Alternative Control Techniques Document:
Stationary Diesel Engines

FINAL REPORT

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List of Acronyms

Alternative Control Techniques	ACT
Ammonium Bisulfate	NH_4HSO_4
Anhydrous Ammonia	NH_3
Barium Carbonate	$BaCO_3$
Barium Hydroxide	$Ba(OH)_2$
Barium Nitrate	$Ba(NO_3)_2$
Best Demonstrated Available Technology	BDAT
California Air Resource Board	CARB
Carbon Dioxide	CO_2
Carbon Monoxide	CO
Catalyzed Diesel Particulate Filter	CDPF
Closed Crankcase Ventilation	CCV
Compression Ignition	CI
Continuous Emission Monitoring Systems	CEMS
Diesel Oxidation Catalyst	DOC
Diesel Particulate Filter	DPF
Dinitrogen Pentoxide	N_2O_5
Dinitrogen Tetroxide	N_2O_4
Diesel Oxidation Catalyst	DOC
Engine Manufacturers Association	EMA
Environmental Protection Agency	EPA
Exhaust Gas Recirculation	EGR
Flow-through Filter	FTF
Fuel-bound Nitrogen	FBN
Lean NO_X Catalyst	LNC
Lean NO_X Traps	LNT
Manufacturers of Emissions Control Association	MECA
National Emission Standards for Hazardous Air Pollutants	NESHAP
New Source Performance Standards	NSPS
Nitrate	NO_3
Nitrogen	N_2
Nitrogen Dioxide	NO_2
Nitrogen Oxide	NO
Nitrogen Oxides	NO_X
Nitrogen Trioxide	N_2O_3
Nitrous Oxide	N_2O
Northeast States for Coordinated Air Use Management	NESCAUM
Office of Transportation and Air Quality	OTAQ
Oxygen	O_2
Open Crankcase Ventilation	OCV

Palladium	Pd
Particulate Matter	PM
Platinum	Pt
Power Systems Research	PSR
Purchased Equipment Cost	PEC
Pyridine	C_5H_5N
Reciprocating Internal Combustion Engines	RICE
Selective Catalytic Reduction	SCR
Soluble Organic Fraction	SOF
Spark Ignition	SI
Sulfur Dioxide	SO_2
Sulfur Oxides	SO_X
Total Hydrocarbons	THC
Ultra Low Sulfur Diesel	ULSD
Urea	$(NH_2)_2CO$
Water	H_2O

List of Units

Horsepower	HP
Parts Per Million	ppm
Revolutions Per Minute	rpm
Pounds	lb
Hour	hr
Kilowatt	kW
Inches	in
Tons Per Year	TPY

1.0 INTRODUCTION AND PURPOSE

This alternative control techniques (ACT) document addresses criteria pollutant control technologies and strategies for stationary diesel reciprocating internal combustion engines (RICE). The criteria pollutants that are addressed include: nitrogen oxides (NO_X), particulate matter (PM), carbon monoxide (CO), and total hydrocarbons (THC). The control technologies that are investigated include selective catalytic reduction (SCR), diesel particulate filter (DPF), catalyzed diesel particulate filter (CDPF), flow-through filtration (FTF), exhaust gas recirculation (EGR), closed crankcase ventilation (CCV), open crankcase ventilation (OCV), diesel oxidation catalyst (DOC), and ultra-low sulfur diesel fuel (ULSD), in addition to some emerging technologies. Previous EPA ACT documents for RICE have focused on only NO_X controls and include: *Alternative Control Techniques Document - NO_X Emissions from Stationary Internal Combustion Engines* (EPA-453/R-93-032) dated July 1993, and *Stationary Reciprocating Internal Combustion Engines - Updated Information on NO_X Emissions and Control Techniques* dated September 2000. This document is the first ACT for RICE that addresses pollutants other than NO_X.

This ACT document provides technical information for use by State and local agencies to develop and implement regulatory programs to control emissions of NO_X, PM, CO, and THC from stationary diesel engines, particularly in ozone and PM nonattainment areas.

Stationary diesel engines are used in a wide range of applications. Diesel engines are known to be durable and long-lasting and can provide work or electricity for just about any industrial or commercial application. They are used in both continuous and emergency applications. It must be recognized that the alternative control techniques and the corresponding achievable criteria pollutant emission levels presented in this document may not be applicable for every stationary diesel engine application. The size and design of the engine, the operating duty cycle, site conditions, and other site-specific factors must be taken into consideration, and the suitability of a control technique must be determined on a case-by-case basis.

The information in this ACT document was generated through a literature search and from information provided by engine manufacturers, control equipment vendors, engine users, and regulatory agencies. Chapter 2.0 presents information on engine operation and industry applications. Chapter 3.0 contains a discussion of NO_X, PM, CO, and THC formation and the uncontrolled emission factors for these pollutants. Control techniques and achievable emission reductions are included in Chapter 4.0. The cost and cost per ton of the control techniques are presented in Chapter 5.0. Chapter 6.0 describes environmental and energy impacts associated with implementing the control techniques.

2.0 DESCRIPTION OF STATIONARY DIESEL ENGINES

Stationary diesel engines are used in a wide variety of applications where mechanical work is performed using shaft power. The mechanical work can be used to generate electricity, drive pumps for irrigation applications and flood control, and to drive compressors. EPA has estimated that 80 percent of the stationary diesel engines in the U.S. are emergency engines.[1] These emergency or standby engines are used to provide electricity to office buildings, industrial plants, hospitals, and homes during emergency situations where the primary power is unavailable. Emergency engines are also used to drive fire and flood control pumps. Stationary diesel engines are designed to meet a wide range of speed and load requirements, to be quickly installed, and to be outfitted with the instrumentation necessary for remote operation. Stationary diesel engines vary in size from 50 horsepower (HP) to as much as 25,000 HP. The smaller sized engines (50 – 500 HP) are typically used at construction sites, farms and households. The larger sized (> 500 HP) engines are generally used for electric generating or industrial applications.

This chapter describes the physical components and operating cycles of stationary diesel engines and includes a description of the applications of these engines in industry and agriculture. The operating design considerations are discussed in Section 2.1. The stationary diesel engine operating cycles are described in Section 2.2. The charging methods used for stationary diesel engines are described in Section 2.3. A summary of the engine sizes is presented in Section 2.4, and a summary industrial applications and population is presented in Section 2.5. Section 2.6 provides a list of the references used in this chapter.

2.1   Operating Design Considerations

A diesel engine is an internal combustion engine that converts the chemical energy in diesel fuel to mechanical energy. This energy conversion takes place in a cylinder equipped with a piston and a diesel fuel injector. The piston compresses the air in the cylinder until it reaches the ignition temperature of the diesel fuel. Then diesel fuel is injected into the hot compressed air which ignites the diesel fuel spontaneously, called compression ignition (CI). This

combustion of the diesel fuel causes the piston to move up and down inside the cylinder. The piston is connected to a crankshaft, which transforms the linear motion of the piston into rotary motion needed to generate electricity, drive a compressor or pump, or produce other kinds of work.

All diesel engines are CI engines that operate at a higher compression ratio (the ratio of the cylinder volume when the piston is at the bottom of its stroke to the volume when it is at the top) than spark ignition (SI) engines (e.g., gasoline-fired, natural gas-fired). This higher compression ratio is needed to reach the ignition temperature of the diesel fuel. The higher compression ratio also makes CI engines more efficient as compared to SI engines.

Two types of diesel engines are manufactured: two-stroke and four-stroke. Two-stroke engines are generally used in small power applications, whereas four-stroke engines are generally used for larger applications. Two-stroke engines have the advantage of a higher horsepower-to-weight ratio compared to four-stroke engines when both are operating at the same speed. In addition, the mechanical design of the two-stroke engine is simplified by using intake and exhaust ports rather than valves. However, four-stroke engines tend to be slightly more efficient and emit lower levels of pollutants than two-stroke engines. Nearly all new diesel stationary engines are four-stroke engines, however some manufacturers still produce two-stroke engines for slow speed oil pumping applications. Four-stroke engines have become the industry standard due to customer demands for efficiency and the need to meet more stringent emission limitations.

2.2 Operating Cycles

For diesel engines, the combustion process may be accomplished with either a two-stroke or four-stroke cycle. For an engine, a stroke is defined as the movement of the piston from one end of the cylinder to the other end. A description of the two-stroke and four-stroke operating cycles is presented in the following sections.

2.2.1 Two-Stroke Cycle

A two-stroke cycle completes the power cycle in one revolution of the crankshaft. As shown in Figure 2-1, the first stroke draws air into the cylinder using a low pressure blower as the piston moves away from the bottom of the cylinder and toward the top. As the piston nears the top of the cylinder, fuel is injected into the combustion air and the mixture is compressed and combusts, forcing the piston downwards. In the second stroke, the piston delivers power to the

1 – SCAVENGING

2 – COMPRESSION

3 – POWER

4 – EXHAUST

AIR

AIR FUEL MIXTURE
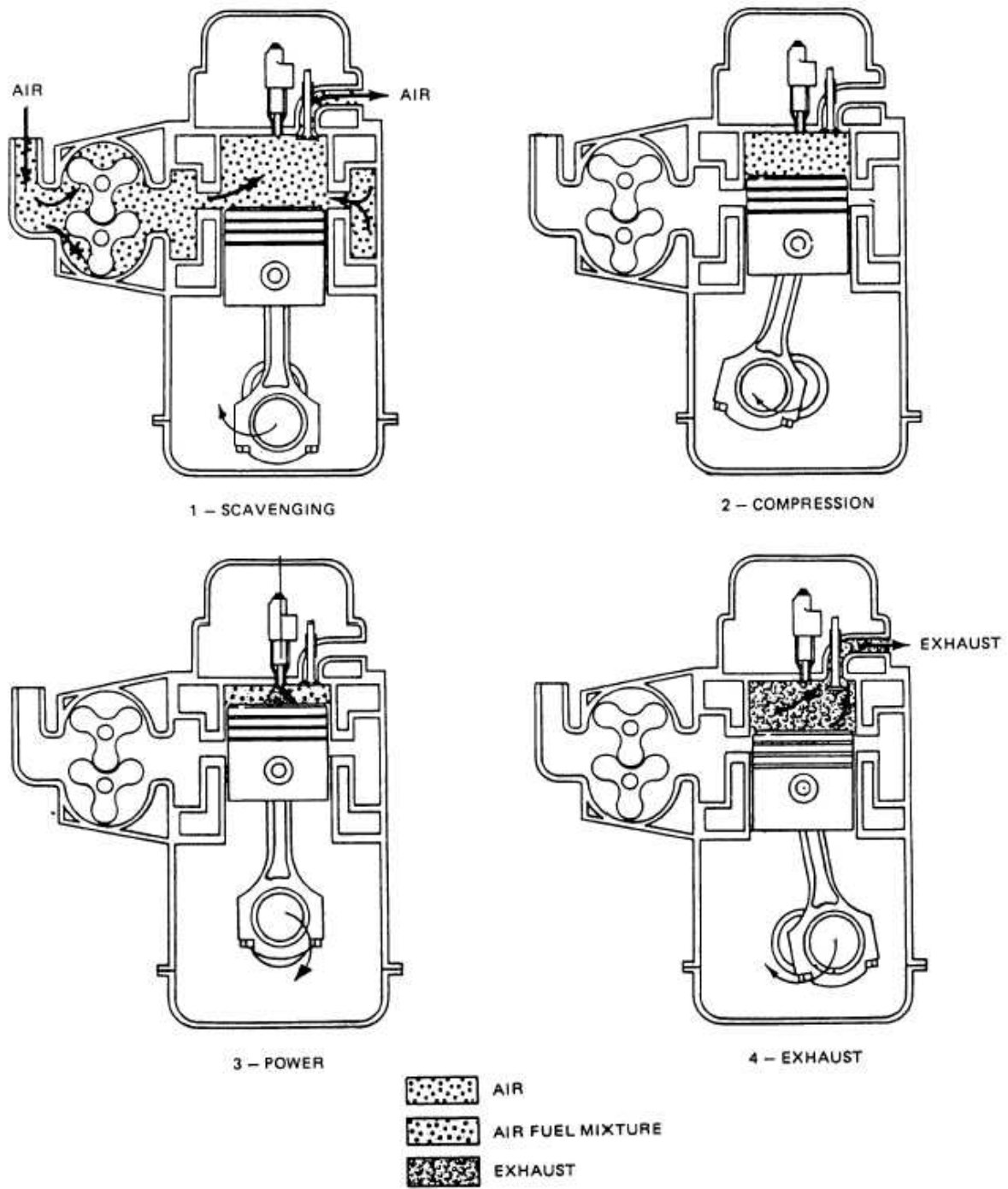
EXHAUST

Figure 2-1. Schematic of Diesel Engine Two-Stroke Cycle[2]

crankshaft as it is forced downwards by the high pressure produced by the combustion of the air and diesel fuel. As the piston moves down the cylinder, exhaust ports are uncovered, allowing the combustion gases to exit from the cylinder. As the piston begins the next cycle, the remaining combusted gas is cleared from the cylinder by the upward motion of the piston and by the introduction of new combustion air into the cylinder as a new cycle begins.

2.2.2 Four-Stroke Cycle

The four-stroke cycle requires two revolutions of the crankshaft to complete the power cycle and generate work. The intake stroke draws air into a cylinder as the piston moves away from the intake valve. In the compression stroke, the piston's ensuing upward push compresses the air, reducing its volume and increasing the temperature of the air. Then fuel is injected under high pressure as the piston approaches the top of its compression stroke, and the fuel spontaneously ignites upon contact with the heated air. As the hot combustion gases expand, the piston moves downward to deliver rotational energy to the crankshaft in what is called the power stroke. In the return swing or exhaust stroke, the piston pushes spent gases from the cylinder, and the cycle starts over with an intake of fresh air. This sequence of events is shown pictorially in Figure 2-2.

2.3 Charging Methods

There are three methods that are used to introduce or charge the air into the cylinder of the diesel engine. These methods are natural aspiration, blower-scavenging, and turbocharging or supercharging. These charging methods are discussed in the following sections.

