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Draft Regulatory Support Document

Control of Emissions from Compression-Ignition Marine Diesel Engines At or Above 30 Liters per Cylinder

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

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CHAPTER 1: Introduction

EPA is proposing emission standards for emissions of oxides of nitrogen (NOx), hydrocarbons (HC), and carbon monoxide (CO) from new marine engines at or above 30 liters per cylinder on U.S. vessels. This Draft Regulatory Support Document provides technical, economic, and environmental analyses of the proposed Tier 1 NOx standards and a second tier of standards currently under consideration of 30 percent below the Tier 1 NOx standards. Nationwide, these engines contribute to ozone and carbon monoxide nonattainment and to ambient particulate matter levels, particularly in commercial ports and along coastal areas.

EPA is proposing a first tier of emission controls that is equivalent to the internationally negotiated oxides of nitrogen standards and would be enforceable under U.S. law for new engines built in 2004 and later. We are also considering adoption of a second tier of standards, which reflect additional reductions that can be achieved through engine-based controls, and would apply to new engines built in 2007 and later.

Chapter 2 reviews information related to the health and welfare effects of the pollutants of concern. Chapter 3 contains an overview of the affected manufacturers, including 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 could be used to meet both tiers of standards. Chapter 5 applies cost estimates for the emission controls. Chapter 6 presents the estimated contribution of these engines to the nationwide emission inventory and discusses the emission reductions that could be achieved by applying both tiers of standards. Chapter 7 presents the cost effectiveness of the emission controls. This chapter also includes analysis of the social and economic costs of the rule and overall environmental benefits. Chapter 8 discusses several alternative approaches we considered for the standards. These technologies hold out the potential for emission improvements in the future, after constraints on their application to large ocean-going marine diesel engines are resolved. Finally, Chapter 9 contains new test procedures for these engines.

The remainder of this Chapter 1 contains the definition of the categories of marine diesel engines and a summary of our analysis of the benefits and costs of this proposal. It should be noted that we are not claiming benefits for the proposed Tier 1 standards. These standards have already been adopted by the international community, although they are not yet enforceable. Because engine manufacturers are already producing engines that achieve these standards, this rule will result in emission reductions only to the extent that owners of U.S. vessels are not currently complying with the standards. The costs of the proposed Tier 1 standards are negligible and reflect certification and compliance costs only.

Table 1-1 contains a general summary of the per vessel costs, projected emissions reductions, and cost per ton of pollutant reduced for the various emission standards we considered for a second tier of NOx limits (all costs are presented in 2002 dollars). These costs should be considered in conjunction with the technical feasibility of the different alternatives as described in Chapters 4 and 8.

Table 1-1
Summary of Vessel Costs, Emissions Reductions in 2030, and Cost per Ton from Category 3 Marine Diesel Engine and Fuel Control Programs (2002 Dollars)

			NOx			PM			SOx		
Scenario	Cost per vessel - (thousand $)[1]	Increased operating costs NPV (thousand $)	Reduction (1000 tons)	Percent reduction	Cost per ton	Reduction (1000 tons)	Percent reduction	Cost per ton	Reduction (1000 tons)	Percent reduction	Cost per ton
30% NOx reduction below Tier 1 - U.S. flagged vessels only	$115	$66	56	10.5%	$145	--	--	--	--	--	--
30% NOx reduction below Tier 1 - U.S. and foreign flagged vessels	$57	$66	139	26.1%	$1,585	--	--	--	--	--	--
50% NOx reduction below Tier 1 - U.S. flagged vessel only	$207	$527	92	17.3%	$370	--	--	--	--	--	--
80% NOx reduction below Tier 1 - U.S. flagged vessel only	$1,014	$9,542	148	27.9%	$3,405	--	--	--	--	--	--
1.5% S fuel - U.S. and foreign flagged vessels	$50	$139	--	--	--	9.7	18%	$38,066	176	44%	$302
0.3% S fuel - U.S. and foreign flagged vessels	$50	$273	53	10%	--	34	63%	$32,968	356	89%	$262

1. These per vessel costs reflect the costs for the first five years of the program. For the technology-based options these costs would go down after five years, as discussed in Chapter 5.

NOTE: Technological feasibility constraints are not reflected in these costs; refer to Chapters 4 and 8.

1.1 Categories of Marine Diesel Engines

In our 1999 commercial marine diesel engine rule, we defined marine engine as an engine 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 that rule, this approach is necessary because marine diesel engines are typically derivatives of land-based diesel engines and the land-based engines are not all subject to the same numerical standards and effective dates. The definitions for the different categories of marine diesel engines are contained in 40 CFR part 94.2 and are summarized in Table 1.1-1.

Table 1.1-1
Marine Engine Category Definitions

Category	Displacement per cylinder	hp range (kW)	rpm range
1	disp. < 5 liters (and power ≥ 37 kW)	37 - 2,300	1,800 - 3,000
2	5 ≤ disp. < 30 liters	1,500 - 8,000	750 - 1,500
3	disp ≥ 30 liters	2,500 - 80,000	80 - 900

1.2 Proposed Standards

Our proposal discusses two tiers of NOx emission controls for these engines. The first tier is equivalent to the internationally negotiated NOx standards 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 (this convention is also known as MARPOL; the standards are referred to as the Annex VI NOx limits). These Tier 1 standards would be enforceable under U.S. law for new engines built in 2004 and later.

The second tier of NOx standards under consideration reflect additional reductions that can be achieved through engine-based emission controls and would apply to new engines built in 2007 and later. We are also considering standards for HC and CO emissions as part of the Tier 2 emission controls to ensure that these emissions do not increase on an engine-specific basis. We would review the Tier 2 standards prior to their effective date to take into consideration continued development of new technologies, such as selective catalyst reduction and water-based emission reduction techniques, and international activity such as action at International Maritime Organization (IMO) to set more stringent international standards.

As discussed in greater detail in Chapter 4, both tiers of standards can be met through engine-based emission-control technologies. The Annex VI NOx limits are based on certification on distillate fuel, which has a lower nitrogen content than the residual fuel that these engines are most likely to use in operation. We are proposing numerical emission limits based on residual fuel, but allow for certification testing using distillate or residual fuel. In either case, we are proposing that the test results be adjusted to account for the nitrogen content of the fuel, and then be compared to the proposed emission limits. The fuel quality adjustment is described in Section IV.A.2 of the preamble for this rule.

Table 1.2-1: Emission Limits for
Category 3 NOx Emission Limits (g/kW-hr)*

Engine Speed (n)	$n \geq 130$ rpm**	$n < 130$ rpm
Tier 1	$49.5\times n^{-0.2}$	18.7
Tier 2 standards under consideration	$31.5\times n^{-0.2} + 1.4$	13.3
Blue Sky	$9.0\times n^{-0.2} + 1.4$	4.8

*The proposed regulations specify emission standards based on testing with measured emission values corrected to take into account the nitrogen content of the fuel. Emission values are corrected to values consistent with testing engines with fuel containing 0.4 weight percent nitrogen. Testing with fuel containing 0.2 weight-percent nitrogen (typical for in-use distillate marine fuels) would have a correction of 1.4 g/kW-hr, so the proposed Tier 1 NOx standards would match the Annex VI NOx standards at this test point.
**No cap would apply to Category 3 engines over 2000 rpm, because these engines all have engine speeds well below that speed.

We are not proposing a standard for particulate emissions from these engines because most of the particulate emissions are a result of the high sulfur and ash content of the fuel used by these engines and because there is no acceptable measurement procedure for fuels with these characteristics. Potential PM reductions can be obtained, however, by setting a fuel sulfur content limit for the fuels used by these engines. One option, for example, would be to set a sulfur content cap equivalent to the limit for fuel used in SOx Emission Control Areas provided in Regulation 14 of MARPOL Annex VI. Pursuant to that regulation, the sulfur content of fuel used by vessels operating in those areas cannot exceed 15,000 ppm. For comparison, the sulfur content of highway diesel fuel is 500 ppm, to be reduced to 15 ppm in 2007. The sulfur content of nonroad diesel fuel is between 2,000 and 3,000 ppm. Additional discussion of this alternative can be found in Chapter 4 of this document.

We are also proposing voluntary low emission NOx standards for Category 3 marine diesel engines. These standards, which represent an 80 percent reduction from the Annex VI NOx limits, are intended to encourage the introduction and more widespread use of low-emission technologies. A discussion of technologies that can be used to achieve these voluntary limits, as well as other approaches we considered for this proposal, can be found in Chapter 8 of this document.

To implement these standards for marine diesel engines at or above 30 liters per cylinder in an effective way, we are proposing several compliance requirements. These requirements are discussed in more detail in Section V of the preamble for this rule. In general, the proposed compliance program reflects our traditional manufacturer-based approach. This is in contrast to the international approach reflected in Annex VI, which holds the vessel owner responsible for compliance once the engine is delivered onboard. We have attempted to propose compliance requirements that are sufficiently consistent with Annex VI that manufacturers would be able to use a single harmonized compliance strategy to certify under both systems. However, the Clean Air Act specifies certain requirements for our compliance program that are different from the Annex VI requirements.

Many of the proposed compliance provisions, including certification application, engine labeling, and warranty requirements, are similar or identical to the compliance provisions that we finalized in our 1999 rulemaking. In addition, we are including a post-installation verification provision which would require an emission test after an engine is installed on a vessel. We are also proposing a field measurement provision that would apply to engines with adjustable parameters or add-on emission control devices. Manufacturers of these engines would be required to equip the engine with a field measurement device. The owner of a vessel with such an engine would have to perform a field measurement when the vessel approaches within 175 nautical miles of the U.S. coastline from the open sea or when it adjusts an engine parameter within that distance. The results of this field measurement will demonstrate that the engine is in compliance with the relevant standards when it is operated in an area that affects U.S. air quality. The field measurement procedure and other testing issues are discussed in Chapter 9.

1.3 Projected Impacts

Because the Tier 1 standards are equivalent to the internationally negotiated NOx limits for these engines, we are not claiming any emission reductions from adopting these standards. The proposed Tier 1 standards have already been adopted by the international community, although they are not yet enforceable. Because engine manufacturers are already producing engines that achieve these standards, this rule will result in emission reductions only to the extent that owners of U.S. vessels are not currently complying with the standards. The costs of the proposed Tier 1 standards are negligible and reflect certification and compliance costs only.

The following paragraphs and tables summarize the projected emission reductions and costs associated a second tier of emission standards under consideration. See the detailed analysis later in this document for further discussion of these estimates as well as estimates for the alternative regulatory approaches we considered. Table 1.3-1 contains the projected emissions from the engines subject to this proposal.

Table 1.3-1
Category 3 Marine Vessel NOx National Emissions Inventories

		1996	2010	2020	2030	2050
Tier 1 (Baseline - thousand short tons)		190	274	367	531	1319
Tier 2 under consideration - 30% below Tier 1	Control (thousand short tons)	190	269	343	475	1168
	Percent reduction (relative to Tier 1)	—	2.0%	6.8%	10.5%	11.5%

Table 1.3-2 summarizes the projected costs to meet a second tier of emission standards. This is our best estimate of the cost associated with adopting the technologies to meet such a second tier of emission standards. The analysis projects that engines will not have increased operating costs to meet such a second tier of emission standards. The same manufacturers produce engines used in U.S. and foreign-flagged vessels. In addition, the majority of the vessels visiting the U.S. are foreign flagged. Therefore, we do not estimate separate costs for applying such a second tier of standards to foreign flagged vessels only.

Table 1.3-2
Summary of Projected Costs to Meet Second Tier of Emission Standards
(30% Below Tier 1)*

Time Frame	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
U.S.-flag only						
Total cost per engine (yr. 1)	$93,587	$98,977	$104,368	$106,414	$129,723	$153,031
Total cost per engine (yr. 6 and later)	$25,452	$28,902	$32,352	$33,661	$48,579	$63,496
Annual operating costs	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000
Including foreign-flag (or foreign-flag only)						
Total cost per engine (yr. 1)	$35,970	$41,360	$46,751	$48,797	$72,106	$95,414
Total cost per engine (yr. 6 and later)	$25,452	$28,902	$32,352	$33,661	$48,579	$63,496
Annual operating costs	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000

*All costs are in 2002 dollars.

We also calculated the cost per ton of emission reductions for a second tier of emission standards. We attributed the entire cost of such standards to the control of NOx, as summarized in Table 1.3-3.

Table 1.3-3
Cost Per Ton of Second Tier of Emission Standards 30% Below Tier 1

Model Year Grouping	NPV Benefits (short tons)	NPV Operating Costs	Engine & Vessel Costs	Discounted Cost Per Ton
U.S.-flag only				
1 to 5	1149	$66,000	$115,000	$145
6 +			$39,000	$87
Foreign-flag only				
1 to 5	45	$66,000	$57,000	$2,590
6 +			$39,000	$2,235
All Vessels				
1 to 5	73	$66,000	$57,000	$1,585
6 +			$39,000	$1,368

CHAPTER 2: Health and Welfare Concerns

The engines and vehicles that would be subject to the proposed standards generate emissions of NOx, PM, HC and CO that contribute to ozone and CO nonattainment as well as adverse health effects associated with ambient concentrations of PM. This section summarizes the general health effects of these substances. In it, we present information about these health and environmental effects, air quality modeling results, and inventory estimates in the absence of emissions controls.

2.1 Ozone

2.1.1 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. Oxides of nitrogen are emitted largely from motor vehicles, off-highway equipment, power plants, and other sources of combustion. 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. Hydrocarbons (HC) are a large subset of VOC, and to reduce mobile source VOC levels we set maximum emissions limits for hydrocarbons.

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.[1] 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.

2.1.2 Health and Welfare Effects of Ozone and Its Precursors

Based on a large number of recent 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.[2, 3] Short-term exposures (1-3 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.

Evidence also exists of a possible relationship between daily increases in ozone levels and increases in daily mortality levels. While the magnitude of this relationship is too uncertain to allow for direct quantification, the full body of evidence indicates the possibility of a positive relationship between ozone exposure and premature mortality.

In addition to human health effects, 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). 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.

2.1.3 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.[4] [5] Nitrogen dioxide can irritate the lungs and lower resistance to respiratory infection (such as influenza). 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”) in the Chesapeake Bay and several nationally important estuaries along the East and Gulf Coasts. Eutrophication can produce multiple adverse effects on water quality and the aquatic environment, including increased algal blooms, excessive phytoplankton growth, and low or no dissolved oxygen in bottom waters. Eutrophication also reduces sunlight, causing losses in submerged aquatic vegetation critical for healthy estuarine ecosystems. Deposition of nitrogen-containing compounds also affects terrestrial ecosystems. Nitrogen fertilization can alter growth patterns and change the balance of species in an ecosystem. In extreme cases, this process can result in nitrogen saturation when additions of nitrogen to soil over time exceed the capacity of plants and microorganisms to utilize and retain the nitrogen. These environmental impacts are discussed further in Sections 2.6.4 and 2.6.5, below.

Elevated levels of nitrates in drinking water pose significant health risks, especially to infants. Studies have shown that a substantial rise in nitrogen levels in surface waters are highly correlated with human-generated inputs of nitrogen in those watersheds.[6] These nitrogen inputs are dominated by fertilizers and atmospheric deposition. 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.

2.1.4 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.

Ground level ozone today remains a pervasive pollution problem in the United States. In 1999, 90.8 million people (1990 census) lived in 31 areas designated nonattainment under the 1-hour ozone NAAQS.[7] This sharp decline from the 101 nonattainment areas originally identified under the Clean Air Act Amendments of 1990 demonstrates the effectiveness of the last decade's worth of emission-control programs. However, elevated ozone concentrations remain a serious public health concern throughout the nation.

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.[8] 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.

To estimate future ozone levels, we refer to the modeling performed in conjunction with the final rule for our most recent heavy-duty highway engine and fuel standards.[9] We performed a series of ozone air quality modeling simulations for nearly the entire Eastern U.S. covering metropolitan areas from Texas to the Northeast.[10] This ozone air quality model was based upon the same modeling system as was used in the air quality analysis for Tier 2 standards for light-duty vehicles and light-duty trucks, with the addition of updated inventory estimates for 2007 and 2030. The model simulations were performed for several emission scenarios, and the model outputs were combined with current air quality data to identify areas expected to exceed the ozone NAAQS in 2007, 2020, and 2030.[11] The results of this modeling are contained in Table 2.1-1. Areas presented in Table 2.1-1 have 1997-99 air quality data indicating violations of the 1-hour ozone NAAQS, or are within 10 percent of the standard, are predicted to have exceedance in 2007, 2020, or 2030. An area was considered likely to have future exceedances if exceedances were predicted by the model, and the area is currently violating the 1-hour standard, or is within 10 percent of violating the 1-hour standard. Table 2.1-1 shows that 37 areas with a 1999 population of 91 million people are at risk of exceeding the 1-hour ozone standard in 2007.

Table 2.1-1: Eastern Metropolitan Areas with Modeled Exceedances of the 1-Hour Ozone Standard in 2007, 2020, or 2030 (Includes all emission controls through HD07 standards)

MSA or CMSA / State	2007	2020	2030	pop (1999)
Atlanta, GA MSA	x	x	x	3.9
Barnstable-Yarmouth, MA MSA *	x			0.2
Baton Rouge, LA MSA	x	x	x	0.6
Beaumont-Port Arthur, TX MSA	x	x	x	0.4
Benton Harbor, MI MSA *	x	x	x	0.2
Biloxi-Gulfport-Pascagoula, MS MSA *	x	x	x	0.3
Birmingham, AL MSA	x	x	x	0.9
Boston-Worcester-Lawrence, MA CMSA	x	x	x	5.7
Charleston, WV MSA *	x	x		0.3
Charlotte-Gastonia-Rock Hill, NC MSA	x	x	x	1.4
Chicago-Gary-Kenosha, IL CMSA	x	x	x	8.9
Cincinnati-Hamilton, OH-KY-IN CMSA *	x	x	x	1.9
Cleveland-Akron, OH CMSA *	x	x	x	2.9
Detroit-Ann Arbor-Flint, MI CMSA	x	x	x	5.4
Grand Rapids-Muskegon-Holland, MI MSA*	x	x	x	1.1
Hartford, CT MSA	x	x	x	1.1
Houma, LA MSA *	x	x	x	0.2
Houston-Galveston-Brazoria, TX CMSA	x	x	x	4.5
Huntington-Ashland, WV-KY-OH MSA	x	x	x	0.3
Lake Charles, LA MSA *	x		x	0.2
Louisville, KY-IN MSA	x	x	x	1
Macon, GA MSA	x			0.3
Memphis, TN-AR-MS MSA	x	x	x	1.1
Milwaukee-Racine, WI CMSA	x	x	x	1.7
Nashville, TN MSA	x	x	x	1.2
New London-Norwich, CT-RI MSA	x	x	x	0.3
New Orleans, LA MSA *	x	x	x	1.3
New York-Northern NJ-Long Island, NY-NJ-CT-PA CMSA	x	x	x	20.2
Norfolk-Virginia Beach-Newport News, VA-NC MSA *	x		x	1.6
Orlando, FL MSA *	x	x	x	1.5
Pensacola, FL MSA	x			0.4
Philadelphia-Wilmington-Atlantic City, PA-NJ-DE-MD CMSA	x	x	x	6
Providence-Fall River-Warwick,RI-MAMSA*	x	x	x	1.1
Richmond-Petersburg, VA MSA	x	x	x	1
St. Louis, MO-IL MSA	x	x	x	2.6
Tampa-St. Petersburg, FL MSA *	x	x		2.3
Washington-Baltimore	x	x	x	7.4
Total number of areas	37	32	32	
Population	91.2	88.5	87.8	91.4

* These areas have registered 1997-1999 ozone concentrations within 10 percent of standard.

