

State of California
California Environmental Protection Agency
AIR RESOURCES BOARD

SOURCES AND CONTROL OF OXIDES OF NITROGEN EMISSIONS

Prepared by

Stationary Source Division
and
Mobile Source Control Division

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PREFACE

This document describes the major sources of emissions of oxides of nitrogen (NO_x) in California and their control technologies. NO_x itself is of concern as an atmospheric pollutant. In addition, NO_x emissions are one of the principle precursors to tropospheric ozone (smog), and also contribute to fine particulate matter (PM₁₀) pollution.

California experiences some of the worst smog in the nation, and so by necessity has led the nation in controlling NO_x emissions from both mobile and stationary sources. This has resulted in the development of new and effective NO_x control technologies. California's emission standards for cars, trucks, buses, motorcycles and other motor vehicles have resulted in much lower NO_x emissions. California's motor vehicle fuels regulations, and controls on stationary fuel combustion sources, have also contributed significantly to reduced NO_x emissions. With those NO_x reductions has come cleaner air.

This report presents a summary of California's NO_x emission standards and applicable regulations. It describes the control technologies that are being applied in California. This document was written to assist the air pollution control and air quality management districts in California in the development of future ozone and particulate matter attainment plans. It should also be of benefit to organizations outside of California in the development of NO_x control strategies.

This document is a revised version of a report with the same title published in August 1992. Extensive revisions have been made to sections dealing with the cost-effectiveness of controls, stationary source regulations, controls for internal combustion engines, and controls for glass melting furnaces. In addition, less extensive revisions or updates were made to sections dealing with the NO_x inventory, motor vehicles, other mobile sources, California Clean Air Act requirements, and control techniques and regulations for most categories of stationary sources.

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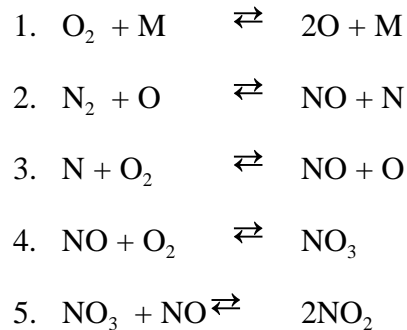
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I. NATURE, SOURCES, AND EMISSIONS OF OXIDES OF NITROGEN

A. Nature

Nitrogen oxides emissions are produced almost entirely by combustion processes. During combustion, oxygen reacts with nitrogen to form nitric oxide (NO), nitrogen dioxide (NO₂), and relatively small amounts of other compounds of oxygen and nitrogen. Both molecular nitrogen (N₂) in the atmosphere and the chemically bound nitrogen in materials being burned (called "fuel nitrogen") can react with oxygen to form oxides of nitrogen (NO_x). When ultraviolet light from the sun reacts with a mixture of oxides of nitrogen and hydrocarbons, ozone is formed. Ozone is the major constituent of what is commonly referred to as smog. In addition, nitrogen dioxide is considered a major pollutant by itself, and there are both State and federal ambient air quality standards for nitrogen dioxide. Also, photochemical reactions in the atmosphere convert oxides of nitrogen into nitrate salts and compounds, which in many areas of California contribute substantially to fine particulate matter pollution.

A set of complex chemical reactions takes place during combustion of fuel in air to form oxides of nitrogen. The most important chemical reactions of thermal NO_x formation are believed to include the following:



Here M is any gas molecule with sufficient energy to initiate dissociation of an oxygen molecule (O₂).

The overall rate of formation of NO from atmospheric N₂ is most influenced by temperature. Reaction 2 is the rate-controlling (slow) reaction for the formation of NO and is dependent on the availability of O radicals. The square of the O radical concentration, the rate of reaction 2, and the overall rate of NO formation increase as exponential functions of temperature.

These equilibrium reactions take place simultaneously. Thus, the proportion of reaction products is a function of combustion temperature, residence time, and reaction rates. Generally, the formation of NO increases with higher temperature, while the formation of NO₂ decreases with higher temperature. At common combustion temperatures, the NOx in the product gas is almost completely composed of NO. As this gas leaves the combustion zone, it cools and some NO is oxidized to NO₂. However, the exhaust NOx is still typically over 90 percent NO as it is emitted into the atmosphere. After entering the atmosphere, both NO and NO₂ participate in a series of chemical reactions to form other compounds such as ozone and particulate nitrate.

B. Sources

The major sources of NOx emissions in California are on-road motor vehicles, other mobile sources (e.g., trains, aircraft), and stationary combustion sources (e.g., oil and gas production and refining, manufacturing and industrial, electric utilities). It is estimated that on-road mobile sources account for about 58 percent of the 1994 statewide NOx inventory. Stationary sources account for 20 percent of this inventory, while the contribution from other mobile sources is 19 percent. Area sources (e.g., residential fuel combustion, lawn and garden equipment) account for 3 percent of this inventory.

C. Emissions

The 1994 statewide NOx emission estimates are tabulated by major source category in Table 1. These NOx emissions are calculated as NO₂ equivalent.¹ A review of the NOx emissions in California shows that most of the emissions are concentrated in areas with the greatest amount of industrial activities. A ranking of the 14 air basins in decreasing order of their 1994 NOx emissions is shown in Table 2. The three air basins having the highest NOx emissions are South Coast, San Francisco Bay Area, and San Joaquin Valley. Together, these three air basins account for approximately 66 percent of the NOx emissions in California.

1. Nitrogen oxide emissions are composed of several oxides of nitrogen, all of which have different molecular weights. In order to report NOx emissions estimates on a equivalent basis, the weight of NOx as emitted is adjusted to the weight after conversion to NO₂. For example, 30 tons of NO as emitted would be expressed as 46 tons of NOx in reported emission estimates.

Table 1

1994 Statewide NOx Emissions

Source Category	NOx Emissions ¹ (tons/average day)
<hr/>	
Stationary Sources	
Fuel Combustion	
Electric Utilities	90
Cogeneration	44
Oil and Gas Production (Combustion)	72
Petroleum Refining (Combustion)	54
Manufacturing and Industrial	250
Food and Agricultural Processes	11
Service and Commercial	58
Other (Combustion)	34
Total Fuel Combustion	610
Waste Disposal	
Sewage Treatment	0.1
Landfills	0.5
Incinerators	1.3
Soil Remediation	0.1
Total Waste Disposal	2.0
Petroleum Production and Marketing	
Oil and Gas Production	2.7
Petroleum Refining	19
Total Petroleum Production and Marketing	22

(cont'd)

¹ Totals may differ from addition of the values for each category due to rounding

Table 1 (Cont'd)

1994 Statewide NOx Emissions

Source Category	NOx Emissions ¹ (tons/average day)
<hr/>	
Industrial Processes	
Chemical	4.3
Food and Agricultural	9.7
Mineral Processes	41
Metal Processes	0.6
Wood and Paper	1.4
Glass and Related Products	16
Other (Industrial Processes)	7.5
 Total Industrial Processes	 80

Total Stationary Sources	720
 Area-Wide Sources	
Miscellaneous Processes	
Residential Fuel Combustion	81
Fires	0.4
Waste Burning and Disposal	4.7
Utility Equipment	1.9
Other	0.2

Total Area-Wide Sources	89
 Mobile Sources	
On-Road Motor Vehicles	
Light Duty Passenger Cars	836
Light and Medium Duty Trucks	636
Heavy Duty Gas Trucks	144
Heavy Duty Diesel Trucks	490
Motorcycles	4.4
Heavy Duty Diesel Urban Buses	17
 Total On-Road Vehicles	 2,100

(cont'd)

¹ Totals may differ from addition of the values for each category due to rounding

Table 1 (Cont'd)

1994 Statewide NOx Emissions

Source Category	NOx Emissions ¹ (tons/average day)
Other Mobile Sources	
Aircraft	33
Trains	150
Ships and Commercial Boats	66
Recreational Boats	9.8
Off-Road Recreational Vehicles	4.9
Commercial/Industrial Mobile Equipment	340
Farm Equipment	90
Total Other Mobile Sources	700

Total Mobile Sources	2,800
Natural Sources	
Wildfires	3.4

Total Natural Sources	3.4

Total All Sources	3,600

¹ Totals may differ from addition of the values for each category due to rounding

Table 2

1994 NOx Emissions by Air Basin

Air Basin	NOx Emissions (tons/average day)	Percent of Total
South Coast	1,300	35.7
San Francisco Bay Area	600	16.5
San Joaquin Valley	510	14.0
Southeast Desert	330	9.1
Sacramento Valley	260	7.1
San Diego	240	6.6
South Central Coast	140	3.8
North Central Coast	93	2.6
Mountain Counties	59	1.6
North Coast	53	1.5
Northeast Plateau	35	1.0
Great Basin Valleys	11	0.3
Lake County	6.1	0.2
Lake Tahoe	3.5	0.1
State Total ¹	3,600	100.1

¹State total does not equal sum of air basin totals due to rounding.

In addition to geographical variations, the NOx emissions in the State also have daily, weekly, and seasonal variations. Most NOx categories have higher emissions during the day than at night, and higher emissions on weekdays than on the weekends. Categories with higher emissions in the summer include on-road motor vehicles and electric utility and industrial fuel combustion. Emissions from fuel combustion for space heating are higher in the winter.

D. Need to Control Emissions of NOx

California has some of the most serious air pollution problems in the country. Eight of the ten regions in the nation that most frequently exceed the federal ozone standard are in California. California also has ten areas that are nonattainment for the federal PM10 (fine

particulate matter) standard, and four of the nation's five nonattainment areas classified as serious for PM10 (fine particulate matter).

California has adopted ambient air quality standards that are more protective than federal standards. All urban areas (and some rural areas) are nonattainment for the State ozone standard, while almost all areas are nonattainment for the State PM10 standard.

As indicated previously, NOx emissions are precursors to the formation of both ozone and the nitrate portion of PM10.

In order to achieve the federal air quality standard for ozone, California submitted a State Implementation Plan (SIP) in 1994. This SIP, which has been approved by the U.S. EPA, is a plan to bring all of California's urban areas and their downwind neighbors into attainment with the federal ozone standard by the year 2010. To achieve this, the SIP calls for NOx reductions of 40 percent in the Sacramento area, 36 percent in Ventura, and 59 percent in the Los Angeles region, all based on 1990 levels. These reductions will come from both mobile and stationary sources, and will be accomplished through application of both new and existing measures.

NOx reductions associated with the 1994 SIP are only the latest in a long history of NOx control in California. For a number of years, ARB and California's air pollution control and air quality management districts (districts) have taken an aggressive approach to the control of NOx emissions. Together, they have adopted the most stringent regulations, rules, guidelines, and determinations in the country. California leads the way in both motor vehicle and stationary source NOx emission controls.

II. MOBILE SOURCES

A. Introduction

As can be seen from Table 1, mobile sources (both on-road and other) account for 78 percent of the total 1994 NO_x emission inventory. The remainder is attributed to stationary and area-wide sources. The mobile source inventory is further divided into two basic categories: on-road vehicles and other mobile. On-road vehicles include cars, vans, trucks, motorcycles, and buses (i.e., vehicles that travel on public roads). The "other mobile" category includes sources such as farm and construction vehicles, utility equipment, trains, ships, and aircraft. For the on-road category of vehicles, light duty passenger cars and light and medium duty trucks represent the greatest proportion of the NO_x emission inventory. These two categories combined account for 70 percent of the on-road inventory and 53 percent of the mobile source inventory. Within the "other mobile" category, commercial and industrial mobile equipment (consisting of construction and mining equipment, fork lifts, and truck and trailer refrigeration units) accounts for 49 percent of the other mobile NO_x inventory and 12 percent of the mobile source inventory.

B. Mobile Source Control Measures

1. On-Road Vehicles

a. Light-Duty Vehicles

i. Emissions Standards for Gasoline-Powered Vehicles

Exhaust emission standards for new gasoline-powered motor vehicles were first implemented for the 1966 model year. For that year, hydrocarbon (HC) and carbon monoxide (CO) emission standards were adopted for domestic passenger cars and light-duty trucks. Vehicle emission standards were applied to new imported gasoline-powered cars and light-duty trucks with the 1968 model year. To meet these early standards, vehicle manufacturers generally used engine modifications that leaned air/fuel mixtures. These modifications reduced HC and CO emissions but generally increased NO_x emissions. To partially remedy this increase in NO_x, the California Air Resources Board (ARB) adopted a program in 1973 to retrofit 1966-1970 model-year vehicles with NO_x control devices.

NO_x emission standards for new vehicles were first required for the 1971 model year. The NO_x standard was initially set at 4.0 grams per mile (g/mi). In the years following, the NO_x standard was progressively lowered. The current NO_x standard is 0.4 g/mi, which was fully phased in for the 1993 model year. Subsequent model-year vehicles will be required to meet progressively more stringent emission levels as part of the low emission vehicle standards discussed later.

Initially, NO_x emissions for motor vehicles were controlled by the use of enriched air/fuel mixtures (within the bounds of HC and CO standards), retarded spark timing, and exhaust gas recirculation (EGR). EGR returns a metered amount of exhaust gas to the engine cylinders, which lowers peak combustion temperatures. Reductions in combustion temperatures generally reduce NO_x formation. EGR was the primary NO_x emission control technique from 1971 until three-way catalyst technology came into widespread use in 1980.

Three-way catalytic converters were developed in the mid-1970s. They were first used to control NO_x emissions on some 1977 Volvo models. A catalytic converter is designed to maximize the conversion of exhaust gases into inert and less harmful compounds. The three-way catalytic converter typically consists of a cylindrical ceramic substrate with many small longitudinal channels. The channels are coated with the metals platinum, palladium, or a combination of platinum and palladium. These two metals oxidize HC and CO to form carbon dioxide and water. The channels are also coated with the metal rhodium, which reduces NO_x to form nitrogen and oxygen. At present, all new gasoline-powered cars, light-duty trucks, and some heavy-duty gasoline trucks are equipped with three-way catalytic converters. Three-way catalysts are popular since they can eliminate more than 90 percent of the engine-out NO_x emissions while maintaining good fuel economy and performance.

A three-way catalytic converter requires the use of an oxygen sensor, which is located upstream of the catalyst. The oxygen sensor maintains a precise air/fuel ratio near stoichiometry. Stoichiometry is the chemically balanced ratio of fuel and air at which complete combustion can occur. The oxygen sensor provides rapid and precise feedback control to the fuel injection system in order to maintain the proper air/fuel ratio. Within the past several years, some auto manufacturers have added a secondary oxygen sensor downstream of the catalyst. This second sensor provides a more precise and durable feedback system.

Precise fuel management is the other critical element required to achieve the stoichiometric air/fuel ratio. Current electronically controlled sequential fuel injection systems maintain much greater control of the air/fuel ratio compared to carbureted systems and early fuel injection systems. The net effect of a precisely controlled air/fuel ratio is increased conversion efficiency and greater durability of the catalytic converter.

Since 1994, vehicles have been required to meet progressively more stringent emission standards (the "low emission vehicles" standards). These emission standards are forcing the development and use of advanced emission control technology, coupled with fuels that burn "cleaner" than conventional gasoline. A low emission vehicle is defined as a vehicle that has been certified by ARB to meet one of four sets of exhaust emission standards. In order of increasing stringency, the emission standards pertain to transitional low emission vehicles (TLEVs), low emission vehicles (LEVs), ultra low emission vehicles (ULEVs), and zero emission vehicles (ZEVs). Vehicles substantially cleaner than the ULEV standards but not

meeting ZEV standards are referred to as super ULEVs (SULEVs). However, there are no defined emission standards for SULEVs at this time. Vehicle manufacturers are required to produce a mix of vehicles that meet the respective TLEV, LEV, ULEV, and ZEV exhaust emission standards such that the established fleet average emission requirements are met. The 50,000-mile NO_x standards for these vehicle categories are 0.4 g/mi for TLEVs, 0.2 g/mi for LEVs and ULEVs, and zero for ZEVs. By model year 2003, the majority of passenger cars will be required to meet a NO_x standard of 0.2 g/mi for 50,000 miles. Additional information on low emission vehicles is provided in the "Mobile Source Emission Standards Summary," which can be obtained from the Air Resources Board, Mobile Source Operations Division, Program Assistance Office. It is envisioned that these more stringent NO_x measures will be accomplished through improvements in catalyst efficiency and durability as well as the use of dual oxygen sensors.

ii. Smog Check Program

The statewide biennial inspection ("smog check") program is an ongoing program for reducing in-use passenger car emissions. The purpose of this program is to identify and repair vehicles that exceed their applicable certification standards. This program requires most light-duty vehicles to be emission tested and inspected every two years. Vehicles failing the inspection or test must have any necessary repairs performed, within specified cost limits, and have any tampering corrected. The vehicle inspection program was modified for 1995, which further enhanced the program's effectiveness. The modifications remove cost limits for "gross emitters," which contribute disproportionately to smog.

iii. On-Board Diagnostics

In 1985, the Board adopted regulations which required 1988 and later model-year vehicles to be equipped with an on-board diagnostic (OBD) system. The OBD system monitors components that provide operational information to the vehicle's computer. EGR and fuel management systems, as well as the computer itself, are checked for proper operation. This regulation became known as "OBD I." The ARB adopted the second phase of on-board diagnostic regulations (OBD II) in 1989 and included the additional monitoring of catalyst condition, supplementary air system function, EGR flow rate, oxygen sensor response rate, and other components or systems which are controlled by the computer. Phase-in began with the 1994 model year. The OBD regulations are designed to reduce excess in-use emissions, and are expected to provide significant NO_x reductions.

iv. Emissions Standards for Diesel-Powered Vehicles

Diesel-powered passenger cars have been required to meet the same primary standards as gasoline-powered cars. However, since 1980, diesel vehicle manufacturers have generally chosen the optional 100,000 mile NO_x standard rather than the numerically lower 50,000 mile standard. The longer mileage standard has been chosen since diesel emissions are fairly stable

during the first 100,000 miles. In addition, NO_x emissions from diesels are more difficult to reduce to levels below 1.0 g/mi. In terms of emission control technology, three-way catalytic converters have not been applied to diesel vehicles since their exhaust contains significant amounts of excess oxygen. This operational condition is important because the exhaust gas must have little or no excess oxygen for a three-way catalyst to reduce NO_x emissions efficiently. NO_x emissions from diesel engines have been controlled by retarding the fuel injection timing, modifying engine design, or using EGR. For the future, it appears that special catalysts may be developed which can reduce NO_x in a lean environment. Due to a variety of reasons, including the stringent particulate standards that went into effect for the 1989 model year, manufacturers have opted to discontinue the sale of diesel passenger cars in California. Since 1988, two light-duty diesel engine families have been certified for sale in California.