2.3.1 Natural Aspiration

In a naturally-aspirated diesel engine, a valve at the top of the cylinder opens which allows air to flow into the cylinder. The air is forced into the cylinder by atmospheric pressure in response to a partial vacuum that occurs as the piston moves toward the bottom of the cylinder during the intake stroke. This charging method is shown in panel A of Figure 2-2. Natural aspiration is found only on four-stroke engines which have an intake stroke that allows the introduction of combustion air into the cylinder.
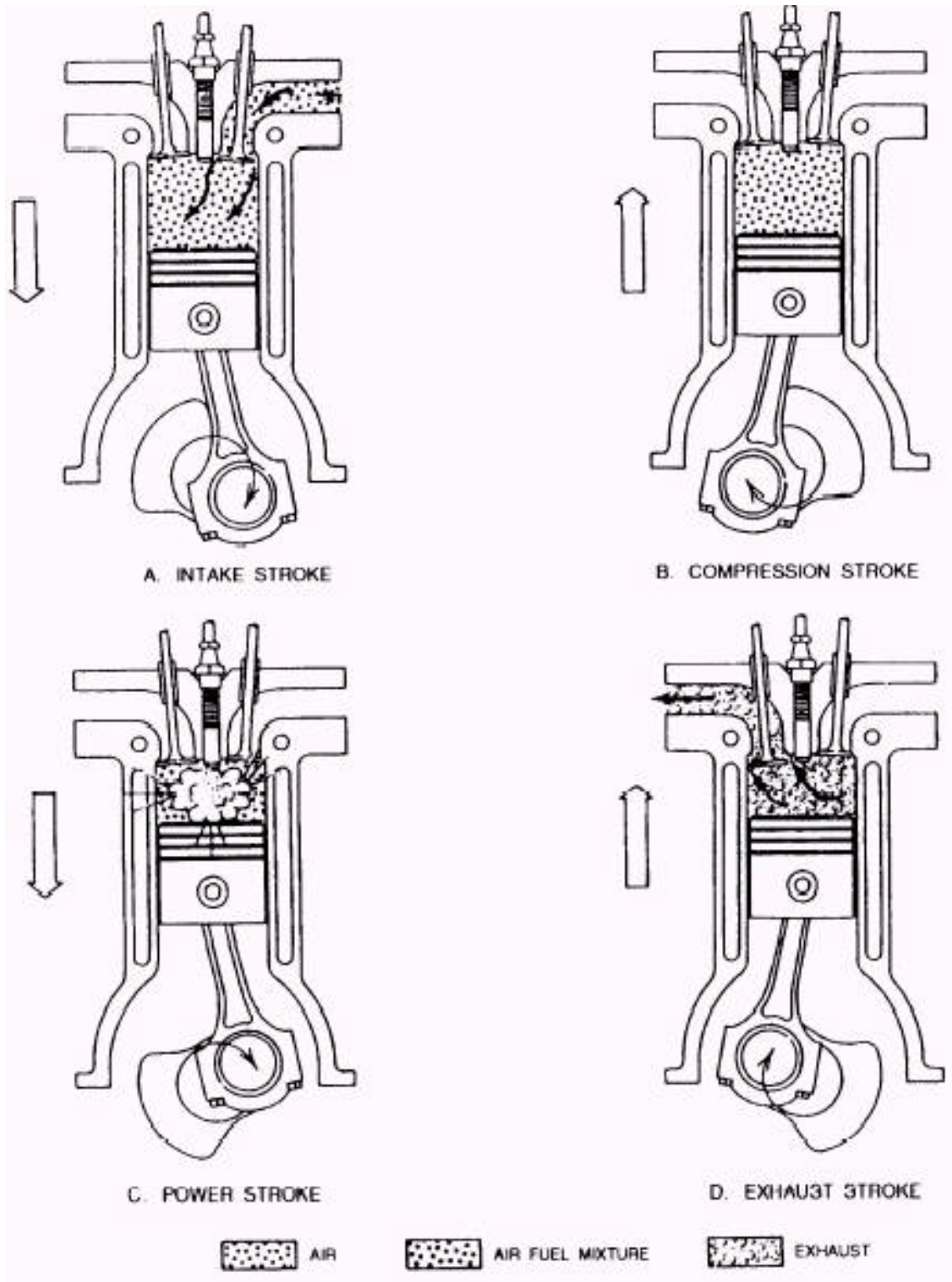
Figure 2-2. Schematic of Diesel Engine Four-Stroke Cycle[3]

2.3.2 Blower-Scavenging

Blower-scavenging is used on two-stroke engines to charge air into the cylinder prior to combustion. A diagram of this charging method is shown in panel A of Figure 2-1. The high volumetric flow rates created by the blower are also effective in purging the cylinder of combustion gases. However, the blower does not increase the overall engine efficiency as much as turbocharging or supercharging.

2.3.3 Turbocharging/Supercharging

Turbocharging or supercharging is the forced-induction of air into the cylinder using an air compressor. This forced-induction is generally found on four-stroke engines; however the two-stroke engine can also be modified to be equipped with a turbocharger. The purpose of turbocharging or supercharging is to increase the mass of air entering the engine to create more power. This is accomplished by placing a compressor wheel upstream of the intake air manifold. The compressor wheel is driven either by the engine crankshaft (supercharging), or it is powered by a turbine driven by the engine's own exhaust gases (turbocharging). These methods were originally designed to overcome performance problems at high altitudes, where air pressure is low. Because a larger mass of air is introduced to the cylinder, additional diesel fuel can also be injected, thereby increasing the cylinder power output. This increase in power also produces an increase in temperature, which may limit the amount of air that could be charged to the cylinder at a given pressure. Therefore, a heat exchanger called an intercooler or aftercooler is normally used to lower the temperature of the intake air. This heat exchanger is located between the turbocharger and the intake manifold.

Turbocharging and supercharging are normally designed to increase an engine's output to approximately 1.5 times its original power. However if an engine is designed to withstand the higher internal pressures, turbocharging or supercharging can be used to increase the engine's power output two to three times its naturally aspirated value. Turbocharging was noted to be the most common method of air pressurization for stationary diesel-fueled engines in a study in Southern California.[4]

2.4   Engine Sizes

There are two size classes that are commonly used to describe stationary diesel engines: medium size engines and large size engines. Although there is some overlap between the classes, the differences tend to be more distinct when viewed on a HP or speed (e.g., revolutions per minute or rpm) basis.

Medium size engines typically produce work outputs of 50 to 1,200 HP (37 to 900 kW) at engine speeds of 1,000 to 4,000 rpm. These are regarded as medium-power, high-speed engines. They have a lower power output per cylinder than do large size engines and therefore require more cylinders to achieve a given engine HP. The high rotary speeds and the wide range of HP available make medium size engines desirable for many uses, including agricultural, non-propulsive marine, commercial, and miscellaneous industrial applications.[5]

Large size engines typically produce work outputs of 400 to 13,000 HP (300 to 9,700 kW) at engine speeds of 250 to 1,200 rpm, and are generally considered low- to medium-speed engines. Large size, high-power engines are usually four-stroke designs that operate on diesel fuel oil. A small percentage of these engines have been modified to operate using a dual-fuel mixture of diesel oil and natural gas. The large size, low-speed engines, with their high power output per cylinder, are more economical to operate than medium-bore engines because of their lower fuel consumption and longer service life. Therefore, they tend to be used in applications requiring continuous operation, such as municipal electrical power generation and oil and gas production.[6]

2.5   Industry Applications

Stationary diesel engines are used in a wide variety of applications. These engines are categorized by charging method, number of stokes per cycle, and by size. The following sections describe the characteristics of stationary diesel engines of various sizes and their applications.

2.5.1 Stationary Diesel Engine Population

The population of existing stationary diesel engines is based on the Power Systems Research's (PSR) North American Engine PartsLink Database.[7] The most recent year for which population information was available from PSR's database was 1998 for CI engines.

The information in PSR's database was separated by engine size range and by application type. The information from PSR includes both mobile and stationary engines, so it was necessary to determine which applications can be used for stationary applications and distinguish the actual fraction of engines used in stationary applications.

The following applications were used to group engine types:

- Generator sets
- Air compressors
- Pumps
- Welders
- Irrigation sets
- Hydro power units.

To estimate the existing stationary diesel engine population in 2008, engine sales information from PSR was used to project the number of new engines that would be sold in the years 1999 through 2007 for CI engines. This same methodology was used to estimate the number of new stationary engines for the CI and SI New Source Performance Standards[8] (NSPS), as well as the RICE National Emission Standards for Hazardous Air Pollutants (NESHAP).[9] Population data gathered by EPA and the California Air Resources Board (CARB) indicate that a majority of stationary diesel engines are greater than 50 HP.[10] The population of stationary diesel engines is broken down by size range and is presented in Table 2-1.

Table 2-1. Total Estimated 2008 Population of Stationary Diesel Engines

Size Range (HP)	CI Engines
50-100	262,505
100-175	328,759
175-300	254,778
300-600	191,239
600-750	31,807
>750	79,976
Total	**1,149,064**

Information received from the Engine Manufacturer's Association (EMA) was used to determine how the population of existing stationary diesel engines was distributed over various model years. A summary of this information is presented in Table 2-2. A similar version of the information in Table 2-2 was presented in an Advanced Notice of Proposed Rulemaking EPA published in 2008 seeking information on stationary diesel engines.[11] Note that the population in Table 2-2 is based on earlier population estimates and does not match the updated estimates presented in Table 2-1 of this document. Table 2-2 is intended to present an overview of how the population of engines are distributed over different model years.

Table 2-2. Breakdown of Stationary Diesel Engines by Model Year

Size Range (HP)	<1980	1980-1994	1994-2001	2002-2005	Totals
50-100	26,200	62,759	49,919	22,521	161,399
100-175	57,426	92,857	61,572	23,634	235,489
175-300	27,198	63,991	57,739	40,877	189,805
300-600	70,303	53,188	38,778	31,403	193,672
600-750	8,562	12,664	10,743	8,648	40,617
>750	6,899	28,357	33,835	10,520	79,611
Total	**196,588**	**313,816**	**252,586**	**137,603**	**900,593**

2.5.2 Stationary Diesel Engine Applications

Stationary diesel engines are used in a number of different applications. These engines are used to generate electricity for industrial plants, office buildings and even cities and towns. In addition, a number of stationary diesel engines are used as air compressors, welders, pumps, and for agricultural irrigation. The stationary diesel engine is ideal for providing work or power to remote areas or for applications that require intermittent power. The PSR data suggests that the largest market for stationary diesel engines under 300 HP (225 kW) is standby power generation applications, followed by agricultural and industrial applications. Fewer than 5 percent of diesel engines less than 300 HP are used in continuous power generation. Installations for diesel engines above 300 HP are primarily power generation and are nearly evenly divided between continuous duty and standby applications. A study prepared by the Northeast States for Coordinated Air Use Management (NESCAUM) estimated that 80 percent of diesel generators in the Northeast (accounting for 74 percent of the total Megawatt capacity) are designated for emergency use.[12]

2.6   References for Chapter 2

1. Memorandum from Tanya Parise, AGTI to Jaime Pagán, EPA Energy Strategies Group, June 26, 2008, Existing Population of Stationary RICE.

2. Integrated Publishing, Engine Mechanics, Figure 1-14.—Two-stroke diesel cycle. http://www.tpub.com/content/engine/14081/css/14081_23.htm

3. Integrated Publishing, Engine Mechanics, Figure 1-10.—Four-stroke diesel cycle. http://www.tpub.com/eqopbas/3.htm

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5. Acurex Corporation. Environmental Assessment of Combustion Modification Controls for Stationary Internal Combustion Engines. Publication No. EPA-600/7-81-127. U. S. Environmental Protection Agency, Research Triangle Park, NC. July 1981. pp. 3-8 through 3-11.

6. Acurex Corporation. Environmental Assessment of Combustion Modification Controls for Stationary Internal Combustion Engines. Publication No. EPA-600/7-81-127. U. S. Environmental Protection Agency, Research Triangle Park, NC. July 1981. pp. 3-8 through 3-11.

7. Memorandum from Tanya Parise, AGTI to Jaime Pagán, EPA Energy Strategies Group, June 26, 2008, Existing Population of Stationary RICE.

8. Memorandum from Tanya Parise, AGTI to Jaime Pagán, EPA Energy Strategies Group, June 26, 2008, Existing Population of Stationary RICE.

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10. Stationary Diesel Engines in the Northeast: An Initial Assessment of the Regional Population, Control Technology Options and Air Quality Policy Issues, Northeast States for Coordinated Air Use Management, June 2003.

11. Emission Standards for Stationary Diesel Engines: Advanced Notice of Proposed Rule Making (73 FR 4136), January 24, 2008. http://www.epa.gov/ttn/atw/rice/ricepg.html

12. Northeast States for Coordinated Air Use Management, Stationary Diesel Engines in the Northeast: An Initial Assessment of the Regional Population, Control Technology Options and Air Quality Issues, June 2003.

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3.0 CHARACTERIZATION OF DIESEL EXHAUST EMISSIONS

This chapter describes the formation of NO_X, PM, CO, and THC from stationary diesel engines. In addition, this section will discuss the factors that influence the rate of formation of these pollutants and the uncontrolled emission factors for these pollutants. Section 3.1 discusses the formation of each of the criteria pollutants. Section 3.2 presents the criteria pollutant emission factors for each of the criteria pollutants. Section 3.3 lists the references used in this chapter.

3.1   *Formation of Diesel Exhaust Emissions*

Stationary diesel engine exhaust emissions (commonly known as 'diesel exhaust') are a mixture of gases, vapors, liquid aerosols and substances made up of particles. The diesel exhaust contains both products of complete combustion: carbon dioxide (CO_2), water (H_2O), NO_X, and sulfur dioxide (SO_2) and products of incomplete combustion. The incomplete combustion products include PM, CO, and THC. The following sections provide a description of the formation of each of these combustion products, and provide emission factors for estimating emissions of these pollutants. The emissions of NO_X and CO are contributors to the formation of ozone in the atmosphere. A growing body of research indicates that black carbon (which is present in diesel exhaust) plays a role in global warming. The emissions of PM, NO_X, sulfur oxides (SO_X), ozone and air toxics contribute to serious public health problems in the United States. These problems include premature mortality, aggravation of respiratory and cardiovascular disease, aggravation of existing asthma, acute respiratory symptoms, chronic bronchitis, and decreased lung function. EPA has concluded that diesel exhaust is likely to be carcinogenic to humans by inhalation.[1]

3.1.1 Formation of Nitrogen Oxides

The combustion of the air/fuel mixture in the cylinder of a diesel engine results in the dissociation of nitrogen (N_2) and oxygen (O_2) into individual N and O atoms. The N and O atoms can react in the cylinder and in the exhaust stream to form seven known oxides of nitrogen: nitrogen oxide (NO), nitrogen dioxide (NO_2), nitrate (NO_3^-), nitrous oxide (N_2O),

nitrogen trioxide (N_2O_3), dinitrogen tetroxide (N_2O_4), and dinitrogen pentoxide (N_2O_5). The main source of nitrogen in the chemical formation of NO_X is atmospheric, and a very small portion is caused by nitrogen compounds found in some fuels.

Virtually all NO_X emissions originate as NO. This NO is further oxidized in the exhaust system or later in the atmosphere to form the more stable NO_2 molecule.[2] There are two mechanisms by which NO_X is formed in a diesel engine:

1) the oxidation of atmospheric nitrogen found in the combustion air (thermal NO_X), and
2) the conversion of nitrogen chemically bound in the fuel (fuel NO_X, or organic NO_X).

Thermal NO_X is the dominant NO_X formation mechanism in stationary diesel engines since nitrogen levels in diesel fuel are generally low. These mechanisms are discussed below.

3.1.1.1 Formation of Thermal NO$_X$

Thermal NO_X is formed in the combustion chamber when N_2 and O_2 molecules dissociate into free atoms at the elevated temperatures and pressures encountered during combustion and then recombine to form NO by the Zeldovich mechanism.[3] The simplified reactions are shown below:

$$O_2 \rightarrow 2O$$
$$O + N_2 \rightarrow NO + N$$
$$N + O_2 \rightarrow NO + O$$
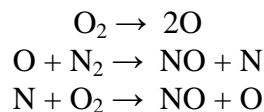
The reaction rate toward NO formation increases exponentially with temperature. The NO further oxidizes to NO_2 and other NO_X compounds downstream of the combustion chamber.

