Stationary Reciprocating Internal Combustion Engines

Updated Information on NO_X Emissions and Control Techniques

REVISED FINAL REPORT

EPA Contract No. 68-D98-026
Work Assignment No. 2-28
EC/R Project No. ISD-228

Prepared for:

Mr. David Sanders
Ozone Policy and Strategies Group
Air Quality Strategies and Standards Division, MD-15
Office of Air Quality Planning and Standards
U. S. Environmental Protection Agency
Research Triangle Park, NC 27711

Prepared by:

Stephen W. Edgerton, Judy Lee-Greco, Stephanie Walsh
EC/R Incorporated
1129 Weaver Dairy Road
Chapel Hill, NC 27514

September 1, 2000

TABLE OF CONTENTS

TABLE OF CONTENTS
(continued)

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

1.1 PURPOSE OF THIS DOCUMENT

The purpose of this document is to update portions of *Alternative Control Techniques Document–NO_X Emissions from Stationary Reciprocating Internal Combustion Engines* (the 1993 ACT document).[1] This update will provide more recent data on emission control technologies and control costs.

This report focuses on the natural gas transmission and storage industry because this is a large segment of stationary reciprocating internal combustion (IC) engine users. In addition, the report focuses on low emission combustion (LEC) control technology because developments in the technology and costs make an update especially necessary.

This document does not replace the 1993 ACT document, but only updates certain portions. The reader should refer to the 1993 ACT document for additional information on the types of IC engines, the mechanisms of the formation of nitrogen oxides (NO_X) in IC engines, the full range of control alternatives and the technical details of each, and the costs and cost effectiveness of controls.

1.2 METHODS

Data were collected for this report primarily through site visits at facilities that operate IC engines equipped with controls for NO_X emissions; contacts with engine manufacturers, control technology vendors, and regulatory agencies; and a literature search. Additional information was obtained through seeking out useful sites on the Internet.

1.3 ORGANIZATION

Chapter 2 presents a summary of the findings of this study. Chapter 3 addresses uncontrolled emissions from selected IC engine types. Chapter 4 presents an update on selected NO_X control technologies. Chapter 5 presents a limited update on control costs and cost effectiveness.

1.4 REFERENCE FOR CHAPTER 1

1. *Alternative Control Techniques Document–NO_X Emissions from Stationary Reciprocating Internal Combustion Engines*. U. S. Environmental Protection Agency, Research Triangle Park, NC. Publication No. EPA-453/R-93-032. July 1993. 315pp. http://www.epa.gov/ttncatc1/products.html.

2.0 SUMMARY

This report primarily addresses nitrogen oxides (NO_X) emissions and cost data from lean-burn, spark-ignited (SI) stationary reciprocating internal combustion (IC) engines equipped with low-emission combustion (LEC) technology. This chapter presents a summary of updated information on these engines. This information is presented in greater depth in subsequent chapters, along with less extensive information on other selected types of IC engines and NO_X control technologies. Section 2.1 includes as summary of performance test data on NO_X emissions from lean-burn SI engines controlled with LEC technology. Section 2.2 presents a summary of updated control costs for these engines.

Throughout this document, NO_X emissions are expressed as grams per brake horsepower hour (g/bhp-hr) and/or parts per million by volume (ppmv). Unless otherwise stated, all concentrations given in units of ppmv are on a dry basis and corrected to 15 percent oxygen. The primary unit is g/bhp-hr because it expresses emissions on a comparable basis across all IC engine types and models, and because it is the standard practice.

In preparing this report, the following conversion factors were used as necessary:

- Uncontrolled rich-burn SI engines and rich-burn engines controlled with nonselective catalytic reduction (NSCR): 67 ppmv = 1 g/bhp-hr

- Uncontrolled lean-burn engines, lean-burn engines controlled with selective catalytic reduction (SCR), and rich-burn engines controlled with prestratified charge™ (PSC) technology: 73 ppmv = 1 g/bhp-hr

- Lean-burn engines controlled with low emission combustion technology: 75 ppmv = 1 g/bhp-hr

For example, when emission test results were reported only in ppmv, these factors were used to convert the results to g/bhp-hr. These conversion factors are consistent with those used in *Alternative Control Techniques Document–NO_X Emissions from Stationary Reciprocating Internal Combustion Engines* (the 1993 ACT document).[1]

The NO_X emission unit of pounds per million British thermal units input (lb/MMBtu) is not used in this report because it is less frequently used in conjunction with IC engines. As a result, a comparison of IC engine NO_X emissions with emission from other types of fuel-burning equipment cannot always be readily made. However, it should be noted that uncontrolled IC engine emissions in terms of heat input can be over an order of magnitude higher than emissions from turbines or boilers. Well controlled IC engines often emit NO_X at higher levels than uncontrolled gas turbines and boilers.

2.1 CONTROLLED NO_X EMISSIONS FROM LEC-EQUIPPED ENGINES

Table 2-1 presents LEC emissions data from several different sources. In a May 2000 memo, the EPA summarized data from 269 emissions tests on a variety of engines makes, models, and sizes. In addition to the data from the EPA memo, Table 2-1 presents data from 476 different NO_X emissions tests for 58 engines with LEC technology. Other sources of data for the table include performance test data bases from the San Diego, Santa Barbara, and Ventura County (California) Air Pollution Control Districts, test data summaries from Southern California Gas Company and Pacific Gas and Electric Company, and a Gas Research Institute (GRI) report prepared by Arthur D. Little, Inc. Note that the EPA memo also includes data from earlier versions of the Ventura and Santa Barbara County data bases.

Table 2-1 shows that the emissions ranged from 0.1 to 4.8 g/bhp-hr. Nearly 97 percent of these tests (460) found emissions less than or equal to 2 g/bhp-hr. Almost 75 percent (354) of the tests found emissions less than or equal to 1 g/bhp-hr, and 25 percent (120) found emissions of less than or equal to 0.5 g/bhp-hr. Only two tests found emissions greater than or equal to 4 g/bhp-hr.

Chapter 4 contains a more detailed update on NO_X control technologies, including LEC, selective catalytic reduction (SCR), Prestratified Charge™ (PSC), and nonselective catalytic reduction (NSCR).

2.2 CONTROL COSTS FOR LEC-EQUIPPED ENGINES

The results of the cost analysis in 1990 and 1997 dollars are summarized in Tables 2-2a and 2-2b, respectively. The tables present total capital investment and annual costs of LEC controls for eight engine sizes ranging from 80 to 8,000 bhp. In addition, the tables include the NO_X emission reductions and cost effectiveness on an annual basis and for the ozone season (May through September). The tables show that capital and annual costs increase with engine size. For example, Table 2-2b (1997 dollars) shows that capital and annual costs for an 80 bhp engine would be $231,000 and $59,100, respectively, whereas for an 8,000 bhp engine, these costs would be $760,000 and $175,000. On the other hand, the cost effectiveness per ton of NO_X reduced varies inversely with engine size. Table 2-2b (1997 dollars) shows that cost effectiveness varies from $6,470 annually and $15,500 for the ozone season for an 80 bhp engine, down to $192 annually and $460 for the ozone season for an 8,000 bhp engine.

As explained in greater detail in Chapter 5, we obtained information on LEC costs from several sources. The cost and cost effectiveness projections presented in Tables 2-2a and 2-2b

TABLE 2-1. NO_X EMISSIONS DATA FROM ENGINES WITH LEC CONTROL TECHNOLOGY

Source	No. of tests	No. of engines	No. of models	Minimum emissions (g/bhp-hr)	Maximum emissions (g/bhp-hr)	Average emissions (g/bhp-hr)	Tests ≤3 g per bhp-hr		Tests ≤2 g per bhp-hr		Tests ≤1 g per bhp-hr		Tests ≤0.5 g per bhp-hr		Tests ≥4 g per bhp-hr	
							No.	%	No.	%	No.	%	No.	%	No.	%
EPA Memo[2]	269	49	≥22	0.1	6.0	NA	266	99%	258	96%	192	71%	NA	NA	1	<1%
Ventura County[3 a]	320	23	8	0.1	4.0	0.7	319	>99%	318	99%	275	86%	102	32%	1	<1%
Santa Barbara County[4 a]	12	3	3	0.1	0.7	0.5	12	100%	12	100%	12	100%	8	67%	0	0%
San Diego County[5]	121	13	5	0.3	4.8	1.1	120	99%	108	89%	52	43%	7	6%	1	1%
So. California Gas Company[6]	7	7	1	0.8	1.5	1.1	7	100%	7	100%	5	71%	0	0%	0	0%
So. California Gas Company[7]	3	3	1	0.5	0.6	0.6	3	100%	3	100%	2	67%	1	33%	0	0%
So. California Gas Company[8]	1	1	1			0.6	1	100%	1	100%	1	100%	0	0%	0	0%
So. California Gas Company[9]	7	5	1	0.4	0.7	0.6	7	100%	7	100%	7	100%	2	29%	0	0%
Pacific Gas and Electric[10]	2	2	1	1.0	1.3	1.2	2	100%	2	100%	1	50%	0	0%	0	0%
GRI Report[11]	3	1	1	1.4	2.4	1.9	3	100%	2	67%	1	33%	0	0%	0	0%
Summary[b]	476	58	15	0.1	4.8	0.8	474	>99%	460	97%	356	75%	120	25%	2	<1%

NA = Not Available
[a]Ventura County and Santa Barbara County data are more recent, more extensive versions of emission test data bases included in the EPA memo (see Section 4.1.3.2).
[b]The summary calculation does not include data from the EPA memo in order to avoid double counting Ventura County and Santa Barbara County data that appear in both data sets. Percentages in this row were calculated relative to a total of 476 tests.

TABLE 2-2a. COSTS AND COST EFFECTIVENESS OF LEC CONTROLS IN 1990 $'s

Engine size, bhp	Total capital investment	Annual cost	NO_X reduction, tons		Cost effectiveness, \$/ton NO_X	
			Annual	O_3 season	Annual	O_3 season
80	\$214,000	\$55,000	9	4	\$6,020	\$14,400
240	\$224,000	\$57,000	27	11	\$2,080	\$4,990
500	\$240,000	\$60,500	57	24	\$1,060	\$2,540
1,000	\$271,000	\$67,100	114	48	\$590	\$1,410
2,000	\$333,000	\$80,400	228	95	\$350	\$840
4,000	\$456,000	\$107,000	457	190	\$240	\$560
6,000	\$580,000	\$134,000	685	285	\$170	\$470
8,000	\$703,000	\$161,000	914	381	\$180	\$420

TABLE 2-2b. COSTS AND COST EFFECTIVENESS OF LEC CONTROLS IN 1997 $'s

Engine size, bhp	Total capital investment	Annual cost	NO_X reduction, tons		Cost effectiveness, \$/ton NO_X	
			Annual	O_3 season	Annual	O_3 season
80	\$231,000	\$59,100	9	4	\$6,470	\$15,500
240	\$242,000	\$61,400	27	11	\$2,240	\$5,380
500	\$259,000	\$65,200	57	24	\$1,140	\$2,740
1,000	\$293,000	\$72,400	114	48	\$630	\$1,520
2,000	\$359,000	\$86,900	228	95	\$380	\$910
4,000	\$493,000	\$116,000	457	190	\$250	\$610
6,000	\$627,000	\$146,000	685	285	\$210	\$510
8,000	\$760,000	\$175,000	914	381	\$190	\$460

are based on new information on actual costs for several LEC retrofits obtained from one engine manufacturer and one third-party LEC vendor. Other inputs include uncontrolled NO_X emissions of 16.8 g/bhp-hr, controlled emissions of 2.0 g/bhp-hr, and capacity utilization of 7,000 operating hours per year (prorated for the 5 months of the ozone season). In most respects, the analysis was conducted according to the methodology of the 1993 ACT document, which, in turn, was based on the *OAQPS Control Cost Manual*. For additional detail, refer to Section 5.1.

No other cost analyses were carried out for this report. However, some cost information was obtained during this study on modern SCR systems that use urea as the reducing agent for control of NO_X emissions from lean-burn SI engines and diesel engines. See Section 5.2 of Chapter 5 for that information.

2.3 REFERENCES FOR CHAPTER 2

1. *Alternative Control Techniques Document–NO_X Emissions from Stationary Reciprocating Internal Combustion Engines*. U. S. Environmental Protection Agency, Research Triangle Park, NC. Publication No. EPA-453/R-93-032. July 1993. 315pp. http://www.epa.gov/ttncatc1/products.html.

2. Memo from D. Sanders, EPA, to D. Grano, EPA, and Docket No. A-98-12. Performance of Low Emission Combustion. May 19, 2000.

3. Memo from S. Edgerton, EC/R Inc., to Project File. Analysis of Ventura County APCD Test Data–Low Emission Combustion. July 28, 2000.

4. Memo from S. Edgerton, EC/R Inc., to Project File. Analysis of Santa Barbara County APCD Test Data–Low Emission Combustion. July 28, 2000.

5. Memo from S. Edgerton, EC/R Inc., to Project File. Analysis of San Diego County APCD Test Data–Low Emission Combustion. July 28, 2000.

6. EC/R Incorporated. Final Site Visit Reports for Southern California Gas Company Facilities, Attachment 5. Prepared for Ozone Policy and Strategies Group, U. S. Environmental Protection Agency, Research Triangle Park, NC. June 26, 2000. 12pp.

7. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Aliso Canyon Station. Southern California Gas Company, Aliso Canyon, CA. December 16, 1999. 26pp.

8. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Goleta Station. Southern California Gas Company, Goleta Station, CA. December 16, 1999. 24pp.

9. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Honor Rancho Station. Southern California Gas Company, Honor Rancho Station, CA. December 16, 1999. 16pp.

10. Pacific Gas and Electric Company. Letter and attachments from C. Burke to W. Neuffer, U. S. EPA. Information on Hinkley Compressor Station Units K-11 and K-12. Pacific Gas and Electric Company. February 3, 2000. 8pp.

11. GRI-98/0117. *NO_X Control for Two-Cycle Pipeline Reciprocating Engines*. Prepared by Arthur D. Little, Inc., for the Gas Research Institute. December 1998.

3.0 UNCONTROLLED NO_X EMISSIONS

This chapter presents information on uncontrolled emissions of nitrogen oxides (NO_X) from stationary reciprocating internal combustion (IC) engines that has been generated since EPA published its *Alternative Control Techniques Document–NO_X Emissions from Stationary Reciprocating Internal Combustion Engines* (the 1993 ACT document).[1] This chapter updates the information in the 1993 ACT document, but is not intended to replace it. For example, this chapter does not discuss NO_X formation mechanisms; the reader should refer to the 1993 ACT document for a discussion of NO_X formation.

For purposes of this report, "uncontrolled emissions" are defined as the NO_X emission level prior to any actions taken to reduce emissions, such as adjusting the engine's operating parameters, retrofitting an engine for combustion modification, installing an add-on control device, or redesigning new engines for improved emissions performance. Thus, engines that include low-emission combustion (LEC) technology as original equipment are considered controlled, rather than uncontrolled. To the extent possible, these engines will be excluded from average uncontrolled emissions values. In contrast, engine technologies that have been incorporated for purposes other than emission reduction that, nevertheless, reduce NO_X emissions (notably turbocharging and intercooling) are not necessarily considered control technologies, unless undertaken as part of a project to reduce emissions.

This chapter addresses lean-burn, spark-ignited (SI) engines fired on pipeline-quality natural gas (Section 3.1) and rich-burn SI engines, also fired on pipeline-quality natural gas (Section 3.2). No additional data on diesel-fueled, compression-ignition (CI) engines and dual-fuel CI engines, which use diesel fuel to initiate combustion of natural gas, were collected for this report. The CI engine types are not addressed in this chapter. Section 3.3 provides the references for this entire chapter.

3.1 LEAN-BURN SI ENGINES

This section presents and discusses information on uncontrolled NO_X emissions from lean-burn SI engines. Section 3.1.1 presents the information, and Section 3.1.2 provides a discussion of the information and presents conclusions.

3.1.1 Information on Uncontrolled NO_X Emissions from Lean-Burn SI Engines

Some information sources reviewed for this report include NO_X emission factors based on aggregated test data or contain actual test results. These information sources are described briefly in the paragraphs that follow.

A 1994 Gas Research Institute (GRI) report includes separate NO_X emission levels for 2-stroke (12.5 grams per brake horsepower-hour [g/bhp-hr]) and 4-stroke (13.2 g/bhp-hr) lean-burn natural gas prime movers. (These are lean-burn SI engines used in natural gas compression, transmission, and storage service, which represents a major segment of the population of this type of engine.) The emission levels included in the report are based on an extensive data base of emission test results, although the number of lean-burn engine tests is not stated. The reported emission levels are weighted averages, weighted based on the natural gas prime mover population (i.e., the number of each engine model in prime mover service according to 1989 data) and on horsepower. Test results for 2-stroke engines ranged from 2 g/bhp-hr to 29 g/bhp-hr. For 4-stroke engines, the results ranged from 1 g/bhp-hr to 25 g/bhp-hr.

This report notes that the higher end of the range (25 to 29 g/bhp-hr) reflects older, uncontrolled engines. Engines equipped with turbochargers and intercoolers as original design features ("pure turbocharged" engines) typically emit NO_X in the 7 to 15 g/bhp-hr range. The lower end of the range often reflects the newer lean-burn engines that are included in the inventory, which achieve very low NO_X emissions (1 to 2 g/bhp-hr) through the use of higher excess air and advanced ignition technology (i.e., engines classified as controlled using LEC technology for purposes of this report–see Section 4.1.1). The GRI report also notes that LEC technology is available for retrofit, although it does not state whether any retrofitted engines are included in the inventory of test results.[2] Thus, the average emission levels presented in this GRI report were calculated including some engines considered controlled for purposes of this report. The number of such engines included and their effect on the reported average is not known.

The EPA's *Compilation of Air Pollutant Emission Factors* (AP-42) current Section 3.2 on natural gas prime movers (dated October 1996) characterizes uncontrolled NO_X emissions as 10.9 g/bhp-hr for 2-stroke engines and as 11.8 g/bhp-hr for 4-stroke engines, based on emission test data. This document includes many of the same test data references as the GRI report discussed above, including compilations of test data prepared for the natural gas industry that contain the bulk of the test results considered.[3] It is not clear why these emission factors are lower than the GRI report's, although it likely relates to the averaging methodology. The AP-42 section indicates that these values represent uncontrolled emissions, and the section also contains NO_X emission factors for controlled lean-burn engines (including factors for two manufacturers' LEC-equipped engines–see Section 4.1.3). However, based on the large overlap with the GRI data, it appears likely that the "uncontrolled" data include test results from newer lean-burn engines that would be considered controlled (i.e., LEC-equipped) for purposes of this report.

The 1997 draft revision for AP-42 Section 3.2 indicates uncontrolled NO_X emissions of 12.2 g/bhp-hr for 2-stroke lean-burn engines and 15.0 g/bhp-hr for 4-stroke lean-burn engines, based on emission test data (38 tests for 2-stroke engines and 18 tests for 4-stroke engines). The draft also includes emission factors for 2-stroke and 4-stroke “clean-burn” engines, referring to these engines as separate “engine families,” distinct from other lean-burn engines.[4, 5] “CleanBurn” is a registered trademark of Cooper Energy Services, denoting that company’s system of precombustion chambers coupled with a high-efficiency turbocharger. This system is included in the definition of LEC technology used in this document.

During comment on the 1997 draft AP-42 section, other companies noted that they also offer similar technology (i.e., LEC), but refer to these engines simply as “lean-burn engines.” Thus, some engines equipped with LEC technology were believed to have been included in the uncontrolled, lean-burn engine category. The draft AP-42 section is being revised to eliminate the separate “clean-burn” engine categories. The final section may include both uncontrolled and LEC-equipped engines in the 2-stroke and 4-stroke lean-burn engine categories because of concern that LEC-equipped engines included in the test data cannot be identified conclusively.[6] This discussion indicates that the “uncontrolled” emission factors given above may be based on data that include test results from lean-burn engines that would be considered controlled (i.e., LEC-equipped) for purposes of this report.

A 1996 GRI report includes emission test data for several lean-burn SI engines. These data include six 2-stroke engines representing five different models and three 4-stroke engines representing two different models. Each engine was tested from two to five times. For the 2-stroke engines, the average NO_X emission levels ranged from 4.9 g/bhp-hr to 20.8 g/bhp-hr. The 4-stroke engines averaged from 7.0 g/bhp-hr to 22.0 g/bhp-hr. In both cases, the test data were more concentrated toward the lower end of the range.[7] These test results were among the data used to develop the 1997 draft revision for the AP-42 Section 3.2 discussed immediately above. This report discriminates clearly between engines equipped with LEC and those that are not.

A 1998 GRI report includes some NO_X emissions data generated during a project with Cooper Energy Systems to develop lower-cost CleanBurn™ retrofit technology for some Cooper-Bessemer 2-stroke lean-burn engine models often used in gas transmission applications. The report indicates that emissions of NO_X from a Cooper Z-330 engine that has not been retrofit range from 24 g/bhp-hr down to 2 g/bhp-hr as the air-to-fuel (A/F) ratio is made leaner. However, engine performance when leaned to below 7 g/bhp-hr is unacceptable due to increased fuel consumption, misfire, and elevated carbon monoxide and hydrocarbon emissions. The typical field operation level is not specified in the report, although the greatest fuel economy appears to be achieved at about the 16 g/bhp-hr level. The document also reports baseline (i.e., prior to retrofit) test results for a GMV-6 model (11.5 g/bhp-hr at 100 percent rated speed and torque) and a GMV-10-TF model (6 to 13 g/bhp-hr at rated conditions).[8]

Test data from Pacific Gas and Electric Company for two Cooper-Bessemer W-330 engines tested in 1995 show uncontrolled NO_X emissions of 18.9 and 16.7 g/bhp-hr (based on a typical conversion factor for lean-burn engines of 1 g/bhp-hr per 73 parts per million by volume [ppmv] at 15 percent oxygen).[9] These engines were tested prior to being retrofitted with LEC technology.

Test data from Southern California Gas Company for two Ingersoll-Rand 412KVS engines tested in 1993 show uncontrolled NO_X emissions of 21.4 and 17.0 g/bhp-hr. These tests were conducted upstream of selective catalytic reduction (SCR) control devices.

