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The US Navy jointly with the EPA under SERDP is conducting a program to develop a NOX and PM control package for its shipboard diesel engines. This report evaluates the feasibility of retrofit NOX and PM control technologies based on impending emission standards, available technologies, cost, and impact of retrofit applications on ship/engine operations.

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# REDUCTION OF $NO_x$ AND PM FROM NAVY DIESEL ENGINES

## A Feasibility Analysis

July 1996

Contract No. 68-D4-0005
Work Assignment No. 2-026
Acurex Project No. 8926.001

Prepared For

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## EXECUTIVE SUMMARY

The U.S. Navy jointly with the EPA under the Strategic Environmental Research and Development Program (SERDP) is conducting a program to develop a $NO_x$ and PM control package for its shipboard diesel engines. This report evaluates the feasibility of retrofit $NO_x$ and PM control technologies based on impending emission standards, available technologies, cost and impact of retrofit applications on ship/engine operations.

In 1994 EPA issued a Notice for Proposed Rule Making (NPRM) addressing emissions from marine engines including diesel engines. The proposed emission standards for diesel engines are 9.2 g/kWh for $NO_x$, 1.3 g/kWh for HC, 11.4 g/kWh for CO, 0.54 g/kWh for PM, and smoke standards of 20/50 maximum percentage opacity for acceleration/peak operating modes. These standards apply to new compression-ignition marine diesel engines, regardless of power rating. Existing in-use engines are not subject to the standards, and as a result most of the engines in the Navy's inventory will not be affected by the NPRM. However, the proposed standards can serve as a guideline target for the emission reduction program.

The Navy has in the order of 2,750 diesel engines in its inventory. Power ratings for these engines range from 250 kW (333 hp) to 12,000 kW (16,000 hp), and the applications are diverse - small boats account for 37 percent; main and emergency generators account for 42 percent; main propulsion engines account for 17 percent; and other applications such as fire pumps, cranes, salvage equipment, etc., account for 4 percent. At about 63 percent of the total engines Detroit Diesel Corporation engines constitute a major fraction of the Navy's diesel engines. The remainder of the engine types include ALCO, Colt PC, Fairbanks-Morse, Cummins, Caterpillar, Isotta Fraschini and

i-ii

EMD. A preliminary survey indicates that the brake-specific $NO_x$ emissions from the above engines range between 5 and 15 g/kWh, and over 40 percent of the engines will require some kind of modification/retrofit to comply with the proposed guideline standard of 9.2 g/kWh $NO_x$.

A number of $NO_x$ and PM reduction methods/strategies were reviewed. From the stand point of effectiveness, cost, and feasibility of application, the following control methods were chosen for potential application to Navy diesels.

$NO_x$ Control

- Injection timing retard
- Exhaust gas recirculation; internal and external
- Water injection; emulsions and fumigation
- Lean $NO_x$ and DENOX

PM Control

- Particulate traps
- Oxidation catalysts
- Fuel additives

Most of the above methods are being further evaluated through testing at the EPA's Environmental Research Center (ERC) in RTP, NC, on a DDC 4-71 two-stroke test engine.

A conceptual control package for ship-board application is presented. After testing on the DDC 4-71 engine at the ERC, a modification package will be developed for further evaluation and demonstration on a shipboard diesel engine. Prior to shipboard demonstration, the control technologies will be tested on the DDC 4-71 test engine using an engine dynamometer test-bed facility at North Carolina State University, Raleigh, NC.

Whether a single method or combination of the above methods are needed will depend on the targeted level of $NO_x$ and PM reductions required from the shipboard engine, and the following parameters:

- Application of engine
- Operating/duty cycles
- Baseline emissions data under typical operating conditions, and
- Other logistical constraints such as availability of space, potable water, etc.

From the information in this report it becomes clear that a single modification package for all Navy engines, for $NO_x$ and PM control, is not a logical option. For maximized benefits a custom modification package will have to be designed for each family of engines (if not for each engine) based on a detailed inventory of Navy diesels that will include: engine application; operating/duty cycle; area of operation, i.e., harbor, coastal-waters, high-seas, etc.; baseline emissions data under typical operating conditions; and other logistics such as available space, availability of potable water, manpower and impact on ship/engine operations.

## TABLE OF CONTENTS

## TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

# LIST OF TABLES

# SECTION 1

# INTRODUCTION

## 1.1 BACKGROUND

Emission of oxides of nitrogen ($NO_x$) and particulate matter (PM) from diesel engines is a major environmental concern. The U.S. Navy has a large number of ship-board diesel engines and is addressing the problem of these emissions through a joint effort with the U.S. Environmental Protection Agency (EPA) under the Strategic Environmental Research and Development Program (SERDP). Federal, state and local agencies in the near future will require a reduction in $NO_x$ and PM from diesel engines operating on board ships in harbors and coastal waters. In addition, proposed $NO_x$ regulations by the International Maritime Organization (IMO) may soon require compliance. While national and international regulations have not been officially set, a 50 to 60 percent reduction in $NO_x$ emission levels is expected.

Under SERDP, EPA has agreed to a joint effort with the Navy to conduct an R&D program to improve the level of $NO_x$ control for diesel engines. EPA has acquired a diesel engine typical of the type operated by the Navy, and is conducting the design and development of a package for shipboard diesel engines that will achieve the required control levels.

## 1.2 OBJECTIVE

The overall objective of this program is to develop a cost effective modification package that will reduce $NO_x$ and PM emissions from shipboard diesel engines to meet future emission standards. The modification package is proposed to be developed in two phases: (i) an initial study evaluating the feasibility of application of control technologies; and (ii) through testing of selected control technologies. The following tasks constituting the first phase will not only address the overall program objective but also serve as a guide for the implementation of the second phase.

(1) Evaluate the impact the proposed emission standards (local, national and international) will have on Navy diesels

(2) Review and identify potential $NO_x$ and PM control technologies applicable to marine diesels

(3) Select potential $NO_x$ control technologies for application testing from a stand point of technical feasibility, cost and impact on ship/engine operations

(3) Prepare a preliminary modification package design plan for application development testing and on-board ship demonstration

In parallel to these tasks, as phase two, the selected technologies will be further evaluated through testing on a DDC 4-71 test engine at the EPA's Environmental Research Center in RTP, NC, and at the North Carolina State University's (NCSU at Raleigh, NC) engine dynamometer facility. The testing phase of this project will be presented in a subsequent report.

The scope of this report is as follows. In Section 2 the impending regulations and their impact (if any) on Navy diesels are discussed. In Section 3, various $NO_x$ and PM control applicable to diesel engines are reviewed. In Section 4, potential $NO_x$ and PM control technologies are selected for application testing and are evaluated from a stand point of technical feasibility, cost and impact on ship/engine operations. In Section 5, a conceptual modification package for shipboard testing and demonstration is presented. Finally in Section 6, the conclusions and recommendations based on this report are summarized.

# SECTION 2

# CURRENT REGULATIONS AND IMPLICATION TO NAVY DIESELS

## 2.1 $NO_x$ AND PM EMISSION STANDARDS

The U.S. EPA promulgated rules in 1994 mandated by Section 213 (a) of the Clean Air Act for nonroad compression-ignition engines above 37 kW, but this rule did not include marine engines. EPA now believes that marine compression engines should be covered by the same regulation as other compression ignition engines above 37 kW engines (Reference 1). Consequently the EPA has issued a Notice of Proposed Rule Making (NRPM) titled "Emission Standards for New Gasoline Spark-Ignition Engines and Diesel Compression Marine Engines" (Reference 2). The proposed standards are summarized in Table 2-1 and would be applicable only to new marine diesel compression ignition engines used for propulsion and auxiliary power units.

**Table 2-1. Proposed U.S. EPA Marine Diesel Engine Emission Standards (Reference 2)**

| Pollutant | Limit, g/kWh |
|---|---|
| $NO_x$ | 9.2 |
| HC | 1.3 |
| CO | 11.4 |
| PM | 0.54 |
| Smoke, maximum percentage opacity | Acceleration: 20%<br>Peak operating mode: 50% |

EPA has proposed that diesel engines less than 560 kW be required to meet the new emission standards beginning January 1, 1999, and those at or above 560 kW meet the standards beginning January 1, 2000. Existing marine engines would not fall under the proposed EPA rule. Exemptions to the ruling include investigations, studies, demonstrations, training and national security. Routine operations of the U.S. Navy and Coast Guard (USCG) are not specified as exemptions (Reference 3).

The International Maritime Organization (IMO), a subgroup of the United Nations is currently developing an agreement to control emissions from ships on international voyages. The IMO proposed $NO_x$ emissions, which are based on a correlation between engine rpm (n) and $NO_x$ emissions are as follows:

$$n < 130\ rpm\ ;\ NO_x < 17\ g/kWh$$

$$130 < n < 2{,}000\ rpm\ ;\ NO_x < 45 \times n^{-0.2}\ g/kWh$$

$$n > 2{,}000\ rpm\ ;\ NO_x < 9.84\ g/kWh$$

The IMO proposed limits are expected to be finalized in 1996 and implemented between 1998 and 2001. The proposed limits would be applicable to only new propulsion and auxiliary diesel engines.

With the exception of the State of California, individual states in the U.S. do not have existing or proposed laws limiting $NO_x$ emissions. Measure M13, the State Implementation Plan (SIP), submitted to EPA in November 1994 by the California Air Resources Board addresses marine vessel emissions and primarily recommends following the proposed EPA and IMO standards.

## 2.2 IMPACT OF PROPOSED STANDARDS ON NAVY DIESELS

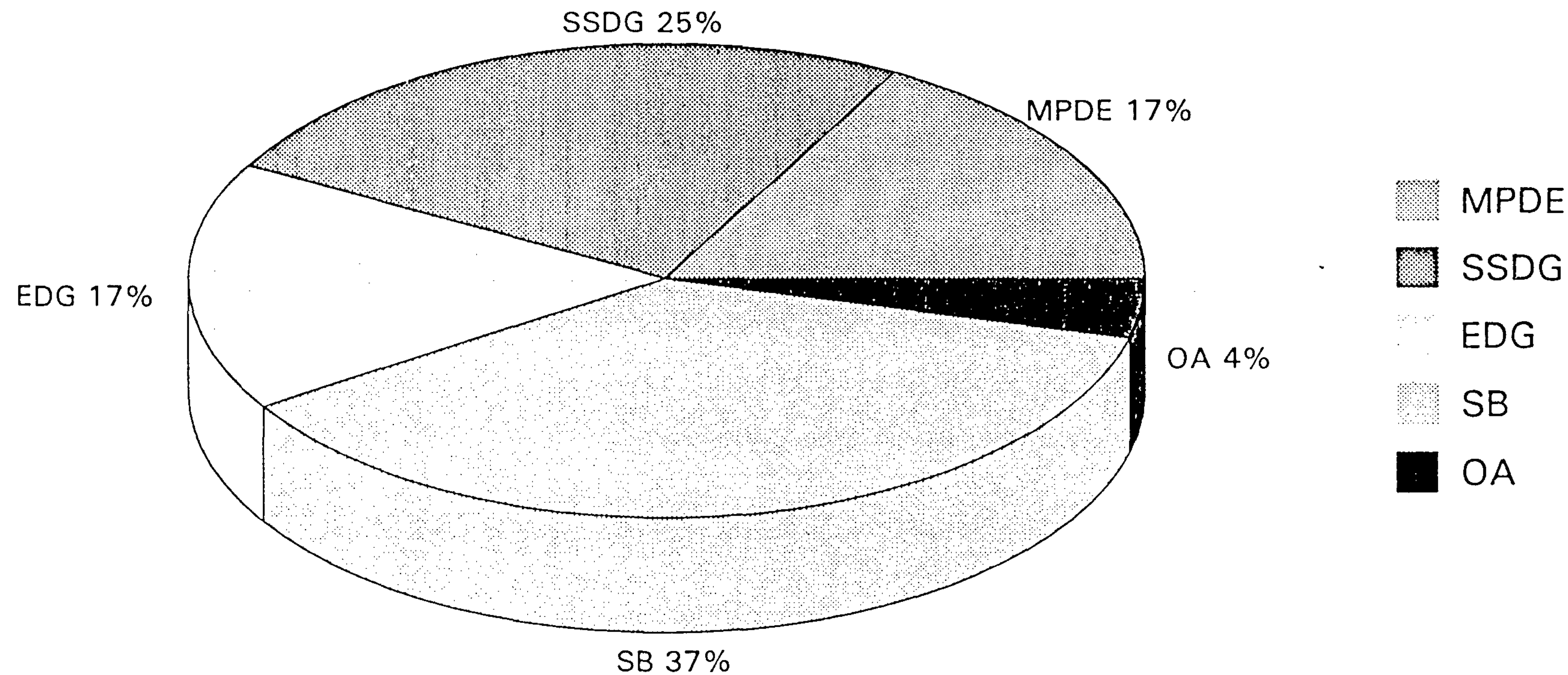
The proposed EPA and IMO rules are directed at new engines and existing in-use engines will not be subject to the proposed emission limits. However, as the Navy is interested in reducing $NO_x$ and PM emissions from its ship-board diesel engines, the proposed regulations are a suitable target guideline for the $NO_x$ and PM reduction program.

Appendix A data has been used in this report as the primary source of information on Navy diesels. It is estimated that the Navy has at least 2,750 diesel engines in service (Appendix A). The power rating for these engines varies from 250 kWh (333 hp) to 12,000 kW (16,000 hp). Applications of the diesel engine are diverse and Figure 2-1 is a summary of the Navy diesel engine applications. As shown in Figure 2-1, small boats (SB) account for 37 percent of the diesel engines, followed by Ship Service Diesel Generators (SSDG) at 25 percent, Emergency Diesel Generators (EDG) and Main Propulsion Diesel Engines (MPDE) both at 17 percent, and other applications (OA) at 4 percent. Other applications include service of the diesel engines as auxiliary power diesel generators, fire pumps, cranes and salvage equipment.

Based on Table 7-28 in Appendix A, the major engine manufacturers representing Navy diesel engines are: Detroit Diesel Corporation (DDC); COLTEC; ALCO; Caterpillar; EMD; Waukesha; Isotta Fraschini; and Cleveland Diesel. Of these, DDC diesel engines (especially Series 71) clearly stand out, at 63 percent, as the major constituency of engines. There may be over 1,700 DDC engines of which about 1,500 are estimated to be the Series 71 models. Figures 2-2(a) and 2-2(b) present a breakdown of the applications for each engine manufacturer and their populations.

### 2.2.1 Navy Diesel Engine Emission Data Summary

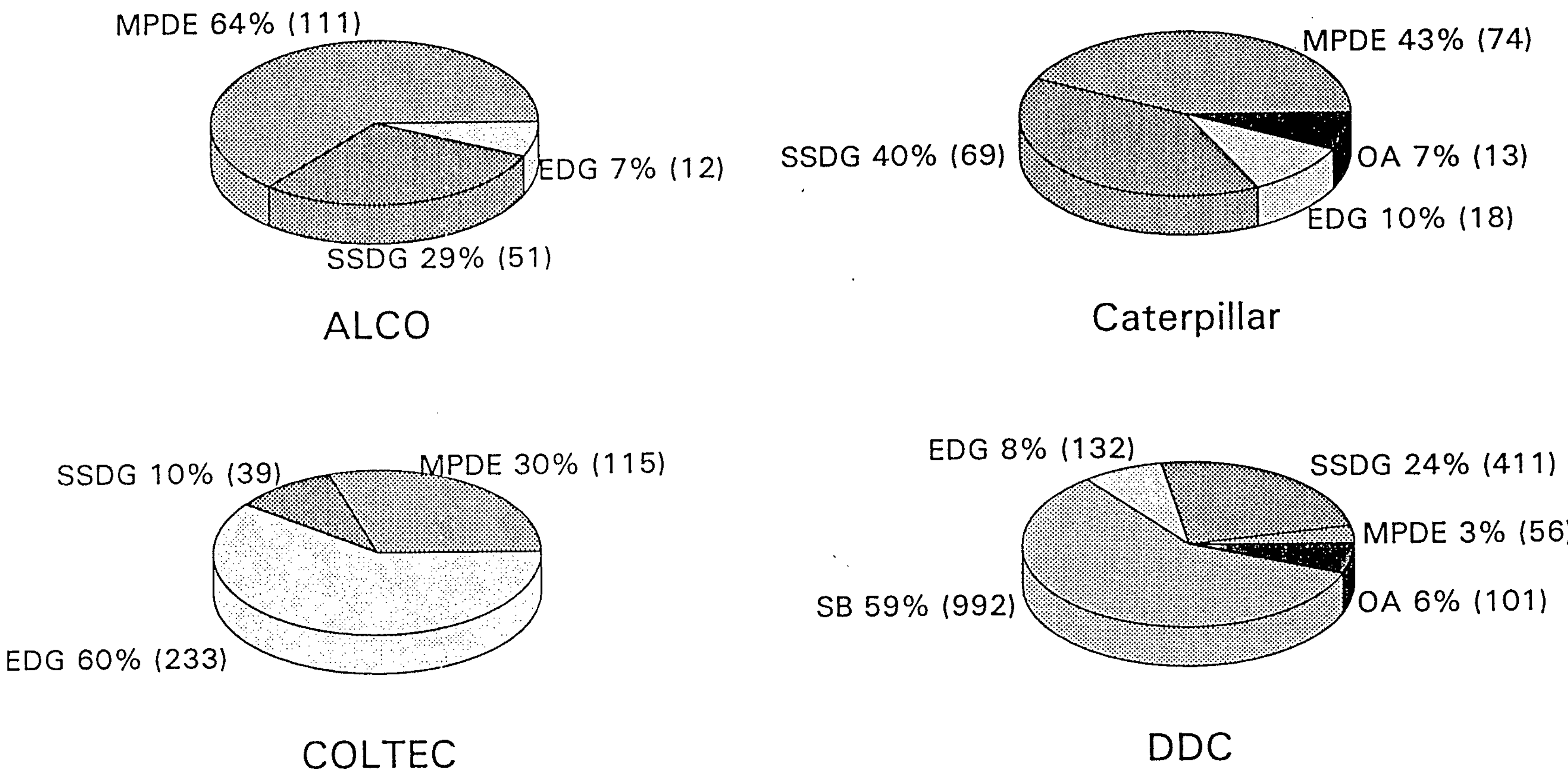
Table 7-8 in Appendix A presents $NO_x$ emission data for some of the engine makes and models in terms of parts per million $NO_x$ emitted. Since engine exhaust flowrate data was not available, the following approach was used to convert the ppm values to the normally used g/kWh when describing diesel engine emissions. Actual measured diesel engine exhaust emission data for 7 engine types was obtained from emission testing data in terms of ppm and g/kWh (Reference 3). A conversion factor was defined as the ratio of the $NO_x$ values in ppm to g/kWh and Table 2-2 presents the $NO_x$ emission test data and the conversion factor for each engine. The conversion factor for each engine make was applied to the $NO_x$ emission data presented in Appendix A to convert the




Total Population: 2709

OA - Other Applications
SB - Small Boats
MPDE - Main Propulsion Diesel Engine
SSDG - Ship Service Diesel Generator
EDG - Emergency Diesel Generator

**Figure 2-1. Diesel engine application summary**




MPDE - main propulsion diesel engine
SSDG - Ship service diesel engine
EDG - Emergency diesel generator
SB - Small boata
OA - Other applications