Table 3 lists the technologies involving hardware installed on gasoline and diesel passenger cars to control NO_x emissions. As previously noted, emission standards for NO_x and other regulated pollutants are provided in the "Mobile Source Emission Standards Summary." This document summarizes the history of emission standards by vehicle class and model year.

Table 3

NOx Control Technology For Passenger Cars

Model Year	Principal Technologies
1966-1970	Retrofit NOx devices (ignition timing retard and exhaust gas recirculation (EGR))
1972-1974	Ignition timing retard and EGR
1975-1979	Ignition timing retard Enriched air fuel mixture ¹ EGR
1980-1988	Three-way catalyst (TWC) Oxygen Sensor EGR Fuel Injection Engine Modification On-board diagnostics I (1988)
1989-1993	TWC/increased catalyst loading Oxygen sensor EGR Improved fuel injection On-board diagnostics I
1994-1997	TWC/increased catalyst loading Dual oxygen sensors EGR Sequential fuel injection On-board diagnostics II
1998+	TWC/increased catalyst loading Dual oxygen sensors EGR Sequential fuel injection On-board diagnostics II Palladium-only catalysts Individual cylinder air/fuel control

¹The use of oxidation catalysts enabled manufacturers to enrich air/fuel mixtures for NOx control without increasing tailpipe emissions of HC and CO.

b. Medium-Duty and Heavy-Duty Vehicles

In 1990, the ARB adopted regulations which reclassified some light heavy-duty vehicles as medium-duty vehicles. These reclassified vehicles require emission certification on a chassis dynamometer and are subject to more stringent emission standards, including NO_x. The more stringent standards require the use of three-way catalytic converters, which will result in significant NO_x reductions.

The current NO_x standard for gasoline and diesel heavy-duty engines, 5.0 grams per brake horsepower-hour (g/bhp-hr), will decrease to 4.0 g/bhp-hr in 1998. This standard is based on the engine transient cycle test protocol, and is significantly lower than the 16 g/bhp-hr standard that existed in 1973 when heavy-duty vehicles were first regulated. The majority of current heavy-duty vehicles are diesel-powered and cannot use three-way catalysts to control NO_x emissions. In general, engine modifications, timing retard, and EGR are used to reduce NO_x emissions in heavy-duty vehicles.

In 1995, the ARB signed a Statement of Principles (SOP) with the U.S. EPA regarding future emission controls for all heavy-duty trucks and buses. This SOP will result in formal rulemaking on the part of the U.S. EPA. The proposed combined hydrocarbon and NO_x standards to be adopted are expected to result in emissions comparable to a NO_x standard of 2.0 g/bhp-hr (i.e., half of the 1998 NO_x standard) beginning with the 2004 model year. This joint action is important because federally certified trucks and buses are used extensively in California, so California standards alone, however stringent, cannot achieve all the reductions necessary from this category.

Alternative fuels such as methanol, compressed natural gas, and liquefied petroleum gas represent another option for reducing emissions of NO_x from medium- and heavy-duty vehicles. Such fuels possess the potential of reducing NO_x emissions in this class of vehicles by 50 percent from current emission levels. This option is being considered in the development of future regulations for transit buses and other heavy-duty vehicles. For model year 1996, twelve medium- and heavy-duty engine families have been certified to operate on compressed natural gas, and one has been certified to operate on liquefied petroleum gas.

Advanced lean-NO_x catalysis is currently being studied as a possible technology for reducing NO_x in diesel exhaust. As mentioned previously, conventional three-way catalytic converters are not effective in reducing NO_x emissions from diesels, since diesel exhaust contains excessive amounts of oxygen. Two potential approaches to this problem are: (1) selective catalytic reduction, which uses ammonia or urea as reducing agents in the presence of a catalyst, and (2) non-selective catalytic reduction, which uses exhaust hydrocarbons to reduce NO_x in the presence of a catalyst. The latter technology appears to offer greater potential for motor vehicle application, but currently exhibits a relatively low conversion efficiency and must be specifically tailored to each engine. Such systems are clearly in the early stages of development for motor vehicles.

2. Other Mobile

a. Heavy-Duty Off-Road Mobile Equipment

In January 1992, the ARB adopted regulations for diesel engines used in heavy-duty off-road mobile equipment. The regulations covered engines with power ratings of 175 horsepower and greater. These regulations are the first in the world to control emissions from construction, farm, mining, and other similar equipment. The initial standards went into effect in 1996 for engines from 175 to 750 horsepower, and are equivalent in stringency to the 1990 on-road heavy-duty diesel standards. The initial standards represent a 52 percent reduction from current engines for brake-specific NO_x emissions (i.e., mass emitted per unit of work delivered by the engine). The primary expected control strategy is injection timing retard. This control technique injects fuel into the combustion chamber later in the compression stroke. This lowers peak temperatures, since not as much fuel is present when peak temperatures occur, and also reduces the time at peak temperature. Turbocharging and aftercooling may also be used to lower brake-specific NO_x emissions. These two methods increase the efficiency of the engine, which tends to lower brake-specific NO_x emissions. In addition, aftercooling reduces intake air temperatures, which reduces peak combustion temperatures. These methods have been successfully used to lower NO_x emissions from on-road vehicles. In 2000, engines greater than 750 horsepower will be required to meet these standards.

In 2001, standards equivalent in stringency to the 1991 on-road heavy-duty standards will be implemented for engines with power ratings from 175 to 750 horsepower. The 2001 standards will probably be met with increased turbocharging and aftercooling, as well as electronic timing control. These techniques have already been proven in on-road use. The standards will result in a significant reduction in the total mobile source NO_x inventory for the year 2010. These standards cover exhaust emissions, test procedures, smoke testing, engine labeling, warranty, new engine compliance testing, and quality audit testing.

b. Utility Equipment

In December 1990, the ARB adopted emission standards and test procedures for certification of new utility and lawn and garden equipment engines produced for sale in California. There are two sets of emission standards, one set for hand-held equipment engines and one for non hand-held equipment engines. These standards commenced with engines produced for sale in 1995. A second, more stringent set of emission standards currently applies to engines produced for sale in the year 1999. This implementation date may be extended for a year or two due to technical problems manufacturers are encountering.

Most emissions from utility engines are HC and CO. In comparison, on a mass basis, NO_x emissions are relatively minor. Most NO_x emissions from utility equipment come from walk-behind mowers, general utility engines, and specialized turf care equipment. These are

typically 4-stroke engines which tend to have much higher NO_x emissions (but much lower HC and CO emissions) than the smaller 2-stroke engines. Methods of reducing NO_x emissions from these engines include modifying the engine and cooling system, improving the ignition system and carburetor, and providing more effective quality control along the production line.

Modifications made to the combustion process for improving fuel economy and specific power output in utility engines have resulted in higher NO_x emission levels due to higher combustion temperatures. One means of controlling NO_x is to retard the timing, thus lowering peak combustion chamber temperatures, but this could affect fuel economy. Exhaust gas recirculation could also be used to limit NO_x formation. The use of a three-way catalytic converter could reduce HC, CO, and NO_x, but this would require precise control of the air/fuel ratio, an oxygen sensor, and a computer controlled feedback carburetor system. Thus, this may not be a feasible technology for use in utility engines until the late 1990s.

c. Locomotives

Train locomotives use large diesel engines as power sources. These diesel engines emit significant quantities of NO_x. To date, locomotive manufacturers and railroads operating in California have not been required to comply with emission-related regulations, other than locally enforced opacity limits. The Federal Clean Air Act Amendments of 1990 require the U.S. EPA to adopt emission standards for new locomotives, and they prohibit California from adopting emission standards for new locomotives. A proposed rulemaking was published by the U.S. EPA in February 1997. The national rulemaking is expected to reduce NO_x emission from new engines by 45 percent in 2000, and 60 percent in 2005. Locomotive emission standards will be met primarily through the transfer of emission control technologies from clean truck engines. These might include engine modifications, electronic fuel injection, improved cooling, after treatment, and/or the use of EGR.

California, the U.S. EPA, and affected railroads have developed a Memorandum of Understanding (MOU). When approved, the MOU will require that the locomotive fleet operating in the South Coast Air Basin in 2010 emit on average no more than the federal 2005 emission level for new locomotives. This compliance requirement will be met by an aggressive five year phase-in program specifying that only the cleanest engines can be used within the area.

d. Commercial Marine Vessels

California has approximately 11,000 commercial ocean-going marine vessel visits per year. In addition, over 9,000 registered harbor and commercial fishing vessels occupy California Coastal Waters. Many ocean-going vessels are registered in foreign countries, and

most use engines produced outside the U.S. The ARB and the U.S. EPA are working with the International Maritime Organization on proposed control measures that would reduce NO_x emissions from new diesel engines used in ocean-going vessels by 30 percent compared to current vessels.

Many non ocean-going vessels use engines derived from heavy-duty truck or locomotive applications. Hence, a 65 percent NO_x reduction for new engines in this segment should be reasonable and cost-effective. The ARB has recommended that the U.S. EPA develop standards for the non ocean-going fleet to achieve this level of emission reductions.

e. Off-Highway Vehicles

In May 1992, the ARB approved a plan for the control of emissions from off-highway vehicles. This plan reorganized the off-highway vehicle category to include three subcategories: off-highway recreational vehicles, federally preempted farm and construction equipment less than 175 horsepower, and off-highway industrial equipment. The plan calls for emission reductions from these vehicles through the adoption of regulations similar to those applicable to on-road and other off-road vehicles. In January 1994, the ARB adopted regulations for the first of these three categories (Off-Highway Recreational Vehicles). However, because the engines currently used in these vehicles tend to be inherently low in NO_x emissions, there was limited reduction in the NO_x levels associated with this particular regulation.

The ARB has recommended that the U.S. EPA adopt emission standards for the federally preempted farm and construction equipment that are comparable to the levels that the ARB has adopted or will adopt for non-preempted engines. The U.S. EPA has begun this process with the signing of the Off-Road SOP in September 1996. Specifically addressing diesel engines, this agreement states the U.S. EPA's intention to adopt, and the manufacturers' intention to accept, upcoming NO_x standards for these equipment. The U.S. EPA is presently drafting the Notice of Proposed Rulemaking (NPRM), and the final rule is expected to be published in 1998. The anticipated standard will utilize a two-tier approach that will ultimately reduce NO_x emission by up to 66 percent. The anticipated standard will likely be phased in between 1999 and 2008.

The final category is that of gasoline and LPG equipment greater than 25 horsepower and less than 175 horsepower. This category includes equipment such as forklifts, pumps, compressors, and preempted construction and farm equipment. Many engines in the category are similar to, or derived from, early 1980s automobile engines. Emission standards for new engines not primarily used in construction or farm equipment are anticipated to be phased in beginning in 2000. These standards will be met by using closed-loop three-way catalyst systems, or other technology achieving NO_x reductions of at least 50 percent. The ARB has asked that the U.S. EPA develop similar requirements for the preempted equipment.

3. Motor Vehicle Fuels Regulations

The ARB has adopted regulations setting specifications for the composition of motor vehicle fuels to reduce emissions of various pollutants, including NO_x, from existing vehicles. In 1988, the ARB adopted a specification for motor vehicle diesel fuel. The specification limited the aromatic hydrocarbon content to 10 and 20 percent, by volume, for large and small refiners, respectively. This regulation took effect in 1993 and reduced NO_x emissions by an estimated 70 tons per day in 1995. This represents a seven percent reduction in NO_x emitted by diesel engines. Alternative formulations that do not meet the aromatic hydrocarbon content limits may be certified by the ARB. These formulations must first go through comparative laboratory testing and statistical analysis to show that they offer the same or better emission reduction benefits for all pollutants.

In 1990, the ARB adopted a regulation requiring certification of gasoline. All gasoline sold in California must be certified as containing deposit control additives which meet specific performance criteria. This regulation took effect in 1992. Deposit control additives have been shown to reduce NO_x emission by controlling deposits on intake valves and in carburetors and port fuel injectors.

In 1991, the ARB adopted regulations for cleaner burning gasoline which specify limits on eight different components and properties of gasoline, including olefin and aromatic hydrocarbon contents, and 50 and 90 percent distillation temperatures. This California cleaner burning gasoline reduced NO_x emissions from gasoline engine motor vehicles by 11 percent, or an estimated 112 tons per day statewide in 1996. Alternative gasoline formulations resulting in equivalent emission reductions may be certified based on a predictive model. These alternative formulations may also be certified if they pass a motor vehicle emission test developed specifically for this purpose.

C. Summary

In summary, gasoline passenger cars and heavy-duty diesel vehicles (both on-road and off-road) account for the greater proportion of NO_x emissions from motor vehicles. The ARB's mobile source emission control strategy of adopting technology-forcing standards has resulted in substantial NO_x emission reductions. These reductions have occurred over the last 20 years, and at reasonable levels of cost-effectiveness (see Table 4). However, mobile sources continue to be a significant contributor to the NO_x emission inventory. One reason for this is that the category of "other mobile" sources represents a large source of NO_x emissions, controls for which have only recently been adopted or are in developmental stages. In addition, the diesel vehicle category, both on-road and off-road, is a significant contributor to NO_x emissions relative to its population. Diesel vehicles are subject to technological limits in achieving the same NO_x emission reductions as gasoline vehicles. A final reason for the

continuing motor vehicle contribution to the NOx inventory is that the California vehicle population has been growing rapidly. Even though the per-vehicle emission rate has been reduced substantially, the growing number of vehicles on the road has increased the aggregate inventory of NOx emissions. This phenomenon will challenge the limits of technological achievement.

Table 4

Cost-Effectiveness of Selected NOx Control Measures¹

Measure	Pollutant	Cost-Effectiveness ² (\$/lb Reduced)	Implementation Date (MY) ³
(1) On-Board Diagnostics II	THC + NOx	0.87 - 1.09	1994
(2) LEV Program ⁴			
TLEV	THC + NOx	1.83	1994 - 2003
LEV	THC + NOx	1.03	
ULEV	THC + NOx	1.80	
ZEV	THC + NOx	5.21 - 19.08	
(3) Medium-Duty Vehicle Reclassification	THC + NOx NOx	0.49 0.62	1995-1996
(4) Utility Engines	THC + NOx THC + NOx	0.09 - 1.17 0.56 - 6.60	1994 1999
(5) Heavy-Duty Off-Road Equipment	NOx NOx NOx	0.21 (175-750 hp) 0.18 (> 750 hp) 0.65 (175-750 hp)	1996 2000 2001

¹Cost-effectiveness is based on the emission reduction and incremental cost over the expected life of the vehicle. Emission standards, where applicable, are provided in the "Mobile Source Emission Standards Summary".

²Costs adjusted to 1996 dollars

³MY = model year

⁴The Low Emission Vehicle (LEV) program includes the following vehicle categories: transitional low emission vehicle (TLEV), low emission vehicle (LEV), ultra-low emission vehicle (ULEV), and zero emission vehicle (ZEV).

