed to be 80 percent. For RSZ operation the load factor is generally between 15 and 35 percent, depending on vessel type and port geography. However, there are a few port areas where the RSZ load factor can go as high as 70 percent for some vessel types. The maneuvering load factor is between ten and 12 percent.

This analysis was intended to characterize emissions specifically from Category 3 Marine diesel engines, rather than vessels powered by Category 3 engines. Emissions from Category 3 vessels also include hotelling emissions, which are emissions generated in the process of generating electric power for the vessel. In general, we assumed that most hotelling emissions from Category 3 vessels are actually generated by Category 1 and 2 auxiliary engines, rather than the main Category 3 propulsion engine. However, in the case of passenger vessels and reefer ships, where the demand for electric power is great, we assumed that the hotel power is generated by the category 3 propulsion engine. Thus, hotelling emissions from passenger and reefer ships are included in the inventories, but not hotelling emissions from any other vessel types.

The ports emissions were calculated by associating and summing the product of the vessel trips (port calls), vessel power, and average load factor by mode of operation and time in mode for all modes of operation. The general equation used for calculating port emissions is shown below.

Emissions = Trips × Power × LF in mode × Time in mode × EF

Where: Trips - number of trips or vessel calls by vessel and engine type
Power - rated power of propulsion engine by vessel and engine type
LF - load factor (fraction of rated power) by mode
Time - average time for each mode by vessel and engine type
EF - emission factor in mode and by engine type

Emission factors were developed separately for slow speed and medium speed Category 3 Marine diesel engines. The emission factors used are shown in Table 7.1-1.

Table 7.1-1
Emission Factors for Category 3 Marine Diesel Engine Transit Emissions (g/hp-hr)

Engine Type	HC	CO	NOx	PM	SOx
Slow Speed	0.395	0.82	17.60	1.29	9.56
Medium Speed	0.395	0.52	12.38	1.31	9.69

Emission factors tend to be relatively steady at loads greater than 20 percent. Thus, emission factors developed from emissions measured at full load were used as the cruise and RSZ emission factors as well. However, at low loads the emission factors tend to increase as compared with higher loads. The emission factors shown in Table 7.1-1 were used for cruise and RSZ modes of operation. For maneuvering operation we adjusted the emission factors based on relationships developed for us by Energy and Environmental Analysis, Inc.[3] The adjustments we applied to the emission factors shown in Table 7.1-1 to develop maneuvering emission factors are shown in Table 7.1-2.

Table 7.1-2
Ratio of Maneuvering Emission Factors at 10 percent Load to Full Load Emission Factors

Engine Type	HC	CO	NOx	PM	SOx
Slow Speed	5.28	8.52	1.36	1.69	1.57
Medium Speed	5.50	7.41	1.36	1.68	1.55

The total national Category 3 Marine diesel inventories for within 25 nautical miles of all U.S. ocean ports and 10 nautical miles of all U.S. Great Lakes ports are shown in Table 7.1-3.

Table 7.1-3
Total U.S. Category 3 Emission Inventories for Port Areas in 1996 (short tons)

HC	CO	NOx	PM	SOx
5,230	1,944	101,137	9,299	97,390

7.1.3 Non-Port Inventories

We developed non-port emission inventories using cargo movements and waterways data, vessel speeds, average dead weight tonnage per ship, and assumed cargo capacity factors. We assumed that all river traffic was handled by vessels with smaller than Category 3 engines, except in river ports serving ocean-going traffic. Further, we assumed that any coastwise cargo movement within 25 nautical miles of the coast, but outside of the port areas analyzed in section 7.1.1 was moved by tow and push boats powered by Category 2 engines. Thus, with the exception of California, only non-port vessel traffic outside of 25 nautical miles from the coast was considered to be Category 3 traffic for the purposes of this analysis. It is possible and, in some cases likely that some Category 3 vessel traffic occurs within 25 nautical miles of the coast. However, the data did not include the type or size of vessel that the cargo was being transported on, only the cargo tonnage. Thus, we were unable to discriminate between cargo carried on Category 2 vessels and cargo carried on Category 3 vessels. Including cargo movement within 25 nautical miles of the coast but outside of ports areas would have resulted in the inclusion of Category 2 vessel emissions in our baseline inventories for Category 3 vessels. Conversely, excluding vessel traffic within 25 nautical miles of the coast likely excludes some Category 3 traffic. However, given that we could not separate Category 2 traffic from Category 3 traffic we needed to err on one side or the other. We believe that excluding all non-port traffic within 25 miles of the coast gives us a more accurate estimate of non-port Category 3 emissions than including it.

The U.S. Army Corp of Engineers provided activity estimates of total and domestic tonnage by waterway links. A map of the waterway links is shown in Figure 7.1-1, at the end of this chapter.

These estimates were converted to ton-miles of cargo by multiplying tonnage by link distance to estimate overall link activity. In order to avoid double-counting the emissions estimated in section 7.1.1 fractional links were estimated such that only traffic between 25 and 175 nautical miles from shore was considered. For Great Lakes links traffic outside of 10 miles was considered. Emission factors in g/ton-nautical-mile were developed using cruise mode emissions divided by the total freight tonnage from the detailed ports analysis. These emission factors were then multiplied by the total links ton-miles to estimate total non-port emissions inventories. The total non-port emission inventories for base year are shown in Table 7.1-4.