With regard to future ozone levels, our photochemical ozone modeling for 2020 predicts exceedances of the 1-hour ozone standard in 32 areas with a total of 89 million people (1999 census; see Table 2.1-1). We expect that the control strategies contained in this proposal for Category 3 marine diesel engines will further assist state efforts already underway to attain and maintain the 1-hour ozone standard.

The inventories that underlie this predictive modeling for 2020 and 2030 include reductions from all current and committed to federal, state and local control programs, including the recently promulgated NOx and PM standards for heavy-duty vehicles and low sulfur diesel fuel. The geographic scope of these areas at risk of future exceedances underscores the need for additional, nationwide controls of ozone precursors.

It should be noted that this modeling did not attempt to examine the prospect of areas attaining or maintaining the ozone standard with possible future controls (i.e., controls beyond current or committed federal, State and local controls). Therefore, this information should be interpreted as indicating what areas are at risk of ozone violations in 2007, 2020 or 2030 without federal or state measures that may be adopted and implemented in the future. We expect many of these areas to adopt additional emission reduction programs, but we are unable to quantify or rely upon future reductions from additional State programs since they have not yet been adopted.

2.1.5 Public Health and Welfare Concerns from Prolonged and Repeated Exposures to Ozone

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 much lower than 0.125 ppm. 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.[12] Monitoring data indicates that 333 counties in 33 states exceed these levels in 1997-99.[13]

To provide a quantitative estimate of the projected number of people anticipated to reside in areas in which ozone concentrations are predicted to exceed the 8-hour level of 0.08 to 0.12 ppm or higher for multiple days, we performed regional modeling using the variable-grid Urban Airshed Model (UAM-V).[14] UAM-V is a photochemical grid model that numerically simulates the effects of emissions, advection, diffusion, chemistry, and surface removal processes on pollutant concentrations within a 3-dimensional grid. As with the previous modeling analysis, the inventories that underlie this predictive modeling include reductions from all current and committed to federal, state and local control programs, including the recently promulgated NOx and PM standards for heavy-duty vehicles and low sulfur diesel fuel. This modeling forecast that 111 million people are predicted to live in areas that areas at risk of exceeding these moderate ozone levels for prolonged periods of time in 2020 after accounting for expected inventory reductions due to controls on light- and heavy-duty on-highway vehicles; that number is expected to increase to 125 million in 2030.[15] Prolonged and repeated ozone concentrations at these levels are common in areas throughout the country, and are found both in areas that are exceeding, and areas that are not exceeding, the 1-hour ozone standard. Areas with these high concentrations are more widespread than those in nonattainment for that 1-hour ozone standard.

Ozone at these levels can have other welfare effects, with damage to plants being of most concern. Plant damage affects crop yields, forestry production, and ornamentals. 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 presented in more detail in Chapter 5, Volume II of the 1996 Criteria Document.

2.2 Particulate Matter

2.2.1 General Background

Particulate pollution is a problem affecting urban and non-urban localities in all regions of the United States. Category 3 marine diesel engines that would be subject to the proposed standards contribute to ambient particulate matter (PM) levels.

Particulate matter 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 cropland, 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, nitrogen oxides or volatile organic compounds (secondary particles). Secondary PM is dominated by sulfate in the eastern U.S. and nitrate in the western U.S.[16] 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.

Table 2.2-1: Percent Contribution to $PM_{2.5}$ by Component, 1998

	East	West
Sulfate	56	33
Elemental Carbon	5	6
Organic Carbon	27	36
Nitrate	5	8
Crustal Material	7	17

Source: 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.

2.2.2 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.[17]

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 studies have found 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.

2.2.3 PM 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 indicate that 14 designated PM_{10} nonattainment areas with a projected population of 23 million violated the PM_{10} NAAQS in the period 1997-1999. Table 2.2-2 lists the 14 areas, and also indicates the PM_{10} nonattainment classification, and 1999 projected population for each PM_{10} nonattainment area. The projected population in 1999 was based on 1990 population figures which were then increased by the amount of population growth in the county from 1990 to 1999.

Table 2.2-2: PM_{10} Nonattainment Areas Violating the PM_{10} NAAQS in 1997- 1999

Nonattainment Area or County	1999 Population (projected, in millions)
Anthony, NM (Moderate)[B]	0.003
Clark Co [Las Vegas], NV (Serious)	1.200
Coachella Valley, CA (Serious)	0.239
El Paso Co, TX (Moderate) [A]	0.611
Hayden/Miami, AZ (Moderate)	0.004
Imperial Valley, CA (Moderate)	0.122
Los Angeles South Coast Air Basin, CA (Serious)	14.352
Nogales, AZ (Moderate)	0.025
Owens Valley, CA (Serious)	0.018
Phoenix, AZ (Serious)	2.977
San Joaquin Valley, CA (Serious)	3.214
Searles Valley, CA (Moderate)	0.029
Wallula, WA (Moderate)[B]	0.052
Washoe Co [Reno], NV (Moderate)	0.320
Total Areas: 14	23.167

[A] EPA has determined that continuing PM_{10} nonattainment in El Paso, TX is attributable to transport under section 179(B).

[B] The violation in this area has been determined to be attributable to natural events under section 188(f) of the Act.

In addition to the 14 PM_{10} nonattainment areas that are currently violating the PM_{10} NAAQS listed in Table 2.2-2, there are 25 unclassifiable areas that have recently recorded ambient concentrations of PM_{10} above the PM_{10} NAAQS. EPA adopted a policy in 1996 that allows areas with PM_{10} exceedances that are attributable to natural events to retain their designation as unclassifiable if the State is taking all reasonable measures to safeguard public health regardless of the sources of PM_{10} emissions. Areas that remain unclassifiable areas are not required under the Clean Air Act to submit attainment plans, but we work with each of these areas to understand the nature of the PM_{10} problem and to determine what best can be done to reduce it. With respect to the monitored violations reported in 1997-99 in the 25 areas designated as unclassifiable, we have not yet excluded the possibility that factors such as a one-time monitoring upset or natural events, which ordinarily would not result in an area being designated as nonattainment for PM_{10}, may be responsible for the problem.

Current 1999 $PM_{2.5}$ monitored values, which cover about a third of the nation's counties, indicate that at least 40 million people live in areas where long-term ambient fine particulate matter levels are at or above 16 $\mu g/m^3$ (37 percent of the population in the areas with monitors).[18] This 16 $\mu g/m^3$ threshold is the low end of the range of long term average $PM_{2.5}$ concentrations in cities where statistically significant associations were found with serious health effects, including premature mortality.[19] To estimate the number of people who live in areas where long-term ambient fine particulate matter levels are at or above 16 $\mu g/m^3$ but for which there are no monitors, we can use modeling. According to our national modeled 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).[20]

To estimate future $PM_{2.5}$ levels, we refer to the modeling performed in conjunction with the final rule for our most recent heavy-duty highway engine and fuel standards using EPA's Regulatory Model System for Aerosols and Deposition (REMSAD).[21] The most appropriate method of making these projections relies on the model to predict changes between current and future states. Thus, we have estimated future conditions only for the areas with current $PM_{2.5}$ monitored data (which covers about a third of the nation's counties). For these counties, REMSAD predicts the current level of 37 percent of the population living in areas where fine PM levels are at or above 16 μg/m3 to increase to 49 percent in 2030.[22]

2.2.4 Diesel Exhaust

Diesel emissions are of concern beyond their contribution to ambient PM. As discussed in detail in the draft RSD, there have been health studies specific to diesel exhaust emissions which indicate potential hazards to human health that appear to be specific to this emissions source. For chronic exposure, these hazards included respiratory system toxicity and carcinogenicity. Acute exposure also causes transient effects (a wide range of physiological symptoms stemming from irritation and inflammation mostly in the respiratory system) in humans though they are highly variable depending on individual human susceptibility. The chemical composition of diesel exhaust includes several hazardous air pollutants, or air toxics. In our Mobile Source Air Toxic Rulemaking under section 202(l) of the Act, we determined that diesel particulate matter and diesel exhaust organic gases be identified as a Mobile Source Air Toxic (MSAT).[23] The purpose of the MSAT list is to provide a screening tool that identifies compounds emitted from motor vehicles or their fuels for which further evaluation of emissions controls is appropriate.

2.3 Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless gas produced through the incomplete combustion of carbon-based fuels. Carbon monoxide enters the bloodstream through the lungs and reduces the delivery of oxygen to the body's organs and tissues. The health threat from CO is most serious for those who suffer from cardiovascular disease, particularly those with angina or peripheral vascular disease. Healthy individuals also are affected, but only at higher CO levels. Exposure to elevated CO levels is associated with impairment of visual perception, work capacity, manual dexterity, learning ability and performance of complex tasks.

High concentrations of CO generally occur in areas with elevated mobile-source emissions. Peak concentrations typically occur during the colder months of the year when mobile-source CO emissions are greater and nighttime inversion conditions are more frequent. This is due to the enhanced stability in the atmospheric boundary layer, which inhibits vertical mixing of emissions from the surface.

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.[24]

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.[25] 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 (LDT2s).[26] CO standards for passenger cars and other light-duty trucks and heavy-duty vehicles did not change as a result of other recent rulemakings.

2.4 Other Adverse Public Health and Welfare Effects Associated with Category 3 Marine Diesel Engines

The previous section describes national-scale adverse public health effects associated with the Category 3 marine diesel engines covered by this proposal. This section describes other adverse health and welfare effects arising from Category 3 marine diesel engines, including regional haze, acid deposition, and water eutrophication and nitrification

2.4.1 Nonroad Engines and Regional Haze

The Clean Air Act established special goals for improving visibility in many national parks, wilderness areas, and international parks. In the 1977 amendments to the Clean Air Act, Congress set as a national goal for visibility the “prevention of any future, and the remedying of any existing, impairment of visibility in mandatory class I Federal areas which impairment results from manmade air pollution” (CAA section 169A(a)(1)). The Amendments called for us to issue regulations requiring States to develop implementation plans that assure “reasonable progress” toward meeting the national goal (CAA Section 169A(a)(4)). We issued regulations in 1980 to address visibility problems that are “reasonably attributable” to a single source or small group of sources, but deferred action on regulations related to regional haze, a type of visibility impairment that is caused by the emission of air pollutants by numerous emission sources located across a broad geographic region. At that time, we acknowledged that the regulations were only the first phase for addressing visibility impairment. Regulations dealing with regional haze were deferred until improved techniques were developed for monitoring, for air quality modeling, and for understanding the specific pollutants contributing to regional haze.

In the 1990 Clean Air Act amendments, Congress provided additional emphasis on regional haze issues (see CAA section 169B). In 1999 we finalized a rule that calls for States to establish goals and emission reduction strategies for improving visibility in all 156 mandatory Class I national parks and wilderness areas. In that rule, we also encouraged the States to work together in developing and implementing their air quality plans. The regional haze program is designed to improve visibility and air quality in our most treasured natural areas. At the same time, control strategies designed to improve visibility in the national parks and wilderness areas will improve visibility over broad geographic areas.

Regional haze is caused by the emission from numerous sources located over a wide geographic area. Such sources include, but are not limited to, major and minor stationary sources, mobile sources, and area sources. Visibility impairment is caused by pollutants (mostly fine particles and precursor gases) directly emitted to the atmosphere by a number of activities (such as electric power generation, various industry and manufacturing processes, truck and auto emissions, construction activities, etc.). These gases and particles scatter and absorb light, removing it from the sight path and creating a hazy condition.

Some fine particles are formed when gases emitted to the air form particles as they are carried downwind (examples include sulfates, formed from sulfur dioxide, and nitrates, formed from nitrogen oxides). These activities generally span broad geographic areas and fine particles can be transported great distances, sometimes hundreds or thousands of miles. Consequently, visibility impairment is a national problem. Without the effects of pollution a natural visual range is approximately 140 miles in the West and 90 miles in the East. However, fine particles have significantly reduced the range that people can see and in the West the current range is 33-90 miles and in the East it is only 14-24 miles.

Because of evidence that fine particles are frequently transported hundreds of miles, all 50 states, including those that do not have Class I areas, will have to participate in planning, analysis and, in many cases, emission control programs under the regional haze regulations. Even though a given State may not have any Class I areas, pollution that occurs in that State may contribute to impairment in Class I areas elsewhere. The rule encourages states to work together to determine whether or how much emissions from sources in a given state affect visibility in a downwind Class I area.

The regional haze program calls for states to establish goals for improving visibility in national parks and wilderness areas to improve visibility on the haziest 20 percent of days and to ensure that no degradation occurs on the clearest 20 percent of days. The rule requires states to develop long-term strategies including enforceable measures designed to meet reasonable progress goals. Under the regional haze program, States can take credit for improvements in air quality achieved as a result of other Clean Air Act programs, including national mobile-source programs.

Nonroad engines (including construction equipment, farm tractors, boats, planes, locomotives, recreational vehicles, and marine engines) contribute significantly to regional haze.

This is because there are nonroad engines in all of the states, and their emissions contain precursors of fine PM and organic carbon that are transported and contribute to the formation of regional haze throughout the country and in Class I areas specifically.

2.4.2 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.[27] 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 (NSWS) 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 NSWS 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 in the NSWS 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. This area includes national parks such as the Shenandoah and Great Smoky Mountain National Parks.

2.4.3 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.[28] 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 (NRC, 1993). Nitrogen is the primary cause of eutrophication in most coastal waters and estuaries.[29] On the New England coast, for example, the number of red and browntides 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.[30] 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.

2.5 Inventory Contributions

2.5.1 National Inventory

We developed baseline Category 3 vessel emissions inventories under contract with E. H. Pechan & Associates, Inc.[31] Inventory estimates were developed separately for vessel traffic within 25 nautical miles of port areas and vessel traffic outside of port areas but within 175 nautical miles of the coastline. Different techniques were used to develop the port and non-port inventories. For port areas we developed detailed emissions estimates for nine specific ports using port activity data including port calls, vessel types and typical times in different operating modes. Emissions 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. We developed non-port emissions inventories using cargo movements and waterways data, vessel speeds, average dead weight tonnage per ship, and assumed cargo capacity factors. More detailed information regarding the development of the baseline emissions inventories can be found in Chapter 6.

There has been little study of the transport of marine vessel NOx emissions and the distance they may travel to impact air quality on 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. When we consider how far off the coast to consider when determining which emissions to include in our baseline the correct answer may well vary depending on geographic area and prevailing atmospheric conditions. In developing baseline emissions inventories we looked at two different scenarios. First, we looked only at the pollutants emitted within 25 nautical miles of a port area as a reasonable lower bound to estimate the national inventory of Category 3 marine diesel engines. The primary reason for choosing the 25-mile radius is that is was used in work done for us in support of previous modeling efforts. We also estimated Category 3 emissions within 175 nautical miles (200 statute miles) of shore as a more reasonable estimate of the distance from shore that vessel emissions may be expected to impact air quality on land. This 175-mile limit was also used in support of previous rulemaking and modeling efforts.

Not surprisingly, these two different distances yield different inventory results. The 1996 NOx and PM emissions inventories under these tow scenarios are shown in Table 2.6-1. 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. As will be discussed later in this section, this initial analysis shows that the contribution from U.S. and foreign flagged vessels differs between these two areas.

Table 2.5-1
Category 3 Marine Diesel Engine 1996 Baseline Emissions Inventories (thousand short tons)

Scenario	NOx	PM
Within 25 nautical miles of ports	101	9.3
Within 175 nautical miles of coast	190	17

For the remainder of this analysis we will consider all emissions that occur within 175 nautical miles from the coast as our primary scenario. However, we will continue to investigate this issue throughout this rulemaking, and will incorporate any new information into the final rule. For example, the U.S. Department of Defense (DoD) has presented information to us recommending that 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 extensive work on the marine vessels issue in Southern California resulted in a conclusion 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. Satellite data however showed 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 which 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 narrower (perhaps 30 nautical miles) region of "coastal influence." The Gulf Coast and the U.S. East coast would similarly have their own unique meteorological conditions that might call for different lines of demarcation between on-shore and off-shore effects.

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 feet turnover based on 25 years as the average age of the world fleet at time of scrappage. We also take the MARPOL Annex VI 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 emissions inventories are based on the assumption that all vessels built after 1999, both U.S. and foreign flagged, will comply with the Annex VI NOx limits. Table 2.6-2 shows the future year NOx and PM inventories for selected years out to 2030. 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 emissions inventories can be found in Chapter 6.

Table 2.5-2
Future Year NOx and PM Inventories for Uncontrolled 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 summarized in Table 2.6-3. 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 2020 for Category 3 marine diesel engines show how emissions from these engines are expected to increase over time if left uncontrolled. The projections for 2020 are summarized in Table 2.6-4 and indicate that Category 3 marine diesel engines are expected to contribute 5.7 percent NOx and 5.8 percent of PM emissions in the year 2020. Population growth and the effects of other regulatory control programs are factored into these projections. The relative importance of uncontrolled nonroad engines in 2020 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 2.5-3
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 proposed standards (U.S. flagged commercial marine - Category 3 - uncontrolled)	**79**	**0.6%**	**2**	**0.0%**	**4**	**0.0%**	**7.0**	**1.0%**
Commercial Marine CI - Category 3 - uncontrolled	195	1.5%	8	0.1%	16	0.0%	18.0	2.6%
Commercial Marine CI - Categories 1 and 2	700	5.2%	22	0.3%	103	0.1%	20	2.9%
Highway Motorcycles	8	0.1%	84	1.1%	329	0.4%	0.4	0.1%
Nonroad Industrial SI > 19 kW	306	2.3%	247	3.2%	2,294	2.9%	1.6	0.2%
Recreational SI	13	0.1%	737	9.6%	2,572	3.3%	5.7	0.8%
Recreation Marine CI	24	0.2%	1	0.0%	4	0.0%	1	0.1%
Marine SI Evap	0	0.0%	89	1.2%	0	0.0%	0	0.0%
Marine SI Exhaust	32	0.2%	708	9.2%	2,144	2.7%	38	5.4%
Nonroad SI < 19 kW	106	0.8%	1,460	18.9%	18,359	23.5%	50	7.2%
Nonroad CI	2,625	19.6%	316	4.1%	1,217	1.6%	253	36.3%
Locomotive	1,192	8.9%	47	0.6%	119	0.2%	30	4.3%
Total Nonroad	5,201	39%	3,719	48%	27,157	35%	418	60%
Total Highway	7,981	60%	3,811	50%	49,811	64%	240	34%
Aircraft	178	1%	183	2%	1,017	1%	39	6%
Total Mobile Sources	13,360	100%	7,713	100%	77,985	100%	697	100%
Total Man-Made Sources	24,444	--	18,659	--	100,064	--	3,093	--
Mobile Source percent of Total Man-Made Sources	55%	--	41%	--	78%	--	23%	–

Table 2.5-4
Modeled Annual Emission Levels for
Mobile-Source Categories in 2020 (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 proposed standards (U.S. flagged commercial marine - Category 3 - uncontrolled)	**150**	**2.3%**	**5**	**0.1%**	**9**	**0.0%**	**14.0**	**2.2%**
Commercial Marine CI - Category 3 - uncontrolled	367	5.7%	17	0.3%	37	0.0%	37.0	5.8%
Commercial Marine CI - Categories 1 and 2	617	9.6%	24	0.4%	125	0.1%	19.0	3.0%
Highway Motorcycles	14	0.2%	144	2.3%	569	0.6%	0.8	0.1%
Nonroad Industrial SI > 19 kW	486	7.6%	348	5.5%	2,991	3.3%	2.4	0.4%
Recreational SI	27	0.4%	1,706	27.1%	5,407	6.0%	7.5	1.2%
Recreation Marine CI	39	0.6%	1	0.0%	6	0.0%	1.5	0.2%
Marine SI Evap	0	0.0%	102	1.6%	0	0.0%	0	0.0%
Marine SI Exhaust	58	0.9%	284	4.5%	1,985	2.2%	28	4.4%
Nonroad SI < 19 kW	106	1.7%	986	15.6%	27,352	30.3%	77	12.0%
Nonroad CI	1,791	28.0%	142	2.3%	1,462	1.6%	261	40.6%
Locomotive	611	9.5%	35	0.6%	119	0.1%	21	3.3%
Total Nonroad	4,116	63%	3,789	60%	40,053	44%	455	70%
Total Highway	2,050	33%	2,278	36%	48,903	54%	145	23%
Aircraft	232	4%	238	4%	1,387	2%	43	7%
Total Mobile Sources	6,398	100%	6,305	100%	90,343	100%	643	100%
Total Man-Made Sources	16,374	--	16,405	--	114,011	--	3,027	--
Mobile Source percent of Total Man-Made Sources	39%	--	38%	--	79%	--	21%	–

2.5.2 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 port areas. Using the port-specific Category 3 inventories developed for use in our national inventory in conjunction with total port area inventories developed in support of the heavy-duty on-highway 2007 rule, we developed estimates of the contribution of Category 3 marine diesel engines to the mobile source NOx and PM inventories of several selected port areas, including several ozone nonattainment areas. The NOx results are shown in Table 2.6-5, and the PM results are shown in Table 2.6-6. As can be seen from these tables, the relative contribution of Category 3 marine diesel engine pollution to mobile source pollution is expected to increase in the future. 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.