Several other documents reviewed for this report include information on uncontrolled NO_X emissions that was not based directly on test data (or, at least, the test data were not included or cited in the document). These are primarily general statements regarding NO_X emissions from knowledgeable sources. This information is described briefly below:

- A 1990 GRI report states that uncontrolled NO_X emissions for natural gas pipeline engines (both lean burn and rich burn) range from about 7 g/bhp-hr to 26 g/bhp-hr.[10] The report reflects the prime mover population prior to widespread use of newer lean-burn engines equipped with LEC technology.

- A 1992 paper prepared for a meeting of the Society of Petroleum Engineers by Cooper Industries personnel states that, prior to regulation, NO_X emissions from natural gas-fired engines ranged from 10 g/bhp-hr to 20 g/bhp-hr.[11] This range would include both lean-burn and rich-burn SI engines.

- A 1997 report prepared by the Manufacturers of Emission Controls Association (MECA) indicates that the typical NO_X emission level for natural gas-fired engines operated slightly lean of the stoichiometric A/F ratio is 18.0 g/bhp-hr.[12]

- A 1994 article in the *Oil & Gas Journal* states that natural gas compressor station engines typically emit NO_X at 15 g/bhp-hr.[13] This would include both lean-burn and rich-burn engines.

- A knowledgeable representative of Southern California Gas Company stated during a site visit that NO_X emissions from the Delaval HVA16C engines at the facility were around 28 g/bhp-hr on hot days, prior to being retrofitted with LEC technology.

- Product literature from the Ajax Superior Division of Cooper Energy Services indicates that uncontrolled NO_X emissions from the Ajax line of relatively small 2-stroke lean-burn engines (110 bhp to 720 bhp) range from 3.0 g/bhp-hr to 9.5 g/bhp-hr. This information indicates that uncontrolled NO_X emissions from the Superior line of 4-stroke lean-burn engines (825 bhp to 2650 bhp) range from 15.0 g/bhp-hr to 22.1 g/bhp-hr.[14]

Another major source of information on uncontrolled NO_X emissions from lean-burn SI engines is the 1993 ACT document. For that document, the EPA collected information from 8 major engine manufacturers on 290 models of IC engines of all types in 1991 and 1992. While most manufacturers provided emissions data only for current (at that time) production engines, some included older engine lines, as well.[15] We were not able to obtain the original information to review for this report. We have assumed that the data comprises guaranteed emission levels for the represented engine models.

The 1993 ACT document presents an average uncontrolled NO_X emission level for lean-burn SI engines of 16.8 g/bhp-hr. This value was calculated based on manufacturers' information on 122 models.[16] The 1993 ACT document did not provide separate uncontrolled NO_X emission factors for 2-stroke and 4-stroke lean-burn engines.

3.1.2 Discussion and Conclusions on Uncontrolled NO_X Emissions from Lean-Burn SI Engines

The primary sources of data on uncontrolled NO_X emissions are engine manufacturers (in the form of guarantees) and emission tests. As discussed above, general statements regarding uncontrolled emissions may be made by sources familiar with these types of primary data.

In Section 3.1.2.1 below, we present considerations related to information from engine manufacturers. Section 3.1.2.2 presents considerations related to emission test results. In Section 3.1.2.3, the potential division of lean-burn SI engines into 2-stroke and 4-stroke subcategories is discussed. Section 3.1.2.4 presents conclusions regarding the appropriate uncontrolled NO_X emission levels for purposes of this report.

3.1.2.1 Discussion of NO_X Emissions Information from Engine Manufacturers. Emissions data from engine manufacturers may tend to overstate emissions to some degree because the manufacturer may be liable if the engine fails to meet emissions guarantees. This potential liability motivates the engine manufacturer to elevate the emissions guarantee to a level that ensures that each individual engine in the model line will meet it. The guaranteed level also must account for the range of operating and ambient conditions to which the guarantee applies. On the other hand, the manufacturer is not motivated to inflate guaranteed emissions unnecessarily because this might make the engines less desirable to many potential customers. Based on these factors, we believe that engine manufacturers' guarantees provide a reasonable upper bound on uncontrolled NO_X emissions from well-maintained, well-operated engines.

Although the data were not available for this study, we believe that the engine manufacturers provided this type of information for the 1993 ACT document. As noted above, the value in that document for the average uncontrolled NO_X emission level for lean-burn SI engines was calculated based on manufacturers' information on 122 models of 2-stroke and 4-stroke engines.

The 1993 ACT document tabulated and averaged the uncontrolled NO_X emissions from lean-burn SI engines in five rated horsepower ranges. The overall average uncontrolled NO_X emission level for these engines was calculated as the weighted average of these averages (weighted by the number of engine models for which data were provided in each horsepower range). Thus, in effect, the overall average for lean-burn SI engines was calculated as the straight, unweighted average NO_X emission level of the engine models for which the manufacturers provided uncontrolled NO_X emissions data.

Given available data, this approach is appropriate. In an ideal situation, one might choose to calculate average uncontrolled emissions based on the actual in-use IC engine population, i.e., calculating an average weighted on the number of each model in service and the rated horsepower of each. However, complete data are not available on the distribution of IC engines by model and size across the entire engine population. Even if such data were available, it is very likely that manufacturers' guarantees for uncontrolled NO_X emissions would be unavailable for many engine models, particularly older, discontinued models. In addition, manufacturers and operators may modify a model's design over time, so current information on uncontrolled emissions may not apply to older versions of the same engine model.

To examine the potential effect of weighting manufacturers' guaranteed uncontrolled NO_X emission levels by horsepower, we recalculated the average for lean-burn SI engines using the data in the 1993 ACT document. For each horsepower range, we multiplied the number of engine models in the range by the horsepower at the midpoint of the range to compute the total capacity for the range. (For the "greater than 4,000 bhp" range, we used 6,000 bhp.) We then computed the weighted average uncontrolled NO_X emissions based on these range capacities. The result was a weighted average of 17.0 g/bhp-hr, only 1 percent different than the unweighted average. When the exercise was repeated for the two rated horsepower ranges greater than 2,000 bhp (i.e., the engines most likely to be affected by EPA's NO_X SIP call or the related FIP), the resulting weighted average was 16.8 g/bhp-hr, which is the same value originally computed for the 1993 ACT document.

3.1.2.2 Discussion of Emission Test Data on NO_X Emissions. In contrast to the conservatism of manufacturers' guarantees, emission tests give an accurate reading of how a particular IC engine performed during a particular test period. However, owners typically have the opportunity to tune their engines prior to testing because emission tests are nearly always scheduled by the engine owner and conducted by a testing firm hired by the engine owner. This ability may affect the relationship between test results and the long-term emissions achieved by the engine. (This statement is not to imply that engine operators routinely manipulate emission test results in a gross manner. Nevertheless, many operators may adjust operation of emission sources, within the range of normal operations, to achieve the most favorable emission rate for the facility during testing.)

As discussed later in Section 4.1.4, when a controlled engine is tested for compliance purposes, the operator may tune the engine to minimize NO_X emissions prior to the test. In such cases, it is reasonable to conclude that test results represent a floor on the NO_X emission level achieved by the tested engine under the operating and ambient conditions of the test. In the case of uncontrolled IC engines, it is not so clear how the existing test data discussed above in Section 3.1.1 are likely to be related to long-term NO_X emissions. This uncertainty stems from the fact that we do not know why most of these tests were conducted.

Different types of regulatory requirements can exert upward or downward pressure on uncontrolled emission test results. For example, an "uncontrolled" engine might be subject to an emission limit that could be met through certain constraints on its operating parameters. While the owner of such a regulated, uncontrolled engine would adjust and operate the engine to reduce NO_X emissions to the required level, operators of unregulated engines of the same type would not need to make such adjustments. Thus, emission test results from an uncontrolled engine that is subject to emission limits may not be representative of other, unregulated engines of the same model. The owner of an uncontrolled engine conducting a test to determine major or minor source status might also have an interest in minimizing the tested NO_X emissions.

In contrast, an emission test on an uncontrolled engine might be carried out prior to installing emission controls to establish the baseline for evaluating percent control and/or emission reduction credits to be generated upon control of the source. In this situation, it would be to the facility's advantage to maximize the tested NO_X emissions.

A third potential situation is the research study. The 1996 GRI document discussed above reports the test results of such a study. In such cases, one would expect the engines to be adjusted to represent typical, well-operated facilities. An unbiased study would not be expected to motivate adjustments either to minimize or to maximize NO_X emissions.

We do not know the circumstances of most of the testing that has been carried out on uncontrolled lean-burn SI engines, particularly that which served as the basis for the 1994 GRI document, the current AP-42 section (1996), and the draft revised AP-42 section (1997) on these engines. Thus, we cannot draw firm conclusions regarding the relationship of these data to typical long-term NO_X emissions.

Another unknown regarding the test data is how representative the data are of the general population of lean-burn SI engines. However, it should be pointed out that the data summary in the 1994 GRI document indicates that test data from a wide variety of engine models and sizes were reviewed for that report. In addition, the current AP-42 section (1996) assigns an A rating (excellent) to the emission factors for 2-stroke and 4-stroke lean-burn SI engines. This rating, while somewhat subjective, generally means that the factors were developed from A-rated test data from many randomly chosen facilities in the industry population.

On the other hand, the authors of 1997 draft revision to the AP-42 section rejected some of the data used for the 1996 AP-42 section on the grounds that the emission tests were not conducted using currently approved test methods and/or the tests did not include sufficient process data to characterize engine operation. The 1997 draft revision assigns an A rating to its NO_X emission factor for 2-stroke lean-burn SI engines, specifically meaning that the factor was developed from A-rated data from eight or more different engine models. This draft section's NO_X emission factor for 4-stroke lean-burn SI engines is assigned a B rating, meaning that the factor was developed from A-rated data from five to seven different engine models.

3.1.2.3 <u>Discussion of Potential Subcategorization of Lean-Burn SI Engines</u>. Some of the sources of information on uncontrolled NO_X emission discussed above in Section 3.1.1 distinguished between 2-stroke and 4-stroke lean-burn SI engines, with uncontrolled NO_X emissions from 2-stroke engines typically lower. These documents include the following:

- The 1994 GRI report includes separate emission factors for 2-stroke (12.5 g/bhp-hr) and 4-stroke (13.2 g/bhp-hr) lean-burn natural gas prime movers, based on emission test data. This represents a difference of about 5 percent. The report uses a generalized emission factor of 13 g/bhp-hr for all lean-burn engines in the text discussion and in its analysis of the cost effectiveness of controls on these engines.[17]

- The current Section 3.2 of the AP-42 (1996) also addresses natural gas prime movers. This document characterizes uncontrolled NO_X emissions as 10.9 g/bhp-hr for 2-stroke engines and as 11.8 g/bhp-hr for 4-stroke engines, based on emission test data.[18] This represents a difference of about 8 percent.

- The draft revision of the AP-42 section (1997) indicates NO_X emissions of 12.2 g/bhp-hr for 2-stroke engines and 15.0 g/bhp-hr for 4-stroke engines, based on emission test data.[19] This indicates a difference of about 20 percent between average uncontrolled NO_X emissions from 2-stroke and 4-stroke lean-burn SI engines. However, this draft is undergoing significant further revision due to an inability to distinguish reliably between engines with and without LEC control technology. As a result, these emission factors cannot be considered final.

- The 1996 GRI document also differentiates between uncontrolled emissions from 2-stroke and 4-stroke engines. For the engines tested in that study, the average NO_X emission levels ranged from 4.9 g/bhp-hr to 20.8 g/bhp-hr for 2-stroke engines and from 7.0 g/bhp-hr to 22.0 g/bhp-hr for 4-stroke engines.[20] There is a great deal of overlap between these ranges.

These differences between uncontrolled NO_X emission levels for the two subcategories of lean-burn SI engines, while not trivial, certainly are not so great as to invalidate the use of a single emission level to characterize the entire lean-burn engine category. The variation among models within each subcategory is much greater than the differences between subcategories indicated in these documents, and there is a great deal of overlap. As noted, the 1994 GRI document reports separate emission levels for the two subcategories where the analysis of emission levels is detailed, but uses a combined emission level for the entire lean-burn category in other portions of the document, including the cost analysis.

The 1993 ACT document does not differentiate between 2-stroke and 4-stroke engines. The single uncontrolled NO_X emissions value in this document for lean-burn SI engines is based on information provided by major manufacturers of both 2-stroke and 4-stroke engines. Thus, this value is an average of data from both subcategories of lean-burn engines. The original data provided by the engine manufacturers for the 1993 ACT document were not available during preparation of this report. Thus, it was not possible to reevaluate the data to differentiate between 2-stroke and 4-stroke engines.

A number of the general statements regarding uncontrolled NO_X emissions cited previously in Section 3.1.1 do not differentiate among natural-gas fired engines at all. These statements provide an average value or typical range of values that would include rich-burn SI engines as well as 2-stroke and 4-stroke lean-burn engines.

3.1.2.4 Conclusions on Uncontrolled NO_X Emissions from Lean-Burn SI Engines. A single uncontrolled NO_X emission level of 16.8 g/bhp-hr published in the 1993 ACT document is appropriate and reasonable for the purposes of this report. While this value based on manufacturers' guarantees may represent the upper bound on well-operated and well-maintained lean-burn engines (as discussed previously in Section 3.1.2.1), it is also based on the most complete and most certain data set of the data reviewed for this report. Much of the other data presented above in Section 3.1.1 generally supports this value, including a number of sources of test data on individual engines. However, the information sources based on aggregated emission test data give lower values.

To reiterate, the uncontrolled NO_X emission level from the 1993 ACT document is based on information for 112 models of lean-burn SI engines gathered by the EPA in 1991 and 1992. Some manufacturers included data on older engine lines, as well as current production engines. We believe that these data are the most representative available for the existing stock of uncontrolled lean-burn engines.

With good maintenance, IC engines often have a very long life. For example, the 1994 GRI report indicates that many lean-burn IC engines used for natural gas compression, transmission, and storage have been in operation for several decades, with discontinued models having greater than 50 years of service.[21] Thus, the in-use lean-burn engine population includes many engines manufactured before NO_X emissions were a concern.

Many lean-burn engine models currently in production incorporate low-NO_X technology. In fact, the term "lean burn" is often used today to refer to what we have defined as LEC technology for purposes of this report. This trend toward producing engines with inherently lower NO_X emissions increasingly is blurring the line between controlled and uncontrolled lean-burn engines. In fact, the 1997 draft AP-42 section defined 2-stroke and 4-stroke "clean burn" engines (i.e., engines equipped with LEC precombustion chamber technology) as separate engine families, distinct from other 2-stroke and 4-stroke lean-burn engines. This draft section attempted to provide uncontrolled emission factors for these clean burn engine families, instead of treating them as controlled lean-burn engines. However, the EPA has been unable to differentiate definitively between prechambered engines and other lean-burn engines in its NO_X emissions data. As a result, the next draft of the AP-42 section is expected to address only 2-stroke and 4-stroke lean-burn engines, combining all the test data without differentiating by combustion system technology.

This trend toward manufacturing LEC-equipped lean-burn engines was well underway when the data for the 1993 ACT were collected. However, it is clear from the data summary in that document that EPA did not include such engines in the uncontrolled data set. The NO_X emission level at the lower end of the each rated horsepower range exceeds the levels that are achieved using LEC technology.

The same cannot be said for the emission test data underlying the 1994 GRI report, the current AP-42 section (1996), or the draft revision to the AP-42 section (1997). The 1994 GRI report acknowledges that new, LEC-equipped engines are included in its data set. Although the authors of the two AP-42 sections attempted to separate such engines from uncontrolled engines, there is some doubt as to whether they were entirely successful, as discussed previously.

Another factor favoring use of the NO_X emission level developed from manufacturers' data for the 1993 ACT document is the completeness of the data set, which includes 122 models of lean-burn SI engine. The test data from the other sources are not as comprehensive.

One potential drawback with the 1993 ACT NO_X emission level for lean-burn SI engines is that it does not differentiate between 2-stroke and 4-stroke engines. However, as discussed above in Section 3.1.2.3, we do not believe that the difference in NO_X emissions between these two types of engines is so great that a single, composite average is unacceptable. On the contrary, we believe that the advantages of the underlying data set outweigh this relatively minor shortcoming.

For the reasons discussed above, we believe that a factor of 16.8 g/bhp-hr for uncontrolled NO_X emissions for lean-burn SI engines is appropriate and reasonable for the purposes of this report. Accordingly, the cost analysis presented in Chapter 5 of this report is based on this uncontrolled NO_X emission level for this class of IC engines.

3.2 RICH-BURN SI ENGINES

This section presents and discusses information on uncontrolled NO_X emissions from rich-burn SI engines. Section 3.2.1 presents the information, and Section 3.2.2 provides a discussion of the information and presents conclusions.

3.2.1 Information on Uncontrolled NO_X Emissions from Rich-Burn SI Engines

Many of the same information sources discussed above for lean-burn engines also contain NO_X emission factors based on aggregated test data or include actual test results for rich-burn engines. The information on rich-burn engine NO_X emissions from these sources is summarized briefly in the paragraphs that follow.

The 1994 GRI report includes a NO_X emission level for rich-burn natural gas prime movers of 8.6 g/bhp-hr. The emission levels included in the report are based on an extensive data base of emission test results, although the number of rich-burn engine tests is not stated. The reported emission level is a weighted average, based on the natural gas prime mover population and on horsepower. The report notes that emissions from these engines typically range from 4 g/bhp-hr to 26 g/bhp-hr, while a few models have very low emissions. (The lowest test result that appears in the report is 1 g/bhp-hr.)[22]

The current AP-42 Section 3.2 on natural gas prime movers characterizes uncontrolled NO_X emissions as 10.0 g/bhp-hr for rich-burn engines, based on emission test data. The section assigns an A rating (excellent) to this emission factor. As noted previously, this document includes many of the same test data references as the GRI report discussed above, including compilations of test data prepared for the natural gas industry that contain the bulk of the test results considered.[23] Differing averaging methodology may explain the difference between this emission factor and that in the GRI report.

The 1997 draft revision for AP-42 Section 3.2 indicates uncontrolled NO_X emissions of 20.9 g/bhp-hr for rich-burn engines, based on eight emission test data points. This emission factor is rated B (above average).[24, 25]

The 1996 GRI report includes emission test data for two uncontrolled rich-burn SI engines of the same model at one facility. Uncontrolled emissions were tested for each engine from two to four times. One of these engines averaged 7.7 g/bhp-hr over four tests, and the other averaged 14.4 g/bhp-hr over two tests. It is of interest to note that the engine with lower NO_X emissions had carbon monoxide emissions nearly 40 times those of the engine with higher NO_X emissions. Engine adjustments often involve tradeoffs between NO_X and carbon monoxide emissions, although there is no information available in the report to allow a conclusive interpretation of the results.[26]

Several other documents noted above in Section 3.1.1 include information on uncontrolled NO_X emissions that was not based directly on test data. These are primarily general statements regarding NO_X emissions from knowledgeable sources. This information is described briefly below:

- The 1990 GRI report states that uncontrolled NO_X emissions for natural gas pipeline engines (both lean burn and rich burn) range from about 7 g/bhp-hr to 26 g/bhp-hr.[27] The report reflects the prime mover population prior to widespread regulation of these engines.

- The 1992 paper prepared for a meeting of the Society of Petroleum Engineers by Cooper Industries personnel states that, prior to regulation, NO_X emissions from natural gas-fired engines (both lean burn and rich burn) ranged from 10 g/bhp-hr to 20 g/bhp-hr.[28]

- The 1997 report prepared by MECA indicates that typical NO_X emission levels for natural gas-fired engines operated slightly rich of the stoichiometric A/F ratio range from 8.3 to 11.0 g/bhp-hr.[29]

- A 1994 article in the *Oil & Gas Journal* states that natural gas compressor station engines typically emit NO_X at 15 g/bhp-hr.[30] This would include both lean-burn and rich-burn engines.

The 1993 ACT document is a comprehensive source of data on uncontrolled NO_X emissions from uncontrolled rich-burn SI engines. This document presents an average uncontrolled NO_X emission level for these engines of 15.8 g/bhp-hr. This value was calculated based on manufacturers' information on 83 models.[31]

3.2.2 Discussion and Conclusions on Uncontrolled NO_X Emissions from Rich-Burn SI Engines

Much of the discussion related to lean-burn SI engines above in Section 3.1.2 applies to rich-burn SI engines, as well. The paragraphs that follow briefly discuss the manufacturer information and test data information reviewed for this project.

As discussed previously for lean-burn SI engines, manufacturers' guaranteed uncontrolled NO_X emission levels provide a reliable upper bound on actual emissions from well-maintained, well-operated engines. Potential liability may motivate engine manufacturers to elevate emissions guarantees slightly to ensure that each individual engine within the model line will meet the guaranteed levels.

The manufacturers' data behind the 1993 ACT document's analysis of uncontrolled NO_X emissions is very comprehensive. Data on 83 engine models provided by several engine manufacturers were included in the analysis. While most manufacturers supplied data only on current production models, some provided data on older models, as well. This is important because with good maintenance, IC engines often have a very long life. For example, the 1994 GRI report indicates that many rich-burn engines used in these natural gas compression, transmission, and storage were installed as early as the 1940's.[32]

It is not clear that the test data underlying the uncontrolled NO_X emission factors from other sources is as comprehensive. We are not able to evaluate from the information reviewed for this study how representative the tested population is. It should be noted that the 1994 GRI report indicates that a large data base of test results from many models of rich-burn engines in the natural gas industry was used to develop the uncontrolled NO_X emission factor (8.6 g/bhp-hr) presented in that document. Using much of the same data, the 1996 AP-42 section assigned an A rating to its emission factor (10.0 g/bhp-hr). However, the 1997 draft AP-42 section dropped some of the data used in the other two documents, indicating that the tests were not conducted using currently approved test methods and/or the tests did not include sufficient process data to characterize engine operation. Using the more limited data (eight tests on from five to seven engine models), the 1997 draft AP-42 section arrived at a B-rated emission factor of 20.9 g/bhp-hr.