**Figure 2-2a. Navy diesel engine population summary (ALCO, Caterpillar, COLTEC, and DDC)**

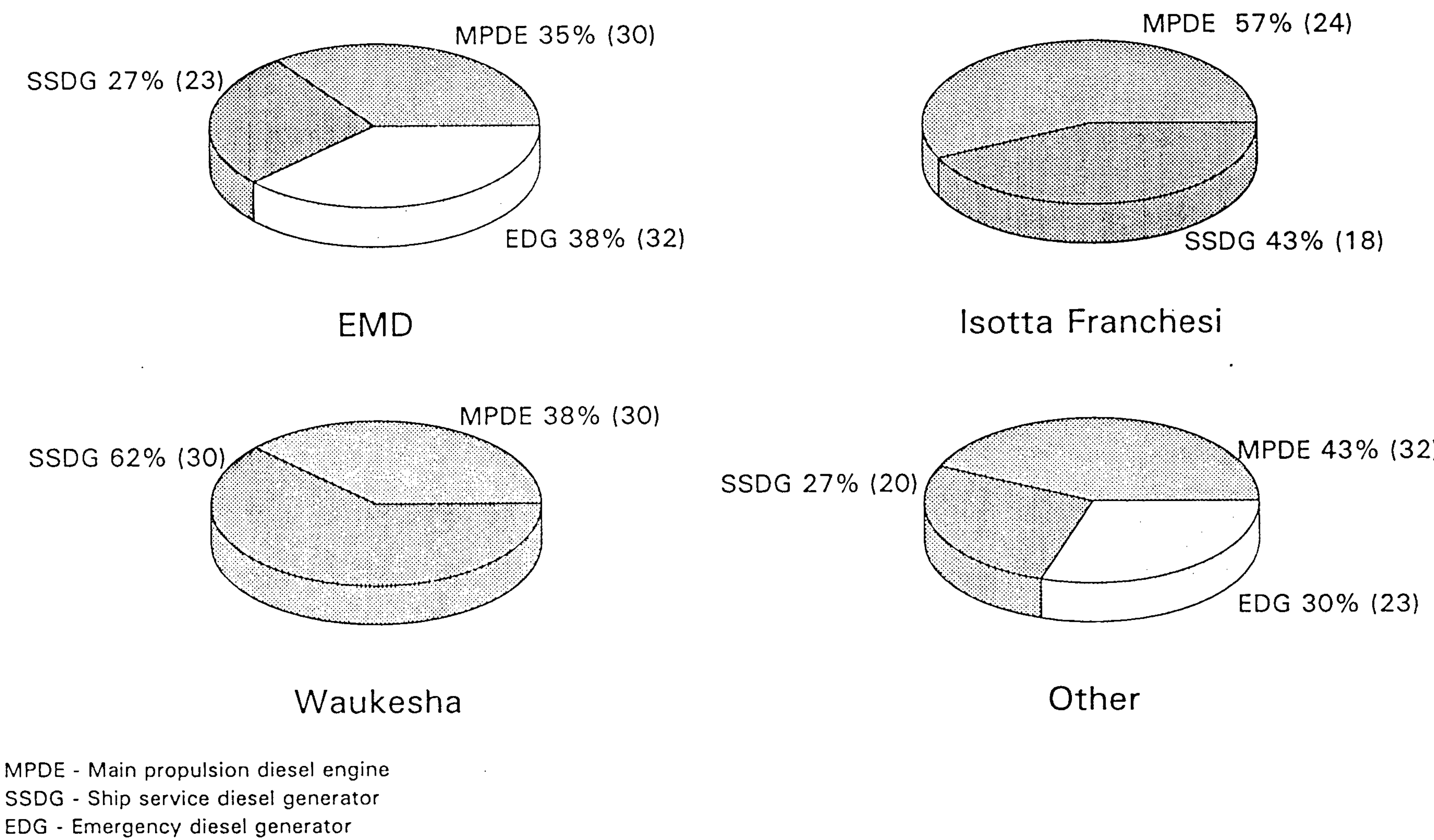



Figure 2-2b. Navy diesel engine population summary (EMD, IF, Waukesha and Other)

$NO_x$ concentration from ppm to g/kWh for similar makes of engines. This method is only an approximation, but after examining engine power and emission data for the engines in Table 2-2, the conversion factor can be used as a reasonable first-estimate of the brake-specific emissions.

In Table 2-3 a summary of the diesel engine emissions is presented for the various engine makes and models listed in Appendix A. Figure 2-3 is a graphical presentation of the same data and provides an overall view of the $NO_x$ emissions for each engine type and their standing with respect to the proposed EPA and IMO regulations described previously.

Prior to making an assessment on the impact a $NO_x$ reduction program will have on Navy diesel operations, it must be pointed out that the Appendix A data is not current (Reference 4); while it provides an approximate estimate, an accurate impact can only be assessed based on a more:

— current inventory of Navy diesel engines (including duty cycles), and

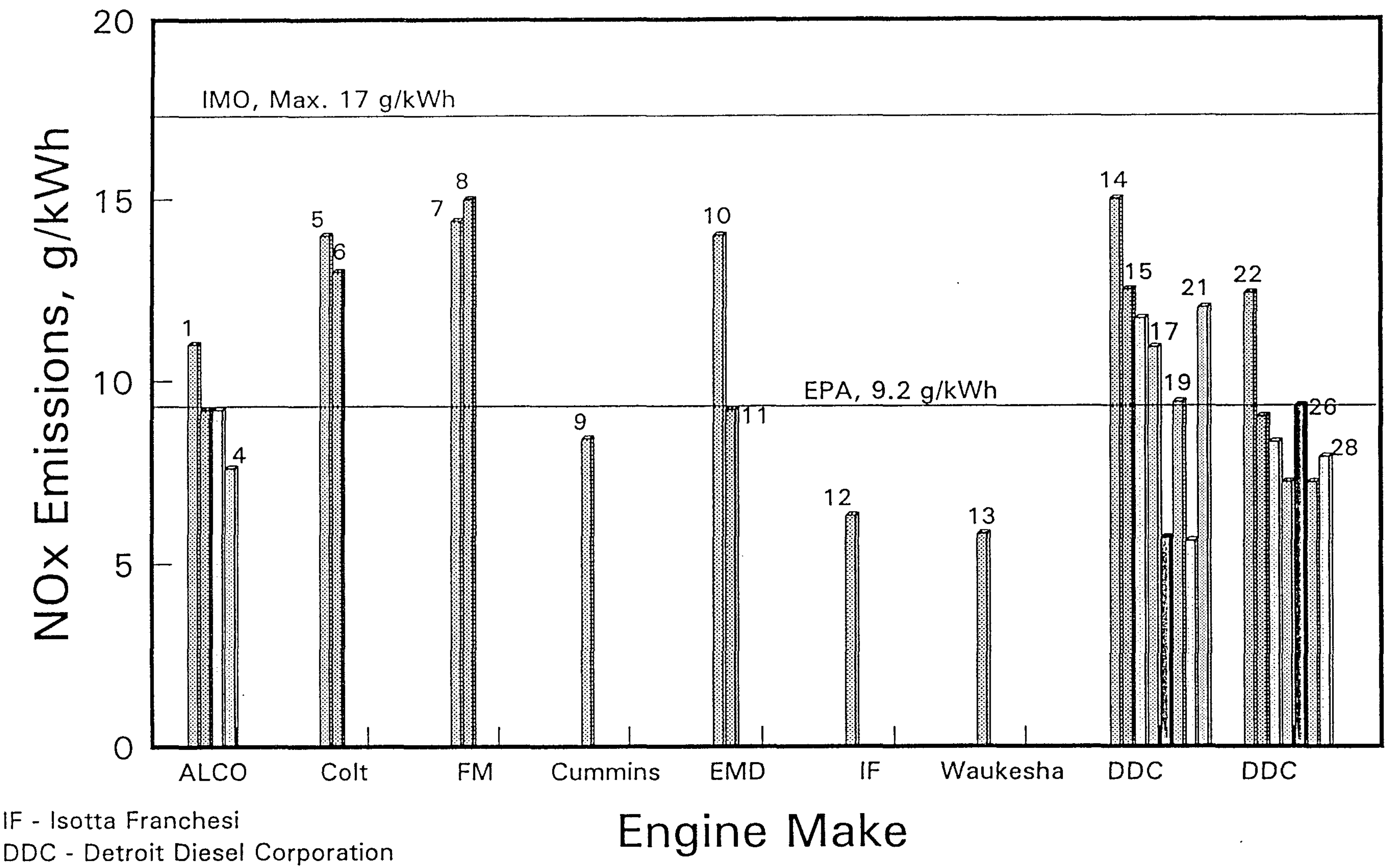
**Table 2-2. Diesel engine $NO_x$ emission test data (Reference 3)**

| Engine Type | $NO_x$ at 100% Load | | Conversion Factor |
|---|---|---|---|
| | ppm | g/kWh | |
| ALCO 16V-251-B<br>2,500 hp @ 1,000 rpm | 1,425 | 17 | 84 |
| ALCO V-18 251-C<br>3,650 hp @ 1,025 rpm | 1,055 | 12 | 88 |
| Fairbanks Morse 3800 TD-1/8<br>3,500 hp @ 900 rpm | 785 | 9.5 | 83 |
| DDC 4-71 1043-7035 | | | |
| 210 hp @ 1,800 rpm | 2,400 | 23 | 104 |
| 180 hp @ 1,500 rpm<br>(based on manufacturer's data) | 1,750 | 17 | 103 |
| Caterpillar 3516 D1TA V-Type<br>2,730 hp @ 1,910 rpm 75% load | 1,860 | 16 | 116 |
| Cummins VT<br>318 hp @ 2,300 rpm | 1,145 | 6.5 | 176 |

## Table 2-3. Navy diesel engines emissions summary

| | Engine Model | Population | NO$_x$ Range (Hp) | NO$_x$ Range (kW) | NO$_x$ Range (ppm) | Average NO$_x$ (g/kWh) | Regulatory Impact EPA 9.2 (g/kWh) |
|---|---|---|---|---|---|---|---|
| 1 | ALCO 12-251 C | 122 | 2,150 | 1,617 | 820-941 | 11.0 | O |
| 2 | ALCO 8-251 E | 51 | 1,075 | 808 | 596-1,647 | 9.2 | O |
| 3 | ALCO 8-251 F | NA | 1,930 | 1,451 | 610-857 | 9.2 | O |
| 4 | ALCO 16-251 F | NA | 3,240 | 2,436 | 573-637 | 7.6 | U |
| | **Total ALCO Population** | **174** | | | | | |
| 5 | COLT PC 4.2 | NA | 16,290 | 12,248 | 1,370 | 14.0 | O |
| 6 | COLT PC 2.5 | 28 | 8,500 | 6,391 | 1,279 | 13.0 | O |
| | **Total Colt Population** | **387** | | | | | |
| 7 | FAIRBANKS MORSE 38D-1/8 | 85 | 1,744 | 1,311 | 1,037 | 14.4 | O |
| 8 | FAIRBANKS MORSE 38F5-1/4 | 274 | 671 | 505 | 1,197 | 15.0 | O |
| | **Total Fairbanks Morse Population** | **359** | | | | | |
| 9 | CUMMINS 5BTA5.9M | NA | 220 | 165 | 830-855 | 8.4 | M |
| | **Total Cummins Population** | NA | | | | | |
| 10 | EMD 16-645E5 | 42 | 2,875 | 2,162 | 852-1,387 | 14.0 | O |
| 11 | EMD 16-710G7A | NA | 3,600 | 2,707 | 410-1,120 | 9.2 | O |
| | **Total EMD Population** | **85** | | | | | |
| 12 | ISOTTA FRASCHINI 1D36V6SSAM | 42 | 600 | 451 | 633 | 6.3 | U |
| | **Total Isotta Fraschini Population** | **42** | | | | | |
| 13 | WAUKESHA 1616DSIN | 69 | 588 | 442 | 349-808 | 5.8 | U |
| | WAUKESHA 1616DN | 11 | NA | NA | NA | — | — |
| | **Total Waukesha Population** | **80** | | | | | |
| | DETROIT DIESEL Corp (DDC) | | | | | | |
| 14 | 12V71 7122-3000 | NA | 480 | 361 | 1,492 | 15.0 | O |
| 15 | 12V71R 7122-7000 | NA | 425-480 | 320-361 | 916-1,492 | 12.5 | O |
| 16 | 12V71 7122-7001 | NA | 395 | 297 | 1,165 | 11.7 | O |
| 17 | 12V71 7122-7300 | NA | 594 | 447 | 1,085 | 10.9 | O |
| 18 | 12V71 7123-3200 | NA | 413 | 311 | 557 | 5.7 | U |
| 19 | 12V71 7123-7000 | NA | 360 | 271 | 935 | 9.4 | O |
| 20 | 12V71 7123-7200 | NA | 413 | 311 | 557 | 5.6 | U |
| 21 | 12V71H 7123-7300 | NA | 510 | 383 | 1,196 | 12.0 | O |
| 22 | 12V71T 7123-7305 | NA | 575 | 432 | 1,238 | 12.4 | O |
| 23 | 12V71LC 7124-3202 | NA | 436 | 328 | 896 | 9.0 | M |
| 24 | 12V71RC 7124-7202 | NA | 354-436 | 266-328 | 896-972 | 8.3 | U |
| 25 | 12V71N 7162-7000 | NA | 504-581 | 379-437 | 495-930 | 7.2 | U |
| 26 | 12V71RC 7163-7000 | NA | 502-581 | 377-437 | 806-1,062 | 9.3 | O |
| | **Total Series 71 Population** | **1,481** | | | | | |
| 27 | 16V149 9163-1305 | NA | 1,542 | 1,159 | 718 | 7.2 | U |
| 28 | 16V149TI | NA | 1,342 | 1,009 | 632-948 | 7.0 | U |
| | **Total DDC Population** | **1,692** | | | | | |
| | **Total Cleveland Diesel Population** | **29** | NA | NA | NA | — | |
| | **Total Caterpillar Population** | **174** | NA | NA | NA | — | |
| | **Total Other Populations** | **46** | NA | NA | NA | — | |
| | **Total Fleet Engines Population** | 2,709 | | | | | |

NA = Not available; O = Over; U = Under; M = Marginal.




IF - Isotta Franchesi
DDC - Detroit Diesel Corporation
FM - Fairbanks Morse
1-28: For details of engine model see Table 4

**Figure 2-3. Navy diesel engines $NO_x$ emissions summary**

— exhaust emission data (including $NO_x$ and PM) for each family of engines in the Navy's inventory.

### 2.2.2 Navy Diesels

Having set the guideline for maximum permissible $NO_x$ emissions as 9.2 g/kWh, the reduction requirements for each family of engines in the inventory is as follows.

**ALCO Engines:** Three out of the four models considered will not meet the proposed guideline of 9.2 g/kWh. These three models constitute 99 percent of the ALCO population. Model 12-251C makes up over 70 percent of the ALCO population and emits the most $NO_x$ (under 100 percent load conditions) at 11.0 g/kWh. A 25 percent reduction in $NO_x$ for the ALCO engines should allow them to meet the 9.2 g/kWh guideline. Majority of the ALCO engines (64 percent) are used as main propulsion diesel engines (MPDEs).

**Colt PC Engines:** The exact number of Colt engines is not known from Appendix A data, but is expected to be between 2 and 3 percent of the total population. Most of the Colt PC engines are used as MPDEs. Both Colt models (Figure 4 and Table 4) exceed the proposed limit of 9.2 g/kWh and will require up to a 50 percent reduction in $NO_x$ emissions.

**Fairbanks Morse (FM) Engines:** These engines constitute about 10 percent of the total population and are mainly used as Emergency Diesel Generators (EDGs) and MPDEs of which 10 percent make up Ship Service Diesel Generators (SSDGs). A 50 percent reduction in $NO_x$ emissions may be required from the FM engines to operate below the proposed guideline of 9.2 g/kWh.

**Cummins Engines:** It is expected that the Cummins engine population is small (less than one percent). The $NO_x$ emissions from the Cummins engines are likely not of concern. The applications of the Cummins engine are not clear from Appendix A data.

**EMD Engines:** These engines make up about 3 percent of the total population. They are mainly used as MPDEs, EDGs and SSDGs. The EMD Model 16-645E5 may need up to 40 percent $NO_x$ reduction to operate below the 9.2 g/kWh guideline. The model 16-710G7A may require at most a 10 percent reduction in $NO_x$ emissions.

**Isotta Fraschini (IF) Engines:** These engines make up about 1.5 percent of the total population. They are mainly used as MPDEs and SSDGs and may not require any $NO_x$ control measures as they emit below the proposed 9.2 g/kWh guideline.

**Waukesha Engines:** These engines constitute about 3 percent of the total population. They are mainly used as MPDEs and SSDGs. These engines may also not require any $NO_x$ control measures.

**Caterpillar Engines:** These engines make up 6.5 percent of the total population. Emission data for these engines was not available from Appendix A data. However, if the Caterpillar engines emission data are similar to that of the 3516 D1TA shown in Table 2-3 (16 g/kWh) (which is an engine in service with the USCG) then a 50 percent reduction in $NO_x$ emissions will be required.

**DDC Engines:** The DDC families of engines constitute about 63 percent of the total engine population. Series 71 models make up about 88 percent of the DDC engines. A significant percentage (59 percent) of the DDC engines is used in small boats (SB) as the main propulsion engine. The $NO_x$ emissions for these engines range from 5.5 g/kWh to 15 g/kWh. About nine models of the Series 71 engines will require a reduction in $NO_x$ emissions to meet the proposed limit of 9.2 g/kWh. $NO_x$ reductions of up to 50 percent will be required depending on the engine model.

Table 2-4 presents a summary of $NO_x$ reductions that will be required from each engine under the guidance limit of a maximum of 9.2 g/kWh $NO_x$. The DDC Series 71 engines are definitely the engines to focus $NO_x$ reduction strategies on. However, prior to recommending and implementing

Table 2-4. Estimated $NO_x$ reduction requirements

| Engine Make | Percentage of Total Population | Percentage of Engines That Will Require $NO_x$ Reduction | Estimated $NO_x$ Reduction Required (%) |
|---|---|---|---|
| ALCO | 6.5 | 99 | 0 to 25 |
| Colt PC | 2 to 3 | 100 | 50 |
| Fairbanks Morse | 10 | 100 | 50 |
| Cummins | NA | 0 | 0 |
| EMD | 3 | 100 | 10 to 40 |
| Isotta Franchosi | 1.5 | 0 | 0 |
| Waukesha | 3 | 0 | 0 |
| Caterpillar | 6.5 | Probably 100 (emission data required) | 50 |
| Detroit Diesel Corp. | 63 | >75 (detailed inventory recommended) | 10 to 50 |

$NO_x$ control strategies across the board, it is recommended that the following issues be thoroughly addressed.

- Current inventory of Navy diesel engines including operations data such as duty cycles
- Exhaust emissions data which may require emissions testing for each family of engines

# SECTION 3

# $NO_x$ AND PM CONTROL TECHNOLOGIES

A detailed review of available $NO_x$ and PM emission control methods for diesel engines was performed, and their potential application to the Navy diesels are discussed in this section. A description of the test engine and the test set-up are also presented in this section.