Table 7.1-4
Total U.S. Category 3 Emission Inventories for Non-Port Areas in 1996 (short tons)

HC	CO	NOx	PM	SOx
2,060	4,186	88,837	7,840	58,856

We are fairly confident in the accuracy of our ports emission inventory estimates given that they were developed from the ground up using accurate port call information as well as information on vessels types, etc. However, our non-port inventory estimate contains a greater level of uncertainty than the in-port inventory estimates due to the exclusion of most Category 3 vessel traffic within 25 nautical miles of the coast. Thus, in support of future rulemaking efforts we plan to continue researching the non-port emissions issue in an effort to further refine our non-port emission inventories.

7.2 Future Year Baseline Inventory Projections

In order to project future year emission inventories for Category 3 Marine diesel engines several factors were taken into account. These included the overall expected growth in cargo movement, the type of vessel that would handle the increased freight movement (i.e., the future makeup of the fleet), and the effect of the internationally negotiated NOx emission limits on fleet emissions as older vessels are scrapped and replaced with new vessels.

The expected increase in freight movement was projected from estimates of freight forecasts done by the U.S. Maritime Administration (MARAD). MARAD supplied estimated freight forecasts for several types of vessels. Thus, rather than a single growth rate for all vessel traffic, we used separate growth rates for tankers, container ships, cruise ships and other bulk and general cargo ships. The MARAD estimates rely on historic freight growth from 1996 to 1999, and varied between 2.2 and 6.6 percent per year, depending on vessel type. The growth rate from 1996 through 1999 was then projected beyond 1999 through 2004 by MARAD. For this analysis the projections supplied by MARAD were used to project freight growth out to 2030. While there is a great deal of uncertainty in projecting growth this far into the future, we did so to show the possible impact of long-term standards on emission inventories. Given that Category 3 vessels typically last for several decades before being scrapped it is important to project inventories out this far.

In order to project future vessel activity based on these forecasts of freight growth, the overall dead weight tonnage (DWT) calling annually at ports and traversing the waterways links was increased in proportion to the projected freight increases. The additional vessel calls needed to accommodate the increased tonnage were added to the largest DWT category by vessel type. In other words, we assumed that the additional tonnage would be handled by the largest vessels and powered by slow speed engines given that predominantly larger vessels are being constructed to replace older vessels, and that ports are making an effort to accommodate larger vessels.

In addition to the effects of increased freight tonnage and future changes in fleet makeup, the effects of the internationally negotiated NOx limits were included in the future year projections. Although these standards have not been ratified and do not yet have the force of international law, they were written to be retroactive to the year 2000 when they do go into effect. It is widely believed that most new vessels constructed beginning in 2000 have been built in compliance with the internationally negotiated NOx limits. This is a trend that we expect to continue. Thus, for this analysis we assumed that all Category 3 vessels constructed in 2000 and later comply with the internationally negotiated NOx limits. The internationally negotiated NOx limits are related to rated engine speed as shown in Table 1.1-1. This means that compliance with the standards we are finalizing is incorporated into our baseline inventory, and we expect no inventory benefits from our standards.

These NOx emission limits are for vessels tested on distillate fuel. However, Category 3 vessels use residual fuel in use. The use of residual fuel results in higher emissions than the use of distillate fuel, and using the NOx limits without correcting for differences in fuels would result in underestimating actual in-use emissions from vessels complying with the internationally negotiated NOx limits. Thus, the standards were increased by ten percent to account for the difference in fuels. In the absence of information regarding certification compliance margins (the practice of producing engines which emit somewhat below the standards in order to provide a compliance cushion) and in-use emission deterioration we used the actual internationally negotiated NOx limits as the emission factors for future vessels in the growth projections.

The projected future emission inventories for the port areas are shown in Table 7.2-1. The non-ports inventory projections are shown in Table 7.2-2. Finally, the total national inventory projections are shown in Table 7.2-3.

Table 7.2-1
Projected Emission Inventories from
Category 3 Marine Diesel Engines in Port Areas (short tons)

Year	HC	CO	NOx	PM	SOx
1996	5,230	11,530	101,137	9,299	97,390
2010	8,501	18,836	146,160	14,199	104,540
2020	12,486	27,716	195,812	20,258	148,575
2030	19,146	42,535	287,511	30,447	222,640

Table 7.2-2
Projected Emission Inventories from
Category 3 Marine Diesel Engines in Non-Port Areas (short tons)

Year	HC	CO	NOx	PM	SOx
1996	2,060	4,186	88,837	7,840	58,856
2010	3,295	6,681	127,955	11,797	88,261
2020	4,729	9,567	171,657	16,443	122,637
2030	7,005	14,088	243,294	23,784	177,106

Table 7.2-3
Projected Emission Inventories
from Category 3 Marine Diesel Engines in All Areas (short tons)

Year	HC	CO	NOx	PM	SOx
1996	7,290	15,716	189,974	17,139	156,246
2010	11,796	25,517	274,115	25,996	192,801
2020	17,215	37,283	367,469	36,701	271,212
2030	26,151	56,623	530,805	54,231	399,746

7.3 Estimated Effects of Advanced Technology Standards on Inventories

This section presents estimated NOx inventory reductions that could occur from standards that reflect the advanced emission-control technologies described in Chapter 5. We examine two scenarios: standards set at 50 percent and 80 percent below the NOx standards we are adopting in this rule (i.e., the internationally-negotiated NOx limits). Our estimated inventory reductions are based on our current understanding of the U.S. fleet characteristics and an effective date of 2007 for the new standards. We will revisit these estimates in our future rule. We are not estimating the benefits of potential PM, HC, or CO standards, but will revisit standards for those pollutants and associated inventory reductions in our future rule.