Table 2.5-5
Uncontrolled Category 3 Marine Diesel Engines NOx Inventories
as a Percentage of Mobile Source NOx in Selected Port Areas

Ozone Nonattainment Area?	Port Area	% of Mobile Source NOx from C3	
		1996	2020[1]
Y	Baton Rouge and New Orleans, LA	7.4	15.8
Y	Los Angeles/Long Beach, CA	2.0	8.6
Y	Beaumont/Port Arthur, TX	1.4	3.1
Y	Houston/Galveston/Brazoria, TX	1.5	4.9
Y	Baltimore/Washington DC	2.1	11.4
Y	Philadelphia/Wilmington/Atlantic City	1.8	6.9
Y	New York/New Jersey	1.0	6.2
N	Seattle/Tacoma/Bremerton/ Bellingham, WA	4.3	26.3
N	Miami/Ft. Lauderdale, FL	5.4	28.1
N	Portland/Salem, OR	1.9	11.9
N	Wilmington, NC	6.9	26.8
N	Corpus Christi, TX	4.8	12.2
N	Brownsville/Harlington/San Benito, TX	1.8	6.6

1. 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 2.5-6
Modeled PM Inventories as a Percentage of Mobile Source PM
in Selected Port Areas

Port Area	% of Mobile Source PM from C3	
	1996	2020[1]
Baton Rouge and New Orleans, LA	12.1	22.6
Los Angeles/Long Beach, CA[2]	3.9	10.8
Beaumont/Port Arthur, TX	7.4	18.3
Houston/Galveston/Brazoria, TX	3.3	8.5
Baltimore/Washington DC	3.2	9.6
Philadelphia/Wilmington/Atlantic City	2.8	6.3
New York/New Jersey	1.6	5.7
Seattle/Tacoma/Bremerton/ Bellingham, WA	8.5	25.5
Miami/Ft. Lauderdale, FL	10.6	28.7
Portland/Salem, OR	3.9	12.1
Wilmington, NC	8.1	22.4
Corpus Christi, TX	6.0	9.6
Brownsville/Harlington/San Benito, TX	3.1	14.9

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

2.5.3 Emissions in Nonport Areas

These ships can also have a significant impact on inventories in areas without large commercial ports. For example, Santa Barbara estimates that engine on ocean-going marine vessels contribute about 37 percent of total NOx in their area. 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.[32] These emissions are expected to increase to 62 percent by 2015. 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 2.5-7
NOx Emissions, Santa Barbara County, California

Source	1999		2015	
	Tons/Day	% total	Tons/day	
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	

Source: *Santa Barbara County Air Quality News*, Issue 62, July-August 2001

2.5.4 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 only proposing to apply the emission standards to U.S. flagged vessels. We estimated the relative contribution of U.S. and foreign flagged vessels separately for the ports areas and the non-ports areas due to the fact the we had different data sets available to us for the two areas.

We estimated the contribution of 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, including the country in which they are flagged and the number of port calls each vessel made. An analysis of the port call data shows that U.S. flagged vessels only account for 6.4 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.

We used freight tonnage data from the U.S. Army Corp of Engineers (USACE) to develop relative U.S. and foreign flagged emissions contributions in non-ports areas within 175 nautical miles of the coast. In contrast to the data for the ports areas, the USACE data suggests that almost 80 percent of the non-ports emissions come from U.S. flagged vessels.

The relative contributions from U.S. and foreign flagged vessels are quite different between the ports areas and the non-ports areas. Some of this difference can be explained through U.S. cabotage law, which requires that any vessel operating between two U.S. ports be U.S. flagged. Thus, while most port traffic is foreign flagged, the foreign flagged vessels would tend to come into a single U.S. port and then leave U.S. waters. In contrast, U.S. flagged vessels would typically travel from one U.S. port to another, thus accounting for a higher percentage of the non-ports emissions. Table 2.5-8 shows the relative contribution of U.S. and foreign flagged vessels to ports emissions (within 25 nautical miles of port areas), non-ports emissions (between 25 and 175 nautical miles from the U.S. coast) and total emissions from Category 3 vessels within 175 nautical miles of the U.S. coast.

Table 2.5-8
Relative Contribution by Vessel Flag to 1996 NOx Emissions Inventories

Area	NOx Emissions (1000 tons)		Percent of total from U.S. Flagged
	U.S. Flagged	Foreign Flagged	
Ports	6.5	94.7	6.4%
Non-port	70.2	18.6	79%
Total	76.7	113.3	40%

Chapter 2 References

1.Carbon monoxide also participates in the production of ozone, albeit at a much slower rate than most VOC and NOx compounds.

2.U.S. EPA, 1996, Review of National Ambient Air Quality Standards for Ozone, Assessment of Scientific and Technical Information, OAQPS Staff Paper, EPA-452/R-96-007. A copy of this document can be obtained from Air Docket A-2001-11, Document No. II-XX-XX.

3.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-2001-11, Document No. II-XX-XX.

4.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.

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

6.Vitousek, Pert 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.

7.National Air Quality and Emissions Trends Report, 1999, EPA, 2001, at Table A-19. This document is available at http://www.epa.gov/oar/aqtrnd99/. The data from the Trends report are the most recent EPA air quality data that has been quality assured. A copy of this table can also be found in Docket No. A-2001-11, Document No. II-XX-XX.

8.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. A copy of this document can also be found in Docket No. A-2001-11, Document No. II-X-XX.

9.Additional information about this modeling can be found in our Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements, document EPA420-R-00-026, December 2000. Docket No. 1-2001-11, Document No. II-XX-XX. This document is also available at http://www.epa.gov/otaq/diesel.htm#documents.

10.We also performed ozone air quality modeling for the western United States but, as described further in the air quality technical support document, model predictions were well below corresponding ambient concentrations for out heavy-duty engine standards and fuel sulfur control

rulemaking. Because of poor model performance for this region of the country, the results of the Western ozone modeling were not relied on for that rule.

11.Additional information about these studies can be found in Chapter 2 of "Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements," December 2000, EPA420-R-00-026. Docket No. A-2001-11, Document Number II-XX-XX. This document is also available at http://www.epa.gov/otaq/diesel.htm#documents.

12.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-2001-11, Document No. II-XX-XX.

13.A copy of this data can be found in Air Docket A-2001-11, Document No. II-XX-XX.

14.Memorandum to Docket A-99-06 from Eric Ginsburg, EPA, "Summary of Model-Adjusted Ambient Concentrations for Certain Levels of Ground-Level Ozone over Prolonged Periods," November 22, 2000. Docket A-2001-11, Document Number II-XX-XX.

15.Memorandum to Docket A-99-06 from Eric Ginsburg, EPA, "Summary of Model-Adjusted Ambient Concentrations for Certain Levels of Ground-Level Ozone over Prolonged Periods," November 22, 2000, at Table C, Control Scenario – 2020 Populations in Eastern Metropolitan Counties with Predicted Daily 8-Hour Ozone greater than or equal to 0.080 ppm. Docket A-2001-11, Document Number II-XX-XX.

16. Air Quality and Emissions Trends Report, 1998, March, 2000. 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. A copy of this document can also be found in Docket No. A-2001-11, Document No. II-X-XX.

17.EPA (1996) Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information OAQPS Staff Paper. EPA-452/R-96-013. Docket Number A-2001-11, Document No. II-XX-XX. The particulate matter air quality criteria documents are also available at http://www.epa.gov/ncea/partmatt.htm.

18.Memorandum to Docket A-99-06 from Eric O. Ginsburg, Senior Program Advisor, "Summary of 1999 Ambient Concentrations of Fine Particulate Matter," November 15, 2000. This memo is also available in the docket for this rule. Docket A-2001-11, Document Number II-XX-XX.

19.EPA (1996) Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information OAQPS Staff Paper. EPA-452/R-96-013. Docket Number A-2001-11, Document No. II-XX-XX. The particulate matter air quality criteria documents are also available at http://www.epa.gov/ncea/partmatt.htm. .

20.Memorandum to Docket A-99-06 from Eric O. Ginsburg, Senior Program Advisor, "Summary of Absolute Modeled and Model-Adjusted Estimates of Fine Particulate Matter for Selected Years," December 6, 2000. This memo is also available in the docket for this rule. Docket A-2001-11, Document Number II-XX-XX.

21.Additional information about the Regulatory Model System for Aerosols and Deposition (REMSAD) and our modeling protocols can be found in our Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements, document EPA420-R-00-026, December 2000. Docket No. A-2001-11, Document No. A-XX-XX. This document is also available at http://www.epa.gov/otaq/diesel.htm#documents.

22. Technical Memorandum, EPA Air Docket A-99-06, Eric O. Ginsburg, Senior Program Advisor, Emissions Monitoring and Analysis Division, OAQPS, Summary of Absolute Modeled and Model-Adjusted Estimates of Fine Particulate Matter for Selected Years, December 6, 2000, Table P-2. Docket Number 2001-11, Document Number II-XX-XX.

23.See our Mobile Source Air Toxics final rulemaking, 66 FR 17230, March 29, 2001, and the Technical Support Document for that rulemaking. Docket No. A-2001-11, Documents Nos. II-A-XX and II-A-YY.

24.National Air Quality and Emissions Trends Report, 1999, EPA, 2001, at Table A-19. This document is available at http://www.epa.gov/oar/aqtrnd99/. The data from the Trends report are the most recent EPA air quality data that have been quality assured. A copy of this table can also be found in Docket No. A-2001-11, Document No. II-A-XX.

25.National Air Quality and Emissions Trends Report, 1998, March, 2000; this document is available at http://www.epa.gov/oar/aqtrnd98/. National Air Pollutant Emission Trends, 1900-1998 (EPA-454/R-00-002), March, 2000. These documents are available at Docket No. A-2000-01, Document No. II-A-72. See also Air Quality Criteria for Carbon Monoxide, US EPA, EPA 600/P-99/001F, June 2000, at 3-10. Air Docket A-2001-11, Document Number II-A-XX. This document is also available at http://www.epa.gov/ncea/coabstract.htm.

26.LDT2s are light light-duty trucks greater than 3750 lbs. loaded vehicle weight, up through 6000 gross vehicle weight rating.

27.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-2001-11, Document No. II-XX-XX.

28.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.

29.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, EPA-453/R-97-011.

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

31.Cite Pechan report(s) when completed.

32.Memorandum to Docket A-2001-11 from Jean Marie Revelt, "*Santa Barbara County Air Quality News*, Issue 62, July-August 2001 and other materials provided to EPA by Santa Barbara County," March 14, 2002. Air Docket A-2001-11, Document No. II-A-47..

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 elsewhere. We do not attempt to perform this analysis on a port-specific basis. However, given that the small number of U.S.-flagged vessels in comparison to the world fleet, it is likely that the contribution of U.S. C3 vessels to local air pollution in any given port is likely to be small compared to that of foreign-flag 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.

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 for 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). The low-speed engines are two-cycle models which are typically connected to a direct drive propulsion system. The medium-speed engines are typically four-cycle engines (a very small percentage are two-cycle). Most of these engines are 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 aspect 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, which make it a very dirty fuel. Because of it's high level of paraffins, bunker fuel is solid at room 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.

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.[1] 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. According tho the US Census Bureau, the total delivered cost of all shipbuilding and repair diesel and semidiesel engines in 1997 was $131 million.[2] Only a fraction of this amount is attributable to Category 3 marine diesel engines.

Category 3 marine diesel engines are unique among engines in the sense that they are incredibly large and many are not 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 designed specifically for that vessel.

Once a vessel manufacturer has determined the size and output of engine necessary for their particular 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 as well as performing Annex VI emission testing. The engines 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, typically 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

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

We have determined that there are at least 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.

The majority of Category 3 diesel engine manufacturers are located in Europe and Japan. Only one engine company which manufactures Category 3 diesel engines is headquartered in the United States. This manufacturer is Caterpillar who 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 currently produce models which are 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 varies 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.[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 1998. These data are presented in Table 3.1-2. 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 3.2-2 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*

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.

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*

3.3 Vessel Manufacturers

This section gives a general characterization of the large vessel manufacturing segment of the marine industry that may be impacted by the proposed regulations. 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 the 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 1,000 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 (RORO), 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 and can take up to 18 months alone. 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 this period of the design process that the owner and architects decide what engine or engines to use. In determining the appropriate 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 to 14 months.

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

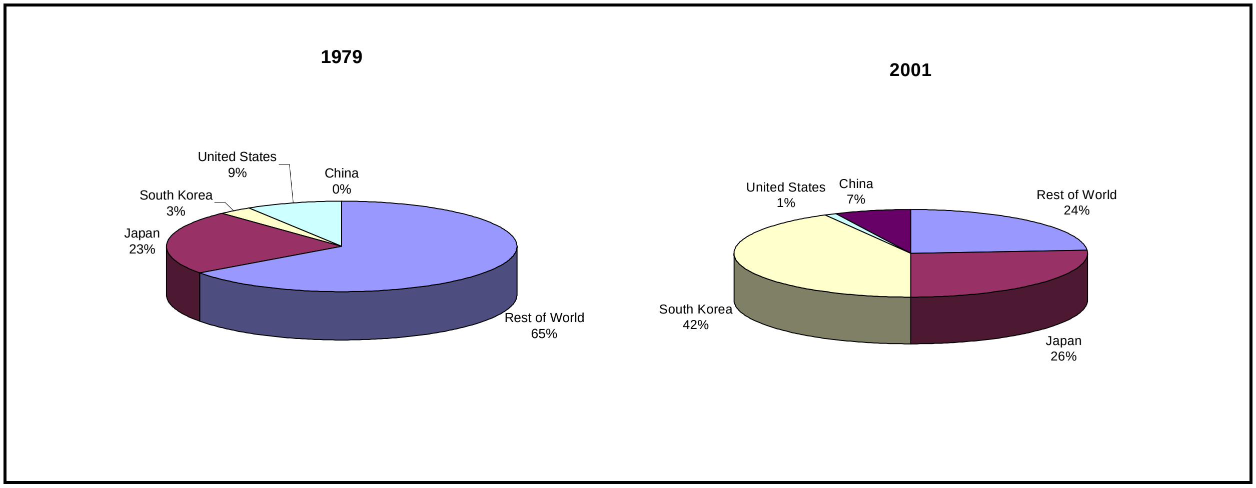
Shipyards that build ships, operate on a job specific basis. Unlike most other industries, only a small number of orders are received each year and they often take years to fill. Orders for vessels are placed by either the private sector or the federal government. Companies that place orders often include commercial shipping companies, passenger and cruise companies, ferry companies, and petrochemical companies.

Shipbuilding has historically been an important industry in the United States. It is dominated by two main components: the commercial market for large vessels and the military market. 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.

Shipbuilding is a global industry. The vast majority of commercial ships used throughout the world are foreign-built. 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. The Japanese and South Korean penetration into the market came at the expense of American (and European) shipbuilders. 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 3.3-2 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 3.3-2.
Deliveries from U.S. Shipyards, 1990 to 2000
(Merchant ships over 1000 GT 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”) is often used to refer 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 to more than 40 nations with significant ocean-going fleets, are designed to ensure a strong national flag merchant marine fleet for defense, employment, and general economic purposes by reserving a country’s domestic maritime transportation for its own citizens. The principles of 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.

In the United States, 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, in 1789. 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.
- 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 the U.S. flag, 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 effected 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.-flagged and registered vessels. In other words, all Jones Act vessels are U.S.-flagged, but all U.S.-flagged vessels are not 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 states that the benchmark used to track the U.S. shipbuilding industry is the U.S. Major Shipbuilding Base (MSB). 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 which 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. Currently, there are only three shipyards building any of these vessels. Table 3.2-3 lists the eight shipyards that have most recently been involved in building large commercial vessels.

Table 3.2-3
U.S. Shipyards Building Large Commercial Vessels

Shipyard	Location
National Steel & Shipbuilding Co. (NASSCO)	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. (NASSCO), Avondale Industries, Inc., and Ingalls Shipyard. A fourth shipyard, Kvaerner Philadelphia Shipyard, Inc. has a long history of producing large oceangoing vessels, primarily for the Navy. In 1996, the Philadelphia shipyard was closed. 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 MSB yards 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 3.2-4 presents the employment and sales for the largest U.S. shipyards still active (or with capacity) to build large commercial vessels by yard.

Table 3.2-4 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. (NASSCO)	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 3.2-5 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. (NASSCO), 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 U.S. 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 related 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 U.S. flag oceangoing self-propelled merchant vessels of 1,000 gross tons and over. The vessel name, ship type, engine type, the year and country in which the operator (government or private) vessel was built, GRT 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

Vessels in the U.S. fleet are subject to the Jones Act and related cabotage laws which require that cargo and passengers moving between U.S. ports, either directly or via a foreign point, be transported on vessels which are owned by U.S. citizens, built in U.S. shipyards, and manned by U.S. citizen crews. U.S. cabotage laws provide reliable domestic shipping, protect the U.S. shipping industry from foreign competition, and ensure a maritime capability that is subject to U.S. government control for national defense purposes. Many countries have cabotage laws to protect both their shipping industry and for national defense purposes.

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.-flag 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. flagged 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. flagged 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 Flag Fleet

The current estimate for the size of the foreign flagged fleet of vessels using Category 3 engines that entered U.S. ports is approximately 7,600 vessels. There are over 25 different types of foreign flagged 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. These ships range from very large passenger vessels that can exceed lengths of 1,000 feet, hold up to 5,000 passengers and crew, contain over 1,600 cabins, and have up to 14 decks to vessels half this size. There are twelve companies that account for the majority of cruise ship activity in U.S. waters. Table 3.3-2 lists these twelve companies.

Table 3.3-2 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 U.S. flagged cruise ships. 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 had planned 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 Francisco. 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 through Los Angeles, New York and San Francisco, while the majority of oil and other tanker-carried products entered and left primarily through Houston and New Orleans.