3.1.1.2 Formation of Fuel NO$_X$

Fuel NO_X (also known as organic NO_X) is formed when fuels containing nitrogen are burned. Nitrogen compounds are present in diesel fuel as pyridine (C_5H_5N) that tends to concentrate in the heavy resin and asphalt fractions upon distillation. When these fuels are burned, the nitrogen bonds break and some of the resulting free nitrogen oxidizes to form NO_X.[4] With excess air, the degree of fuel NO_X formation is primarily a function of the nitrogen content

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in the fuel. The fraction of fuel-bound nitrogen (FBN) converted to fuel NO_X decreases with increasing nitrogen content, although the absolute magnitude of fuel NO_X increases. For example, a fuel with 0.01 percent nitrogen may have 100 percent of its FBN converted to fuel NO_X, whereas a fuel with a 1.0 percent FBN may have only a 40 percent fuel NO_X conversion rate. While the low-percentage-FBN fuel has a 100 percent conversion rate, its overall NO_X emission level would be lower than that of the high-percentage FBN fuel with a 40 percent conversion rate.[5]

3.1.2 Other Products of Incomplete Combustion

The remaining diesel pollutants of concern (PM, THC, and CO) are all products of incomplete combustion of the diesel fuel in the combustion chamber. The degree of fuel mixing and the resulting air-to-fuel ratios, combustion temperature, and residence time all affect the formation of these products to varying degrees. In general, when diesel fuel is injected into the combustion cylinder filled with compressed air, it creates a heterogeneous mixture which combusts when the compressed air reaches the combustion temperature of the fuel. However, in some areas adjacent to the combustion chamber surface, the heat transfer outward through the cylinder walls causes the temperature to be too low to support combustion. The development of oxygen-depleted (fuel-rich) regions in the combustion zone also leads to pollutant formation.

3.1.2.1 Formation of PM

Diesel particulate emissions contain a mixture of soot (unburned carbon), sulfates (from the diesel fuel or oil sulfur), dust (from combustion air), inorganic materials (from fuel, fuel additives, lube oil and lube oil additives), and trace metals (from engine component wear). In addition to these components, diesel exhaust emissions also contain a soluble organic fraction (SOF) that is composed of lube oil derived hydrocarbons and unburned diesel fuel. The majority of emissions of PM from stationary diesel engines are particulate matter less than 2.5 microns ($PM_{2.5}$). The Office of Transportation and Air Quality (OTAQ) estimated that $PM_{2.5}$ comprises 97 percent of the particulate matter less than 10 microns (PM_{10}) emissions from nonroad diesel engines.[6]

The formation of soot is the result of fuel rich conditions in the cylinder caused by the heterogeneous mixing of the fuel and the compressed combustion air. The fuel rich areas of the diesel fuel/compressed air mixture does not have enough oxygen to complete combustion. This results in the decomposition of the diesel fuel by the combustion heat in the cylinder. The decomposition produces solid particles of carbon or soot that are exhausted from the cylinder.

Other types of PM emissions can be caused by the introduction of organic and inorganic compounds into the combustion cylinder. The organic compounds contain a combination of both volatile and semi-volatile compounds that contribute to PM and are often referred to as the SOF. Inorganic components, such as sulfur in diesel fuel and lube oil, contribute to the formation of sulfate particles. Approximately 1 to 3 percent of the sulfur in diesel fuel is converted to sulfate, while the remainder is emitted as gaseous SO_2.[7] The formation of sulfate PM and SOF typically occur after cooling and air-dilution of the exhaust gas from the combustion chamber. Post-combustion treatment of the exhaust using platinum catalysts can oxidize the SOF, thereby lowering PM emissions. However, the catalyst-based post-combustion controls can also oxidize up to 50 percent or more of the SO_2 to sulfate PM, depending on the exhaust temperature and the platinum content of the catalyst.[8]

3.1.2.2 Formation of THC

Hydrocarbons consist of hydrogen/carbon compounds with a variety of different chemical bonds. Most of the gaseous hydrocarbons in diesel exhaust are the result of unburned fuel, although some are formed as combustion products. Engine operating conditions play a role in the formation of THC emissions from the diesel engine. During idle and light load conditions, the engine can operate at an air-to-fuel ratio of 100:1, which produces lean regions of diesel fuel within the combustion zone. These lean regions cause the THC emissions to be much greater during light load or idle conditions than full load.[9] At high load conditions, the increase of diesel fuel to the combustion chambers produces rich regions that do not have enough oxygen to support combustion. This leads to the emission of the unburnt fuel, hence increasing THC emissions. Injection timing also affects THC emissions from the diesel engine. Advancing the start of injection (injecting the diesel fuel before the piston reaches top dead center) produces more areas of lean mixtures, decreasing the combustion efficiency and increasing the amount of

unburned diesel fuel.[10] Delayed injection timing produces overly rich regions which causes incomplete combustion, reduced fuel efficiency, and an increase in exhaust smoke, containing a considerable amount of PM and unburned hydrocarbons.

Hydrocarbon emissions are measured in a number of different forms: THC, non-methane hydrocarbons (NMHC), and volatile organic compounds (VOC). Most hydrocarbon emissions are reported as THC, which is measured using a flame ionization detector (FID) calibrated with propane. Most hydrocarbons respond to the FID nearly identically as propane except for oxygenated hydrocarbons such as alcohols and aldehydes. EPA defines VOC as carbon based compounds that are photochemically reactive in the atmosphere, and are measured with a gas chromatograph using EPA Method 18. Using exhaust emissions data from a diesel highway truck engine, OTAQ calculated the proportion of VOC in THC is 1.053.[11] Based on these data, it can be assumed that THC and VOC diesel engine exhaust emissions are comparable.

3.1.2.3 Formation of CO

Emissions of CO are an intermediate product produced by the incomplete combustion of hydrocarbons. The emissions are formed in hot, oxygen-depleted regions of the combustion chamber and at the edges of the lean flame zone where the temperature is lower. Short residence times also contribute to CO formation. During complete combustion, CO reacts with various oxidants to form CO_2 through recombination reactions. However, these recombination reactions cannot proceed to completion if the combustion temperature is low or there is a deficient amount of oxidants in the combustion gas. Diesel engines do not tend to form as much CO as uncontrolled gasoline engines because the diesel engines generally operate at overall lean air to fuel ratios compared to the fuel rich combustion environments found in gasoline engines.

3.2   Criteria Pollutant Emission Factors

The CO, NO$_X$, PM, and THC emission factors for stationary diesel engines vary by both size (i.e., rated HP) and by model year of the engine. Smaller sized engines tend to produce more PM, CO, and THC per unit of work than larger sized engines. This is because the smaller sized engines are not as energy efficient as the larger sized engines, therefore producing more products of incomplete combustion per unit of work. However, because of their size larger engines tend to produce more NO$_X$ on a mass emission basis than smaller sized engines.

The emission factors also vary by model year of the engine. Federal standards were adopted in 1994, 1998 and 2004 that required manufacturers of new nonroad diesel engines over 50 HP to meet emission standards using a three tier approach. The Tier 1 standards were phased-in from 1996 to 2000. The more stringent Tier 2 standards took effect from 2001 to 2006, and even more stringent Tier 3 standards were phased-in from 2006 to 2008. In 2004, EPA adopted the Tier 4 emission standards, which are to be phased-in over the period of 2008 to 2015. The Tier 4 standards require 90 percent reduction of PM and NO$_X$ emissions. These emission reductions can be achieved through the use of control technologies, including advanced exhaust gas aftertreatment, similar to those required by the 2007-2010 standards for highway engines. Manufacturers that produce nonroad diesel engines also sell some of the same models for stationary applications. Therefore, the criteria pollutant emission levels for newer stationary diesel engines tend to be less than the criteria pollutant emissions from older models.

Criteria pollutant emission factors for stationary diesel RICE are available from a number of different sources. The Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources[12] presents various pollutant emission factors for both large stationary diesel engines (Chapter 3.4), and for stationary industrial diesel engines (Chapter 3.3). Other sources of criteria pollutant emission factors for stationary RICE include: CARB[13] and the Northeast States for Coordinated Air Use Management (NESCAUM).[14] Each of these sources provide emission factors based on collected emission tests for their respective regions.

For purposes of estimating criteria pollutant emissions in this document, the emission factors used in the EPA nonroad engine modeling will be used.[15] The report lists steady-state, zero-hour emissions factors for CO, NO_X, PM and THC, grouped by engine size and model year. A summary of the emission factors are presented in Table 3-1 and Table 3-2. Table 3-1 presents the emission factors in grams per horsepower-hour (g/HP-hr) and Table 3-2 presents the emission factors in pounds per horsepower-hour (lb/HP-hr). Actual in-use emissions from stationary diesel engines may vary considerably and these emission factors should not be used for purposes of calculating emission reductions for State Implementation Plans.

Table 3-1. Criteria Pollutant Emission Factors (g/HP-hr)

Engine Size (HP)	Technology Type	Emission Factors (g/HP-hr)			
		THC	CO	NO$_X$	PM[a]
50 - 75	(pre-1998)	0.99	3.49	6.9	0.722
	Tier 1 (1998-2003)	0.5213	2.3655	5.5988	0.4730
	Tier 2 (2004-2007)	0.3672	2.3655	4.7	0.24
	Tier 3/4 (2008-2012)	0.1836	2.3655	3.0	0.20
	Tier 4 final (2013+)	0.1314	0.237	3.00	0.0184
75-100	(pre-1998)	0.99	3.49	6.9	0.722
	Tier 1 (1998-2003)	0.5213	2.3655	5.5988	0.4730
	Tier 2 (2004-2007)	0.3672	2.3655	4.7	0.24
	Tier 3 (2008-2011)	0.1836	2.3655	3.0000	0.30
	Tier 4 (2012-2013)	0.1314	0.237	3.00	0.0092
	Tier 4 final (2014+)	0.1314	0.237	0.276	0.0092
100 - 175	(pre-1997)	0.68	2.70	8.38	0.402
	Tier 1 (1997-2002)	0.3384	0.8667	5.6523	0.2799
	Tier 2 (2003-2006)	0.3384	0.8667	4.1	0.18
	Tier 3 (2007-2011)	0.1836	0.8667	2.5	0.22
	Tier 4 (2012-2013)	0.1314	0.087	2.50	0.0092
	Tier 4 final (2014+)	0.1314	0.087	0.276	0.0092
175 - 300	(pre-1996)	0.68	2.70	8.38	0.402
	Tier 1 (1996-2002)	0.3085	0.7475	5.5772	0.2521
	Tier 2 (2003-2005)	0.3085	0.7475	4.0	0.1316
	Tier 3 (2006-2010)	0.1836	0.7475	2.5	0.15
	Tier 4 (2011-2013)	0.1314	0.075	2.50	0.0092
	Tier 4 final (2014+)	0.1314	0.075	0.276	0.0092
300 - 600	(pre-1996)	0.68	2.70	8.38	0.402
	Tier 1 (1996-2000)	0.2025	1.3060	6.0153	0.2008
	Tier 2 (2001-2005)	0.1669	0.8425	4.3351	0.1316
	Tier 3 (2006-2010)	0.1669	0.8425	2.5	0.15
	Tier 4 (2011-2013)	0.1314	0.084	2.50	0.0092
	Tier 4 final (2014+)	0.1314	0.084	0.276	0.0092
600 - 750	(pre-1996)	0.68	2.70	8.38	0.402
	Tier 1 (1996-2001)	0.1473	1.3272	5.8215	0.2201
	Tier 2 (2002-2005)	0.1669	1.3272	4.1	0.1316
	Tier 3 (2006-2010)	0.1669	1.3272	2.5	0.15
	Tier 4 (2011-2013)	0.1314	0.133	2.50	0.0092
	Tier 4 (2014+)	0.1314	0.133	0.276	0.0092

Engine Size (HP)	Technology Type	Emission Factors (g/HP-hr)			
		THC	CO	NO$_X$	PM[a]
750-1200	(pre-2000)	0.68	2.70	8.38	0.402
	Tier 1 (2000-2005)	0.2861	0.7642	6.1525	0.1934
	Tier 2 (2006-2010)	0.1669	0.7642	4.1	0.1316
	Tier 4 (2011-2014)	0.2815	0.076	2.392	0.069
	Tier 4 (2015+)	0.1314	0.076	0.460	0.0184
>1200	(pre-2000)	0.68	2.70	8.38	0.402
	Tier 1 (2000-2005)	0.2861	0.7642	6.1525	0.1934
	Tier 2 (2006-2010)	0.1669	0.7642	4.1	0.1316
	Tier 4 (2011-2014)	0.2815	0.076	0.460	0.069
	Tier 4 (2015+)	0.1314	0.076	0.460	0.0184

Source: Table A2 of Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling--Compression Ignition (EPA420-P-04-009) April 2004
[a] All PM emissions are assumed to be smaller than 10 microns (PM$_{10}$) and 97 percent of the PM is assumed to be smaller than 2.5 microns (PM$_{2.5}$).