Product literature from one engine manufacturer provides an example of the enormous effect engine adjustments can have on uncontrolled NO_X emissions. This manufacturer lists four different carburetor settings for its rich-burn engine families: (1) Lowest Manifold (Best Power), (2) Equal NO_X and CO, (3) Catalytic Converter Input (3-way), and (4) Standard (Best Economy). For all the engine families and models, the Lowest Manifold setting (operating slightly fuel rich with an excess air ratio of 0.97) gives the lowest NO_X emissions, ranging from 8.5 g/bhp-hr to 12 g/bhp-hr. The Standard setting (operating slightly fuel lean with an excess air ratio of 1.06 to 1.12) results in the highest NO_X emissions, ranging from 18.0 to 28.0 g/bhp-hr. For every engine family, the Standard setting results in emissions at more than twice the level of the Lowest Manifold setting, with one model at nearly three times (28.0 versus 9.5 g/bhp-hr).[33]

The tested NO_X level upstream of an add-on control device is sometimes represented as "uncontrolled" test data. However, some control devices, such as nonselective catalytic reduction (NSCR), dictate certain engine adjustments. For the rich-burn engine families presented in the product literature discussed above, the Standard (Best Economy) carburetor setting results in NO_X emissions from 50 to 75 percent higher than the Catalytic Converter Input setting.[34] Thus, "uncontrolled" test data from an engine equipped with an NSCR control system may be significantly lower than actual uncontrolled emissions from the same model engine in the absence of the control system (or other constraints on emissions).

For this reason, "inlet" values from NSCR-equipped engines in available data bases of emission test results were not analyzed for this report. Similarly, test results from engines equipped with prestratified charge (PSC) control technology with the PSC system turned off were not analyzed. (In the case of PSC, we have no information to indicate whether the modifications necessary to install PSC would affect "uncontrolled" emissions measured with the PSC system turned off.) We were unable to evaluate the test data underlying the 1994 GRI report, the 1996 AP-42 section, or the 1997 draft AP-42 section to determine whether any of the "uncontrolled" NO_X emissions data were from controlled engines (particularly NSCR-equipped engines).

Based on the discussion above, the uncontrolled NO_X emission level of 15.8 g/bhp-hr published in the 1993 ACT document is appropriate and reasonable for the purposes of this report. While this value based on manufacturers' guarantees may represent the upper bound on well-operated and well-maintained lean-burn engines, it is also based on the most complete and most certain data set of the data reviewed for this report. The 1993 ACT document's analysis of uncontrolled NO_X emission levels remains the most comprehensive and representative analysis to date. Much of the other data presented above in Section 3.2.1 generally supports this value. The range of values in the information sources based on aggregated emission test data (i.e., the 1994 GRI report, the 1996 AP-42 section, and the 1997 draft AP-42 section) span this value.

3.3 REFERENCES FOR CHAPTER 3

1. *Alternative Control Techniques Document–NO_X Emissions from Stationary Reciprocating Internal Combustion Engines*. U. S. Environmental Protection Agency, Research Triangle Park, NC. Publication No. EPA-453/R-93-032. July 1993. 315pp. http://www.epa.gov/ttncatc1/products.html. (1993 ACT document)

2. GRI-94/0329. *Retrofit NO_X Control Technologies for Natural Gas Prime Movers.* Final Report. March 1994. Prepared by Accurex Environmental Corporation, Mountain View, California. (actual period of the report 9/91-7/92) pp. 2-2, 2-4, 2-11 - 2-14, 4-1, 4-29.

3. *Compilation of Air Pollutant Emission Factors*, 5th Edition, Section 3.2. EPA Document AP-42. October 1996. Pp. 3.2-7, 3.2-8, 3.2-12 - 3.2-14

4. *Compilation of Air Pollutant Emission Factors*, 5th Edition, Supplement C, Draft Section 3.2. EPA Document AP-42. February 1997. http://www.epa.gov/ttn/chief/dsur/d03s02.zip.

5. *Emission Factor Documentation for AP-42 Section 3.2, Natural Gas-Fired Reciprocating Engines*. Draft. Prepared by Eastern Research Group for EPA. http://www.epa.gov/ttn/chief/dsur/d03s02.zip.

6. Telecon. B. Richani, Alpha-Gamma Technologies, Inc. (EPA contractor working on revised AP-42 Section 3.2) with S. Edgerton, EC/R Incorporated. October 29, 1999 and January 14, 2000.

7. GRI-96/0009. *Measurement of Air Toxic Emissions from Natural Gas-Fired Internal Combustion Engines at Natural Gas Transmission and Storage Facilities*. February 1996. Prepared G. Shareef, et al. Table 5-3, pp. 5-5 and 5-6.

8. GRI-98/0117. *NO_X Control for Two-Cycle Pipeline Reciprocating Engines*. Final Report, December 1998. Prepared by K. Asherwood, Arthur D. Little, Inc., Cambridge, MA. Pp. 1-2, 1-3, 5-2, and 5-8.

9. Pacific Gas and Electric Company. Letter and attachments from C. Burke to W. Neuffer, U. S. EPA. Information on Hinkley Compressor Station Units K-11 and K-12. Pacific Gas and Electric Company. February 3, 2000. 8pp.

10. GRI-90/0215. *NO_X Reduction Technology for Natural Gas Industry Prime Movers*. Special Report, August 1990. Prepared by C. Castaldini, Accurex Corporation, Mountain View, CA. Pg. 3.

11. SPE 24306. “An Overview of Exhaust Emissions Regulatory Requirements and Control Technology for Stationary Natural Gas Engines.” Prepared by H. N. Ballard, et al., Cooper Industries, for the Society of Petroleum Engineers Mid-Continent Gas Symposium in Amarillo, Texas, April 13-14, 1992.

12. Manufacturers of Emission Controls Association. *Emission Control Technology for Stationary Internal Combustion Engines*. Status Report. Table 2, July 1997. Pg. 4.

13. *Oil & Gas Journal*, Volume 92. "CNG Installing NO_X-Reduction System in Compressor Stations," September 26, 1994. Pg. 91.

14. Ajax Superior Division of Cooper Energy Systems. "Ajax and Superior CleanBurn Conversion Packages," March 1993. (Transmitted to W. Neuffer, EPA, from L. Palmer, Cooper Energy Services, March 1999.)

15. 1993 ACT document. Pp. 4-11 and 4-12, and Chapter 4.0 References 18-25.

16. 1993 ACT document. Table 2-1, Pg. 2-3, and Chapter 4.0 References 18-25.

17. GRI-94/0329. *Retrofit NO_X Control Technologies for Natural Gas Prime Movers*. Final Report. March 1994. Prepared by Accurex Environmental Corporation, Mountain View, California. (actual period of the report 9/91-7/92) pp. 2-11 - 2-13, 4-29, A-39 - A-45.

18. *Compilation of Air Pollutant Emission Factors*, 5th Edition, Supplement B, Section 3.2. EPA Document AP-42. October 1996. Pg. 3.2-7

19. *Compilation of Air Pollutant Emission Factors*, 5th Edition, Supplement C, Draft Section 3.2. EPA Document AP-42. February 1997. http://www.epa.gov/ttn/chief/dsur/d03s02.zip.

20. GRI-96/0009. *Measurement of Air Toxic Emissions from Natural Gas-Fired Internal Combustion Engines at Natural Gas Transmission and Storage Facilities*. February 1996. Prepared G. Shareef, et al.

21. GRI-94/0329. *Retrofit NO_X Control Technologies for Natural Gas Prime Movers*. Final Report. March 1994. Prepared by Accurex Environmental Corporation, Mountain View, California. (actual period of the report 9/91-7/92) pp. 2-13 - 2-15

22. GRI-94/0329. *Retrofit NO_X Control Technologies for Natural Gas Prime Movers*. Final Report. March 1994. Prepared by Accurex Environmental Corporation, Mountain View, California. (actual period of the report 9/91-7/92) pp. 2-14 and 2-15.

23. *Compilation of Air Pollutant Emission Factors*, 5th Edition, Supplement B, Section 3.2. EPA Document AP-42. October 1996. Pp. 3.2-7, 3.2-13, and 3.2-14

24. *Compilation of Air Pollutant Emission Factors*, 5th Edition, Supplement C, Draft Section 3.2. EPA Document AP-42. February 1997. http://www.epa.gov/ttn/chief/dsur/d03s02.zip.

25. *Emission Factor Documentation for AP-42 Section 3.2, Natural Gas-Fired Reciprocating Engines*. Draft. Prepared by Eastern Research Group for EPA. http://www.epa.gov/ttn/chief/dsur/d03s02.zip.

26. GRI-96/0009. *Measurement of Air Toxic Emissions from Natural Gas-Fired Internal Combustion Engines at Natural Gas Transmission and Storage Facilities*. February 1996. Prepared G. Shareef, et al. Table 5-3, pg. 5-6.

27. GRI-90/0215. *NO_X Reduction Technology for Natural Gas Industry Prime Movers*. Special Report, August 1990. Prepared by C. Castaldini, Accurex Corporation, Mountain View, CA. Pg. 3.

28. SPE 24306. "An Overview of Exhaust Emissions Regulatory Requirements and Control Technology for Stationary Natural Gas Engines." Prepared by H. N. Ballard, et al., Cooper Industries, for the Society of Petroleum Engineers Mid-Continent Gas Symposium in Amarillo, Texas, April 13-14, 1992.

29. Manufacturers of Emission Controls Association. *Emission Control Technology for Stationary Internal Combustion Engines.* Status Report. Table 2, July 1997. Pg. 4.

30. *Oil & Gas Journal*, Volume 92. "CNG Installing NO_X-Reduction System in Compressor Stations," September 26, 1994. Pg. 91.

31. 1993 ACT document. Table 2-1, Pg. 2-3, and Chapter 4.0 References 18-25.

32. GRI-94/0329. *Retrofit NO_X Control Technologies for Natural Gas Prime Movers*. Final Report. March 1994. Prepared by Accurex Environmental Corporation, Mountain View, California. (actual period of the report 9/91-7/92) pp. 2-13 - 2-15

33. Waukesha Engine Division, Dresser Equipment Group. "Gas Engine Exhaust Emission Levels," technical data sheet no. S-8483-2, February 1999.

34. Waukesha Engine Division, Dresser Equipment Group. "Gas Engine Exhaust Emission Levels," technical data sheet no. S-8483-2, February 1999.

4.0 UPDATE ON NO_X CONTROL TECHNOLOGIES

This chapter presents information on nitrogen oxides (NO_X) control technologies for stationary reciprocating internal combustion (IC) engines that has been generated since EPA published its *Alternative Control Techniques Document–NO_X Emissions from Stationary Reciprocating Internal Combustion Engines* (the 1993 ACT document).[1] This chapter updates the information in the 1993 ACT document, but is not intended to replace it. For example, this chapter does not present an in-depth description of the control technologies; the reader should refer to the 1993 ACT document for a complete description of each control technology.

For purposes of this report, "control technologies" include any measures undertaken primarily to reduce NO_X emissions. This definition includes modifying or adjusting the combustion system to reduce NO_X formation, as well as installing add-on control devices to remove NO_X from the engine exhaust. The definition includes modifying engine design to produce new engines with inherently lower NO_X emissions. Thus, for example, new engines manufactured with low-emission combustion (LEC) technology are considered controlled, just as are engines retrofitted with LEC. In contrast, turbocharging and intercooling alone are not necessarily considered NO_X control technologies (despite the fact that they typically reduce NO_X emissions) because these technologies may be introduced primarily to increase power and efficiency.

This chapter focuses primarily on LEC technology (Section 4.1), with less extensive updates on selective catalytic reduction (SCR) in Section 4.2, nonselective catalytic reduction (NSCR) in Section 4.3, and prestratified charge™ (PSC) technology in Section 4.4. Section 4.5 presents information on high-energy ignition system (HEIS) technology, which was not addressed in the 1993 ACT document. Section 4.6 presents information on emerging NO_X control technologies that have been developed since release of the 1993 ACT document. References for the entire chapter appear in Section 4.7.

This chapter concentrates on the more effective control technologies because these controls are of primary interest in nonattainment areas seeking significant emission reductions from IC engines. The chapter does not address air-to-fuel (A/F) ratio adjustment, ignition timing retard, or a combination of the two; see the 1993 ACT document for a discussion of these less effective technologies.[2]

4.1 LOW-EMISSION COMBUSTION TECHNOLOGY

This section on LEC updates Section 5.2.5 of the 1993 ACT document, which addresses application of LEC to lean-burn, spark-ignited (SI) engines. This section includes a brief description of the technology (Section 4.1.1) and its applicability (Section 4.1.2), new information on NO_X emissions (Section 4.1.3), a discussion of the emissions data (Section 4.1.4), and conclusions regarding the level of NO_X emissions achievable using LEC (Section 4.1.5).

4.1.1 Technology Description–LEC

Low-emission combustion in IC engines involves modifying the combustion system to achieve very lean combustion compared to the A/F ratios that are used in "conventional" lean-burn engines. The additional combustion air acts as a heat sink, lowering the temperature in the cylinder and reducing NO_X formation.

To deliver the additional combustion air required for LEC, turbocharging and intercooling capacity normally are required. In retrofit situations, this typically involves upgrading or replacing the turbocharger and intercooler, or adding this equipment where it is not already present (i.e., on naturally aspirated engines). Although they typically reduce NO_X emissions, turbocharging and intercooling alone do not qualify as LEC because additional engine modifications are required to minimize NO_X emissions and because these technologies may have been originally introduced to improve engine performance. However, turbocharging and intercooling are integral to LEC technology; in LEC applications they are considered part of the control system.

Other equipment associated with increased air flows may also need to be modified for LEC, such as the air intake and filtration system, the intercooler radiator, and the exhaust system and muffler. To maintain the optimum A/F ratio, an automated A/F ratio controller typically is used.

The challenge with this very lean combustion is to achieve proper ignition and stable combustion. Vendors of LEC technology (i.e., engine manufacturers and third-party retrofitters) have met these requirements with some combination of improved combustion chamber design, enhanced air-fuel mixing, and improved ignition systems.

In many cases, a precombustion chamber is used for enhanced ignition. In this system, ignition is initiated in a small chamber in a fuel-rich environment. The flame propagates rapidly and forcefully from this chamber into the main combustion chamber, providing uniform ignition of the very lean air-fuel mixture in the main chamber, as well as improved mixing.

Some engine manufacturers offer their smaller engines with "open chamber" LEC design. These engines feature a redesigned combustion chamber, rather than a precombustion chamber. These open-chamber LEC designs typically incorporate improved air-fuel mixing systems to achieve stable combustion under very lean conditions.

Engines with open-chamber LEC technology typically are designed for excess air levels only slightly above 50 percent, while engines with precombustion chambers typically are designed for excess air levels of 75 percent to over 100 percent. Consequently, prechambered engines have generally lower NO_X emissions than do open-chamber models.

Low-emission combustion based on precombustion chamber technology has been in use for about 20 years, when Cooper-Bessemer began manufacturing CleanBurn™ engines. Subsequently, other engine manufacturers began to manufacture LEC-equipped engines (open chamber and/or prechambered models). Presently, all major manufacturers of lean-burn SI engines offer LEC-equipped models, and many models are available only with LEC. At least two manufacturers offer some models that are available either in a rich-burn configuration or in an LEC configuration.[3, 4]

Shortly after beginning to offer new LEC-equipped engines, some engine manufacturers began to offer retrofit "kits" and installation services for existing engines. Originally, the retrofits involved completely replacing the cylinder heads with redesigned heads and replacing or modifying numerous other engine components. The retrofit cylinder heads are cast with a precombustion chamber within the interior of the head. This type of retrofit was all that was commercially available at the time the data were gathered for the 1993 ACT document. These retrofits understandably involve relatively high capital costs, although the incremental expense is reduced if the retrofit is undertaken when the cylinder heads and other engine components are to be replaced anyway as part of an engine overhaul.

In more recent years, simpler and less expensive LEC retrofit technologies have been developed. One advance has been the development of "screw-in" precombustion chambers. These precombustion chambers screw into the existing spark plug hole in each cylinder head, eliminating the need to replace the existing cylinder heads. These screw-in precombustion chambers now are offered for retrofits by some engine manufacturers, as well as by third-party vendors. In addition, advances have been made in upgrading existing turbocharging systems, with the result that retrofits do not as often require replacement of the turbocharger. Contemporary retrofits may involve modifications to improve air-fuel mixing, as well, such as installing higher-pressure fuel valves. Chapter 5 includes a reevaluation of LEC retrofit costs based on more recent capital cost data.

4.1.2 Applicability of LEC

Low-emission combustion technology is applicable to IC engines fired with gaseous fuels. This includes both SI engines and dual-fuel engines operating in dual-fuel mode (as opposed to firing only diesel fuel). No additional information on dual-fuel engine applications was gathered for this report; refer to the 1993 ACT document for information on LEC technology for dual-fuel engines.

New SI engines equipped with LEC technology are, by definition, lean-burn engines. Both 2-stroke and 4-stroke lean-burn SI engines equipped with LEC technology are available in a full range of sizes, and many models are available only with LEC.

Low-emission combustion retrofit equipment and services are generally available, particularly for the most plentiful engine models. Cooper Energy Services, maker of Cooper-Bessemer, Ajax, Superior, and Delaval engines provides CleanBurn™ retrofits for all of its larger models and offers these services for engines manufactured by other companies, as well.[5, 6, 7] Dresser-Rand, manufacturer of Ingersoll-Rand, Clark, and Worthington engines also offers retrofit services for its lean-burn engines.[8] The Waukesha Engine Division of Dresser Industries manufactures two engine families that are available either in rich-burn or LEC configurations. The company offers LEC retrofit services for those engines originally sold in the rich-burn configuration.[9] At least three third-party vendors (Diesel Supply Company; Enginuity, Inc.; and Emissions Plus, Inc.) offer retrofit services for a wide variety of engine makes and models. These vendors will work with any model engine, although economies of scale can reduce capital costs for plentiful engines. For other engines, customized precombustion chambers can result in somewhat higher costs.[10]

This report evaluates LEC retrofits only for lean-burn engines. In practice, although not impossible for rich-burn engines (as noted above for certain Waukesha engine families), LEC retrofits are primarily applied to lean-burn engines. Other control technologies, notably NSCR and PSC, are much more common for rich-burn engines. These technologies are discussed in later sections of this chapter.

4.1.3 Data on NO_X Emissions from LEC-Equipped IC Engines

For this report, we reviewed a variety of information on LEC performance that has become available in the years since the 1993 ACT document was published. This information includes information from LEC technology vendors, test data, analyses of test data carried out by EPA and others, and other "anecdotal" data obtained from a variety of sources. These new data are presented below in Sections 4.1.3.1 through 4.1.3.3. Section 4.1.3.4 summarizes the LEC test data.

4.1.3.1 Information from LEC Vendors. Information from several engine manufacturers indicates that they guarantee NO_X emissions at or below 2.0 grams NO_X per brake horsepower hour (g/bhp-hr) for nearly all new LEC-equipped engines. Some new models are guaranteed at up to 3.0 g/bhp-hr, but these are smaller models with open-chamber designs. These smaller engines are generally less than 1,200 bhp. Some new models are guaranteed to 1.0 g/bhp-hr.[11]

Information from engine manufacturers that provide retrofit equipment and services indicates guaranteed levels typically in the range from 1.5 to 3.0 g/bhp-hr.[12] These guarantees reflect the performance of standard retrofit "kits" that have been developed by these engine manufacturers. A number of sources have indicated that retrofits can be tailored to meet a target emission level, although the cost may be greater than for the standard retrofit kit.[13, 14, 15]

One third-party retrofitter has guaranteed emissions as low as 1.0 g/bhp-hr. This vendor has retrofitted approximately 125 engines to improve NO_X emissions. These retrofits are designed to achieve the applicable emission limit on a site-specific basis, so not all have involved LEC. Approximately one third of these retrofits have been guaranteed to meet 2.0 g/bhp-hr or lower, and all guarantees have been met. Many of the vendor's other retrofits have achieved this level as well, based on test data. This vendor estimated that 90 percent of engine models can be retrofitted to achieve 2.0 g/bhp-hr using the screw-in precombustion chambers the company manufactures, along with associated upgrades to the turbocharger, intercooler, air-fuel mixing system, etc.[16]

This vendor cannot achieve 2.0 g/bhp-hr for some engine models. In particular, some Worthington models are designed so that adequate air cannot be delivered to achieve the necessary A/F ratio. The design of others prevents adequate air-fuel mixing. In some Worthington engines, the precombustion chamber is extended deep inside the cylinder head, which makes chamber cooling and engine misfires a real concern. This vendor has achieved a level of 6 g/bhp-hr for certain Worthington engines.[17, 18] As an example of uncontrolled emissions from Worthington engines, the vendor indicated that he has measured the uncontrolled emissions of one Worthington Model SUTC located in New York at 18 to 22 g/bhp-hr and another located in the Gulf Coast at 24 to 28 g/bhp-hr using a portable NO_X emissions monitor (uncertified).[19]

The vendor noted that the original engine manufacturers have the capability to reduce NO_X emissions to lower levels on engines that third-party vendors find problematic. The engine manufacturers are able to replace engine parts, such as the cylinder heads, with redesigned parts to overcome the impediments to low NO_X emissions. However, significant use of redesigned parts involves increased costs.[20]

The information provided by engine manufacturers does not suggest any notable difference in the guaranteed NO_X emission level for new 2-stroke and 4-stroke lean-burn engines equipped with LEC. Similarly, no significant difference based on operating cycle is apparent in the guaranteed performance of engines retrofit with LEC.

It should be noted that NO_X emission guarantees most often are made for specific operating conditions, typically firing pipeline-quality natural gas and operating at 100 percent of rated speed and torque. Most sources of information indicate that NO_X emissions are highest at full load and fall as load declines.[21, 22, 23] However, some sources indicate otherwise, and emission test results sometimes show an inconsistent relationship between NO_X emissions, engine speed, and engine torque.[24, 25, 26] All sources indicate that guaranteed NO_X emission levels can be maintained over a wider operating range through the use of good A/F ratio controls.