## 3.1 $NO_x$ CONTROL TECHNOLOGIES

The $NO_x$ control methods discussed here are applicable to diesel engines in general, regardless of the engine's application. The $NO_x$ control measures that were evaluated are:

- Catalytic Aftertreatment
- Injection Timing Retard
- Exhaust Gas Recirculation
- Ceramic Coating
- Alternative Fuels
- Engine Electronic Controls
- Fuel Injection Rate Tailoring
- Variable Geometry Turbocharging
- Atomic Oxygen Aftertreatment
- Ceramic Coating of Engines

### 3.1.1 Catalytic Aftertreatment Technologies

Oxidation catalysts which oxidize PM, CO and HC, and lean $NO_x$ catalysts which reduce $NO_x$ are emerging as possible aftertreatment control technologies. Lean $NO_x$ catalysts use zeolite catalysts and a reducing agent to reduce $NO_x$ to $N_2$. Selective catalytic reduction (SCR) is widely used to reduce $NO_x$ in process and utility industries. SCR requires injection of ammonia (or a similar reducing agent such as cyanuric acid) into the exhaust, upstream of a catalyst, with the exhaust gas temperature between 570 and 800°F. The catalyst used (noble metals, non-noble metals, molecular sieves, zeolites, ceramics, etc.) determine the temperature of the exhaust gas stream for optimal $NO_x$ reduction. SCR systems are successful in removing $NO_x$ in the 90 percent range. Typically the amount of ammonia (or other reducing agents) depends on the $NO_x$ content and a 1:1 ammonia to $NO_x$ ratio is maintained.

This technology is well proven and is used in stationary diesel engines and a few marine propulsion engines mainly in Europe. Haldor Topsoe (DENOX SCR system) and Siemens are two major companies that have demonstrated/installed proprietary systems on low-speed high hp diesel engines.

Issues and concerns in the application to marine diesels are typical to SCR systems, and are:

- Catalyst fouling due to high sulfur content in the fuel
- Particulate deposition on the catalysts
- Large size of the system
- Ammonia slip
- Operational costs

Diesel Engine $NO_x$ (DENOx) catalysts have recently received some attention, and have the potential of reducing $NO_x$ emissions from fuel lean environments. In principle a copper-zeolite catalyst is used to trap large molecule hydrocarbons which then catalytically reduce the $NO_x$. The effectiveness of these catalysts is sensitive to temperature (they operate best between 175° and 350°F) and the type of hydrocarbons trapped. Some developers are proposing the addition of diesel fuel to the exhaust upstream of the catalyst to enhance reduction. This technology is still in a developmental stage and not mature enough for near term applications.

### 3.1.2 Injection Timing Retard

The time between the start of fuel injection and the first appearance of flame or pressure rise is termed as the delay period in compression engines. The delay period is optimized for maximized combustion and thus power. Changing the delay time (by either shortening or lengthening) results in lower peak temperatures and pressures and therefore less $NO_x$ is formed. If the beginning of fuel injection is retarded, the maximum pressure decreases, the main combustion part is delayed from the top dead center (TDC) resulting in a decrease in the gas temperature since combustion now occurs during the expansion stroke, and the duration of the peak temperature decreases. NO formation is essentially frozen, thus restricting $NO_x$ formation.

Injection timing retard is easy to implement. No modifications to the engine or new hardware are required. As a general rule for every 1° delay in the timing a 1 percent increase in the BSFC is expected. Table 3-1 presents data on $NO_x$ reduction and fuel consumption increase for a few engine types based on actual tests (Reference 5). Discussions with Detroit Diesel Corporation engineers have indicated that a 4° retard can produce up to 25 percent reduction in $NO_x$ in a 4-71 type engine (Reference 6).

**Table 3-1. Effect of injection timing retard**

| Engine | Degrees Retarded | $NO_x$ Reduction (%) | Increase in BSFC (%) |
|---|---|---|---|
| Fairbanks Morse 38TDD-8-1/8 | 5.5 | 30 | 1 to 2 |
| Caterpillar 6V396 TC/TB33 | 8 | 53 | 6 |
| EMD 2-567 | 4 | 25 to 32 | — |
| SEMT PA-6 | 8 | 27 | 5 |

In addition to increase in the BSFC injection timing retard is also restricted by engine startup performance; excessive retard will result in failure of the fuel to auto-ignite. Additionally, injection timing changes cause an increase in the PM , HC and CO emissions requiring possible control of these emissions.

### 3.1.3 Exhaust Gas Recirculation

The principle behind exhaust gas recirculation (EGR) is such that a portion of the exhaust gas is recirculated back or retained in the cylinder; the $O_2$ concentration is lowered which in turn results in lower peak temperatures and $NO_x$ formation. EGR methods are classified into internal and external.

**Internal EGR:** In internal EGR the exhaust gas is not completely removed from the cylinder during the exhaust/scavenging cycle. The incoming fresh charge of air is diluted with exhaust from the previous cycle. Internal EGR can be accomplished in a number of ways depending on the engine type. Valve overlap or variable valve timing; reducing the airbox/air manifold pressure thus decreasing scavenging efficiency; and throttling the exhaust to increase exhaust back pressure are some of the possible methods of implementing internal EGR.

**External EGR**: External EGR is also relatively simple in concept. A fraction of the exhaust gases are returned to the combustion chamber reducing the combustion efficiency slightly, hence the combustion temperature, thereby, resulting in lower $NO_x$ levels. Studies have shown that EGR is not applicable under all load conditions, and is most effective under higher engine loads in general. Optimum EGR varies with the load. As the degree of EGR increases to large values, at high loads, soot, CO and to a lesser extent HC also increase. EGR studies have shown that 15 to 20 percent EGR has little or no effect on these emissions while still reducing $NO_x$. Table 3-2 presents limited data on $NO_x$ emission reductions with EGR for actual marine diesels (Reference 6).

Table 3-2. $NO_x$ reduction with EGR

| Engine Type | EGR (%) | $NO_x$ Reduction (%) |
|---|---|---|
| EMD 2-567 (Blower Scavenged 2-5) | 10 to 30 | 25 to 64 |
| Delaval R5V-12 | 15 | 31 |
| SEMT PA-6 | 14 to 15 | 45 to 55 |

Increases in PM, HC and CO follow EGR. The challenge in applying EGR to diesel engines is the PM in the exhaust gas stream; if the recirculated gas is not clear from PM, engine components could be severely damaged. Depending on the fuel sulfur content, sulfuric acid in the exhaust stream could also damage engine components. However, if a PM and acid free exhaust gas is available, EGR is a viable $NO_x$ reduction strategy.

### 3.1.4 In-Cylinder Ceramic Coating

This is a proprietary technology of Engelhard Corporation and has been demonstrated to show up to a 40 percent reduction in $NO_x$ in some cases (Reference 7). Engelhard's GPX Diesel 4M is a ceramic surface treatment applied to combustion area components such as the piston head, the valve faces and the piston crown. In principle the ceramic coating reduces heat rejection through the cylinder, thereby through increased temperatures promotes combustion. Increased temperatures would lead to higher $NO_x$ levels, however, Engelhard claims that the injection timing can be sufficiently retarded not only to offset the $NO_x$ increase but actually decrease it. The GPX system has been tested on diesel engines such as the DDC 6V92, CAT 3306 and EMD 16V645E3A. A picture of the coating process is shown in Figure 3-1. A summary of the emissions and fuel consumption data from a test study using the coating is presented in Figure 3-2.

This technology may be considered developmental with respect to marine diesel engines. However, the Engelhard system appears to be easy to implement, cost effective and requires no

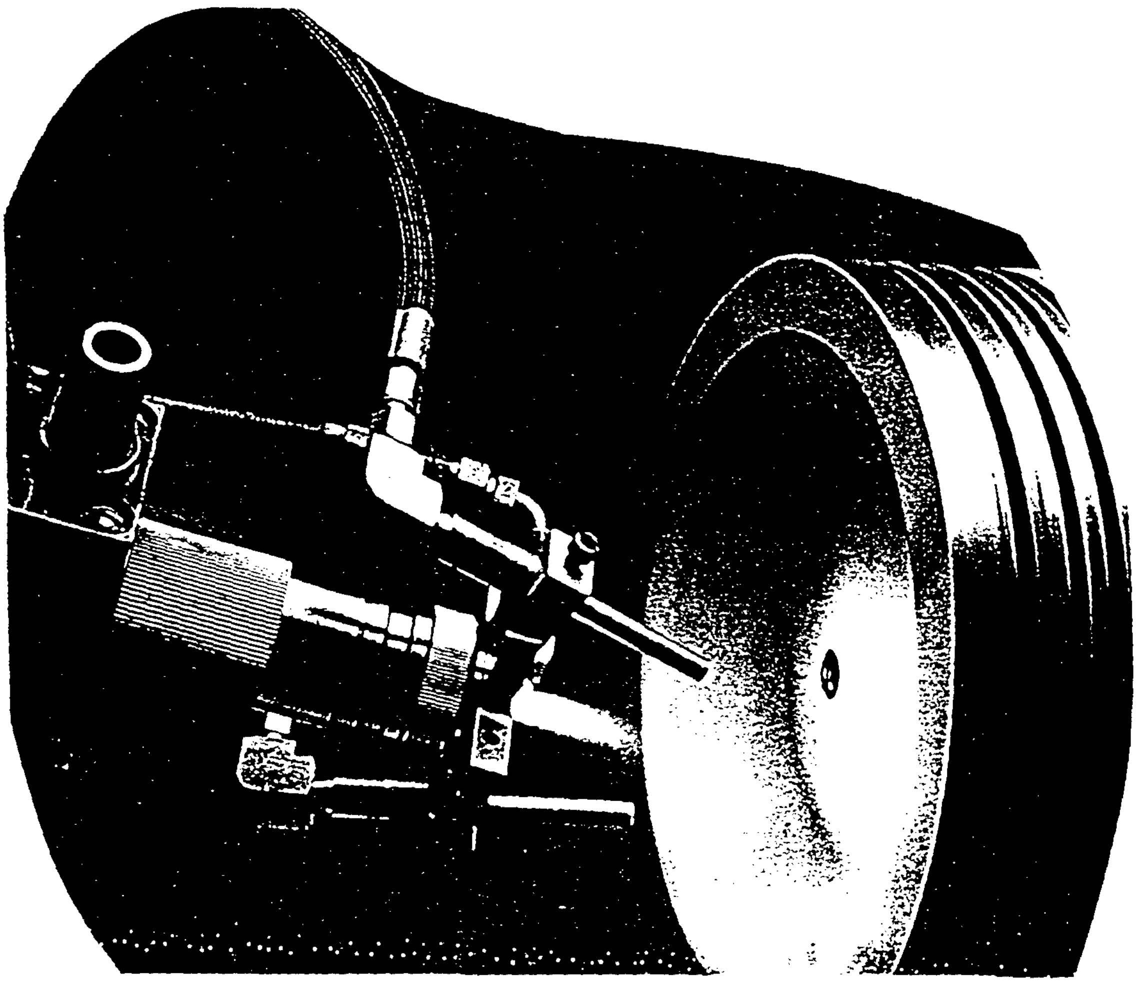
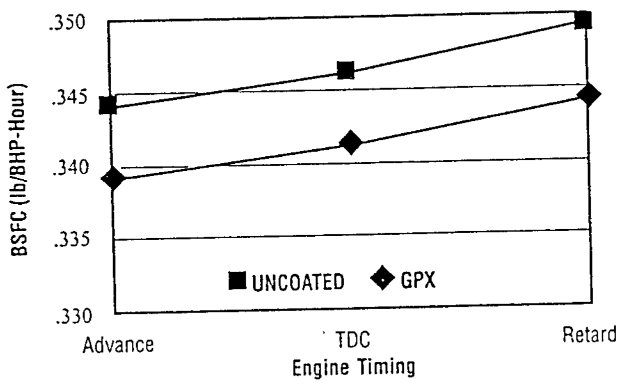


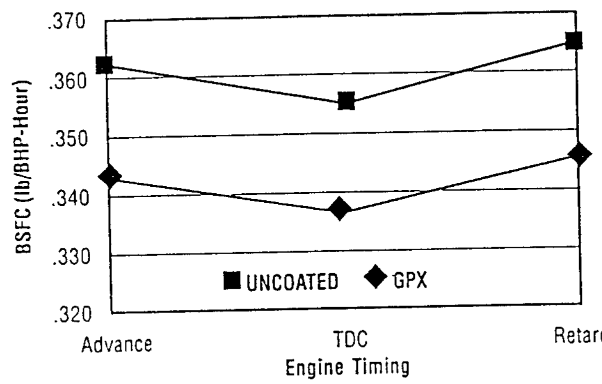
Figure 3-1. Englehard in-cylinder ceramic coating process (Reference 7)

Fuel consumption tests run on EMD 16V645E3A engine by independent testing agency.

Fuel Consumption with GPX Diesel-4M
Engine at full throttle (notch 8)



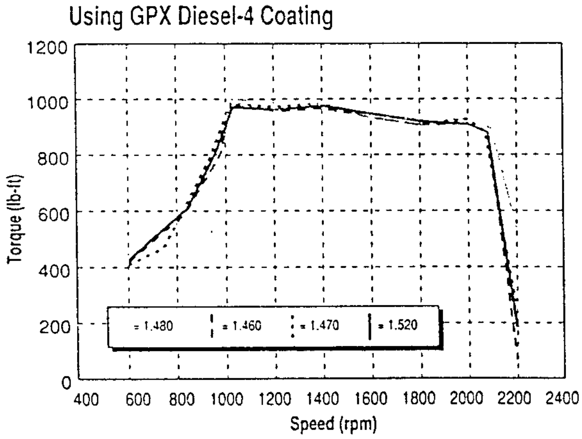

Fuel Consumption with GPX Diesel-4M
Engine at part throttle (notch 5)




| | $NO_x$ emissions at full throttle (notch 8) (G/BHP-hr) | | | $NO_x$ emissions at part throttle (notch 5) (G/BHP-hr) | | |
|---|---|---|---|---|---|---|
| | Engine Timing | | | Engine Timing | | |
| | Advance | TDC | Retard | Advance | TDC | Retard |
| GPX | 19.1 | 12.8 | 11.1 | 22.7 | 13.6 | 12.0 |
| UNCOATED | 18.1 | 11.4 | 10.7 | 23.9 | 14.1 | 12.2 |

## Engine Power Curve

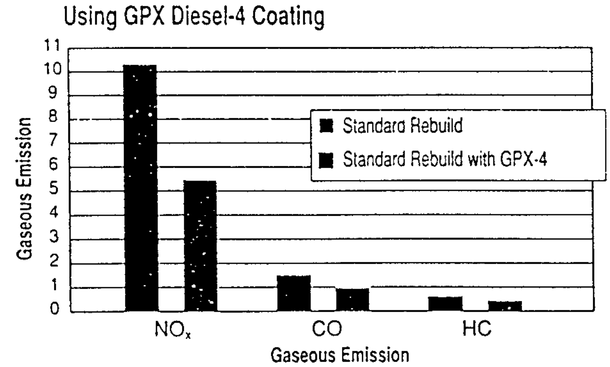
Using GPX Diesel-4 Coating




Transient Torque-Map Data for Ceramitized Rebuild at Different Injection Timing Setpoints

## Emission Reductions

Using GPX Diesel-4 Coating




Gaseous Emission Based on EPA's FTP Certification Test

**Figure 3-2. Emissions reduction and engine performance results with GPX Diesel 4 coating (Reference 7)**

maintenance, and warrants further investigation as a potential $NO_x$ reduction technology for marine diesels.

### 3.1.5 Alternative Fuels

Conversion of diesel engines to natural gas (CNG or LNG), methanol, ethanol, or propane fueled engines results in significantly lower $NO_x$ (nominally 3.4 g/kWh) and substantially lower PM emissions. Techniques for modification of diesel engines to operate on low-cetane alternative fuels include conversion to spark-ignition, pilot-ignition (with diesel), and direct-injection plus other means to enable "dieseling" on alternative fuels. Various natural gas and methanol bus engines have received EPA certification.

Changing fuels has profound implications on the fuel system, refueling equipment, fuel supply and storage infrastructure, and safety issues to name a few. Conversion of diesels to alternative fuels decreases energy-based fuel efficiency and may affect engine durability and reliability. Overall, conversion of Navy diesel engines to alternative fuel engines is not a viable option currently.

### 3.1.6 Engine Electronic Controls

Microprocessor control of diesel engine operation can manage injection timing, injection duration, valve control, and other variables to provide optimum performance at each operating condition thereby simultaneously minimizing $NO_x$, PM and BSFC. The inventory of Navy diesels in Appendix A indicates that most of the navy diesels are not electronically controlled. Electronic controls are generally more beneficial when transient performance is important (e.g., trucks, buses, etc.). Electronic controls alone do not ensure low $NO_x$ and may even compromise engine reliability and maintainability in marine applications. Furthermore, changing manually controlled engines to electronic controlled engines can be very expensive.

### 3.1.7 Fuel Injection Tailoring

Fuel injection rates can affect both $NO_x$ and PM emissions. Increased fuel injection pressure combined with retarded timing can provide good $NO_x$, PM and BSFC optimization. Most all diesel engine manufacturers are investigating this technology. This has lead to technologies such as hydraulically actuated electronically controlled unit injectors (HEUI) and common-rail systems. Injectors with pressures up to 35,000 psi have been developed.

To implement this technology a whole new high pressure injection system will be needed. Further, these systems involve electronic controls and are best suited for new engines than retrofit to engines without electronic controls. Finally, the high-pressure injection pump systems are large in size and expensive.

### 3.1.8 Intake Charge Cooling, Aftercooling

Lowering the intake charge temperature decreases the combustion temperature and in turn decreases $NO_x$. In the case of turbocharged diesels, this is accomplished by adding an aftercooler.

Heavy-duty truck and engine manufacturers are replacing waterjacket aftercooling with air-to-air aftercoolers to decrease $NO_x$ up to 15 percent. In one case, Chevron crew boats with EMD diesels reduced $NO_x$ by 17 percent using seawater aftercooling. This technology is not practical for diesel engines without turbochargers. The size of the air-to-air heat exchangers and corrosivity of seawater as a coolant may prove to be limiting factors in some applications.

### 3.1.9 Tailored or Variable Geometry Turbocharging

Turbocharging increases power more than $NO_x$, so a decrease in brake-specific $NO_x$ may be seen. Variable geometry turbochargers are being developed primarily for diesel truck engines. Laboratory tests have demonstrated their ability to improve the $NO_x$-PM-BSFC trade-off. Variable geometry turbochargers provide leaner air/fuel mixtures which in turn reduce PM and $NO_x$. Further $NO_x$ reduction by charge cooling through expansion following a turbocharger and aftercooler is also possible. $NO_x$ reduction is not substantial if PM and BSFC increases are restricted. Variable geometry turbochargers are developmental and currently expensive. Expansion cooling for $NO_x$ reduction involves expensive equipment and pumping losses. Further, retrofit of turbochargers to naturally aspirated diesels is complicated.

### 3.1.10 Atomic Oxygen Aftertreatment

A proprietary atomic oxygen generator is employed to pump oxygen atoms into the exhaust stream in the aftertreatment device. The $O_2$ reacts with the $NO_x$ to form $N_2$ and $O_2$. Up to a 30 percent reduction in $NO_x$ has been demonstrated in laboratory test cells. This technology is at a very preliminary stage and has not yet been applied to diesel engines.

### 3.1.11 Water Injection

This technology has been well tested as a method to reduce thermal $NO_x$ produced during combustion. Water in the combustion gases reduces the flame temperature which results in a decrease in the $NO_x$ production. A small amount of $NO_x$ reduction also occurs through the scavenging of atomic oxygen by water molecules, however, this mechanism is a minor source of $NO_x$ reduction. Some studies have shown that water injection has the added benefit of improving the specific fuel consumption.

In general, water injection may be classified into direct injection methods (fuel side) and fumigation (air side) methods. In direct injection water is added to the combustion chamber in the form of a fuel-water emulsion through the fuel injector, by stratification where the fuel and water are injected alternatively through the fuel injector, and/or by using a separate water-injection system. Fumigation involves the addition of water to the intake air. Both these methods are known to reduce $NO_x$ and PM emissions and both have their advantages and disadvantages. Direct injection requires greater control and is more complicated in general. Fumigation while easier to implement can contaminate engine parts with water leading to corrosion. An important concern to the users of this technology is the quality of the water injected - there is very limited information available concerning the effect of long term water injection on engine durability.