To model the benefits of NOx standards that reflect application of the advanced technologies, we applied an engine replacement schedule and the potential emission standards to our inventory projections based on the standards we are finalizing in this rule (our baseline inventory). For the purpose of estimating ship turnover rates, we used an average vessel age of 23 years. This is based on a study done by Corbett and Fishbeck in support of our 1999 rule which estimated the average age of the U.S. fleet as 23 years.[4] A separate analysis of MARAD data on ship calls to U.S. ports, which contained vessel age and flag information, showed that the average age of U.S. vessels in 1999 was 24.2 years, with a median age of 22 years. The results of this analysis are shown in Figure 7.3-1. It should be noted that the Corbett and Fishbeck study suggests that the average age of the world fleet is lower than that of the U.S. fleet, which would result in a faster turnover rate in the U.S. fleet than the in the world fleet. For the sake of this study, however, we applied the U.S. turnover rate to all vessels, representing a worst-case scenario. We intend to revisit this issue in our future rule.

Table 7.3-1 shows the Category 3 marine diesel engine NOx emission inventory estimates for the two advanced technology standard scenarios, a 50 percent and 80 percent NOx reduction from the levels we are finalizing in this rule, applied to U.S. vessels only and to foreign vessels. According to these estimates, standards that reflect a 50 percent reduction from the standards we are finalizing in this rule would result in an additional 2 percent reduction by 2030 when applied to Category 3 marine diesel engines on U.S. vessels only, and an additional 43 percent reduction when applied to Category 3 marine diesel engines on all vessels that enter U.S. ports. Standards that reflect an 80 percent reduction from the standards we are finalizing would result in an additional 4 percent reduction by 2030 if applied to Category 3 marine diesel engines on U.S. vessels only and nearly 70 percent reduction if applied to Category 3 marine diesel engines on all ships that enter U.S. ports. The reductions associated with all vessels would be even larger if a faster vessel turnover is assumed.

These estimates illustrate the importance of applying advanced technology standards to engines on the broad group of vessels that use U.S. ports.

Table 7.3-1
Estimated 2030 Emission Inventories under Various
Scenarios of Applying Long-Term Emission Standards

Scenario	2020		2030	
	NOx (1000 tons)	percent reduction	NOx (1000 tons)	percent reduction
Baseline (Annex VI)	367	--	531	--
50% Reduction—U.S. vessels only	360	2.1%	519	2.3%
50% Reduction—All vessels	266	27.7%	301	43.3%
80% Reduction—U.S. vessels only	355	3.4%	511	3.7%
80% Reduction—All vessels	204	44.6%	160	69.8%

Figure 7.3-1

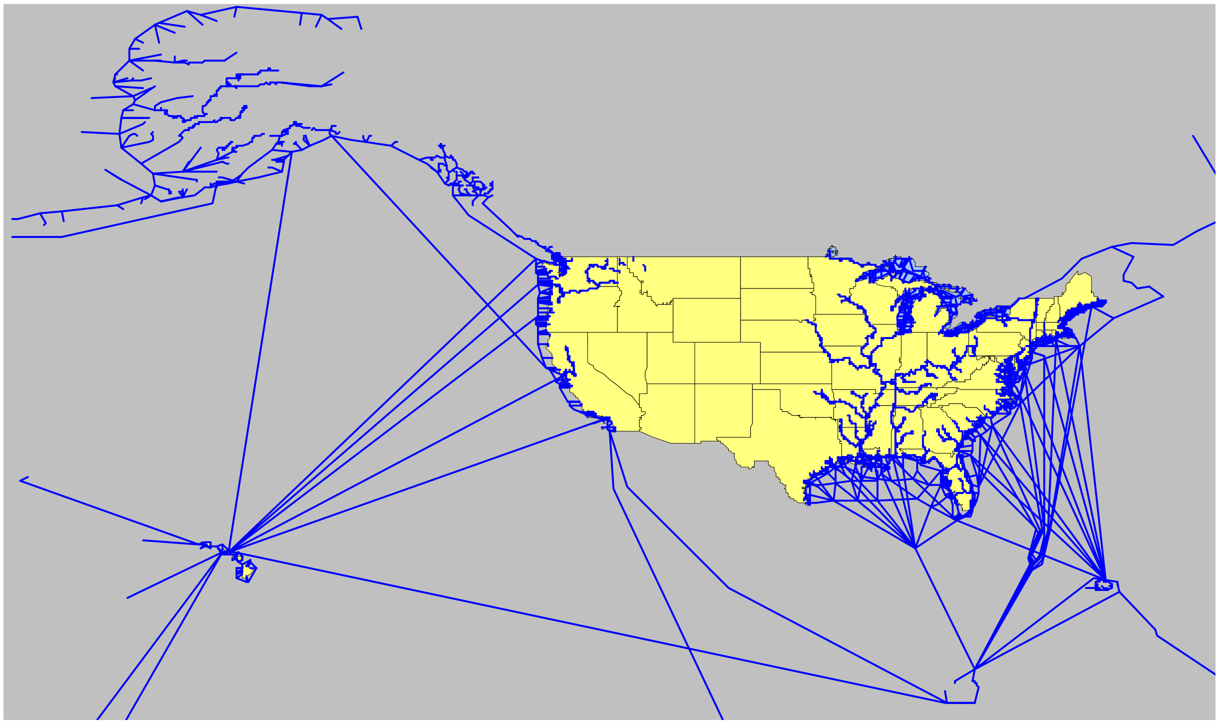


Table 7.3-2
Number of Category 3 Vessels in the U.S. Fleet by Age

Age (years)	Number of vessels
0 - 9	32
10 - 19	65
20 - 29	130
30 - 39	40
40 - 49	11
50+	15