4.1.3.2 Emission Test Data. A considerable body of test data has accumulated in the years since LEC was first introduced. Some of the data were available when the 1993 ACT document was developed, but additional data have come available in the intervening years. Test data and associated analyses that were reviewed for this report are summarized in the paragraphs that follow. Except as otherwise noted, the test data are from short-term emission tests conducted at or near rated speed and load. Where necessary, test data were converted to brake-specific terms using a factor of 1 g/bhp-hr per 75 parts per million by volume (ppmv), dry basis, at 15 percent oxygen, consistent with the 1993 ACT document.[27]

A May 2000 memo prepared by the EPA compiles data from seven different sources of NO_X emission test data. In all, the memo summarizes the results of 269 emission tests conducted on 49 different engines, including a wide variety of makes, models, and sizes. The memo notes that only 11 of the 269 tests exceeded 2 g/bhp-hr; 96 percent of the test results were below this level. Only one test was above 4 g/bhp-hr, and 71 percent of the tests were below 1 g/bhp-hr. A few of these tests were conducted under part speed, part load conditions.[28]

One of the sources of data compiled in the EPA memo discussed above is the Ventura County, California, Air Pollution Control District (VCAPCD). Ventura County has regulated IC engine NO_X emissions since 1981. As a result, VCAPCD has an extensive data base of short-term emission test results, including many engines that have been tested multiple times over the years. The version of the data base evaluated for the EPA memo includes test data only through 1992. A more recent version of the data base, including data through 1999, was obtained for this report. This version of the data base includes the results of 320 tests conducted on 23 engines equipped with LEC. Eight different engine models are included, with five models of 4-stroke engines and three models of 2-stroke engines. The NO_X emissions range from a low of 0.08 g/bhp-hr up to a high of 4.0 g/bhp-hr, with a mean of 0.66 g/bhp-hr. Only two of the tests (less than 1 percent) are greater than 2.0 g/bhp-hr. Almost 86 percent of the tests are below 1.0 g/bhp-hr, and nearly 32 percent are below 0.5 g/bhp-hr.[29]

A 1998 paper based on the VCAPCD emission test data base examined long-term test results for three engine models equipped with LEC technology. For these three engine models, the results were as follows:

- Ajax DPC-180 (180-bhp, 2-stroke engine): Sixty-eight individual tests were conducted on four different engines fired with natural gas between 1982 and 1996. The engines averaged NO_X emissions of 0.6 g/bhp-hr, with a high of 1.1 g/bhp-hr and a low of 0.2 g/bhp-hr.

- Waukesha L7042GL (1,100-bhp, 4-stroke engine): One hundred twenty-eight individual tests were conducted on eight different engines fired with natural gas between 1987 and 1995. The engines averaged 0.8 g/bhp-hr, with a high of 2.3 g/bhp-hr and a low of 0.2 g/bhp-hr. Besides the one test at 2.3 g/bhp-hr, the remaining tests were at or below 1.9 g/bhp-hr, with most well below this level.

- Superior 16SGTA (2,650-bhp, 4-stroke engine): Eighty-nine individual tests were conducted on three different engines fired with landfill waste gas between 1986 and 1997. The engines averaged NO_X emissions of 0.7 g/bhp-hr, with a high of 1.2 g/bhp-hr and a low of 0.3 g/bhp-hr.[30]

Another source of data included in the EPA memo discussed above is the Santa Barbara County, California, Air Pollution Control District (SBCAPCD). A recent version of the SBCAPCD emission test data base, including data from 1991 through 1999, was obtained and evaluated. This data base contains results for 14 NO_X emission tests conducted on 4 engines equipped with LEC. Of these, the results of 12 tests on 3 engines included NO_X data that could be converted to terms of grams NO_X per brake horsepower hour. These 12 tests averaged about 0.5 g/bhp-hr, ranging from a low of 0.14 g/bhp-hr to a high of 0.67 g/bhp-hr.[31]

Test data from the San Diego County, California, Air Pollution Control District (SDCAPCD) also were reviewed for this report. These data include the results of 121 NO_X emission tests conducted between 1991 and 1996 on 13 engines equipped with LEC. Overall, the emissions ranged from 0.3 g/bhp-hr to 4.8 g/bhp-hr with a mean of 1.1 g/bhp-hr.[32]

Eleven of the engines represented in the SDCAPCD data are of open-chamber LEC design. In 107 tests, NO_X emissions from these engines ranged from 0.4 g/bhp-hr to 4.8 g/bhp-hr, with a mean of 1.2 g/bhp-hr. Only one test was over 3.0 g/bhp-hr, and five tests were between 2 and 3 g/bhp-hr. Fifty-two percent of the tests were between 1 and 2 g/bhp-hr, and 42 percent were less than or equal to 1 g/bhp-hr. By engine, the highest average NO_X emission rate was 1.5 g/bhp-hr, and the lowest was 0.9 g/bhp-hr.

The two remaining engines included in the SDCAPCD data are prechambered models fired with landfill waste gas. In 14 tests, these engines averaged NO_X emissions of 0.5 g/bhp-hr, with a range from 0.3 to 1.0 g/bhp-hr.

Another source of NO_X emission data is the EPA’s *Compilation of Air Pollutant Emission Factors*, commonly known as the "AP-42." This document presents emission factors for various types of emission sources based on aggregated source test data. The current AP-42 section on IC engines was published in October 1996. This section lists the following two NO_X emission factors for 2-stroke, lean-burn engines equipped with LEC:

- Clean Burn–2.3 g/bhp-hr

- Precombustion Chamber–2.9 g/bhp-hr

We believe that this terminology corresponds to trademarks used by two engine manufacturers that offer precombustion chamber LEC technology. These technologies are not differentiated in this report; both are considered LEC.

The AP-42 assigns these emission factors a rating of C, or average. The references for the AP-42 section reveal that the test data behind these factors are from 1990 or earlier.[33] The AP-42 section does not state that the data are from short-term emission tests, but this appears likely based on the references. The engine operating conditions (load and speed) of the testing are not specified in the section.

The EPA has begun a revision of the AP-42 section on IC engines. A draft section dated February 1997 was posted on the Internet for public comment. This draft section classifies lean-burn engines equipped with LEC as distinct “engine families” and specifies the following terminology and NO_X emission factors:

- 2-stroke clean-burn engines–1.1 g/bhp-hr

- 4-stroke clean-burn engines–0.5 g/bhp-hr

These emission factors are rated C (average) and D (below average), respectively. The draft AP-42 section includes some more recent references, as well as some of the same references as the current section.[34, 35]

Commenters from industry on the draft AP-42 section objected to the “clean burn” designation. They noted that “CleanBurn” is a trademark of Cooper Energy Systems. Today, many engine manufacturers refer to their engines equipped with precombustion chambers simply as “lean-burn engines.” The EPA has recognized that it is unable to distinguish with certainty between engines with and without prechamber LEC technology on the basis of the test reports it is using to develop the revised AP-42 section. As a result, the EPA plans to further revise the section.

Additional NO_X emission test information obtained for this report are summarized below:

- Seven Clark Model TLA-6, 2-stroke, lean-burn, 2,000-bhp engines retrofitted with LEC, tested in April 1998. Six engines retrofitted by a third-party vendor ranged from 0.8 to 1.4 g/bhp-hr, with a mean of 1.0 g/bhp-hr. One engine retrofitted by the original equipment manufacturer (OEM) tested at 1.7 g/bhp-hr.[36]

- Three Ingersoll-Rand Model 412KVS, 4-stroke, lean-burn, 2,000-bhp engines retrofitted with LEC by the OEM, tested in August 1992. Tested at 0.51, 0.62, and 0.64 g/bhp-hr, with a mean of 0.59 g/bhp-hr.[37]

- One Cooper-Bessemer Model GMV-10C, 2-stroke, lean-burn, 1,100-bhp engine retrofitted with LEC by the OEM, tested in September 1999. Tested at 0.61 g/bhp-hr.[38]

- Five Delaval Model HVA16C, 4-stroke, lean-burn, 5,500-bhp engines retrofitted with LEC by the OEM. Test results from June 1991 (four engines) and May 1996 (three engines) range from 0.43 to 0.68 g/bhp-hr, with a mean of 0.59 g/bhp-hr.[39]

- Two Cooper-Bessemer Model W-330, 2-stroke, lean-burn engines retrofitted with LEC by the OEM, tested in 1995 or 1996. Tested at 1.0 and 1.3 g/bhp-hr.[40]

- Two engines retrofitted as a research project for the OEM attempting to develop a lower-cost retrofit kit. One Cooper-Bessemer Model GMV-6, 2-stroke, lean-burn engine tested at 1.4 g/bhp-hr immediately after the retrofit (September 1992), at 2.4 g/bhp-hr after the A/F ratio controller was adjusted to achieve low NO_X emissions over the widest range of operating conditions (September 1992), and at 1.8 g/bhp-hr after 4,000 operating hours (April 1993). These emission levels all were measured at rated load and speed. One Cooper-Bessemer Model GMV-TF-10, 2-stroke, lean-burn engine was tested after retrofit at a variety of horsepowers ranging from approximately 50 percent to 110 percent of rated horsepower. The maximum NO_X emission level was about 5 g/bhp-hr and the minimum was less than 0.5 g/bhp-hr. All but one test point were at or below about 4 g/bhp-hr. The emission rate generally increased as the horsepower increased. (The uncertainty for this engine stems from test results displayed only in a plot of emissions versus horsepower.) The research project report indicated that both these engines met their target NO_X emission rates (2 to 5 g/bhp-hr).[41]

In all, the sources of NO_X emission test data summarized above include the results of 476 individual tests conducted on 58 engines. (This count does not include the aggregated data in some of the sources discussed above, such as the May 2000 EPA memo and the AP-42 sections.) In these tests, NO_X emissions ranged from 0.1 g/bhp-hr to 4.8 g/bhp-hr. Ninety-seven percent of these tests (460) found emissions less than or equal to 2 g/bhp-hr. Almost 75 percent (356) of the tests found emissions less than or equal to 1 g/bhp-hr, and 25 percent (120) found emissions of less than or equal to 0.5 g/bhp-hr. Only two tests measured NO_X emissions greater than or equal to 4 g/bhp-hr. The emission test data are summarized by information source in Table 2-1 of Chapter 2 of this report.

4.1.3.3 Other Information on LEC Performance. Some additional information on the level of NO_X emissions that is achievable with LEC technology was obtained for this report. This "anecdotal" information consists of statements regarding LEC performance that are not accompanied by documentation (e.g., test data) or vendor guarantees. The additional information is summarized below:

- A 1990 report prepared for the Gas Research Institute (GRI) states that new engines equipped with precombustion chamber LEC technology can often achieve NO_X emission levels of 2 g/bhp-hr or below, corresponding to 80 to 90 percent reduction from conventional spark plug designs. The report indicates that this technology is well demonstrated in retrofit applications for newer, turbocharged lean-burn engines, and ascribes the same 80 to 90 percent emission reduction to such retrofits.[42]

- A 1994 report prepared for GRI states that an engine retrofitted with precombustion chamber LEC technology can average NO_X emissions of less than 2 g/bhp-hr, but for purposes of its cost analysis assumes emissions of 2.5 g/bhp-hr. The report notes that retrofits have been carried out and successfully demonstrated on many lean-burn engines, with the most likely candidates for retrofit being newer model designs. The report also states that improvements are routinely incorporated into the retrofit kits. This is the final report for a project developed in 1991 and 1992.[43]

- Three GRI flyers from 1994 and 1995 advertize new, low-cost NO_X controls for Ingersoll-Rand, Clark, and Cooper-Bessemer engines. The controls offered are the newer generation of OEM LEC retrofit technologies, featuring such improvements as screw-in precombustion chambers and turbocharger upgrades. The flyers indicate that the retrofit controls can reduce NO_X emissions to below 3 g/bhp-hr, which appears to be the target level based on expectations at that time regarding upcoming reasonably available control technology (RACT) requirements for lean-burn engines.[44]

- A paper prepared by the Manufacturers of Emission Controls Association (MECA) in 1997 indicates that NO_X emissions of 0.7 g/bhp-hr are typical from natural gas-fired engines operating at 74 percent excess air (lambda equal to 1.74).[45] Engines operating at such excess air levels typically require precombustion chambers to achieve stable combustion.

- Material submitted to the EPA by the Interstate Natural Gas Association of America (INGAA) in 1999 states that most existing engine models with OEM LEC retrofit equipment can achieve 4 g/bhp-hr at 100 percent torque and 100 percent speed. However, INGAA stated that some engines with poor air-fuel mixing characteristics can achieve only 7 g/bhp-hr at 100 percent torque and speed. The latter engines include some models manufactured by Worthington (ML and UTC models). This material also indicates that OEM LEC retrofit technology is available for most lean-burn engine models found at natural gas transmission and storage facilities, but is not available for a few models.[46]

- Southern California Gas Company operates continuous emissions monitoring systems (CEMS) on five engines equipped with LEC at a natural gas storage facility.[47] Based on knowledge of the CEMS data, the company has indicated that NO_X emissions from the engines are typically about 1.0 g/bhp-hr, and normally range from about 0.5 to 3.0 g/bhp-hr.[48] (Three of these engines are the Ingersoll-Rand Model 412KVS for which August 1992 emission test data are presented in the preceding section.)

Another source of information on achievable NO_X emissions is the 1997 California Air Resources Board (CARB) proposed determinations of RACT and best available retrofit control technology (BARCT) for stationary IC engines. These proposed determinations have not yet been finalized.

The proposed NO_X RACT for lean-burn SI engines is an 80 percent reduction in emissions, or emissions not to exceed 125 ppmv, dry basis, at 15 percent oxygen. This emission level corresponds to 1.7 g/bhp-hr based on the conversion factor used in this report for LEC-equipped engines. The basis for the proposed NO_X RACT is the VCAPCD rule that applied between September 1989 and December 1993. The CARB document also cites the VCAPCD test data in support of the proposed level. The document indicates that LEC is expected to be the most popular means of meeting the RACT requirements, although SCR may be used as an alternative if LEC is unsuitable for a particular model engine.

The proposed NO_X BARCT for lean-burn SI engines is a 90 percent reduction in emissions, or emissions not to exceed 65 ppmv, dry basis, at 15 percent oxygen. This corresponds to 0.9 g/bhp-hr. The basis for the proposed NO_X BARCT is the current VCAPCD rule, the Federal Implementation Plan for the Sacramento area, and the Sacramento Metropolitan Air Quality Management District rule. The proposed BARCT is identical to the latter two rules, but less stringent than the current VCAPCD rule (94 percent control or 45 ppmv limit). The CARB document also cites the VCAPCD test data to support the proposed level, noting that the majority of tests showed compliance with the proposed level despite the fact that the applicable requirement at the time of testing was 125 ppmv. The document indicates that LEC is expected to be the most common control method for meeting the proposed BARCT, although SCR may be used as an alternative if LEC is unsuitable for a particular model engine.[49]

4.1.4 Discussion of NO_X Emissions Data for LEC

The primary sources of data on controlled NO_X emissions are control equipment vendors (in the form of guarantees) and emission tests. As discussed above, general statements regarding achievable emissions may be made by sources familiar with these types of primary data.

Emissions data from LEC vendors (both engine manufacturers and third-party retrofit vendors) may overstate emissions somewhat. The vendor typically must provide a performance guarantee to the engine owner, leaving the vendor potentially liable if the engine fails to meet the guaranteed emission level.

This potential liability may motivate the control equipment vendor to design the LEC system to comfortably meet guaranteed performance, which is generally dictated by regulatory requirements. The typical result is LEC-equipped engines that meet or outperform the guarantee, as evidenced by information from retrofit vendors that all installations have met guaranteed emission levels, by one vendor's statement that many retrofits guaranteed at higher levels have achieved NO_X emissions of 2 g/bhp-hr, and by the test data discussed above that are consistently well below the applicable emission limits.[50, 51] Given these considerations, vendor guarantees provide a reasonable upper bound on NO_X emissions from well-maintained, well-operated engines equipped with LEC technology.

In contrast to the conservatism of guarantees, emission tests give an accurate picture of how a particular IC engine equipped with LEC performed during a particular test period. However, test results may tend to understate long-term emissions from the tested engine because owners may typically tune engines to minimize NO_X prior to testing. For example, a 1994 rule effectiveness study in Ventura County, California found that 5 out of 22 engines subjected to unannounced emission testing (23 percent) violated the NO_X limit. In comparison, the study found that only 1 out of 11 engines (9 percent) failed the regularly scheduled annual compliance test. One of the conclusions of the study was that most non-compliant engines can come into compliance easily and quickly with minor adjustments. (The source of these data does not identify the types of controls included in the study. Nonselective catalytic reduction clearly was included; it is not clear whether LEC was included.)[52] Because nearly all emission testing is scheduled by the engine owner, it is reasonable to conclude that test results represent a floor on the NO_X emission level achieved by the tested engine under the operating and ambient conditions of the test.

Other factors can also confound the relationship between test data and the performance of which a control technology is capable. Control systems typically are designed to meet the emission limits that apply to each individual engine. Therefore, test data from controlled engines do not necessarily reflect what the technology is capable of achieving, but rather what the engine is required to meet. In addition, control technologies evolve and improve over time as vendors and operators gain experience. For this reason, older test results may not reflect the emission levels achievable with current technology.

4.1.5 Achievable NO_X Emissions from Lean-Burn SI Engines Equipped with LEC

Based on information from engine manufacturers, available emission test data, and the considerations presented in the preceding section, 2.0 g/bhp-hr is representative of the NO_X emission level achieved across all new engines equipped with LEC, including open-chamber designs. Among new engines equipped with precombustion chamber LEC technology (which includes some smaller engines and all larger engines), this level is achieved by all models.

Further, 2.0 g/bhp-hr also is a representative NO_X emission level that can be achieved in nearly all LEC retrofit situations, based on the use of precombustion chambers and associated equipment. Suppliers of retrofit equipment and services (both engine manufacturers and third-party vendors) typically guarantee NO_X levels in the range from 1.5 to 3.0 g/bhp-hr. However, a number of sources have indicated that retrofits can be tailored to the emission limit the engine is required to meet, so, for example, 2.0 g/bhp-hr is often achievable even for engines where the guarantee associated with the standard retrofit kit is higher. Nevertheless, it is to be expected that some engines will not be able to achieve 2.0 g/bhp-hr, particularly certain Worthington models.

The NO_X emission test results discussed previously support the conclusion that 2.0 g/bhp-hr is achievable for new engines and most engines retrofitted with LEC technology. While emission test results generally represent a floor on the long-term emissions from a particular engine, the available test data are dominated by very low NO_X test results, in some cases numerous tests of the same engines over the course of years. The test results from California are frequently well below the applicable NO_X emission limits, which were in the range of 2 g/bhp-hr when most of the tests were conducted. These data suggest a long-term emission level no greater than 2.0 g/bhp-hr for the tested engines.

4.2 SELECTIVE CATALYTIC REDUCTION

This section on SCR primarily updates Sections 5.2.4, 5.3.1.2, and 5.3.2.2 of the 1993 ACT document, which address application of SCR to lean-burn SI engines, diesel compression-ignition (CI) engines, and dual-fuel CI engines, respectively. The primary reason for the update is to describe new SCR technology and its implications for IC engines in load-following service. This section includes a brief description of the technology (Section 4.2.1) and its applicability (Section 4.2.2), information gathered on SCR for this report (Section 4.2.3), and conclusions regarding the level of NO_X control achievable using SCR (Section 4.2.4).

4.2.1 Technology Description–SCR

Conventional SCR technology, as described in the 1993 ACT document, involves injecting anhydrous ammonia into the exhaust gas stream upstream from a catalyst bed. As the exhaust passes through the catalyst bed, the ammonia and NO_X react to form nitrogen gas and water. The system typically includes a NO_X CEMS upstream and/or downstream of the catalyst bed as a feedback mechanism to ensure that the proper quantity of ammonia is injected to avoid emissions of either unreacted ammonia or NO_X.

In recent years, the technology has been undergoing a change. The systems marketed today typically use an aqueous solution of urea in place of anhydrous ammonia as the reducing agent. This reduces the hazard and handling costs associated with anhydrous ammonia, because urea is not classified as a hazardous material as anhydrous ammonia is. Sometimes an aqueous solution of ammonia is used, which is less hazardous than anhydrous ammonia, although not as safe as urea.

For urea systems, the first stage of the catalyst bed is a hydrolysis catalyst, which converts the urea to ammonia. In the second stage of the catalyst, the ammonia and NO_X react to form nitrogen gas and water. As a beneficial secondary reaction, hydrocarbons react with oxygen to form water, carbon dioxide, and some carbon monoxide. The third stage of the catalyst bed is an oxidation catalyst where any unreacted ammonia is oxidized to nitrogen gas and water. A beneficial secondary reaction in this stage is the oxidation of carbon monoxide to carbon dioxide.

These systems use a “feedforward” system for determining the urea injection rate based on engine operating parameters (load, speed, and type of fuel, if variable) and exhaust temperature. The feedforward system is essentially a predictive emissions monitoring system (PEMS). The PEMS is calibrated by “mapping” the engine as part of the SCR system installation. Some systems complement the feedforward system with a feedback NO_X CEMS downstream from the catalyst to “trim” the urea injection rate.[53, 54, 55]

4.2.2 Applicability of SCR

As discussed in the 1993 ACT document, the types of IC engines that SCR can be applied to include lean-burn SI engines, diesel CI engines, and dual-fuel CI engines. To date in the United States, diesel engines are the most prevalent applications. Available data gathered for this report indicate that at least 44 IC engines at 12 facilities have had SCR installed since 1991. Thirty-eight of these are CI engines, with 31 fired with diesel fuel, 4 fired with distillate fuel oil (#2), 1 fired with residual fuel oil (#6), and 1 dual-fuel engine fired with diesel and natural gas. The remaining seven engines are lean-burn SI engines fired with natural gas. These include three engines at a natural gas pipeline compressor station in Southern California. Most of these SCR systems use anhydrous ammonia, although at least six of the engines use urea as the reducing agent. One source indicates that there are over 700 IC engines controlled with SCR systems in Europe and Japan, including approximately 80 to 100 2-stroke engines. (From the context, we believe that the source of this last data meant 2-stroke lean-burn SI engines fired with natural gas, although it is not explicit in the reference.)[56, 57, 58, 59]

An issue with SCR technology has been its ability to maintain a high level of control, while minimizing emissions of unreacted ammonia (referred to as "ammonia slip"), on IC engines in load-following applications. This issue has specifically been raised for natural gas-fired, lean-burn SI engines at natural gas compressor stations. The potential problems associated with load following include variations in NO_X emissions, variations in exhaust gas flow and temperature, and thermal cycling (rising and falling gas temperature, which can degrade the catalyst). The natural gas transmission industry does not believe these concerns have been resolved sufficiently for their applications.[60] Vendors of SCR equipment believe that these issues have been addressed in modern, feedforward systems using improved catalysts.

4.2.3 Information on SCR-Equipped Engines

Although SCR technology was not a major focus, some information came to light during data gathering for this report. This information includes one facility's operational experience with SCR, some emission test data, and information from vendors of modern SCR equipment.