Overall, water injection is a promising retrofit technology for $NO_x$ and PM emissions reduction from Navy diesels. Figures 3-3 and 3-4 present a summary of $NO_x$ reduction data from various studies (Reference 8,9). Depending on the engine type, operating cycles, load and the method of water injection up to a 60 percent reduction in $NO_x$ can be achieved. Some of the techniques of direct injection and fumigation that can be realistically applied to Navy diesels are discussed next.

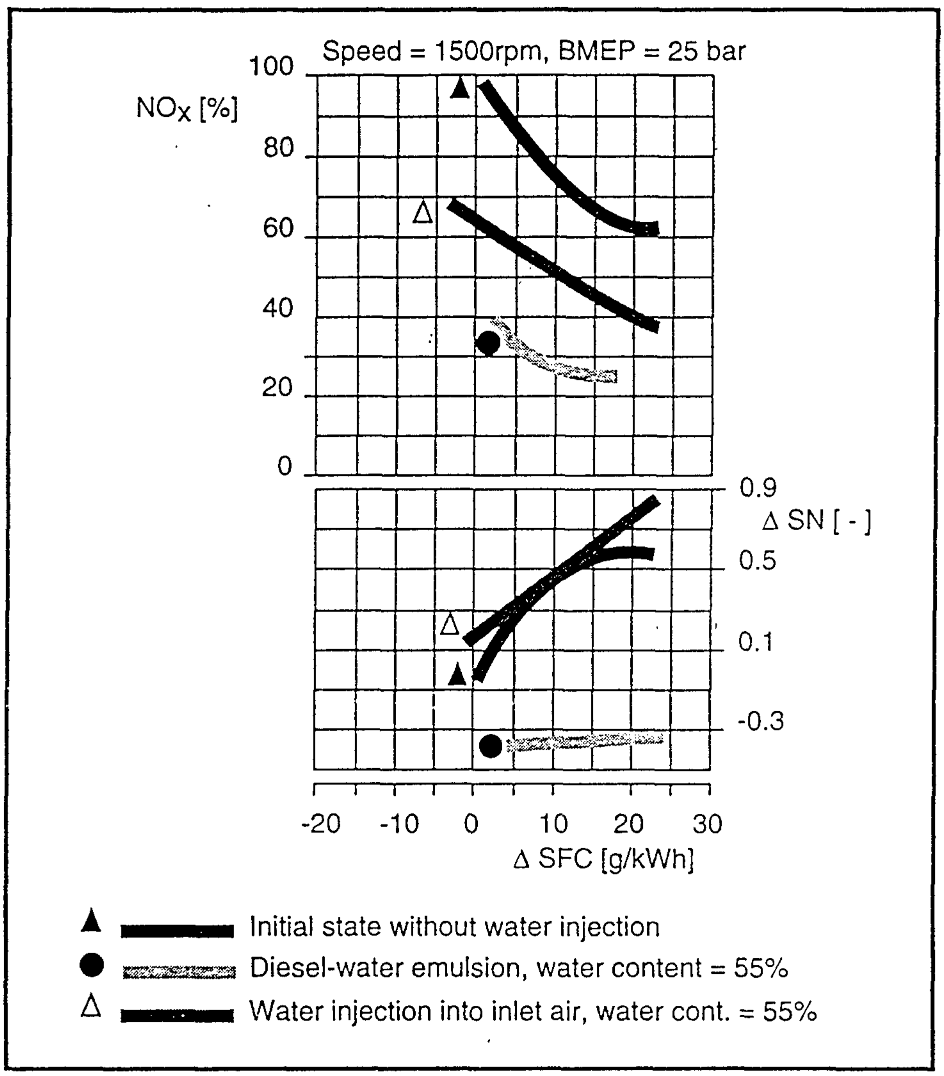



**Figure 3-3. Effect of water injection on $NO_x$ emissions (Reference 8)**

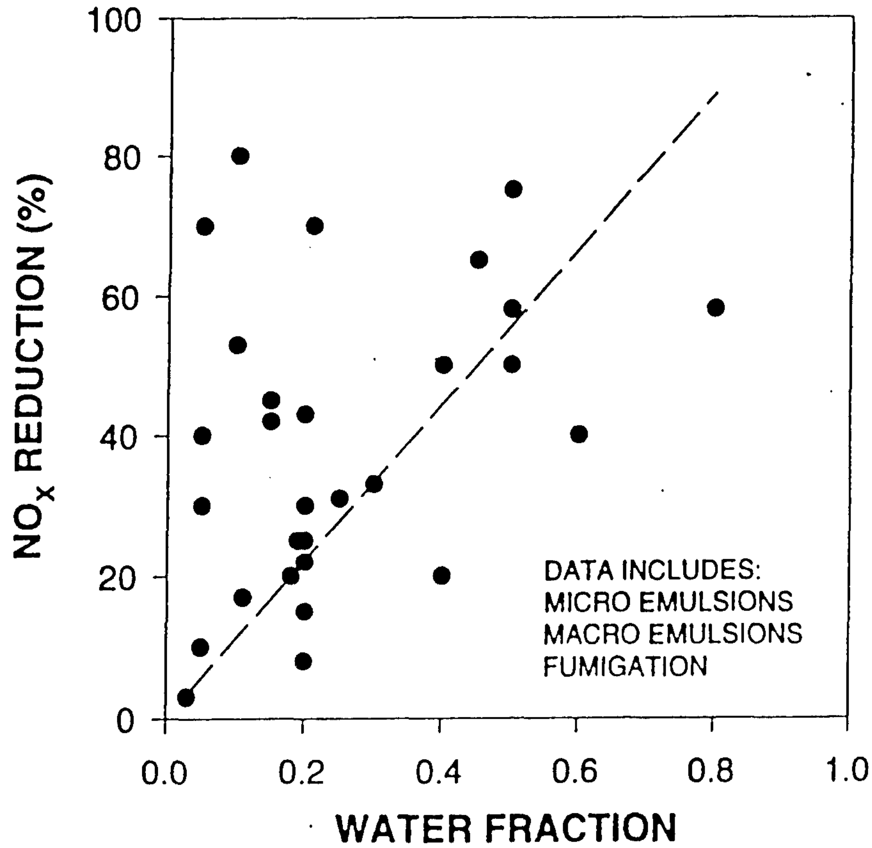



**Figure 3-4. Effect of water injection on $NO_x$ reduction: summary data (Reference 9)**

**Direct Injection:** A common way of injecting water into the combustion chamber is by using a water-in-fuel emulsion. Preemulsified fuels or in situ emulsifiers are used. While the use of preemulsified fuels is attractive from the stand point of minimum modifications and hardware requirements, issues related to increased fuel storage, emulsion stability, and effect of stabilizers on combustion are of concern. In situ emulsification, that is, emulsification of water into the diesel fuel just before injection can be achieved mechanically and eliminates some of the problems associated with preemulsified fuels. One distinct advantage of in situ emulsification is that the fuel to water ratio can be controlled and altered easily during operation. The fuel to water ratio is an important parameter governing $NO_x$ reduction and engine operation in general. Maximum benefits of water injection can be realized through control over the fuel to water ratio for different speeds and loads

(Reference 9). Demonstration of water-injection on highly transient applications (e.g., trucks, buses, etc.) has shown that this technology is best suited for steady-state applications (Reference 9).

**Fumigation:** In this method water is sprayed into the intake air which results in lower combustion temperatures and therefore lower $NO_x$ emissions. Combustion air humidification has been successfully applied to control $NO_x$ emissions (Reference 9). A recent study under SERDP has shown that water when carefully added into the bellmouth or the combustor of a marine gas turbine reduces $NO_x$ emissions and increases the output power (Reference 10). In another study conducted by Loscutoff and Hooper, two methods of air humidification were tested on a CAT 3116 diesel engine (Reference 11). They showed that with water injection rates at 60 percent of the fuel rate (W/F = 0.6), a 50 percent reduction in $NO_x$ could be achieved under steady state conditions. In one method, water was introduced into the inlet of the air-intake manifold at the air cleaner before the turbocharger. A schematic of this system is shown in Figure 3-5. The second method sprayed water into individual ports. A schematic of the port injection system is shown in Figure 3-6. Both these systems were implemented without any major modifications to the engine. While manifold injection is comparably easier to implement, exposure of the turbo charger to water leading to thermal stresses, deposition of minerals on the compressor blades and maldistribution of water between cylinders are of potential concern. In port injection, the water is sprayed directly into the individual intake ports (see Figure 3-6). The maldistribution and turbocharge wear problems are eliminated, however, much more sophisticated hardware and electronic controls are required. Other problems with port-injection may arise from water in the cylinders during shut down causing the cylinders to rust, and in some older engines water may tend to pass into the lubricating oil with blowby past the rings resulting in increased wear.

In summary, water injection is a well proven $NO_x$ reduction technology in combustion systems and is viable for application to Navy diesel engines.

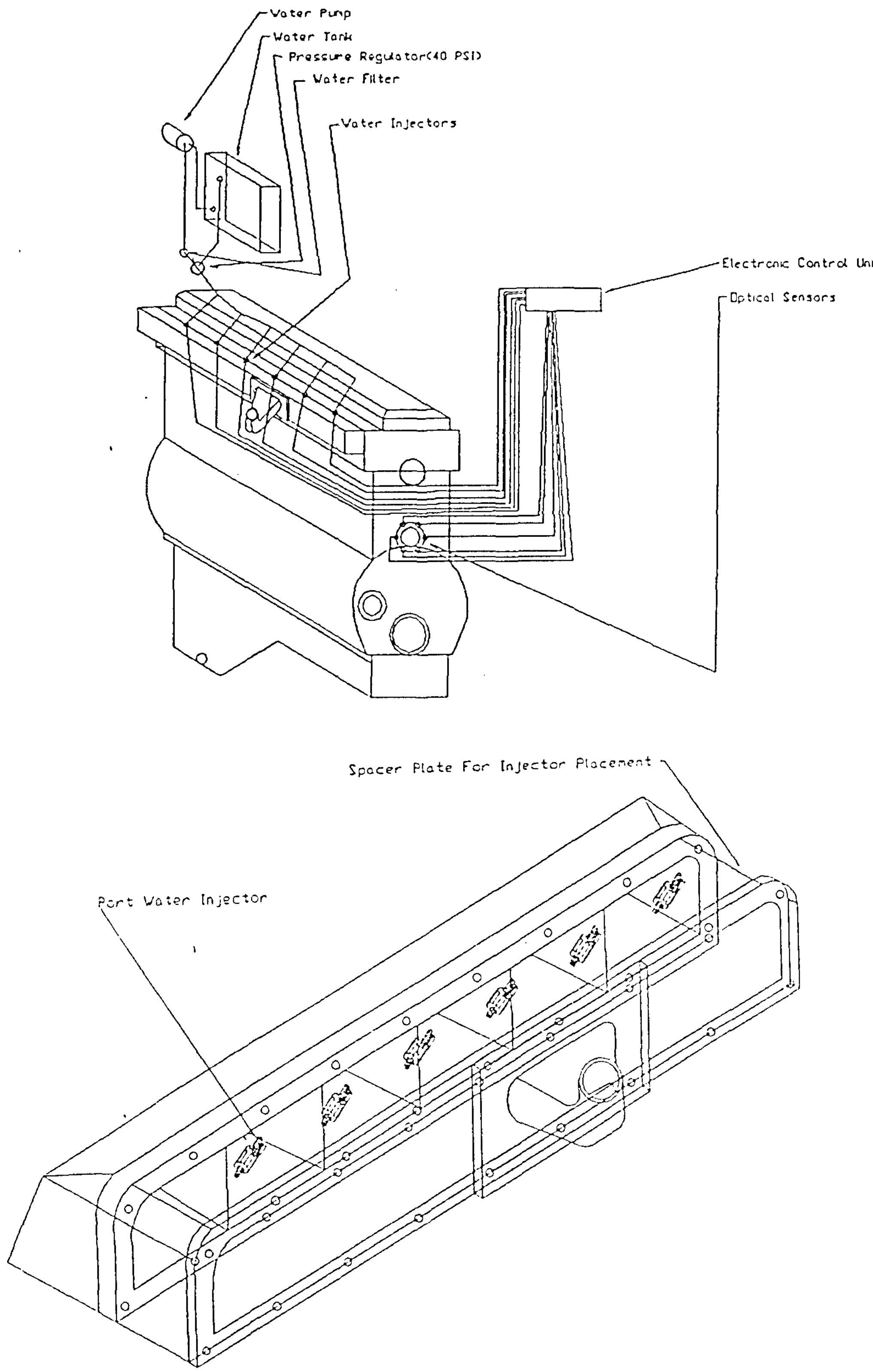



Figure 3-5. Water injection into air intake manifold: fumigation (Reference 10)

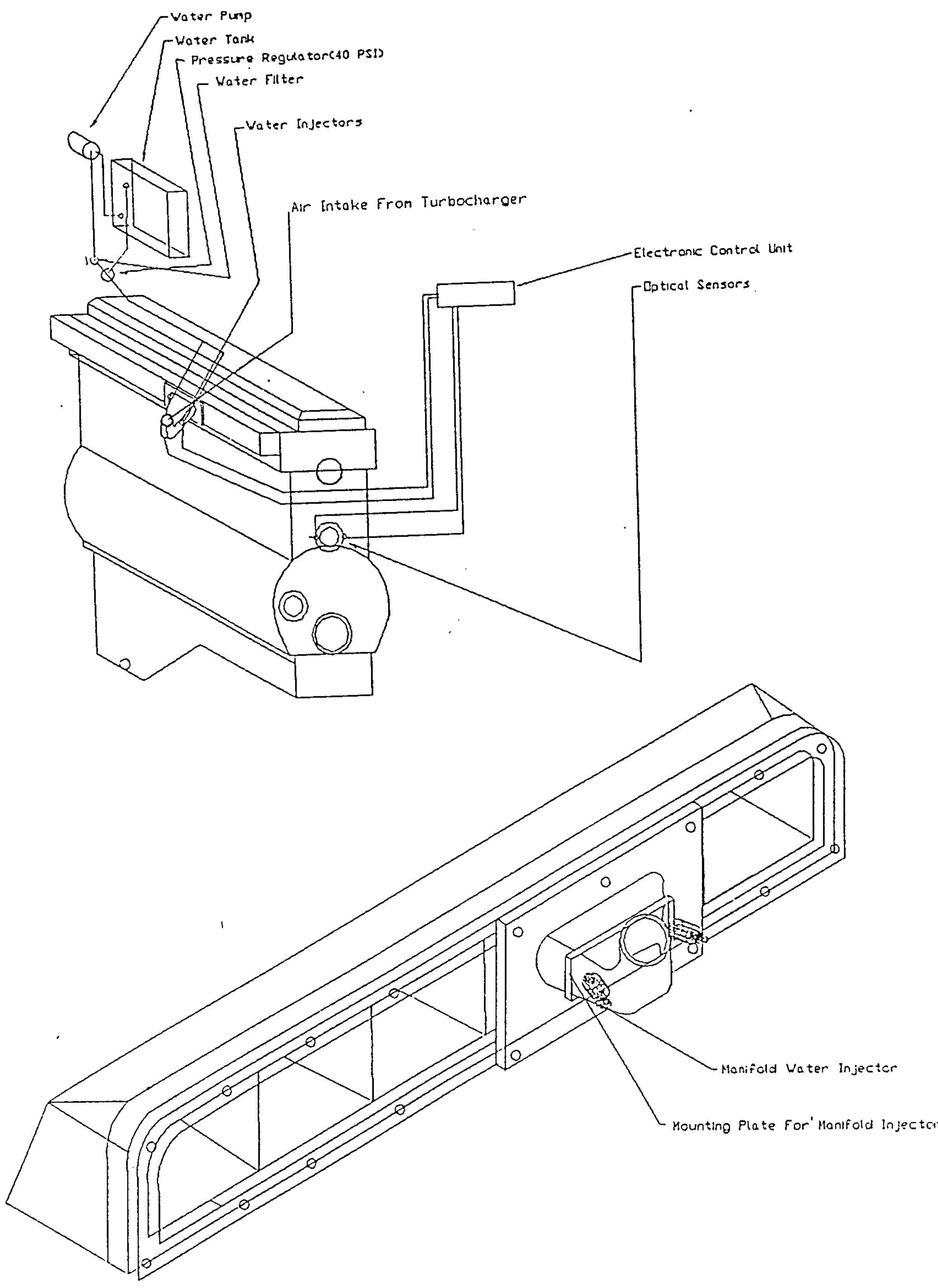



Figure 3-6. Water injection into intake ports: port-injection (Reference 10)

## 3.2 PARTICULATE MATTER CONTROL TECHNOLOGIES

While the primary emphasis of this work assignment is the reduction of $NO_x$ from Navy diesels, control of particulate matter (PM) from Navy diesels is of interest because: (1) most $NO_x$ control technologies tend to increase PM; and (2) reduced PM from Navy ships (especially smoke) is generally desirable. Methods for controlling PM emissions from diesel engines are listed and described next:

- Engine tuning
- Fuel composition
- Combustor chamber design
- Fuel injection system
- Particulate traps
- Oxidation catalysts

### 3.2.1 Engine Tuning

Marine diesel engines are adjusted by the manufacturers for maximum performance. Various diesel engine adjustments affect PM emissions. For example, adjustment of the maximum rack position to increase fuel-air ratio (may decrease $NO_x$) increases smoke. Retarding the fuel injection timing decreases the $NO_x$ but increases the PM (and smoke). Adjustments in the engine to reduce PM typically have an adverse effect on the $NO_x$. Adjustments to the engine to reduce $NO_x$ and PM are limited, and will depend on each engine.

### 3.2.2 Fuel Composition

PM emission increase as diesel fuel volatility decreases and/or the fuel sulfur content increases. Use of fuel additives to reduce emissions from diesel engines has received considerable attention and some of the results achieved appear to be promising for diesel engine applications. Metal containing fuel additives (e.g., cerium, copper and platinum) are used to enhance the oxidative process during and after combustion. The metals in the additives are oxidized in the combustion chamber and become embedded in the core of the solid carbon (soot) particles formed. The metal oxides then serve as effective catalytic surfaces for the oxidation of the carbonaceous PM at temperatures well below the otherwise combustion temperature of the carbon particle. Metal additives are formulated such that neither the fuel quality nor the resulting combustion processes are adversely affected (Reference 12). Some additive manufacturers in fact claim benefits in fuel consumption from the addition of their product to the fuel. The fuel additives are used in conjunction with particulate traps/catalytic oxidizers for maximum benefit. Considerable amount of research and demonstration of additive based technologies has occurred to address on-road diesel engines. Some of the additive based technologies currently being marketed in the United States are described next (Reference 12).

- Clean Diesel Technologies Inc. (CDTI) has developed a platinum based fuel additive for use in conjunction with diesel particulate trap/burnout systems. The additive is mixed with the fuel in extremely low concentrations of 0.15 to 0.25 ppm, to assist in regeneration of a loaded diesel particulate filter and provide additional gaseous emission reductions. Testing on a Cummins L-10 single-cylinder test engine has shown substantial reductions in CO, HC and PM.
- Lubrizol/Engine Control Systems Ltd. has been demonstrating and developing a particulate filter system which uses a copper-based fuel additive for regeneration and have recently applied for certification under U.S. EPA's urban bus retrofit/rebuild program. Certification data has shown filtration efficiencies in excess of 95 percent. This system also uses small quantities (50 ppm) of additive to lower the temperature required for regeneration. Demonstration programs for urban bus applications have shown that addition of the additive to the fuel in very low concentrations allows regeneration to occur in the 575°F range.