III. STATIONARY SOURCES

A. Introduction

Significant stationary fuel combustion sources in California include petroleum refinery boilers, oil field steam generators, process heaters, electric utility boilers, other boilers, gas turbines, stationary internal combustion engines, cement kilns, glass melting furnaces, and institutional, commercial, and residential water and space heaters. Waste combustion is also a significant stationary source which includes municipal waste and sludge incinerators.

Nitric oxide (NO) forms from the combustion of fuel in stationary equipment. Small amounts of nitrogen dioxide (NO₂) are also formed in the combustion process. These pollutants are emitted into the atmosphere when the combustion byproduct gases exit the stack.

The formation of NO by combustion processes is governed primarily by (1) the chemically-bound nitrogen content of the fuel, (2) the oxygen concentration of the flame, (3) the temperature of the flame, and (4) the length of time the combustion gases are held at the flame temperature.

Generally, under identical combustion conditions, premixed flames such as natural gas combustion will produce less NO than diffusion flames such as oil droplet combustion. The reason for this result is that diffusion flames contain localities of theoretically correct air/fuel ratios, where high peak temperatures occur. Premix flames tend to have excess air dilution and thus lower peak temperatures.

1. Control Technology

A number of different techniques are available for reducing NO_x emissions from stationary sources. Process and combustion modifications are proven control techniques that control thermal NO_x formation by modifying the combustion process to quench combustion gases or to shorten residence times at high temperatures and oxygen availability. Low excess air firing, staged combustion, and flue gas recirculation are types of combustion modifications capable of reducing NO_x emissions. These technologies are capable of achieving 5 to 70 percent reductions in NO_x emissions and are currently being used on sources such as electric utility boilers, oil field steam generators, and glass melting furnaces. Other equipment-specific combustion modifications, capable of achieving even higher reductions, include low NO_x burners for boilers and heaters, water injection or dry low NO_x combustors for gas turbines, and prestratified charge and precombustion chamber systems for reciprocating internal combustion engines. Combustion modifications can be used alone or in combination with other control technologies.

Different fuels produce different amounts of NO_x for a given amount of energy released in the combustion process. This is due to differences in methods of combustion and chemical composition, including fuel nitrogen content. Generally, with respect to NO_x and other pollutant emissions, natural gas burns cleaner than petroleum distillate fuels, which burn cleaner than residual fuels, which burn cleaner than solid fossil fuels. Fuel switching can be an effective method of emission reduction for many applications. Alternative fuels such as methanol may burn cleaner than natural gas in some applications.

There are also control techniques for reducing NO_x emissions downstream of the combustion zone. Some of these techniques convert NO_x emissions already formed in the combustion process into nitrogen gas (N₂) and water vapor (H₂O) by using reducing agents composed of hydrogen and nitrogen. This process is called selective reduction. In other techniques, the reducing agent is a hydrocarbon fuel or partially burned hydrocarbon fuel, in which case the oxygen in NO_x combines with the hydrocarbon to form carbon monoxide (CO), carbon dioxide (CO₂), and H₂O. This process is called nonselective reduction.

The three most prevalent post-combustion NO_x control methods include selective catalytic reduction (SCR), selective noncatalytic reduction (SNCR), and nonselective catalytic reduction (NSCR). Selective NO_x reduction methods inject ammonia (NH₃), urea, or similar compounds into the post-combustion region. When a catalyst is employed, the technology is known as SCR. When the reducing compound is injected in the absence of a catalyst, the technique is known as SNCR. For rich burning internal combustion engines, CO and hydrocarbons nonselectively reduce NO_x over a catalyst bed, and this technology is therefore referred to as NSCR. The NO_x emission removal efficiency of these technologies typically ranges from 40 to 95 percent. A summary of the various technologies, typical applications, and estimated control efficiencies are presented in Table 5.

2. Cost-Effectiveness

While emission reduction is the primary consideration in evaluating control technology in developing regulations, cost-effectiveness is also a necessary consideration. Cost-effectiveness is defined as the annualized cost of control divided by the annual mass of emissions reduced. Cost-effectiveness is primarily used to compare control technologies and regulations based on relative costs to benefits. The cost-effectiveness ranges for adopted stationary source NO_x emission control measures are presented in Table 6.

Table 5

Applications of NOx Emission Controls in California

Control	Applicable Sources	Percent Reduction In NOx Achievable
Combustion Modifications	Utility Boilers, Boilers, Heaters, and Steam Generators ¹ , Glass Melting Furnaces, Cement Kilns	5 - 70
Low NOx Burners	Utility Boilers, Boilers, Heaters, and Steam Generators ¹	10 - 90
Dry Low NOx Combustors	Gas Turbines	70 - 90
Water Injection	Gas Turbines	50 - 85
Prestratified Charge	Rich-Burn Reciprocating Internal Combustion Engines	up to 90
Precombustion Chamber	Lean-Burn Reciprocating Internal Combustion Engines	up to 90
Selective Noncatalytic Reduction	Utility Boilers, Boilers, Heaters, and Steam Generators ¹ , Glass Melting Furnaces, Municipal Solid Waste, Biomass	10 - 90
Non Selective Catalytic Reduction	Rich-Burn Reciprocating Internal Combustion Engines	80 - 95
Selective Catalytic Reduction	Utility Boilers, Boilers, Heaters, and Steam Generators ¹ , Gas Turbines, Lean-Burn Reciprocating Internal Combustion Engines	80 - 95

¹ Boilers, heaters, and steam generators are used in oil fields, refineries, and other industrial and commercial facilities and institutions.

Table 6

Cost-Effectiveness of Rules Regulating Stationary Source NOx Emissions

Source Category	Control Level ¹	District ² / Rule	Year Adopted	Cost-Effectiveness ³ (\$/lb NOx)
Refinery Boilers and Heaters	0.03 lbs/MMBTU	SCAQMD Rule 1109	1988	4.81
Boilers, Steam Generators, And Heaters	30-40 ppm	SCAQMD Rule 1146	1989	10.88
	40 ppm	VCAPCD Rule 74.15	1991	1.17 - 14.37
	30-40 ppm	SBCAPCD Rule 342	1992	1.83 - 11.60
	30-40 ppm	SJVUAPCD Rule 4305	1993	0.83 - 2.49
	30-40 ppm	SDCAPCD Rule 69.2	1994	7.41 ⁴
	70-115 ppm	MDAQMD Rule 1157	1994	0.88
	30-40 ppm	SMAQMD Rule 411	1995	0.67 - 5.79

(cont'd)

¹ppm = parts per million

lbs/MMBTU = pounds per million British Thermal Units

²SCAQMD = South Coast Air Quality Management District

VCAPCD = Ventura County Air Pollution Control District

SBCAPCD = Santa Barbara County Air Pollution Control District

SJVUAPCD = San Joaquin Valley Unified Air Pollution Control District

SDCAPCD = San Diego County Air Pollution Control District

MDAQMD = Mojave Desert Air Quality Management District

SMAQMD = Sacramento Metropolitan Air Quality Management District

³All costs are adjusted to 1996 dollars.⁴Worst-case scenario used to calculate cost-effectiveness

Table 6 (Cont'd)

Cost-Effectiveness of Rules Regulating Stationary Source NOx Emissions

Source Category	Control Level ¹	District ² / Rule	Year Adopted	Cost-Effectiveness ³ (\$/lb NOx)
Small Boilers, Steam Generators, and Heaters	30 ppm	SCAQMD Rule 1146.1	1990	5.79
Oil Field Steam Generators	0.20-0.38 lbs/MMBTU	SJVUAPCD Rule 4405	1980	0.39
Electric Power Generation	0.15-0.20 lbs/MWH	SCAQMD Rule 1135	1991	3.39 - 12.75
	0.10-0.20 lbs/MWH	VCAPCD Rule 59	1991	4.67 - 9.21
	10-30 ppm	MBUAPCD Rule 431	1993	2.77 - 6.57
	10 ppm	SLOCAPCD	1993	2.71 - 9.23
	10-30 ppm	BAAQMD Reg. 9 Rule 4	1994	3.26 - 7.05
	0.15-1.20 lbs/MWH	SDCAPCD Rule 69	1994	0.95 - 4.41
Stationary Gas Turbines	9-25 ppm	SCAQMD Rule 1134	1989	1.87 - 6.15

(cont'd)

¹ppm = parts per million

lbs/MMBTU = pounds per million British Thermal Units

lbs/MWH = pounds per megawatt-hour of electricity generated

²SCAQMD = South Coast Air Quality Management District

SJVUAPCD = San Joaquin Valley Unified Air Pollution Control District

VCAPCD = Ventura County Air Pollution Control District

MBUAPCD = Monterey Bay Unified Air Pollution Control District

SLOCAPCD = San Luis Obispo County Air Pollution Control District

BAAQMD = Bay Area Air Quality Management District

SDCAPCD = San Diego County Air Pollution Control District

³All costs are adjusted to 1996 dollars.

Table 6 (Cont'd)

Cost-Effectiveness of Rules Regulating Stationary Source NOx Emissions

Source Category	Control Level ¹	District ² / Rule	Year Adopted	Cost-Effectiveness ³ (\$/lb NOx)
Stationary Gas Turbines	9-65 ppm	SJVUAPCD Rule 4703	1995	0.67 - 1.70
	9-42 ppm	SMAQMD Rule 413	1995	1.85 - 4.42
Stationary IC Engines	90-150 ppm	SCAQMD Rule 1110.1	1985	1.10
	36-45 ppm	SCAQMD Rule 1110.2	1990	1.07 - 12.50
	50-125 ppm	VCAPCD Rule 74.9	1981	0.07 - 3.64
	25-125 ppm	VCAPCD Rule 74.9	1993	0.55 - 7.05
	50-125 ppm (700 ppm diesel)	SDCAPCD Rule 69.4	1994	0.98
Glass Melting Furnaces	4 lbs/ton	SCAQMD Rule 1117	1984	3.09
	5.5 lbs/ton (12-32 for flat glass)	SJVUAPCD Rule 4354	1994	0.65 - 1.90
	5.5 lbs/ton	BAAQMD Reg. 9 Rule 12	1994	1.31 - 2.17

(cont'd)

¹ppm = parts per million

lbs/ton = pounds per ton of glass pulled

²SJVUAPCD = San Joaquin Valley Unified Air Pollution Control District

SMAQMD = Sacramento Metropolitan Air Quality Management District

SCAQMD = South Coast Air Quality Management District

VCAPCD = Ventura County Air Pollution Control District

SDCAPCD = San Diego County Air Pollution Control District

BAAQMD = Bay Area Air Quality Management District

³All costs are adjusted to 1996 dollars.

Table 6 (Cont'd)

Cost-Effectiveness of Rules Regulating Stationary Source NOx Emissions

Source Category	Control Level ¹	District ² / Rule	Year Adopted	Cost-Effectiveness ³ (\$/lb NOx)
Cement Kilns	6.4-11.6 lbs/ton	SCAQMD Rule 1112	1986	0.47
Residential Water Heaters	40 ng/J	SCAQMD Rule 1121	1978	0.08
Residential Space Heaters	40 ng/J	SCAQMD Rule 1111	1983	0.08

¹Values for Cement Kilns are in lbs per ton of clinker produced. The 6.4 lbs value has a 30-day averaging period, while the 11.6 lbs value has a 24-hour averaging period.

ng/J = nanograms of NOx per joule of useful heat output

²SCAQMD = South Coast Air Quality Management District

³All costs are adjusted to 1996 dollars.

B. Requirements of the California Clean Air Act

1. Reasonably Available Control Technology and Best Available Retrofit Control Technology

The California Clean Air Act (CCAA) of 1988 requires the districts to attain and maintain the State ozone standard. Specifically, each district that is in violation must develop an attainment plan. The attainment plan must include a commitment to adopt specific rules to reduce NO_x emissions from existing sources. To the extent necessary to show attainment, these rules must require the use of reasonably available control technology (RACT) or best available retrofit control technology (BARCT) for reducing emissions.

RACT is required for areas designated as moderate nonattainment (ozone concentration of 0.09 to 0.12 parts per million (ppm)), except sources permitted to emit five tons or more per day or 250 tons or more per year must use BARCT. RACT for existing sources is considered to be those emission limits achievable from the application of demonstrated technology to reduce emissions. BARCT is an emission limitation that is based on the maximum degree of reduction achievable, taking into account environmental, energy, and economic impacts by each class or category of sources. BARCT is required for areas with an ozone concentration of 0.13 ppm or greater (i.e., serious, severe, or extreme designation).

RACT and BARCT guidance for individual source categories has been developed by ARB staff in conjunction with the California Air Pollution Control Officers Association (CAPCOA) to assist districts in determining appropriate RACT and BARCT standards for their rules. Additionally, the guidance serves to help streamline the rule development process and promote statewide uniformity.

2. New Source Review

The CCAA also requires district plans to include requirements for a permitting program designed to achieve "no net increase in emissions" of nonattainment pollutants or their precursors from new and modified stationary sources. In addition, these new or modified sources must use best available control technology (BACT) to control emissions. These requirements apply to all new or modified stationary sources which emit, or have the potential to emit, more than a specified amount of nonattainment pollutants or their precursors. A summary of the designations and associated emissions levels at which the "no net increase" and BACT requirements apply is presented in Table 7. Legislation passed in 1996 allows the use of alternative emission reduction strategies to the "no net increase" provisions if certain conditions are met and certain procedures are followed.

Table 7

Summary of "No Net Increase" and BACT Requirements

Area Designation	"No Net Increase Requirement" (Emissions \geq stated value)	BACT Requirement (Emissions \geq stated value)
Moderate	25 tons/year	25 pounds/day
Serious	15 tons/year	10 pounds/day
Severe	10 tons/year	10 pounds/day
Extreme	Any Increase	10 pounds/day

BACT for a particular piece of equipment is the most stringent of: (1) the most effective control device, emission limit, or technique achieved in practice for that equipment type; or (2) any other control device or technique that is feasible and cost-effective. Determinations of BACT are made at the district level and are submitted to the CAPCOA BACT Clearinghouse. An updated compilation of California BACT determinations can be acquired upon request from the ARB, Stationary Source Division, Project Support Section, or can be obtained via the Internet (address: <http://www.arb.ca.gov>).

Offsets are emission reductions at the project location or at a nearby location and can be used to mitigate the expected increase in emissions from the project to meet the "no net increase" requirements. The concept of offsets is not new, as offsets were an integral part of permitting programs before passage of the CCAA. However, the CCAA has required many districts to lower their offset thresholds, above which offsets are required (see Table 7). Offset requirements have been a driving force behind advances in equipment and control technologies. Use of the most effective equipment and control technologies can minimize emissions from new or modified sources, which will reduce offset requirements. In addition, use of highly effective equipment and control technologies on existing sources can create offsets.

In addition to State requirements, there are also federal requirements under the federal Clean Air Act Amendments (FCAA) of 1990 for control of NO_x emissions from stationary sources. These federal requirements are similar to the State requirements, with RACT required on existing sources and BACT and offsets required for new and modified sources. However, the FCAA requirements apply only to areas that are nonattainment for the federal ozone ambient air quality standard (which include most, but not all, areas that are nonattainment for the State standard). In addition, the FCAA requires the use of RACT, but

not BARCT, on existing stationary sources. The federal RACT requirements apply only to major sources, whereas State RACT or BARCT requirements apply to all stationary sources. For federal purposes, major sources vary in emissions from 100 tons per year of NO_x down to as low as 10 tons per year, depending on the severity of ozone standard violations. Federal BACT and offset requirements also only apply to major sources.

Although federal NO_x control requirements for stationary sources are generally less stringent than State requirements, in some instances they may be more stringent. For example, federal NO_x RACT controls had to be in place and operating by May 31, 1995, whereas State NO_x RACT and BARCT requirements specify the earliest practicable date for implementation, which for some districts and sources has been interpreted to be after 1995.

C. Stationary Source Categories and Control

1. Boilers, Steam Generators and Process Heaters

Stationary sources such as boilers, steam generators, and process heaters are used in many applications that require process steam and heat production in such operations as oil refineries, electric utilities, oil production, metallurgical industries, and chemical industries.

a. Control Technology

There are basically five methods for reducing NO_x emissions from existing industrial, institutional and commercial boilers, steam generators, and process heaters. These are: (1) low excess air, (2) retrofitting of low NO_x emitting burners, (3) retrofitting of flue gas recirculation systems, (4) installation of reducing agent (such as ammonia or urea) injection systems for selective noncatalytic reduction (SNCR), and (5) installation of reducing agent injection systems with catalysts for selective catalytic reduction (SCR). The SNCR and SCR methods are post combustion technologies. All five methods are discussed in the following pages.

In the future, burners designed for firing alternative fuels such as methanol may provide another NO_x reduction technique. Methanol has a high latent heat of vaporization and its combustion products have a high heat capacity. These properties should result in lower flame temperatures and lower NO_x production than with liquid fossil fuel combustion.