7.4 Per-Vessel Emission Reductions

This section describes our estimates of the emission reductions over the lifetime of an average vessel for the two scenarios discussed above. These scenarios are a 50% reduction beyond Tier 1 based on water injection and an 80% NOx reduction beyond Tier 2 based on selective catalytic reduction. Under the 80% reduction scenario, we consider the use of distillate fuel to be necessary to enable the use of SCR technology. Therefore, we calculate reductions in PM (primarily direct sulfate PM) and SOx emissions due to the use of distillate fuel with a sulfur content of 1.0% rather than residual fuel with a sulfur content of 2.7%.

To calculate the baseline per vessel annual emissions, we divide the total emissions inventory presented in section 7.2 by our estimates of the number of vessels presented in Chapter 3. Emission reductions are determined by applying a percent reduction to the baseline emissions. Lifetime reductions are presented in Table 7.4-1 for applying future standards to U.S. vessels only and for applying future standards to all vessels. The emission reductions are discounted at 7% and are based on the useful life discussed in section 7.3. Note that lifetime reductions are lower for the entire fleet than for U.S. vessels. This is because we only count the emission reductions within 175 miles of the U.S. coast. We estimate that the average U.S. vessel spends about six times as much operation near our coast than the average foreign vessel.

Table 7.4-1: Discounted Per Vessel Lifetime Emission Reductions Beyond Tier 1 [short tons]

	Pollutant	U.S. Vessels Only	All Vessels
50% Beyond Tier 1	NOx	639	112
80% Beyond Tier 1	NOx	1,022	179
	PM	32	6
	SOx	451	79

7.5 Cost Per Ton

Because we are not adopting long-term standards at this time, we have not calculated cost per ton estimates for the future approaches. However this discussion gives guidelines on how calculations could be made to provide information to facilitate comparison of options we will consider in the future rulemaking. We will re-evaluate the costs and emission reductions of specific standards and emission-control technologies when we propose the long-term standards.

The cost per ton is generally the per-engine costs divided by the per-engine emission reductions. This analysis would examine total costs and total emission reductions over the typical lifetime of an average marine diesel engine discounted to the beginning of the engine's life. This cost information is provided in Chapter 6 and the and emission information is provided above. In calculating net present values that were used in our cost per ton estimates, we generally use discount rates of 7 percent and 3 percent. OMB Circular A-94 directs us to generate benefit and cost estimates reflecting a 7 percent rate. The 3 percent rate is consistent with that recommended by the Science Advisory Board's Environmental Economics Advisory Committee for use in EPA social benefit-cost analyses, a recommendation incorporated in EPA's new "Guidelines for Preparing Economic Analyses" (November 2000).

Chapter 7 References

1. “Commercial Marine Emission Inventory Development,” E.H. Pechan and Associates, Inc. and ENVIRON International Corporation, April, 2002. Air Docket A-2001-11, Document No. II-A-67.

2. “Final Regulatory Impact Analysis: Control of Emissions from Marine Diesel Engines,” U.S. EPA, November 1999. Air Docket A-2001-11, Document No. IV-A-05.

3. “Analysis of Commercial Marine Vessels Emissions and Fuel Consumption Data,” EPA420-R-00-002, Prepared for EPA by Energy and Environmental Analysis, Inc., February, 2000. Air Docket A-2001-11, Document No. II-A-64.

4. “Commercial Marine Emissions Inventory for EPA Category 2 and 3 Compression Ignition Marine Engines in United Sates Continental and Inland Waterways,” James J. Corbett, Jr. and Paul S. Fishbeck, Carnegie Mellon University, August 21, 1998. Air Docket A-2001-11, Document No. II-A-65.

CHAPTER 8: Test Procedure

In nonroad engine emission-control programs, the test procedures we use to measure emissions are as important as the standards we put into place. These test procedure issues include duty cycle for certification, in-use verification testing, emission sampling methods, and test fuels. This chapter describes the test procedures specified in this rulemaking for the Tier 1 standards. It also includes information related to test procedure issues discussed in the Draft Regulatory Support Document and likely to be considered again in the process of setting Tier 2 standards.

8.1 Certification Test Procedures

We are specifying MARPOL NOx Technical Code (NTC) engine test procedures with some modifications. These modifications are described in Section 8.1.4. Other sections describe issues such as the duty cycle, test fuel and sampling procedures, which are not significantly different from the NTC requirements. These procedures will be required for certification testing. We may allow other procedures to be used in the future if we adopt production testing and in-use testing requirements.

8.1.1 Duty Cycle

We are specifying the same duty cycles as are used for testing NOx emissions under the NTC requirements. These test cycles are designated by the International Organization for Standardization (ISO) as the E3 and E2 cycles.[1] The E3 duty cycle is designated for propulsion marine diesel engines operating on a propeller curve. It represents heavy-duty diesel marine engine operation on vessels greater than 24 meters in length. Many larger propulsion marine engines do not operate on a propeller curve. These engines may run at a constant speed and use a variable-pitch propeller to control vessel speed. The E2 constant-speed propulsion marine duty cycle applies to these engines. Tables 8.1-1 presents duty cycles for main drive engines as discussed above.