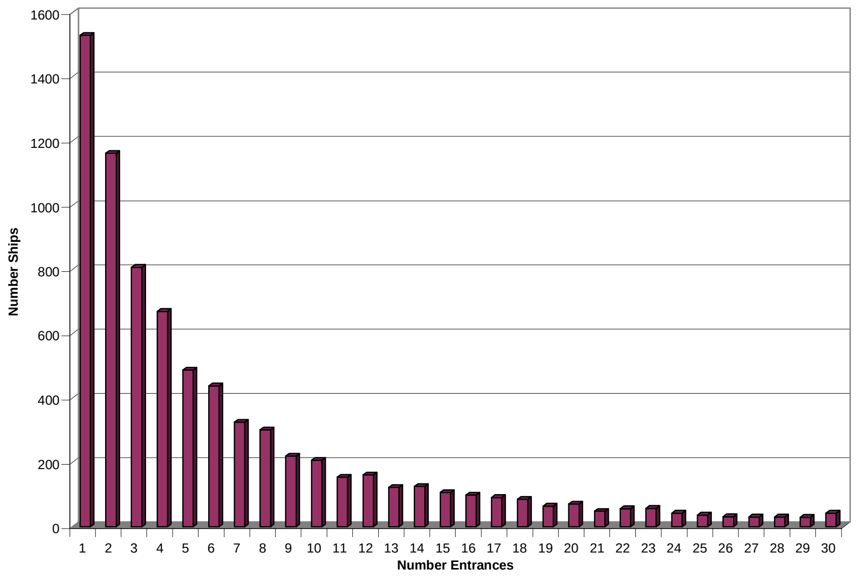
Table 3.5-1 Top Five U.S. Commercial Ports in 2000 - Based on Calls

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 Francisco	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 7,800 vessels powered by or equipped with Category 3 engines visited U.S. ports in 1999. The vast majority of these ships were foreign flagged. In fact, about 97 percent of the total number of Category 3-powered vessels that made calls to U.S. ports were foreign flagged. U.S. flagged vessels accounted for about three percent of the total

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



number of vessels visiting U.S. ports. Approximately 200 U.S. flagged vessels visited U.S. ports in 1999. Table 3.5-2 lists the ten most common U.S. flagged vessel type for 1999 and the number of each vessel.

Table 3.5-2 MARAD Summary of U.S. Flagged 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 flagged vessels. As stated above, 7,800 vessels visited U.S. ports in 1999. These vessels made a total of 72,200 entrances to U.S. ports. Of these entrances, 67,500 or 93 percent, were made by foreign flagged vessels. Only 4,700 entrances or seven percent were made by U.S. flagged 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, foreign flagged and

U.S. flagged 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 flagged) for 1999.

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 has had an adverse impact on the U.S. tourism industry. The September 11th attacks exacerbated this impact, and 2001 is expected to be the first year in a decade in which embarkations actually decrease. At this point it is difficult to predict when the cruise industry and the number of embarkations will recover from these economic and political events.

3.6 Conclusion

The Category 3 marine diesel engine and vessels industry is relatively small. 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 foreign flagged. Approximately 200 vessels entering U.S. ports in 1999 were U.S. flagged vessels. 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.-flagged vessels is small in comparison to the world fleet, it is likely that the contribution of U.S. Category 3 vessels to local air pollution in any given port is likely to be small compared to that of foreign-flag vessels.

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CHAPTER 4: Technological Feasibility

This chapter describes the current state of compression-ignition technology for Category 3 marine engines and the feasibility of achieving emission reductions for the proposed Tier 1 NOx standard (which is equivalent to the Annex VI NOx limit) and an additional Tier 2 standard under consideration that would be 30 percent below the proposed Tier 1 standard. Engine manufacturers are already producing engines that meet the Annex VI NOx limit and therefore this chapter focuses on technologies under development for meeting the Tier 2 emission standards under consideration. These technologies generally include internal engine modifications, fuel injection, internal exhaust gas recirculation and electronic controls. The combustion process and potential technologies described herein are basically the same for the Category 3 marine engine types, slow-speed, two-stroke engines or medium-speed four-stroke engines, and will be differentiated only where significant differences exist. The technologies described in this Chapter apply to all Category 3 engines, regardless of the flag state of the vessel in which the engines are ultimately installed. U.S.-flag vessels and foreign-flag vessels would face the same issues and constraints regarding engines and emission-control technologies.

4.1 Overview of Category 3 Marine Engine Technology

4.1.1 Diesel Engine Emission Formation in Category 3 Marine Engines

Category 3 marine diesel engines operate by compressing and cooling the charge air before it fills the cylinder where fuel is injected, which auto-ignites under pressure. 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.

As shown in Table 4.1-1, the majority of PM from engines running on heavy fuel oil (residual fuel) comes from the high level of sulfur in the fuel. The highest portion of PM (by weight) is from ash, metal, oxides, and sulfates. 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 both emissions 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. The engines are so large, three stories tall for example, that they are an integral part of the ship's infrastructure. 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 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, RO-ROs, 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 engines burn heavy fuel oil, also known as residual fuel. 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 a filter to remove larger particles. In addition, vessel operators must verify engine safety 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.[6] 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 Annex VI, 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.

4.2 General Description of Emission-Control Strategies

Manufacturers have already developed and implemented technologies to reach the Tier 1 standards on some if not most engines and will be shown later in this chapter. The following sections focus on describing technologies to reach the Tier 2 levels under consideration. These reflect NOx reductions 30 percent below the Tier 1 standards. The technologies available to reduce exhaust emissions from Category 3 marine engines include better fuel and ignition control, combustion optimization, and improved charge air characteristics. The costs associated with applying these technologies to marine engines are considered in the next chapter. More advanced technologies are discussed in Chapter 8 of this draft RSD.

4.2.1 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

4.2.1.1 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.[7] 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.[8] 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. Section 4.2.4 describes this in further detail.

As vessels move toward shore they begin to slow their engines. In the case of cruise ships or other vessels with electric-drive propulsion from multiple engines, engines may be shut down individually for decreased propulsion power approaching port. As vessels enter the mileage limit for compliance with EPA NOx emissions, engines must meet emission standards. Operators may show this by measuring NOx emissions at a known speed and power, comparing the measured emission level with that required for that speed and power. An onboard NOx measurement would enable operators to ensure compliance by adjusting injection timing or other parameters as needed to keep emission levels controlled appropriately. For the engines that are slowed from cruising speed where fuel injection timing is set, the engine cylinders may again need to be adjusted. EPA assumes this is not currently common practice with engines that have mechanical controls, but such an adjustment could be made easily for an engine with electronic controls. For vessels in which engines are shut down one by one, the engines that continue operating likely don’t experience a big change in operating speeds, so readjusting may not be necessary.

4.2.1.2 Combustion Chamber Geometry

Parameters within the combustion chamber geometry that yield reduced emissions include the shape of the chamber and reduced crevice volumes. Listed below are excerpts from several sources which describe their experiences with this concept.

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."[9]

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.[10] 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.[11]

4.2.1.3 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.[12] 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.[13] 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.

4.2.1.4 Valve Timing

Medium speed-four-stroke engines employ valves in their design whereas 2-stroke generally operate with ports. This technology is only relative for designs with valves. The efficiency of a diesel engine generally increases with its expansion ratio[14] because more work is generated by the engine for a given stroke. 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.[15] 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.[16] 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.[17]

4.2.1.5 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.[18]

4.2.2 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 Chapter 8).

4.2.3 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.[19,20]

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.[21] 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.[22] 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.[23]

Exhaust gas recirculation has also been shown on a slow-speed two-stroke engine, in conjunction with direct water injection, to achieve a 70% reduction in NOx.[24] Without EGR, only a 50% 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.[25] 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, 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.

4.2.4 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.

4.2.4.1 Fuel Injection Pressure

Particle emissions and fuel consumption generally go down with increasing injection pressure.[26] 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.[27]

Manufacturers continue to investigate new injector configurations for nozzle geometry and higher injection pressure (in excess of 2300 bar (34,000 psi)).[28,29] 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.[30] 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.[31]

4.2.4.2 Nozzle Geometry

Nozzle geometry is a very important parameter for combustion development.[32] 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.[33]

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. Testbed 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."[34] 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.

4.2.4.3 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.[35]

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.[36] This strategy is most effective in conjunction with retarded timing, which leads to reduced NOx emissions without the attendant increase in PM.

4.2.4.4 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.[37] 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 that will now be discussed.[38] 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 assure the life of the solenoid armature which can be affected by high temperatures such as the temperature of heavy fuel oils (150C+). In addition, to assure the injection will not be affected by erosion wear and clogging of the small drillings. The design also does not have the rail (accumulator) pressure prevailing at the nozzle seat in between the injection events. The main reason is to avoid leaking nozzles for 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 engine 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."[39]

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."[40]

The system is controlled and monitored through the manufacturer developed electronic control system. The modular system with separate microprocessor control units for each cylinder and overall control and supervision by duplicated microprocessor control units, which provides the usual interface for the electronic governor and the shipboard remote control and 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.

4.2.4.5. 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.[41] 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, 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, 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 of 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.[42] 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 which may be seen in common rail fuel systems. The manufacturer includes discussion on closed loop NOx control in the reference paper. They state 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.

4.2.5 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 minimized. 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. Electronic control is already used in limited marine applications including vessels mentioned in the section above.

4.2.6 Lube Oil Consumption

Many of the Category 3 marine diesel engine manufacturers are working to reduce the consumption of lubricating oil from their engines, because customers are pressing to reduce 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.

This is not the case 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 Figure 4.2-1). Reducing oil consumption in

Category 3 marine engines will decrease PM emissions to a lesser degree than the same kind of improved oil control in highway diesel engines.

4.2.7 Distillate Fuel

The use of distillate fuel has the potential to further increase NOx emissions. Residual fuel typically has an amount of elemental nitrogen bound up in the fuel, which likely participates more actively in the combustion reactions than airborne, molecular nitrogen. Also, poor ignition quality of residual fuel leads to increased ignition delay and higher peak temperatures. Marine fuels are discussed in more detail later in chapter 8.

4.2.8 Emission-Controls and System Approaches

Table 4.2-3 identifies several technologies that individual manufacturers have already incorporated to reduce emissions and may likely be used to meet the proposed Tier 1 standards and the second tier of emission standards currently under consideration. The table also identifies several technologies that are beginning to gain field experience on engines in-use and can be used to meet such a second tier of standards.

Table 4.2-3: “In-Engine” Combustion Process Changes Currently In-Use or Being Investigated by Marine Diesel Engine Design and Manufacturing Companies[43]

Component or Operation Changed	Change	Parameter Affected	Slow-Speed 2-Stroke	Medium Speed 4-Stroke
Tier 1 and Tier 2				
turbocharger	improved efficiency, variable flow	SFC, 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
Tier 2				
electronic control	replaces mechanical control	engine operation, SFC	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

Table 4.2-4 summarizes published results showing emission reductions associated with application of specific combinations of emission-control technologies manufacturers have adopted to reduce NOx emissions below Annex VI standards.

Table 4.2-4: Summary of "In-Engine" NOx Reduction Techniques and NOx Reductions Achieved from IMO Listed by Manufacturer from Selected 2001 References

Mfr.	Engine Model	In-Engine changes	NOx Red from IMO	SFC Change
Wartsila[44]	4-stroke	Retard injection Miller cycle valve timing Higher compression ratio Increased turbo efficiency Higher max cyl pressure Common rail injection	40%	unknown
Caterpillar[45] (MaK)	4-stroke	Higher compression ratio Higher cylinder pressure Higher charge pressure Flexible injection system	33%	0
FMC[46]	4524 4-stroke	Two stage injection Miller cycle valve timing Greater stroke/bore ratio Adjustable compression Two stage turbocharger Low intake temperature	34%	-2%
Yanmar[47]		Retard injection Shorter combustion time Higher compression ratio Higher boost pressure Reduced nozzle hole size Increased number of holes	met IMO std	5% or greater

4.3 Anticipated Technology to Meet Emission Standards

This section describes how we think manufacturers can draw from the catalog of available technologies described above to meet emission standards.

4.3.1 Tier 1 (Annex VI) Standards

Engine manufacturers are meeting the MARPOL Annex VI standards today with a variety of emission-control technologies. Table 4.2-4 identifies several technologies that individual manufacturers have already incorporated to reduce emissions. 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.

4.3.2 Additional Tier 2 Standards

As listed in Table 4.2-3, manufacturers have a wide range of technologies and strategies available to reduce emissions below Tier 1 standards. In making specific projections regarding technologies that could be used to meet Tier 2 standards under consideration (30 percent NOx reduction from Tier 1), many of these can be treated together for consideration of related changes.

First, all manufacturers could upgrade their engines to better control fuel-injection variables. This can be done through incorporation of common rail with electronic controls in which the engine can have flexible injection timing with high injection pressure within the whole engine map[48]. We expect manufacturers would implement a degree of timing retard, but simultaneously making other changes to offset any negative effects of the delayed timing. Electronic controls with rate-shaping capability would be one example.

Category 3 Marine engines are already operating with sophisticated turbocharging and aftercooling systems, but some manufacturers would likely find ways to optimize both turbochargers and aftercoolers to reduce emissions. The aftercooler especially provides a potent means of controlling NOx emissions, without compromising engine performance.

Adjusting valve timing and the location of intake ports to vary expansion and compression ratios is another air-handling approach that holds promise for reducing NOx emissions. We expect that many manufacturers would pursue this technology to varying degrees. These same parameters can be adjusted to recirculate small amounts of exhaust gases into the cylinder, which alone can substantially reduce NOx emissions.

Reviewing the combustion chamber’s design involves consideration of several different variables, including higher compression ratios, piston geometry, and injector location. These fundamental parameters affect the compression and mixing of the fuel-air mixture before and during combustion, which may greatly affect emission formation during the combustion event.

Test data in Table 4.2-3 show that these technologies can reduce emissions up to 40 percent below Annex VI standards.[49] We believe manufacturers could incorporate emission-control technologies to achieve a 30-percent reduction below Annex VI standards for all their Category 3 Marine engines. Engine manufacturers have affirmed that this level of control is achievable.[50] A 30-percent reduction would allow for a compliance margin for manufacturers to ensure that they meet emission standards consistently with all the engines they produce in an engine family. This would also allow for manufacturers to show that they meet emission standards under the range of prescribed testing and operating conditions, as described above, including measures to cap emission levels at low-power modes. These technologies, and accompanying emission data, are described in more detail in the preceding sections of this chapter. Chapter 5 adds specific detail regarding our estimated deployment of each of the targeted control technologies to develop costs estimates related to the Tier 2 emission standards under consideration.

4.4 Impact on Noise, Energy, and Safety

The Clean Air Act requires EPA to 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 of the technology changes anticipated in response to the new standards, however, have the potential to reduce fuel consumption as well as emissions. Redesigning combustion chambers, incorporating improved fuel injection systems, and introducing electronic controls provide the engine designer with powerful tools for improving fuel efficiency while simultaneously controlling emission formation.

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.

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CHAPTER 5: Estimated Costs

This chapter describes our approach to estimating the cost of complying with emission standards. We start with a general description of the approach to estimating costs, then describe the technology changes we expect and assign costs to them. We also present an analysis of the estimated aggregate cost to society.

It should be noted that the costs of the proposed Tier 1 standards are negligible and reflect certification and compliance costs only. We do not anticipate that there will be any engineering or design costs associated with the Tier 1 standards because manufacturers are already certifying engines to the Annex VI standards through our voluntary certification program (see Section E.2 of the preamble for this rule). While there will be certification and compliance costs, these costs will be negligible. Specifically, we estimate the costs of certification and providing the capability for onboard NOx measurement to be $18,000 per new engine, and $5,000 for annual operating costs (calibrating, cleaning, and maintaining the onboard NOx measurement device; see certification and compliance discussion below). These new engine costs would add less than 1 percent to the price of a new engine, which cost about 2.5 to 3 million dollars (and even less to the price of a new vessel, which averages about $150 million, with container ships averaging $50 million and cruise ships averaging $500 million per vessel).[1]

The remainder of this chapter presents the estimated costs associated with a second tier of NOx standards set 30 percent below Tier 1. We also present information for standards that reflect the use of direct water injection and selective catalyst reduction.

5.1 Methodology

We have developed estimated costs for a variety of technologies available to reduce emissions. We developed the costs for individual technologies in cooperation with ICF, Incorporated and A.D. Little.

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 5-1 highlights the key operating characteristics of these engines.

Similarly, we developed cost estimates for a specific technology scenario. This approach does not reflect the wide range of approaches that manufacturers might pursue in meeting emission standards. We believe that the projections presented here provide a cost estimate representative of the different approaches manufacturers may ultimately take. In fact, further research may well lead to advances that involve simpler approaches or more cost-effective strategies, resulting in lower overall costs.

Costs of control include variable costs (for incremental hardware and assembly) and fixed costs (for tooling, R&D, and certification). 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.

Table 5-1
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

5.2 Technology Costs

The total estimated cost impact of a second tier of emission standards set 30 percent below the Tier 1 NOx limits was 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.

5.2.1 Fuel Injection Improvements

Fuel-injection improvements are one of the most important areas with potential to reduce emissions from Category 3 Marine engines. Some manufacturers would 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. Common rail 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. In this cost analysis, we project that all manufacturers would need to adopt common-rail technology to achieve a 30 percent reduction from the Tier 1 limits.

Table 5-2 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 not be affected whether the standards apply to U.S.-flag vessels or whether they also apply to foreign-flag vessels. Fixed costs for development and tooling are considered in the next section.

Table 5.2-1
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

5.2.2 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.

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 4. 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 meet emission standards to certify 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.-flag 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 several reasons. First, we believe that manufacturers meeting Tier 2 emission standards would 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, new ship construction in the last several years has fallen behind the rate necessary for ongoing replacement of vessels, resulting in an overall aging of the U.S. fleet. Also, requirements related to double-hull tanker designs are leading many ship owners to consider retrofitting or replacing existing ships. Together, these factors will likely 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 foreign-flag 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.

The estimated costs for a second tier of standards at 30 percent below the Tier 1 NOx limits are summarized in Table 5.2-2. Estimated costs are about $64,000 per engine. If the standards were to apply to engines for both U.S.- and foreign-flag vessels, the estimated cost per engine drops nearly to $6,000.

The kind of changes addressed in this section do not necessarily involve variable costs (except fuel injection, as noted above). Changing valve timing, and redesigning the geometry of engine components would generally not involve cost increases beyond those considered for development time and tooling.

Table 5.2-2
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.-flag only	Engines per year	4	4
	Fixed cost per engine	$64,019	$64,019
Including foreign-flag	Engines per year	40	40
	Fixed cost per engine	$6,402	$6,402

5.2.3 Direct Water Injection

Table 5.2-5 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. Total costs range from about $120,000 to $320,000 depending on engine size. If emission standards apply also to engines on foreign-flag vessels, the estimated cost range is $50,000 to $250,000.

In addition, any ship using direct water injection would incur operating costs to provide a supply of fresh water to the engine. At a cost of $0.10 per gallon for distilled water, total estimated costs per year for U.S.-flag vessels range from $11,000 to $64,000. This is based on an average of 2683 hours per year within175 nautical miles of the U.S. Coast. Foreign-flag vessels spend much less time operating near the U.S., so their estimated annual water costs range from $400 to $2,500. Calculated as a net present value, with 7 percent discounting to the point of sale, estimated composite costs are $360,000 for U.S.-flag vessels and $23,000 if we include foreign-flag vessels (see Table 5.2-6). 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 unit).