- Rhone-Poulenc, in a partnership with other companies is developing a cerium-based fuel additive to be used in conjunction with a particulate trap/burnout system to reduce PM from diesel engines. The cerium promotes combustion of trapped particulates, and the particulates are claimed to be reduced by 90 percent with no increase in $NO_x$. The system is still being evaluated worldwide.

### 3.2.3 Combustion Chamber Design

Advanced design combustion chambers that promote mixing and complete burning also decrease PM emissions. A classical measure of the quality of a diesel engine combustion chamber is the fuel to air ratio at the smoke limit. However, combustion chamber design modifications to favorably affect $NO_x$ and PM emissions are expensive as a retrofit technology.

### 3.2.4 Fuel Injection

Most diesel engine manufacturers are developing advanced fuel injection systems with higher injection pressures and electronic controls with an aim to decrease $NO_x$ and PM, and at the same time improve combustion. This technology is developmental and will require adding expensive electronic controls and injection systems, and may not be feasible for mechanically controlled engines.

### 3.2.5 Particulate Traps

Diesel particulate traps have been in commercial use since 1986. However, the biggest challenge that is yet to be successfully overcome is an easy way to regenerate the traps. Common methods of active regeneration include burnout of the collected soot through electrical heaters and blowout of the particulate from the trap using compressed air. Passive methods include catalytic burnout of the soot. Research is still underway to develop better active methods and newer passive methods.

### 3.2.6 Oxidation Catalysts

Diesel oxidation catalysts reduce the soluble organic fraction (SOF) part of the PM, which typically makes up 50 percent of the total PM. The oxidation catalysts rapidly lose efficiency with increasing fuel sulfur content and increasing PM deposition on the catalyst. In addition the oxidation catalysts operate most efficiently between temperatures of 350 and 600°F. This technology is commercially available and must be considered on a case-by-case (engine type) basis.

## 3.3 ENGINE UPGRADES AND ENGINE MANUFACTURER RETROFIT KITS

Inquiries were made concerning the possibility of repowering (and upgrade) existing Navy DDC diesel engines to meet the proposed low $NO_x$ targets. Communications with DDC representatives (technical and sales) are summarized below (Reference 13):

- Even current Detroit Diesel Electronically Controlled (DDEC) marine engines may not meet the proposed standards.
- The marine DDC engines (old and new) were built for power, economy and smoke control, and will conflict with $NO_x$ emissions.
- Upgrade of mechanical unit injectors (MUIs) engines (most Navy DDC engines are mechanically controlled) to electronic unit injectors (EUIs) may not be realistic and would still require DDC to evolve an engineering development project at significant cost.

Therefore, unless the manufacturers (DDC in this case) forsee a significant demand in terms of regulations or market, manufacturer upgrade of retrofit of the existing mechanically controlled engines may not be realistic.

## 3.4 TEST-ENGINE SPECIFICATIONS AND TEST SET-UP

A DDC Series 71, 4-cylinder, 2-stroke, Model 1043-7305 (DDC 4-71) diesel engine was chosen as the test engine to evaluate applicable $NO_x$ and PM reduction technologies described in this section. A summary of the basic technical data and engine performance curves are shown in Table 3-3 and Figure 3-7, respectively.

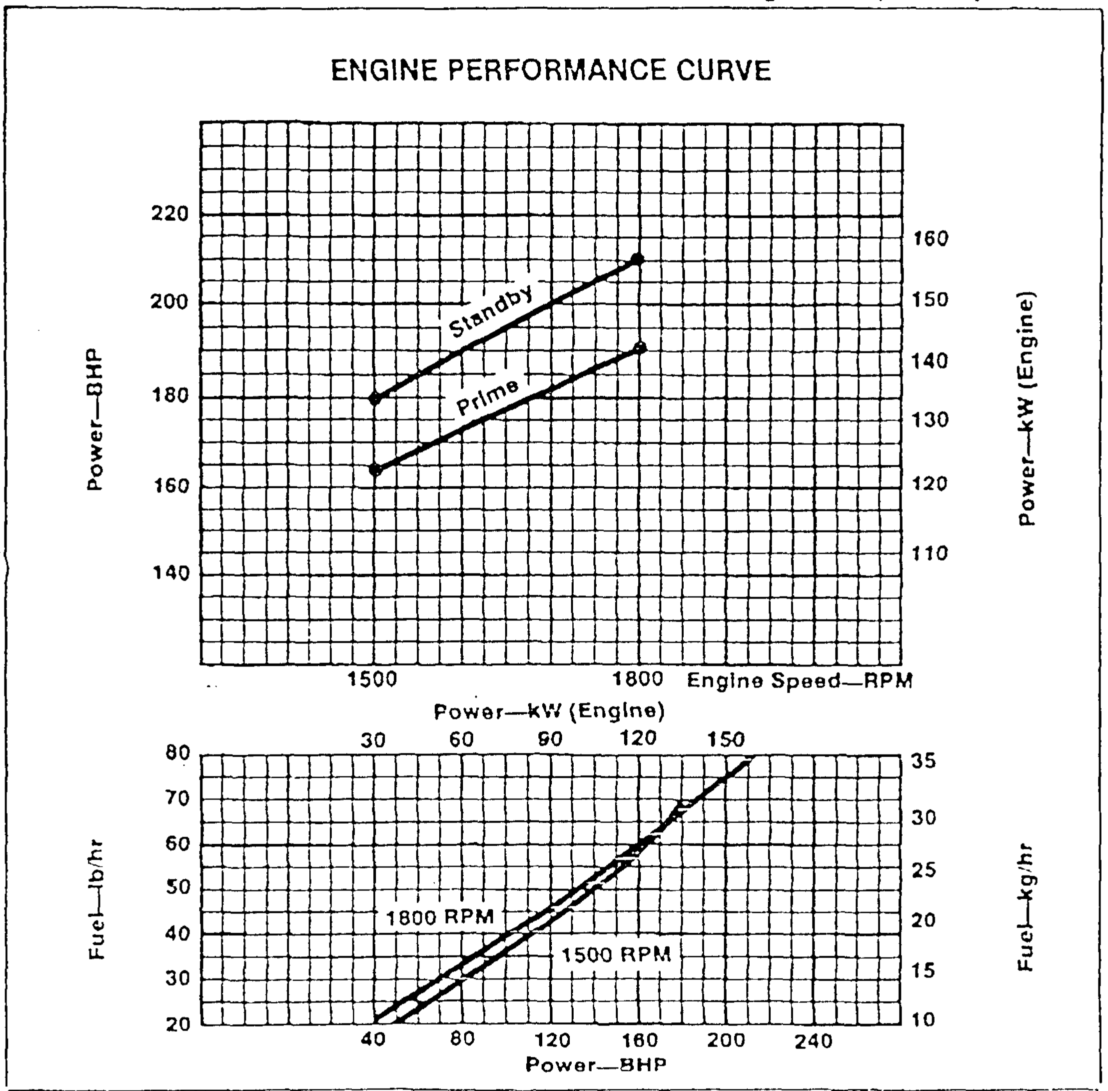
The baseline $NO_x$ emission for various loads (manufacturer's data) are plotted in Figure 3-8 and it can be seen that at greater than 50 percent load the $NO_x$ emissions exceed the target limit of 9.2 g/kWh. The DDC 4-71 engine is primarily used to generate power and is not very populous in the Navy. However, it is representative of the most populous engine category in the Navy, the Series 71, which make up over 60 percent of Navy diesels. Testing of the control technologies is being performed using this engine at the EPA's Environmental Research Center in Research Triangle Park, NC. A schematic of the test-engine is shown in Figures 3-9 and Figure 3-10 is a schematic of the test set-up.

Table 3-3. DDC Series 71 Model 1043-7305 basic technical data

| | | |
|---|---|---|
| Number of cylinders | 4 | |
| Cylinder arrangement | Inline | |
| Cycle | 2-stroke | |
| Induction system | Turbocharged | |
| Combustion System | Direct injection | |
| Bore | 108 mm (4.25 in) | |
| Stroke | 127 mm (5.0 in) | |
| Compression ratio | 17:1 | |
| Firing order | 1, 3, 4, 2 | |
| **Test Conditions** | | |
| Prime power | Equivalent to ISO 3046; 77°F (25°C) Air inlet temperature; 29.5" Hg total Barometric pressure; 30% relative humidity | |
| Standby power | Equivalent to SAE J1349; 77°F (25°C) Air inlet temperature; 29.31" Hg Dry barometer | |
| Diesel fuel | To conform to 'ASTM D9T5 66T #2D or BS 2669 1983 Class A2 | |
| Lubricating oil | SAE 40 conforming to MIL->-2104D or API CD11 | |
| Fuel injector Timing | M95/1.46" | |
| | **Prime** | **Standby** |
| Rated engine power (kW (bhp) | | |
| 1,500 rpm | 122 (164) | 180 (134) |
| 1,800 rpm | 191 (143) | 210 (157) |
| Fuel consumption 100% load kW/h (lb/h) | | |
| 1,500 rpm | 28 (62) | 32 (70) |
| 1,800 rpm | 33 (72) | 36 (79) |

**DETROIT DIESEL**
CORPORATION

**4-71T**
**Generator Set**
**Rated BHP**
**Standby:** 210 BHP @ 1800 RPM
180 BHP @ 1500 RPM
**Prime:** 191 BHP @ 1800 RPM
164 BHP @ 1500 RPM
**Injector:** M95
**Turbocharger:** T04B (1.14 A/R)



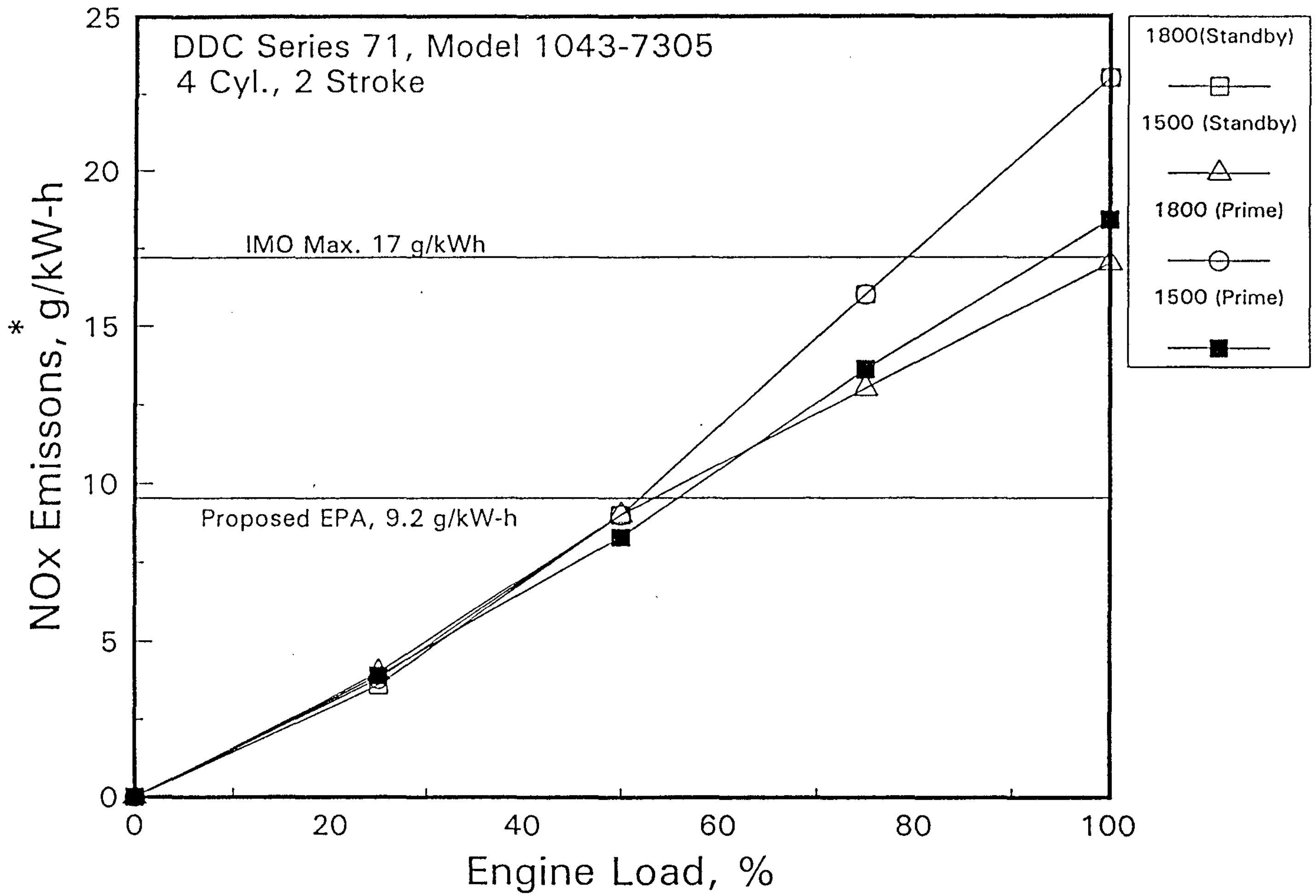

- Rated power output shown represents engine performance capabilities at ambient conditions equivalent to ISO 3046 BS 5514 100 KPA total baro press, 25°C air inlet, 30% relative humidity
- Curves also represent capabilities at the following ambient conditions DIN 6270 736 torr baro press, 20° air inlet, 60% relative humidity JIS D1005-1976 760 MM HG baro press 20°C air inlet 11.4 MM HG vapor press
- Indicated performance is based on minimum intake and exhaust restrictions
- Fuel consumption data is based on diesel fuel no. 2 with a fuel weight of 7.11 lb U.S. gal (.85kg/Litre). Fuel heating value is 18370 BTU/lb (10210 CAL/GM)
- Values are derived from currently available data and subject to change without notice.
- Conversion factors Power kW = bhp x 0.746
  Fuel L/hr = gal/hr x 3.785

Certified by:

Mark S. Kuhn

Curve No.
E4-1045-32-8
Date: 12-22-82
Rev./Date: 4/3-16-90
Sht. 1 of 4

Figure 3-7. Manufacturer's engine performance curves DDC 4-71 Model 1043-7305

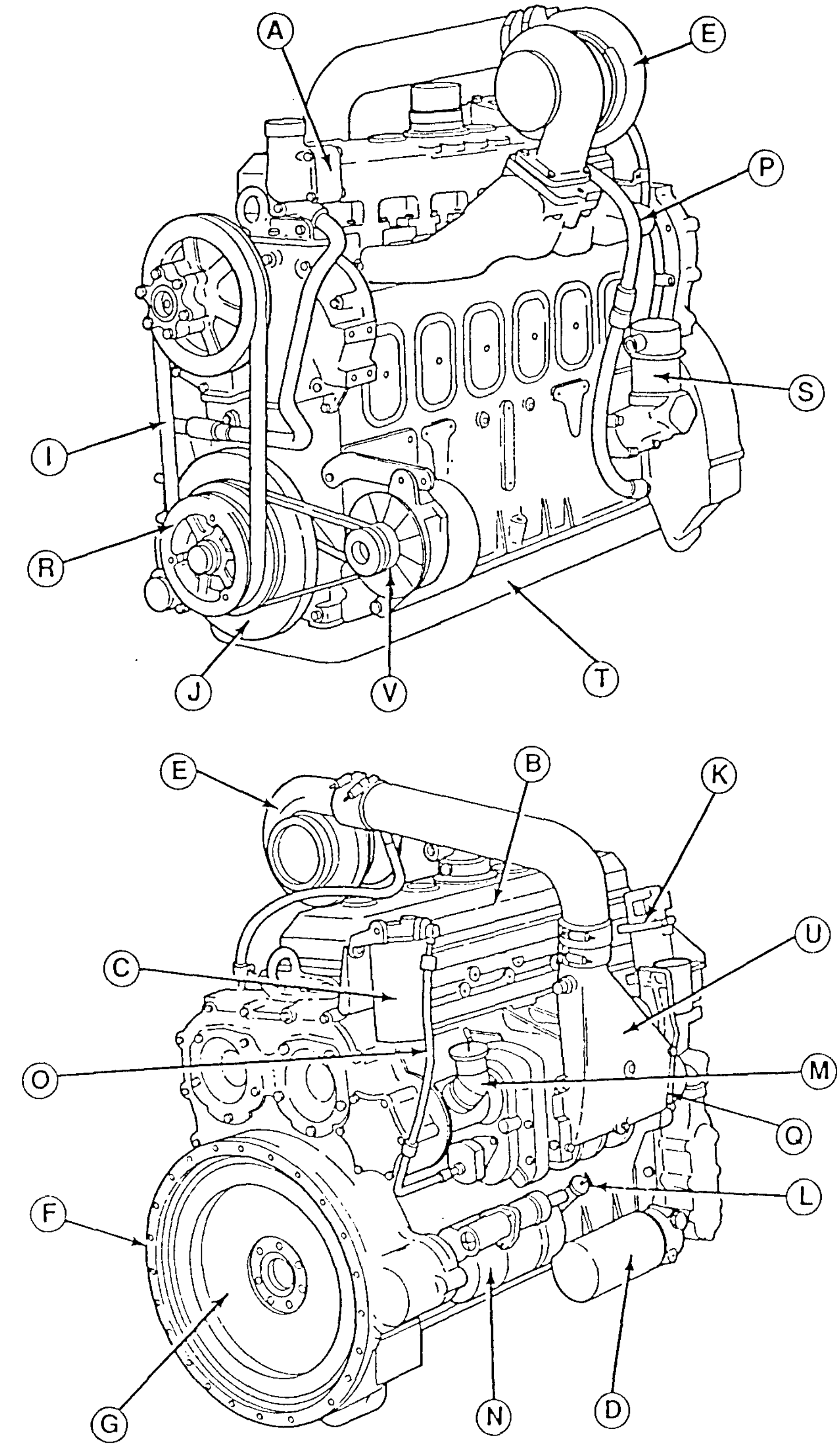



Prime Power: 77°F airinlet, 29.5" Hg total pressure, 30% rel. hum
Standby Power: 77°F airinlet temperature, 29.31" Hg dry barometer

* - Manufacturer's data

Figure 3-8. $NO_x$ emissions at various engine load conditions

| ITEM | DESCRIPTION |
|---|---|
| A | Thermostat |
| B | Injector |
| C | Fuel Filter |
| D | Oil Filter |
| E | Turbocharger |
| F | F/W Housing |
| G | Flywheel |
| H | Fan |
| I | Fan Belt |
| J | Vibration Damper |
| K | Governor |
| L | Oil Dipstick |
| M | Oil Filler Tube |
| N | Starter Motor |
| O | Fuel Lines |
| P | Exhaust Manifold |
| Q | Air Box Drain |
| R | C/S Pulley |
| S | Breather System |
| T | Oil Pan |
| U | Air Inlet Housing |
| V | Battery Charging Alternator |