Table 8.1-1
Test Cycle Types E2 and E3

Test Cycle Type E2[a]				
Speed	100%	100%	100%	100%
Power	100%	75%	50%	25%
Weighting Factor	0.2	0.5	0.15	0.15
Test Cycle Type E3[b]				
Speed	100%	91%	80%	63%
Power	100%	75%	50%	25%
Weighting Factor	0.2	0.5	0.15	0.15

[a] E2: for constant-speed main propulsion application (including diesel-electric drive or variable-pitch propeller installation)
[b] E3: for propeller-law-operated main and propeller-law-operated auxiliary engine application

8.1.2 Test Fuel

Category 3 engines are typically designed to burn residual fuel, which is a heavy by-product of the refining processes used to produce lighter petroleum products such as gasoline, diesel fuel and kerosene. However they can also burn distillate fuel. In order to harmonize with the NTC testing provisions in the near term, we are specifying distillate fuel for Tier 1 testing. However, this section provides additional information regarding residual fuels, and discusses why we may need to specify one or more residual fuels when we consider more stringent standards in the future.

Residual fuel is a dense and viscous fuel that is a byproduct of distillate fuel productions. It typically has higher ash, sulfur and nitrogen content than marine distillate fuels. Some Category 3 engines can burn straight residual fuel, but many burn a blend of residual and distillate, which is called intermediate fuel (IF). The two most common IF blends burned in Category 3 engines are IF 180, which contains about 88 percent residual fuel and IF 380 which contains about 98 percent residual fuel.[2] Table 8.1-2 summarizes current ASTM standards for a marine distillate oil, residual fuel, and these two common IF blends.

Table 8.1-2
Comparison of ASTM Fuel Specifications[3]

	Units	Distillate fuel	IF 180	IF 380	Residual fuel
ISO-F symbol		DMA	RMF-25	RMH-35	RML-55
Density @ 15C, max	kg/m^3	890	991	991	no max
Viscosity @ 40C	cSt	1.5-6.0	316	~710	—
Viscosity @ 50C	cSt	—	180	380	—
Viscosity @ 100C	cSt	—	25	35	55
Carbon Residue, max	wt%	0.20[a]	20[b]	22[b]	no max
Ash, max	wt%	0.01	0.15	0.2	0.2
Sulfur, max	wt%	1.5	5	5	5

[a] Ramsbottom test
[b] Conradson test

The use of residual fuel has two important consequences. First, it is more difficult to handle. Because of its high viscosity and high impurities, the fuel must be heated and filtered before it can be passed to the engine. This requires additional equipment and space. Bunker fuel is kept in a main fuel tank where it is kept heated, generally using steam coils, to just above its pour point. Prior to use, this fuel is pumped into a settling tank, where the heavier portions settle to the bottom. Fuel is pumped from the top of the settling tank through heaters, centrifugal separators, and filters before entering the fuel metering/injection pump(s). The centrifugal separators and filters remove water and remaining sludge from the fuel. The sludge is then routed to a sludge tank. In addition, a separate fuel tank is usually necessary to store a lighter fuel which is used to start a cold engine.

Second, residual fuels can have detrimental effects on engine emissions. These fuels can contain one percent or more nitrogen by weight, and fuel-bound nitrogen is completely converted to NOx in diesel engines.[4] Assuming complete conversion to NO_2, one gram of nitrogen in the fuel would result in 3.28 grams of NOx, based on the ratio of molecular weight of NO_2 (46.005) to the atomic weight of nitrogen(14.007). Based on the currently available information, it is appropriate to assume conversion to NO_2, since our proposed test procedures convert NO emissions to NO_2 before measurement and calculates the total NOx emissions assuming the molecular weight of NO_2. It is possible that some of the fuel nitrogen would be converted to other nitrogen compounds such as NH_3 (ammonia) or N_2O (nitrous oxide), or remain bound to organic molecules in the HC or PM emissions. However, since about 99 percent of the fuel mass consumed by a Category 3 engine is typically converted to CO or CO_2, it is unlikely that a large amount of the fuel nitrogen remains organically bound. Also, given the high air/fuel ratios, it seems unlikely that a significant amount of NH_3 or N_2O would be produced. The primary uncertainty is related to the formation of elemental nitrogen (N_2). One commenter suggested that some of the combustion occurs at equilibrium conditions, where a significant fraction of the fuel-bound nitrogen would be converted to N_2.

Residual fuel quality can effect emission in ways other than the effect of fuel nitrogen. Bastenhof analyzed emission results for ISO E3 test results of a Category 3 engine that showed a 22 percent increase in ISO weighted NOx when residual fuel was substituted for distillate fuel.[5] However, most of the difference could not be attributed to the effect of the fuel-bound nitrogen (0.4 percent). A large fraction of the NOx increase was attributed to the fuel's poor ignition quality, which caused excessive ignition delay at part load. At 25 percent load on residual fuel, the engine produced 50 percent more NOx than on distillate, while at full load it produced only 25 percent more than on distillate.

We recognize that the effects of fuel-bound nitrogen are not yet fully understood, and we are not aware of any accurate corrections for fuel effects other than the effect of fuel nitrogen. Thus we believe that it is appropriate to specify distillate fuel as an interim provision limited to Tier 1 testing. However, we believe that for the longer term, it will probably be necessary to base our standards on more representative test fuels. We expect to work with manufacturers to develop more accurate corrections for nitrogen and other fuel effects.