One facility that was visited for this project discussed experiences with SCR control on one lean-burn SI engine from 1984 to 1996. The SCR system met or exceeded the guaranteed level of NO_X control (70 percent), allowing the facility to meet the applicable emission limit. However, the facility found the system difficult and expensive to operate. Operating expenses included the CEMS needed for control system feedback, the anhydrous ammonia reducing agent, and catalyst replacement. The facility found operation and maintenance difficult because it required work beyond that normally required for an engine. The CEMS was especially problematic because it required facility personnel to learn new analytical and instrumental skills. Some neighbors objected to the facility transporting and storing the hazardous anhydrous ammonia. The company ultimately took this engine out of service, as well as a second identical engine controlled with SCR at another facility, shifting all duty to LEC-equipped engines located at these sites.[61] Emission test results from 1993 for these two engines show outlet NO_X emissions of 2.86 and 2.80 g/bhp-hr, corresponding to reductions of 87 and 84 percent, respectively.[62]

The VCAPCD emission test data base includes seven lean-burn SI engines equipped with SCR control technology. Five models ranging from 291 bhp to 800 bhp are represented. In 49 tests of these engines, NO_X emissions ranged from 0.1 g/bhp-hr to 3.0 g/bhp-hr, with a mean of 1.1 g/bhp-hr. Six tests of three engines (two different models) found emissions greater than 2 g/bhp-hr. For 43 tests, NO_X emissions upstream of the catalyst bed also were provided, allowing the percent reduction to be calculated. The reductions ranged from 41 to 97 percent, with an average percent reduction of 84 percent.

The test dates in the VCAPCD data range from 1986 to 1993. During this period, lean-burn SI engines were subject to a NO_X emission limit of 125 ppmv, dry basis, at 15 percent oxygen, or an emission reduction of 80 percent. In all but two tests of one engine, the test results indicate compliance with at least one of these alternative standards. The engine that failed two emission tests was taken out of service after the second test.

In 1993, the VCAPCD tightened the NO_X emission limit for lean-burn SI engines to 45 ppmv, dry basis, at 15 percent oxygen, or an emission reduction of 94 percent. We do not know what the phase-in period for the new limits was, but the VCAPCD data base includes no test results for lean-burn SI engines equipped with SCR after 1993. This suggests that these engines were removed from service. The data base indicates that three of the seven engines were removed from service and replaced with electric motors.[63] According to a 1998 paper by a representative of the VCAPCD, one aim of VCAPCD's tighter NO_X emission limits was to encourage electrification of IC engines.[64]

Test result summary data also were obtained for 1997 emission tests of three 3,130-bhp, 4-stroke, lean-burn SI engines equipped with SCR control systems, which we believe to be urea based. These engines are located at a liquid fuel pipeline pumping station and operate at variable load and variable speed depending on the quantity, pressure, and density of the fuel being pumped. The SCR system utilizes a feedforward system based on engine load and speed and on exhaust temperature. The engines are subject to stringent permit emission limits for NO_X, volatile organic compounds (VOC), and carbon monoxide which correspond to 15 ppmv, 25 ppmv, and 32 ppmv, respectively (all on a dry basis corrected to 15 percent oxygen). This NO_X limit corresponds to about 0.2 g/bhp-hr. During testing in January 1997, the engines achieved the NO_X and carbon monoxide limits, but exceeded the limit for VOC. In repeat testing in March 1997 after the catalyst was checked and cleaned, the engines achieved all the emission limits. In 20 individual test runs on these three engines, NO_X emissions ranged between 0.11 g/bhp-hr and 0.21 g/bhp-hr.[65, 66, 67]

These test results indicate that SCR can achieve design NO_X control levels during short-term emission tests, including, in the case of the VCAPCD data, multiple tests on the same engine over the course of several years. However, these test results do not directly address performance during engine load swings. Continuous emissions data are necessary to address this issue fully.

We obtained one plot of continuous data over a 10 minute period from a trade association that includes SCR vendors. This figure plots data from a heavy duty diesel truck engine equipped with a feedforward urea SCR system. During this period, the engine varied from a speed of about 700 rotations per minute (rpm) at idle to about 2,300 rpm, with load varying concurrently from nearly 0 foot-pounds (ft-lbs) to about 800 ft-lbs. Inlet NO_X concentrations varied closely with load, ranging from a less than 10 ppmv up to over 150 ppmv. Outlet NO_X concentrations remained relatively stable, varying from nearly 0 ppmv up to about 20 ppmv. It is not clear from the figure at what percent oxygen the NO_X concentrations are expressed.[68]

Vendors of SCR systems indicate that the feedforward controls on modern systems provide for excellent NO_X control in load-following applications. One representative indicated that the advance in technology has been driven by the interest of diesel engine manufacturers, working with catalyst vendors, in developing urea SCR for on-road vehicles. Such vehicles exhibit varying load by nature.[69] Another source also stressed that the PEMS feedforward system, with optional CEMS feedback system, has been advanced by a strong research and development effort. This vendor has supplied such SCR systems for a variety of applications, including stationary IC engines, ship engines, railroad engines, and diesel truck engines.[70]

Selective catalytic reduction system vendors also believe that they have solved other problems with SCR systems for IC engines. Advances in catalysts have eliminated thermal shock and vibration impacts and broadened the available temperature operating window.[71]

Vendors of SCR systems typically indicate that NO_X control efficiencies greater than 90 percent are achievable. These systems typically are designed on a case-by-case basis to achieve the required emission reduction, so design values do not necessarily represent the limit of the technology. One vendor source indicates that a number of SCR systems installed on U.S. IC engines since 1993 have been designed for NO_X control ranging from 80 percent to 95 percent. The design outlet NO_X emission level for three lean-burn SI engines at one natural gas pipeline compressor facility is less than 30 ppmv (oxygen concentration not specified by this information source). Another vendor source indicates that one urea SCR system installed in 1999 on a natural gas-fired, 389-bhp, lean-burn SI engine was guaranteed at 90 percent NO_X control, but has achieved over 95 percent control. Another such system on a diesel electric generator was designed for 70 percent reduction, but achieved 79 percent.[72, 73]

4.2.4 Achievable Level of NO_X Control with SCR

Based on the information presented and discussed above, 90 percent control of NO_X emissions is generally achievable through use of SCR systems on IC engines, including lean-burn SI engines, diesel CI engines, and dual-fuel CI engines. Recent installations with lower control levels are the result of the systems' having been designed to meet applicable NO_X emission limits, rather than any inherent limitation of the technology.

Based on information provided by SCR vendors, the shortcomings of earlier SCR systems have been corrected by the new generation of the technology, which includes improved catalysts, PEMS feedforward system controls (with the option for supplemental CEMS feedback control, where desired), and use of urea as the reducing agent. However, this technology has yet to be widely demonstrated in the United States on lean-burn SI engines in load-following applications. Vendors of this technology still must convince U.S. lean-burn SI engine operators that modern SCR systems are as effective, reliable, easy to operate, and cost effective as alternative control technologies, most notably LEC.

4.3 NONSELECTIVE CATALYTIC REDUCTION

This section on NSCR primarily updates Section 5.1.5 of the 1993 ACT document, which addresses application of NSCR to rich-burn SI engines. This technology was not a focus for this effort, but some information was gathered during the course of the project. This section includes a brief description of the technology (Section 4.3.1) and its applicability (Section 4.3.2), information gathered on NSCR (Section 4.3.3), and conclusions regarding the level of NO_X control achievable using NSCR (Section 4.3.4).

4.3.1 Technology Description–NSCR

In NSCR, the engine exhaust is routed to a catalyst bed across which NO_X is reduced to nitrogen gas. At the same time, VOC and carbon monoxide are oxidized to water and carbon dioxide. Because emissions of these three pollutants all are reduced by the catalyst, NSCR is often referred to as a "three-way catalyst" system. These systems are similar to the catalytic converters used on automobiles.

For an NSCR system to operate optimally (i.e., to minimize NO_X emissions), the inlet exhaust stream must have very low oxygen content, as well as proper concentrations of NO_X, VOC, and carbon monoxide. This requires initial engine adjustments, followed by careful monitoring of oxygen content in the exhaust. For this reason, an automatic A/F ratio controller typically is used to regulate the exhaust oxygen content entering the catalyst bed. The controller adjusts the A/F ratio based on input from an oxygen sensor upstream from the catalyst bed.

The engine adjustments required to optimize NSCR systems typically reduce the efficiency of the engine, harming fuel economy. One source indicated that the brake-specific fuel consumption (BSFC) of these engines increases to 8,500 Btu/bhp-hr, at best.[74] Without the NSCR operating constraints, the BSFC is typically well below 8,000 Btu/bhp-hr for rich-burn engines, depending on model and other operational factors.

4.3.2 Applicability of NSCR

Because of the requirement for low oxygen content, NSCR systems are limited to rich-burn SI engines. As noted above, the engines must be adjusted to generate exhaust gas with specified characteristics.

4.3.3 Information on NSCR-Equipped Engines

A number of facilities in California that operate NSCR-equipped engines were visited during information-gathering for this report. The biggest operational problem associated with NSCR at these facilities has been damage to the catalyst caused by excessive temperature. This is caused when the exhaust stream is too fuel rich. In this situation, the uncombusted natural gas is rapidly oxidized in the catalyst bed, burning it out.

One natural gas storage facility that uses NSCR uses a bypass system during engine startup, in case the engine backfires and exhausts uncombusted fuel. The engine exhaust at this facility is typically about 950 °F. If the temperature reaches 1,200 °F, the system shuts down. At about 1,300 °F, the catalyst sustains damage. Another facility that uses NSCR-equipped engines to pump a variable water flow has had a significant problem with catalyst burnout.[75, 76]

Most of the visited facilities have achieved applicable NO_X emission limits using NSCR. Depending on jurisdiction and installation date, these NO_X limits are equal to or less than 50 ppmv, dry basis, at 15 percent oxygen (approximately 0.75 g/bhp-hr). However, one facility with very low permitted emission levels (equivalent to about 0.2 g/bhp-hr) has had difficulty maintaining this level. To improve system performance, this facility replaced the standard ignition systems on its engines with improved electronic ignition systems. A recent measure that has been successful for the facility has been to install an insulation blanket on the exhaust piping upstream from the catalyst bed, thereby maintaining a higher temperature when the exhaust stream reaches the catalyst bed. This has moved the exhaust into a temperature range where the NSCR system is more efficient.[77]

At one facility visited for this project, the rich-burn engines are subject to emission limits of 50 ppmv for NO_X and 1,700 ppmv for carbon monoxide, both on a dry basis at 15 percent oxygen. The carbon monoxide limit is a facility-specific limit based on an offset agreement with the SBCAPCD; otherwise, the limit would be 4,500 ppmv. A facility representative indicated that tuning these NSCR-equipped engines to achieve the NO_X emission limit is relatively easy because of the less-restrictive carbon monoxide limit. In contrast, best achievable control technology (BACT) for new engines in California is 9.5 ppmv or 0.15 g/bhp-hr for NO_X and 225 ppmv or 0.6 g/bhp-hr for carbon monoxide (concentrations on a dry basis at 15 percent oxygen). This NO_X level is only achievable with rich-burn engines controlled with NSCR. The combination of these restrictive levels for both NO_X and carbon monoxide makes the engine operating window for compliance very narrow.[78]

Emission test data for NSCR-equipped engines from three local air pollution agencies in California were reviewed for this report. These data from VCAPCD, SBCAPCD, and SDCAPCD are summarized below:

- The VCAPCD test data include 114 engines equipped with NSCR control technology. Forty-seven models ranging in size from 25 bhp to 1,250 bhp are represented in the data. In 902 tests of these engines, NO_X emissions ranged from less than 0.01 g/bhp-hr to 19 g/bhp-hr, with a mean of 0.3 g/bhp-hr. Ninety-nine percent of the tests (893) found emissions of less than 1 g/bhp-hr. For 543 tests, inlet NO_X emissions are included in the data base, allowing the percent reduction to be calculated. Percent reductions range from 0 to nearly 100 percent, with an average reduction of 92 percent. It should be noted that for the two tests with 0 percent emission reduction the inlet NO_X value was unusually low (0.12 and 0.03 g/bhp-hr), giving the appearance that the NO_X outlet value was mistakenly entered as the inlet value as well. Among tests that show NO_X reductions of less than 70 percent, the majority have NO_X inlet values of less than 2 g/bhp-hr.[79]

- The SBCAPCD test data include 78 engines equipped with NSCR. Seventeen models ranging in size from 48 bhp to 747 bhp are represented. In 163 tests of these engines, NO_X emissions ranged from less than 0.01 g/bhp-hr to 1.5 g/bhp-hr, with a mean of 0.17 g/bhp-hr. Tests dates range from 1991 to 1999.[80]

- The SDCAPCD test data include 33 engines equipped with NSCR. In 249 tests of 7 different models, NO_X emissions ranged from 0 g/bhp-hr (reported in the data we reviewed as 0 ppmv at 3 percent oxygen) to 18 g/bhp-hr, with a mean of about 1.0 g/bhp-hr. Fifty-eight percent of the tests found emissions less than or equal to

0.5 g/bhp-hr. Over 85 percent of the tests (217) found emissions of 2.0 g/bhp-hr or less. The tested engines apparently had site-specific emission limits, which ranged from 180 ppmv at 3 percent oxygen (equivalent to about 0.9 g/bhp-hr) to 456 ppmv at 3 percent oxygen (equivalent to about 2.2 g/bhp-hr). All but 1 of the 32 tests with emissions greater than 2.0 g/bhp-hr were out of compliance with their permitted NO_X limits; an additional 9 tests with emissions less than 2.0 g/bhp-hr were out of compliance. A percent NO_X reduction was provided for 27 tests of 7 engines. The reductions ranged from 87 to 100 percent, with a mean of 97 percent. Tests dates ranged from 1984 to 1996.[81]

Test result summaries for two additional NSCR-equipped engines not included in the data above were received from one natural gas storage facility in California. In these 1997 tests, the NO_X emissions from these engines were less than 10 ppmv (dry basis at 15 percent oxygen) and less than 0.1 g/bhp-hr.[82]

As noted above in Section 4.1.3.3, another source of information on achievable NO_X emissions is the 1997 CARB proposed determinations of RACT and BARCT for stationary IC engines. These proposed determinations have not yet been finalized.

The proposed NO_X RACT for rich-burn SI engines is a 90 percent reduction in emissions, or emissions not to exceed 50 ppmv, dry basis, at 15 percent oxygen. This emission level corresponds to about 0.75 g/bhp-hr. The basis for the proposed NO_X RACT is the VCAPCD rule that applied between September 1989 and December 1993. The CARB document also cites the VCAPCD test data in support of the proposed level. The document indicates that NSCR is expected to be the most popular means of meeting the RACT requirements, although PSC may be used for engines fired with waste-derived fuels (e.g., landfill gas or sludge digester gas) where contaminants may poison the NSCR catalyst.

The proposed NO_X BARCT for rich-burn SI engines is a 96 percent reduction in emissions, or emissions not to exceed 25 ppmv, dry basis, at 15 percent oxygen. This corresponds to about 0.37 g/bhp-hr. (For engines fired with waste-derived fuel, the limits are 90 percent reduction of 50 ppmv.) The basis for the proposed NO_X BARCT is the current VCAPCD rule, the Federal Implementation Plan for the Sacramento area, and the Sacramento Metropolitan Air Quality Management District rule. The proposed BARCT is identical to these rules. The CARB document also cites the VCAPCD test data to support the proposed level, noting that the majority of tests showed compliance with the proposed level despite the fact that the applicable requirement at the time of most testing was 50 ppmv. The document indicates that NSCR is expected to be the most common control method for meeting the proposed BARCT, except for engines fired with waste-derived fuel. These engines are expected to use PSC.[83]

Information from vendors of NSCR systems indicates that NSCR three-way catalysts have been installed on over 1,000 IC engines in the United States and have been in use for over 10 years. This source indicates that these catalyst systems reduce NO_X emissions by over 98 percent, while reducing VOC by 80 percent and carbon monoxide by over 97 percent.[84]

4.3.4 Achievable Level of NO_X Control with NSCR

Based on the information presented and discussed above, 95 percent control of NO_X emissions is generally achievable through the use of NSCR systems on rich-burn SI engines. These systems typically are designed on a case-by-case basis to meet applicable emission limits, with percent reduction more a function of design than any inherent limitation in the control technology.

Consistent operation at this level of control requires an automatic A/F ratio controller and implementation by the facility of a good inspection and monitoring program. The inspection and monitoring program is necessary to ensure that engines remain adjusted to optimize the NSCR systems' effectiveness and to detect signs of catalyst inactivity at the earliest possible time.

4.4 PRESTRATIFIED CHARGE™

This section on PSC primarily updates Section 5.1.4 of the 1993 ACT document, which address application of PSC to rich-burn SI engines. This technology was not a focus for this effort, but some information was gathered during the course of the project. This information is presented briefly below.

Prestratified charge technology involves injecting air into the intake manifold so that during the intake stroke, the piston initially draws in air, followed by a fuel-rich air-fuel mixture. Thus, the mixture near the spark plug is fuel rich, promoting good combustion, while the mixture away from the spark plug is very lean, acting as a heat sink and suppressing NO_X formation. Prestratified charge technology is applicable only to carbureted (i.e., non-fuel-injected) rich-burn engines.

Some California facilities using PSC technology were visited during information-gathering for this report. In the mid-1980's, one company retrofitted seven engines at two facilities with PSC technology. These engines are used to generate electricity for onsite consumption. The technology has performed well, achieving NO_X emission reductions of 85 to 90 percent, although the vendor guarantee was for only 80 percent. However, the PSC retrofit has resulted in a 20-percent power derating for the engines. In addition, while the PSC system itself requires very little maintenance, the engines are more "touchy"and require more frequent overall maintenance. Results from 11 emission tests of these 7 engines submitted by this source show NO_X emissions ranging from 1.0 g/bhp-hr to 3.2 g/bhp-hr. The average over the tests is about 2.0 g/bhp-hr.[85, 86]

Another facility located in the VCAPCD retrofitted several engines with PSC to meet the older emission standard that required a 90 percent reduction in NO_X emissions or a limit of 50 ppmv. When the VCAPCD standard was tightened to 96 percent reduction or 25 ppmv, the facility removed the PSC system and added NSCR. Other engines at this facility that are fired with waste-derived fuel continue to use PSC technology. These engines also use exhaust gas recirculation (EGR), with the air injected by the PSC system coming from the engines' exhaust.

Emission test data for PSC-equipped engines from two local air pollution agencies in California were reviewed for this report. These data from VCAPCD and SBCAPCD are summarized below:

- The VCAPCD test data include tests of 18 engines equipped with PSC control technology. Ten models ranging in size from 100 bhp to 800 bhp are represented. In 150 tests of these engines, NO_X emissions ranged from about 0.1 g/bhp-hr to 9.5 g/bhp-hr, with a mean of 0.6 g/bhp-hr. Eighty-nine percent of the tests (134) found emissions of less than 1 g/bhp-hr. The 16 tests with emissions greater than 1 g/bhp-hr were from 8 engines ranging in size from 300 bhp to 800 bhp. For 37 tests, the data base includes NO_X emissions without PSC so that the percent change in emissions can be calculated without and with control. (In a number of tests, it appears that the value without PSC is repeated from an earlier test without retesting.) In one test, the emissions increased by about 6 percent with PSC. In the remaining 36 tests, the lowest percent reduction is 90 percent, with an average reduction of 95 percent. The data base includes tests from 1987 to 1999.[87]

- The SBCAPCD test data include tests of 32 engines equipped with PSC control technology. Six different models are represented in 126 tests. The engines range in size from 49.5 bhp to 410 bhp. Fifty-four tests (67 percent) were on engines of less than 50 bhp. Many of the engines are fired on field gas. These are likely to be cyclical load engines powering rod pumps in oil and natural gas fields. Emissions of NO_X ranged from less than 0.1 g/bhp-hr to 12.5 g/bhp-hr, with a mean of 1.3 g/bhp-hr. All of the fifteen tests (19%) that found emissions greater than 2.0 g/bhp-hr were on engines of less than 50 bhp. For 17 of the engines, there were comparison test runs with the PSC turned off and turned on. Emissions of NO_X with the PSC turned on were on average 77 percent less than with the PSC turned off. All these comparison tests were conducted on engines less than 50 bhp. Test dates ranged from 1991 to 1999.[88]

The 1993 ACT document found that the achievable NO_X emission level for PSC is 2.0 g/bhp-hr, based on the vendor's guarantees. This value is generally consistent with the information gathered for this project and is a representative value for the NO_X emission level that can be achieved using PSC control technology.

4.5 HIGH-ENERGY IGNITION SYSTEMS

With traditional spark plug ignition, the life of the spark is very short–only a fraction of a degree of crankshaft rotation. If the mix of air and fuel in the area of the spark is not exact, there is poor combustion or no combustion at all. With HEIS technology, also known as plasma ignition systems, a continuous electrical discharge is provided at the gap of a conventional spark plug for 10 to 90 degrees of crankshaft rotation. This extended energy delivery ensures combustion will occur even in the leanest of conditions. High-energy ignition systems can be used only in lean-burn, natural gas-fired SI engines.

One well-known high-energy ignition system was developed by ENOX Technologies under the trade name of INOx™. With the INOx™ system, a very lean air-fuel mixture is fired using a turbocharger to boost pressure, thus reducing combustion temperatures. The lower combustion temperatures results in reduced NO_X formation. The electronic plasma combustion system ignites the mixture through a conventional spark plug opening; therefore, installation does not require modification to the engine's head and can be accomplished in 3 to 5 days.[89]

During development, the INOx™ system was tested in the laboratory and on at least two field engines. The lowest NO_X emission level achieved on a 2,750-bhp V-275 Cooper-Bessemer engine while maintaining acceptable engine operation was 2.5 g/bhp-hr, an 84 percent reduction from the uncontrolled level.[90]

Since that time, HEIS has been installed on numerous engines to meet NO_X RACT requirements in the range of 2.5 to 3.0 g/bhp-hr in the Eastern United States. One source indicates that a natural gas transmission company purchased INOx™ technology for installation on as many as 53 compressor station engines in New York and Pennsylvania.[91] Another source indicates that ENOX has successfully retrofitted over 100 engines with its INOx™ technology. Several clients have reported over 80 percent reduction in NO_X emissions.[92]

Another company, Plasmachines, Inc., has also developed HEIS technology that has been demonstrated on two operating IC engines. This ignition system has demonstrated the capability to reduce NO_X emissions from these engines from the level of 10 g/bhp-hr to the regulatory level at or near 2.0 g/bhp-hr.[93]

Stack test data from between 1995 and 1998 for three Clark TLA-8 reciprocating engines retrofitted with HEIS technology (make unknown) found average NO_X emission rates ranging from 1.2 to 4.2 g/bhp-hr, with an average of 2.05 g/bhp-hr.[94] There is little information available on the effects of HEIS technology on other pollutants.