**Series 71 (Inline 4/Inline 6)**

Figure 3-9. Schematic of Series 71 DDC engine

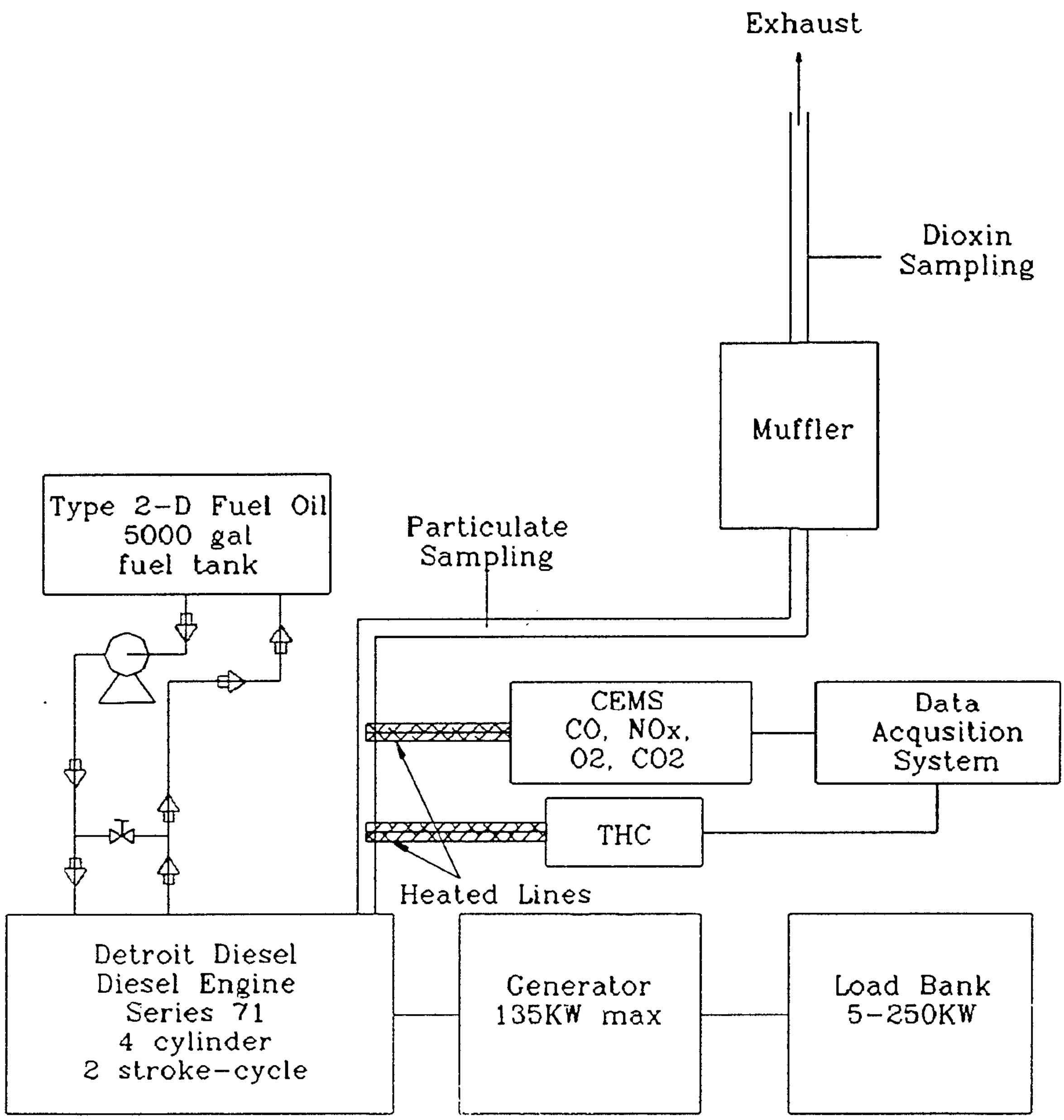



Figure 3-10. Schematic of the test set-up

## SECTION 4

## CONTROL TECHNOLOGY APPLICATION FEASIBILITY

A number of technologies for $NO_x$ and PM control were discussed in Section 3. Retrofit application of some of those technologies to the test DDC 4-71 engine in particular and Navy diesels in general from a stand point of feasibility and cost on ship/engine operations are discussed in this section. Based on the review of the existing $NO_x$ and PM control technologies, the following were chosen for application testing and feasibility.

- $NO_x$ Control
  - Injection timing retard
  - Exhaust gas recirculation
  - Water injection
  - In-cylinder ceramic coating
  - Lean $NO_x$ methods
- PM Control
  - Oxidation catalysts
  - Particulate traps
  - Fuel additives

### 4.1 $NO_x$ CONTROL METHODS

#### 4.1.1 Injection Timing Retard

Injection timing retard is the easiest to implement and a very effective $NO_x$ reduction strategy. No modifications to the engine or new hardware are required. In general, for the 71 series engines, a 4° retard is expected to result in up to a 25 percent reduction in $NO_x$. For the test DDC 4-71 engine, the factory set injection timing is 1.460 inches. A 4° retard will approximately set the injector at 1.490 inches. Tests will be performed to measure $NO_x$ and PM emissions at 1° increments in the injection timing.

The direct costs involved in implementing injection timing retard are almost none. A few hours of labor of an experienced diesel mechanic is all that may be required. Engine downtime will not exceed a maximum of 2-4 hours for each change in the injection timing. Injection timing retard is a powerful tool for $NO_x$ reduction. However, the degree of retard will vary not only for each engine family but on an engine-by-engine basis. Some amount of baseline testing will be required for each engine prior to applying injection timing retard. There will be no maintenance costs associated with the application of injection timing retard. However, long term durability and reliability of the engine (especially older engines) will be of concern. As a general rule, for every 1° delay in timing, a 1 percent increase in the fuel consumption can be expected. Therefore, a nominal increase in the fuel costs by 5 percent may result. Prior to the application of timing retard to Navy diesels baseline testing and engine mapping will be necessary.

### 4.1.2 Exhaust Gas Recirculation

Exhaust gas recirculation, as discussed in Section 3, can be applied internally or externally. Figure 4-1 is a drawing showing the scheme for applying internal and external EGR to the DDC 4-71 test engine.

**Internal EGR:** In the DDC 4-71 an efficient way to induce internal EGR is by reducing the airbox pressure. The easiest way to accomplish this is by by-passing the blower or "bleeding" a portion of the intake charge air after the turbo charger. Figure 4-1 shows how this is planned to be implemented in the test engine.

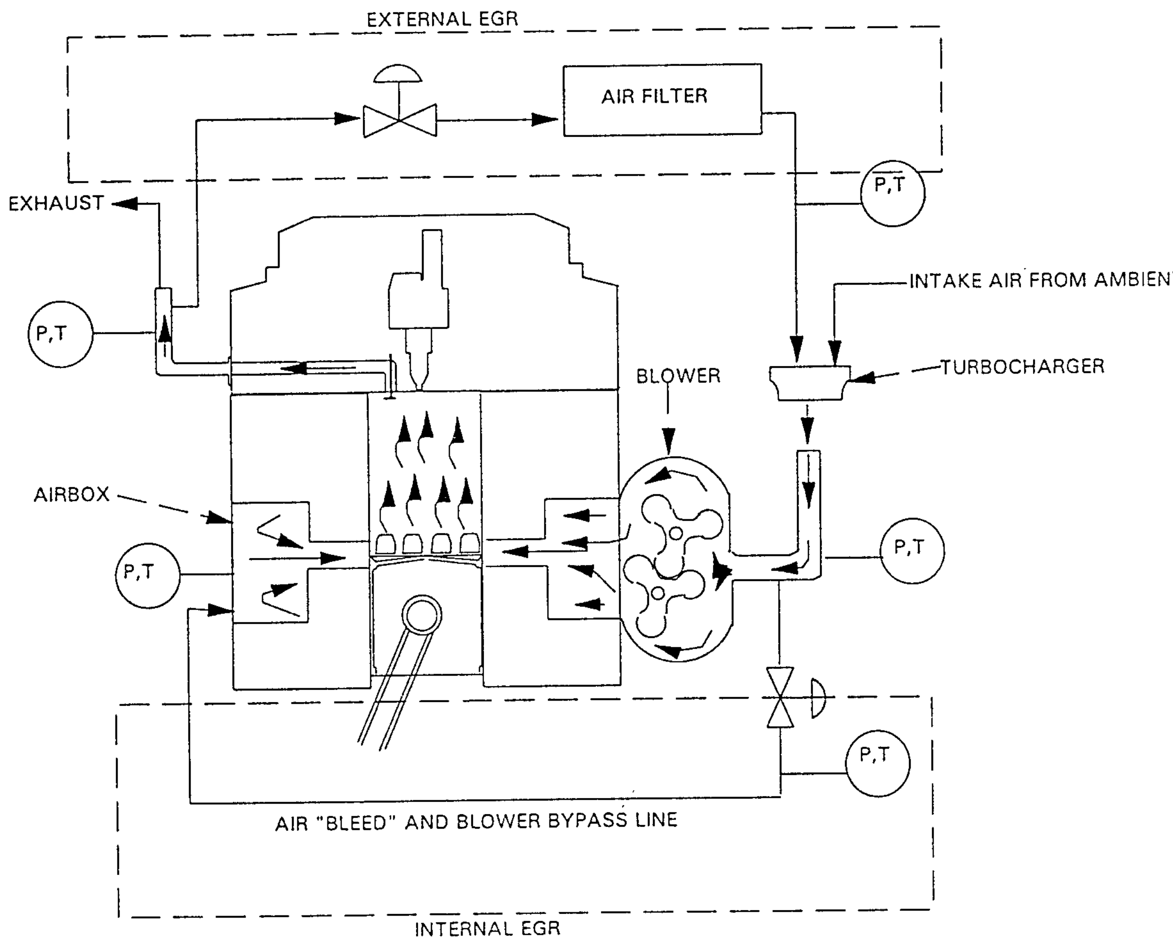



**Figure 4-1. Internal and external EGR schemes for the DDC 4-71 test engine**

Implementation of internal EGR to the DDC 4-71 will have minimal direct costs. About $250 in hardware and 4-8 hours of engine downtime is expected. Some increase in the BSFC, about 5 percent, is expected.

**External EGR**: The planned scheme for external EGR is also shown in Figure 4-1. About 10 to 15 percent of the exhaust gas stream will be recirculated back into the engine. The exhaust stream will be returned through a commercially available HEPA filter into the inlet of the turbocharger. The hardware for such a simple system is expected to cost about $2,000. Addition of electronic controls to manipulate the EGR as a function of engine speed and load will increase the cost substantially. The addition of regenerative filters or a duplex filter system will increase the cost by 2-3 fold and will also require some amount of research and development. However, for the application to Navy diesels, if baseline emissions data and operation cycle of the engine (EGR is recommended under steady-state and high load conditions) are known, then a simple, inexpensive, preset EGR system is viable. Expected downtime for implementation on the test engine is about 2 to 3 days. A 5 percent increase in BSFC can be expected.

### 4.1.3 Water Injection

As described in Section 3 the two methods of water injection are direct-injection and fumigation. Direct injection into the combustion chamber can be accomplished as a water-in-fuel emulsion, Peremulsified fuels are attractive in that they do not require special hardware or modifications to the engine. However, preemulisfied fuels will not allow variable water to fuel (W/F) ratios, and optimum benefits from water injection are best realized when there is the ability to alter the W/F ratio to suit different engine speed and load conditions. For engines operating mostly under steady state conditions use of preemulsified fuels is viable. Increased fuel storage volume, long term emulsion stability, inability to return rapidly to no-diesel "normal" operating conditions (dual storage systems can over come this problem) and the effect of emulsion stabilizers on the combustion process are potential limitations to using preemulsified fuels. In situ emulsification on the other hand is significantly more complicated and requires expensive hardware but allows more flexibility in operation.

**In situ emulsification:** Figure 4-2 is the schematic for a water-in-diesel emulsification system. In a typical emulsifying system, water is sprayed into the diesel fuel which then flows into the emulsifying device. The mechanical emulsifier usually consists of a static mixer and a high energy device that would utilize a high pressure pump (2,500 to 3,000 psi) to produce emulsification through cavitation. In diesel engines such as the test 4-71 DDC engine a part of the fuel is returned to the system. In this case, the excess fuel (emulsified by this stage) would be returned to the static mixer after passing through a degasifier to prevent frothing. An emergency pump system, in case the emulsifier is shutdown is designed to take over and drain the emulsified fuel into the diesel engine till it is burned out. An optional viscosity control unit is also incorporated into the design. Viscosity control may become necessary depending on the W/F ratio and the injector type. Figure 4-3 shows the planned scheme for the in situ emulsification system on the DDC 4-71 test engine.

An emulsification system such as that shown in Figure 4-2 would cost between $10,000 and $15,000 depending on the level of sophistication required. For application to Navy diesels an emulsification system package will have to be custom designed on case-by-case basis for each family of engines. Some amount of research, design and development is expected. Engine downtime to implement the emulsification system on the DDC 4-71 is expected to take about 2 to 3 man-days after shakedown of the system. No major modifications to the engine will be required to install the emulsification system.

**Fumigation:** Humidification of the intake charge-air (fumigation) has been shown to be an easy and effective to introduce water into the combustion process. In the case of the DDC 4-71 engine the best way to accomplish this is by adding water at the inlet of the turbocharger. Figure 4-3 also shows a schematic of this approach for the test engine. A simple system would require a water atomizing injector/nozzle, a water pump, compressed air and a control valve. Such a system would cost around $2,500 to $3,500. An electronically automated system could double the cost of the system. As mentioned previously the quality of the water remains a serious concern from a stand point of damage to the engine. The addition of a water deionizing system will significantly boost the price of the system. For example, the DDC 4-71 test engine consumes about 35 kg/hr of diesel at full load (190 bhp and 1,800 rpm) and the water requirement at a W/F of 0.6 could be up to 20 kg/hr. A deionization system rated for this costs about $10,000.

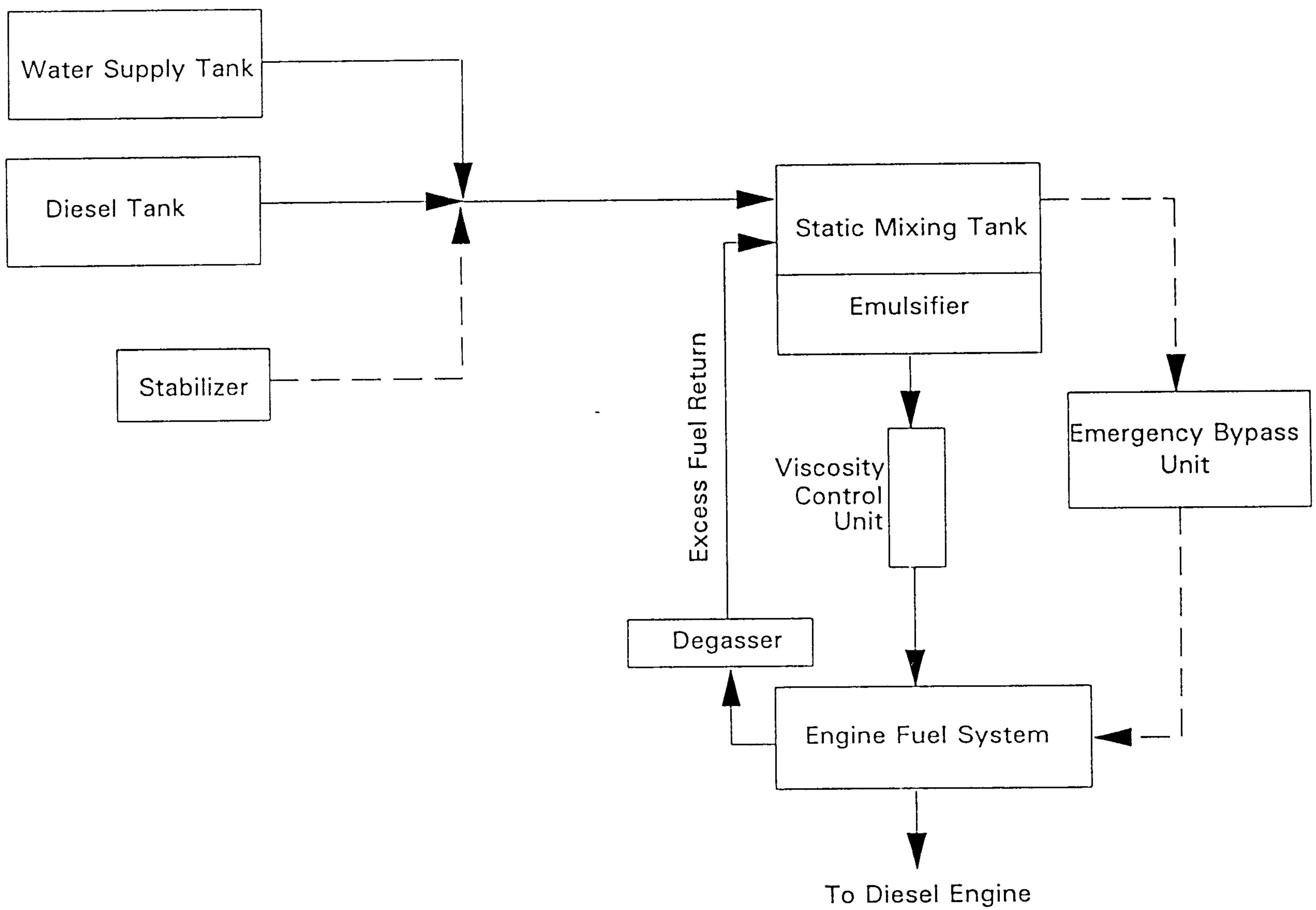



Figure 4-2. Water-in-diesel emulsification system

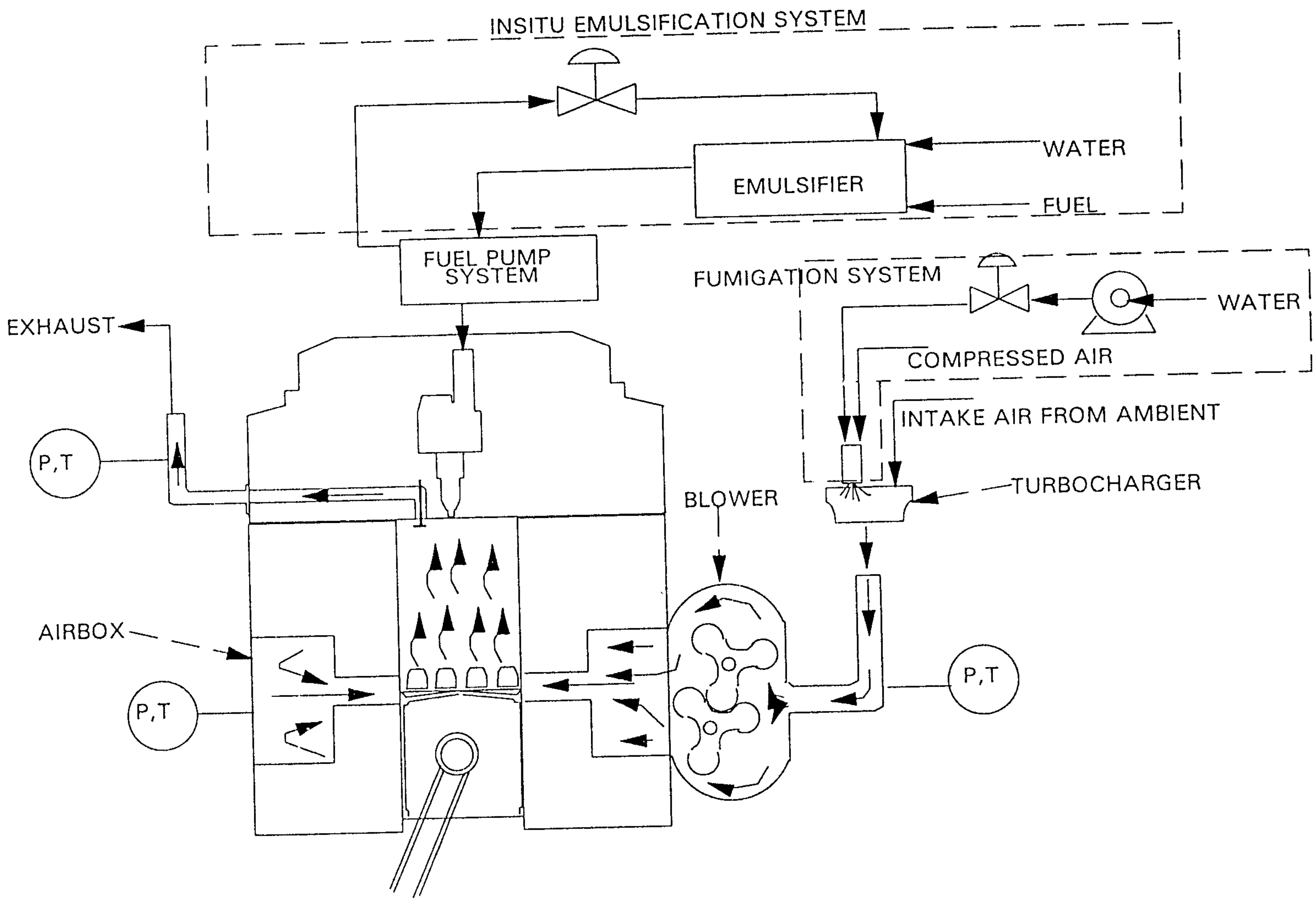



Figure 4-3. Water-fuel emulsification and fumigation schemes for the DDC 4-71 test engine

Implementation of this technology would not require any modifications to the engine. Installation of the system on the DDC 4-71 engine is expected to take between 2 to 3 man-days after shakedown of the system. For installation on Navy diesels, this system is relatively easier compared to the fuel emulsification system.