Low NO_x methanol burners with flue gas recirculation have been demonstrated in the field to achieve 40 parts per million by volume (ppmv) NO_x, corrected to 3 percent oxygen (O₂) dry (excluding water). However, burners using staged air and flue gas recirculation, fired on a specially blended "clean" fuel oil, have achieved less than 30 ppmv NO_x. Natural gas firing with low NO_x burners and flue gas recirculation can typically achieve emissions in the 9 to 30 ppmv range. It is not known whether lower emissions can be attained with methanol firing than with natural gas firing.

Low Excess Air. All conventional combustion processes require excess air in order to ensure that all fuel molecules react with oxygen (O_2). With low excess air (LEA), less O_2 is supplied to the burner than normal. As a result, the combustion zone receives less O_2 . This reduces the equilibrium concentration of oxygen atoms (O), and thus less thermal NOx is formed. In addition, in the starved-air flame zone, more of the fuel bound nitrogen is converted into molecular nitrogen (N_2), lowering the formation of fuel NOx. Low excess air can be used in all combustion sources and with all fuels. As stated previously, combustion modifications can be used alone or in combination. LEA alone can achieve a NOx reduction effectiveness between 5 and 35 percent for gas firing and up to 25 percent for other fuels.

Low NOx Burners. Low NOx burners employ low excess air combustion, flue gas recirculation (FGR), lean premix, air staging, fuel staging, or a combination of these techniques to lower NOx formation in the flame. Low excess air combustion and FGR decrease the oxygen available for NOx formation. FGR and lean premix lower the flame temperature, and consequently lower the NOx formation rate and equilibrium concentration. Staged-air burners lower available oxygen at points in the combustion chamber where the temperature is high. Staged-fuel burners lower the temperature at points in the combustion chamber where available oxygen is high. The retrofitting of some types of low NOx burners may require derating of equipment, as some of these burners have long flame lengths which may impinge on parts of the boiler or heater when operated at full rating.

Low NOx burners are applicable to most gas-fired and oil-fired units. For gas-fired units, the control effectiveness ranges from 10 to over 90 percent, depending on the design of the low NOx burner and the burner to be replaced. The latest generation of low NOx burners use lean premix in combination with FGR to reduce NOx concentrations below 10 parts per million. For units fired with low nitrogen oil, NOx concentrations below 30 ppm are achievable.

Flue Gas Recirculation. With flue gas recirculation (FGR), NOx control consists of extracting a portion of the flue gas from the economizer outlet and returning it to the furnace, admitting the flue gas through the furnace windbox. Flue gas recirculation lowers the furnace gas temperatures and reduces oxygen concentration in the combustion zone.

A retrofit installation of FGR consists of adding a fan, ductwork, dampers, and controls as well as possibly increasing existing fan horsepower due to increased draft loss.

FGR is an effective control technique for both gas-fired and distillate oil-fired units. FGR is not effective at reducing NOx formation originating from fuel-bound nitrogen. The control effectiveness of FGR ranges from 60 to 70 percent for gas-fired units. For units firing low nitrogen oil, the control effectiveness is expected to be within the same range.

Selective Noncatalytic Reduction. Two selective noncatalytic control (SNCR) methods have been used predominantly in industry applications to reduce NO_x emissions: "Thermal DeNO_x," and "NO_xOUT."

"Thermal DeNO_x," developed and patented by Exxon Research and Engineering Company, is based on the gas phase homogeneous reaction between NO_x in flue gas and ammonia (NH₃), which produces nitrogen and water. In general, NH₃ is injected into the hot flue gas by means of either air or steam carrier gas at a point in the flue specifically selected to provide optimum reaction temperature and residence time. In the temperature range of 1650°F. to 1850°F., the reaction occurs through the injection of NH₃ alone. Hydrogen (H₂) can also be injected along with NH₃ to lower the temperature range of the reaction down to 1300°F. NO_x reductions of up to 90 percent have been demonstrated for applications of "Thermal DeNO_x" on oil field steam generators where favorable process conditions exist. "Thermal DeNO_x" performance using earlier technology ranges from 50 to 70 percent reduction for most oil-fired and gas-fired process heaters and steam boilers.

The other noncatalytic control technology is the "NO_xOUT" method which injects a urea type (or amine salt) compound into the oxygen-rich upper furnace or high temperature convection section of the boiler to promote NO_x reduction. This technology was originally developed for the Electric Power Research Institute and is currently licensed by Fuel Tech. Proprietary additives have been developed that allow this technology to achieve NO_x reductions over a temperature range of 800°F. to 2100°F. The urea injection performance is limited by the temperature, residence time, and flow characteristics of the flue gas. Temperature is the primary control variable for the selective reactions. As with "Thermal DeNO_x," the performance is impacted by the residence time in the temperature window and the reducing agent-to-NO_x ratio. Since the residence time in the temperature window is usually short for retrofit applications, the NO_x reduction capability is limited. "NO_xOUT" technology has demonstrated NO_x reductions of up to 80 percent.

Selective Catalytic Reduction. Selective catalytic reduction (SCR) is a process that chemically reduces NO_x with a reducing agent (usually ammonia or urea) over a heterogeneous catalyst in the presence of oxygen (O₂). The process is termed selective because the reducing agent preferentially reacts with NO_x rather than O₂. In fact, the O₂ enhances the reaction and is a necessary part of the reaction scheme. SCR is potentially applicable to flue gas under oxidizing conditions greater than one percent O₂.

In theory, a 1:1 stoichiometric molar ratio of ammonia to NO is sufficient to reduce NO_x to molecular nitrogen (N₂) and water vapor (H₂O). In practice a ratio of 1:1 has typically reduced NO_x emissions by at least 80 percent with a residual ammonia concentration of less than 20 parts per million volume (ppmv). Temperature, space velocity, and catalyst surface are the primary variables affecting NO_x reduction.

The active ingredients in SCR catalysts are either base metals, zeolite, or precious metals. Most SCR catalysts contain base metals such as titanium or vanadium oxides, and are active at temperatures above 450°F., although the optimum temperature range is above 570°F. Excessive temperatures above 800°F. or 850°F. can cause thermal breakdown of base metal catalysts. Zeolite type catalysts are active at temperatures above 675°F., and can operate continuously at temperatures in excess of 1000°F. Catalysts containing precious metals (platinum and palladium) are effective at temperatures between 300°F and 550°F.

b. Regulations

Rules or standards controlling NO_x emissions from boilers, steam generators, and process heaters have been adopted by a number of districts. The applicability and requirements of these rules are summarized in Table 8.

Table 8

Standards For Boilers, Steam Generators, and Process Heaters

Agency ¹	Rule	Date Adopted	Applicability ²	Standards ³ (NO _x as NO ₂)
SCAQMD	1109	Aug. 1988	oil refineries, > 40 MMBTU/hr	0.03 lbs/MMBTU
SCAQMD	1146	Jan. 1989	≥ 5 MMBTU/hr	40 ppmv
SCAQMD	1146.1	Oct. 1990	> 2 and < 5 MMBTU/hr	30 ppmv
VCAPCD	74.15	Dec. 1991	≥ 5 MMBTU/hr	40 ppmv
VCAPCD	74.15.1	May 1993	≥ 1 and < 5 MMBTU/hr	30 ppmv
SBCAPCD	342	Mar. 1992	≥ 5 MMBTU/hr	30 ppmv (gas) 40 ppmv (liquid)
BAAQMD	9-7	Sep. 1993	≥ 10 MMBTU/hr and ≥ 90,000 therms/yr	30 ppmv (gas) 40 ppmv (other)
BAAQMD	9-10	Jan. 1994	Oil refineries, ≥ 10 MMBTU/hr	0.033lbs/MMBTU, refinery average
YSAQMD	2.27	Oct. 1993	≥ 5 MMBTU/hr and ≥ 90,000 therms/yr	30 ppmv (gas) 40 ppmv (other)

(cont'd)

¹SCAQMD = South Coast Air Quality Management District

VCAPCD = Ventura County Air Pollution Control District

SBCAPCD = Santa Barbara County Air Pollution Control District

BAAQMD = Bay Area Air Quality Management District

YSAQMD = Yolo-Solano Air Quality Management District

² lbs/MMBTU = pounds per million British Thermal Units

ppmv = parts per million by volume, dry, at 3 percent oxygen.

³MMBTU/hr = millions of British Thermal Units per hour

Table 8 (Cont'd)

Standards For Boilers, Steam Generators, and Process Heaters

Agency ¹	Rule	Date Adopted	Applicability ²	Standards ³ (NO _x as NO ₂)
SJVUAPCD	4305	Dec. 1996	> 5 MMBTU/hr and ≥ 30 billion BTU/yr (≥ 90 billion BTU/yr for replacement standby units)	box or cabin units, or vertical cylindrical heaters 147 ppmv (gas) 155 ppmv (oil) all others: 30 ppmv (gas) 40 ppmv (oil)
SJVUAPCD	4352	Sept. 1994	Biomass Mult. Hearth Municipal Solid Waste All Other Solid Waste	0.35 lbs/MMBTU 200 ppmv at 12% CO ₂ 0.20 lbs/MMBTU
SDCAPCD	69.2	Sept. 1994	≥ 5 MMBTU/hr	30 ppmv (gas) 40 ppmv (oil)
EDCAPCD	229	Sept. 1994	≥ 5 MMBTU/hr	30 ppmv (gas) 40 ppmv (other)
EDCAPCD	232	Oct. 1994	≥ 5 MMBTU/hr, Biomass fuel	115 ppmv at 12% CO ₂ or 50% reduction
MDAQMD	1157	Oct. 1994	≥ 5 tons/day or ≥ 250 tons/yr NO _x ; ≥ 5 MMBTU	30 ppmv (gas) 40 ppmv (oil) 70 ppmv (gas) 115 ppmv (oil)

(cont'd)

- ¹SCAQMD = South Coast Air Quality Management District
VCAPCD = Ventura County Air Pollution Control District
SJVUAPCD = San Joaquin Valley Unified Air Pollution Control District
SDCAPCD = San Diego County Air Pollution Control District
EDCAPCD = El Dorado County Air Pollution Control District
MDAQMD = Mojave Desert Air Quality Management District
- ²MMBTU/hr = million British Thermal Units per hour
- ³ppmv = parts per million by volume, dry, at 3 percent oxygen,
unless otherwise indicated
- lbs/MMBTU = pounds per million British Thermal Units

Table 8 (Cont'd)

Standards For Boilers, Steam Generators, and Process Heaters

Agency ¹	Rule	Date Adopted	Applicability ²	Standards ³ (NO _x as NO ₂)
KCAPCD	425.2	Oct. 1994	≥ 5 MMBTU/hr	70 ppmv (gas) 115 ppmv (oil)
PCAPCD	231	Oct. 1994	≥ 5 MMBTU/hr and ≥ 90,000 therms	30 ppmv (gas) 40 ppmv (other)
PCAPCD	232	Oct. 1994	Biomass Suspension	80+% reduction
PCAPCD	233	Oct. 1994	Biomass Boilers	115 ppmv at 12% CO ₂ or 50% reduction
CCAPCD	2.39	Jan. 1996	≥ 5 MMBTU/hr and > 15% capacity factor	70 ppmv (gas) 115 ppmv (other)
SMAQMD	411	Feb. 1995	≥ 5 MMBTU/hr	30 ppmv (gas) 40 ppmv (other) 70 ppmv (biomass)
SLOCAPCD	430	July 1995	≥ 5 MMBTU/hr	30 ppmv (gas) 40 ppmv (other)
SCAPCD	3:26	Dec. 1995	≥ 5 MMBTU/hr and > 15% capacity factor	70 ppmv (gas) 115 ppmv (other)
TCAPCD	4:14	Sept. 1985	All fuel burning equipment	125 ppmv (gas) 225 ppmv (other)

(cont'd)

¹KCAPCD = Kern County Air Pollution Control District

PCAPCD = Placer County Air Pollution Control District

CCAPCD = Colusa County Air Pollution Control District

SMAQMD = Sacramento Metropolitan Air Quality Management District

SLOCAPCD = San Luis Obispo County Air Pollution Control District

SCAPCD = Shasta County Air Pollution Control District

TCAPCD = Tehama County Air Pollution Control District

²MMBTU/hr = millions of British Thermal Units per hour³ppmv = parts per million by volume, dry, at 3 percent oxygen,
unless otherwise indicated

Table 8 (Cont'd)

Standards For Boilers, Steam Generators, and Process Heaters

Agency ¹	Rule	Date Adopted	Applicability ²	Standards ³ (NO _x as NO ₂)
ARB/ CAPCOA	RACT	July 1991	≥ 5 MMBTU/hr and ≥ 90,000 therms	70 ppmv (gas) 115 ppmv (other)
	BARCT	July 1991	≥ 5 MMBTU/hr and ≥ 90,000 therms	30 ppmv (gas) 40 ppmv (other)

¹ARB/CAPCOA = Air Resources Board/California Air Pollution Control Officers Association approved guidance

²MMBTU/hr = millions of British Thermal Units per hour

³ppmv = parts per million by volume, dry, at 3 percent oxygen.

ARB staff has developed a RACT and BARCT guidance document to reduce NO_x emissions from industrial boilers, steam generators, and process heaters. This guidance document was approved in July 1991, by the Technical Review Group of CAPCOA as a RACT and BARCT determination. The RACT and BARCT standards are shown at the end of Table 8.

Recent BACT determinations for new gas-fired sources include 9 parts per million by volume NO_x (ppmv) at 3 percent O₂ for boilers and process heaters with SCR, 12 ppmv at 3 percent O₂ for steam generators with low NO_x burners, FGR and SCR. These emission levels are also achievable through use of the latest generation of low NO_x burners. Recent BACT determinations for new coal-fired sources include 30 ppmv NO_x at 3 percent O₂ for a fluidized bed combustor using Thermal DeNO_x.

2. Utility Boilers

Utility boilers combust fuels to generate steam that is expanded in a turbine which drives an electric generator. In California, utility boilers burn either natural gas or fuel oil. Almost all large (i.e., electric utility sized) electricity generating boilers in California are operated by public utilities.

A number of technologies can be used to control NO_x from utility boilers. Currently, five methods have been demonstrated to achieve NO_x emission reductions. They are: (1) air-fuel staging, (2) low NO_x burners, (3) flue gas recirculation (FGR), (4) selective catalytic reduction (SCR), and (5) selective noncatalytic reduction (SNCR) using ammonia, urea, or a similar reducing agent.

a. Control Technology

Air-Fuel Staging. Air-fuel staging techniques include overfire air (OFA), burners-out-of-service (BOOS), and off-stoichiometric firing.

The OFA combustion system employs conventional burners to introduce the fuel and sub-stoichiometric quantities of combustion air (primary air). The remaining combustion air (secondary air) is introduced downstream, near the firebox exit, through overfire air ports. The OFA technique limits NO_x formation by two mechanisms. Staging the combustion air partially retards the combustion process, producing a cooler flame. Staging also reduces the amount of oxygen available in the combustion region, and reduces mixing of fuel and air in this region. The cooler flame suppresses the formation of thermal NO_x, while the reduced oxygen and mixing suppresses the formation of fuel NO_x.

Burners-out-of-service, or BOOS, is a variation of the staged combustion technology for limiting NO_x emissions. Fuel flow to certain burners is totally cut off and diverted to other, operating burners. Airflow remains unchanged for the operating burners. As a result, the operating burners fire more fuel-rich than normal. The remaining air required for combustion is admitted through the inactive burners.

Off-stoichiometric firing is a variation of BOOS. In off-stoichiometric firing, some burners are fired fuel-rich while others are fired fuel-lean.

Other Methods. The theory and application of low NO_x burners, FGR, SCR, and SNCR do not vary significantly from those for boilers, steam generators, and process heaters. See Section C.1.a. for a discussion of these methods.

The SCR method has been demonstrated to be the most effective of all NO_x controls for utility boilers. The most recent applications of SCR have placed the catalyst within existing ductwork at the air preheater or economizer section of the utility boiler. The capital cost of these in-duct SCR systems is about one-third of the cost of a conventional, stand-alone SCR system. Although control efficiencies for the in-duct SCR systems are lower than for stand-alone SCR, other controls such as FGR and low NO_x burners can be added to achieve equivalent reductions.

Work is currently planned or being conducted to develop low NO_x burners having the emission reduction performance of stand-alone SCR. These burners would be a further development of the latest generation of low NO_x industrial boiler burners. Once developed, these burners are expected to achieve NO_x concentrations as low as 10 parts per million. Capital costs for these low NO_x utility burners are expected to be about 20 percent of the capital costs for stand-alone SCR. Operating costs for these new burners are expected to be only slightly greater than for burners for an uncontrolled utility boiler.

b. Regulations

Six districts have recently adopted rules or standards limiting NOx emissions from utility boilers. These utility boiler rules are considered BARCT for utility boilers. The applicability and requirements of these rules are summarized in Table 9. This summary includes only final NOx limits. For most rules, interim limits apply prior to the compliance date for the final limits.