4.6 EMERGING NO_X CONTROL TECHNOLOGIES

Three emerging technologies that show promise for reducing NO_X emissions from IC engines were identified during information-gathering for this project. The SCONOx® system uses a single catalyst to remove NO_X, carbon monoxide, and VOC. The NOxTech® system uses a non-catalytic chemical reaction to reduce NO_X, particulate matter, VOC, and carbon monoxide emissions. High-pressure fuel injection enhances mixing of air and fuel in the combustion chamber. These emerging technologies are described briefly below.

4.6.1 SCONOx® Technology

The SCONOx® system, developed by Goal Line Environmental Technologies, uses a single catalyst to remove NO_X, carbon monoxide, and VOC. Initially applied to gas turbines, SCONOx® IC-N and IC-D have been developed for use on internal combustion engines that are, respectively, natural gas-fired and diesel-fired.

According to product literature, the SCONOx® process uses no hazardous materials; all utilities required to operate the system–natural gas, steam, water, ambient air, and electricity–are often already present at the site.[95] At temperatures between 300 and 700 °F, nitrogen dioxide (NO_2) is absorbed onto the catalyst surface through the use of a potassium carbonate coating, which reacts with the NO_2 to form potassium nitrites. The SCONOx® catalyst undergoes regeneration periodically to maintain the maximum NO_X absorption. The catalyst is regenerated by passing a controlled mixture of regeneration gases across its surface in the absence of oxygen. The regeneration gases react with the nitrites to form water and elemental nitrogen. Carbon dioxide in the regeneration gas reacts with potassium nitrites to form potassium carbonate–the absorber coating that was on the surface of the catalyst before the oxidation cycle began. Water (as steam) and elemental nitrogen are exhausted up the stack and potassium carbonate is once again present on the surface of the catalyst allowing the oxidation adsorption cycle to begin again. There is no net gain or loss of potassium carbonate.[96]

Testing conducted by the vendor shows SCONOx® IC-N reduces NO_X, carbon monoxide, and VOC up to 95 percent in lean-burn engine exhaust.[97] Three SCONOx® IC-N systems were purchased for natural gas-fired IC engines and were scheduled to go one line in May 2000.[98]

Cummins Engine Company is testing SCONOx® IC-D for use on mobile and stationary diesel IC engines.[99] Preliminary testing in diesel IC engines found the SCONOx® and the related SCOSOx® catalyst systems reduced NO_X by 98.9 percent to 0.4 g/bhp-hr.[100] The fuel penalty for use of these systems was 1 percent or less. Three SCONOx® IC-D units have been sold but have not yet been commissioned.

4.6.2 NOxTech® Emission Control System

According to product literature, the NOxTech® emission control system, developed by NOxTech Inc., involves chemically treating exhaust gases with a nonhazardous liquid chemical. NOxTech® can be used on both diesel and lean-burn natural gas-fired IC engines. It replaces the exhaust silencer on IC engines with a reaction chamber. The non-catalytic chemical reagent is injected into the exhaust at temperatures between 1,400 and 1,500 °F. The NO_X and reagent react to form nitrogen, water vapor, and carbon dioxide. There is no toxic waste, although there are trace ammonia emissions of less than 2 to 5 ppmv.[101] The NOxTech® system is fully automated. Installation requires no major modifications and takes 2 to 3 weeks.

The exhaust gas must be heated to achieve the temperatures necessary for the NOxTech® system reactions. A heat exchanger is located downstream from the reactor to reclaim and reuse this heat energy.

The NOxTech® system has been installed and is operating on several diesel generators owned by Southern California Edison. Its Catalina Island facility uses NOxTech® on 2.5 MW and 3.8 MW diesel electric generators. Southern California Edison also uses NOxTech® on 1.5 MW and 2.8 MW diesel generators at its Pebbly Beach generating station.

According to the vendor, NOxTech® has been proven to remove 90 to 95 percent of NO_X, 60 to 80 percent of particulate matter, 90 percent of VOC, and 50 to 70 percent of carbon monoxide from the exhaust of the 4,000-bhp diesel-powered generator on Catalina Island.[102] Based on its demonstrated commercial performance, NOxTech® has been demonstrated as BACT for some diesel engines.[103]

4.6.3 <u>High-Pressure Fuel Injection</u>

Another technology with potential for reducing NO_X emissions from IC engines is the use of high-pressure fuel injector systems to enhance the mixing of air and fuel in the combustion cylinder. According to one vendor of NO_X control equipment and retrofit services, this technology represents a "second generation" LEC, which may accomplish the same emission reductions without requiring precombustion chambers or as much excess air. Reducing the quantity of excess air would diminish the turbocharging and intercooling retrofit requirements. High-pressure fuel injection could significantly reduce the cost and complexity of retrofitting IC engines to control NO_X emissions.[104]

A representative of a company visited during this project to collect information on IC engine control technology discussed high-pressure fuel injection as a potential NO_X-reduction technology. He mentioned that in a test, a high-pressure fuel injection system reduced NO_X emissions by 80 percent from a large (around 5,000 bhp) turbocharged Clark engine. He also noted, however, that Clark engines typically have relatively poor mixing, so reductions from other engines might not be as great.[105]

It should be noted that another LEC retrofit vendor stated that NO_X emissions cannot be reduced to 2 g/bhp-hr through the use of a high-pressure fuel system alone. This vendor noted that less stringent regulatory requirements can sometimes be met with a combination of ignition timing adjustment, high-pressure fuel injectors, and improved A/F ratio and ignition system controls. This vendor's LEC retrofits typically include high-pressure fuel injectors.[106]

4.7 REFERENCES FOR CHAPTER 4

1. *Alternative Control Techniques Document–NO_X Emissions from Stationary Reciprocating Internal Combustion Engines*. U. S. Environmental Protection Agency, Research Triangle Park, NC. Publication No. EPA-453/R-93-032. July 1993. 315pp. http://www.epa.gov/ttncatc1/products.html. (1993 ACT document)

2. 1993 ACT document. Pp. 5-3 - 5-14, 5-41 - 5-55, 5-70 - 5-71, and 5-76 - 5-78.

3. Caterpillar, Inc. Facsimile from K. S. King to W. Neuffer, U. S. EPA. Information on Low Emission Combustion for Gaseous Fueled Engines. Caterpillar, Inc., Lafayette, IN. March 31, 1999. 7pp.

4. Waukesha. Letter and attachments from R. W. Stachowicz to W. Neuffer, U. S. EPA. Information on Low Emission Combustion for Lean Burn Engines. Waukesha Engine Division, Waukesha, WI. March 22, 1999. 19pp.

5. Cooper-Bessemer. Facsimile from J. W. Hibbard to W. Neuffer, U. S. EPA. Information on Low Emission Combustion. Cooper-Bessemer, Cooper Energy Services, Mount Vernon, OH. March 3, 1999. 4pp.

6. Ajax Superior. Memo and attachments from L. Palmer to W. Neuffer, U. S. EPA. Information on Low Emission Combustion. Cooper Energy Services, Ajax Superior Division, Springfield, OH. March 20, 1999. 86pp.

7. Delaval Division. Facsimile from R. G. Billig to W. Neuffer, U. S. EPA. Information on Low Emission Combustion. Cooper Energy Services, Delaval Division.

8. Dresser-Rand. Facsimile from C. F. Willke to W. Neuffer, U. S. EPA. Information on Low Emission Combustion. Dresser-Rand Services, Painted Post, NY. May 7, 1999. 2pp.

9. Waukesha. Letter and attachments from R. W. Stachowicz to W. Neuffer, U. S. EPA. Information on Low Emission Combustion for Lean Burn Engines. Waukesha Engine Division, Waukesha, WI. March 22, 1999. 19pp.

10. Diesel Supply Company. Facsimile from R. Faulkner to S. Edgerton, EC/R Inc. Information on Low Emission Combustion Retrofits. Diesel Supply Company, Odessa, TX. April 17, 2000. 5pp.

11. W. Neuffer, U. S. EPA. Summary of Information Provided by Engine Manufacturers on Low Emission Combustion.

12. W. Neuffer, U. S. EPA. Summary of Information Provided by Engine Manufacturers on Low Emission Combustion.

13. Telecon. R. Faulkner, Diesel Supply Company, with S. Edgerton, EC/R. April 6, 2000.

14. Cooper-Bessemer. Facsimile from J. W. Hibbard to W. Neuffer, U. S. EPA. Information on Low Emission Combustion. Cooper-Bessemer, Cooper Energy Services, Mount Vernon, OH. March 3, 1999. 4pp.

15. Dresser-Rand. Facsimile from C. F. Willke to W. Neuffer, U. S. EPA. Information on Low Emission Combustion. Dresser-Rand Services, Painted Post, NY. May 7, 1999. 2pp.

16. Telecon. R. Faulkner, Diesel Supply Company, with S. Edgerton, EC/R. April 6, 2000.

17. Telecon. R. Faulkner, Diesel Supply Company, with S. Edgerton, EC/R. April 6, 2000.

18. Diesel Supply Company. Facsimile from R. Faulkner to S. Edgerton, EC/R Inc. Information on Low Emission Combustion Retrofits. Diesel Supply Company, Odessa, TX. April 17, 2000. 5pp.

19. Telecon. R. Faulkner, Diesel Supply Company, with S. Edgerton, EC/R. July 21, 2000.

20. Telecon. R. Faulkner, Diesel Supply Company, with S. Edgerton, EC/R. April 6, 2000.

21. Telecon. R. Faulkner, Diesel Supply Company, with S. Edgerton, EC/R. April 6, 2000.

22. Ajax Superior. Memo and attachments from L. Palmer to W. Neuffer, U. S. EPA. Information on Low Emission Combustion. Cooper Energy Services, Ajax Superior Division, Springfield, OH. March 20, 1999. 86pp.

23. Delaval Division. Facsimile from R. G. Billig to W. Neuffer, U. S. EPA. Information on Low Emission Combustion. Cooper Energy Services, Delaval Division.

24. Interstate Natural Gas Association of America. "IC Engine OTAG Questions," Attachment D. February 17, 1999.

25. Caterpillar, Inc. Facsimile to Bill Neuffer, U.S. EPA. Information on Low Emission Combustion for Gaseous Fueled Engines. Caterpillar, Inc., Lafayette, IN. March 31, 1999. 7pp., Pg. 3

26. W. Neuffer, U. S. EPA. Summary of Information Provided by Engine Manufacturers on Low Emission Combustion. Summary indicates that the response from J. Hibbard of Cooper Energy Services (Cooper-Bessemer) states that emission test results show NO_X rising as engine speed decreases.

27. 1993 ACT document, pg. 5-68.

28. Memo from D. Sanders, EPA, to D. Grano, EPA, and Docket No. A-98-12. Performance of Low Emission Combustion. May 19, 2000.

29. Memo from S. Edgerton, EC/R Inc., to Project File. Analysis of Ventura County APCD Test Data–Low Emission Combustion. July 28, 2000.

30. Donald R. Price, "NO_X Control Options for Gas-Fired Stationary Internal Combustion Engines." Prepared for A&WMA Annual Meeting, June 1998.

31. Memo from S. Edgerton, EC/R Inc., to Project File. Analysis of Santa Barbara County APCD Test Data–Low Emission Combustion. July 28, 2000.

32. Memo from S. Edgerton, EC/R Inc., to Project File. Analysis of San Diego County APCD Test Data–Low Emission Combustion. July 28, 2000.

33. *Compilation of Air Pollutant Emission Factors*, 5th Edition, Supplement B, Section 3.2. EPA Document AP-42. October 1996.

34. *Compilation of Air Pollutant Emission Factors*, 5th Edition, Supplement C, Draft Section 3.2. EPA Document AP-42. February 1997. http://www.epa.gov/ttn/chief/dsur/d03s02.zip.

35. *Emission Factor Documentation for AP-42 Section 3.2, Natural Gas-Fired Reciprocating Engines*. Draft. Prepared by Eastern Research Group for EPA. http://www.epa.gov/ttn/chief/dsur/d03s02.zip.

36. EC/R Incorporated. Final Site Visit Reports for Southern California Gas Company Facilities, Attachment 5. Prepared for Ozone Policy and Strategies Group, U. S. Environmental Protection Agency, Research Triangle Park, NC. June 26, 2000. 12pp.

37. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Aliso Canyon Station. Southern California Gas Company, Aliso Canyon, CA. December 16, 1999. 26pp.

38. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Goleta Station. Southern California Gas Company, Goleta Station, CA. December 16, 1999. 24pp.

39. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Honor Rancho Station. Southern California Gas Company, Honor Rancho Station, CA. December 16, 1999. 16pp.

40. Pacific Gas and Electric Company. Letter and attachments from C. Burke to W. Neuffer, U. S. EPA. Information on Hinkley Compressor Station Units K-11 and K-12. Pacific Gas and Electric Company. February 3, 2000. 8pp.

41. GRI-98/0117. *NO_X Control for Two-Cycle Pipeline Reciprocating Engines*. Prepared by Arthur D. Little , Inc., for the Gas Research Institute. December 1998.

42. GRI-90/0215. *NO_X Reduction Technology for Natural Gas Industry Prime Movers*. Special Report, August 1990. Prepared by Carlo Castaldini, Acurex Corp., for GRI. Pp. 2, 10, and 11.

43. GRI-94/0329. *Retrofit NO_X Control Technologies for Natural Gas Prime Movers*. Final Report, March 1994. Prepared by Acurex Corp. for GRI. Pp. 4-17, 4-20, A-39 – A-44.

44. GRI-94/0470. *Low-Cost NO_X Controls for Pipeline Engines, Ingersoll-Rand/4-Cycle*. December 1994.
GRI-95/0102. *Low-Cost NO_X Controls for Pipeline Engines, Cooper-Bessemer/GMV Series*. March 1995.
GRI-95/0103. *Low-Cost NO_X Controls for Pipeline Engines, Clark™/2-Cycle*. March 1995.

45. Manufacturers of Emission Controls Association. *Emission Control Technology for Stationary Internal Combustion Engines*. Status Report, July 1997. Pg. 4.

46. Interstate Natural Gas Association of America. *IC Engine OTAG Questions*. February 17, 1999. Pp. 6-9.

47. EC/R Incorporated. Final Site Visit Reports for Southern California Gas Company Facilities. Prepared for Ozone Policy and Strategies Group, U. S. Environmental Protection Agency, Research Triangle Park, NC. June 26, 2000. 12pp.

48. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Aliso Canyon Station. December 16, 1999. 26pp.

49. *CAPCOA/ARB Proposed Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Internal Combustion Engines*. State of California Air Resources Board, December 3, 1997. Pp. 6, 7, 25, 26, 28, 29.

50. W. Neuffer, U. S. EPA. Summary of Information Provided by Engine Manufacturers on Low Emission Combustion.

51. Telecon. R. Faulkner, Diesel Supply Company, with S. Edgerton, EC/R. April 6, 2000.

52. *CAPCOA/ARB Proposed Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Internal Combustion Engines*. State of California Air Resources Board, December 3, 1997. Pg. 58 (Citing "Phase III Rule Effectiveness Study, VCAPCD Rule 79.4, Stationary Internal Combustion Engines," October 1, 1994.)

53. Manufacturers of Emission Controls Association. *Available Technology Options for Short-Term VOC, NO_X, CO, PM and Toxic Emission Reductions*. Slides from a presentation. November 1999.

54. Telecon. W. Chu, Johnson Matthey, with S. Edgerton, EC/R. Selective catalytic reduction systems. February 29, 2000.

55. Facsimile. M. Grove, Intermacom A.G., to Bolstrum, EPA/Region 3. Technology assessment on NO_X reduction for 2-cycle gas engines at gas pipeline compressor stations. December 12, 1998.

56. Telecon. W. Chu, Johnson Matthey, with S. Edgerton, EC/R. Selective catalytic reduction systems. February 29, 2000.

57. E-mail message. R. Mueller, Siemens Westinghouse, to B. Richani, Alpha-Gamma. Information on engines controlled with SCR at Buckeye Pipeline in New Jersey. January 22, 1999.

58. Institute of Clean Air Companies, SCR Committee. *Selective Catalytic Reduction (SCR) Control of NO_X Emissions*. White Paper. November 1997. Pg. 33.

59. Facsimile. M. Grove, Intermacom A.G., to Bolstrum, EPA/Region 3. Technology assessment on NO_X reduction for 2-cycle gas engines at gas pipeline compressor stations. December 12, 1998.

60. Interstate Natural Gas Association of America. *Technical Feasibility of SCR Control of NO_X Emissions from Lean-Burn Load Following Natural Gas Engines*. Overheads. December 15, 1998. Pp. 13-16.

61. EC/R Incorporated. Site visit report for Southern California Gas Company's Aliso Canyon Station in Northridge, California. June 20, 2000. Pp. 5 and 6.

62. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Aliso Canyon Station Unit K-6 and Montebello Station Unit 9. Southern California Gas Company, CA. December 16, 1999. 26pp.

63. Memo from S. Walsh, EC/R Inc., to Project File. Explanation of NO_X Emissions Data Analysis. July 27, 2000.

64. Donald R. Price, "NO_X Control Options for Gas-Fired Stationary Internal Combustion Engines." Prepared for A&WMA Annual Meeting, June 1998.

65. Memo from D. Strochak, NJ DEP, to M. Klein, NJ DEP. Test results for Sycom Enterprises, Linden Pumping Facility. October 16, 1997.

66. E-mail message. R. Mueller, Siemens Westinghouse, to B. Richani, Alpha-Gamma. Information on engines controlled with SCR at Buckeye Pipeline in New Jersey. January 22, 1999.

67. Telecon. W. Chu, Johnson Matthey, with S. Edgerton, EC/R. Selective catalytic reduction systems. February 29, 2000.

68. Manufacturers of Emission Controls Association. *Available Technology Options for Short-Term VOC, NO_X, CO, PM and Toxic Emission Reductions*. Slides from a presentation. November 1999.

69. Telecon. W. Chu, Johnson Matthey, with S. Edgerton, EC/R. Selective catalytic reduction systems. February 29, 2000.

70. R. Mueller, et al., Siemens Power Corporation. *SINOx SCR Systems–An Experience Report on Reducing Emissions of Criteria Pollutants of Stationary and Mobile Sources*. ICAC Forum '98.

71. Siemens Power Corp. *SINOx™ (SCR) System Fact Sheets*. July 1997.

72. Institute of Clean Air Companies, SCR Committee. *Selective Catalytic Reduction (SCR) Control of NO_X Emissions*. White Paper. November 1997. Pg. 33.

73. Manufacturers of Emission Controls Association. *Urea SCR for Stationary IC Engines*. Slides from a presentation to the NESCAUM Stationary Source and Permits Committee. October 6, 1999.

74. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Low Emission Combustion Engines. Southern California Gas Company, CA. December 17, 1999. 2pp.

75. EC/R Incorporated. Site visit report for Southern California Gas Company's Goleta Station in Goleta, CA. June 20, 2000. Pg. 13.

76. EC/R Incorporated. Site visit report for Oxnard Wastewater Treatment Plant in Oxnard, California. July 2000.

77. EC/R Incorporated. Site visit report for South Coast Area Transit in Oxnard, California. June 26, 2000.

78. EC/R Incorporated. Site visit report for Southern California Gas Company's Goleta Station in Goleta, California. June 20, 2000. Pp. 13 and 14.

79. Memo from S. Walsh, EC/R Inc., to Project File. Explanation of NO_X Emissions Data Analysis. July 27, 2000.

80. Memo from S. Walsh, EC/R Inc., to Project File. Explanation of NO_X Emissions Data Analysis. July 27, 2000.

81. Memo from S. Walsh, EC/R Inc., to Project File. Explanation of NO_X Emissions Data Analysis. July 27, 2000.

82. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Honor Rancho Station. Southern California Gas Company,

Honor Rancho Station, CA. December 16, 1999. 16pp.

83. *CAPCOA/ARB Proposed Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Internal Combustion Engines*. State of California Air Resources Board, December 3, 1997. Pp. 6, 7, 22-24, 27, 28.

84. Manufacturers of Emission Controls Association. *Emission Control Technology for Stationary Internal Combustion Engines*. Status Report, July 1997. Pg. 7.

85. EC/R Incorporated. Site visit reports for Southern California Gas Company's Aliso Canyon Station in Northridge, California, and Honor Ranch Station in Santa Clarita, California. June 20, 2000. Pp. 6, 9 and Attachments 1 and 2.

86. Southern California Gas Company. Facsimile from G. Arney to S. Edgerton, EC/R Incorporated. Information on Honor Rancho Station. Southern California Gas Company, Honor Rancho Station, CA. December 16, 1999. 16pp.

87. Memo from S. Walsh, EC/R Inc., to Project File. Explanation of NO_X Emissions Data Analysis. July 27, 2000.

88. Memo from S. Walsh, EC/R Inc., to Project File. Explanation of NO_X Emissions Data Analysis. July 27, 2000.

89. GRI-94/0329. *Retrofit NO_X Control Technologies for Natural Gas Prime Movers*. Final Report, March 1994. Prepared by Acurex Corp. for GRI.

90. GRI-94/0329. *Retrofit NO_X Control Technologies for Natural Gas Prime Movers*. Final Report, March 1994. Prepared by Acurex Corp. for GRI.

91. *Oil & Gas Journal*. "CNG installing NO_X-reduction system in compressor stations." September 26, 1994. Pg. 91.

92. National Center for Environmental Research, U. S. EPA Office of Research and Development. "ENOX Technologies, Inc." http://es.epa.gov/ncerqa/sbir/enox.html.

93. National Center for Environmental Research, U. S. EPA Office of Research and Development. "1994 Phase II Abstracts: Plasma Ignition Retard for NO(x) Reductions." http://es.epa.gov/ncerqa_abstracts/sbir/94/topics43.html.

94. Rhode Island Department of Environmental Management. Letter and attachments from D. McVay to D. Grano, U. S. EPA. April 1999.

95. Reyes, Boris and Timothy Cutshaw, Goal Line Environmental Technologies. "SCONOx® Catalytic Absorption System." Dec 8, 1998.

96. Press Release. "ABB Alstom Power to supply groundbreaking SCONOx® technology." Knoxville, TN. December 1, 1999.

97. Goal Line Environmental Technologies. "SCONOx® IN-N for natural gas i.c. engines for NOx, CO and VOC destruction." website. www.glet.com/pr_sconox_icn_info.htm.

98. Goal Line Environmental Technology News. "Texas Instruments Purchases SCONOx® IC-N for 3 IC Engines." Jan 2000. Vol 2, Issue 1.