Table 3-2. Criteria Pollutant Emission Factors (lb/HP-hr)

Engine Size (HP)	Technology Type	Emission Factors (lb/HP-hr)[a]			
		THC	CO	NO_X	PM[b]
50 - 75	(pre-1998)	2.18E-03	7.69E-03	1.52E-02	1.59E-03
	Tier 1 (1998-2003)	1.15E-03	5.22E-03	1.23E-02	1.04E-03
	Tier 2 (2004-2007)	8.10E-04	5.22E-03	1.04E-02	5.29E-04
	Tier 3/4 (2008-2012)	4.05E-04	5.22E-03	6.61E-03	6.61E-04
	Tier 4 final (2013+)	2.90E-04	5.22E-04	6.61E-03	4.06E-05
75-100	(pre-1998)	2.18E-03	7.69E-03	1.52E-02	1.59E-03
	Tier 1 (1998-2003)	1.15E-03	5.22E-03	1.23E-02	1.04E-03
	Tier 2 (2004-2007)	8.10E-04	5.22E-03	1.04E-02	5.29E-04
	Tier 3 (2008-2011)	4.05E-04	5.22E-03	6.61E-03	6.61E-04
	Tier 4 (2012-2013)	2.90E-04	5.22E-04	6.61E-03	2.03E-05
	Tier 4 final (2014+)	2.90E-04	5.22E-04	6.08E-04	2.03E-05
100 - 175	(pre-1997)	1.50E-03	5.95E-03	1.85E-02	8.86E-04
	Tier 1 (1997-2002)	7.46E-04	1.91E-03	1.25E-02	6.17E-04
	Tier 2 (2003-2006)	7.46E-04	1.91E-03	9.04E-03	3.97E-04
	Tier 3 (2007-2011)	4.05E-04	1.91E-03	5.51E-03	4.85E-04
	Tier 4 (2012-2013)	2.90E-04	1.92E-04	5.51E-03	2.03E-05
	Tier 4 final (2014+)	2.90E-04	1.92E-04	6.08E-04	2.03E-05
175 - 300	(pre-1996)	1.50E-03	5.95E-03	1.85E-02	8.86E-04
	Tier 1 (1996-2002)	6.80E-04	1.65E-03	1.23E-02	5.56E-04
	Tier 2 (2003-2005)	6.80E-04	1.65E-03	8.82E-03	2.90E-04
	Tier 3 (2006-2010)	4.05E-04	1.65E-03	5.51E-03	3.31E-04
	Tier 4 (2011-2013)	2.90E-04	1.65E-04	5.51E-03	2.03E-05
	Tier 4 final (2014+)	2.90E-04	1.65E-04	6.08E-04	2.03E-05
300 - 600	(pre-1996)	1.50E-03	5.95E-03	1.85E-02	8.86E-04
	Tier 1 (1996-2000)	4.46E-04	2.88E-03	1.33E-02	4.43E-04
	Tier 2 (2001-2005)	3.68E-04	1.86E-03	9.56E-03	2.90E-04
	Tier 3 (2006-2010)	3.68E-04	1.86E-03	5.51E-03	3.31E-04
	Tier 4 (2011-2013)	2.90E-04	1.85E-04	5.51E-03	2.03E-05
	Tier 4 final (2014+)	2.90E-04	1.85E-04	6.08E-04	2.03E-05
600 - 750	(pre-1996)	1.50E-03	5.95E-03	1.85E-02	8.86E-04
	Tier 1 (1996-2001)	3.25E-04	2.93E-03	1.28E-02	4.85E-04
	Tier 2 (2002-2005)	3.68E-04	2.93E-03	9.04E-03	2.90E-04
	Tier 3 (2006-2010)	3.68E-04	2.93E-03	5.51E-03	3.31E-04
	Tier 4 (2011-2013)	2.90E-04	2.93E-04	5.51E-03	2.03E-05
	Tier 4 (2014+)	2.90E-04	2.93E-04	6.08E-04	2.03E-05

Engine Size (HP)	Technology Type	Emission Factors (lb/HP-hr)[a]			
		THC	CO	NO_X	PM^b
750-1200	(pre-2000)	1.50E-03	5.95E-03	1.85E-02	8.86E-04
	Tier 1 (2000-2005)	6.31E-04	1.68E-03	1.36E-02	4.26E-04
	Tier 2 (2006-2010)	3.68E-04	1.68E-03	9.04E-03	2.90E-04
	Tier 4 (2011-2014)	6.21E-04	1.68E-04	5.27E-03	1.52E-04
	Tier 4 (2015+)	2.90E-04	1.68E-04	1.01E-03	4.06E-05
>1200	(pre-2000)	1.50E-03	5.95E-03	1.85E-02	8.86E-04
	Tier 1 (2000-2005)	6.31E-04	1.68E-03	1.36E-02	4.26E-04
	Tier 2 (2006-2010)	3.68E-04	1.68E-03	9.04E-03	2.90E-04
	Tier 4 (2011-2014)	6.21E-04	1.68E-04	1.01E-03	1.52E-04
	Tier 4 (2015+)	2.90E-04	1.68E-04	1.01E-03	4.06E-05

Source: Table A2 of Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling--Compression Ignition (EPA420-P-04-009) April 2004
[a] Emission factors converted from g/HP-hr to lb/HP-hr
[b] All PM emissions are assumed to be smaller than 10 microns (PM_{10}) and 97 percent of the PM is assumed to be smaller than 2.5 microns ($PM_{2.5}$).

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4.0 DIESEL ENGINE CONTROL TECHNIQUES

This chapter describes criteria pollutant emission control techniques for stationary diesel engines. For each control technique, the process description, extent of applicability, factors that affect performance and achievable controlled emission levels are presented. The diesel engine control techniques that will be presented include: diesel particulate filters (DPF) and catalyzed diesel particulate filters (CDPF) discussed in Section 4.1, selective catalytic reduction (SCR) discussed in Section 4.2, diesel oxidation catalyst (DOC) discussed in Section 4.3, and flow-through filtration (FTF) discussed in Section 4.4. Additional diesel engine control techniques include: exhaust gas recirculation (EGR) discussed in Section 4.5 and open and closed crankcase ventilation (OCV, CCV) discussed in Section 4.6. The use of ultra low sulfur diesel (ULSD) is essential to the operation of many of the exhaust aftertreatment control technologies and is discussed in Section 4.7. New and emerging control techniques for stationary diesel engines are presented in Section 4.8. A discussion of the selection of diesel engine control techniques is presented in Section 4.9. References for this chapter are presented in Section 4.10.

Both California and EPA have developed diesel engine control technology verification programs that verify the emission reduction claims by vendors of retrofit control technology equipment. The three main sources of verified engine technologies are the CARB Diesel Emission Control Verified Technologies[1], EPA Office of Transportation and Air Quality (OTAQ) Diesel Retrofit Technology Verification Program[2], and the EPA Environmental Technology Verification Program.[3] An agreement between CARB and EPA allows for coordination and reciprocity in diesel retrofit device verification. Although there is reciprocity of test data the EPA and CARB programs are independent and have specific requirements that must be met in order to achieve dual verification. The objective of this joint effort is to encourage the verification of innovative emission control technologies and promote their use in retrofitting diesel vehicles and engines.

4.1   *Diesel Particulate Filter/Catalyzed Diesel Particulate Filter*

These emission control technologies are designed to remove PM from the diesel engine exhaust stream using a wall flow filter material in which the exhaust gas must pass through a ceramic wall. In addition to PM, the catalyst in the CDPF also reduces emissions of THC and CO.

4.1.1 Process Description

The DPF is generally designed around a wall flow substrate that captures PM from the diesel engine exhaust in the cell walls. As the diesel exhaust gas passes through the particulate filter unit, PM is collected and stored in the unit. The collected PM is oxidized either through the use of a catalyzed DPF or CDPF (passive DPF device), or through a fuel burner or electrical heater which heats the filter to the combustion temperature of the PM (active DPF device). For the purpose of this document, we will use the terminology of CDPF to represent a passive device that incorporates a catalyst either upstream of the filter or coated onto the filter substrate itself. The DPF designation will refer to an active device that may be regenerated by the high temperature exhaust gas, or by the installation of an electrical heating element or fuel burner positioned upstream to increase the temperature of the filter to allow the particulate to be oxidized. Passive DPF devices or CDPFs are used when the exhaust gas temperature of the engine is high enough over an extended period of time to allow for filter regeneration. Active DPF devices are used when the exhaust temperature is not high enough or does not remain elevated for a sufficient period to allow for the accumulated particulate to be oxidized. For DPFs, the exhaust gas needs to reach approximately 500°C to regenerate the filter substrate. The catalyst in the CDPF lowers the regeneration temperature to around 250°C to 300°C and allows the collected PM to be oxidized using the available exhaust heat.

A diagram of a square pattern DPF is shown in Figure 4-1. As the figure shows, the exhaust gas is routed into cells that are blocked at one end. The gaseous components of the exhaust gas diffuse through the cell walls leaving the particulate behind. The gaseous compounds then exit out of the filter to the atmosphere. The CDPF works the same way as the DPF, except that the filter substrate contains a base or precious metal coating that helps oxidize

the deposited PM. The oxidized compounds diffuse through the filter wall and are exhausted from the filter device. Manufacturers have developed dual passive and active regenerating DPF systems that utilize both methods of regeneration in order to extend the operating time in between active regenerations.
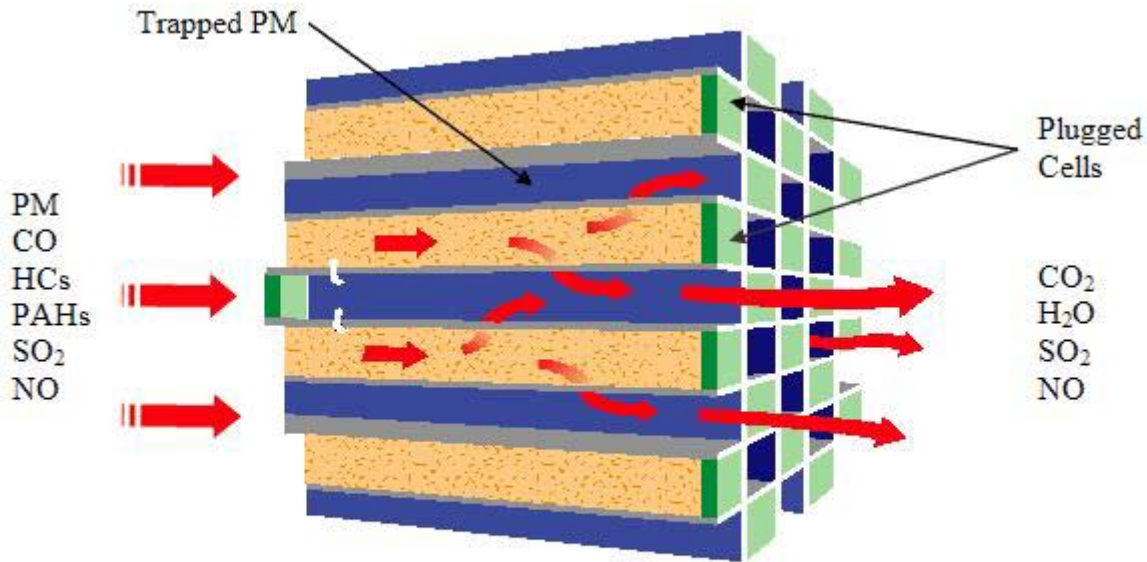
Figure 4-1. Diesel Particulate Filter[4]

The most common material used to construct DPFs and CDPFs is cordierite. Cordierite is a ceramic material that is made from a magnesium aluminum silicate, and it has been commonly used in catalytic converters. The cordierite filters are constructed of extruded cells, with the alternate ends closed. The closed channels force the diesel exhaust gas to flow through the wall, leaving the particulate behind. Other types of materials used in wall flow DPFs include silicon carbide, aluminosilicate (mullite) and metal fiber which have a higher thermal shock resistance and are used in active DPF designs. Manufacturers of DPFs and CDPFs have continued to improve filter efficiency, minimize back pressure, increase the filter regeneration rate, and improve the durability of the filter system.[5]

4.1.2 Potential Pollutant Reductions

Verifications by CARB have shown that a number of diesel particulate filter systems are able to achieve at least 85 percent reduction of PM from on-road, off-road and stationary diesel engines. CARB reports PM emission reductions of 85 to 97 percent for various types of verified DPF or CDPFs.[6] The EPA has verified DPF and CDPF systems that achieve up to 90 percent reduction. In addition to the PM reductions, the CDPF filter also reduces emissions of CO and THC by 90 percent but requires sufficient exhaust temperatures to facilitate regeneration by the catalyst. These reductions have been verified by both the CARB and EPA diesel control technology verification programs.

4.1.3 Potential Problems/Issues with DPF/CDPF

Some potential issues that can affect the performance of DPFs and CDPFs include: PM loading, exhaust temperature, amount of sulfur in the fuel, and maintenance. Each of these parameters should be taken into account when purchasing the DPF or CDPF. There may be a slight fuel penalty with the installation of a DPF or CDPF.

The PM emission rates from older model year engines may overload the DPF storage capability, causing the unit to plug. This may be especially true for engines built prior to the Tier 1 nonroad emission standards. Special designs of the DPF with additional heating elements may be incorporated into the unit to ensure complete oxidation of the PM. In other active system designs, manufacturers use a diesel fuel burner upstream of the DPF to heat up the exhaust to sufficient temperatures to oxidize the PM.

Exhaust gas temperature also has an effect on the performance of the CDPF and DPF. For DPF systems, the exhaust gas temperature needs to be approximately 500°C to regenerate the filter substrate. At lower temperatures, the potential for the DPF to plug increases due to the inability of all of the collected PM to oxidize. Installing an active DPF, which includes a secondary heating source, will alleviate problems with exhaust temperatures below 500°C. For CDPF systems, the exhaust temperature needs to be in the range of 250°C to 300°C. At exhaust

gas temperatures below 250°C, the CDPF may begin to plug because the collected PM cannot be completely oxidized, even in the presence of a catalyst.

There have been issues with CDPFs when using high sulfur diesel fuel due to the catalysts propensity to oxidize SO_2 to SO_3. The Department of Energy conducted a study on the effects of sulfur concentration in diesel fuel on DPF and CDPF performance.[7] The study found that the CDPF units did not reduce emissions of PM when using diesel fuel containing 150 parts per million (ppm) sulfur. At 350 ppm sulfur levels, the PM emissions from the CDPF began to increase from baseline levels. This was likely due to the production of sulfate PM from the sulfur in the fuel. The CDPF reduced emissions PM by 95 percent when using 3 ppm sulfur diesel fuel, and reduced PM by 72 percent when using 30 ppm sulfur diesel fuel. Therefore, CDPF manufacturers require diesel engines equipped with CDPF to use of ULSD (<15 pm sulfur). In addition, EPA requires the use of ULSD for both mobile engines and stationary engines.

The installation of a DPF or CDPF as a retrofit results in a slight fuel penalty. This fuel penalty is a result of the backpressure created by non-oxidized PM in the filter system. For active DPF systems utilizing fuel burners, there may be a 1-2 percent fuel penalty associated with the operation of the burner. In mobile source retrofit applications the DPF is often installed in place of the muffler. In such situations, the backpressure change and thus the fuel penalty will be slightly less.

4.2   Selective Catalytic Reduction

The SCR control technology is a NO_X add-on control placed in the exhaust stream of the engine. This technology is commonly used on gas turbines, IC engines, generators, and fossil fuel-fired utility boilers to reduce the emissions of NO_X formed by combustion of fossil fuels. The SCR technology is capable of reducing NO_X emissions by up to 90 percent. The SCR system can be combined with a particulate filter to reduce both NO_X and PM emissions.

4.2.1 Process Description

The SCR control technology uses a chemical reagent (also called a reductant or diesel emission fluid (DEF)), like anhydrous or aqueous ammonia (NH_3) or, more commonly, urea ((NH_2)$_2$CO), to convert NO_X into N_2 and H_2O. The SCR system dilutes the reductant using air or steam and injects the diluted reductant into the engine exhaust gas stream. The reductant reacts with NO and NO_2 in the presence of a catalyst to form nitrogen gas and water. The rate at which the reductant is added can be determined either stoichiometrically or by using an algorithm that estimates the NO_X concentration upstream or downstream (when applicable) of the catalyst or by calculating the NO_X concentration via engine operating conditions (e.g., revolutions per minute (rpm) and load). Ongoing monitoring of the temperature inside the SCR reactor is required for appropriate system adjustment and control. Additional monitoring equipment is needed to document levels of NO_X and ammonia slip from gases leaving the system, as well as the quantity of ammonia entering.

The formulas below present the reactions that occur over the catalyst bed when using an ammonia reducing agent.

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

$$NO + NO_2 + 2NH_3 + O_2 \rightarrow 2N_2 + 3H_2O$$
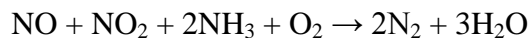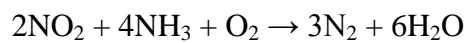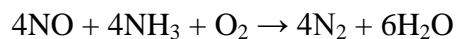
The urea based SCR system includes a separate hydrolysis reaction that occurs when the urea is mixed with water prior to injection into the exhaust gas stream.

$$(NH_2)_2CO + H_2O + O_2 \rightarrow 2NH_3 + CO_2$$
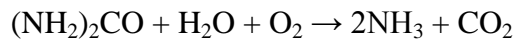
After injection, the NO_X in the diesel exhaust reacts with the NH_3 to form nitrogen and water using the same reactions as shown for the ammonia based SCR system.