Table 9

Standards For Utility Boilers

Agency ¹ /rule	Date Adopted	Applicability	Standards (NOx)	Averaging Time
VCAPCD Rule 59	June 1991	≤ 43 MW power gener. ≥ 2150 MMBTU/hr	0.20 lbs/MWH ² 0.10 lbs/MWH	Rolling 24 hr. avg.; recal. every hr.
SCAQMD Rule 1135	July 1991	Burbank, Glendale, and Pasadena systems	0.20 lbs/MWH	Daily avg.
MBUAQMD Rule 431	Sept. 1993	750 MW units 110, 120 MW units	10 ppm (gas) ² 25 ppm (oil) ³ 30 ppm (gas) 110 ppm (oil) ⁴	1-hr. avg.
SLOCAPCD Rule 429	Nov. 1993	> 1500 but < 2000 MMBTU/hr ≥ 2000 MMBTU/hr	30 ppm (gas) 110 ppm (oil) ³ 10 ppm (gas) 25 ppm (oil) ⁴	1-hr avg.

(cont'd)

¹VCAPCD = Ventura County Air Pollution Control District

SCAQMD = South Coast Air Quality Management District

MBUAQMD = Monterey Bay Unified Air Pollution Control District

SLOCAPCD = San Luis Obispo County Air Pollution Control District

²lbs/MWH = pounds of NOx per megawatt-hour of electricity generated

ppm = parts per million by volume, corrected to 3 percent oxygen

³Oil allowed to be used only if gas not available or if testing is performed

⁴From May 1 through October 31, oil allowed to be used only if gas is not available or if testing is performed

Table 9 (Cont'd)

Standards For Utility Boilers

Agency ¹ /rule	Date Adopted	Applicability	Standards ² (NOx)	Averaging Time
SDCAPCD Rule 69	Dec. 1995	All utility boilers	650 tons total	Calendar year
BAAQMD Reg. 9 Rule 11	Nov. 1995	≥ 1750 MMBTU/hr	10 ppm (gas) 25 ppm (non-gaseous) ³	1-hr avg.
		< 1750 and ≥1500 MMBTU/hr	25 ppm (gas) 110 ppm (non-gaseous) ⁴	
		< 1500 MMBTU/hr	30 ppm (gas) 110 ppm (non-gaseous) ⁴	

¹SDCAPCD = San Diego County Air Pollution Control District

BAAQMD = Bay Area Air Quality Management District

²Optional system-wide NOx limit of 0.018 pounds of NOx per million BTU of heat input applies to BAAQMD.

³From May 1 through October 31, oil allowed to be used only if gas is not available or if testing is performed

⁴Oil allowed to be used only if gas not available or if testing is performed

3. Gas Turbines

A gas turbine is an engine which consists of a compressor, a combustor, and a power turbine. The compressor provides pressurized air to the combustor, where fuel is injected and burned. Hot combustion gases leave the combustor and enter the turbine section. In the turbine section, the gases are expanded across the power turbine blades to rotate one or more shafts. The shaft(s) drive the compressor. In industrial applications, the shaft(s) also drive either an electric generator or other mechanical equipment. Frequently, heat from the exhaust of the gas turbine is also used. This exhaust can be used directly to provide process heat for industrial processes, or can be ducted to a waste heat boiler to produce steam. The steam can be used in industrial processes, or can pass through a steam turbine/generator to produce electrical energy.

There are two major types of gas turbines: industrial and aeroderivatives. Industrial gas turbines, which evolved from jet engines, generally have tubular or can combustors, are very durable, and cover power outputs ranging from a fraction of a megawatt to over 200 megawatts. Aeroderivatives are based on jet aircraft engines, and have modified power turbines so that they can be used for ground installations. Aeroderivatives usually have annular combustors, are lightweight, compact, and cover a more restrictive power output range (typically from 3 to 50 megawatts) than industrial turbines. Newer aeroderivatives operate at much higher compression ratios and are more efficient than most industrial turbines. Aeroderivatives, by design, are also more suitable for improvements such as intercooling, reheat, and chemical recuperation. These improvements can increase efficiency to levels above 60 percent.

a. Control Technology

The three methods of control that are currently available for gas turbines are water or steam injection, dry low NO_x combustors, and post combustion control such as selective catalytic reduction. The use of methanol fuel is another alternative that may be available in the future.

Water or Steam Injection. In gas turbines, the injection of water or steam into the combustor tends to quench the flame and absorb heat, which reduces the combustion temperature and consequently the formation of thermal NO_x. As a secondary benefit, water or steam injection will allow more fuel to be burned without overheating critical turbine parts, and this effect can be used to increase the maximum power output of a gas turbine. The water or steam used must be of extremely high purity, with a total dissolved solids content no greater than about one part per million. This high purity requirement dictates the use of a water purification system.

In most cases, the use of water or steam injection can reduce NO_x in dry exhaust gas to a concentration below 42 ppmv at 15 percent O₂ when firing on natural gas, and below 65 ppmv when firing on oil, without subjecting the internal parts to a rapid increase in wear. Some aeroderivative gas turbines using water or steam injection can tolerate much higher injection rates without significant wear problems and can achieve NO_x levels below 25 ppmv.

Unlike aeroderivatives, industrial gas turbines generally cannot tolerate high injection rates of water or steam. As water injection levels increase, these units experience a significant increase in dynamic pressure activity (noise) and engine wear. General Electric offers one model that can achieve NO_x levels of 25 ppmv on gas-fired units and 42 ppmv on fuel oil-fired units using a "quiet" combustor that is designed to tolerate higher levels of water without causing excessive dynamic pressure activity. However, there are no plans to make the quiet combustor available for other models.

Dry Low NO_x Combustors. The lean premix type is the most popular dry low NO_x combustor available. Other types of dry low NO_x combustors include catalytic combustors and rich-quench-lean combustors. Combustors using a catalyst to assist combustion appear to be on the verge of commercialization, while in the future combustors using the rich-quench-lean method may also be available.

Conventional combustors are diffusion controlled. The fuel and air are injected separately. Combustion occurs locally at stoichiometric interfaces, resulting in hot spots which produce higher levels of NO_x. In contrast, lean premix combustors mix the air and fuel before they enter the combustor. In premixed flames, the reaction rate is limited more by chemical reaction rates than mixing rates. In a lean premix combustor, the maximum flame temperature can be controlled by changing the air/fuel ratio.

Many new gas turbines are offered with dry low NO_x combustors, and dry low NO_x combustor retrofits are available for some existing gas turbines. In fact, the popularity of water or steam injection for NO_x control is rapidly losing favor to dry low NO_x combustors.

Lean premix combustors have only been developed for gaseous fueled turbines. Lean premix combustors are capable of achieving a 70 to 90 percent NO_x reduction (i.e., 10 to 40 ppm NO_x). Some lean premix combustors have dual fuel capability, and can be fired on distillate oil. However, when using oil, these combustors operate only in the diffusion mode, and water or steam injection is generally used to control NO_x emissions. When a lean premix combustor turbine is operating on oil with water or steam injection, NO_x emissions are typical of a turbine with conventional combustors using water or steam injection.

The rich-quench-lean combustor is a two stage combustor. In the first stage, a rich fuel mixture is burned. The partially burned combustion gases then pass through a narrow neck, where the reaction is quenched. The quenching is generally assisted by water or steam injection. The combustion gases exit the neck into the second stage, where excess air is fed into the combustor to complete the reaction.

In catalytic combustion, a catalyst is placed into the combustor, and the air/fuel mixture passes through the catalyst. Compared to a conventional combustor, combustion of the air/fuel mixture occurs at much lower temperatures in a catalytic combustor, which greatly reduces the formation of thermal NO_x. Emissions from catalytic combustors can be below 5 ppm NO_x. Catalytic combustion has been applied to several combustion processes at atmospheric pressure, but application to gas turbines has been delayed due to special problems involving the design, combustion, and operation of gas turbines. These difficulties may have recently been resolved, and commercialization of this technique may be imminent.

Post Combustion Controls. Many gas turbines are used in combined cycle or cogeneration applications, in which the exhaust gases from the turbine pass through a waste heat boiler. As discussed in Section C.1.a., selective catalytic reduction (SCR) is a post

combustion control technology applicable to boilers, and when SCR is used to control NO_x gas turbines, it is typically placed inside the waste heat boiler. The catalyst most commonly used is titanium dioxide, but vanadium pentoxide, zeolite, and noble metals are also used.

High temperature catalysts (up to 960°F.) are available that can be placed upstream of the boiler. These high temperature catalysts can be used in conjunction with air dilution to maintain the correct temperature range. High temperature catalysts can also be used when a waste heat boiler is not present.

SCR is capable of over 90 percent NO_x removal. When combined with dry low NO_x combustors or water or steam injection, very low NO_x emissions levels (below 10 ppmv at 15 percent oxygen when firing on gas) are achievable.

Methanol. The use of methanol fuel will result in lower NO_x emissions than the use of gas or oil. Methanol burns at a lower flame temperature, thus generating less NO_x. Burning methanol fuel instead of natural gas in a gas turbine produces about a 60 percent reduction in NO_x emissions. If a methanol/water mixture (containing about 10 to 20 percent water) is burned, NO_x reductions are increased to about 80 to 90 percent. The conversion to methanol fuel requires equipment modifications to accommodate the differences in properties between methanol and gas or fuel oil. Methanol is generally not used as a fuel for gas turbines, primarily due to its high cost in comparison to other fuels.

b. Regulations

Rules and standards have been adopted for gas turbines by several districts in California. A summary of these rules is displayed in Table 10. The ARB/CAPCOA RACT and BARCT determination for gas turbines is also included in Table 10.

Table 10

Standards For Gas Turbines

Agency ¹	Rule	Date Adopted	Applicability	Standards (ppmv NO _x @ 15% O ₂)
GBUAPCD	404-B	Mar. 1976	> 110 MW	42 (gas) 75 (liquid)
SCAQMD	1134	Aug. 1989	≥ 0.3 and < 2.9 MW ≥ 2.9 and < 10 MW ≥ 10 MW ≥ 60MW, cogeneration	25 9 (with SCR) 15 (w/o SCR) 9 (with SCR) 12 (w/o SCR) 15 (w/o SCR)
BAAQMD	9-9	May 1993	≥ 0.3 and < 10.0 MW ≥ 10.0 MW with SCR ≥ 10.0 MW without SCR ≥ 4.0 MW (operating < 877 hrs/yr)	42 X EFF ² /25% 9 X EFF/25% 15 X EFF/25% 42 X EFF/25%
KCAPCD	425	Aug. 1993	All but 1 turbine 1 turbine	9 (gas) 25 (oil) 20 (gas) 42 (oil)

(cont'd)

¹GBUAPCD = Great Basin Unified Air Pollution Control District

SCAQMD = South Coast Air Quality Management District

BAAQMD = Bay Area Air Quality Management District

KCAPCD = Kern County Air Pollution Control District

²EFF is efficiency of the gas turbine in percent. An efficiency less than 25 percent is assigned a value of 25 percent.

Table 10 (Cont'd)

Standards For Gas Turbines

Agency ¹	Rule	Date Adopted	Applicability	Standards (ppmv NO _x @ 15% O ₂)
YSAQMD	2.34	July 1994	≥ 0.3 to < 2.9 MW, and ≥ 4.0 MW and < 877 hr. ≥ 2.9 to < 10.0 MW ≥ 10.0 MW, SCR ≥ 10.0 MW, no SCR	42 (gas) 65 (oil) 25 X EFF ² /25% (gas) 65 (oil) 9 X EFF/25% (gas) 25 X EFF/25% (oil) 15 X EFF/25% (gas) 42 X EFF/25% (oil)
SDCAPCD	69.3	Sept. 1994	≥ 0.3 MW (new) ≥ 1.0 MW (existing)	42 (gas) 65 (oil)
PCAPCD	250	Oct. 1994	≥ 0.3 to < 2.9 MW, and ≥ 4 MW and < 877 hr. ≥ 2.9 to < 10 MW ≥ 10 MW, SCR ≥ 10 MW, no SCR	42 (gas) 65 (oil) 25 X EFF/25% (gas) 65 (oil) 9 X EFF/25% (gas) 25 X EFF/25% (oil) 15 X EFF/25% (gas) 42 X EFF/25% (oil)
MDAQMD	1159	Feb. 1995	≥ 0.3 MW, except GE GE LM 1500	42 (gas) 65 (oil) 90 (gas)

(cont'd)

¹YSAQMD = Yolo-Solano Air Quality Management District

SDCAPCD = San Diego County Air Pollution Control District

PCAPCD = Placer County Air Pollution Control District

MDAQMD = Mojave Desert Air Quality Management District

²EFF is efficiency of the gas turbine in percent. An efficiency less than 25 percent is assigned a value of 25 percent.

Table 10 (Cont'd)

Standards For Gas Turbines

Agency ¹	Rule	Date Adopted	Applicability	Standards (ppmv NO _x @ 15% O ₂)
SJVUAPCD	4703	Mar. 1995	≥ 4 MW, < 877 hr.	42 (gas) 65 (oil)
			≥0.3 MW, < 10 MW, and ≥ 877 hr.	42 (gas) 65 (oil)
			≥ 10 MW, no SCR, and ≥ 877 hr.	15 X EFF ² /25% (gas) 42 X EFF/25% (oil)
			≥ 10 MW, SCR, and ≥ 877 hr.	9 X EFF/25% (gas) 25 X EFF/25% (oil)
			GE Quiet Comb.	18 X EFF/25% (gas) 42 X EFF/25% (oil)
			Solar Saturn	50 (gas) 50 (oil)
			VCAPCD	74.23
			≥ 2.9 to < 10.0 MW	25 X EFF ² /25% (gas) 65 (oil)
			≥ 10.0 MW, SCR	9 X EFF/25% (gas) 25 X EFF/25% (oil)
			≥ 10.0 MW, no SCR	15 X EFF/25% (gas) 42 X EFF/25% (oil)
SMAQMD	413	Apr. 1995	≥ 0.3 to < 2.9 MW, and ≥ 2.9 MW, < 877 hr.	42 (gas) 65 (oil)
			2.9 to < 10.0 MW	25 (gas) 65 (oil)
			≥ 10.0 MW, SCR	9 (gas) 25 (oil)
			≥10.0 MW, no SCR	15 (gas) 42 (oil)

(cont'd)

¹SJVUAPCD = San Joaquin Valley Unified Air Pollution Control District

VCAPCD = Ventura County Air Pollution Control District

SMAQMD = Sacramento Metropolitan Air Quality Management District

²EFF is efficiency of the gas turbine in percent. An efficiency less than 25 percent is assigned a value of 25 percent.

Table 10 (Cont'd)

Standards For Gas Turbines

Agency ¹	Rule	Date Adopted	Applicability	Standards (ppmv NO _x @ 15% O ₂)
ARB/ CAPCOA	RACT	May 1992	≥ 0.3 MW	42 (gas) 65 (oil)
	BARCT		≥0.3 and < 2.9 MW and units ≥ 4 MW, operating < 877 hrs/yr	42 (gas) 65 (oil)
			≥ 2.9 and < 10 MW	25 X EFF ² /25% (gas) 65 (oil)
			> 10 MW (w/o SCR)	15 X EFF/25% (gas) 42 X EFF/25% (oil)
			> 10 MW (with SCR)	9 X EFF/25% (gas)
				25 X EFF/25% (oil)

¹ARB/CAPCOA = Air Resources Board/California Air Pollution Control Officers Association

²EFF is the efficiency in percent of the turbine. An efficiency less than 25 percent is assigned a value of 25 percent.

Recent NO_x BACT determinations for gas turbines include 3.5 ppmv at 3 percent O₂ using steam injection and SCR, and 6 ppmv at 15 percent O₂ using dry low NO_x combustors and SCR.

4. Internal Combustion Engines

Stationary reciprocating internal combustion (IC) engines generate power by combustion of a fuel-air mixture. IC engines are typically used to power pumps, compressors, and electrical generators. Applications include oil and gas pipelines, oil and gas production, water transport, agriculture, building, industrial uses, and power production. IC engines can be either two stroke or four stroke, rich-burn or lean-burn, and spark ignited or compression ignited. IC engines can burn natural gas, oil field gas, digester gas, landfill gas, propane, butane, liquified petroleum gas (LPG), gasoline, methanol, ethanol, diesel, fuel oil, or a combination of these fuels. IC engines can also be naturally aspirated or use a supercharger or turbocharger. IC engines can be used as standby sources of power or they can be operated on a continuous basis. IC engines can be operated at a continuous power output, or can be operated cyclically, with power output varying over time.

Two methods are used to ignite the fuel-air mixture: compression ignition and spark ignition. Compression ignition engines generally use diesel or a combination of natural gas and diesel as fuel. Spark ignition engines generally use gaseous fuels or gasoline. Most of the fuel consumed by stationary IC engines is natural gas.