We also estimate a 2-percent increase in fuel consumption for engines using direct water injection. As shown in Section 5.2-7, this involves annual costs of $6,000 to $10,000 per year for U.S-flag vessels. Including foreign-flag vessels would drop these costs to $100 to $800. This analysis considers increased operating costs only for operation near the U.S. coast.

Table 5.2-5
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-flag 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 5.2-6
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
avg. hours per call	17.0	17.0	17.0	17.0	17.0	17.0
water used per call (kg)	2,584	3,876	5,168	5,168	10,336	15,504
avg. calls per year	10	10	10	10	10	10
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.-flag only)	$10,732	$16,098	$21,464	$21,464	$42,928	$64,392
Present value (U.S.-flag only)	$131,793	$197,690	$263,587	$263,587	$527,174	$790,761
total cost per year (foreign-flag)	$416	$624	$832	$832	$1,664	$2,496
Present value (foreign-flag)	$5,109	$7,663	$10,217	$20,217	$20,435	$30,652
total cost per year (composite)	$680	$1,020	$1,360	$1,360	$2,720	$4,080
Present value (composite)	$8,351	$12,526	$16,701	$16,701	$33,403	$50,104

5.2.4 Selective Catalytic Reduction

Table 5.2-7 presents estimated costs for selective catalytic reduction. Variable costs consider 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. Total costs range from about $260,000 to$1.23 million depending on engine size. If emission standards apply also to engines on foreign-flag vessels, the estimated cost range is $220,000 to $1.18 million

In addition, any ship using selective catalytic reduction would incur operating costs to provide urea to the engine. At a cost of $1.30 per gallon for aqueous urea, total estimated costs per year for U.S.-flag vessels range from $24,000 to $144,000. This is based on an average of 2683 hours per year within 175 nautical miles of the U.S. Coast. Foreign-flag vessels spend much less time operating near the U.S., so their estimated annual urea costs range from $1,500 to $9,000. Calculated as a net present value, with 7 percent discounting to the point of sale, estimated composite costs are $820,000 for U.S.-flag vessels and $52,000 if we include foreign-flag vessels (see Table 5.2-6).

SCR operation also is more durable when engines operate on fuels of a higher grade than residual fuel. Calculating the cost of using a 0.5 percent sulfur distillate fuel depends on an estimated load factor of 50 percent. Using current prices for the different fuel types results in annual costs ranging from $60,000 to $360,000 for U.S.-flag vessels. Including foreign-flag vessels would drop these costs to $4,000 to $23,000. Fuel costs are discussed further below and presented in Table 5.2-10. This analysis considers increased operating costs only for operation within 175 nautical miles of the U.S. coast.

The analysis also considers two additional cost estimates related to system maintenance. First, 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 for a period of time periodically during the operation of the engine. The air pulsation from the horn will prevent soot that is building up in the catalyst. The horn may be driven by air from the normal air system installed on the vessel. While this method requires no engine shutdown, compressed air cleaning does require a period of engine shut down. In this method, a soot-blowing probe is inserted into the catalyst unit to remove soot. It is envisioned that the reactor will be cleaned during each port call (10 per year) taking 4 person hours for medium speed engines and 6 person hours for low speed engines. This results in net-present value costs ranging from $19,300 to $28,850, as shown in Table 5.2-9.

The second maintenance-related item is for replacing reactor elements after 10 and 20 years of operation. This would likely occur during a substantial engine-rebuilding effort. We estimate the hardware cost to be three-fourths of the estimated long-term cost for the whole reactor, since the reactor elements are a central part of the overall reactor design. These hardware costs are then increased by a factor three to account for the higher cost of aftermarket parts, which is consistent with previous analysis of component cost estimates related to rebuild; this accounts for the higher cost of aftermarket parts. The resulting SCR rebuilds are estimated to cost from $175,000 to $1 million, with net-present values per engine (discounted to the point of sale at a 7-percent discount rate) ranging from $134,000 to $800,000, as shown in Table 5.2-9.

Table 5.2-7
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-flag 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 5.2-8
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
avg. hours per call	17.0	17.0	17.0	17.0	17.0	17.0
aqueous urea per call (kg)	485	727	969	969	1,938	2,907
avg. calls per year	10	10	10	10	10	10
aqueous urea cost per kg	$0.3173	$0.3173	$0.3173	$0.3173	$0.3173	$0.3173
total cost per year (U.S.-flag only)	$24,147	$37,562	$48,294	$48,294	$96,588	$144,882
Present value (U.S.-flag only)	$296,535	$461,276	$593,070	$593,070	$1,186,139	$1,779,209
total cost per year (foreign-flag)	$936	$1,456	$1,872	$1,872	$3,744	$5,616
Present value (foreign-flag)	$11,494	$17,880	$22,989	$22,989	$45,978	$68,967
total cost per year (composite)	$1,530	$2,380	$3,060	$3,060	$6,120	$9,180
Present value (composite)	$18,789	$29,227	$37,578	$37,578	$75,156	$112,734

Table 5.2-9
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	$19,300	$19,300	$19,300	$28,850	$28,850	$28,850
Rebuild—per event	$174,682	$261,082	$347,482	$349,363	$694,963	$1,040,563
Rebuild—NPV	$133,941	$200,189	$266,438	$267,880	$532,876	$797,871

5.2.5 Certification and Compliance

Manufacturers must generate test data and other information to demonstrate compliance with emission standards. To estimate these costs, we have allocated $40,000 to conduct testing to show that an engine family meets emission standards. An additional $20,000 per engine family is estimated to cover the cost of engineering and clerical effort to prepare and submit the required information.

The capability for onboard NOx measurement is estimated to cost $15,000, which includes sensors, data logging, equipment, and installation. An additional $5,000 annually would cover the cost of calibration, cleaning, and replacing any worn components. An estimated $1,000 per engine is allocated to cover the cost of onboard testing at the point of installation. Once the system is operating, the ship’s crew could perform periodic measurements at no significant additional cost beyond that estimated for maintaining the unit.

Until engine designs are significantly changed, engine families can be recertified each year using carryover of the original test data. Since these engines are currently not subject to any emission requirements, the analysis includes a cost to recertify an upgraded engine model every five years.

5.2.6 Fuel Costs

Table 5.2-10 presents the fuel costs we use in our analyses of various emission control approaches. These analyses include the costs of reducing fuel sulfur for PM and SOx benefits, using very low sulfur fuel to enable SCR technology, and baseline fuel costs for a fuel consumption sensitivity analysis. These fuel costs come from two sources. The cost estimates for residual fuel and Marine diesel oil come from Marine Bunker News.[3] Costs for number 2 diesel and for on-highway diesel fuel are based on prices (excluding taxes) reported by the Department of Energy.[4]

Table 5.2-10: Fuel Costs

Fuel Type	Sulfur Level	Cost per Metric Tonne
Residual	27,000 ppm	$98
Marine diesel oil	15,000 ppm	$158
Number 2 diesel	3,000 ppm	$215
Highway diesel	500 ppm	$245

5.2.7 Sensitivity

As described above, manufacturers have a wide range of technology options to reduce emissions. We believe that manufacturers can combine technologies to meet NOx standards 30 percent below the proposed Tier 1 emission standards without increasing fuel consumption. Table 5.2-11 shows a calculation of costs or savings associated with a one-percent change in fuel consumption. If engines that meet standards set 30 percent below Tier 1 have changes in fuel consumption, or if manufacturers need to rely on timing retard to achieve the last step of controlling emissions to meet emission standards, the table provides a framework for quantifying this cost or benefit. The calculation is presented for U.S. flagged vessels operating within175 nautical miles of the U.S. coast. To calculate this effect for all vessels with Category 3 engines operating within 175 nautical miles of the U.S. coast, an average annual operation of 170 hours per year would be used. Also, the calculations are based on a one-percent change in fuel consumption. Any bigger or smaller change in fuel consumption could be scaled from the results in the table using a linear relationship.

Table 5.2-11
Costs or Savings for Each One-percent Change in Fuel Consumption

Parameter	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
baseline BSFC (g/kW-hr)	190	190	190	190	190	190
load factor	50%	50%	50%	50%	50%	50%
annual operating hours	170	170	170	170	170	170
baseline hourly fuel cost	$37	$56	$74	$74	$149	$223
delta hourly fuel cost per 1-percent bsfc change	$0.37	$0.56	$0.74	$0.74	$1.49	$2.23
cost change per year (U.S.-flag only)	$993	$1,502	$1,985	$1,985	$3,998	$5,983
Present value (U.S.-flag only)	$12,263	$18,402	$24,542	$24,542	$49,067	$73,609
cost change per year (foreign-flag)	$38	$58	$77	$77	$155	$232
Present value (foreign-flag)	$475	$713	$951	$951	$1,902	$2,853
cost change per year (composite)	$63	$95	$127	$127	$253	$380
Present value (composite)	$777	$1,166	$1,555	$1,555	$3,109	$4,664

5.3 Total Engine Costs

5.3.1 Distribution of Category 3 Marine Engines

Before presenting the total costs for meeting the second tier of standards under consideration, it is helpful to establish a distribution of the modeled engines for calculating a composite cost for the category. Population data for vessels with Category 3 Marine engines shows that 60 percent of these engines are two-stroke.[5] As described in Chapter 7, the average power rating for all Category 3 Marine engines is 11,000 kW. Using these parameters, we estimated the distribution of engines shown in Table 5.3-1. While the actual distribution clearly covers a much wider range of engines, this analysis provides an effective way of creating a composite assessment of costs for comparison with the projected emission reductions.

Table 5.3-1
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%

5.3.2 Projected Costs for Engines on U.S.-flag Vessels

Total projected costs for standards set 30 percent below the Tier 1 NOx limits are based on combining the anticipated fuel injection improvements and other engine modifications to meet emission standards, as described in Sections 5.2.1 and 5.2.2. Factoring in the estimated compliance costs results in a total estimated cost impact ranging from $94,000 to $153,000 (see Table 5.3-2). Using the engine distribution described above leads to a calculated composite cost for all Category 3 engines of $115,000. The cost analysis also includes an estimated $5,000 of annual expenses to maintain equipment for onboard emission measurement, which corresponds with a net-present-value at the point of sale of $61,000. We believe that manufacturers would integrate a combination of emission-control strategies to meet emission standards without increasing fuel-consumption rates. The sensitivity of this assumption is explored in Section 5.2.6 above.

Long-term costs decrease due to two principal factors. First, the analysis anticipates that manufacturers recover their initial fixed costs for tooling, R&D, and certification, after which they are no longer applied as a per-engine cost for meeting emission standards. Second, manufacturers are expected to learn over time to produce the engines with the new technologies at a lower cost. Because of the very low sales volumes, manufacturers are less likely to put in extra R&D effort for low-cost manufacturing. As production starts, assemblers and production engineers will have great opportunities to fine-tune the designs and the production processes. Consistent with analyses from other programs, we reduce estimated variable costs by 20 percent beginning with the third year of production and an additional 20 percent beginning with the sixth year of production.[6] We believe it is appropriate to apply this factor here, given that the industries are facing EPA emission regulations for the first time and it is reasonable to expect learning to occur with the experience of producing and improving emission-control technologies, especially with such low sales volumes.

Table 5.3-2
Summary of Projected Costs to a Second Tier of NOx Limits
30 Percent Below Tier 1 — U.S.-flag only

Cost Parameter	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
Total cost per engine (yr. 1)	$93,587	$98,977	$104,368	$106,414	$129,723	$153,031
Total cost per engine (yr. 6 and later)	$25,452	$28,902	$32,352	$33,661	$48,579	$63,496
Operating costs (NPV)	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000

5.3.3 Cost Considerations Related to Including Engines on Foreign-Flag Vessels

If emission standards would apply to engines on foreign-flag vessels, we would estimate no change in per-engine variable costs or operating costs. Amortizing fixed costs and compliance costs over a wider set of engines decreases estimated per-engine costs to a composite value of $57,000. See Table 5.3-3. However, as discussed in Chapter 7, per-ton costs would be higher since only tons emitted near the U.S. are counted in the cost per ton estimates here.

Table 5.3-3
Summary of Projected Costs to Meet
a Second Tier of NOx Limits
30 Percent Below Tier 1 — Including Foreign-flag

Cost Parameter	Medium-speed Engines			Slow-speed Engines		
	6 cyl.	9 cyl.	12 cyl.	4 cyl.	8 cyl.	12 cyl.
Total cost per engine (yr. 1)	$35,970	$41,360	$46,751	$48,797	$72,106	$95,414
Total cost per engine (yr. 6 and later)	$25,452	$28,902	$32,352	$33,661	$48,579	$63,496
Operating costs (NPV)	$5,000	$5,000	$5,000	$5,000	$5,000	$5,000

Including foreign-flag vessels would also affect Category 1 and Category 2 engines. In general, the same cost estimates published for the December 1999 final rule for commercial marine diesel engines apply equally to engines on foreign-flag vessels. Again, fixed costs are the exception warranting further consideration. In many cases, foreign-flag vessels would be using the same kind of engines that would go into U.S.-flag vessels. In these cases, engine manufacturers would already be applying sufficient fixed costs to meet emission standards (including certification and compliance costs). The only new costs for these engines is therefore the variable costs involved in producing them to meet emission standards. Other foreign-flag vessels may be using engines from manufacturers not selling engines into the U.S. market. These engine manufacturers would need to produce compliant engines, likely with a smaller sales volume than that projected for the average manufacturer selling engines for U.S.-flag vessels. While these different factors are difficult to quantify, they are offsetting, so we estimate near-term and long-term costs for these engines that are neither higher nor lower than that already estimated for U.S.-flag vessels. These costs are summarized in Table 5.3-4.

Table 5.3-4
Estimated Costs to Include Category 1 and Category 2 Engines on Foreign-Flag Vessels

Cost Parameter	100 kW	400 kW	750 kW	1500 kW	3000 kW
Total cost per engine (yr. 1)	$1,806	$3,208	$25,395	$22,818	$54,192
Total cost per engine (yr. 6 and later)	$486	$846	$856	$1,120	$13,019
Rebuild costs (NPV)	$441	$703	$207	$635	$12,430

5.4 Aggregate costs

The above analysis presents unit cost estimates for each power category. With current data for engine and vessel sales for each category and projections for the future, these costs can be translated into projected direct costs to the nation for the new emission standards in any year. Aggregate annual costs (based on a 20-year analysis) of a second tier of NOx limits under consideration, set at 30 percent below the Tier 1 levels, are estimated to be about $1.6 million per year. Applying the second tier of emission standards also to engines on foreign-flag vessels would increase aggregate costs to about $54 million. In both cases, estimated aggregate costs fall substantially after five years as manufacturers would no longer need to recover their amortized costs. See Chapter 7 for further discussion of aggregate costs.

Chapter 5 References

1. See Chapter 7 references, note 4.

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. Bunker News, “Bunker Prices,” www.lloydslist.com/NASApp/cs/ContentServer?pagename=BunkerNews/home, January 24, 2002 (Docket A-2001-11, document II-A-31).

4. U.S. Energy Information Administration, “International Petroleum Information,” www.eia.doe.gov/emeu/international/petroleu.html, March 11, 2002 (Docket A-2001-11, document II-A-30).

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

6.For further information on learning curves, see Chapter 5 of the Economic Impact, from Regulatory Impact Analysis - Control if Air Pollution from New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements, EPA420-R-99-023, December 1999. The interested reader should also refer to previous final rules for Tier 2 highway vehicles (65 FR 6698, February 10, 2000), marine diesel engines (64 FR 73300, December 29, 1999), nonroad diesel engines (63 FR 56968, October 23, 1998), and highway diesel engines (62 FR 54694, October 21, 1997).

CHAPTER 6: Emissions Inventory

This chapter presents our analysis of the emission impact of the regulatory program under consideration. The first section contains a description of the methodology used to develop the baseline emissions inventories for the base year (1996). The second section contains a description of the methodology used to develop future year inventory projections. Finally, the last section contains the expected emissions reductions that would result from the regulatory program under consideration.

It should be noted that we are not claiming emission reductions for the proposed Tier 1 standards. These standards have already been adopted by the international community, although they are not yet enforceable, and engine manufacturers are already producing engines that achieve these standards. As a result, this rule will result in emission reductions only to the extent that owners of U.S. vessels are not currently complying with the standards.

The remainder of this chapter presents the estimated emission reductions associated with a second tier of NOx standards set 30 percent below Tier 1.

6.1 Baseline Inventories

We developed baseline Category 3 vessel emissions inventories under contract with E. H. Pechan & Associates, Inc.[1] An important part of this analysis is the geographic area that we model for emissions. For other nonroad sectors we have typically modeled only emissions that occur within the U.S. Sometimes we have modeled emissions on a county-by-county basis, or based on whether the emission occur within an ozone nonattainment area. However, for Category 3 Marine engines, the vast majority of the emissions that occur within the territorial limits of the U.S. occur outside of the land boundaries of the U.S. Thus, it is essential that we model emissions that occur in ocean and Great Lakes waters. Moreover, it is clear that emissions that occur outside of our territorial seas (i.e., more than 12 miles from the U.S. coastline) can affect U.S. air quality. NOx can be stable for days in the atmosphere. 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 (200 statute miles) from the coast could reach the coast in less than a day. We will continue to investigate this issue throughout this rulemaking, and will incorporate any new information into the final rule. For example, as discussed in Chapter 2, the U.S. Department of Defense (DoD) has presented information to us recommending that a 60 nautical mile 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.

For this analysis, inventory estimates were developed separately for vessel traffic within 25 nautical miles of port areas and vessel traffic outside of port areas but within 175 nautical miles of the coastline. Different techniques were used to develop the port and non-port inventories due to the availability of different types of data for each.

6.1.1 Ports Inventories

For port areas we developed detailed emissions 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 (roro) tanker, vehicle carrier, and other miscellaneous vessels.

Emissions 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 any vessel movement from one berth to another within the actual port. 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 6.1-1.

Table 6.1-1
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, emissions at full load were used to develop cruise and RSZ emission factors. However, at low loads the emission factors tend to increase as compared with higher loads. The emission factors shown in Table 6.1-1 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.[2] The adjustments we applied to the emission factors shown in Table 6.1-1 to develop maneuvering emission factors are shown in Table 6.1-2.

Table 6.1-2
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 6.1-3.

Table 6.1-3
Total U.S. Category 3 Emissions Inventories for Port Areas in 1996 (short tons)

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

6.1.2 Non-Port Inventories

We developed non-port emissions 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 6.1.1 was moved by tow and push boats powered by Category 2 engines. Thus, 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 that some Category 3 vessel traffic occurs within 25 nautical miles of the coast. However, due to limitations in the data we were unable to discriminate between cargo carried on Category 2 vessels and cargo carried on Category 3 vessels. Thus, 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.

The U.S. Army Corp of Engineers (USACE) provided activity estimates of total and domestic tonnage by waterway links. A map of the waterway links is shown in Figure 6.1-1, 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 6.1.1 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 emissions inventories for base year are shown n Table 6.1-4.

Table 6.1-4
Total U.S. Category 3 Emissions Inventories for Non-Port Areas in 1996 (short tons)

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

6.2 Future Year Baseline Inventory Projections

In order to project future year emissions 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 Annex VI emissions regulations 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 relied upon 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 in order to show the long term impact of the emission control program under consideration on the emissions inventories. Given that Category 3 vessels typically last for several decades before being scrapped it was 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 Annex VI NOx standards 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. Thus, most new vessels constructed beginning in 2000 have been built in compliance with the Annex VI standards. 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 Annex VI standards. The Annex VI NOx standards are related to rated engine speed as shown in the following relationship.