99. Goal Line Environmental Technology News. "Cummins Engine Co. Tests SCONOx® for Diesel IC Engines." Oct 1999. Vol 1, Issue 3.

100. Goal Line Environmental Technology News. "Cummins Engine Co. Tests SCONOx® for Diesel IC Engines." Oct 1999. Vol 1, Issue 3.

101. NOxTech Inc. "NOxTech® Technology." website. www.noxtechinc.com/products.htm.

102. NOxTech Inc. Letter and attachments from E. Cazzola to Mary Jo Krolewsky, U. S. EPA Acid Rain Division. April 12, 1999.

103. NOxTech Inc. Letter and attachments from E. Cazzola to Mary Jo Krolewsky, U. S. EPA Acid Rain Division. April 12, 1999.

104. Telecon. C. Fletcher, Enginuity, Inc., with S. Edgerton, EC/R Inc. Information on low-emission combustion and high-pressure fuel injection. April 6, 2000

105. EC/R Incorporated. Site visit reports for Southern California Gas Company's Aliso Canyon Station in Northridge, California, and Honor Ranch Station in Santa Clarita, California. June 20, 2000. Pg. 10.

106. Telecon. R. Faulkner, Diesel Supply Company, with S. Edgerton, EC/R. July 21, 2000.

5.0 CONTROL COSTS

This chapter presents information on the costs associated with nitrogen oxides (NO_X) emission controls for stationary reciprocating internal combustion (IC) engines. The primary emphasis is on low-emission combustion (LEC) control for lean-burn, spark-ignited (SI) engines, for which an updated cost analysis is included in Section 5.1. Some cost data on modern selective catalytic reduction (SCR) systems are presented Section 5.2. Section 5.3 provides the references for this chapter.

5.1 COSTS FOR LEC NO_X CONTROL OF LEAN-BURN SI ENGINES

A primary emphasis of this report is to update the information on LEC technology for lean-burn SI engines, including costs. There are two reasons for this emphasis. First, many of the IC engines that will be affected by the NO_X State implementation plan (SIP) call in the Eastern United States are lean-burn SI engines. Second, developments in LEC technology have brought retrofit costs down in recent years. Accordingly, capital and annual costs have been reevaluated, as has cost effectiveness. In general, this cost analysis follows the methodology used in *Alternative Control Techniques Document–NO_X Emissions from Stationary Reciprocating Internal Combustion Engines* (the 1993 ACT document), which is based on the *OAQPS Control Cost Manual*.[1, 2] Deviations from that methodology are pointed out in the material below.

This section presents costs in terms of both 1990 and 1997 dollars. Costs in terms of 1990 dollars have been used for many past analyses produced by the U. S. Environmental Protection Agency's Office of Air Quality Planning and Standards (OAQPS), including the cost analysis for the NO_X SIP call affecting the Eastern United States. In recent years, a number of regulatory analyses prepared by OAQPS have been conducted in terms of 1997 dollars. To facilitate comparison with other analyses, this report presents both.

5.1.1 Capital Costs

Section 5.1.1.1 below discusses the methodology used to determine representative purchased equipment costs (PEC) for LEC retrofits. Section 5.1.1.2 presents the methodology for determining total capital investment (TCI), which includes expenses incurred by the facility in addition to the PEC. Section 5.1.1.3 presents additional cost data and a discussion of how site-specific and engine-specific factors influence costs.

5.1.1.1 Purchased Equipment Costs. One engine manufacturer and one third-party vendor provided actual installed costs for recent LEC retrofits in 1999 dollars.[3, 4] The cost data include costs for low-speed and medium-speed engines. The costs provided by the vendors are believed to represent the installed costs of all equipment related to the LEC retrofit, including any equipment required for increased air flows (e.g., inlet air filtration ductwork, exhaust silencers and ductwork, and aerial coolers). For this reason we have not inflated this hardware cost by a factor of 30 percent as was done for the LEC analysis in the 1993 ACT document.[5]

To conform to the 1993 ACT document analysis, this report assumes that the vendors' installed costs do not include such items as the purchaser's engineering and project management costs, field connections, painting, and training. (The third party vendor's cost data included a number of such items, but costs were aggregated in such a way that these items could not be backed out.) Accordingly, we have treated the vendor cost data as the purchased equipment costs (PEC).

After adding in the cost of an electronic air-to-fuel (A/F) ratio controller, the vendors' cost data were aggregated and plotted against horsepower, and a linear regression was carried out. Figure 5-1 presents the results. As can be seen from the figure, the data are reasonably linear (R-square value of 0.78). There is no sign of the pronounced divergence between costs for low-speed and medium-speed engines presented in the 1993 ACT document. In addition, no one contacted during the preparation of this report indicated that LEC costs differ substantially between low-speed and medium-speed engines. Accordingly, this report addresses LEC costs for all lean-burn SI engines together, without the subdivisions used in the 1993 ACT document. Based on the regression analysis, PEC ranges from $171,000 for a 1,000 brake horsepower (bhp) engine to $444,000 for an 8,000 bhp engine.

5.1.1.2 Total Capital Investment. To account for costs incurred by the facility beyond the PEC, we followed the 1993 ACT document methodology in applying the following cost elements: (1) direct installation–25 percent of PEC, (2) indirect installation–20 percent of PEC, (3) contingency–20 percent of PEC, (4) sales tax–3 percent of PEC, and (5) freight–5 percent of PEC. To calculate TCI, we summed PEC and these five cost elements. Figures 5-2a and 5-2b present the results in 1990 dollars and 1997 dollars, respectively. To de-escalate the LEC equipment costs from 1999 dollars to 1990 and 1997 dollars, the *Chemical Engineering* plant cost indices for each year were used. See Chapter 2, Tables 2-2a and 2-2b for a summary of TCI values for selected engine sizes in 1990 dollars and 1997 dollars, respectively.

5.1.1.3 Discussion of Capital Costs. The current capital cost of LEC retrofits was discussed with representatives of one natural gas supply company during site visits and follow-up contacts. The company has a current estimate for a third-party retrofit of a Clark Model HSRA, 2-stroke, 1,000 bhp, 8-cylinder engine at a pipeline station. The estimate for the total capital investment for this project, which would use screw-in precombustion chambers, is $710,000, including $570,000 to be paid to the LEC vendor and $140,000 in in-house expenses. The estimate includes $93,000 for an oxidation catalyst to reduce carbon monoxide emissions, as will be required in this Southern California air pollution control district if carbon monoxide emissions

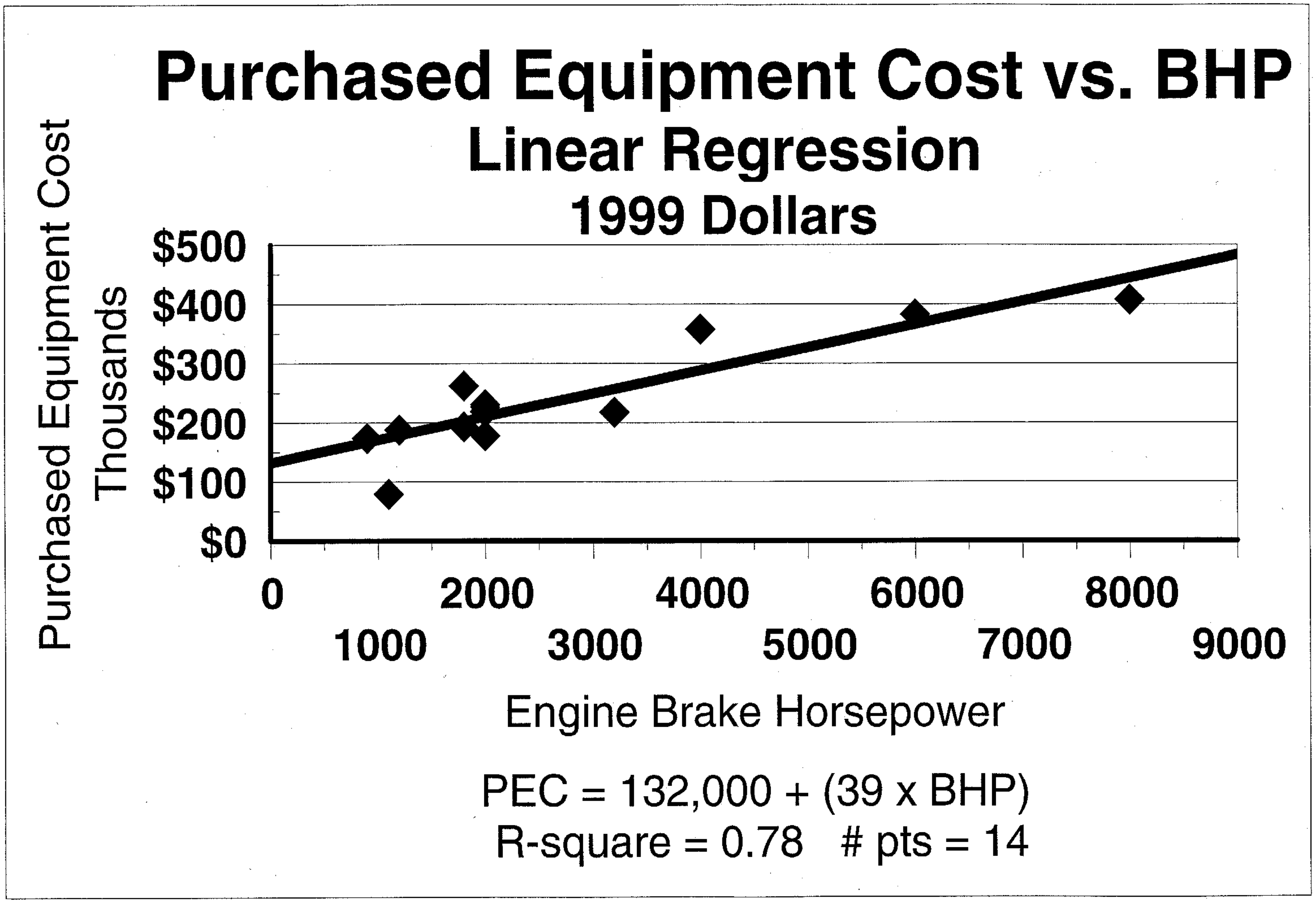

Figure 5-1. Purchased equipment cost for LEC retrofit versus rated brake horsepower.

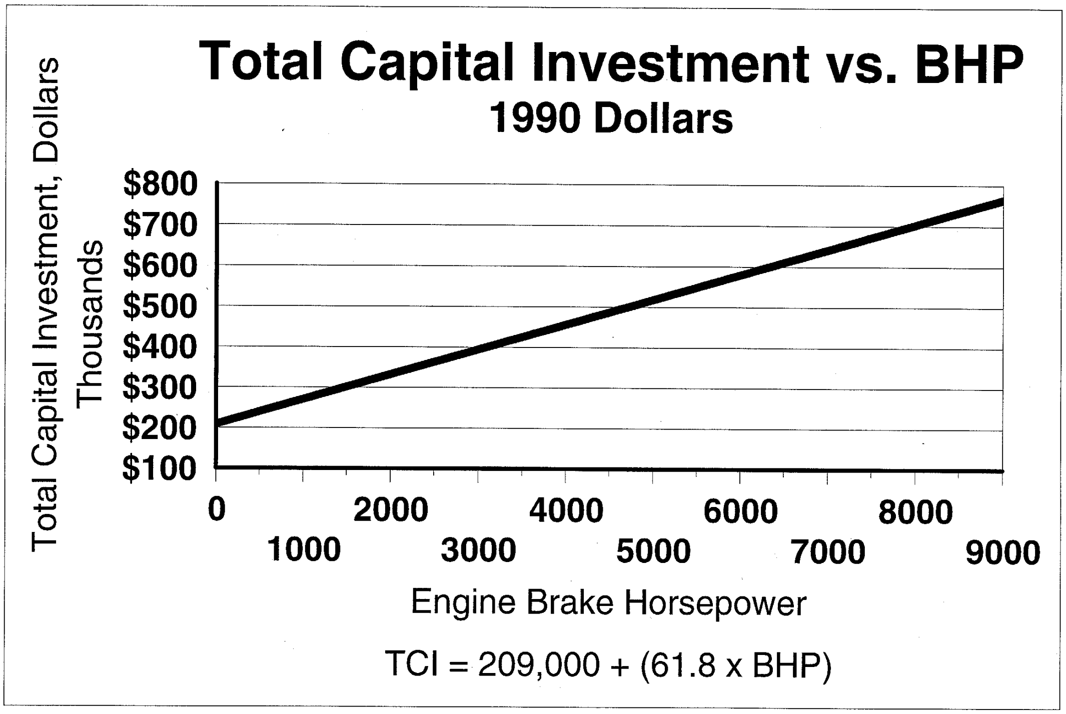

Figure 5-2a. Total capital investment for LEC retrofit (1990 Dollars) versus rated brake horsepower.

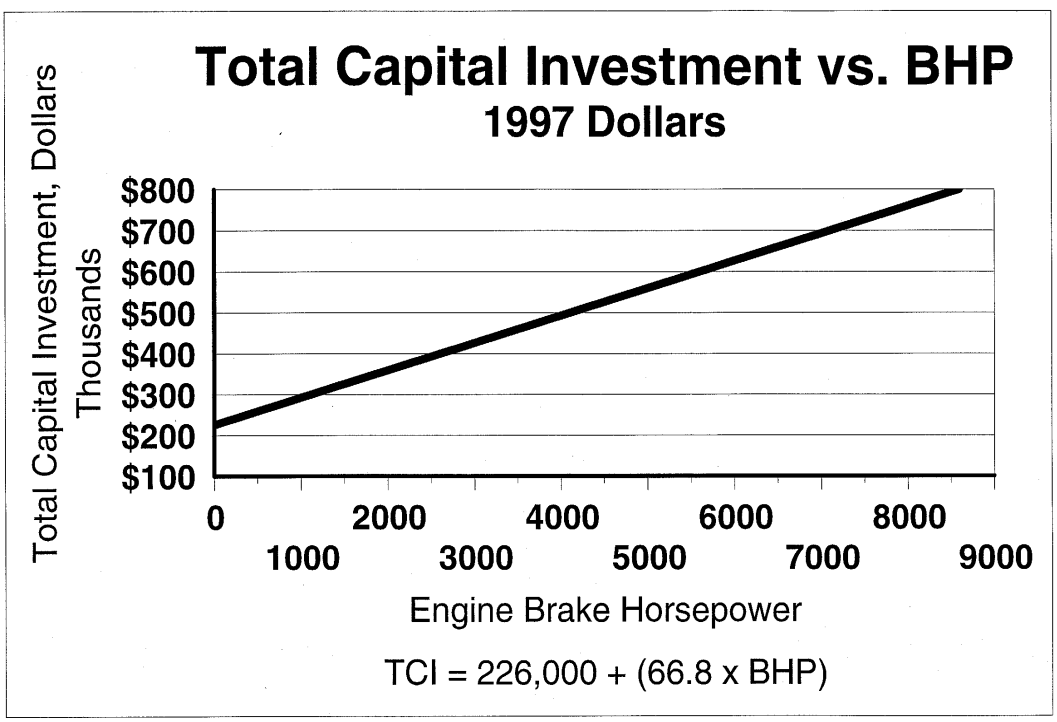

Figure 5-2b. Total capital investment for LEC retrofit (1997 Dollars) versus rated brake horsepower.

increase as a result of the retrofit. In addition to the oxidation catalyst itself, the $93,000 includes the cost of engineering, structural support, instrumentation, and exhaust piping changes. Of the $140,000 in in-house expenses, about 70 percent is for the labor required for engineering, construction coordinating, testing, permitting, etc. About 20 percent of the in-house expenses is for construction work (foundations, conduit, electric power) that was outside the scope of the LEC vendor. The remaining 10 percent is for the cost of the permit and other expenses.

Representatives of the company estimated that an LEC retrofit by the original equipment manufacturer (OEM) of a 2,000 bhp engine like the Ingersoll-Rand Model KVS engines at their facilities would cost approximately $1 million today. This estimate was based on the quote for the Clark engine retrofit discussed above, scaled up to account for the fact that the KVS engines have four more cylinders and would require a much larger turbocharger. In addition, the OEM retrofit would involve replacing the cylinder heads, rather than the use of screw-in precombustion chambers. However, the largest single component of the cost would be the new turbocharger and intercooler. For example, they noted that the current price for the turbochargers on some 5,500 bhp Delaval engines they had retrofitted with LEC is $350,000 apiece.

The company representatives indicated that LEC vendors typically state that retrofits cost $200,000 to $300,000, which includes $200,000 paid to the vendor and $100,000 in other costs incurred by the facility. This company has accomplished LEC retrofits at about this cost, but only when all conditions were right, including an existing turbocharger with adequate capacity and use of screw-in precombustion chambers. These representatives indicated that LEC retrofit costs at the levels discussed in the previous paragraphs are more typical because LEC vendors' quotes do not include all the options that the engine operator may feel are necessary. Site-specific situations such as safety concerns, limited room for the turbocharger, out-of-the-ordinary permit conditions, unmanned operation, company procedures, construction schedule restrictions, warranty requirements, more stringent acceptance testing, and so forth can have a great impact on costs. Because the engine operator is liable if the engine fails to meet the applicable NO_X emission limit, the operator needs a good specification and contract to hold the LEC vendor accountable in the event of a violation.[6, 7, 8]

These costs are well in excess of the costs predicted by Figure 5-2b, which would be about $290,000 for a 1,000 bhp engine and $360,000 for a 2,000 bhp engine. The amounts estimated by these company representatives are over twice as much.

There is a large divergence between the information from LEC retrofit vendors and this information from company representatives. One of the recently-retrofitted engines included in the cost information provided by the third-party LEC retrofit vendor is an Ingersoll-Rand Model KVS412, 2,000 bhp engine. The retrofit included replacing the engine's turbocharger and cleaning the intercooler for reuse. The cost of the retrofit (i.e., the amount paid to the vendor) was about $218,000. Adding $8,000 for an electronic A/F ratio controller and applying the factors for installation, etc. discussed in Section 5.1.1.2 above would bring the TCI to about $390,000.

One explanation for the discrepancy between this estimate and the company's estimate of $1 million for an OEM retrofit was offered by the third-party vendor. This vendor indicated that conventional OEM retrofits have high costs because they involve a nearly complete make-over of the engine. This involves replacement of many engine components in addition to the cylinder heads, including cylinder sleeves, pistons, the exhaust manifold, etc. As an example, the third-party vendor noted that one client had several identical Clark Model TLA-6 2,000 bhp engines retrofitted with LEC. One engine was retrofitted by the OEM at a cost of $1.1 million. The remaining six engines were retrofitted by the third-party vendor at a cost of $205,000 each. This vendor also indicated that the cost of some OEM retrofits has come down. In cases where the engine owner does not wish to purchase the full engine make-over, the OEM may offer less extensive modifications. These retrofits may include screw-in precombustion chambers manufactured by a third-party vendor.[9]

The third-party vendor also noted that the cost of an LEC retrofit is very dependent on the particular engine being serviced. Many engines have been upgraded and modernized over time with such improvements as electronic ignition systems. However, others have not, and such engines require these additional upgrades at the time of the LEC retrofit. In some cases, other atypical costs may be incurred, such as foundation improvements to bear the weight of added equipment.[10] Foundation requirements appear to be a factor in the case of the relatively costly Clark Model HSRA retrofit mentioned above. In addition, the cost of an oxidation catalyst is included in the costs provided by the company. It is not appropriate to include this cost in a nationwide cost analysis because it is specific to the Southern California area where the company is located.

In light of the discussion above, the cost analysis in this report was conducted based on the regression curves derived from LEC retrofit vendor data. These cost data represent the actual costs for recent LEC retrofits and are believed to be typical. However, in some cases, costs may be higher due to site-specific and/or engine-specific factors.

5.1.2 Annual Costs

This report closely follows the 1993 ACT document methodology for calculating annual costs, including the following cost elements:

- Maintenance: labor and materials calculated as 10 percent of PEC. (Based on available information, this factor is high for LEC. The factor was retained in the interests of conservatism and consistency with the 1993 ACT document.)

- Overhead: 60 percent of maintenance costs.

- Fuel savings: 1 percent of annual fuel cost, based on the average 1998 cost of natural gas to industrial users. This is consistent with the ACT document and appears conservatively representative. Other information indicates that the effect has ranged from a fuel penalty of 2 or 3 percent to a fuel savings of up to 10 percent.

- Taxes, insurance, and administration: 4 percent of TCI.

- Annual compliance test: $3,270. (Based on the value of $2,440 and escalation methodology [5 percent per year] used in the 1993 ACT document.)

- Capital recovery factor: 0.1098. (Based on 15-year equipment life and 7 percent interest rate.)

Annual costs were calculated by summing these cost elements based on 7,000 hours of operation annually. (Capacity utilization affects annual costs only in the fuel credit, which is based on annual operating hours, brake horsepower, and heat rate.) Figures 5-3a and 5-3b show the results in 1990 and 1997 dollars, respectively. See Chapter 2, Tables 2-2a and 2-2b for a summary of annual costs for selected engine sizes in 1990 dollars and 1997 dollars, respectively.

The 1993 ACT document primarily used 8,000 hours of operation in its calculations, but also showed the effect of some different levels of capacity utilization. This report uses 7,000 hours per year based on information obtained for IC engines used in the natural gas transmission and storage industry.

The natural gas transmission and storage industry accounts for a significant portion of the larger SI engines in the United States. A 1994 report prepared for the Gas Research Institute (GRI) states that 7,000 hours per year (80 percent capacity utilization) is representative of engines in natural gas transmission service. That report indicates that engines in natural gas storage service are typically smaller and operate at capacity utilizations in the range of 25 to 40 percent.[11]

The data base of large IC engines compiled by the Ozone Transport Assessment Group (OTAG) indicates a higher capacity utilization. This data base includes engines in the 22 Eastern States with average daily NO_X emissions of 1 ton or more during the ozone season (May through September).[12] Based on an analysis of the seasonal throughput and operating hours per day, days per week, and weeks per year listed in the data base for these engines, they average about 93 percent capacity utilization during the ozone season. On an annual basis, this corresponds to about 8,150 hours per year.