Most NO_x formed by IC engines is thermal NO_x due to the high temperatures and pressures of combustion. A small amount of fuel NO_x is formed as a result of burning diesel or fuel oil.

Stationary IC engines are categorized based on the oxygen content of the exhaust gases. Engines designed to run with exhaust streams having more than about four percent oxygen content are referred to as "lean-burn." Engines designed to run with exhaust streams having less than about four percent oxygen content are referred to as "rich-burn." Compression ignition engines are lean-burn. Larger spark ignition engines tend to be lean-burn, while smaller spark ignition engines tend to be rich-burn.

a. Control Technology

There are a wide variety of control techniques that can be applied to IC engines. The feasibility and effectiveness of each technique depends on the general characteristics of the engine (e.g., rich-burn or lean-burn, compression ignition or spark ignition). These control techniques include combustion modifications, exhaust control, replacement with a lower NO_x emitting engine or electric motor, and switching to a cleaner fuel such as methanol or clean diesel.

Combustion modifications that can be used on compression ignition engines include injection timing retard, modified injectors, supercharging or turbocharging in conjunction with aftercooling, exhaust gas recirculation, precombustion chambers, water injection, and thermal barrier coatings.

Combustion modifications that can be used on spark ignition engines include prestratified charge retrofit, ignition timing retard, air/fuel ratio changes, precombustion (i.e., clean burn) retrofit, improved ignition systems, turbocharging or supercharging in conjunction with aftercooling, and exhaust gas recirculation.

Exhaust controls include nonselective catalytic reduction (NSCR) for rich-burn engines, and selective catalytic reduction (SCR) for lean-burn engines.

Retrofitting existing engines to burn other fuels can also reduce NO_x emissions significantly. Based on fleet vehicle demonstrations, converting diesel engines to methanol or natural gas fuels will reduce NO_x emissions by 60 to 90 percent.

The previously mentioned combustion modification control techniques are described on the following pages. Techniques applicable to compression ignition engines are listed first, followed by techniques applicable to spark ignition engines. Exhaust gas treatment techniques are discussed last.

i. Compression Ignition Engines

Injection Timing Retard. Injection of fuel for most compression ignition engines begins shortly before the piston reaches the top dead center (TDC) position during the compression stroke. If injection can be delayed or retarded slightly, more of the combustion will take place as the piston begins its downward movement. This will reduce both the magnitude and duration of peak temperatures, pressures, and residence times, thus reducing NO_x formation. Injection timing retard can be used to control NO_x on all compression ignition engines where timing is adjustable. The timing of many diesel engines can be retarded by about four degrees from the manufacturer's specifications without problem. However, if the injection is retarded too much, operational problems will be encountered such as decreased power, fuel economy, and throttle response, along with increased emissions of particulate matter and other pollutants. At four degrees of retard, NO_x reductions are typically 15 to 25 percent.

Modified Injectors. Several changes in the design of older, conventional injectors can be made that can reduce NO_x emissions. They include electronic controls, which allow more flexibility in adjusting timing for various operational modes. With this added flexibility, timing can be retarded further in certain modes where operational problems are not encountered, and less in other modes where such problems are encountered. In this fashion, NO_x can be minimized while also minimizing the adverse effects of retard.

Another design change is improved injector nozzles, which provide a finer, more uniform spray pattern. The improved pattern tends to reduce hydrocarbon, carbon monoxide, and particulate emissions, while also reducing NO_x slightly. Use of such nozzles can allow greater injection retard without introducing operational problems or increased emissions of other pollutants.

Another change is the use of high pressure fuel injector pumps. At higher pressures, the spray pattern can be even finer and more uniform, and the injection process can take less time. Thus, injection can begin later in the engine cycle and end earlier. Starting injection later is effectively the same as retarding the injection timing, which reduces NO_x emissions. Shortening the injection duration tends to increase engine efficiency, which reduces some of the adverse effects of injection timing retard. This technique has been used in on-road diesel truck engines to help meet State and federal NO_x emissions standards.

Supercharging or Turbocharging in Conjunction with Aftercooling. Superchargers and turbochargers compress combustion air, which results in a greater mass of air in the

combustion chamber. This allows more fuel to be injected into the combustion chamber which increases power output, and also slightly increases engine efficiency. At maximum power, turbocharged or supercharged engines will emit more NO_x per hour than the same engine without turbocharging or supercharging. However, the NO_x emissions per unit of power output tend to be slightly less. Compression of the combustion air heats this air, which tends to increase peak combustion temperatures. However, the heat sink effect of the additional air in the combustion chamber, combined with the increased efficiency of the engine, tend to result in a slight reduction in NO_x emissions per unit of power output.

Significant reductions in NO_x emissions can occur if the temperature of combustion air is reduced. On supercharged or turbocharged engines, this can be accomplished by use of an aftercooler (sometimes also called an intercooler). An aftercooler uses a heat exchanger to cool the compressed, heated combustion air before it is introduced into the combustion chamber. The cooling medium can be ambient air, water from the radiator, or water from a source outside of the engine. Use of radiator water will typically cool the combustion air to a temperature slightly greater than 200°F., while use of outside water or ambient air will typically reduce this temperature to about 100°F. NO_x reductions associated with aftercooling range from about 3 to 35 percent, with the greater reductions associated with the higher temperature decreases. Since aftercoolers increase engine efficiency, retrofit of an aftercooler to an engine often results in a cost savings.

Exhaust Gas Recirculation. Exhaust gas recirculation (EGR) consists of diverting a portion of the exhaust gas from the exhaust manifold and injecting it into the intake manifold. Another method of adding EGR is to adjust an engine's operating parameters so that a greater amount of exhaust remains in the combustion chamber after the exhaust stroke. The added exhaust gas reduces peak combustion temperatures by acting as a heat absorber and by diluting the air-fuel mixture. EGR tends to reduce peak power and slightly reduces engine efficiency. At high levels of EGR, operational characteristics of the engine can be adversely affected. Reductions of up to 30 percent in NO_x emissions are possible before operational difficulties occur. When EGR is used, steps must be taken to minimize particulate in the exhaust. Otherwise, excessive wear of the turbocharger or supercharger and internal engine parts could occur. In addition, on some large engines the exhaust may have to be cooled before being injected into the intake manifold.

Precombustion Chambers. A precombustion chamber is a small combustion chamber that is connected to the main combustion chamber by a passageway. In compression ignition engines, fuel is injected into the precombustion chamber, where it ignites. The combustion gases then pass into the main combustion chamber. Precombustion engines are sometimes also called indirect injection engines, since the fuel is not directly injected into the main combustion chamber. Engines with conventional combustion chambers are called direct injection engines.

The use of a precombustion chamber effectively retards the injection timing. This occurs since there is a delay between ignition of the air-fuel mixture in the precombustion

chamber and passage of the exhaust gases into the main combustion chamber. NO_x emissions from a precombustion engine are typically slightly more than half that of an uncontrolled direct injection engine. Retarding the injection timing on a precombustion engine does not result in NO_x reductions as great as those associated with retarding direct injection engines. Precombustion retrofits are not generally available for diesel engines.

Dual fuel engines (i.e., engines using a combination of diesel and gaseous fuels) can also use precombustion chambers. Dual fuel engines are compression ignition engines, and operate exclusively on diesel fuel when idling. As the load increases, a lean mixture of gaseous fuel is added to the combustion air. At full power, diesel may represent about five percent of the energy input to the engine, although some of the newer precombustion dual fuel engines operate on as little as one percent diesel at full power. Dual fueled engines can also operate at full power using diesel fuel exclusively. When operated on diesel fuel only, NO_x emission levels for dual fueled engines are similar to those for conventional diesel engines. When operating on a mixture of diesel and gas, NO_x from an uncontrolled dual fueled engine is about half as great as that from a comparable uncontrolled diesel engine. The use of precombustion chambers on dual fueled engines can reduce NO_x emissions by as much as 80 or 90 percent. Some manufacturers offer both new precombustion chamber dual fueled engines and dual fueled precombustion retrofits for their older engines.

Water Injection. Water can be introduced into the combustion process in three ways: water/fuel emulsions, direct injection of water into the cylinder, and fumigation of water into the intake system. The water acts as a heat sink to reduce peak combustion temperatures, thus reducing NO_x emissions. NO_x reductions up to 50 percent are typical for water injection. The water used must be extremely pure, otherwise engine deposits may result. Other potential problems include water system reliability, corrosion of engine parts, breakdown of motor oil by dilution with water, and separation of the water from diesel fuel when water/fuel emulsions are used. Separation problems can be solved by emulsifying the water and diesel immediately before injection into the engine, or by using an emulsifying agent. There are few examples of this method currently in operation.

Thermal Barrier Coatings. This technique consists of applying a ceramic thermal barrier coating to combustion chambers, valve faces, and the tops of pistons. The coating thermally insulates the combustion system components, which keeps more heat in the combustion chamber. In compression ignition engines, this effect of the coating reduces ignition delay between the start of fuel injection and ignition of the fuel. This results in spreading the combustion over a longer period of time, which reduces peak temperatures and NO_x formation. Although the direct impact of thermal barrier coatings on NO_x emissions are minimal, the use of these coatings can allow the use of other NO_x reduction techniques (such as injection timing retard) without adverse effects such as increased fuel consumption and a reduction in maximum power output. The thermal barrier coating technique is available as an after-market item which can be used on replacement parts during an engine rebuild. It is also available from some manufacturers on a limited number of new engine models.

ii. Spark Ignition Engines

Prestratified Charge. The prestratified charge (PSC) process is only applicable to 4-stroke, rich-burn, spark ignited engines. PSC is a retrofit process in which modifications are made to the intake manifold to allow a pulse of ambient air to be injected into the intake manifold before each engine cycle. When intake air is drawn into the combustion chamber, a stratified mixture results, with a layer of ambient air next to the piston and lower parts of the combustion chamber, and a rich mixture near the upper parts of the combustion chamber near the spark plug. NO_x emissions are reduced due to the rich ignition mixture at the spark plug, and also due to the dilution and heat sink effects of the ambient air layer near the piston. An engine operating at less than about 70 percent of its rated load can achieve over 80 percent control of NO_x with air injection only. To obtain the same percentage reduction for greater percentage loads, a turbocharger must be added, or the existing turbocharger must be modified to provide greater volumes of air to the engine.

Ignition Timing Retard. This technique is equivalent to injection timing retard for compression ignition engines, but is used on spark ignition engines. Ignition is retarded in spark ignition engines by delaying the pulse of current to the spark plug. In general, ignition timing retard is not as effective in reducing NO_x levels as injection timing retard is for compression ignition engines. In addition, spark ignition engines are more sensitive to operational problems (such as misfiring and poor transient performance) from high levels of retard.

Air/fuel Ratio. Changing the air/fuel ratio is an effective NO_x control technique for spark ignition engines. NO_x formation reaches a maximum at an air/fuel ratio that is slightly lean (i.e., a slight amount of excess air present). If mixtures are leaner or richer than the mixture necessary for peak NO_x formation, NO_x emissions decreases. Leaning the mixture beyond the NO_x formation peak increases the amount of excess air, which acts as a heat sink and lowers the peak combustion temperature. Enriching the mixture decreases the amount of oxygen available for NO_x formation, since oxygen will preferentially combine with hydrocarbons. A rich mixture also tends to reduce peak temperatures due to incomplete combustion.

For NO_x control, leaning the air/fuel ratio is generally preferred, due to increased engine efficiencies and reductions in emissions of other pollutants. A limit is reached, however, when a mixture is leaned beyond its flammability limit. In such cases, the mixture does not ignite, misfiring occurs, and hydrocarbon emissions increase dramatically. For turbocharged engines, a larger turbocharger may have to be installed to maintain the engine's original power rating when the mixture is leaned.

Precombustion Chamber or "Clean Burn." As indicated above, the lean air/fuel ratio technique for NO_x control is limited by the flammability limit of the fuel. In reality, since there are nonuniformities in the air/fuel ratio within the combustion chamber, the actual

air/fuel ratio limit before misfiring occurs is somewhat richer than the flammability limit. However, the air/fuel ratio can approach the flammability limit more closely without misfiring if the engine is designed to ignite extremely lean air/fuel mixtures. Such engines are often referred to as "clean burn" engines. On smaller engines, the cylinder head can be redesigned to promote improved swirl patterns which result in thorough mixing. On larger engines, the use of a precombustion chamber is needed to ignite the lean mixture. For precombustion engines, a rich mixture is introduced into the precombustion chamber to assure that the mixture is ignited. Flames from the precombustion chamber move through passageways into the main combustion chamber, where the lean mixture is ignited. NO_x emission reductions in excess of 80 percent are achievable with the use of clean burn engines. At the 80 percent reduction level, the efficiency of the precombustion chamber engine is often improved over that of an uncontrolled engine. By carefully controlling operating parameters and extreme leaning of the mixture, emissions can be reduced by more than 90 percent. However, at these extreme conditions, there is usually some decrease in engine efficiency.

Improved Ignition Systems. Improved ignition systems use higher voltages, and either spark several times or continuously near the end of the compression stroke. Such systems do not directly affect NO_x formation. However, they tend to provide stable combustion, which allows the air/fuel ratio to be leaned further towards the flammability limit without encountering misfiring. Emission reductions can reach nearly 80 percent for a combination of air/fuel ratio leaning and a continuous spark ignition system.

Other Combustion Modifications. Other combustion modifications applicable to spark ignited engines include turbocharging or supercharging in conjunction with aftercooling, and exhaust gas recirculation. These techniques do not differ significantly from the description previously provided for compression ignition engines.

iii. Exhaust Gas Treatment Techniques

Nonselective Catalytic Reduction. Nonselective catalytic reduction (NSCR) is applicable to rich-burn engines. NSCR can be applied to lean-burn spark ignited engines, but these engines must first be converted to rich-burn engines by altering the air/fuel mixture. NSCR uses automotive "three-way" catalyst technology. Engine exhaust passes through the catalyst, which uses metals (e.g., platinum, rhodium, and palladium) to convert NO_x, carbon monoxide, and hydrocarbons into water, nitrogen, and carbon dioxide. Control equipment to maintain the proper air/fuel mixture is required to maintain high NO_x removal efficiencies. When applying NSCR, sulfur content of the fuel must be limited to about 800 ppm by weight, or the catalyst may experience significant deactivation. NO_x reduction efficiencies for NSCR can exceed 90 percent. The highest efficiencies are related to carefully controlled air/fuel ratios, use of catalysts with high concentrations of active materials, and use of larger catalysts to increase the residence time of exhaust gases. Maintaining the proper temperature window (about 500°F. to 900°F.) is also important. In cases where an engine operates at idle for extended periods or is cyclic in operation, the catalyst system may have to be specially designed to maintain the proper temperature.

Selective Catalytic Reduction (SCR). This process is described in Section C.1.a. (boilers, steam generators, and process heaters). The application of SCR to internal combustion engines is limited to lean-burn engines. The NO_x removal efficiency of SCR is typically above 80 percent.

b. Regulations

Eleven districts have adopted rules for IC engines. The applicability and requirements of these rules are summarized in Table 11.

Table 11

Agency ²	Rule	Date Adopted	Standards For Internal Combustion Engines		
			Applicability	Standard ¹ (ppm)	(% reduction)
SCAQMD	1110.1	10/84	>50 hp, gaseous fuels		
			-rich burn	90	80
			-lean burn	150	70
	1110.2	8/90	>50 hp, permanent >100 hp, portable		
			- \geq 500 hp	36 ³	--
			-50 to 500 hp	45 ³	
VCAPCD	74.9	12/81	\geq 50 hp, gaseous fuels		
			-rich burn	50 ⁴	90
			-lean burn	125 ⁴	80
	74.9	12/93	\geq 50 hp, all fuels		
			-rich burn	25	96
			-lean burn	45	94
			-diesel	80	90
			-rich (waste gas)	50	--
			-lean (waste gas)	125	--
			74.16	1/91	oil drilling engines
SBCAPCD	333	12/91	\geq 50 hp, all fuels except landfill gas		
			-rich burn	50	90
			-lean burn	125	80

(cont'd)

¹Either the ppm or the percent reduction limits must be met. Limits in ppm are parts per million by volume, dry, and corrected to 15 percent oxygen.

²SCAQMD = South Coast Air Quality Management District

VCAPCD = Ventura County Air Pollution Control District

SBCAPCD = Santa Barbara County Air Pollution Control District

³The ppm limits are adjusted for engines with efficiencies \geq 25 percent. For example, a 50 percent efficient engine's ppm limit is twice that of a 25 percent efficient engine.

⁴The ppm limits are adjusted for engines with efficiencies \geq 30 percent.