Engine speed < 130 rpm; 17.0 g/kW-hr
130 rpm $\leq$ Engine speed < 2,000 rpm; $45 * n^{-0.2}$ g/kW-hr
Engine speed $\geq$2,000 rpm; 9.8 g/kW-hr

where "n" is the rated engine speed in rpm

These NOx emissions limits are for vessels tested on distillate fuel. However, Category 3 vessels use residual fuel in use. 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 emissions deterioration we used the actual Annex VI emissions limits as the emission factors for future vessels in the growth projections.

The projected future emissions inventories for the port areas are shown in Table 6.2-1. The non-ports inventory projections are shown in Table 6.2-2. Finally, the total national inventory projections are shown in Table 6.2-3.

Table 6.2-1
Projected Emissions 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 6.2-2
Projected Emissions 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 6.2-3
Projected Emissions 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

6.3 Inventory Effects

To model the benefits of the regulatory program under consideration we applied an engine replacement schedule and the emissions standards to the baseline inventory. Our proposed Tier 1 standards are based on the Annex VI NOx standards. Although these standards have not been ratified by enough countries to be given the force of law, they are being largely complied with around the world, and we expect this trend to continue. Thus, we are using the proposed Tier 1 standards as the baseline, and showing the benefits of the second tier of NOx reductions under consideration relative to this baseline.

For vessel turnover rates we were primarily concerned with the average age of the U.S. fleet, since we are only proposing to apply the standards to U.S. flagged vessels. In a study done by Corbett and Fishbeck in support of our previous rulemaking relating to emissions from Category1 and 2 Marine diesel engines the average age of the U.S. flagged fleet was 23 years.[3] 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. flagged vessels in 1999 was 24.2 years, with a median age of 22 years. The results of this analysis are shown in Figure 6.3-1, at the end of this chapter. Thus, we assumed that the average age of the U.S. fleet is 23 years old for purposes of estimating fleet turnover rates. The Corbett and Fishbeck study showed evidence that the average age of the world fleet is somewhat lower than that of the U.S. fleet. However, we relied upon the U.S. flagged fleet information because our standards are proposed to apply only to U.S. flagged vessels.

We are only proposing that standards apply to U.S. flagged vessels. Thus, we only applied the expected emissions reductions to the portion of the national inventory attributable to U.S. flagged vessels. Also, because the second tier of standards we are considering seek to reduce only NOx emissions, we are claiming no emissions reductions in HC, CO, PM or SOx. Table 6.3-1 shows our estimates of Category 3 vessel NOx emissions with and without the second tier of standards currently under consideration.

Table 6.3-1
Category 3 Marine Vessel NOx National Emissions Inventories

		1996	2010	2020	2030
No control baseline (thousand short tons)		190	303	439	659
Tier 1/ MARPOL Annex VI	(thousand short tons)	190	274	367	531
	Percent reduction (relative to no control)	—	9.6%	16.2%	19.5%
Tier 2 under consideration (30% below Tier 1)	Control (thousand short tons)	190	269	343	475
	Percent reduction (relative to MARPOL Annex VI)	—	2.0%	6.8%	10.5%

The effect of applying a second tier of NOx standards to both U.S. and foreign flagged vessels is shown in Table 6.3-2. For modeling simplicity we assumed that the average age of all vessels covered would be that same as that of the U.S. flagged fleet. However, as was previously discussed, the average age of the world fleet is likely lower than that of the U.S. flagged fleet as a result of faster turnover rates. Thus, the impact of applying the second tier of standards currently under consideration to all vessels could possibly be seen somewhat sooner than Table 6.3-2 suggests. As can be seen from this table, the projected percentage of emissions reductions would almost triple by 2030 if the application of the proposed standards is extended to foreign flagged vessels.

Table 6.3-2
Effect of Application of Second Tier of NOx Limits
Based on Vessel Flag
(U.S. Flagged Vessels vs. All Vessels)

	2020		2030	
Scenario	NOx (1000 tons)	% reduction	NOx (1000 tons)	% reduction
Baseline (Annex VI)	367	--	531	--
U.S. Flagged Only	343	6.8%	475	10.5%
All Vessels	306	16.7%	392	26.1%

Figure 6.1-1: USACE Waterway Link Network

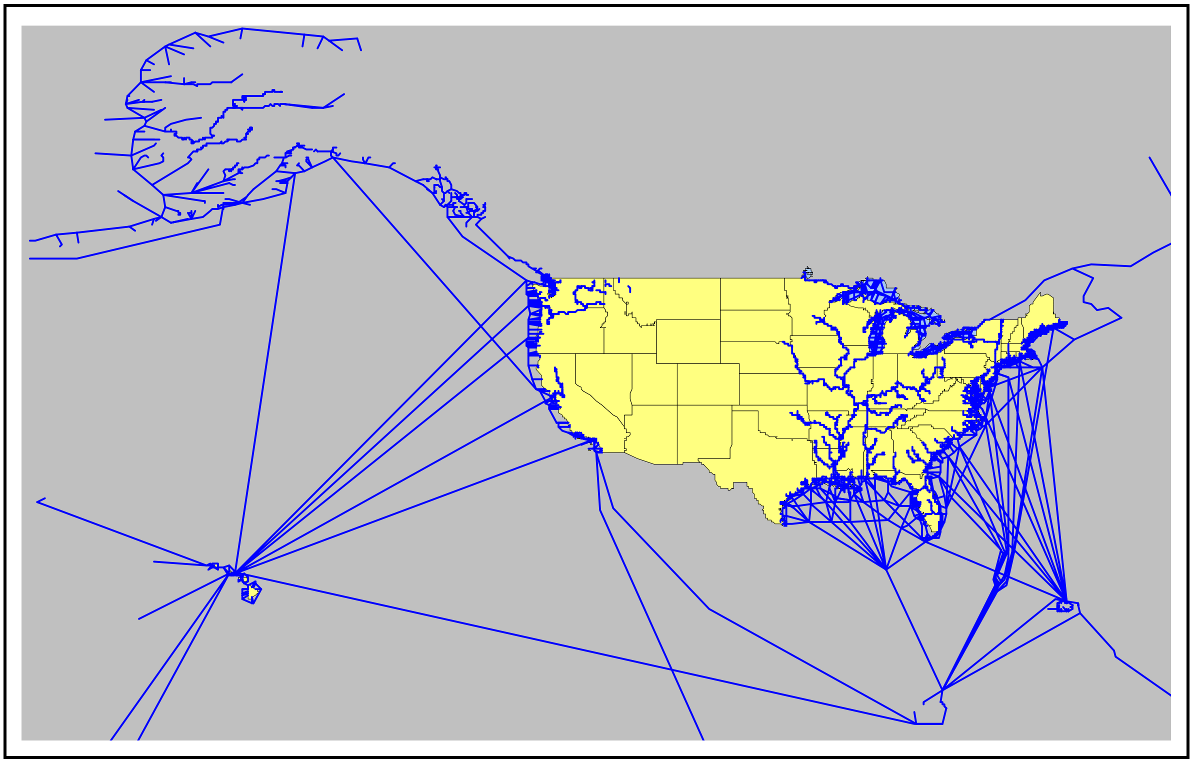
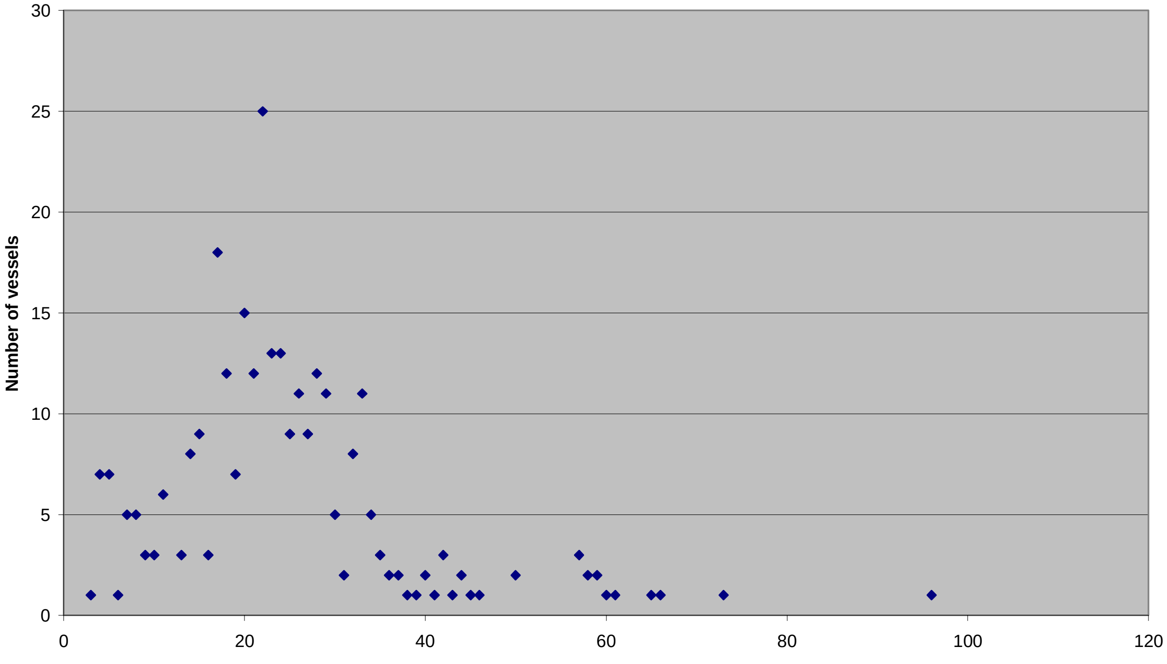


Figure 6.3-1
Number of C3 Vessels in U.S. Fleet by Age



Chapter 6 References

1. “Commercial Marine Emission Inventory Development,” E.H. Pechan and Associates, Inc. and ENVIRON International Corporation, April, 2002.

2. “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.

3. “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.

CHAPTER 7: Cost Per Ton

7.1 Methodology

This chapter assesses the cost per ton of emission reduction for the second tier of NOx limits under consideration, set at 30 percent below the Tier 1 limits. This analysis relies in part on cost information from Chapter 5 and emissions information from Chapter 6 to estimate the cost per ton of such a second tier of NOx standards in terms of dollars per short ton of NOx emission reductions (all costs are presented in 2002 dollars). This chapter also compares the cost per ton of such standards with the cost per ton of other NOx control strategies from previous EPA rulemakings. Finally, this chapter presents results of a screening level economic impact analysis.

We are not performing a similar analysis for Tier 1. As indicated in Chapters 5 and 6, the costs associated with this rule are negligible. These standards have already been adopted by the international community, although they are not yet enforceable, and engine manufacturers are already producing engines that achieve these standards. As a result, this rule will result in emission reductions only to the extent that owners of U.S. vessels are not currently complying with the standards.

The analysis presented in this chapter is performed for Category 3 Marine diesel engines and vessels using the same engine types presented in Chapter 5. An estimate of the industry-wide cost per ton of the new emission standards, combining all of the nominal engine sizes, is also presented.

Two types of cost-per-ton analyses are performed in this chapter. The first analysis focuses on individual engines and examines 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. The second method looks at the net present value (NPV) of a stream of costs and benefits over a standardized period of time (30 years). Over this period, the calculation includes the whole set of new requirements.

In calculating net present values that were used in our cost per ton estimates, we used a discount rate of 7 percent, consistent with the 7 percent rate reflected in the cost per ton analyses for other recent mobile source programs. OMB Circular A-94 requires us to generate benefit and cost estimates reflecting a 7 percent rate. Using the 7 percent rate allows us to make direct comparisons of cost per ton estimates with estimates for other, recently adopted, mobile source programs.

However, we also calculated the primary cost and cost per ton estimates using a 3 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). Therefore, we have also calculated the overall cost per ton of new emission standards based on a 3 percent rate to facilitate comparison of the cost per ton of this rule with future proposed rules which might use the 3 percent rate. The results using both a 3 percent and 7 percent discount rate are provided in this Chapter.

7.2 Engine Lifetime Cost per ton of the New Standards

The cost per ton of the second tier of NOx standards under consideration, set at 30 percent below the Tier 1 standards, was calculated for the engine types described in Chapter 5. For this analysis, the entire cost of the program is attributed to the control of HC and NOx emissions. As discussed in Chapter 5, the estimated cost of complying with the new emission standards varies depending on the model year under consideration (i.e., year 1 versus year 6). Therefore, this analysis includes the per-engine cost per ton results for the different model years during which the costs are expected to change. This analysis focuses on costs and emissions reductions for individual engine types; therefore, the costs presented in this section represent the actual cost per ton as it affects a given engine. All of the costs and benefits are discounted at seven percent to the model year of the Marine engine.

EPA calculated the costs and emissions reductions achieved from the second tier of NOx standards under consideration beyond the Tier 1/Annex VI requirements. To come up with an average cost we looked at an engine with an average kW of 11,000. This average kW is based on data collected on seven U.S. ports which accept ocean-going vessels.[1] Table 7-1 presents the cost per ton of a second tier of NOx standards for U.S. flagged category 3 Marine diesel engines discounted at 3 and 7 percent.

Table 7-1
Cost per ton ($/short ton) of the Second Tier of NOx Standards
Under Consideration – U.S. Vessels Only

Discount Rate	Model Year Grouping	NPV Benefits (short tons)	NPV Operating Costs	Engine & Vessel Costs	Discounted Cost Per Ton
3 percent	1 to 5	1728	$99,000	$115,000	$120
	6 +			$39,000	$78
7 percent	1 to 5	1150	$66,000	$115,000	$145
	6 +			$39,000	$87

Because we requested comment on applying the standards to all vessels operating within 175 miles of the U.S. coast, we also calculated the cost per ton of including foreign-flagged vessels. Table 7-2 presents the cost per ton including both U.S. and foreign-flagged vessels in the program.

Table 7-2
Cost per ton ($/short ton) of the Second Tier of NOx Standards
Under Consideration – Including Foreign Flag Vessels

Discount Rate	Model Year Grouping	NPV Benefits (short tons)	NPV Operating Costs	Engine & Vessel Costs	Discounted Cost Per Ton
Foreign Flag Only					
3 percent	1 to 5	67	$99,000	$57,000	$2,271
	6 +			$39,000	$2,017
7 percent	1 to 5	45	$66,000	$57,000	$2,590
	6 +			$39,000	$2,235
All Vessels					
3 percent	1 to 5	110	$99,000	$57,000	$1,390
	6 +			$39,000	$1,234
7 percent	1 to 5	73	$66,000	$57,000	$1,585
	6 +			$39,000	$1,368

7.3 Comparison with Cost Per Ton of Other Control Programs

In an effort to evaluate the cost per ton of the second tier of NOx standards currently under consideration, we have summarized the cost per ton results for several other recent EPA mobile source rulemakings that required reductions in NOx emissions from diesel engines. Where NOx cost per ton was not reported, HC+NOx cost per ton figures are reported. HC+NOx cost per ton figures should be close to NOx cost per ton figures because NOx is the primary focus of most standards for diesel engines and because emissions (and emission reductions) for NOx are generally much greater than for HC from diesel engines. Table 7-3 summarizes the cost per ton results from the three highway heavy-duty vehicle programs, locomotive standards, nonroad Tier 2 standards, and Category 1 and 2 commercial marine engine standards.

A comparison of the cost per ton numbers in Table 7-3 with the cost per ton results presented throughout this chapter for marine diesel engines shows that the cost per ton of applying the second tier of NOx standards under consideration to U.S. vessels only are favorable in comparison. However, EPA is interested in addressing the emissions from foreign flav vessels and believes that these can be most effectively addressed through the IMO process. To be consistent with the cost per ton values for other programs, the marine diesel numbers shown in

Table 7-3 reflect the aggregate cost per ton for the program rather than the high and low for individual engines.

Table 7-3
Summary of Cost Per Ton for Recent EPA NOx Control Programs ($2001)

EPA Rule	Pollutants Considered in Calculations	Cost per ton ($/ton)
Tier 2 Vehicle/Gasoline Sulfur	NOx	$1,400 - $2,400
2004 Standards for Highway Heavy-Duty Engines	NMHC*+NOx	$230 - $440
2007 Standards for Highway Heavy-Duty Engines/Diesel Sulfur	HC+NOx	$1,600 - $2,000
Locomotive Engine Standards	NOx	$200 - $300
Nonroad Tier 2 Standards	NMHC*+NOx	$460 - $720
Commercial Marine Standards	HC+NOx	$30 - $190

* nonmethane hydrocarbons (roughly equivalent to total HC for diesel engines)

7.4 20-Year Cost Per Ton

Another tool that can be used to evaluate the cost per ton of a regulatory program is to look at the costs incurred and the emissions benefits achieved over a fixed period of time. This section presents the year-by-year cost and emission reductions for the 20-year period after implementation of the second tier of NOx standards under consideration. Table 7-4 presents the undiscounted stream of costs and benefits associated with the second tier of NOx standards currently under consideration.

Table 7-4
20-Year Stream of Costs and Reductions for a Second Tier of NOx Limits
(30 Percent Below Tier 1)

Calendar Year	Costs	Reductions (tons)
2007	$1,242,702	1,219
2008	$1,343,872	2,533
2009	$1,450,937	3,946
2010	$1,564,197	5,465
2011	$1,683,971	7,021
2012	$862,633	8,658
2013	$960,420	10,377
2014	$1,064,392	12,182
2015	$1,174,880	14,075
2016	$1,292,228	16,058
2017	$1,416,798	18,135
2018	$1,548,969	20,308
2019	$1,689,139	22,580
2020	$1,837,726	24,955
2021	$1,995,166	27,495
2022	$2,161,917	30,165
2023	$2,338,461	32,971
2024	$2,525,301	35,922
2025	$2,722,963	39,025
2026	$2,932,001	42,318

Table 7-5 presents the sum of the costs and emission reductions over the 20-year period after the second tier of NOx standards under consideration would take effect, on both an undiscounted and 7-percent discounted basis. The annualized present value of the costs and NOx reductions, assuming a 7 percent rate, are also presented. It should be noted that these cost per ton figures are a little higher than those presented above for year 6 on a per-engine basis. This difference is caused by the fact that the per-engine analysis relates costs to their resulting benefits while the stream of costs analysis compares costs incurred to benefits achieved in a fixed time frame. In other words, many of the costs incurred prior to 2026 would not achieve benefits until after that time. This is, in part, due to the long lives and slow turnover of Marine diesel engines.

Table 7-5
Annualized Costs and Reductions
for the Period 2007-2026 due to a Second Tier of NOx Limits

	NOx Reductions (tons)	Cost
Undiscounted 20 year value	375,000	$33,800,000
Discounted 20 year value	161,000	$17,400,000
Annualized value	15,200	$1,640,000

7.5 Potential Economic Impacts

The second tier of NOx limits under consideration for Category 3 Marine rule would require controls on new vessel engines to reduce emissions. Chapter 8 provides details on the development of other NOx levels for this rule. As described in Chapter 5, the costs to comply with a second tier of standards would vary by engine type (number of cylinders and speed) and across shipyards depending upon the number of Category 3 Marine vessels being manufactured at any time. These regulatory costs may have financial implications for the affected producers, and possibly broader implications as these effects are transmitted through market relationships to other producers and consumers.

7.5.1 Summary of Compliance Costs

As described in Chapter 5, we estimate that the total net present value of the compliance costs of a second tier of NOx standards set at 30 percent below Tier 1 would be $115,000 per vessel (no monitoring costs) over a 30 year period during the first 5 years. After that time, the compliance costs would likely fall after that as described in Chapter 5. Overall, in the first five years, all U.S. shipyards could experience costs ranging from $0 to $1 million depending on the number and type of Category 3 Marine vessels under construction at any given time. This range reflects a given shipyard building no Category 3 Marine vessels at the low end to a given shipyard building all the vessels in that year (e.g., projected seven vessels in 2007). There are uncertainties regarding the projected growth in the industry and the number of orders any given shipyard may secure in a given time period.