### 4.1.4 Lean $NO_x$ Methods

Generally SCR technologies such as Lean $NO_x$ and DENOx are bulky and expensive. However, if significant reductions in $NO_x$ from large engines without compromising power and performance (for example, main propulsion diesel engines), then aftertreatment using SCR techniques are a viable alternative. The cost of such systems depending on the size of the engine(s) ranges from $10,000 to $150,000 in hardware alone. Additional operation costs will include the cost of the reducing agent (ammonia, cyanuric acid, diesel, etc.).

## 4.2 PARTICULATE MATTER CONTROL

### 4.2.1 Oxidation Traps

Oxidation traps remove the soluble organic fraction (SOF) from the diesel exhaust PM. The SOF constitutes about 50 percent of the total PM. The oxidation trap under consideration for evaluation with the DDC 4-71 test engine is Johnson-Matthey's catalytic exhaust muffler (CEM) system. The CEM has been certified by EPA for use on urban buses and claims to reduce the PM by at least 25 percent depending on the operating conditions. The CEM is most effective within a temperature window of 350 and 600°F and for low sulfur (<200 ppm) content diesel oil. The cost of such a system for the DDC 4-71 is about $2,000. The CEM is designed to replace the existing muffler of the DDC 4-71 engine and will not require any further maintenance after installation. The installation is expected to take 1 to 2 man-days. Application to Navy diesels must be treated case-by-case based on PM emissions information for each engine.

### 4.2.2 Particulate Traps

Particulate traps capture the PM on filters (typically honeycomb ceramic monoliths) and very high capture efficiencies can be achieved. However, continuous regeneration of the traps is the biggest challenge posed in the use of these filters. Most manufacturers are still researching better ways to actively and passively regenerate these filters with minimum disruption to engine operations. The cost of these systems range between $5,000 to $15,000 depending on the level and ease of regeneration desired. Particulate traps however can provide greater PM removal than oxidation catalysts because oxidation catalysts are operated as passive devices and remove only the SOF. For Navy diesel applications the choice between particulate traps and oxidation catalysts will depend on the level of PM removal required. The baseline and preliminary tests with injection timing retard on the DDC 4-71 test engine indicate that PM emissions are not excessive and an oxidation trap is sufficient to reduce the PM levels to below the target level of 0.54 g/kWh.

### 4.2.3 Fuel Additives

Metallic additives such as platinum, copper and cerium when added to the fuel at very low concentrations (less than 1 ppm to 50 ppm) have been demonstrated to catalytically reduce temperatures at which soot oxidation occurs (see Section 3). The fuel additive compositions are proprietary and the costs vary. Application of the fuel additives to the DDC 4-71 test engine, with a maximum load fuel consumption of about 75 kg/hr, is expected to cost around $0.50/hr. The additives can be added to the fuel tank of the engine and usually take about 100 hours of operation before becoming effective.

## 4.3 SUMMARY

A number of $NO_x$ and PM reduction technologies have been chosen for evaluation on the DDC 4-71 test engine and potential application to shipboard Navy diesel engines. Table 4-1 presents an overview of these technologies and the feasibility of their application to the DDC 4-71 test engine

Table 4-1. Summary of $NO_x$ and PM control applications

| Control Method | Maximum Expected Reduction (%) | | Advantages/Benefits | Concerns | Status | (1) **Hardware Costs**<br>(2) **Installation Costs**<br>(3) **R&D Costs**<br>(4) **Increased Fuel Costs** |
|---|---|---|---|---|---|---|
| | $NO_x$ | PM | | | | |
| Injection Timing Regard | 25 | — | (1) Easy to implement<br>(2) No engine modifications | (1) Decrease combustion efficien cy followed by increases in PM, HC, CO and BSFC<br>(2) Increased PM may damage combustion chamber and other components<br>(3) Cold-start problems<br>(4) Engine will have to be shutdown to return to "normal" operating conditions | (1) Commonly used<br>(2) Testing will be required to address cold-start issues, produce engine performance and emission maps and develop standard operating procedures | (1) None<br>(2) 2 to 4 hours; 1 person labor<br>(3) Engine mapping and emissions testing<br>(4) 5% |
| Internal EGR | 25 | — | (1) Easy to implement on the DDC 4-71<br>(2) No engine modifications to the DDC 4-71 | (1) Decreased combustion efficie ncy followed by increases in PM, HC, and BSFC<br>(2) Damage to combustion chamber and other engine components<br>(3) Engine will have to be shutdown to return to "normal" operating conditions | (1) Implementation will be dependent on engine type<br>(2) Testing will be required to produce engine performance and emissions maps, and develop standard operating procedures | (1) $250<br>(2) 4 to 8 hours, 1 person labor<br>(3) Testing costs<br>(4) 5% |
| External EGR | 40 | — | (1) Proven $NO_x$ reduction strategy<br>(2) NO engine modifications<br>(3) System can be bypassed to return engine to "normal" operating conditions without engine shutdown | (1) Increases in PM, HC, and CO at high EGR (>20%) rates<br>(2) Increases in BSFC (5%) expected<br>(3) Considerable "clean-up" of exhaust gas may be necessary to eliminate PM and sulfuric acid in the case of high sulfur diesel oil | (1) No demonstrated applications on marine diesel engines<br>(2) Testing will be required to produce engine performance and emission maps, evaluate engine durability and develop standard operating procedures | (1) $2,000 without electronic controls or filter regeneration<br>(2) 2 to 3 days; 1 person labor<br>(3) (a) Design and development costs for the DDC test engine<br>(b) Testing costs<br>(4) 5% |

## Table 4-1. Summary of $NO_x$ and PM control applications (continued)

| Control Method | Maximum Expected Reduction (%) | | Advantages/Benefits | Concerns | Status | (1) **Hardware Costs**<br>(2) **Installation Costs**<br>(3) **R&D Costs**<br>(4) **Increased Fuel Costs** |
|---|---|---|---|---|---|---|
| | $NO_x$ | PM | | | | |
| Water Injection Water-in-diesel Emulsions (WDE) | 60 | 30 | (1) Best proven retrofit $NO_x$ reduction strategy on shipboard engines to date<br>(2) Claims of decreases in PM and BSFC<br>(3) No modifications to engine<br>(4) System can be bypassed to return engine "normal" operating conditions without engine shutdown | (1) Complex emulsification and control system for in situ emulsion applications<br>(2) Emulsion stability issues for preemulsified fuels | (1) Commonly used water injection retrofit technology<br>(2) Testing will be required to produce engine performance maps and emission maps, WDE system performance and develop standard operating procedures | (1) $10,000 to $15,000<br>(2) 3 to 4 days; 1 person labor<br>(3) (a) Design and development costs for the DDC test engine<br>(b) Testing costs<br>(4) 5% |
| Water Injection Fumigation | 40 | 30 | (1) Relatively easy to implement on the DDC 4-71 test engine<br>(2) May see decrease in BSFC and PM<br>(3) System can be bypassed to return engine to "normal" operating conditions without engine shutdown | (1) Water quality an important issue and may require expensive water deionizing systems<br>(2) Water condensation leading to damage of engine parts | (1) Technology has been demonstrated on marine diesels mainly in Europe<br>(2) Considerable laboratory test data available for diesel engines<br>(3) Testing will be required to produce engine performance and emission maps, evaluate fumigation system durability, address water damage issues, and develop standard operating procedures | (1) $2,500 to $3,500<br>(2) 2 to 3 days; 1 person labor<br>(3) (a) Design and development of injection fumigation system for DDC 4-71<br>(b) Testing costs<br>(4) None expected |

**Table 4-1. Summary of $NO_x$ and PM control applications (continued)**

| Control Method | Maximum Expected Reduction (%) | | Advantages/Benefits | Concerns | Status | (1) Hardware Costs (2) Installation Costs (3) R&D Costs (4) Increased Fuel Costs |
|---|---|---|---|---|---|---|
| | $NO_x$ | PM | | | | |
| Lean $NO_x$ DENOx | 90 | — | (1) Proven technology<br>(2) No engine modifications<br>(3) After treatment; no PM-$NO_x$-BSFC tradeoffs<br>(4) Technology is useful when significant $NO_x$ reductions are needed with no compromise in BSFC and PM (for example, MPDEs) | (1) Bulky systems<br>(2) Very expensive<br>(3) Reducing agents are ammonia, cyanatic acid or diesel. Possibility of ammonia slip.<br>(4) Sensitive to exhaust gas temperature and fuel sulfur content | (1) Application on marine diesels proven to be effective<br>(2) Not recommended for testing on the DDC 4-71 test engine | (1) $10,000 to $150,000<br>(2) —<br>(3) —<br>(4) None expected. Reducing agent costs. |
| Particulate Traps | — | 90 | (1) High efficiency PM removal<br>(2) Replace existing diesel engine mufflers | (1) Uninterrupted regeneration is a challenge | (1) Commercially available<br>(2) Manufacturers are continuously working to develop better active and passive regeneration systems | (1) $2,000 to $15,000<br>(2) 1 to 2 days; 1 person labor<br>(3) Testing to determine efficiency<br>(4) None expected |
| Oxidation Catalysts | — | 50 | (1) Replace existing mufflers<br>(2) Passive Regeneration | (1) Catalyst fouling<br>(2) Sensitive to exhaust temperature and fuel sulfur content | (1) Commercially available<br>(2) Manufacturers are continuously working to develop more about systems — larger temperature window | (1) $2,000 to $8,000<br>(2) 1 to 2 days; 1 person labor<br>(3) Testing to determine efficiency<br>(4) None expected |
| Fuel Additives | — | 40 | (1) Low concentrations, can be added to fuel tank<br>(2) Improve combustion in some cases | (1) Long term build up of metals in engine and emission of the same<br>(2) Require a catalytic trap/oxidizer to actually reduce exhaust PM<br>(3) Require at least 100 hours of engine operation to realize benefits | (1) From developmental to commercially available | (1) None<br>(2) None<br>(3) Testing<br>(4) None expected |

and Navy diesels in general. Application to Navy diesel engines will have to be decided case-by-case based on a current inventory and emissions data.

# SECTION 5

# PRELIMINARY MODIFICATION PACKAGE

The Navy diesel inventory (Section 2 and Appendix A) shows that DDC Series 71 engines constitute about 60 percent of Navy diesels. Therefore, the likely choice for testing a retrofit $NO_x$ and PM reduction will be a DDC 71 Series engine. Figure 5-1 is a conceptual schematic of the $NO_x$ and PM reduction strategies that can be implemented singly or in combination to attain the desired emission reduction targets. The $NO_x$ and PM reduction strategies that are most likely to be applied are:

- Injection timing retard
- Internal EGR
- External EGR
- Water Injection — water/fuel emulsions and/or fumigation
- Additives for enhanced combustion and PM burnout
- PM removal using particulate traps or oxidation catalysts

Whether a single method or a combination of the above methods are needed will depend on the targeted level of $NO_x$ and PM reductions and the following information:

- Application of engine
- Operating/duty cycles
- Baseline emissions data under typical operating conditions
- Engine layout and space availability

EXHAUST GAS RECIRCULATION (EGR)
-External
-Internal
WATER INJECTION
-Manifold injection "fumigation"
-Port injection
WATER/FUEL EMULSIONS
ADDITIVES
INJECTION TIMING RETARD
PARTICULATE CONTROL
-Particulate Traps
-Oxidation Catalysts

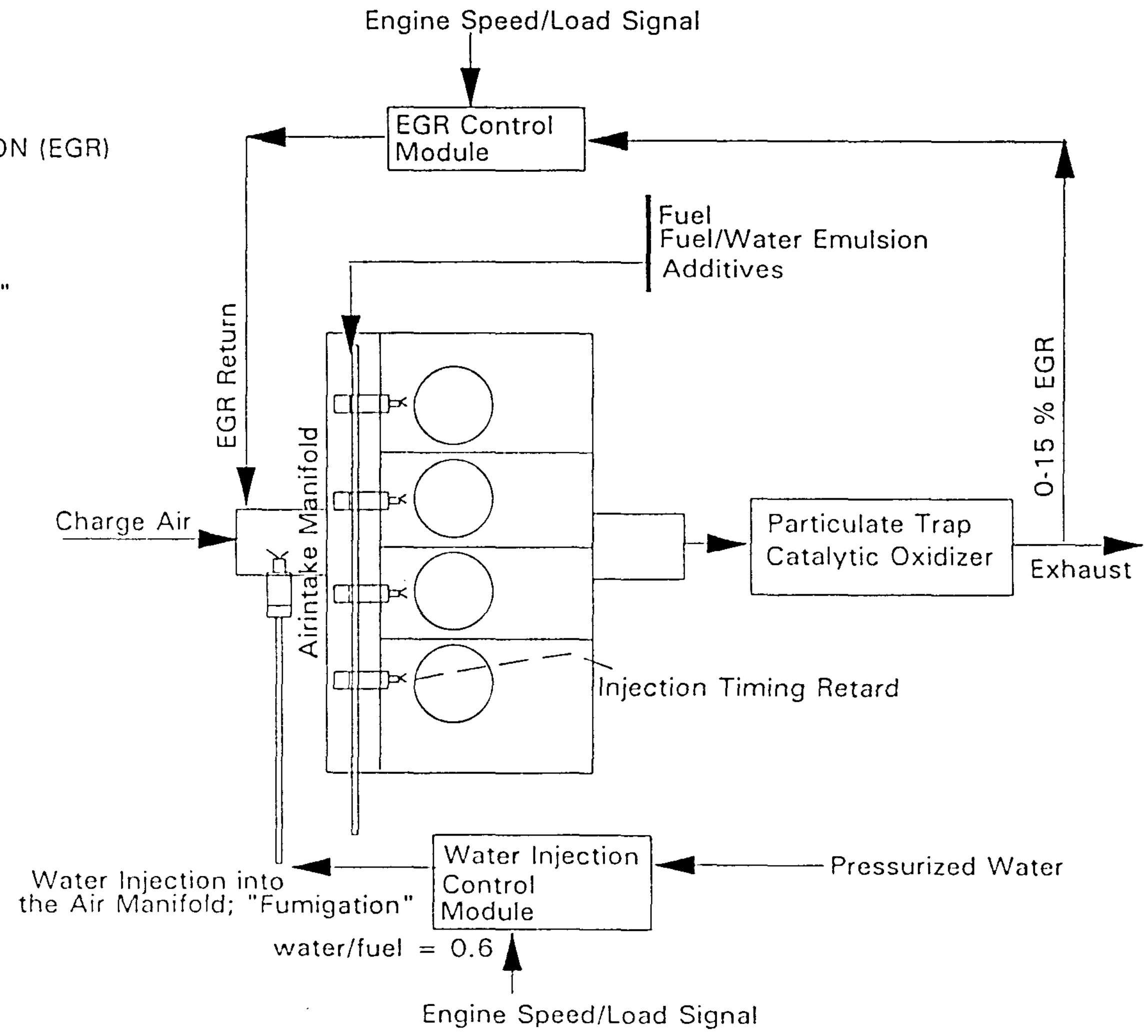



**Figure 5-1. Schematic of retrofit applications in the modification package**

The modification package will be installed and demonstrated tested to demonstrate and evaluate its ability to reduce $NO_x$ and PM emissions to the target levels, its durability and reliability under shipboard conditions, durability of the engine with the retrofit addition and the impact on ship/engine operations. Testing will be performed under typical operating conditions of the selected engine. A bank of continuous emission monitors (CEMs) will be used to measure $NO_x$, CO, HC, $CO_2$, and $O_2$ levels in the exhaust gas. PM measurements will be performed using a standard EPA method, such as Method 5, which is an extractive sampling method (Reference 13). If a continuous and realtime measurement of the PM is preferred then laser based measurements can be used. Figure 5-2 is a schematic of the emissions measurement system. Table 5-1 is a brief description of the typical CEMs that will be used.

The preliminary modification package is expected to provide critical information on the applicability of retrofit packages to address the Navy's plan to reduce $NO_x$ and PM emissions from its diesel engines.