The composition and shape of the catalyst depends on the application. There are several types of catalysts that are compatible with SCR, including base and precious metals. The optimum temperature for the NO_X/NH_3 reaction to occur depends on the type of catalyst used. Base metals, such as vanadium and titanium react at temperatures between 450^oF (232^oC) and 800^oF (427^oC). Zeolite-based materials react at higher temperatures between 675^oF (357^oC) to 1100^oF (593^oC). In contrast to base metals, precious metals can react at much lower temperatures (350^oF to 550^oF). The catalyst can be supported on either ceramic or metallic substrate materials (e.g., cordierite or metal foil) constructed in a honeycomb configuration (see Figure 4-2). In some designs, the catalyst material is extruded directly into the shape of a honeycomb structure.

Figure 4-2. SCR Honeycomb Configuration[8]

4.2.2 Potential Pollutant Reductions

In a SCR system, there are three key factors that influence the NO_X removal efficiency: exhaust temperature, the molar ratio of ammonia to NO_X and NO_2 to NO_X as well as the flue gas residence time in the catalyst bed. Therefore, these factors should be taken into account when calibrating the desired NO_X reduction, reagent ratios, catalyst bed volume, temperature, and operating conditions. Vendors and manufacturers of SCR systems state that 90 percent or greater NO_X reduction can be achieved when using ammonia or urea as the chemical reagent.

4.2.3 Potential Problems/Issues with SCR

One of the main concerns with the use of SCR is the lack of certainty that the reducing agent (diesel emission fluid) will be replenished as needed. Without the reducing agent, the efficiency of the SCR catalyst drops to zero and NO_X emissions can potentially increase substantially. Another concern with the use of SCR is that in colder climates the diesel emission fluid solution may freeze, which would prevent the SCR system from functioning properly. Precautions need to be made to assure that the diesel emission fluid remains above its freezing point. Other potential problems/issues with using SCR technology include ammonia slip, poisoning of the catalyst, masking, thermal sintering, and high dust loading. The following paragraphs summarize each one of these issues.

One potential problem with SCR is the emissions of unreacted ammonia from the SCR reactor called ammonia slip. Most states and local authorities place a limit on ammonia emissions that may affect the design and NO_X reduction capabilities of the SCR system. Newer designs of the SCR system have alleviated many of the ammonia slip issues. Sensors and advanced electronic control units have been added to the SCR control systems to precisely add the correct amount of ammonia needed to reduce the NO_X concentration in the exhaust stream. Manufacturers have also incorporated catalysts downstream of the SCR to oxidize any unreacted ammonia prior to exiting the exhaust system.

Catalyst poisoning occurs when contaminants found in the flue gas react with the catalyst causing it to deactivate. For example, sulfur in the exhaust stream can produce high levels of water-soluble particles that when in contact with the SCR surface could potentially poison the active ingredient (e.g., vanadium). Catalytic poisoning can be temporary or permanent. Temporary poisoning (e.g., oxides of sulfur from diesel fuel sulfur) can be corrected by exposing the catalyst to temperatures greater than 400°C. In order to prevent catalytic chemical poisoning, manufacturers have developed catalyst formulations that are more resistant to sulfur poisoning. Other chemicals, like phosphorous, chromium, and lead compounds also contribute to catalytic poisoning. However, these pollutants are less influential than sulfur due to low concentration levels in diesel fuel. Sources should have a monitoring program that includes; (1) catalyst washing procedures, (2) laboratory catalyst evaluations, and (3) lubricating oil specifications to prevent poisoning.

One of the primary limitations of SCR operation under low load/low temperature scenarios is the formation of undesirable byproducts, e.g., ammonium bisulfate (NH_4HSO_4). These by-products can result in masking, which refers to the materials that condense onto catalyst pores, thus masking active catalytic sites. In urea-SCR systems, the urea cannot be injected below about 200 ºC because it will not hydralize to form ammonia. Similar to catalyst poisoning prevention procedures, a series of best practices including routine maintenance, catalytic sampling, and regular catalytic cleaning can restore or maintain catalytic activity.

Thermal sintering refers to the loss of catalyst surface area due to high-temperature conditions. Increases in temperature can result in the agglomeration and growth of active species resulting in a reduction in the number of active sites on the catalyst surface. The creation and implementation of a maintenance program is recommended by manufacturers. The components of the program should include over-temperature monitoring and control.

Dust loading reduces the overall effectiveness of the catalyst by plugging catalyst/catalyst beds with debris and contaminants. As the catalyst becomes plugged, the pressure drop across the catalyst amplifies. The pressure drop across the catalyst should be monitored regularly to ensure that there is sufficient exhaust flow through the SCR to minimize the effects of high-dust

loading. Wastewater and solids generated during cleaning processes must be effectively and appropriately managed and discarded.

4.3 Diesel Oxidation Catalyst

A DOC is a commonly used flow through control device to reduce emissions from both mobile and stationary diesel engines. This control device has been in commercial use since the late 1960s in off-road applications and since the mid 1970s in on-road applications.

4.3.1 DOC Process Description

The DOC unit contains a honeycomb-like structure or substrate with a large surface area that is coated with an active catalyst layer, such as, platinum (Pt) or palladium (Pd) that reduces emissions of PM, THC, and CO. The DOC works by oxidizing CO, gaseous hydrocarbons and liquid hydrocarbon particles (unburned fuel and oil) in the exhaust gas to CO_2 and H_2O. The reduction of PM, THC, and CO varies depending on the catalyst formulations in the DOC. Figure 4-3 is a schematic of a DOC.

Figure 4-3. Schematic of a Diesel Oxidation Catalyst[9]

4.3.2 Potential Pollutant Reductions

The CARB found that approximately 30 percent of the total PM mass of diesel exhaust are liquid hydrocarbons, or SOF.[10] Under certain operating conditions, DOCs have achieved SOF removal efficiencies of 80 to 90 percent. Therefore, the overall PM emission reduction is often cited at 20 to 50 percent.[11] Actual emission reductions vary however, as a result of engine type, size, age, duty cycle, condition, maintenance procedures, baseline emissions, test procedure, product manufacturer and the fuel sulfur level. In addition, DOCs have been verified to reduce emissions of CO and THC by as much as 90 percent.

4.3.3 Potential Issues/Problems with DOCs

The DOC is designed as a flow-through device with the catalytic reaction occurring on the surface of the honeycomb structure. Therefore, DOC devices are not as easily affected by the higher PM emissions rates from older engines. However, these devices should be monitored to ensure that the catalyst does not become blocked.

High sulfur concentrations in diesel fuel may affect the performance of the DOC control device. At high temperatures, SO_2 can oxidize to form sulfates. The sulfates contribute to increasing the PM emissions from the engine exhaust. As a result, some manufacturers recommend a maximum sulfur content of 500 parts per million or less to maintain the durability and performance of the DOC.[12]

Several chemical elements, such as phosphorous, lead and heavy metals, may also damage the catalyst in the DOC. Some of these elements can be found in engine lube oils. Therefore, some manufacturers recommend the use of low-phosphorous oils that contain less of these elements when using a DOC.

4.4 Flow-Through Filter

Flow-through filters (FTF) or partial filters is another technology that reduces the emission of PM from the diesel exhaust stream. This technology can be retrofit on most

stationary diesel engines, including stationary diesel engines where wall-flow type filters are unsuitable. These types of engines may include light-duty cycle diesel engines, older diesel engines, and 2-stroke diesel engines. The technology filters a portion of the PM emissions as the name implies, and it oxidizes the PM using a catalyst as the exhaust gas flows through the system.[13] Similar to the case of CDPFs, the catalyst on an FTF can be applied directly to the wire mesh or a sintered metal sheet or incorporated on a separate DOC substrate upstream of the flow-through filter element.

4.4.1 FTF Process Description

The FTF contains a network of flow-through channels consisting of a catalyzed wire mesh or a corrugated metal foil. The exhaust gas flows through channels in the filter medium collecting PM on the surface of the metal fibers, which is then oxidized by the catalytic coating. The FTF provides a PM reduction across a wide range of exhaust flows and temperatures, with back-pressure characteristics similar to DOCs. The FTF requires no maintenance and can operate in a number of operating conditions/environments. A picture of a FTF is presented Figure 4-4.

Figure 4-4. Flow-through Filter Technology[14]

4.4.2 Potential Pollutant Reductions for FTF

A manufacturer of this technology has been verified by CARB to provide Level 2 PM reductions of 50 percent on 1991-2002 on-road diesel engines. Recently, a manufacturer of an FTF has been conditionally verified by EPA. Several manufacturer also market verified FTF technology for use with stationary engines. The Manufacturers of Emissions Control Association (MECA) stated that flow-through systems are capable of achieving PM reductions of about 30 to 75 percent.[15] A catalyzed FTF can offer similar co-benefits of PM reduction as well as THC and CO reduction as discussed for CDPFs. At least one manufacturer has demonstrated a 90 percent reduction in THC and CO in conjunction with a 50 percent reduction in PM emissions that combines a DOC with a metal flow-through filter.

4.4.3 Potential Issues/Problems with FTF

There is limited experience with the use of FTF technology on stationary diesel engines. The FTF technology is less susceptible than other filtration systems to plugging or blockage of the exhaust gas channels when used on engines with high PM emissions. Manufacturers of FTF systems noted that visible smoke is normal from the FTF during periods when the stationary diesel engine shifts from low- to high-speed operation or high- to low-speed operation. If black smoke is visible during steady speed operation, the injectors need to be serviced or replaced.

4.5   Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is a NO_X emissions reduction technique that works by lowering the combustion temperature and reducing the oxygen content of the combustion air. This technology has been applied by manufacturers to new engines to meet the diesel engine NSPS standards. It has also been used on new mobile source engines. Further, there are some verified EGR technologies that can be retrofitted to older engines. The verified technologies also include the incorporation of a DPF to remove PM from the recirculated exhaust gas. Low-pressure and high-pressure EGR systems have been applied to diesel engines, however the low-pressure EGR is most suitable for retrofit applications because it does not require engine modifications.[16]

4.5.1 EGR Process Description

The EGR works by circulating a portion of an engine's exhaust gas back to the combustion air that is fed into the engine cylinders. The exhaust gas is first cooled, which allows for more recirculated gas to enter the combustion cylinder. Since diesel engines operate with excess air, as much as 50 percent recirculated exhaust gas can be mixed with the combustion air. The exhaust gas/combustion air mixture lowers the temperature and also reduces the oxygen content in the combustion cylinder. These conditions reduce the formation of thermal NO_X in the combustion cylinder. A schematic of the EGR system is shown in Figure 4-5.

4.5.2 Potential Pollutant Reductions

Few examples of EGR applied to stationary diesel engines were found during the literature search. Many of the current applications of EGR are on mobile diesel engines. One study found that the application of DPF and EGR reduced NO_X emissions by 25 to 50 percent on urban buses.[17] The EGR/DPF system that was verified by CARB showed a NO_X reduction of 50 percent.

4.5.3 Potential Issues/Problems with EGR

Applying EGR to a stationary diesel RICE can reduce the power that is generated by the engine. This is because the EGR system reduces the specific heat ratio of the combustion gases in the power stroke, which in turn reduces the amount of power or work that can be extracted by the piston.

The combustion air/exhaust gas mixture may also reduce the amount of fuel that is completely burned during combustion. This incomplete combustion increases the PM emission rate in the exhaust stream. Many EGR-equipped diesel engines are also equipped with a filter system to further reduce the amount of PM in the exhaust stream.
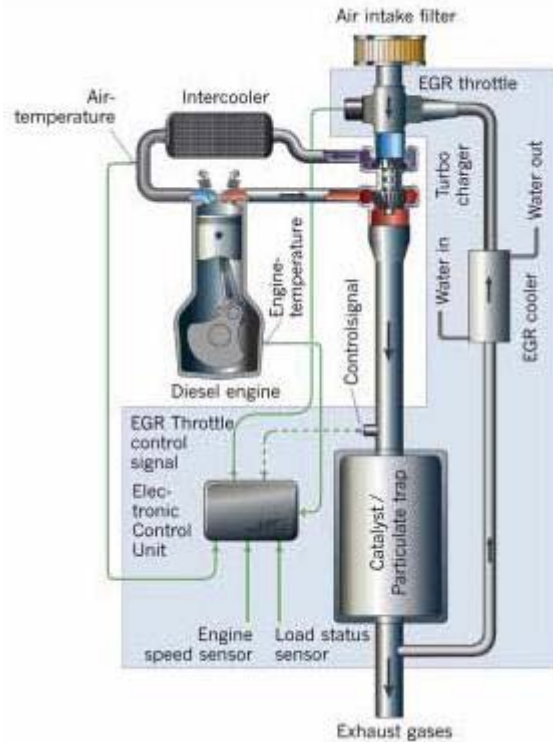
Figure 4-5. Example of an EGR/DPF System[18]

4.6   Open and Closed Crankcase Ventilation System

During normal diesel engine combustion, a small portion of combustion gas, or commonly referred to as "blowby gas," escapes past the piston rings and enters the crankcase. The blowby gas mixes with oil in the crankcase to produce a gaseous stream that contains products of fuel combustion, partially combusted engine lubricating oil, and oil droplets. The crankcase gas must be then vented through a tube into the atmosphere (open crankcase) or routed back into the incoming combustion air (closed crankcase) to avoid pressurizing and damaging the oil pan. The OCV system is installed on open crankcase diesel engines and removes oil mist and particulates from the crankcase gases before they are discharged to the atmosphere. The CCV system is installed on closed crankcase engines and also removes oil mist and particulates filters the crankcase gases, however the cleaned is gas is returned to the engine intake to be used as combustion air.

4.6.1 Open and Closed Crankcase Ventilation System Process Description

In OCV systems, the crankcase gases are routed to an OCV device that uses either centrifugal force or filtration to remove oil mist and particulates from the crankcase gas stream. The gas then exits the OCV device and is exhausted to the atmosphere. The centrifugal method captures oil and soot out of the vapor stream from the crankcase and returns it to the oil pan using centrifugal force. This method does not require periodic cartridge filter replacement, but is generally less efficient than cartridge filter technologies. The filtration method uses pleated cartridges to remove the PM from the crankcase ventilation stream and has the advantage of working at a wider range of operating loads and rpm.

The CCV systems are comparable in design to the OCV systems, except that the exhaust gas from the CCV control system is routed to the air intake manifold of the engine, where it is used as combustion gas. Engines equipped with closed crankcases have an oil separator or filtration system that removes condensed oil from the crankcase gas and returns it back to the oil pan. The oil free gas is then routed to the engine intake where it is used as combustion gas. The CCV unit can be used in conjunction with the installed separator to remove other particulates in the crankcase gas stream or can replace the oil separator. The CCV device also uses either centrifugal force or filtration to remove contaminants from the crankcase exhaust. The removal of the contaminants from the crankcase gas by the CCV system protects the diesel engine's turbochargers and aftercoolers from damage by small particulates.

4.6.2 Potential Pollutant Reductions

No specific information on the reductions of retrofitting a CCV or OCV system on a stationary diesel engine was found.