8.1.3 Sampling Procedures and Calculations

The NTC test procedures use a conventional raw sampling system, in which a small sample of the exhaust gases is drawn from the exhaust stack and pumped through chemical analyzers. NOx concentrations in the sample are measured using a chemiluminescence analyzer. CO_2 concentrations are measured using a Non-Dispersive Infrared analyzer. These analyzers are the same as the analyzers specified by EPA for other nonroad standards.

The NTC provisions specify that NOx emissions be corrected to be equivalent to measurements made at a reference humidity of 10.71 g of water per kg of dry air (g/kg). They also specify that NOx emissions be corrected for the effect of seawater temperature on charge air cooling.

8.1.4 Modifications to the NOx Technical Code Test Procedures

We are adopting test procedures with several modifications and additions relative to the NTC test procedures to better ensure that the emission measurements will accurately represent in-use performance. We require that inlet air and exhaust restrictions be set at the average in-use levels. Similarly, engine coolant and engine oil temperatures must be equivalent to the temperatures that will occur in-use under ambient conditions identical to the test conditions. Measurements must be valid only for sampling periods in which the temperature of the charge air entering the engine is within 3°C of the temperature that would occur in-use under ambient conditions (temperature, pressure, and humidity) identical to the test conditions. Manufacturers may measure emissions within larger discrepancies, but may not use those measurements to demonstrate compliance with these regulations. The NTC procedures allow manufacturers significantly more discretion with respect to these parameters.

The NTC allows g/kW-hr emission rates to be calculated using measured exhaust flow rates. However, we do not believe that exhaust can be reliably measured for Category 3 engines. Measuring exhaust flow rates in general is difficult due to the high temperatures and the variability of exhaust temperatures. We believe it would be even more difficult for very large engines. Exhaust stacks for Category 3 engines can be over a meter in diameter, which allows for significant spatial variation in the flow rate. Exhaust flow rates must therefore be calculated using measured fuel flow rates.

The duty cycle used for NTC testing specifies the test points based on the manufacturer's specified rated speed. We have concerns about the subjective nature of the NTC requirement and believe that the test cycle needs to be defined more objectively. Test cycles must therefore be denormalized based on the maximum test speed described in §94.107, which is derived from the lug curve for the engine. This maximum test speed is not intended to fundamentally change the test procedure, but merely makes the procedure less subjective. We are including an option for manufacturers to use the maximum in-use engine speed for governed engines.

8.2 Shipboard NOx Emission Measurement System

We proposed that Category 3 diesel engines have a direct exhaust NOx monitoring system. This system was to be used to verify that engines are adjusted properly in use. It could also be used for production testing. We are not finalizing this requirement for Tier 1, but expect to adopt such a requirement when we consider more stringent standards in the future.

Category 3 engines typically have fuel injection timing and other adjustments that are optimized to accommodate a range of fuel qualities and environmental conditions. Since these engine adjustments also affect NOx emissions, it would be valuable to have a shipboard means of monitoring NOx to ensure that the engine is adjusted to remain in compliance with the applicable standards. Indirect methods for inferring NOx emissions based on engine operating temperatures, pressures or flows will not ensure compliance with applicable standards due to the complex relationship between these parameters and NOx emissions. Onboard measurements would also be necessary for other treatment technologies that can be adjusted to operate at different emission-control efficiencies, such as water injection. Another one of the reasons we proposed to require these measurement systems was to enable operators to effectively turn emission controls off under certain conditions by adjusting the engine.

We envision that the NOx monitoring system would perform the following functions. It would detect exhaust NOx concentration in parts per million (ppm) and integrate this measurement with other shipboard measurements so that the measured concentration may be compared with emission limits (or targets) for an engine’s operating conditions. These targets would be determined by the engine manufacturer, and would vary with operating conditions and fuel quality. The system would display the NOx concentration and the respective specified emission limit at the engine control room. This kind of system would give the marine engineer immediate and specific feedback regarding any recent adjustments to the engine or any recent changes in fuel quality or environmental conditions. Displaying actual values of emissions rather than merely activating an alarm would serve to familiarize the marine engineer with the magnitude of the change in NOx emissions versus various changes in engine operation, fuel quality, or environmental conditions. As the marine engineer incorporates NOx monitoring with the rest of the ship's engine monitoring, it is likely that NOx emissions may be incorporated to troubleshoot or optimize the engine's operation. NOx is sensitive to combustion temperature which is a function of engine load, fuel injection timing, fuel ignition delay, combustion air inlet temperature, and a few other engine parameters to a lesser extent. Unusually high or low NOx emissions might indicate to the marine engineer that these parameters should be carefully inspected to ensure proper engine operation.