In 2007, the annualized cost of the Tier 2 program under consideration (not including NOx monitoring operating costs) is estimated to be $1,000,000, which represents 0.17 percent of total 1997 industry revenues (based on 1997 value of shipments for NAICS 3366115124 and assuming no corresponding revenue growth).[2]

7.5.2 Market Impacts

Typically, our economic analyses take several data elements as input to a model that determines changes in market prices, output, and total social cost (via the change in producer and consumer surplus). We are not projecting any costs or economic impacts associated with the Tier 1 proposed standards; thus, this section focuses on the Tier 2 standards under consideration, incremental to the Tier 1 proposed standards. In this screening analysis, we examine potential financial impacts on engine manufacturers and vessel manufacturers.

7.5.2.1 Engine Manufacturers Impacts

The impacts of the Tier 2 standards under consideration applied to U.S. flagged vessels are not expected to produce any measurable changes in an economic model of the Category 3 Marine diesel engine industry for the following reasons:

- No Category 3 engines are currently produced in the US (although they are assembled in U.S. shipyards).
- Total U.S. flagged annualized compliance cost represents a small percentage (0.03 %) of global annual Category 3 Marine engine revenue.[3]
- The number of active new construction U.S. shipyards building large ocean-going vessels was 3 in 2001.
- The Jones Act requirements will be a determining factor in decisions to contract with U.S. shipyards (see Section 3.3.1.4).

We can conclude in general that because a model of the market is not likely to show any changes resulting from the costs imposed by this regulation, the market as a whole will not show adjustments in price and production. Because of the Jones Act requirements, it is likely that affected producers will be able to recover any of the compliance costs incurred by raising prices. Even if engine manufacturers were not able to do so, the costs are a small percentage of the overall cost of a vessel for U.S. flagged vessels (on average 0.08 percent, ranging from about 0.23 percent for containerships and 0.02 percent for a cruise ship in the first five years).[4] Thus, it is unlikely that it would affect profitability. For these reasons, overall industry production is not expected to change if these standards were adopted.

If the second tier of NOx standards under consideration were applied to all vessels, including foreign flagged vessels, the costs would be 40 to 60 percent lower per engine, as described in Section 5.3.3, Table 5.3-2 above. However, costs per ton are higher for foreign-flagged vessels since we count only tons emitted near the U.S. We would anticipate that the total compliance costs would be an even smaller percentage of the cost of a vessel. We would also anticipate the annual compliance costs would be an even smaller percentage of annual global revenues.

7.5.2.2 Vessel Manufacturers Impacts

The impacts of the Tier 2 standards under consideration applied to U.S. flagged vessels are not expected to produce any measurable changes in an economic model of the Category 3 Marine shipbuilding industry for the following reasons:

- Total annualized compliance cost represents a small percentage (0.17 percent) of total annual shipments.
- The Jones Act requirements will be a determining factor in decisions to contract with U.S. shipyards (see Section 3.3.1.4).
- The number of active new construction U.S. shipyards building large ocean-going vessels was 3 in 2001.
- The largest producers account for a large percentage of market share (i.e., percentage of total production).[5]

We can conclude in general that because a model of the market is not likely to show any changes resulting from the costs imposed by this regulation, the market as a whole will not show adjustments in price and production. Furthermore, because of the Jones Act requirements, it is likely that affected producers will be able to recover any of the compliance costs incurred by raising prices. Even if shipbuilders were not able to do so, the costs are such a small percentage of the overall cost of a vessel that it is unlikely that it would affect shipyard profitability. Thus, overall industry production is not change expected to change.

Rather than perform a full market analysis, we take a closer look at the firm-level impacts assuming all costs will be absorbed by the owner of the shipyard. We do this by determining the percentage of revenues that the compliance cost will consume. Using data presented in Chapter 3, the 8 facilities with capacity for building large commercial vessels are owned by 6 ultimate parent firms. One of the eight shipyards filed for bankruptcy in 2001, and two other shipyards focus on military and smaller vessel markets. Two parent companies own 3 each of the largest commercial and military shipyards in the U.S. We were able to obtain employment data for 6 of the 8 firms and revenues for 4 of the 8 firms, including the shipyards currently engaged in commercial shipbuilding. For the shipyards engaged in building, the annualized compliance cost (not including NOx monitor operating cost) as a percentage of annual firm revenues ranges from 0.05 to 0.2 percent.[6] In addition, the annualized compliance cost as a percentage of parent company revenue ranges from 0.005 to 0.016 percent. Therefore, the impacts presented by this rule are likely to be minimal on all of the firms owning the affected shipyards.

If the second tier of NOx standards under consideration were applied to all vessels, including foreign flagged vessels, the costs would be 40 to 60 percent lower per engine, as described in Section 5.3.3, Table 5.3-2 above. However, costs per ton are higher for foreign-flagged vessels since we count only tons emitted near the U.S. We would anticipate that the total compliance costs would be an even smaller percentage of the overall cost of a vessel. We would also anticipate the annual compliance costs would be an even smaller percentage of annual global revenues. In addition, the largest foreign shipyards receive substantial subsidies.[7] Foreign countries confer a variety of subsidies on their shipyards including grants, favorable loans, export credits, restructuring aids, and even government ownership.[8]

Chapter 7 References

1. "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.

2. U.S. Census Bureau. 1997 Economic Census. Manufacturing Industry Series, Shipbuilding and Ship Repair. NAICS 336611. July 1999.

3. The annualized compliance cost is divided by an estimate of annual global engine revenue for Category 3 marine engines. The annual global engine revenues were estimated by multiplying range of engine costs ($2.5 to $3 million) by the number of worldwide engines produced in a typical year (1,262 produced in 1998).

4. Although it is difficult to develop an average price for a custom-designed and built ship, we estimate that the average price of a Category 3 vessel is $150 million, with containerships averaging $50 million and cruise ships averaging $500 million per vessel. (See ASA 1993 report, Revelt memo to docket 2002, and Koman memo to docket 2002).

5. U.S. EPA, Economic Impact Assessment of the Industrial Surface Coating of Shipbuilding and Ship Repair National Emission Standard for Hazardous Air Pollutants (NESHAP). 1994.

6. This assumes that all of the compliance costs for the entire program falls on a single shipyard, and thus this is a high end estimate. The upper bound calculation assumes the total annualized cost is divided by the shipyard annual revenue (here using the shipyard annual revenues from Table 3.2-4 and parent company annual revenues from Table 3.2-5).

7. American Shipbuilding Association. 1993. International Shipbuilding Aid: Shipbuilding Aid Practices of the Top OECD Subsidizing Nations and Their Impact on U.S. Shipyards. June 1993.

8. Potomac Institute for Policy Studies. 1998. Maritech Program Impacts on Global Competitiveness of the U.S. Shipbuilding Industry and Navy Ship Construction. PIPS-98-4. Dr. James Richardson, Study Director. July 1, 1998.

CHAPTER 8: Analysis of Alternatives

This chapter presents an analysis of three approaches that we considered as other alternatives for a second tier of NOx standards. This analysis includes technological feasibility, costs, emission reductions, and cost per ton and is performed using the same methodologies described in earlier chapters.

8.1 Overview of Alternative Approaches

In addition to standards equivalent to a 30 percent reduction from Tier 1, we also considered two other scenarios for a second tier of standards: 50 and 80 percent below the proposed Tier 1 standards. In addition, we considered setting a fuel sulfur cap of 1.5 weight percent for operation in U.S. waters. Table 8.1-1 presents these three scenarios and the technology we considered in our analysis of these approaches. For all three of these alternative approaches, this analysis uses an implementation date of 2007 so that a direct comparison can be made to the 30 percent reduction scenario. However, additional lead time would likely be necessary for manufacturers apply the technology needed for the more stringent NOx alternatives compared with the implementation date under consideration for a second tier of NOx limits. Also, we considered applying the two NOx control alternatives to just U.S. flagged vessels and to all vessels operating near the U.S. coast. For the low sulfur fuel alternative, we only considered applying this approach to all vessels operating near the U.S. coast.

Table 8.1-1: Alternative Approaches Considered in this Chapter

Alternative Standard	Technology
NOx 50% below Tier 1	Water introduction into the combustion process
NOx 80% below Tier 1	Selective catalytic reduction or fuel cell technology
Fuel sulfur cap of 1.5 percent	Low sulfur fuel use and fuel system modifications

The remainder of this chapter is divided into four sections. First is a discussion of the technological feasibility of each of the alternative standards shown in Table 8.1-1. Second, we present the emissions inventory impacts for each of the approaches. This is followed with a comparison of the cost per ton estimates and a discussion of our conclusions.

8.2 Anticipated Technology for Alternative Approaches

This section describes several technologies that could be used to achieve additional NOx reductions beyond 30 percent reduction from Tier 1 currently under consideration. In addition, it discusses the feasibility of using low sulfur fuel to reduce PM, SOx, and NOx emissions.

8.2.1 Water Introduction into the Combustion Process

To achieve 50 percent reduction beyond the proposed Tier 1 NOx standard, we believe that introducing water into the combustion process could be an effective strategy. Water can be used in the combustion process to lower maximum combustion temperature, and therefore lower NOx formation, without an increase 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.

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-fuel ratio of 50 percent[a] with only a slight increase in smoke.[1] Two power plants with slow-speed diesel engines are using water emulsification today to reduce NOx.[2] In this 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 which are similar in design and operation. Water emulsification requires changes to the engine and fuel system. 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 their 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.[3] 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.[4] 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% of rated), no water is added, from 30-40 percent of rated power, 20 percent water is added, above 40% 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 which was

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[a] 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.

eroded by cavitation and water wear after 900 hours. An example of stratified injection was developed for a slow-speed diesel engine.[5] 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).[6] Further work on another engine achieved a NOx reduction of 70 percent with 90 percent water (6 g/kW-hr).[7] With only 50 percent water, a 40 percent reduction in NOx from this engine was observed.

One manufacturer is also evaluating two other methods introducing water into the combustion process.[8] 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 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 a 85 percent NOx reduction with a 3.0-3.5 steam 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.

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.

Durability issues may be a concern with water emulsification or injection systems. For onboard water emulsifying units, cavitation is used to atomize the water and mix it into the fuel. Although this works well at emulsifying the fuel, the water can cause significant wear of the injection pump. For water injection systems, high pressure water is injected similar to in a fuel injector. However, water does not have the inherent lubrication properties found in fuel. Therefore, more research may be necessary on more durable materials.

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.

8.2.2 Selective Catalytic Reduction

We believe reductions of 80 percent beyond the proposed Tier 1 NOx standard could be achieved through the use of selective catalytic reduction (SCR). SCR is one of the most effective means of reducing NOx from large diesel engines. 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.[9] 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 large stationary source applications, which 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.[10,11] 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.[12] Another manufacturer 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.[13] 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 3 Marine engines operating on both residual and distillate fuel oil at the end of the year 2000.[14] A list of the systems is contained in Appendix A to this Chapter.

SCR systems available today are effective only over a narrow range of exhaust temperatures (above 300°C). To date, these systems have primarily been applied to four-stroke medium speed engines which have exhaust temperatures above 300°C at least at high load. Two-stroke slow speed engines have lower exhaust temperatures and are discussed later. The effectiveness of the SCR system is decreased at reduced temperatures exhibited during engine operation at partial loads. 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 required, engines may operate at less than 25 percent power in a reduced speed zone. During this low load operation, no NOx reduction would be expected, therefore SCR would be less effective than standards based on in-engine controls (i.e., the 30 percent reduction scenario) 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.

SCR systems traditionally have required a significant amount of space on a vessel; in some cases the SCR was as large as the engine itself. However, at least one manufacturer is developing a compact system which uses 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 S 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).[15]

Information from one manufacturer who has 40 installations of SCR reveals that the engines using the technology are either using low sulfur residual fuel (0.5%-1% S) or distillate fuel. 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. However, distillate fuel is available. 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. The operation characteristics of ocean going vessels may interfere with correct maintenance of the SCR system. Ferries which have incorporated this technology to date 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 for they do not have regular down times.

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.[16] Depending on the precious metals used in the SCR unit, it could be possible to 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 S to direct sulfate PM. Direct sulfate PM emissions could be reduced by using lower sulfur fuel such as distillate.

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. Also, 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 increase operating costs.

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 could be used downstream of the reactor to burn off the excess ammonia.

Slow-speed Marine engines generally have even 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 on these four in-service engines, highway diesel fuel (0.05% S) is required. In addition, these ships only operate with the exhaust routed through the SCR unit when they enter port 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.

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 will prevent dirt that is building up on the catalyst. The horn may be driven by air from the normal air system installed on the vessel. While this method requires no engine shutdown, compressed air cleaning does require a period of engine shut down. In this method, 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 also will need to be replaced after about 20,000 hours of operation.

8.2.3 Fuel Cells

Another approach for meeting a level of 80 percent below the proposed Tier 1 NOx standard 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.[17] The U.S. Navy in early 2000 sponsored an effort to continue the development of the molten carbonate fuel cell for Marine use.[18] The Society of Naval Architects and Marine Engineers released the technical report “An Evaluation of Fuel Cells for Commercial Ship Applications.” This report examines fuel cells for application in commercial ships of all types for electricity generation for ship services and for propulsion.[19]

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.

8.2.4 Low Sulfur Fuel

Another emission control standard we considered was to require that Category 3 Marine engines operate on fuel with a sulfur level less than 1.5 percent (15,000 ppm) in U.S. waters. This limit is the same as the requirement for SOx emission control areas under Regulation 14 of MARPOL. Annex VI.

The majority of Category 3 engines are designed to run on residual fuel, which can have sulfur levels as high as 4.5 percent although the global average is about 2.7 percent.[20] Distillate fuel, on the other hand, generally has a fuel sulfur level well below 1.5 percent. Operating on lower sulfur fuel reduces both SOx emissions and direct sulfate PM emissions. In addition, because residual fuel is made from the very end products of the oil refining process, formulated from residues remaining from the primary distilling stages of the refining process, it has higher contents of ash, metals, nitrogen, and other undesirable constituents than distillate fuel, especially from an exhaust emission standpoint. Switching to distillate would reduce the fraction of PM made up by ash and metals and, because of the lower density, could reduce soot emissions too. NOx reductions may also result, because distillate fuel contains less nitrogen and has better ignition qualities.

Alternatively, ships can use residual fuels produced to meet the 1.5 percent sulfur requirement. Refiners can produce low-sulfur residual fuel from a low-sulfur crude oil or they can put the fuel through a de-sulfonation step in the refinery process. They can also produce it by blending Marine distillate fuel, which typically has fuel sulfur levels between 0.2 and 0.3 percent.

For a ship to operate on residual fuel, certain design requirements are necessary. First, the fuel must be heated before it will flow through the fuel lines because residual fuel is a waxy solid at room temperature. In addition, the fuel is processed through centrifuges and filters to remove water and other impurities. Fuel pumps and injectors must be designed to operate well with a high density fuel. In fact, these fuel pump designs generally rely on the higher density and better lubrication properties of the residual fuel.

Engines designed to operate on residual fuel are generally also capable of operating on distillate fuel. In fact, most ships have the ability to switch back and forth between distillate and residual fuels. Although most ships have multiple fuel tanks, these tanks sized would likely have to be modified to account for increased operation on low sulfur fuel. The amount of fuel carried is small compared with the displacement of ship, so the ship can tolerate a wide range of fuel levels and weight distributions. Because of this and because tankers are converting to double-walled hulls (which provides more room for ballast tanks), commercial ships generally no longer use fuel tanks to balance the weight of the ship. This is still done on some navy vessels.

Most ships have the ability to switch to distillate fuel. If the engine is to be shut down for maintenance, distillate fuel is often used to flush out the fuel system. Switching to distillate fuel generally requires 20 to 60 minutes and is governed by the time desired for fuel temperature cooldown. Switching from a heated residual fuel to a cool distillate fuel too fast could cause damage to fuel pumps. Industry has claimed that there could be fuel pump durability problems if the engine is operated on distillate fuel for more than a five or six days. In the Baltic Sea, which is a SOx emission control area under Annex VI, ships often run up to two or three days on distillate. For continued operation on distillate fuel, separate pumps and lines may be necessary. In addition, modification to the fuel tanks may be necessary in some vessels to ensure proper capacity for distillate fuel.

Today's Marine distillate fuel can be split into three subgroups: 1) Pure distillate , 2) Distillate supplied via shore tanks, lines, and barges which may have contained some residual fuel resulting in some contamination of the distillate fuel, and 3) Distillate intentionally blended by the supplier with a residual fuel component up to 10 or 15 percent of the total supplied; the overall product, however, does not require preheating to reduce viscosity prior to use in engines or boilers. For the first of these two types of fuel, the ash content is generally below 0.01 percent (the test reporting limit) unless some extraneous contamination (such as seawater) has occurred during delivery or storage. In the case of third fuel type, the ash content could be up to 0.02 percent (again excepting unforeseen contamination) and that ash will normally be the product of the vanadium and (to a lesser extent nickel) present in the residual fuel fraction.

Regulating fuel sold in the U.S. would not necessarily ensure that low sulfur fuel was used near the U.S. coast because ships may choose to bunker before entering or after leaving the U.S. However, regulation 14 of MARPOL Annex VI allows areas in need of SOx emission reductions to petition to be designated as SOx Emission Control Areas (SECA). Within such waters, the maximum sulfur content of the fuel will be limited to 1.5 percent.[b] We intend to work through the MARPOL process to designate certain areas in the U.S. as sulfur control areas which would require the use of low sulfur fuel.

8.3 Emissions Inventory

This section presents our analysis of the potential environmental impacts of the alternative standards. As with for the cost analysis, the emission reductions are only included for operation within 175 nautical miles of the U.S. coast. Tier 1 inventories of NOx, PM, and SOx are taken from Chapter 6.

NOx emission reductions for each of the alternative standards were calculated using the same methodology as presented in Chapter 6. The only differences in this analysis are the percent reductions in NOx from Tier 1 and an implementation date of 2010 instead of 2007. Tables 8.3-1 and 8.3-2 present the potential NOx reductions from the two alternative NOx standards applied to U.S. flagged ships and applied to all ships.

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[b] Unless SOx emission controlled by secondary means which at present is not clear.

Table 8.3-1: Potential NOx Reductions from Alternative Tier 2 Standards
Applied to U.S. Flagged Vessels Only (1000 short tons)

Year	Tier 1	50% Below Tier 1		80% Below Tier 1	
		Control	% Reduction	Control	% Reduction
1996	190.0	190.0	--	190.0	--
2010	274.1	265.6	3.1	260.0	5.0
2020	367.5	326.8	11.1	301.9	17.8
2030	530.8	439.1	17.3	382.9	27.9

Table 8.3-2: Potential NOx Reductions from Alternative Tier 2 Standards
Applied to All Vessels (1000 short tons)

Year	Tier 1	50% Below Tier 1		80% Below Tier 1	
		Control	% Reduction	Control	% Reduction
2000	190.0	190.0	--	190.0	--
2010	274.1	260.7	4.9	252.5	7.9
2020	367.5	276.9	24.7	221.4	39.8
2030	530.8	311.2	41.4	176.7	66.7

For the 1.5 percent sulfur residual fuel scenario, our estimates of SOx and PM reductions are based strictly on the reduction of sulfur in the fuel from 2.7 to 1.5 percent. In this case, no NOx reductions are anticipated. Table 8.3-3 presents the emission reductions due to using this low sulfur fuel for all vessel operation within 175 nautical miles of the U.S. coast from all vessels with Category 3 Marine engines regardless of flag state.