4.6.3 Potential Issues/Problems with OCV/CCV

No operational problems were found in the reviewed literature or from studies done on the CCV system. However, control device manufacturers have noted there are some challenges that arise in closing crankcases for turbocharged engines because the blow-by gases, when routed

through turbochargers and aftercoolers, can cause fouling and engine performance degradation.[19] Most 2007 and newer on-road engines use CCV devices to control crankcase PM to meet the U.S. EPA 2007-2010 highway regulations. The filtration CCV systems require regular replacement of the CCV filter element.

4.7   Ultra Low Sulfur Diesel (ULSD) Fuel

In January 2001 and in June 2004, EPA finalized the Highway Diesel and Nonroad Diesel Rules, respectively, to implement more stringent standards for mobile source diesel engines and fuels. The rules require the introduction of ULSD fuel for highway diesel engines in 2006, for nonroad diesel engines in 2010, and for locomotive and marine engines in 2012. EPA also finalized NSPS for stationary CI engines that require all new stationary diesel engines to use ULSD in 2010. This ULSD fuel enables the use of aftertreatment technologies for new and existing diesel engines and can also by itself reduce emissions of criteria pollutants.

4.7.1 Potential Pollutant Reductions

The use of ULSD reduces the formation of sulfur oxides and particulate sulfates from the diesel engine exhaust. The reductions in PM are expected to be approximately 5 to 30 percent depending on the sulfur content of the fuel that is replaced. There are no NO_X or CO emission reductions that occur when using ULSD.

4.7.2 Potential Issues/Problems with ULSD

There were some early issues with lubricity during the first few months after the ULSD rule went into effect. Since then, ULSD producers have adjusted their lubricity additives to ensure adequate lubricity of the fuel. The aromatic content of ULSD has also affected the swelling of seals, which may cause fuel leakage. This problem has been solved by replacing the seals and hoses with Viton seal material. The use of ULSD may also require more frequent changing of fuel filters when first used on existing diesel engines. Initial introduction of ULSD to the fuel delivery system removes deposits from tanks and the pipelines, causing the fuel filter to plug more frequently at first. The ULSD fuel may also slightly reduce the amount of power or work done by the diesel engine per gallon of fuel. This is because the energy content of the

ULSD is slightly lower than that of higher sulfur diesel fuels. It should be noted that ULSD is prevalent in the fuel pool today, including in some nonroad fuels that may not be labeled as such, and therefore may already be used in many stationary diesel engines.

4.8   Emerging Control Technologies

A few new technologies have emerged that have demonstrated criteria pollutant emission reductions from stationary diesel engines. A summary of these new technologies is provided in the following sections.

4.8.1 Lean NO_X Catalysts

The lean NO_X catalyst (LNC) controls NO_X emissions by injecting a small amount of diesel fuel or other hydrocarbon reductant into the exhaust upstream of a catalyst. The fuel or other hydrocarbon reductant serves as a reducing agent for the catalytic conversion of NO_X to N_2. Because the mechanism is analogous to SCR but uses a different reductant, LNC technology is sometimes referred to as hydrocarbon selective catalytic reduction or HC-SCR. Other systems operate passively without any added reductant at reduced NO_X conversion rates. The typical lean NO_X catalyst is constructed of a porous material made of zeolite (a micro-porous material with a highly ordered channel structure), along with either a precious metal or base metal catalyst. The zeolites provide microscopic sites that attract hydrocarbons and facilitate NOx reduction reactions. Without the added fuel and catalyst, reduction reactions that convert NO_X to N_2 would not take place because of excess oxygen present in the exhaust. Currently, peak NO_X conversion efficiencies typically are around 10 to 30 percent. The CARB has verified a lean NO_X catalyst/DPF system that achieves a Level 3 reduction PM reduction of 85 percent and 25 percent reduction of NO_X for on-road applications.

4.8.2 NO_X Adsorbers

Another type of control technology that has been developed and commercialized for on-road diesel engines is known as a NO_X adsorber or lean NO_X trap (LNT). The design of the NO_X adsorber functions by trapping the NO_X in the form of a metal nitrate during lean operation of the engine. Unlike catalysts, which continuously convert NO_X to N_2, NO_X adsorbers are materials

which store NO_X under lean conditions and release and catalytically reduce the stored NO_X under rich conditions. The NO and NO_2 are acidic oxides and can be trapped on basic oxides.

The majority of NO_X emitted from the engine is in the form of NO. The following are the chemical reactions representing the oxidation and adsorption of NO:

$$\text{Oxidation: } 2NO + O_2 \rightarrow 2NO_2$$
$$\text{Adsorption: } 2NO + 1.5O_2 + MO \rightarrow M(NO_3)_2$$
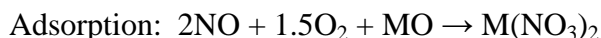
The most common compound used to capture NO_X is barium hydroxide $(Ba(OH)_2)$ or barium carbonate $(BaCO_3)$. Under lean air to fuel operation, NO_X reacts to form NO_2 over a platinum catalyst followed by reaction with the barium compound to form barium nitrate $(Ba(NO_3)_2)$. The barium nitrate is stored in the unit until it becomes saturated, and then must be regenerated. This is commonly done by operating the engine in a fuel rich mode for a brief period of time to facilitate the conversion of the barium compound back to its original hydrated or carbonated form and giving up NO_X in the form of N_2 or NH_3. The LNT catalyst can be combined with a zeolite based SCR catalyst to trap ammonia and further reduce NO_X via a selective catalytic reduction reaction to nitrogen.

Fuel sulfur can be converted to stable sulfates providing competition with NO_X for storage sites. Current sulfur levels in typical stationary engine diesel fuels present a significant challenge for the application of NO_X adsorbers. The stability of $BaSO_4$ makes it difficult to reverse the poisoning effect of sulfur. Regenerable sulfur traps currently under development for gasoline applications might be effective, however, sulfur levels in diesel fuels will still need to be controlled at lower levels.

Vendors of NO_X absorber technologies have stated that greater than 90 percent NO_X reduction is achievable. However, there were no studies or examples that were found for stationary diesel engines. At least one manufacturer is working to verify a diesel retrofit technology for on-road applications that combines a DPF and a NO_X adsorber catalyst. In this

case a non-catalytic reformer is included to convert a small amount of diesel fuel to CO and hydrogen that is then used to regenerate the NO_X adsorber catalyst and DPF.

4.9   Selection of Stationary Diesel Control Techniques

The selection of an appropriate control technique depends on a number of different factors: pollutant or pollutants to be controlled, any applicable emission limits, make/model of engine, space limitations, engine-out emissions, exhaust temperatures, and cost. Each of these factors should be taken into account before selecting an appropriate control technique. Engine and equipment manufacturers should be consulted about proper sizing and formulation of any retrofit products. Control technology vendors are also a good source of information regarding emission control options for a diesel engine.

Each of these diesel engine control techniques reduces one or more criteria pollutants. Add-on control techniques that employ a filter reduce PM emissions, and control techniques that contain a catalyst reduce CO, THC, or NO_X emissions. Engine retrofit control techniques are available to reduce the formation of NO_X or THC and can enhance the operation of add-on control technologies. The use of ULSD fuel reduces the formation of SO_X and PM, and is essential in the operation of many of these add-on control technologies. When choosing a control technology, the owner/operator should be assured that the selected product will comply with the applicable emission standards over the useful life of the product.

Some of the control techniques are designed to be retrofitted on specific engine makes and models. The control technology vendor should be contacted to determine if the control technique can be retrofitted to your engine before purchasing.

The limitation of space may also be a factor when deciding which control technique to use. Engines located in a confined space, such as a mining operation, oil/gas platform, or industrial operation, may not allow the installation of an add-on control technology. The size of the add-on control technology should be factored into the design of a control strategy.

Another factor that should be used to determine which control techniques should be applied to an engine is cost. The purchased equipment cost of each of these control techniques varies widely. In addition, catalyst-based control techniques require additional maintenance which may include cleaning or replacement of the catalyst, or the storage and addition of a reductant to reduce pollutant emissions. These additional costs should be considered before selecting a diesel engine control technique or techniques.

Based on these factors, another consideration to reduce pollutant emissions is the replacement of the older diesel engine with a new diesel engine that meets the state or federal pollutant emission limits. The cost of purchasing a new diesel engine can range from $10,000 for a 100 HP engine to $180,000 for a 1,500 HP diesel engine. [20]

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5.0 CONTROL COSTS

This chapter presents estimates of costs and cost per ton of pollutant reduced for the stationary diesel engine control techniques discussed in Chapter 4. Section 5.1 presents the cost evaluation methodology used to develop capital and annual costs for these techniques. Section 5.2 presents the costs and cost per ton for diesel engines. A discussion of the effect of remaining equipment life on capital and annual costs is presented in Section 5.3. References for the chapter are listed in Section 5.4. Control technique costs are presented in 2005 dollars, unless otherwise noted.

5.1   *Cost Evaluation Methodology*

Three cost evaluations are presented in this chapter for the control techniques discussed in Chapter 4 (SCR, DPF, DOC): total capital costs, total annual costs, and annual cost per ton pollutant reduced. The EPA estimated the costs for these control devices in previous rulemakings for stationary diesel engines. The capital and annual costs were determined using the methodology outlined in the EPA Air Pollution Control Cost Manual.[1] The total capital cost is the sum of the purchased equipment costs, direct installation costs, indirect installation costs, and contingency costs. Annual costs consist of:

- Direct operating costs of materials and labor for maintenance, operation, utilities, and material replacement and disposal (e.g., spent catalyst material);
- Indirect operating charges, including plant overhead, general administration, and capital recovery charges;
- Capital recovery cost, which assumes a 15 year equipment life and 7 percent interest rate.

Cost per ton of criteria pollutant removed is calculated for each control technique by dividing the total annual cost by the annual tons of criteria pollutant removed. The criteria pollutant emission factors presented in Table 3-2 were used to estimate the emissions from the stationary diesel engines. The approach outlined in an EPA memorandum[2] on estimating hours

of operation for stationary RICE was used to estimate the average number of operating hours for a diesel engine. Based on this memorandum, the annual hours of operation for a stationary diesel engine used to estimate the pollutant emissions in this ACT document was 1,000 hours per year. This average number of hours is for a prime stationary diesel engine, emergency engines operate on average 50 hours or less for required maintenance and testing only. A summary of average annual operating hours from available sources is presented in Table 5-1. (Note that the cost per ton increases as operating hours decrease, because capital costs remain unchanged while annual criteria pollutant emission reductions decrease with operating hours. This is especially true for emergency stationary diesel engines that generally operate less than 100 hours per year.)

Table 5-1. Summary of the Average Hours of Operation for Prime Stationary Diesel Engines from Available Data Sources

Engine Type	PSR (hr/yr)	CARB[3] (hr/yr)	NESCAUM[4] (hr/yr)	RICE NESHAP[5] (hr/yr)	Web Permits (hr/yr)	CI NSPS (hr/yr)
Compression Ignition	657	953	3,790 (Fairfield)	2,160	3,750	1,000

5.2   Control Costs for Diesel Engines

The control techniques for diesel engines are discussed in Chapter 4. The cost methodologies for control techniques applied to diesel engines are presented in this section. The estimated control costs were developed for four size range engines: 50-100 HP, 175-300 HP, 600-750 HP, and >750 HP. For the >750 HP category, we assumed an engine size of 1,000 HP to calculate the control costs. In addition, the cost per ton values were calculated for prime engines operating 1,000 hours per year. It should be noted that the cost per ton values would be much higher for emergency engines that generally operate less than 100 hours per year.

5.2.1 Control Costs for SCR

5.2.1.1 Capital Costs

A memorandum[6] on control technologies for internal combustion engines provided capital cost estimates for diesel engine SCR applications. The estimated costs were derived from

average equipment costs supplied by Miratech and Caterpillar. The costs developed in this memorandum were comparable to other estimates for SCR in the ACT update[7] and NESCAUM status report.[8] The memorandum indicates that the capital costs are estimated to be $98 per HP. The capital costs include the catalyst, reactor housing and ductwork, ammonia injection system, controls, and engineering and installation of this equipment.

5.2.1.2 Annual Costs

The anticipated annual costs associated with SCR include:

- An increase in operating labor and maintenance due to the addition of the ammonia injection;
- An increase in brake specific fuel consumption (BSFC);
- Catalyst cleaning, replacement, and disposal; and
- Capital recovery.

The cost methodology used to estimate the costs for operating/supervisory labor, maintenance, ammonia, steam diluent, and fuel penalty were calculated using the EPA Control Cost Manual.

Using this methodology, the total annual costs for diesel engine SCR applications was estimated to be $40 per HP based on 1,000 hours of operation per year.

5.2.1.3 SCR Cost per Ton of NO_X Removed

Most vendors of SCR technology guarantee a 90 percent NO_X reduction efficiency for diesel engines. Therefore a 90 percent NO_X reduction efficiency was used to calculate cost per ton in this section. The cost per ton for diesel engines is presented in Table 5-2. The NO_X cost per ton for the engines range from $4,805 to $16,129 per ton of NO_X removed for engine size ranges.

Table 5-2. SCR Cost per Ton Summary for NO_x[a]

Size Range (HP)	Average HP in Size Range (HP)	Average HP in Size Range (HP)	Uncontrolled NO_X Emission Factor (lb/HP-hr)[b]	Uncontrolled NO_X Emissions (Ton/year)[c]	Average Capital Cost ($)	Average Annualized Cost ($/year)[d]	Cost/Ton of NO_X Removed ($/Ton)[e]
50 – 100	Tier 0 (pre- 1998)		1.52E-02	0.570			$5,848
	Tier 1 (1998-2003)	75	1.23E-02	0.463	$7,350	$3,000	$7,199
	Tier 2 (2004-2007)		1.04E-02	0.389			$8,569
	Tier 3 (2008-2011)		6.61E-03	0.248			$13,441
175 - 300	Tier 0 (pre- 1996)		1.85E-02	2.20			$4,808
	Tier 1 (1996-2002)	238	1.23E-02	1.46	$23,324	$9,520	$7,245
	Tier 2 (2003-2005)		8.82E-03	1.05			$10,074
	Tier 3 (2006-2010)		5.51E-03	0.656			$16,125
600 - 750	Tier 0 (pre- 1996)		1.85E-02	6.24			$4,808
	Tier 1 (1996-2001)	675	1.28E-02	4.33	$66,150	$27,000	$6,928
	Tier 2 (2002-2005)		9.04E-03	3.05			$9,836
	Tier 3 (2006-2010)		5.51E-03	1.86			$16,129
>750	Tier 0 (pre- 1996)		1.85E-02	9.25			$4,805
	Tier 1 (1996-2001)	1,000	1.28E-02	6.40	$98,000	$40,000	$6,944
	Tier 2 (2002-2005)		9.04E-03	4.52			$9,833
	Tier 3 (2006-2010)		5.51E-03	2.76			$16,103

[a] Costs are expressed in 2005 dollars.
[b] Table A2 of Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition (EPA420-P-04-009), April 2004.
[c] Uncontrolled emissions were calculated using the average HP in the range and assuming 1,000 hours of operation.
[d] The annualized cost is calculated assuming a 15 year equipment life and 7% interest.
[e] The cost/ton was calculated assuming 90 percent NO_X reduction by the SCR.