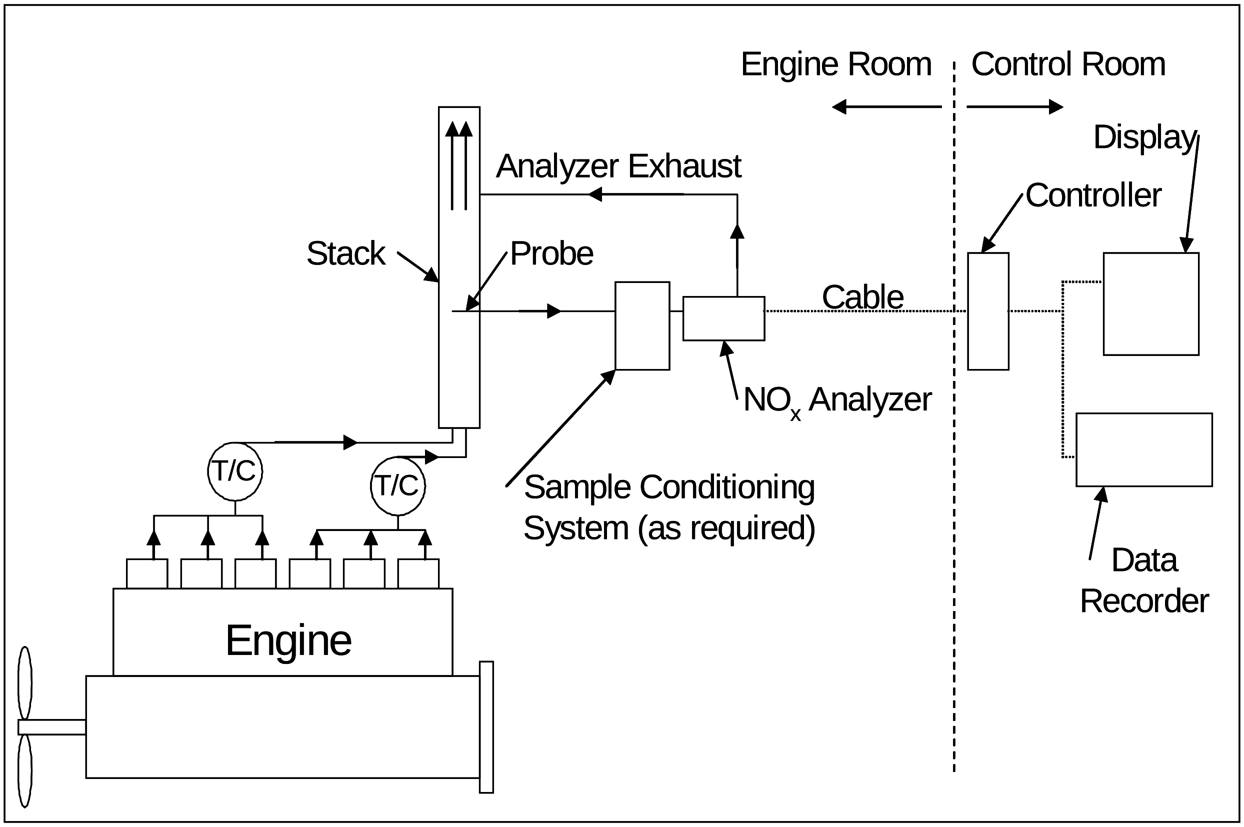
The system should also provide automated calibration and error handling, including audible and visual alarms to ensure proper operation with a minimum of maintenance. In order for a system such as this to be well-received and properly used aboard ship, the system must not significantly increase the day-to-day work load of the marine engineer. It is expected that periodic repair and maintenance would be required to keep the system in proper working order, however, it should be designed to require tedious calibration or frequent maintenance, since that would likely discourage operators from using it properly.

The system should also permanently record the NOx concentration and any other measured or calculated parameters, including the respective limit for the engine operating conditions, the calibration results, plus any system alarms or malfunctions. This record would be used to determine whether or not the engine is being operated consistent with its intended operation (i.e. operation during engine certification.) This record would also be useful in determining how well the NOx monitoring system is maintained.

8.2.1 System Description and Component Specifications

The NOx monitoring system that we proposed consisted of several components, and the system is illustrated in the figure below.

Figure 8.2-1



8.2.1.1 Location of Sample Extraction Point

A sensor or sampling probe would be located at a position in the exhaust stream where the exhaust from all engine cylinders are well-mixed. It is important that the exhaust be well-mixed because each fuel injection pump and after-cooler may be adjusted individually on a typical Category 3 engine. This means that some cylinders of the engine might be producing more NOx than others. A well-mixed sample would not only help ensure compliance to the applicable standard, but it would also prevent false positive indications that the engine is emitting excessive NOx emissions. A multi-point transverse sampling probe would need to be used only if the exhaust system does not provide for a single point location where the exhaust is well-mixed. Sound engineering judgment must be used to determine this position in the exhaust system, however, it is recommended that the Reynolds number of the exhaust flow at the sampling position remain greater than 4000 and that the sensor or sampling position be in the free stream flow at least five exhaust trunk diameters downstream of any trunk junctions or 90° bends.

The sampling position should be selected to prevent periodic exhaust system cleaning from adversely affecting the sensor or probe. Category 3 engines often have exhaust heat recovery devices such as economizer boilers. These components require periodic steam cleaning (soot-blowing). The action of the soot blowers might damage a NOx sensor or sample probe placed in the exhaust stream, therefore the sample location should be upstream of these devices.

This location must also be upstream of any other exhaust stream that might be introduced into the exhaust system. Other engines or boilers might exhaust to the same system, and their exhaust would most certainly cause the recording of erroneous data.

8.2.1.2 Sample conditioning system

Depending on which NOx detection method is used, a sample conditioning system may be needed. The sample conditioning system could consist of filters, scrubbers, or chillers. However, no component of the sampling system should affect the NOx concentration of the sample. For example, if a sample conditioning system utilized unheated lines or a chiller that brings the sample below its dewpoint, an NO_2 to NO converter would have to be used upstream to prevent the precipitation of NO_2 as nitric acid.