Table 8.3-3: Potential Emissions Reductions from Using 1.5% Sulfur Fuel for all Vessel Operations Within 175 Nautical Miles of U.S. Coast (1000 short tons)

		1996	2010	2020	2030
PM	Baseline case (thousand short tons)	17.1	26.0	36.7	54.2
	Control case (thousand short tons)	17.1	21.3	30.1	44.5
	Percent reduction from Tier 1	--	18	18	18
SOx	Baseline case (thousand short tons)	156.2	192.8	271.2	399.7
	Control case (thousand short tons)	156.2	108.0	151.9	223.9
	Percent reduction from Tier 1	--	44	44	44

For the 0.3 percent sulfur fuel case, our estimates of SOx reductions are based on a reduction of sulfur in the fuel from 2.7 to 0.3 percent. We estimate that about 98 percent of the sulfur in the fuel is converted to SOx while the rest is converted to direct sulfate PM.[21] Our estimates of PM reductions are based on this and changes to other fuel components. We estimate that PM from a Marine engine operating on residual fuel is made up of 45 percent sulfate, 25 percent carbon soot, 20 percent ash, and 10 percent soluble organic hydrocarbons.[22] Reducing sulfur in the fuel would reduce direct sulfate PM by about 90 percent. In addition, if distillate fuel is used, the ash content and the density of the fuel would be reduced. This analysis results in a total PM reduction of 63 percent. Using residual fuel can lead to NOx increases due to nitrogen in the fuel. For this analysis we use a NOx reduction of ten percent based on a reduction of nitrogen in the fuel on the assumption that distillate fuel would be required to meet this sulfur level. Table 8.3-4 presents the potential SOx, PM, and NOx reductions from using distillate fuel for all vessel operation within 175 nautical miles of the U.S. coast from all vessels with Category 3 Marine engines regardless of flag state.

Table 8.3-4: Potential Emissions Reductions from Using 0.3% Sulfur Fuel for all Vessel Operations Within 175 Nautical Miles of U.S. Coast (1000 short tons)*

		1996	2010	2020	2030
NOx	Baseline case (thousand short tons)	190.0	274.1	367.5	530.8
	Control case (thousand short tons)	190.0	246.7	330.7	477.7
	Percent reduction from Tier 1	--	10	10	10
PM	Baseline case (thousand short tons)	17.1	26.0	36.7	54.2
	Control case (thousand short tons)	17.1	9.6	13.6	20.1
	Percent reduction from Tier 1	--	63	63	63
SOx	Baseline case (thousand short tons)	156.2	192.8	271.2	399.7
	Control case (thousand short tons)	156.2	21.2	29.8	44.0
	Percent reduction from Tier 1	--	89	89	89

*For standards applying only to U.S.-flagged vessels.

8.4 Cost per Ton

This section assesses the cost per ton of emission reduction for the two alternative NOx emission standards and the low sulfur fuel standard using the methodology presented in Chapter 7. This analysis relies in part on cost information from Chapter 5 and emissions information from section 8.3 to estimate the cost per ton of the alternative standards in terms of dollars per short ton of NOx emission reductions. All of the cost per ton estimates presented here are based on the costs and benefits beyond Tier 1.

Table 8.4-1 presents aggregate cost per ton estimates for the three alternative NOx standards for U.S. flagged ships only and then for all ships. By including foreign flagged vessels under these alternative approaches, the cost per engine decreases because the development costs can be distributed across more engines. However, the cost per ton actually increases because U.S. flagged vessels spend about 16 times as much of their operating time within 175 nautical miles of the U.S. coast. Therefore, the tons of NOx reduced per year in U.S. waters for an average foreign flagged vessel (which make up about 97 percent of the vessels[23]) are lower. Operating costs, which are proportional to the amount of time the ship operates in U.S. waters, do not depend on the vessel's flag state. For water injection, the operating costs include the effective cost of the water. For SCR, the operating costs include urea consumption as well as ship operation on 0.05 percent sulfur fuel.

Table 8.4-1
Cost per ton ($/short ton) of the Alternative NOx Standards Discounted at 7 Percent

Alternative Standards	Model Year Grouping	NPV Benefits (short tons)	NPV Operating Costs	Engine & Vessel Costs	Discounted Cost Per Ton
U.S. Flagged Vessels Only					
50% below Tier 1	1 to 5	1,915	$527,000	$207,000	$370
	6 +			$89,000	$316
80% below Tier 1	1 to 5	3,064	$9,543,000	$1,014,000	$3,405
	6 +			$776,000	$3,337
Foreign Flagged Vessels Only					
50% below Tier 1	1 to 5	74	$84,000	$137,000	$2,737
	6 +			$89,000	$2,174
80% below Tier 1	1 to 5	119	$410,000	$972,000	$10,607
	6 +			$776,000	$9,159
All Vessels					
50% below Tier 1	1 to 5	122	$95,000	$137,000	$1,768
	6 +			$89,000	$1,424
80% below Tier 1	1 to 5	195	$629,000	$972,000	$7,618
	6 +			$776,000	$6,732

Table 8.4-2 presents aggregate cost per ton estimates for using low sulfur Marine diesel oil for all ships (regardless of flag) operating within 175 nautical miles of the U.S. coast. Although all of the costs could be applied to PM and the SOx reductions could be considered "free," we recognize that there is benefit to reducing both PM and SOx. Therefore, we apply 10 percent of the cost to SOx reductions. If all the costs were applied to PM, the estimated $/ton for PM control would be about 10 percent higher than shown below. No costs are applied to NOx control, so a cost per ton value is not presented.

Table 8.4-2
Cost per ton ($/short ton) of Low Sulfur Approach Discounted at 7 Percent

Alternative Standards	Pollutant	NPV Benefits (short tons)	NPV Operating Costs	Engine & Vessel Costs	Discounted Cost Per Ton
1.5% Sulfur	PM	4.3	$125,000	$45,000	$38,066
	SOx	61	$14,000	$5,000	$302
0.3% Sulfur	PM	8.7	$246,000	$45,000	$32,968
	SOx	122	$27,000	$5,000	$262

8.5 Summary

We considered two alternative approaches to reduce NOx emissions: 50 and 80 percent below Tier 1. We also considered a third approach of using low sulfur (distillate) fuel in U.S. waters.

For a 50-percent reduction, we considered water injection with 0.5 water to fuel ratio. At the present time, the cost per ton for the water injection system ranges from $370 to $1,768 depending on if it applies to U.S. flagged vessels only or all vessels operating within 175 nautical miles of the U.S. coast. This analysis does not consider the lost space on a vessel due to water storage, nor does it consider the alternative of adding water distillation boilers which would add cost to the vessel, require space, and require additional fuel consumption. Water storage would either displace fuel storage and reduce the range of the vessel or reduce cargo space which would slightly affect a vessel's profitability. This technology is in operation on a pilot basis, with promising results so far. At the same time, we are aware that water injection would represent a very significant departure from established technology. While this may have a continuing presence in niche applications, we do not believe the technology has matured enough for us to adopt standards that would effectively mandate its use on all Category 3 Marine engines. We expect that this technology will continue to develop over time and that the various concerns related to universal application of this technology will eventually be addressed. In addition, more information is necessary on the effects of this technology on PM emissions. Therefore, we have decided not to propose standards at this level at this time.

For the 80 percent NOx reduction case, we considered the use of selective catalytic reduction with a urea consumption rate of about 8 percent of the fuel consumption rate. Our estimated cost per ton for this approach ranges from $3,405 to $7,618 depending on if it applies to U.S. flagged vessels only or all vessels operating within 175 nautical miles of the U.S. coast. This is considerably higher than the cost per ton figures for the recent mobile source programs presented in Chapter 7 (Table 7.3). The cost per ton estimate for the use of SCR includes the cost of using lower sulfur fuel which we believe would be necessary for the durability of the system and to prevent increases in direct sulfate PM. In the future, however, technological advances increase the effectiveness of these units at lower temperatures and may reduce the cost of this system and may improve the durability of the system on higher sulfur fuels.

For SCR to be effective, an infrastructure would be necessary to ensure that ships could refuel at ports they visit. We believe that it would take some time to set up a system for getting fuel to ships that fill up using barges, especially if the standard were only to apply to U.S. flagged ships due to the low production volume. SCR would require space for urea storage, but it would likely be much less than that for water storage in the above approach because the volume of urea needed is only 5-10 percent of the volume of water needed for the water injection case considered above. In addition, at least one manufacturer is developing a compact SCR unit that will minimize the space needed for this system. We also believe that there are technical issues that need to be resolved such as effectiveness at low loads and the effect of the catalyst in the exhaust on direct sulfate PM emissions. As with water injection, we believe SCR may be appropriate for certain applications, but also believe that the remaining technology development and system cost prevent us from expecting manufacturers to apply SCR to all Category 3 Marine engines at this time. We are therefore proposing to designate 80-percent reductions as a target for recognition as voluntary low-emission engines, rather than adopting mandatory standards based on this technology.

We are not proposing low sulfur fuel requirements in this rule, in large part because regulating fuel sold in the U.S. would not necessarily ensure that the cleaner fuel was used in U.S. waters. The Clean Air Act limits us to setting requirements on fuel entered into commerce in the U.S. It is not clear if fuel on ships operating in waters under U.S. jurisdiction is “entered into commerce.” If we can regulate only the fuel sold in the U.S., then a fuel sulfur standard would be unlikely to have a significant impact on emissions because ships would likely choose to bunker before entering or after leaving the U.S. However, Regulation 14 of MARPOL Annex VI allows areas in need of SOx emission reductions to petition to be designated as SOx Emission Control Areas. Within these designated areas, the maximum sulfur content of the fuel is limited to 1.5 percent.[c] We intend to work through the MARPOL process to designate certain areas in the U.S. as sulfur control areas, which would require the use of distillate fuel by all vessels operating there.

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[c] Unless SOx emission controlled by secondary means which at present is not clear.

Chapter 8 References

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APPENDIX TO CHAPTER 8

SIEMENS SINOx Exhaust Gas Treatment Plants and Systems Marine

Customer Operator	Field of Application	Fuel	Capacity in kW	Volume flow in Nm3/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 3x11.435	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
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 Nm3/h	Extent of Delivery	Delivery Date
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
MS Forester(S) Roerd Braren	Ship propulsion 1 main engine 2 aux engines	HFO MDO	3.840 239	21.000 1.200	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 aux engines	HFO	4x12.600 3x1,530	4 x 63.000 3 x 9.000	SINOx	2000

Reference: SINOx Exhaust Gas Treatment Plants and Systems, Marine, Sales brochure from Siemens Westinghouse Power Corp.

Chapter 9: 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 being proposed in this rulemaking.

9.1 Proposed Certification Test Procedures

We are proposing to use the Annex VI engine test procedures with some modification exceptions. The Annex VI test procedures are set out in the NOx Technical Code. The exceptions we are proposing are described in Subsection 9.1.4. The other subsections describe issues such as the duty cycle, test fuel and sampling procedures. These procedures will be required for certification testing. We will allow other procedures to be used for production testing and in-use testing.

9.1.1 Duty Cycle

We are proposing to use the same duty cycles as are used for testing NOx emissions under the Annex VI requirements. These test cycles are designated by the International Standards Organization (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 9.1-1 presents duty cycles for main drive engines as discussed above.

Table 9.1-1
Test Cycle Types E2 and E3

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

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

9.1.2 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. Therefore, we are proposing to specify residual fuels for certification testing. This subsection provides additional information regarding residual fuels.

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 9.1-2 summarizes current ASTM standards for a Marine distillate oil, residual fuel, and the two most common IF blends.

Table 9.1-2
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*	20**	22**	no max
Ash, max	wt%	0.01	0.15	0.20	0.20
Sulfur, max	wt%	1.5	5.0	5.0	5.0

* Ramsbottom test
** Conradson test

The use of residual fuel has two important consequences. First, it is more difficult to handle. Because of it's 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 almost 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). It is appropriate to assume to 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. Therefore, we are estimating that 99 percent of the fuel nitrogen is converted into NOx during the combustion process. This means that one gram of nitrogen in the fuel would result in 3.25 grams of NOx.

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. Since we are not aware of any accurate corrections for fuel effects other than the effect of fuel nitrogen, we are not proposing to correct them. To a large extent, we believe that manufacturers and ship operators will account for these other effects in determining how to best adjust the engine. To the extent that they do not, we consider these effects to be a part of the normal variability between tests. It is also important to note that our proposed adjustment to the IMO emission standard to correct for fuel nitrogen (1.4 g/kW-hr) is comparable to the entire IMO allowance for the difference between tests conducted using distillate and tests conducted using residual fuel (10 percent).

9.1.3 Sampling Procedures and Calculations

The Annex VI 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 (CL) analyzer. CO_2 concentrations are measured using a Non-Dispersive Infrared (NDIR) analyzer. These analyzers are the same as the analyzers specified by EPA for other nonroad standards.

The Annex VI 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.

9.1.4 Modifications to the Annex VI Test Procedures

We are proposing several modifications and additions to the Annex VI test procedures to better ensure that the emission measurements will accurately represent in-use performance. We would require that inlet air and exhaust restrictions be set at the average in-use levels. Similarly, engine coolant and engine oil temperatures would need to be equivalent to the temperatures that would occur in-use under ambient conditions identical to the test conditions. We are also proposing that measurements would only be valid 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 would be allowed to measure emissions within larger discrepancies, but would not be allowed to use those measurements to demonstrate compliance with these regulations.

Annex VI 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 that 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. Therefore, we are proposing that exhaust flow rates be calculated using measured fuel flow rates.

We are proposing to allow tests to be performed at any representative pressure and humidity levels, and at any ambient air temperature from 13°C to 30°C. The Annex VI requirements specify a narrower range of conditions. We believe that the broader range of conditions is necessary to ensure that the emission controls would be broadly effective. We are also proposing to allow testing with charge air cooling water temperatures from 17°C to 27°C.

The duty cycle used for Annex VI testing specifies the test points based on the manufacturer's specified rated speed. We have concerns about the subjective nature of the Annex VI requirement and believe that the test cycle needs to be defined more objectively. Therefore, we are proposing that the test cycles be denormalized based on the maximum test speed described in §94.107. This maximum test speed is not intended to fundamentally change the test procedure, but is merely being proposed to make the procedure less subjective.

9.2 Shipboard NOx Emission Measurement System

We propose that Category 3 diesel engines have a direct exhaust NOx monitoring system. This system would be used to verify that engines are adjusted properly in use. It could also be used for production testing. Category 3 engines typically have fuel injection timing and other adjustments that are optimized to accommodate a range of fuel qualities and environmental conditions. These engine adjustments also affect NOx emissions; therefore a shipboard means of monitoring NOx is a prudent requirement to ensure 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.

We are not proposing to require a specific type onboard NOx measurement system. Rather, we are proposing general specifications for the systems. 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 to emission limits for an engine’s operating conditions.

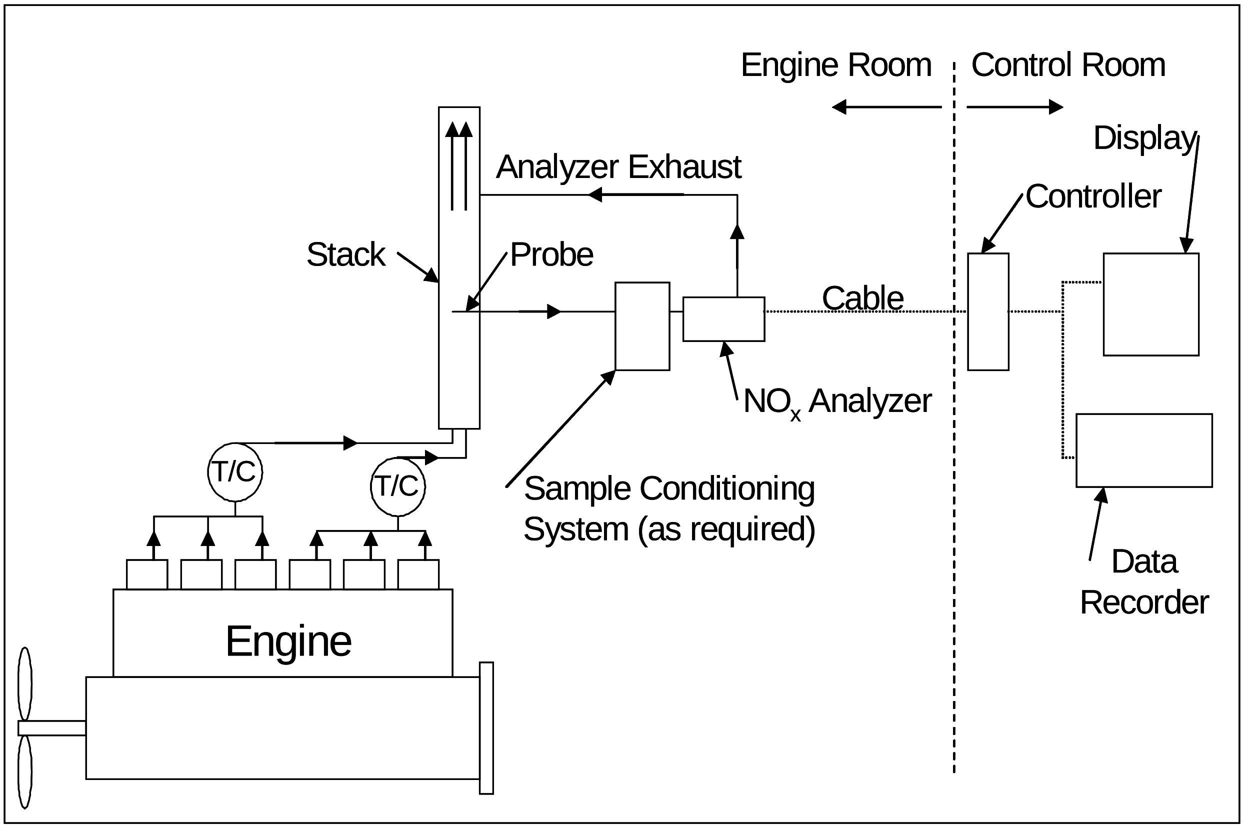
In addition, the system would display the NOx concentration and the respective specified emissions limit at the engine control room. Such a provision is important as it would give the Marine engineer immediate and specific feedback regarding any recent adjustments to the engine or any recent changes 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 would 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, tedious calibration or frequent maintenance of the system would ensure that it is not used properly.

The system would 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.

9.2.1 System Description and Component Specifications

The proposed NOx monitoring system would consist of several components, and the system is illustrated in the figure below.



9.2.1.1 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 on Category 3 engines typically each fuel injection pump and after-cooler on the engine may be adjusted individually. 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.

9.2.1.2 Sample conditioning system

A sample conditioning system may be used if the NOx detection method requires it. The sample conditioning system may 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.

9.2.1.3 NOx Analyzer

To quantify total NOx (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.

It is anticipated that analyzers based on chemiluminescent, non-dispersive ultra-violet, zirconia cell, or fourier transform infra-red measurement techniques may be appropriate for shipboard use, however any instrument manufacturer would have to ensure that an analyzer meets the specifications outlined in this section. 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 one of the most cost-effective of these detectors, 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.

9.2.1.4 Programmable Controller

It is anticipated that a programmable electronic controller would 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.

9.2.1.5 Engine Control Room Display

An engine control room display would 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.

9.2.1.6 Data Recorder

A data recorder would permanently document on either magnetic or paper media 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.

9.2.2 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 would require the engine manufacturer to develop NOx-ppm emission targets for any given set of conditions.

Chapter 9 References

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