5.2.2 Control Costs for CDPF

5.2.2.1 Capital Costs

Control costs developed for the RICE NESHAP[9] were used to provide capital cost estimates for stationary diesel engine CDPF applications. These capital cost estimates were calculated using from a study that provided average equipment cost data from stationary diesel engine retrofits ranging from 40 HP to 1,400 HP. A linear regression of the cost data and horsepower size of the stationary engines provided the following capital cost formula:

$$y = 63.4(x) + 5,699$$

where;

x = engine size in HP, and

y = total capital cost for CDPF in 2008 dollars.

5.2.2.2 Annual Costs

The RICE NESHAP control cost memorandum also provided the annual cost for retrofitting a CDPF on a stationary diesel engine. The annual cost was calculated using operating and maintenance costs provided in a control cost study for stationary diesel engines ranging from 40 HP to 1,400 HP. Using these data, and assuming a 10-year equipment life, the linear regression of the annual cost data provided the following annual cost formula:

$$y = 11.6(x) + 1,414$$

where;

x = engine size in HP, and

y = total annualized cost for CDPF in 2008 dollars.

5.2.2.3 CDPF Cost per Ton of PM and THC Removed

Most vendors of the CDPF technology guarantee a 90 percent reduction efficiency in both PM and THC for diesel engines; this reduction was used to calculate the cost per ton reduced in this section. The cost per ton estimations for PM, CO, and THC are presented in

Tables 5-3, 5-4, and 5-5. The PM cost per ton values range from $32,641 to $134,461. The CO cost per ton values range from $4,852 to $23,668. The THC cost per ton values range from $19,280 to $166,959. Using the data from the tables, the cost per ton for to control all three pollutants; PM, CO, and THC was calculated to be $5,895 for a 75 HP Tier 0 engine and $3,465 for a 1,000 HP Tier 0 engine.

5.2.3 Control Costs for DOC

5.2.3.1 Capital Costs

The RICE NESHAP control cost memorandum provides capital cost estimates for diesel engine DOC applications. Average equipment cost data was obtained from an engine control technology study for diesel engines ranging from 40 HP to 1,400 HP. These data and the EPA cost methodology were used to calculate a capital cost equation to be applied to all engines in the range. Based on the data the capital cost was estimated using the following linear regression formula;

$$y = 27.4(x) - 939$$

where;

x = engine size in HP, and

y = total capital cost for DOC in 2008 dollars.

Table 5-3. CDPF Cost per Ton Summary for PM[a]

Size Range (HP)	Average HP in Size Range (HP)	Average HP in Size Range (HP)	Uncontrolled PM Emission Factor (lb/HP-hr)[b]	Uncontrolled PM Emissions (Ton/year)[c]	Average Capital Cost ($)	Average Annualized Cost ($/year)[d]	Cost/Ton of PM Removed ($/Ton)[e]
50 – 100	Tier 0 (pre- 1998)		1.59E-03	0.0597			$42,509
	Tier 1 (1998-2003)	75	1.04E-03	0.0391	$10,454	$2,284	$64,905
	Tier 2 (2004-2007)		5.29E-04	0.0198			$128,171
	Tier 3 (2008-2011)		6.61E-04	0.0248			$102,330
175 - 300	Tier 0 (pre- 1996)		8.86E-04	0.105			$44,180
	Tier 1 (1996-2002)	238	5.56E-04	0.0661	$20,788	$4,175	$70,180
	Tier 2 (2003-2005)		2.90E-04	0.0345			$134,461
	Tier 3 (2006-2010)		3.31E-04	0.0394			$117,738
600 - 750	Tier 0 (pre- 1996)		8.86E-04	0.299			$34,352
	Tier 1 (1996-2001)	675	4.85E-04	0.164	$48,494	$9,244	$62,629
	Tier 2 (2002-2005)		2.90E-04	0.0979			$104,914
	Tier 3 (2006-2010)		3.31E-04	0.112			$91,706
>750	Tier 0 (pre- 1996)		8.86E-04	0.443			$32,641
	Tier 1 (1996-2001)	1,000	4.85E-04	0.243	$69,099	$13,014	$59,506
	Tier 2 (2002-2005)		2.90E-04	0.145			$99,724
	Tier 3 (2006-2010)		3.31E-04	0.166			$87,108

[a] Costs are expressed in 2008 dollars.

[b] Table A2 of Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition (EPA420-P-04-009), April 2004.

[c] Uncontrolled emissions were calculated using the average HP in the range and assuming 1,000 hours of operation.

[d] The annualized cost is calculated assuming a 10 year equipment life and 7% interest.

[e] The cost/ton was calculated assuming 90 percent PM reduction by the CDPF.

Table 5-4. CDPF Cost per Ton Summary for CO[a]

Size Range (HP)	Average HP in Size Range (HP)	Average HP in Size Range (HP)	Uncontrolled CO Emission Factor (lb/HP-hr)[b]	Uncontrolled CO Emissions (Ton/year)[c]	Average Capital Cost ($)	Average Annualized Cost ($/year)[d]	Cost/Ton of CO Removed ($/Ton)[e]
50 – 100	Tier 0 (pre- 1998)		7.69E-03	0.289			$8,781
	Tier 1 (1998-2003)	75	5.22E-03	0.196	$10,454	$2,284	$12,948
	Tier 2 (2004-2007)		5.22E-03	0.196			$12,948
	Tier 3 (2008-2011)		5.22E-03	0.196			$12,948
175 - 300	Tier 0 (pre- 1996)		5.95E-03	0.708			$6,552
	Tier 1 (1996-2002)	238	1.65E-03	0.196	$20,788	$4,175	$23,668
	Tier 2 (2003-2005)		1.65E-03	0.196			$23,668
	Tier 3 (2006-2010)		1.65E-03	0.196			$23,668
600 - 750	Tier 0 (pre- 1996)		5.95E-03	2.01			$5,110
	Tier 1 (1996-2001)	675	2.93E-03	0.988	$48,494	$9,244	$10,396
	Tier 2 (2002-2005)		2.93E-03	0.988			$10,396
	Tier 3 (2006-2010)		2.93E-03	0.988			$10,396
>750	Tier 0 (pre- 1996)		5.95E-03	2.98			$4,852
	Tier 1 (1996-2001)	1,000	2.93E-03	1.47	$69,099	$13,014	$9,837
	Tier 2 (2002-2005)		2.93E-03	1.47			$9,837
	Tier 3 (2006-2010)		2.93E-03	1.47			$9,837

[a] Costs are expressed in 2008 dollars.

[b] Table A2 of Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition (EPA420-P-04-009), April 2004.

[c] Uncontrolled emissions were calculated using the average HP in the range and assuming 1,000 hours of operation.

[d] The annualized cost is calculated assuming a 10 year equipment life and 7% interest.

[e] The cost/ton was calculated assuming 90 percent CO reduction by the CDPF.

Table 5-5. CDPF Cost per Ton Summary for THC[a]

Size Range (HP)	Average HP in Size Range (HP)	Average HP in Size Range (HP)	Uncontrolled THC Emission Factor (lb/HP-hr)[b]	Uncontrolled THC Emissions (Ton/year)[c]	Average Capital Cost ($)	Average Annualized Cost ($/year)[d]	Cost/Ton of THC Removed ($/Ton)[e]
50 – 100	Tier 0 (pre- 1998)		2.18E-03	0.0818			$31,024
	Tier 1 (1998-2003)	75	1.15E-03	0.0431	$10,454	$2,284	$58,881
	Tier 2 (2004-2007)		8.10E-04	0.0304			$83,480
	Tier 3 (2008-2011)		4.05E-04	0.0152			$166,959
175 - 300	Tier 0 (pre- 1996)		1.50E-03	0.178			$26,061
	Tier 1 (1996-2002)	238	6.80E-04	0.0809	$20,788	$4,175	$57,341
	Tier 2 (2003-2005)		6.80E-04	0.0809			$57,341
	Tier 3 (2006-2010)		4.05E-04	0.0482			$96,243
600 - 750	Tier 0 (pre- 1996)		1.50E-03	0.506			$20,299
	Tier 1 (1996-2001)	675	3.25E-04	0.110	$48,494	$9,244	$93,374
	Tier 2 (2002-2005)		3.68E-04	0.124			$82,832
	Tier 3 (2006-2010)		3.68E-04	0.124			$82,832
>750	Tier 0 (pre- 1996)		1.50E-03	0.750			$19,280
	Tier 1 (1996-2001)	1,000	3.25E-04	0.163	$69,099	$13,014	$88,712
	Tier 2 (2002-2005)		3.68E-04	0.184			$78,587
	Tier 3 (2006-2010)		3.68E-04	0.184			$78,587

[a] Costs are expressed in 2008 dollars.
[b] Table A2 of Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition (EPA420-P-04-009), April 2004.
[c] Uncontrolled emissions were calculated using the average HP in the range and assuming 1,000 hours of operation.
[d] The annualized cost is calculated assuming a 10 year equipment life and 7% interest.
[e] The cost/ton was calculated assuming 90 percent THC reduction by the CDPF.

5.2.3.2 Annual Costs

The annual cost for retrofitting a stationary diesel engine with a DOC was provided in the RICE NESHAP control cost memorandum. In the memorandum, the annual cost was calculated using operation and maintenance cost data collected in the control technology study. Using this cost data and assuming a 10-year equipment life, the linear regression formula was calculated to be;

$$y = 4.99(x) + 480$$

where;

x = engine size in HP, and

y = total annualized cost for DOC in 2008 dollars.

5.2.3.3 DOC Cost per Ton of PM, CO, and THC Removed

Most vendors of the DOC technology guarantee 90 percent emission reduction efficiency for both CO and THC, and a 30 percent emission reduction in PM. These reductions were applied to the uncontrolled emission factors for each of these pollutants to calculate the cost per ton based on 1,000 hours per year engine operation; this information is presented in Tables 5-6, 5-7, and 5-8. The pollutant cost per ton values ranged from $14,394 to $85,354 per ton of PM reduced, $713 to $4,280 per ton of CO reduced, and $2,834 to $37,061 per ton of THC reduced. Using the data from the tables, the cost per ton for controlling all three pollutants is $1,442 for a 75 HP diesel engine (Tier 0) and $548 for a 1,000 HP diesel engine (Tier 0).

5.2.4 Control Costs for FTF

5.2.4.1 Capital Costs

Capital cost estimates for diesel engine FTF applications were provided by a vendor of FTF control technologies.[10] The vendor provided cost data for three different sized engines, 75 HP, 238 HP, and 675 HP. These data and the EPA cost methodology were used to calculate an

Table 5-6. DOC Cost per Ton Summary for PM[a]

Size Range (HP)	Average HP in Size Range (HP)	Average HP in Size Range (HP)	Uncontrolled PM Emission Factor (lb/HP-hr)[b]	Uncontrolled PM Emissions (Ton/year)[c]	Average Capital Cost ($)	Average Annualized Cost ($/year)[d]	Cost/Ton of PM Removed ($/Ton)[e]
50 – 100	Tier 0 (pre- 1998)		1.59E-03	0.0597			$47,683
	Tier 1 (1998-2003)	75	1.04E-03	0.0391	$1,116	$854	$72,805
	Tier 2 (2004-2007)		5.29E-04	0.0198			$143,771
	Tier 3 (2008-2011)		6.61E-04	0.0248			$114,785
175 - 300	Tier 0 (pre- 1996)		8.86E-04	0.105			$52,952
	Tier 1 (1996-2002)	238	5.56E-04	0.0661	$5,582	$1,668	$84,115
	Tier 2 (2003-2005)		2.90E-04	0.0345			$161,159
	Tier 3 (2006-2010)		3.31E-04	0.0394			$141,117
600 - 750	Tier 0 (pre- 1996)		8.86E-04	0.299			$42,899
	Tier 1 (1996-2001)	675	4.85E-04	0.164	$17,556	$3,848	$78,211
	Tier 2 (2002-2005)		2.90E-04	0.0979			$131,018
	Tier 3 (2006-2010)		3.31E-04	0.112			$114,524
>750	Tier 0 (pre- 1996)		8.86E-04	0.443			$41,159
	Tier 1 (1996-2001)	1,000	4.85E-04	0.243	$26,461	$5,470	$75,034
	Tier 2 (2002-2005)		2.90E-04	0.145			$125,747
	Tier 3 (2006-2010)		3.31E-04	0.167			$109,182

[a] Costs are expressed in 2008 dollars.
[b] Table A2 of Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition (EPA420-P-04-009), April 2004.
[c] Uncontrolled emissions were calculated using the average HP in the range and assuming 1,000 hours of operation.
[d] The annualized cost is calculated assuming a 10 year equipment life and 7% interest.
[e] The cost/ton was calculated assuming 30 percent PM reduction by the DOC.

Table 5-7. DOC Cost per Ton Summary for CO[a]

Size Range (HP)	Average HP in Size Range (HP)	Average HP in Size Range (HP)	Uncontrolled CO Emission Factor (lb/HP-hr)[b]	Uncontrolled CO Emissions (Ton/year)[c]	Average Capital Cost ($)	Average Annualized Cost ($/year)[d]	Cost/Ton of CO Removed ($/Ton)[e]
50 – 100	Tier 0 (pre- 1998)		7.69E-03	0.289			$3,283
	Tier 1 (1998-2003)	75	5.22E-03	0.196	$1,116	$854	$4,841
	Tier 2 (2004-2007)		5.22E-03	0.196			$4,841
	Tier 3 (2008-2011)		5.22E-03	0.196			$4,841
175 - 300	Tier 0 (pre- 1996)		5.95E-03	0.708			$2,618
	Tier 1 (1996-2002)	238	1.65E-03	0.196	$5,582	$1,668	$9,456
	Tier 2 (2003-2005)		1.65E-03	0.196			$9,456
	Tier 3 (2006-2010)		1.65E-03	0.196			$9,456
600 - 750	Tier 0 (pre- 1996)		5.95E-03	2.01			$2,127
	Tier 1 (1996-2001)	675	2.93E-03	0.988	$17,556	$3,848	$4,327
	Tier 2 (2002-2005)		2.93E-03	0.988			$4,327
	Tier 3 (2006-2010)		2.93E-03	0.988			$4,327
>750	Tier 0 (pre- 1996)		5.95E-03	2.98			$2,040
	Tier 1 (1996-2001)	1,000	2.93E-03	1.47	$26,461	$5,470	$4,135
	Tier 2 (2002-2005)		2.93E-03	1.47			$4,135
	Tier 3 (2006-2010)		2.93E-03	1.47			$4,135

[a] Costs are expressed in 2008 dollars.

[b] Table A2 of Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition (EPA420-P-04-009), April 2004.

[c] Uncontrolled emissions were calculated using the average HP in the range and assuming 1,000 hours of operation.

[d] The annualized cost is calculated assuming a 10 year equipment life and 7% interest.

[e] The cost/ton was calculated assuming 90 percent CO reduction by the DOC.