**Table 5-1. Description of emission measurement systems**

| Constituent | Principle | Sampling Mode |
|---|---|---|
| $O_2$ | Paramagnetic | Extractive/continuous |
| $CO_2$ | Non-dispersive infrared | Extractive/continuous |
| CO | Non-dispersive infrared | Extractive/continuous |
| $NO_x$ | Chemiluminescent | Extractive/continuous |
| THC | Flame ionization detector | Extractive/continuous |
| PM | Extractive sampling — by weight difference<br>(or)<br>Laser scattering | Extractive/Batch<br><br>In Situ/Continuous |

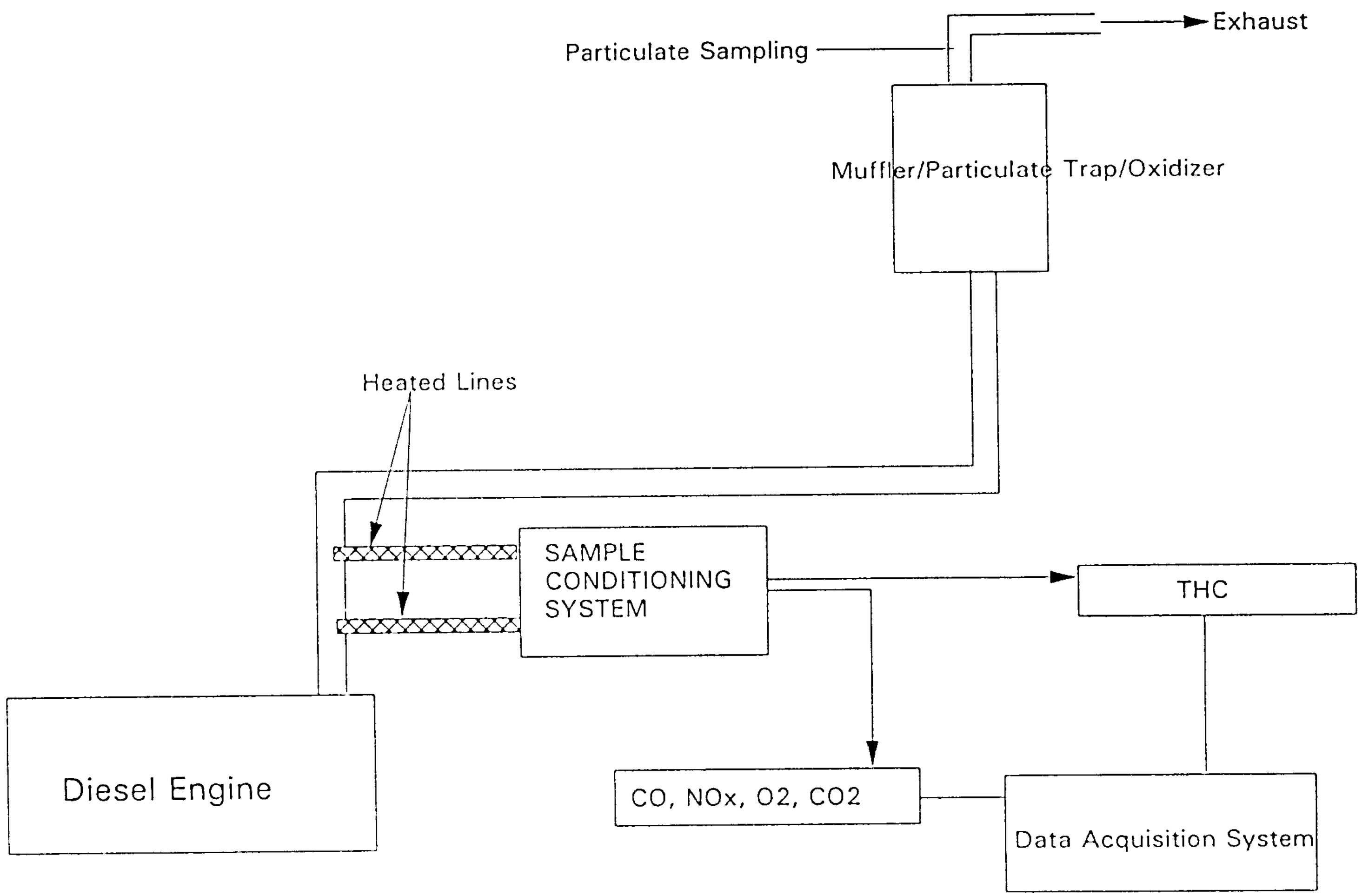



Figure 5-2. Schematic of continuous emission monitoring system

# SECTION 6

# CONCLUSION

This report evaluates the feasibility of application of retrofit $NO_x$ and PM control technologies to Navy diesel engines. The U.S. Navy has a large number of ship-board diesel engines and is addressing the problem of $NO_x$ and PM emissions through a joint effort with the U.S. Environmental Protection Agency (EPA) under the Strategic Environmental Research and Development Program (SERDP). The overall objective of this program is to develop a cost-effective modification package that will reduce $NO_x$ and PM emissions from ship-board diesel engines to meet the proposed, future, national and international standards. The following tasks were undertaken in this report to achieve this objective.

- Evaluate the impact the proposed emission standards (local, national and international) will have on Navy diesels.
- Review and identify potential $NO_x$ and PM control technologies applicable to marine diesels.
- Select potential $NO_x$ control technologies for application testing from a stand point of technical feasibility, cost and impact on ship/engine operations.
- Prepare a preliminary modification package design plan for the application development testing and on-board ship demonstration.

In parallel to these tasks, the selected technologies will be further evaluated through testing on a DDC 4-71 test engine at the EPA's Environmental Research Center in RTP, NC, and at the North Carolina

State University's (NCSU at Raleigh, NC) engine dynamometer facility. The results from these testing efforts will be presented in a subsequent report.

The following is a summary of the recommended courses-of-action and conclusions reached to meet the overall objective of this program, and the above mentioned specific tasks in particular.

(1) In 1994 EPA issued a Notice for Proposed Rule Making (NPRM) addressing emissions from marine engines including diesels. The proposed emission standards for diesel engines are 9.2 g/kWh for $NO_x$. 1.3 g/kWh for HC, 11.4 g/kWh for CO, 0.54 g/kWh for PM, and smoke standards of 20/50 maximum percentage opacity for acceleration/peak operating modes. These standards apply to new compression-ignition marine diesel engines, regardless of power rating. Existing in-use engines are subject to the standards, and as a result most of the engines in the Navy's inventory will not be affected by the proposed standards. However, they can serve as a target guideline to determine the emission reductions.

(2) The Navy has in the order of 2,750 diesel engines (Appendix A) in its inventory. Power ratings for these engines range from 250 kW (333 hp) to 12,000 kW (16,000 hp), and the applications are diverse - small boats account for 37 percent; main and emergency generators account for 42 percent; main propulsion engines account for 17 percent; and other applications such as fire pumps, cranes, salvage equipment, etc., account for 4 percent. At about 63 percent of the total engines Detroit Diesel Corporation engines constitute a major fraction of the Navy's diesel engines. The remainder of the engine types include ALCO, Colt PC, Fairbanks-Morse, Cummins, Caterpillar, Isotta Fraschini and EMD. A preliminary survey indicates that the brake-specific $NO_x$ emissions from the above engines range between 5 and 15 g/kWh (see Table 2-3), and over 40 percent

of the engines will require some kind of modification/retrofit to comply with the proposed guideline standard of 9.2 g/kWh $NO_x$.

(3) A number of $NO_x$ and PM reduction methods/strategies were reviewed. From the standpoint of feasibility of application and cost, the following control methods were chosen for further evaluation:

$NO_x$ Control

- Injection timing retard
- Exhaust gas recirculation; internal and external
- Water injection; emulsions and fumigation
- Lean $NO_x$ and DENOX

PM Control

- Particulate traps
- Oxidation catalysts
- Fuel additives

Most of the above methods are being evaluated at the EPA's Environmental Research Center (ERC) at RTP, NC on a DDC 4-71 two-stroke test engine. A brief description of each of the method follows.

**Injection Timing Retard:** A powerful yet easy method to implement where the ignition time is delayed by varying the physical location of the injector. $NO_x$ reductions up to 25 percent are expected on the test engine, however PM and BSFC increases are likely to follow.

**Exhaust Gas Recirculation (EGR):** Proven technology in gasoline engines. EGR affects a decrease in engine $NO_x$ emissions by diluting the charge air entering the cylinder through either recirculating a portion of the exhaust gas (external EGR) or by decreasing the efficiency of scavenging/exhaust stroke and retaining a portion of the exhaust gas in the cylinder (internal EGR). Up to a 25 percent $NO_x$ reduction is expected in the test engine. PM and BSFC increases are expected to follow.

**Water Injection:** Proven technology for $NO_x$ control in many applications including marine applications of gas turbines and heavy fuel oil engines. Application to diesel engines is still mostly developmental. Water injection is accomplished either in the form of a water-in-fuel emulsion or by humidification of the charge air (fumigation). Available data on diesel engines has shown a $NO_x$ reduction of up to 60 percent depending on the mode of water injection, engine type and operating conditions. Most users of this technology claim a decrease in PM and improvements in BSFC.

**Lean $NO_x$ and DENOX:** Proven technology where $NO_x$ is reduced selectively on a catalyst (SCR) using reducing agents such as ammonia, cyanuric acid, diesel, etc. SCR systems are successful in removing $NO_x$ in the 90 percent range. This technology is gaining acceptance (mostly in europe) in marine applications on large main propulsion engines where compromises in performance are not acceptable, yet substantial $NO_x$ reductions are desired. SCR systems are typically bulky and expensive. This technology will not be tested at the ERC.

**Particulate Traps:** Strategies to reduce $NO_x$ emissions almost always are followed by increases in PM. Particulate traps are used to capture exhaust PM. Efficiencies of the particulate traps can be very high (> 99 percent) depending on the level of clean-up required. However, the biggest challenge in the application of the particulate traps is the continuous regeneration of the particulate traps without hindering engine operations.

**Oxidation Catalysts:** Oxidation catalysts catalytically oxidize the soluble organic fraction of the PM which typically constitutes 50 percent of the total PM. The oxidation catalysts operate most efficiently under low fuel-sulfur conditions and with exhaust gas temperatures between 350 and 600°F. For testing on the DDC 4-71 test engine, Johnson-Matthey's catalytic emission muffler (CEM) system will be used. This system has been certified by EPA for use in the urban-bus retrofit program and is expected to remove at least 25 percent of the PM.

**Fuel Additives:** Addition of metals into the fuel at very low concentrations (< 1 ppm to 50 ppm) such as platinum, copper and cerium has been shown by developers to enhance reduction of PM when used in conjunction with oxidation catalysts. The metals in the fuel during combustion form nucleation sites for deposition of soot and other organic carbon which then are oxidized at substantially lower temperatures than that required by a typical oxidation catalyst. Substantial reduction in the PM (up to 90 percent) have been claimed by one vendor at least.

(4) A conceptual control package is presented in Section 5. Based on further evaluation of the above technologies through testing on the DDC 4-71 engine at the ERC, a modification package will be developed for demonstration on a shipboard diesel engine. Prior to shipboard demonstration, the control technologies will be tested on the DDC 4-71 test engine at the engine dynamometer test-bed facility at NCSU. Whether a single method or combination of the above methods are needed will depend on the targeted level of $NO_x$ and PM reductions from the shipboard engine and the following information:

- application of engine
- operating/duty cycles
- baseline emissions data under typical operating conditions, and
- other logistical constraints such as availability of space, potable water, etc.

(5) From the information in this report it becomes clear that a single modification package for all Navy engines, for $NO_x$ and PM control, is not a logical option. For maximized benefits a custom modification package will have to be designed for each family of engines (if not for each engine) based on a detailed inventory of Navy diesels that will include: engine application; operating/duty cycle; area of operation, i.e., harbor, coastal-waters, high-seas, etc.; baseline emissions data under typical operating conditions; and other logistics such as available space, availability of potable water, manpower and impact on ship/engine operations.

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# APPENDIX A

# NAVY DIESELS INVENTORY

Table 7-8. Diesel Engine Exhaust Emission Data

| Engine Model | Hp | $NO_x$ Range (ppm) | Cycle | Typical Application [Main Propulsion Diesel Eng] |
|---|---|---|---|---|
| ALCO 12-251C[1] | 2,150 | 820-941 | 4 | MPDE -12 cyl 251B-YTB 752, 16 cylinder - LST 1182-1198 EDG - 16 cyl - LHA 1-5 [Emergency Diesel Gen.] |
| ALCO 8-251E[2] | 1,075 | 596-1647 | 4 | SSDG - LST 1182-1198 |
| ALCO 8-251F[1] | 1,930 | 610-857 | 4 | N/A [Ships Service Diesel Generator] |
| ALCO 16-251F[1] | 3,240 | 573-637 | 4 | N/A |
| Caterpillar D353 | 550 | Proprietary[3] | 4 | SSDG - ATS 1, ARS 8 |
| Caterpillar D399 | 1,350 | Proprietary[3] | 4 | MPDE - ARS 39, SSDG - ARDM 2, and EDG - AFDM 7 |
| Caterpillar 3508 | 1,000 | Proprietary[3] | 4 | N/A |
| Caterpillar 3512 | 1,501 | Proprietary[3] | 4 | MPDE - TWR 821, SSDG AFDM 7 |
| Caterpillar 3516 | 2,001 | Proprietary[3] | 4 | MPDE - ATS 1, SSDB - AFDB 7 |
| Caterpillar 3606 | 2,390-2,548 | Proprietary[3] | 4 | N/A |
| Caterpillar 3608 | 3,084-3,393 | Proprietary[3] | 4 | SSDG - AOE 6-8 |
| Caterpillar 3612 | 4,640-5,096 | Proprietary[3] | 4 | N/A |
| Caterpillar 3616 | 6,169-6,786 | Proprietary[3] | 4 | N/A |
| Colt PC 4.2 | 16,290 | 1,370[4] | 4 | MPDE - TAO 187 |
| Colt PC 2.6 | 8,500 | 1,279[4] | 4 | MPDE - LSD 41-50 |
| Fairbanks Morse 38D8-1/8 | 1,744 | 1,037[4] | 2 | MPDE - YTB 757, SSDG - LSD 41-50, and EDG - CGN 9, SSN 688, SSBN 726-736 |
| Fairbanks Morse 38F5-1/4 | 671 | 1,197[4] | 2 | EDG - SSN 637, FF1098 |
| Cummins 6BTA5.9M[2] | 220 | 830->855 | 4 | Unknown |
| Detroit Diesel 12V71 7122-3000 | 480 | 1,492 | 2 | MPDE - AGSS 555 |
| Detroit Diesel 12V71R 7122-7000[5] | 425-480 | 916-1,492 | 2 | [Auxiliary Power Diesel Gen] APDE - LKA 113, 114, 117 |
| Detroit Diesel 12V71 7122-7001 | 395 | 1,165 | 2 | MPDE - YTL 588 |
| Detroit Diesel 12V71 7122-7300 | 594 | 1,085 | 2 | APDE - CG 47 |
| Detroit Diesel 12V71 7123-3200 | 413 | 557 | 2 | EDG - CG 29-31 |

Table 7-8. Diesel Engine Exhaust Emission Data (Continued)

| Engine Model | Hp | $NO_x$ Range (ppm) | Cycle | Typical Application |
|---|---|---|---|---|
| Detroit Diesel 12V71 7123-7000 | 360 | 935 | 2 | SSDG - AS 14, EDG - ATF 110 |
| Detroit Diesel 12V71 7123-7200 | 413 | 657 | 2 | EDG - CG 29-31 |
| Detroit Diesel 12V71H 7123-7300 | 510 | 1,196 | 2 | EDG - LSD 36-40, LPD 14,15 |
| Detroit Diesel 12V71T 7123-7305 | 575 | 1,238 | 2 | EDG - AR 5 |
| Detroit Diesel 12V71LC 7124-8202 | 436 | 896 | 2 | SSDG - AFDM 6, EDG AOR 1-7, AE 27-29 |
| Detroit Diesel 12V71RC 7124-7202[1] | 354-436 | 898-972 | 2 | SSDG - AFDM 6 |
| Detroit Diesel 12V71N 7162-7000[3] | 504-581 | 495-930 | 2 | EDG - AFS 3-7 |
| Detroit Diesel 12V71RC 7163-7000[3] | 502-581 | 806-1,062 | 2 | SSDG - FF 1052 Class |
| Detroit Diesel 16V149 9163-1305 | 1,542 | 718 | 2 | SSDG - FFG 7 Class |
| Detroit Diesel 16V149TI[1] | 1,342 | 632-948 | 2 | SSDG - FFG 7 Class |
| EMD 16-645E5 | 2,875 | 852-1,387[6] | 2 | MPDE - LST 1179-1181, YTB 799-802, SSDG - AS 19, and EDG - CVN 68-75 |
| EMD 16-710G7A | 3,600 | 410-1,120[4] | 2 | N/A |
| Isotta Fraschini 1D36V6SSAM[2] | 600 | 633 | 4 | MPDE - MCM 3-5, SSDG - MCM 3-5 |
| Waukesha 1616DSIN[2] | 588 | 349-808 | 4 | MPDE MCM 1-2, SSDG - MCM 1-2 |

NOTES:
1. Engine data provided not for exact model in fleet
2. Navy-collected emission test data
3. Proprietary data - Contact SEA 05X31 for additional information
4. Data reported on a mass basis only - converted to ppm
5. Multiple injector size combinations included in data
6. Data not corrected to 15% $O_2$

Figure 7-2 shows graphically some of the diesel engine emissions broken down into main propulsion two- and four-cycle engines and diesel generator two- and four-cycle engines. The ship and engine models identified represent some of the largest population of engines in the fleet: approximately 550 main propulsion diesel engines and 923 ship service and emergency diesel generators in operation.

## Table 7-28. Fleet Diesel Engine Population Summary

| Manufacturer | Total of fleet population | | MPDE | | SSDG | | EDG | | Small boat | | Other applications | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Percent[1] | Number | Percent[2] | Number | Percent[2] | Number | Percent[2] | Number | Percent[1] | Number | Percent[2] |
| ALCO/GE of Canada | 174 | 6.4 | 111 | 63.8 | 51 | 29.3 | 12 | 6.9 | | | | |
| Caterpillar | 174 | 6.4 | 74 | 42.5 | 69 | 39.7 | 18 | 10.3 | | | 13 | 7.5 |
| COLTEC | 387 | 14.3 | 115 | 29.7 | 39 | 10.1 | 233 | 60.2 | | | | |
| Cleveland Diesel | 29 | 1.1 | 8 | 27.6 | 8 | 27.6 | 13 | 44.8 | | | | |
| Detroit Diesel | 1692 | 62.5 | 56 | 3.3 | 411 | 24.3 | 132 | 7.8 | 992 | 58.6 | 101 | 6.0 |
| EMD | 85 | 3.1 | 30 | 35.3 | 23 | 27.1 | 32 | 37.6 | | | | |
| IF | 42 | 1.6 | 24 | 57.1 | 18 | 42.9 | | 0.0 | | | | |
| Waukesha | 80 | 3.0 | 30 | 37.5 | 50 | 62.5 | | 0.0 | | | | |
| Other | 46 | 1.7 | 24 | 52.2 | 12 | 26.1 | 10 | 21.7 | | | | |
| | | | | | | | | | | | | |
| Total | 2709 | 100 | 472 | 17.4 | 681 | 25.1 | 450 | 16.6 | 992 | 36.6 | 114 | 4.2 |

Notes
[1] Percentage of total fleet population for the particular manufacturer
[2] Percentage of application population by manufacturer

Table 7-29. Fleet Diesel Engine Population

| Manufacturer | Series/model number | Engine population | Bhp rating | Application |
|---|---|---|---|---|
| ALCO | 251B | 1 | 1000 | MPDE |
| | 251C | 122 | 1530-2750 | MPDE, EDG |
| | 251E | 51 | 1075 | SSDG |
| Caterpillar | D326F, D330B, D333, D348, D353 | 47 | 122-405 | Crane, fire pump, salvage, SSDG |
| | D379, D397, D398, D399 | 99 | 450-1125 | MPDE, SSDG, EDG |
| | 3300, 3400, 3500 | 28 | 100-1700 | MPDE, SSDG, EDG, fire pump |
| Coltec | 38F5-1/4 | 55 | 428-716 | EDG |
| | 38D8-1/8 | 274 | 700-2660 | MPDE, SSDG, EDG |
| | PC 2.5 | 28 | 8500 | MPDE |
| Detroit Diesel | Series 53 | 7 | 100-175 | Fire pump, crane |
| | Series 71 | 1451 | 100-400 | Tube cleaning, fire pump, SSDG, EDG, and small boat |
| | Series 149 | 204 | 1600 | SSDG |
| EMD | 567C | 9 | 1400-1490 | EDG |
| | 645E2 | 34 | 1125-1420 | MPDE, SSDG, EDG |
| | 645D5 | 42 | 2150-2750 | MPDE, EDG |
| Waukesha | L1616DN | 11 | 300 | SSDG |
| | L1616DSIN | 69 | 600 | MPDE, SSDG |
| Total | | 1602 | | |

Notes:
- MPDE - Main propulsion diesel engine
- EDG - Emergency diesel generator
- SSDG - Ship service diesel generator
- Crane - Crane service
- Fire pump - Fire pump engine
- Salvage - Salvage engine