8.2.1.3 NOx Analyzer

To quantify total NO + NO_2, a NOx analyzer would be used to quantify the exhaust NOx concentration in parts per million by volume (ppm). The performance specifications of the NOx analyzer would be as follows: the detection range of the analyzer would be at least 100-5000 ppm with a NIST traceable accuracy of ±2% at each calibration point (i.e. ±10 ppm at 500 ppm concentration of an NIST traceable calibration gas), a precision of ±5% based on two standard deviations (2σ) and a 90% response time of less than 5 seconds to an 80% of full-scale step change in NOx. These specifications ensure that the analyzer would be able to detect a significant change in NOx emissions without over-specifying an analyzer that might require more frequent maintenance or a more complicated calibration procedure.

In addition the analyzer must have an automated calibration subsystem that would perform quality control and quality assurance checks to ensure that NOx is measured at the stated specification. This level of automation is required to prevent an undue increase in the marine engineer's day-to-day workload. Automated calibration subsystems are commercially available for gas detection systems and are already used aboard tankships that require gas detection systems for safety purposes.

Any analyzer must be designed to perform under typical shipboard temperature, humidity, shock, vibration, electromagnetic and radio frequency interference. It is also important that the analyzer not have any cross-sensitivity to other exhaust constituents. Several different NOx detectors have been used successfully to detect NOx of roadway diesel engine exhaust. However, Category 3 engines frequently use residual fuel that contains high concentrations of components not found in distillate diesel fuel. These components include sulfur at 100 times distillate diesel concentrations plus metallic ash from crude oil and catalytic refining processes. Such components might cause fouling or corrosion of wetted parts of the NOx monitoring system. Analyzer manufacturers would have to use care when selecting certain materials and detectors for use in this application.

Analyzers based on chemiluminescent, non-dispersive ultra-violet, zirconia cell, or Fourier transform infra-red measurement techniques could likely work for shipboard use. However, the instrument manufacturer would have to ensure that an analyzer meets the necessary specifications. Except for the zirconia cells that can be inserted directly into the free stream exhaust, all of these analyzers would require a sample of the exhaust to be extracted. This means that these analyzers would have to include their own pumping subsystem. In addition the analyzer exhaust would have to be routed back to the engine's exhaust.

There is already an indication that the zirconia cell shows promise in the harsh residual fuel exhaust. A report submitted to the International Maritime Organization indicated that a zirconia cell sensor was used aboard three different Category 3 engine-equipped vessels using seven different residual fuels, and after six months of use the zirconia sensor continued to perform acceptably.[7] Some of the advantages of the zirconia sensor include its cost, currently in the several hundred U.S. dollar range for the sensor, and under $4,000 for the entire analyzer. It is anticipated that a complete NOx monitoring system might cost approximately $15,000 with annual operating costs (including labor) of approximately $5,000. Cost of the complete system is minimal because the zirconia cell does not require a sample conditioning system or pump. However, a pump and a sample conditioning system might be used to prolong a zirconia cell's life.

8.2.1.4 Programmable Controller

A programmable electronic controller should be able to execute all of the system functions such as sampling, calibrating, purging, and error handling. The controller would integrate other shipboard measurements and make all necessary calculations. The controller would also allow for manual operation of the system. Such a controller may vary in sophistication depending upon the needs of the ship and the availability of other centralized automation systems, which might be able to perform the NOx monitoring functions.

8.2.1.5 Engine Control Room Display

In a well-designed system, an engine control room display would probably provide the marine engineer with a continuous display of measured NOx concentration and the respective NOx limit for the engine operating condition, plus any other relevant measurements or calculated values. The display would also indicate any alarms or faults so that repair or maintenance could be promptly performed. The display would also provide for remote control of the system.

8.2.1.6 Data Recorder

To make the system reliable as an enforcement tool, a data recorder would be needed to permanently document all of the NOx monitoring system's measured and calculated parameters, calibration results, and system errors. All data would be recorded along with date and time stamps, and this record would be used to determine compliance with applicable NOx emission requirements. It would also be used by the marine engineer to determine day-to-day changes in NOx emissions or even NOx trends over the life of the engine. This data would be permanently archived consistent with shipboard practices for retaining records such as the course recorder logs or other similar permanent records.

8.2.2 Emission Targets

We expect that the typical onboard measurement system would report the concentration of NOx in the exhaust (ppm) along with other test conditions (e.g., engine speed, shaft torque, fuel properties, ambient temperature and humidity, etc.). We do not expect that these results would be directly comparable to the weighted g/kW-hr emission standards. Thus, we will likely need to require the engine manufacturer to develop NOx-ppm emission targets for each set of conditions if we adopt in a future rule the kind of adjustability allowances that we proposed. These targets would be indicative of equivalent emission-control performance.

Equivalent emission-control performance could be defined relative to optimal engine performance that could be achieved in the absence of emission standards (i.e., the calibration that result in the lowest fuel consumption and/or maximum firing pressure). This approach would work for NOx controls in which there would be a tradeoff between NOx emissions and fuel consumption rates. The most obvious example of this would be fuel injection timing. In this case, equivalent performance could mean the same percent reduction in NOx emissions from the optimal calibration as is achieved under the test conditions. Alternatively, the manufacturer could achieve equivalent performance by specifying that the timing be retarded the same number of degrees from the optimal calibration as was done under the test conditions. In this alternative approach, the calibration would be conceptually equivalent to a mechanically-controlled engine.

Chapter 8 References

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