Table 11 (Cont'd)

Standards For Internal Combustion Engines					
Agency ²	Rule	Date Adopted	Applicability	Standard ¹	
				(ppm)	(% reduction)
BAAQMD	Reg. 9, Rule 8	1/93	≥ 250 hp, gaseous or combination of gas and liquid		
			-rich burn	56	--
			(waste gas)	210	--
			-lean burn	140	--
YSAQMD	2.32	8/94	≥50 hp		
			-rich burn	640	--
			-lean burn	740	--
			-diesel	700	--
SDCAPCD	69.4	9/94	≥50 hp and major (>25 tons/yr)		
			-rich burn	50	90
			-lean burn and all waste gas	125	80
			-diesel	700	25
MDAQMD	1160	10/94	≥500 hp		
			-rich burn	50	90
			-lean burn	140	80
			-diesel	700	30

(cont'd)

¹Either the ppm or the percent reduction limits must be met. Limits in ppm are parts per million by volume, dry, and corrected to 15 percent oxygen.

²BAAQMD = Bay Area Air Quality Management District

YSAQMD = Yolo-Solano Air Quality Management District

SDCAPCD = San Diego County Air Pollution Control District

MDAQMD = Mojave Desert Air Quality Management District

Table 11 (Cont'd)

Standards For Internal Combustion Engines					
Standard ¹					
Agency ²	Rule	Date Adopted	Applicability	(ppm)	(% reduction)
EDCAPCD	233	10/94	> 50 hp		
			-rich burn	90	--
			-lean burn	150	--
			-diesel	600	--
KCAPCD	427	10/94	>250 hp		
			-rich burn	50	90
			-lean burn	125	80
			-diesel	600	30
SJVUAPCD	4701	12/96	>50 hp		
			-rich burn	50	90
			-lean burn	75	85
			-diesel	80	90
			-oil pumping engines	300	-
			-waste fuel	125	80
SMAQMD	412	6/95	>50 hp		
			-rich burn	25	90
			-lean burn	65	90
			-diesel	80	90
SLOCAPCD	431	11/96	>50 hp		
			-rich burn	50	90
			-lean burn	125	80
			-diesel	600	30

(cont'd)

¹Either the ppm or the percent reduction limits must be met. Limits in ppm are parts per million by volume, dry, and corrected to 15 percent oxygen.

²EDCAPCD = El Dorado County Air Pollution Control District

KCAPCD = Kern County Air Pollution Control District

SJVUAPCD = San Joaquin Valley Unified Air Pollution Control District

SMAQMD = Sacramento Metropolitan Air Quality Management District

SLOCAPCD = San Luis Obispo County Air Pollution Control District

Table 11 (Cont'd)

Standards For Internal Combustion Engines					
Agency ²	Rule	Date Adopted	Applicability	Standard ¹	(% reduction)
SCAQMD	3:28	4/97	>50 bhp, ≤ 300 bhp		
			-rich-burn	640 ppm	---
			-lean-burn	740 ppm	---
			>300 bhp		
			-rich-burn	90 ppm	---
			-lean-burn	150 ppm	---
			>50 bhp		
-liquid fuel	600 ppm	---			
TCAPCD	4:34	6/97	>50 bhp, ≤ 300 bhp		
			-rich-burn	640 ppm	---
			-lean-burn	740 ppm	---
			>300 bhp		
			-rich-burn	90 ppm	---
			-lean-burn	150 ppm	---
			>50 bhp		
-liquid fuel	600 ppm	---			

¹Either the ppm or the percent reduction limits must be met. Limits in ppm are parts per million by volume, dry, and corrected to 15 percent oxygen.

²SCAQMD = Shasta County Air Quality Management District
TCAPCD = Tehama County Air Pollution Control District

In addition, RACT and BARCT guidance for stationary internal combustion engines is currently being developed jointly by the ARB and CAPCOA.

Recent BACT determinations include NOx limits of 1.5 grams per brake horsepower-hour for diesel emergency generators using SCR, 1.5 grams per brake horsepower-hour for gas-fired engines using stratified charge systems, 0.75 grams per brake horsepower-hour for engines using precombustion chambers and air/fuel ratio controllers, and 9 ppm for engines using three-way catalysts.

5. Cement Kilns

Portland, or hydraulic cement, is the most common type of cement produced. Although more than 30 raw materials are used in its manufacture, it is made of four basic components: lime, silica, alumina, and iron. These raw materials undergo separate crushing after they are quarried. These raw materials are then proportioned, ground, and blended either dry or in a wet slurry. Wet slurry cement requires more energy than dry, since water in the wet slurry must be evaporated by the kiln. Due to the higher energy requirements, the wet slurry process tends to have higher NO_x emissions. Most cement kilns are of the dry variety.

Rotary kilns are the most common type of kiln used in the cement industry. They consist of a long, cylindrical, slightly inclined, refractory lined furnace. The raw materials are fed into the upper end of the rotary kiln and travel slowly down to the lower end. The kilns are fired from the lower end so that the hot gases pass up and through the raw material. Typical temperatures in the flame combustion zone are 2550°F. to 2750°F. The raw material is dried, decarbonated and calcined in the kiln. The heating process causes the raw material to fuse together, producing a round, marble-sized, glass-hard material known as clinker. The clinker is cooled, mixed with four to five percent gypsum by weight, and ground to the desired fineness to produce cement.

The kiln can be fired with coal, petroleum coke, oil, natural gas, rubber tires, or a combination of these fuels. Cement kilns in California use coal or petroleum coke as their primary fuel, although most also use small amounts of other fuels such as oil, natural gas, or rubber tires.

In cement kilns, most NO_x is formed from the oxidation of nitrogen in the combustion air, with smaller amounts formed from nitrogen contained in the fuel and in the raw materials. The formation of NO_x is a function of the type of fuel used to heat the kiln, the flame and kiln temperatures, the residence time of the combustion gases, the rate of cooling of the gases, and the quantity of excess air present.

a. Control Technology

Emission control techniques that can be applied to cement kilns include combustion modifications, process modifications, use of either a preheater or a precalciner kiln, and post-combustion control equipment such as selective catalytic reduction (SCR). Post-combustion equipment has not been used on cement kilns due to the absence of regulations requiring a high level of NO_x reduction, and due to the high costs of post-combustion controls.

Combustion Modifications. Combustion modifications can reduce NO_x formation by minimizing both thermal and fuel-bound NO_x production. These techniques include low

excess air, modified burners, limestone injection, and indirect coal firing. NO_x reductions are typically 10 to 60 percent for these techniques.

By controlling excess air, optimum combustion and burning conditions can be maintained in the kiln while lowering NO_x emissions. Burner modifications can provide favorable and homogeneous air/fuel ratios, thereby minimizing hot spots and lowering peak flame temperatures. Limestone injected with the fuel during combustion will also reduce peak flame temperatures, thereby reducing thermal NO_x emissions.

Another combustion modification technique is indirect coal firing. In this technique, coal is pulverized, then preheated under limited oxygen conditions while being supplied to the burner. The preheating promotes conversion of fuel nitrogen to molecular nitrogen, which reduces NO_x emissions. Further NO_x reductions occur from burning less fuel to heat the decreased volume of carrier air in the coal feed.

Process Modifications. Process modifications include preheating the raw feed and varying its composition, use of a different fuel, and cement dust recycling. These techniques may achieve emission reductions up to 35 percent.

For raw feed preheat, exhaust gases from the kiln are used as a heat source. This reduces fuel use and thus NO_x emissions. For composition variations, it has been found that heating requirements vary from cement plant to cement plant. This implies that the raw feed composition can be formulated to require less heat input per ton of clinker produced. Thus, less fuel would be used, resulting in lower NO_x emissions.

Use of a different fuel in the kiln can also lower NO_x emissions. Although natural gas has a lower flame temperature than coal when used in boilers, due to the special nature of the combustion process in a cement kiln, natural gas tends to have a higher flame temperature than coal. Thus, switching from natural gas to coal in a cement kiln will generally reduce NO_x emissions. Switching to a fuel with a higher heating value and lower nitrogen content (i.e., from a high nitrogen coal to a low nitrogen petroleum coke) will also reduce NO_x emissions.

Recycling cement dust, known as insufflation, can also reduce NO_x emissions. In this process, cement dust from the dust collectors is injected into the flame zone of the kiln. This reduces peak flame and kiln temperatures due to heat absorption by the insufflated dust.

Preheater Kiln System. In systems with preheaters, the dry, pulverized feed passes through a series of cyclones where it is separated and preheated several times, typically in a four-stage cyclone system. After being preheated, the feed enters the kiln partially calcined (typically 40 to 50 percent). The kiln length required for completion of the cement formation is considerably shorter than for conventional kilns, and preheaters provide a very efficient use of energy compared to long wet or dry kilns. Typically, preheater kiln systems can achieve about a 30 percent reduction in NO_x emissions.

Precalciner Kiln System. The precalciner cement kiln is energy efficient and may achieve emission reductions of 30 to 45 percent. Reductions in energy requirements are accomplished through the use of a flash furnace. The flash furnace calcines almost 95 percent of the raw materials before they enter the rotary kiln. The combustion gases from the flash furnace continue upward through successive cyclone preheater stages in a manner similar to the preheater kiln system. With this type of a system, smaller, shorter kilns can be used. The fuel required to produce a ton of clinker is reduced in a precalciner kiln, which reduces the amount of NO_x formed.

Post-Combustion Controls. Post-combustion controls have not been used on cement kilns. One such control is selective catalytic reduction (which was discussed previously in Section C.1.a). SCR has been applied to processes similar to cement kilns, such as coal-fired power plants. The application of SCR to cement kilns may require redesign of the preheat section to obtain the proper temperature. SCR may achieve emission reductions of 80 to 90 percent.

Reburn is another post-combustion control. In a reburn system, exhaust gases from the kiln are heated, or "reburned" using natural gas. In the reburn, exhaust gases are heated from 1000°F. at the kiln exit to about 1600°F. after being reburned. At this higher temperature, NO_x molecules are broken down into nitrogen and oxygen. The nitrogen and oxygen then recombine to form molecules of nitrogen, oxygen, water vapor, and carbon dioxide. This breakdown and recombination process can be enhanced with the use of a metal oxide catalyst. Control efficiencies in excess of 70 percent are expected with the use of a catalyst. A reburn system may be tested on a California kiln in the future.

b. Regulations

There are four districts that have adopted rules limiting emissions from cement kilns. These rules are summarized in Table 12.

Table 12

Standards For Cement Kilns

Agency ¹	Rule	Date Adopted	Standard (pounds per ton of clinker)
SCAQMD	1112	June 1986	11.6, 24-hour avg.; 6.4, 30 day avg.
BAAQMD	(SIP) ²	Oct. 1994	6.4, 30 day avg.
KCAPCD	425.3	Oct. 1994	11.6, 24-hour avg.; 6.4, 30 day avg.
MDAQMD	1161	June 1995	6.4, 30-day avg. (long dry, preheat-precalciner kilns) 7.2, 30 day avg. (short dry kilns)

¹SCAQMD = South Coast Air Quality Management District

BAAQMD = Bay Area Air Quality Management District

KCAPCD = Kern County Air Pollution Control District

MDAQMD = Mojave Desert Air Quality Management District

²Permit conditions submitted as part of the State Implementation Plan (SIP).

6. Glass Melting Furnaces

The glass manufacturing process consists of preparing raw materials, melting and firing these materials in a furnace to produce glass, and forming and finishing the final product. The main types of glass produced include flat glass, container glass, pressed and blown glass, and fiberglass. In the glass manufacturing process, raw materials such as sand, limestone, soda ash, and cullet (scrap and recycled glass) are fed into a melting furnace where the temperature is kept in the range of 2700°F. to 3100°F. After a sequence of chemical reactions, the raw mixture becomes molten glass. After sufficient time at high temperature, the molten glass is drawn off either in a continuous process or a batch process, and is formed into the final product.

The furnace most commonly used is a continuous regenerative furnace. The furnace may have either side or end ports that connect two brickwork lattices (the regenerator) to the interior of the furnace. High temperature exhaust from the furnace passes through the ports and into the brickwork lattice on one side of the furnace, heating the bricks. At the same time, combustion air is heated by passing it through a second, hot brickwork lattice. Every 20 to 30 minutes the combustion air and exhaust flow is reversed, so that the brickwork lattice that was cooled by the combustion air is then heated by the exhaust, and the brickwork lattice that was heated by the exhaust then heats the combustion air.

The furnace is generally a large, shallow, and well insulated vessel. Heat is supplied by oil or natural gas fired burners located above the vessel. These burners are unlike conventional burners found in most boilers and heaters. Conventional burners mix fuel and combustion air within the burner, whereas glass furnace burners inject fuel into the combustion air.

Glass plants generally operate continuously. After 8 to 12 years of operation, they undergo a major rebuild. In addition, a minor rebuild, consisting of replacing many of the bricks, usually occurs midway between major rebuilds.

a. Control Technology

The methods use to achieve emissions reductions from glass melting furnaces include combustion modifications, process modifications, and postcombustion controls. Combustion modifications include staged combustion, low excess air, low NO_x burners, conversion from gas to oil firing, and oxy-fuel firing. Process modifications include electric boosting, increased cullet usage, and batch preheat. Postcombustion controls include SNCR and SCR (which are discussed in Section C.1.a.). These methods can be successfully applied to many existing glass furnaces. An additional postcombustion control, hydrocarbon injection, is undergoing development and may soon be used in some California glass melting furnaces.

Currently, the most effective controls for retrofitting existing glass furnaces are SCR and oxy-fuel firing. These two methods can reduce NO_x emissions from an uncontrolled level of 12 to 15 pounds per ton of glass produced to about one pound per ton of glass produced.

Some new glass furnaces have been designed which also achieve a NO_x emissions rate of about one pound per ton of glass produced. These new furnaces are designed to operate at a lower temperature, use a higher percentage of cullet, and use preheat.

Staged Combustion. Although glass furnace burners are substantially different from boiler burners, they can still be designed to produce fuel rich zones and air rich zones (i.e., staged combustion). Peak flame temperatures are reduced in this fashion, resulting in lower NO_x emissions. However, only limited reductions in NO_x are usually achievable by this method, and an increase in fuel consumption of 10 to 20 percent often results.

Low Excess Air. NO_x can be reduced from glass furnaces by reducing the amount of excess combustion air. Most furnaces can operate satisfactorily at 5 percent excess air; however, some furnaces are operated at 15 to 25 percent excess air. For every 5 percent reduction in excess air, NO_x emissions are reduced by 25 to 30 percent. Reducing the excess air also results in a significant reduction in energy requirements. For this reason, many glass furnaces already operate at reduced excess air. Emissions reduction is typically 20 to 30 percent for this method.

Low NOx Burners. As indicated earlier, glass furnace burners are actually fuel injectors. The burners can be designed or adjusted to inject fuel in a fashion that minimizes NOx emissions. Low NOx burners generate a much longer flame, and some furnaces cannot accommodate long flames. Specifically, side port furnaces, with their shorter length from burner to wall, cannot obtain major NOx reductions before the flame impinges on the brickwork at the opposite side of the furnace. Flame impingement greatly reduces the life of the furnace. End port furnaces, however, can accommodate much longer flames, and NOx reductions can be much greater. NOx emission rates ranging from 5.5 to 9 pounds per ton of glass produced are achievable for end port and side port furnaces, respectively, when using low NOx burners. Emissions reduction are typically 40 percent for this method.

Conversion from Gas to Oil Firing. A significant reduction in NOx emissions may be obtained if a gas fired furnace is converted to oil firing. Oil produces a flame higher in luminosity than gas, and this greater luminosity results in a more efficient transfer of heat. This allows lower flame temperatures to be maintained, and lower energy consumption (reportedly 10 percent) for the same amount of glass production. The NOx reduction by converting from gas to oil firing is typically 30 to 50 percent.

Oxy-fuel Firing. In this NOx reduction method, nearly all the combustion air is replaced with pure oxygen. This nearly eliminates nitrogen from the combustion air, leaving little nitrogen available for the formation of NOx. Furnace efficiencies are also improved, since flue gas volumes are greatly reduced. When an existing furnace is retrofitted with this technology, the new equipment includes burners, heat recovery equipment, an air separation unit, piping, and controls. Modifications to the flue gas system are also required, and the regenerator is removed. If this technology is retrofitted during a major rebuild, there is often a net decrease in capital costs. This decrease occurs since the cost of the new and modified oxy-fuel equipment is less than the cost of replacing the regenerator. However, operating costs for the oxy-fuel equipment are greater than costs for a conventional glass melting furnace, and there is usually an increase in the overall cost of producing glass. The additional cost of operating an oxy-fuel furnace is estimated to be five to thirteen dollars per ton of glass produced.

Electric Boosting. In electric boosting, an electric current is passed through the glass in the furnace, heating the glass mixture by electrical resistance. NOx is reduced since less fuel must be combusted for the same amount of glass production, and combustion temperatures do not need to be as great. Electric boost is the least expensive way to increase the capacity of an existing glass furnace without investing in new or larger furnaces. However, electric boost may be the most expensive way to reduce NOx, primarily due to the high cost of electricity. Many glass furnaces have had to increase capacity and already use electric boost. At high rates of boost (e.g., 20 percent of the total energy input), NOx emissions can be reduced by 50 percent.