Table 5-8. DOC Cost per Ton Summary for THC[a]

Size Range (HP)	Average HP in Size Range (HP)	Average HP in Size Range (HP)	Uncontrolled THC Emission Factor (lb/HP-hr)[b]	Uncontrolled THC Emissions (Ton/year)[c]	Average Capital Cost ($)	Average Annualized Cost ($/year)[d]	Cost/Ton of THC Removed ($/Ton)[e]
50 – 100	Tier 0 (pre- 1998)		2.18E-03	0.0818			$6,887
	Tier 1 (1998-2003)	75	1.15E-03	0.0431	$1,116	$854	$13,070
	Tier 2 (2004-2007)		8.10E-04	0.0304			$18,531
	Tier 3 (2008-2011)		4.05E-04	0.0152			$37,061
175 - 300	Tier 0 (pre- 1996)		1.50E-03	0.179			$4,687
	Tier 1 (1996-2002)	238	6.80E-04	0.0809	$5,582	$1,668	$10,369
	Tier 2 (2003-2005)		6.80E-04	0.0809			$10,369
	Tier 3 (2006-2010)		4.05E-04	0.0482			$17,404
600 - 750	Tier 0 (pre- 1996)		1.50E-03	0.506			$3,116
	Tier 1 (1996-2001)	675	3.25E-04	0.110	$17,556	$3,848	$14,333
	Tier 2 (2002-2005)		3.68E-04	0.124			$12,715
	Tier 3 (2006-2010)		3.68E-04	0.124			$12,715
>750	Tier 0 (pre- 1996)		1.50E-03	0.750			$2,834
	Tier 1 (1996-2001)	1,000	3.25E-04	0.163	$26,461	$5,470	$13,040
	Tier 2 (2002-2005)		3.68E-04	0.184			$11,552
	Tier 3 (2006-2010)		3.68E-04	0.184			$11,552

[a] Costs are expressed in 2008 dollars.

[b] Table A2 of Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition (EPA420-P-04-009), April 2004.

[c] Uncontrolled emissions were calculated using the average HP in the range and assuming 1,000 hours of operation.

[d] The annualized cost is calculated assuming a 10 year equipment life and 7% interest.

[e] The cost/ton was calculated assuming 90 percent THC reduction by the DOC.

equation to be applied to all engines in the range. Based on the data the capital cost was estimated using the following linear regression formula;

$$y = 22.7(x) + 6,057$$

where;

x = engine size in HP, and

y = total capital cost for FTF.

5.2.4.2 Annual Costs

The annual cost for retrofitting a stationary diesel engine with a FTF was calculated using the equipment information provided by the vendor and the EPA control cost methodology. For purposes of this document, it was assumed that there are no direct annual cost (i.e., no maintenance or operating costs), and the indirect annual cost was calculated assuming a 5-year equipment life for the FTF. Using these assumptions, the annual cost was calculated to be;

$$y = 2.89(x) + 772$$

where;

x = engine size in HP, and

y = total annualized cost for FTF.

5.2.4.3 FTF Cost per Ton of PM Removed

Most vendors of the FTF technology guarantee 50 percent emission reduction efficiency in PM. This reduction was applied to the uncontrolled emission factor for PM to calculate the cost per ton based on 1,000 hours per year engine operation; this information is presented in Table 5-8. The PM cost per ton values range from $16,533 to $99,899. One manufacturer of the FTF system has included an oxidation catalyst to their design which reduces CO and THC

Table 5-8. FTF Cost per ton Summary for PM[a]

Size Range (HP)	Average HP in Size Range (HP)	Average HP in Size Range (HP)	Uncontrolled PM Emission Factor (lb/HP-hr)[b]	Uncontrolled PM Emissions (Ton/year)[c]	Average Capital Cost ($)	Average Annualized Cost ($/year)[d]	Cost/Ton of PM Removed ($/Ton)[e]
50 – 100	Tier 0 (pre- 1998)		1.59E-03	0.0597			$33,132
	Tier 1 (1998-2003)	75	1.04E-03	0.0391	$7,760	$989	$50,588
	Tier 2 (2004-2007)		5.29E-04	0.0198			$99,899
	Tier 3 (2008-2011)		6.61E-04	0.0248			$79,758
175 - 300	Tier 0 (pre- 1996)		8.86E-04	0.105			$27,810
	Tier 1 (1996-2002)	238	5.56E-04	0.0661	$11,460	$1,460	$44,175
	Tier 2 (2003-2005)		2.90E-04	0.0345			$84,638
	Tier 3 (2006-2010)		3.31E-04	0.0394			$74,112
600 - 750	Tier 0 (pre- 1996)		8.86E-04	0.299			$18,214
	Tier 1 (1996-2001)	675	4.85E-04	0.164	$21,380	$2,723	$33,207
	Tier 2 (2002-2005)		2.90E-04	0.0979			$55,628
	Tier 3 (2006-2010)		3.31E-04	0.112			$48,625
>750	Tier 0 (pre- 1996)		8.86E-04	0.443			$16,533
	Tier 1 (1996-2001)	1,000	4.85E-04	0.243	$28,757	$3,662	$30,140
	Tier 2 (2002-2005)		2.90E-04	0.145			$50,510
	Tier 3 (2006-2010)		3.31E-04	0.167			$43,856

[a] Costs are expressed in 2005 dollars.
[b] Table A2 of Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition (EPA420-P-04-009), April 2004.
[c] Uncontrolled emissions were calculated using the average HP in the range and assuming 1,000 hours of operation.
[d] The annualized cost is calculated assuming a 15 year equipment life and 7% interest.
[e] The cost/ton was calculated assuming 50 percent PM reduction by the FTF.

emissions from the device by 90 percent. This FTF system has been conditionally
verified by EPA for model years 1988 – 1993 on-road and off-road engines.

5.2.5 EGR Cost

No specific costs were found for retrofitting a stationary diesel engine with EGR. A
study conducted by MECA stated that manufacturers of heavy-duty diesel engines estimated that
the cost of retrofitting the EGR system hardware and control equipment to be $500 to $700 per
engine.[11] This cost should be similar to the cost for retrofitting the EGR to a stationary diesel
engine. An EPA report did provide an estimated cost of $15,000 for a EGR/DPF system.[12]
Another project stated in the report lists the installed cost of EGR/DPF systems for refuse trucks,
transit buses, and commuter costs to be $18,000.

5.2.6 Control costs for OCV/CCV

5.2.6.1 Capital Costs

The RICE NESHAP control cost memorandum provides capital cost estimates for open
crankcase ventilation (OCV) systems for diesel engines. The OCV system is comparable to the
CCV system, therefore for the purposes of this document, the costs for OCV and CCV will be
assumed to be the same. Average equipment cost data was obtained from a company that sells
and installs the CCV systems. These cost data and the EPA cost methodology were used to
calculate a capital cost equation to be applied to all engines in the range. Based on the data the
capital cost was estimated using the following linear regression formula;

$$y = 0.26(x) + 997$$

where;

x = engine size in HP, and

y = total capital cost for OCV/CCV in 2008 dollars.

5.2.6.2 Annual Costs

The annual cost for retrofitting a stationary diesel engine with an OCV/CCV system was calculated using the equipment information provided by the company and the EPA control cost methodology. For purposes of this document, it was assumed that the filter would be replaced annually, and the indirect annual cost was calculated assuming a 10-year equipment life for the OCV/CCV system. Using these assumptions, the annual cost was calculated to be;

$$y = 0.065(x) + 254$$

where;

x = engine size in HP, and

y = total annualized cost for the OCV/CCV system in 2008 dollars.

5.2.7 ULSD Cost

The cost of switching from a high sulfur diesel fuel to ULSD varies in different parts of the U.S. A cost difference as high as $0.20 per gallon has been reported in some areas and is due to special handling and delivery requirements. Programs that use a lot of ULSD have obtained supplies of ULSD that increases cost by only $0.03 to $0.05 per gallon.[15]

5.2.8 LNC Cost

No specific data for LNC costs were found during the literature search. The literature search did provide purchased equipment costs for a DPF/LNC unit that reduces both PM and NO_X.[16] The data also provided purchased equipment costs for just the DPF system. To estimate the purchased equipment cost of the LNC, the high DPF cost was subtracted from the high DPF/LNC cost. This provided a purchased equipment cost of $12/HP for the LNC system in 2003 dollars. Using the EPA control cost methodology, the capital cost is calculated to be $19/HP in 2003 dollars. Converting to 2007 dollars using the Marshall & Swift Equipment Cost

Index, the total capital cost would be $23/HP. Another source of information stated that the installed cost of the CARB-verified LNC/DPF technology ranged from $15,000 to $20,000 for off-road vehicles.[17] The cost varied depending on the vehicle/equipment application, the engine horsepower rating, and the number of engines being retrofitted. Maintenance costs for this LNC/DPF system include only the cost for periodic DPF filter cleaning. In addition, the LNC/DPF system uses diesel fuel as the reducing agent, therefore a fuel economy penalty (up to approximately 3 percent) results in an increase in operating costs. The annual cost of operating a LNC is difficult to estimate without knowing the rate of fuel or reductant added to the system to achieve the NO_X reduction, therefore the annual cost and the cost per ton were not calculated for this control technique.

5.2.9 NO_X Adsorber Cost

Capital and annual costs were estimated in an EPA technical memorandum[18] for retrofitting a stationary diesel engine with a NO_X adsorber. The document estimated the total capital cost to be $7/HP and the annual cost to be $1/HP expressed in 2002 dollars. Converting to 2007 dollars using the Marshall & Swift Equipment Cost Index, the total capital cost would be $8.7/HP and the annual cost would be $1.2/HP. Assuming 90 percent NO_X reduction on a 75 HP stationary diesel engine (Tier 0), the cost per ton would be $175 per ton of NO_X reduced. Using these same assumptions for a 1,000 HP stationary diesel engine the cost per ton would be $72.1 per ton of NO_X reduced. Another source of information stated that EPA estimated a NO_X adsorber system would add approximately $1,500 to $3,000 to the capital cost of an on-road vehicle.[19] This cost is based on the size or the horsepower of the engine (i.e., the lower the horsepower, the less expensive the NO_X adsorber would be). In addition, EPA noted that the fuel economy of the vehicle would decrease approximately 1 to 3 percent, depending on the truck's mode of operation.

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6.0 ENVIRONMENTAL AND ENERGY IMPACTS

This chapter presents environmental and energy impacts for the emission control techniques described in Chapter 4. The impacts of the control techniques on air pollution, solid waste disposal, and energy consumption are discussed in this chapter. This chapter is organized in three sections. Section 6.1 presents air pollution impacts; Section 6.2 presents solid waste impacts; and Section 6.3 presents energy consumption impacts. References for this chapter are provided in Section 6.4.

6.1 Air Pollution

Applying the control techniques discussed in Chapter 5 reduces PM, CO, THC, and NO_X emissions from diesel engines. Table 6-1 presents the percent reduction of pollutants by control technique. Actual reductions will vary depending on the design of the control device, age and condition of the engine, and usage patterns.

Table 6-1. Summary of Pollutant Reduction of Stationary Diesel Emission Control Techniques

Control Technique	*NO_X Reduction (%)*	*CO Reduction (%)*	*PM Reduction (%)*	*THC Reduction (%)*
Currently Available Control Techniques				
SCR	>90			
DPF			20-90	
CDPF		>90	>90	>90
DOC		>90	20-50	>90
FTF			30-70	
EGR	>50			
ULSD			5-30	
Emerging Control Techniques				
Lean NO_X	10-30			
NO_X Adsorber	>90			

6.1.1 Emissions Trade-offs

Control techniques that modify combustion conditions to reduce some of the pollutants may increase the emission of other pollutants. Control techniques used on diesel engines to reduce NO_X generally have less effect on CO and hydrocarbon emissions, because they are the products of incomplete combustion. At fuel-lean conditions, CO and THC emissions increase slightly as excess oxygen cools combustion temperatures and inhibits complete combustion. As NO_X control techniques increase CO and hydrocarbon emissions to unacceptable levels, an oxidation catalyst can be used to reduce these emissions.

Many of these control techniques listed in this document will increase the emissions of CO_2, either by the oxidation of hydrocarbons or CO in the exhaust stream, or from the generation of electricity required to operate the control systems. The CO_2 oxidation reaction occurs in the catalyst-based control systems, DOC and CDPF; however, no data were found that provided CO_2 emissions from these control systems. The increase in CO_2 emissions from the generation of electricity required to operate the control systems is approximately 1.0 ton of CO_2 per MW-hr of additional electricity needed.[1]

6.1.2 Ammonia Emissions from SCR

As mentioned in Chapter 4, the SCR process may result in ammonia slip from the unit. Although some ammonia slip is unavoidable because of ammonia injection control limitations and imperfect distribution of the reacting gases, a properly designed SCR system will limit ammonia slip to less than 10 ppmv for base-load applications. Some manufacturers have also developed ammonia slip catalysts that are used in conjunction with the SCR. This additional catalyst reduces the ammonia emissions from the SCR to nearly zero.

6.2   Solid Waste Disposal

Catalytic materials used in many of the diesel control techniques have a catalyst life of approximately 2 to 3 years in stationary applications. The spent catalyst material must be disposed of or recycled. Most catalyst suppliers accept return of spent catalyst materials.[2]

While spent precious metal and zeolite catalysts are not considered hazardous waste, it has been argued that vanadium- and titanium-based catalysts are classified as hazardous waste and therefore must be handled and disposed of in accordance with hazardous waste regulations. According to the Best Demonstrated Available Technology (BDAT) Treatment Standards for Vanadium P119 and P120, spent catalysts containing vanadium pentoxide are not classified as hazardous waste.[3] State and local agencies are authorized to establish their own hazardous waste classification criteria, however, and spent catalyst material may be classified as a hazardous material in some areas. For example, the State of California has reportedly classified spent catalyst material containing vanadium pentoxide as a hazardous waste.[4]

The ash collected in a DPF or DOC consists of inorganic materials that include phosphorus, sulfur, calcium and zinc. These inorganic materials are generated from the combustion of the engine lube oil. Depending on the concentration levels of these inorganic materials, the ash may be considered to be a hazardous waste. The ash should tested to quantify the inorganic concentrations and local waste disposal regulations should be checked prior to ash disposal.

6.3   Energy Consumption

Fuel consumption increases as a result of some of the control techniques. In particular, those techniques that adjust operating or combustion parameters often increase BSFC.

Some control techniques may reduce the engine power output due to lower fuel input to the engine, or increased backpressure on the engine caused by placement of a catalyst in the exhaust. Although this reduction in power output produces lower emissions for the engine, the

lost power must be produced by another source, such as a utility. Increased emissions may result at these alternative power sources. These reductions in power output, where applicable, are discussed in Chapter 4.

When retrofitted on stationary engines, diesel oxidation catalyst and diesel filtration technologies could produce a small increase in fuel consumption in order to overcome the pressure drop through the catalyst bed and the filter.[5] Installation of SCR on stationary diesel engines could cause a small increase in fuel consumption, about 0.5 percent, in order to force the exhaust gas through the catalyst bed.[6] This increase in fuel consumption could produce an increase in CO_2 emissions, in addition to the generation of electricity required to operate the SCR control system. Other control technologies, use additional diesel fuel, such as an active DPF system, which uses diesel fuel to regenerate the filter substrate, or NO_X adsorbers, which require fuel rich conditions to convert the barium nitrate back to the hydrated or carbonated form.

6.4   References for Chapter 6

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