Increased Cullet Usage. Glass furnaces use cullet in addition to raw materials as furnace feed. Cullet is crushed recycled glass. Some of this cullet may be reject glass produced on site, but much of the cullet is recycled from used glass containers. The use of cullet reduces the energy requirements to produce a ton of glass, and thereby reduces NOx emissions per ton of glass produced. From 1993 through 1995, State law required the feed of glass furnaces to be 25 percent cullet. This percentage increased to 35 percent in 1996, and will increase to 45 percent in 1999. The demand for cullet has increased its value, and it is now more expensive than raw materials. In addition, the maximum amount of cullet that can be used is a function of plant design. NOx reductions average about 20 percent from increasing the usage of cullet.

Batch Preheat. In batch preheat, the exhaust gases from the furnace, which are typically 600°F. to 900°F., are used to heat the raw materials and cullet before it is introduced into the furnace. In this fashion, reductions in energy requirements, and thereby NOx emissions, can be realized. However, the preheat equipment adds significantly to the complexity and maintenance costs of the glass plant.

Another variation on this technology is to use a conventional burner to preheat the cullet to 900°F. to 1100°F. The conventional burner can be a low NOx design, which produces only a small fraction of the NOx produced by furnace burners. Since the furnace burners are not as efficient at transferring heat as the conventional burners, total facility fuel usage is reduced, which further reduces NOx emissions. In addition, maintenance problems associated with the use of exhaust gas for preheat are eliminated.

Emissions reductions associated with batch preheat are generally minimal, with an expected reduction of only about 5 percent.

SNCR. Selective noncatalytic reduction (SNCR) has been applied to several glass plants. Its effectiveness is fairly good for some types of glass manufacturing where temperatures are fairly constant, but is less effective for other types where temperatures vary significantly over short periods of time. Since SNCR only works when ammonia or another reducing agent is introduced into the flue gas within a narrow temperature window, fluctuations in temperature can seriously affect NOx reduction. Reductions in NOx vary typically from about 20 to 60 percent.

SCR. Selective catalytic reduction (SCR) has been used in Japan, but not in this country. NOx reductions of 90 percent have been recorded, but the metal substrate catalysts that were used were fouled by alkali metal deposits. Use of a zeolite catalyst may solve this problem. Otherwise, particulate control upstream of the catalyst may be necessary. The cost of SCR appears to be lower than the cost of oxy-fuel.

Hydrocarbon Injection. In this method, a hydrocarbon fuel is injected into a hot region of either the furnace or the exhaust gas. Reactions between the fuel and NOx occur which reduce the NOx to N₂ and produce water vapor and carbon dioxide. Only a few glass plants have been retrofitted with this technology and all of these facilities are outside of California. Experimental work using this technology on a California glass plant is continuing in an attempt to improve the NOx control efficiency. This technology is expected to reduce emissions to less than three pounds of NOx per ton of glass produced, at a cost lower than SCR or oxy-fuel.

b. Regulations

Three districts in California have adopted rules regulating NOx emissions from glass melting furnaces. Table 13 presents a summary of these rules. Most glass melting furnaces in California use several methods for reducing NOx emissions. The most frequently used methods include electric boost, oxy-fuel firing, SNCR, increased cullet usage, and low excess air. In the future, hydrocarbon injection may be used on several facilities in California.

Table 13

Summary of Glass Melting Furnace Rules

District ¹	Rule	Type of Glass	NOx Emissions (lbs NOx/ton of glass)
SCAQMD	1117	Container	4.0
BAAQMD	9-12	All	5.5
SJVUAPCD	4354	Container, Fiberglass	5.5 or 80% reduction
		Flat glass	12-32 (depends on capacity factor)

¹South Coast Air Quality Management District
 Bay Area Air Quality Management District
 San Joaquin Valley Unified Air Pollution Control District

Recent BACT determinations for glass melting furnaces include limits of 5.5 pounds of NOx per ton of glass for a container glass facility, and 8.01 pounds of NOx per ton of glass for a flat glass facility.

7. Waste Combustion

Waste combustion occurs when refuse such as municipal solid waste, sludge, biomass, landfill gas, or digester gas is burned. The production of process steam or electric power is a frequent byproduct of waste combustion. The method of incineration can vary depending on the waste being burned, but the most common type of incinerator for solid waste combustion consists of a refractory-lined chamber with a grate. Gaseous wastes are combusted in the same types of devices that burn natural gas, such as gas turbines, IC engines, boilers, and flares.

The factors influencing production of fuel NO_x in a solid fueled incinerator include the distribution of combustion air (underfire versus overfire), the fuel or waste nitrogen content, and total excess air. Thermal NO_x formation rates increase with temperature, oxygen availability, heat release rate, and flue gas residence time at high temperature.

Following is a discussion of each waste category and its associated combustion technologies.

Municipal Solid Waste Combustors. Municipal solid waste (MSW) combustors include mass burning furnaces, rotary combustor furnaces and semi-suspension furnaces. In a mass burning furnace, unprocessed waste is fed onto an inclined grate and slowly tumbles down onto a burning grate. The tumbling action ensures even combustion. In a rotary combustor furnace, as the unit slowly revolves about its axis, unprocessed waste tumbles down through the furnace as it burns, thereby promoting good mixing of air and refuse. Semi-suspension furnaces are used to burn processed waste. These furnaces are equipped with bottom grates to ensure the combustion of finely ground waste that is ignited in suspension.

Sewage Sludge Incinerators. The most prevalent types of sewage sludge incinerators are multiple hearth and fluidized bed units. In multiple hearth units, the sludge enters the top hearth of the furnace, where it is dried by contact with the hot, rising, combustion gases. The sludge then is transferred to lower hearths, where it is heated further and burns. At the bottom hearth, any residual ash is removed. In fluidized bed reactors, the combustion takes place in a hot, suspended bed of sand. Much of the ash residue is swept out with the flue gas. In both types of furnaces, an auxiliary fuel may be required either during start-up or when the moisture content of the sludge is too high to support combustion.

Biomass Incinerators. Combustion devices for biomass (e.g., wood chips, field crop residues, orchard prunings, and forest residues) include pile burners, spreader stokers, suspension burners, and fluidized bed systems. Pile burners burn the waste in a thick pile or bed. Spreader stokers spread the waste pneumatically or mechanically across the furnace, where some of it burns in suspension while the remainder falls onto the grate and burns. Suspension burners pneumatically inject finely ground waste into the furnace, where it burns in suspension. As described previously, fluidized bed systems burn fuel in a pneumatically suspended media of hard noncombustible material such as sand.

Digester and Landfill Gas. Digester and landfill gas is the byproduct of anaerobic decomposition of components in sewage and garbage, respectively. Digester gas is contained in a digester tank, while landfill gas emissions are collected through a gas collection system. These gases typically are composed of methane, carbon dioxide, water vapor, and lesser amounts of other gases, including hydrogen sulfide. The gases may receive minimal treatment before being combusted, or can receive further treatment, including removal of carbon dioxide, water vapor, and hydrogen sulfide. This further treatment can produce a gas that is essentially identical to natural gas. Flares are used if the gases are combusted without energy recovery. Boilers, gas turbines, or internal combustion engines are used if energy is to be recovered. For energy recovery applications, natural gas is sometimes used as a fuel supplement. In the future, projects may be developed that convert the methane in landfill gas into methanol for use as a fuel.

a. Control Technology

A number of NO_x control technologies are applicable to waste combustion facilities. The following describes these control methods by waste type.

Municipal Solid Waste, Sludge and Biomass. NO_x control technologies for MSW, sludge and biomass incineration include SCR and SNCR. Flue gas recirculation (FGR) is another control that is used for sewage sludge. These control technologies were discussed previously in Section C.1.a.

Digester and Landfill Gas. NO_x emission controls applicable to digester and landfill gas combustion are similar to controls for natural gas combustion. Following are examples of controls which have been used on digester or landfill gas combustion devices. For flares, controls include modified burners and combustion air control. Boiler controls include low NO_x burners, FGR, and thermal DeNO_x or urea injection. For gas turbines, controls include water or steam injection, and for IC engines controls include prestratified charge combustion and clean burn engines. All of these combustion controls have been discussed in detail in previous sections. Catalysts generally have not been successfully used on these waste gases, due to impurities in the gases. The sulfur and particulate in these gases tend to mask or poison the catalyst.

Recent legislation (AB 2809, passed in 1996) directs the ARB to conduct a study and prepare a report by January 1, 1998, on the control of landfill gas emissions. Commercially available technologies that are not based on combustion are to be identified, and their effects on air quality are to be analyzed and compared to established best available control technologies.

b. Regulations

Many districts have a general rule regulating incinerators. These rules require all incinerators to be as effective as multiple chamber incinerators. A multiple chamber incinerator consists of three or more refractory lined combustion furnaces in series. Each furnace is physically separated by refractory walls with gas passage ports or ducts between furnaces. The multiple chamber incinerator is designed to assure that all waste is completely burned. In addition to these general rules, Placer County's Rule 206 contains a specific NOx emissions limit for multiple chamber incinerators of 50 parts per million dry volume (ppmdv), corrected to 12 percent carbon dioxide (CO₂), for any 1-hour interval.

In addition to Placer's multiple chamber incinerator rule, Santa Barbara adopted Rule 359, "Flares and Thermal Oxidizers," in June 1994. Rule 359 limits NOx from thermal oxidizers and ground-level enclosed flares that are operated continuously and consume more than 120,000 standard cubic feet per day of waste gas. Table 14 summarizes the NOx limits of Rule 359.

Table 14

Santa Barbara County APCD Rule 359 - Flares and Thermal Oxidizers

Description	Heat Release	NOx Limit (lbs NOx/MMBTU)
Without steam assist	<10 MMBTU/hr	0.0952
	10-100 MMBTU/hr	0.1330
	>100 MMBTU/hr	0.5240
With steam assist	all	0.068

Recent BACT determinations have required the use of FGR and thermal De-NOx for refuse incineration. For a landfill gas-fired IC engine, the BACT determination required use of a prestratified charge system to reduce NOx emissions to two grams per brake horsepower-hour.

To assist districts in making BACT determinations, the ARB issued the report Air Pollution Control at Resource Recovery Facilities, May 24, 1984. This report describes available incineration control technologies and presents emission limit guidelines for several pollutants of concern. This report was updated in 1991 (see Air Pollution Control at Resource Recovery Facilities 1991 Update). The NOx emission guidelines for resource recovery facilities described in these two reports are shown in Table 15. Information on control approaches and emission levels achieved by existing facilities is presented in Table 16. Except

for flares, control approaches and emission levels for digester and landfill gas are not presented in Table 16. For digester and landfill gas, the control approaches and levels for devices other than flares are similar to those for natural gas, which were presented earlier.

Table 15

NOx Emission Guidelines for Resources Recovery Facilities

Report	Sources	Standards (ppmdv NOx @ 12% CO ₂ ; 8-hr. avg. ¹)
1984	Municipal Solid Waste Incinerators	140-200
1991	Municipal Solid Waste Incinerators Landfill Gas Control Devices	30-50 10-60 (@ 7% O ₂)

¹8-hour average if the source has a continuous emission monitor (CEM)

Table 16

NOx Control Effectiveness on Waste Combustion

Source	Control	Percent Control	Outlet Concentration (ppmdv NOx @ 7% O ₂)
MSW	SNCR & FGR	80%	52 ²
MSW and Biomass	SNCR	45 - 66%	100 - 140 ²
	SCR	55 - 90%	30 - 80
Sewage Sludge	FGR	--	60 (@ 12% CO)
Landfill Gas	Flare	--	17 - 33

¹Source test data.

²8-hour rolling average

8. Residential Water Heaters

Residential water heaters are small, low pressure, furnace tanks used mainly for heating and storing hot water. Most water heaters that burn fuel use natural gas. Fuel use averages about 65 cubic feet per day, and water heaters have an average life of about fifteen to twenty years.

a. Control Technology

NO_x emissions from natural gas fired water heaters can be controlled by replacing the existing unit with a new unit that uses either a low NO_x burner, electric heating, or is solar assisted.

Low NO_x burners. Low NO_x burners used in gas fired water heaters are based on the same general principals used for low NO_x burners discussed in Section C.1.a. The burner design for gas fired water heaters, however, is greatly simplified, and the more elaborate types of low NO_x burners are not used.

Electric Heating. Water heaters can use electrical resistance heating or a heat pump to generate hot water. NO_x emissions from the water heater are eliminated in this fashion. However, in determining the net reduction in emissions, NO_x emissions increases from utility power plants must be taken into account. The capital cost of a resistance type electric water heater is slightly less than for a natural gas fired water heater, but operating costs are generally much greater.

Solar Assisted. Solar water heating technology, such as flat plate solar panels, can yield water with temperatures from 100°F. to 200°F. depending on conditions, and has been employed to supply domestic hot water in many areas of the world with prevalent incidental sunlight. Conventional natural gas fired or electric water heaters are used to supplement the solar heating. Application of domestic solar water heating offers a means to reduce natural gas consumption and NO_x emissions simultaneously.

b. Regulations

Four districts have adopted rules for new residential water heaters. These rules apply only to new heaters, and are summarized in Table 17.

Table 17

Summary of Residential Water Heater Rules

Control Level

District ¹	Rule	Effective Date	(ng/J) ²	Exemptions
SCAQMD	1121	1983	40 (residential) 50 (mobile home)	≥ 75,000 BTU/hr Recreational vehicles
VCAPCD	74.11	1986	40 (residential)	≥ 75,000 BTU/hr Recreational vehicles Non-natural gas fuels Mobile homes
BAAQMD	9-6	1992	40 (all homes)	> 75,000 BTU/hr Recreational vehicles Non-natural gas fuels Swimming pools/hot tubs
SJVUAPCD	4902	1993	40 (all homes)	> 75,000 BTU/hr Recreational vehicles Non-natural gas fuels Swimming pools/hot tubs

(cont'd)

¹SCAQMD = South Coast Air Quality Management District

VCAPCD = Ventura County Air Pollution Control District

BAAQMD = Bay Area Air Quality Management District

SJVUAPCD = San Joaquin Valley Air Pollution Control District

²nanograms of NOx per joule of heat output.

Table 17 (cont'd)

Summary of Residential Water Heater Rules

Control Level

District ¹	Rule	Effective Date	(ng/J) ²	Exemptions
KCAPCD	424	1993	40 (all homes)	≥ 75,000 BTU/hr Recreational vehicles Mobile homes
YSAQMD	2.37	1995	40 (all homes)	≥ 75,000 BTU/hr Recreational vehicles Swimming pools/hot tubs
SLOCAPCD	4.28	1996	40 (all homes)	≥ 75,000 BTU/hr Recreational vehicles Mobile homes
SMAQMD	414	1997	40 (residential) 50 (mobile homes)	≥ 75,000 BTU/hr Recreational vehicles Swimming pools/hot tubs Non-natural gas fuels

¹KCAPCD = Kern County Air Pollution Control District

YSAQMD = Yolo-Solano Air Quality Management District

SLOCAPCD = San Luis Obispo County Air Pollution Control District

SMAQMD = Sacramento Metropolitan Air Quality Management District

²nanograms of NOx per joule of heat output.

9. Residential Space Heaters

Fuel burning residential space heaters or furnaces generally use natural gas in California. Most heaters use a fan to pass air through the furnace, where it is heated before circulating through the house. The furnaces have input rates of less than 175,000 BTU/hr for heating alone, and cooling rates of less than 65,000 BTU/hr for combination units. The units use fuel at an average rate of 40,000 cubic feet per year and have an average life of about 20 years.

a. Control Technology

NO_x emissions from a residential space heater can be reduced by replacing the existing heater with a new one. The new heater can use either low NO_x burners or electric heating. The technology used for low NO_x burners is similar to that for water heaters, although for some more expensive units more sophisticated low NO_x burners may be used. The electric heater replacements are generally heat pumps. Heat pumps work well in areas where the minimum temperature is above 40°F., but are not economically practical for cold climates where auxiliary heating requirements would be high.

b. Regulations

Four districts have adopted rules for new residential space heaters: the South Coast Air Quality Management District (SCAQMD), the Bay Area Air Quality Management District (BAAQMD), the Ventura County Air Pollution Control District (VCAPCD), and the San Luis Obispo County Air Pollution Control District (SLOCAPCD). These rules prohibit the sale, installation, or offer for sale within the district of any stationary residential natural gas-fired fan-type central furnace that emits more than 40 nanograms of oxides of nitrogen (expressed as NO₂) per joule of useful heat delivered to the heated space. The SCAQMD and the VCAPCD rules exempt furnaces that are to be installed in mobile homes. The SCAQMD and the BAAQMD rules became effective January 1, 1984, the Ventura County APCD rule became effective May 31, 1994, and the SLOAPCD rule became effective January 26, 1996.