A data base of IC engines also was compiled for the Industrial Combustion Coordinated Rulemaking (ICCR) effort. This is a nationwide data base. The IC engines in this data base with the Standard Industrial Classification (SIC) code for natural gas transmission and storage (SIC code 4922) average about 6,900 operating hours per year.[13]

One source indicated that capacity utilization might be lower, at least for larger engines. In comments on the final NO_X SIP call, the Interstate Natural Gas Association of America (INGAA) indicated that IC engines with horsepower greater than or equal to 4,000 bhp at natural gas transmission facilities in the OTAG States average less that 25 percent capacity usage during the 2nd and 3rd quarters, which encompass the ozone season. These data are based on a survey of the natural gas industry conducted by the industry.[14]

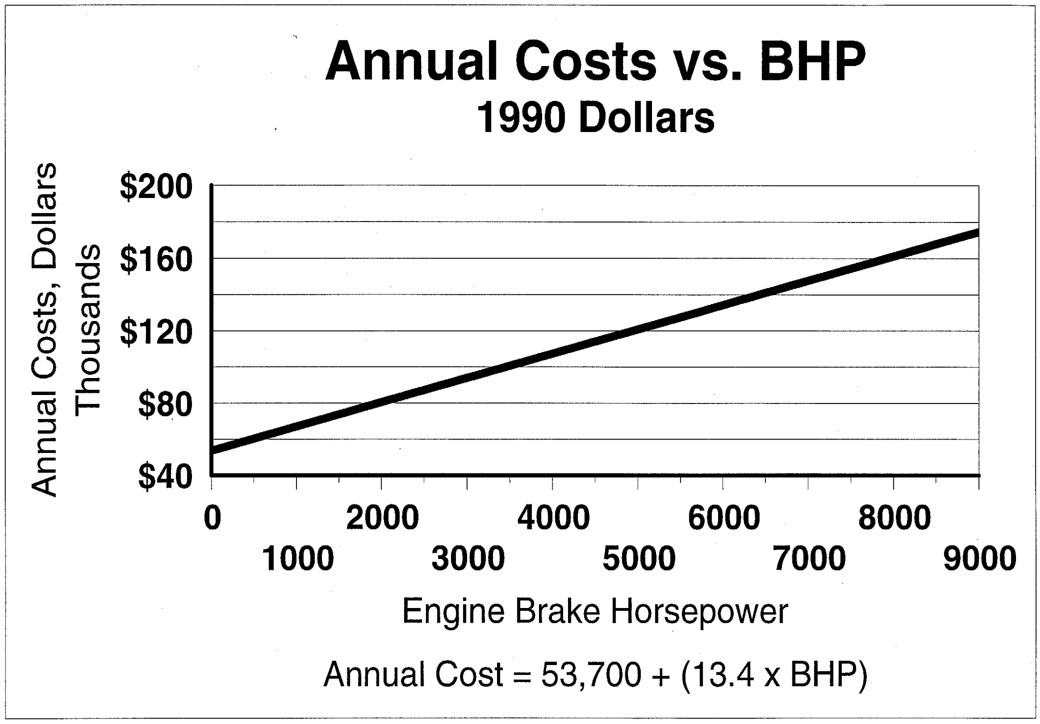

Figure 5-3a. Annual costs for LEC retrofit (1990 Dollars) versus rated brake horsepower.

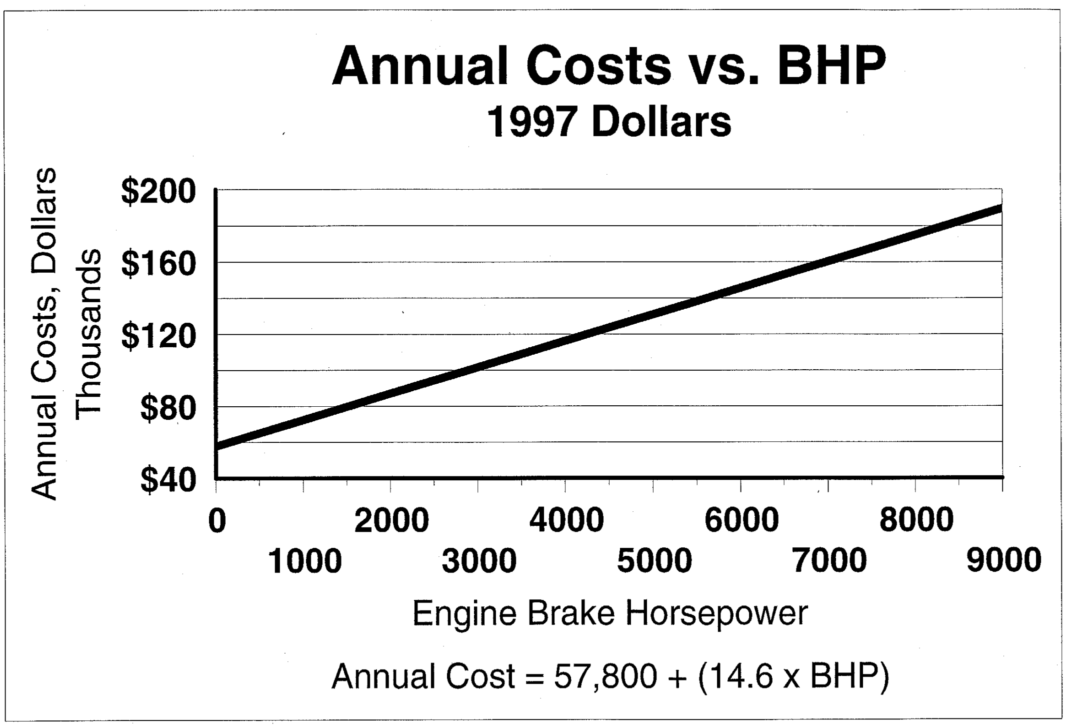

Figure 5-3b. Annual costs for LEC retrofit (1997 Dollars) versus rated brake horsepower.

Based on all this information, 7,000 hours per year is a representative value for IC engines used in the natural gas transmission and storage industry. Because this industry represents a significant fraction of all SI engines likely to come under NO_X regulations, it is reasonable to use this value for the entire population of SI engines, as well.

5.1.3 Cost Effectiveness

This report closely follows the 1993 ACT document methodology for calculating cost effectiveness on an annual basis. In addition, cost effectiveness based only on the ozone season was calculated.

On an annual basis, cost effectiveness is determined for an engine by calculating the tons of NO_X emissions reduced through the use of the control technique, and dividing this quantity into the annual cost. The results of this analysis for lean-burn SI engines appear in Figures 5-4a and 5-4b for 1990 dollars and 1997 dollars, respectively. These figures show cost effectiveness below $500 per ton of NO_X reduced for all engines larger than 2,000 bhp.

For the ozone season, a similar approach was used. However, in this case the NO_X emission reduction was calculated for the 5 months of the ozone season. This value was divided into the total annual costs to determine cost effectiveness for the ozone season. The entire annual cost was used because LEC technology is integral to the engine and must be operated and maintained throughout the year. Figures 5-5a and 5-5b present the results of this analysis in 1990 dollars and 1997 dollars, respectively. These figures show cost effectiveness below $1,000 per ton for all engines larger than about 2,000 bhp, falling to $500 per ton for engines larger than about 5,000 bhp. See Chapter 2, Tables 2-2a and 2-2b for a summary of annual and ozone season cost-effectiveness values for selected engine sizes in 1990 dollars and 1997 dollars, respectively.

The NO_X emission reductions used in the annual cost effectiveness calculations were based on uncontrolled emissions of 16.8 grams per brake horsepower hour (g/bhp-hr), controlled emissions of 2.0 g/bhp-hr, and 7,000 operating hours. For the ozone season cost effectiveness, the NO_X emission reduction was prorated to the 5 months of the ozone season. The rationale for these uncontrolled and controlled emissions values appears in Chapters 3 and 4, respectively. As discussed in Section 5.1.2, this capacity utilization value is believed to be representative based on available information.

Some other sources also have estimated the cost effectiveness of LEC. A 1990 GRI report estimated cost effectiveness at about $500 to $700 per ton of NO_X reduced. These calculations included a significant cost savings for improved engine performance (increased power and better fuel efficiency).[15] Another GRI report published in 1994 included LEC cost analyses for three engines of 1,100 bhp, 1,800 bhp, and 2,000 bhp. The cost effectiveness values for these engines were calculated to be about $1,700 to $1,800 per ton. These values exceed those of this report’s analysis because the GRI report estimated higher capital costs and smaller NO_X emission percent reductions (80 percent). That report was prepared before LEC technology was simplified and improved in the later 1990's.[16]

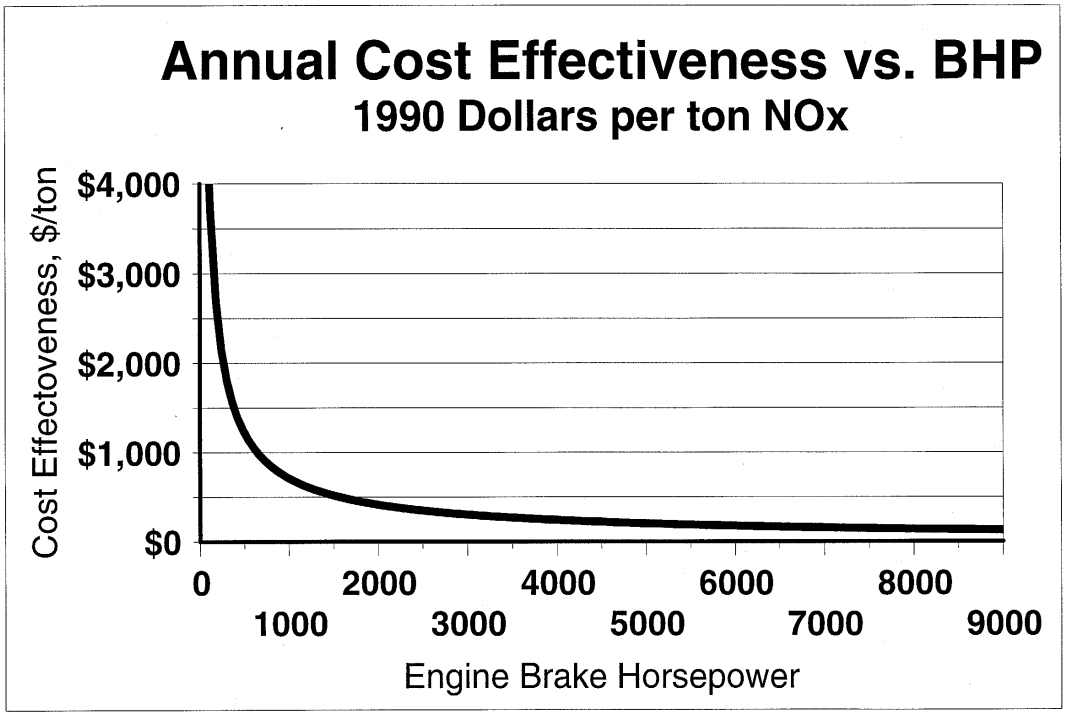

Figure 5-4a. Annual cost effectiveness of LEC retrofit (1990 Dollars) versus rated brake horsepower.

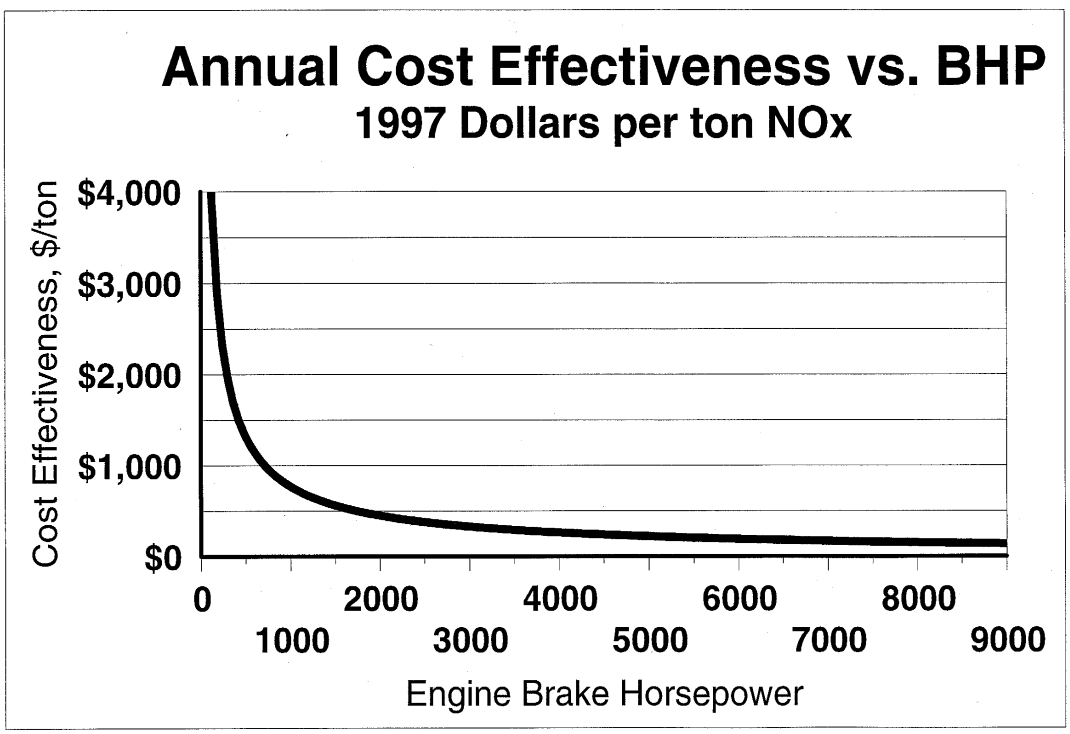

Figure 5-4b. Annual cost effectiveness of LEC retrofit (1997 Dollars) versus rated brake horsepower.

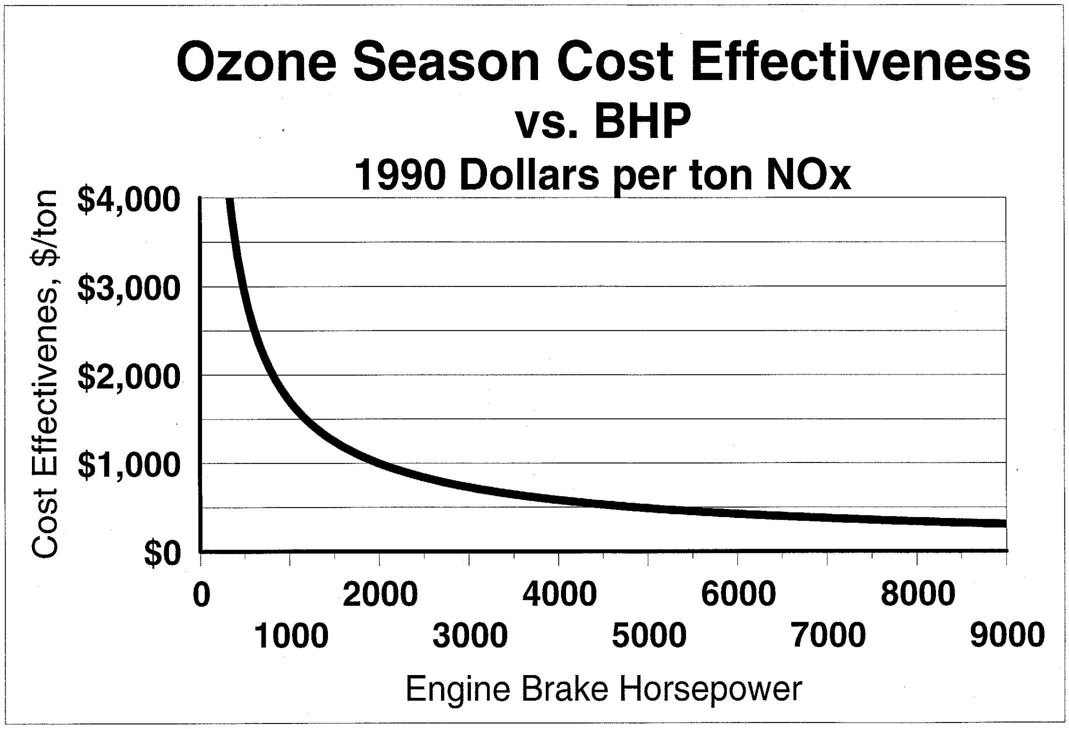

Figure 5-5a. Ozone season cost effectiveness of LEC retrofit (1990 Dollars) versus rated brake horsepower.

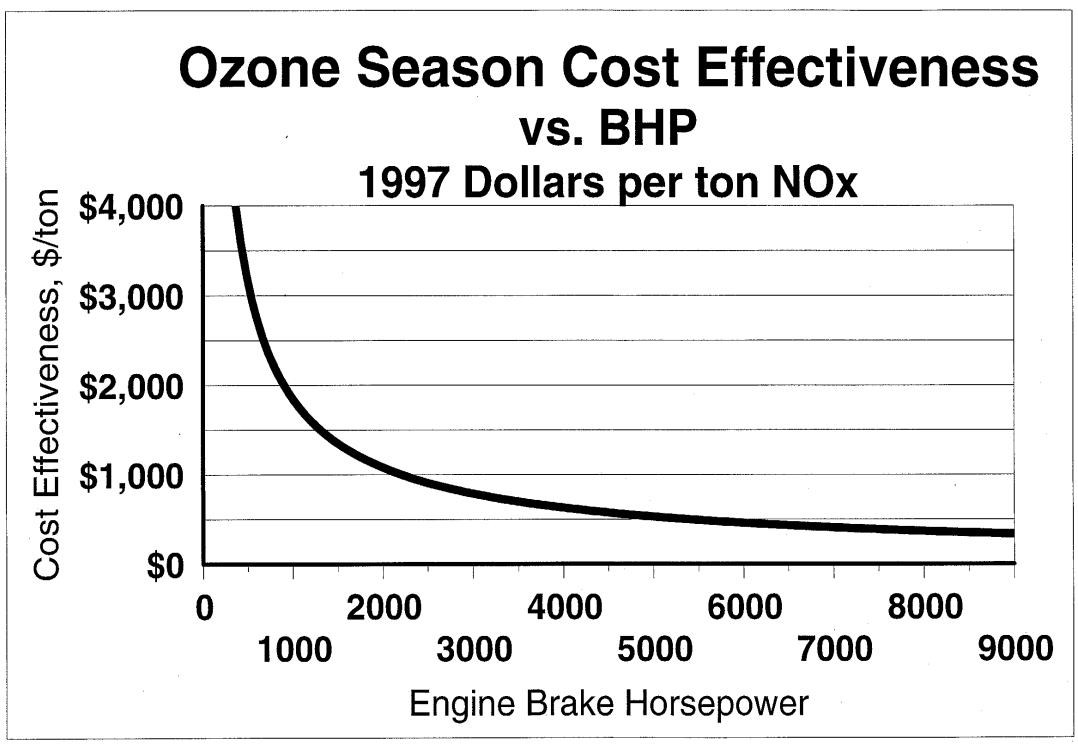

Figure 5-5b. Ozone season cost effectiveness of LEC retrofit (1990 Dollars) versus rated brake horsepower.

A 1997 proposed determination of reasonable available control technology (RACT) and best available retrofit technology (BARCT) prepared by the California Air Resources Board (CARB) also includes some cost effectiveness estimates. This document reproduces findings from a 1991 Santa Barbara County Air Pollution Control District (SBCAPCD) staff paper that indicate that LEC retrofits have a cost effectiveness of $7,400 per ton for 500 bhp to 1,100 bhp engines. The document also includes recalculated cost effectiveness based on the SBCAPCD data and 1996 LEC vendor prices. The updated cost effectiveness is $1,300 to $2,000 per ton for 300 bhp to 500 bhp engines.[17] These figures are higher than this report's analysis because SBCAPCD used a much lower capacity utilization, presumably based on actual data from the engines in the district, and included relatively small engines. The combination of low capacity utilization, smaller engines, and old, higher capital costs resulted in the very high cost effectiveness values in the original SBCAPCD analysis.

Data on LEC cost effectiveness also were received from an engine manufacturer that provides OEM retrofit services. This vendor prepared a curve relating annual cost effectiveness to engine horsepower, much like Figures 5-4a and 5-4b. This curve shows cost effectiveness falling to below $500 per ton for engines larger than 500 bhp. These estimated costs are lower than those of this report's analysis because of lower capital cost estimates, based largely on lower direct and indirect installation costs.[18]

A 2000 report prepared by E. H. Pechan & Associates, Inc. for the U. S. Environmental protection Agency (EPA) estimated annual and ozone season cost effectiveness for 2,000 bhp, 4,000 bhp, and 8,000 bhp engines under a variety of scenarios. In most scenarios, costs were based on the LEC retrofit cost information from an engine manufacturer that was also used for the analysis carried out for this report, although one scenario involved costs from the 1993 ACT document. The other scenarios involved variations in the uncontrolled NO_X emission level, the controlled NO_X emission level, or the capacity utilization. For these scenarios, the average annual cost effectiveness varied between $168 per ton and $390 per ton in 1990 dollars. The average ozone season cost effectiveness varied between $404 per ton and $936 per ton in 1990 dollars.

Overall, these other cost analyses are not inconsistent with the analysis in this report. When the reasons for the differences in cost effectiveness values are understood, particularly the reduced cost of modern retrofits, these results are reasonable.

5.1.4 Monitoring Costs

Costs for monitoring are not included in the cost analyses above. For information on the cost of a continuous emissions monitoring system (CEMS) for NO_X, see the *U. S. Environmental Protection Agency's Continuous Emission Monitoring System Cost Model Version 3.0* (available at www.epa.gov/ttn/emc/cem.html).

One natural gas storage facility that was visited for this study operates predictive emissions monitoring systems (PEMS) on some engines. A new type of PEMS the company is beginning to install and certify utilizes a pressure sensor in each cylinder. The sensors cost only

$800 apiece, and are expected to last about 8,000 hours of engine run time. Currently, the company is required to certify the PEMS using the procedures of 40 CFR part 75, subpart E. This requires 800 hours of testing against a certified CEMS or EPA test method, which greatly increases the cost of the PEMS. The company and its PEMS vendor believe that they have demonstrated that good PEMS models can be developed with only a few days of testing.

The company prefers PEMS to CEMS. The equipment is much cheaper, easier to maintain, and more reliable. In addition, the skills required for a PEMS match the skills of the engine personnel. Finally, the PEMS generates data that are useful in determining engine health, unlike a CEMS which only indicates that emissions are high. The company believes that the full cost of a CEMS is greater than indicated by the EPA cost model.[19]

5.2 COSTS FOR SCR

As discussed in Section 4.2, SCR technology is undergoing a change. An analysis of the costs of modern SCR systems was not conducted for this study, but a cost analysis was obtained from an SCR vendor.[20] The costs are presented below.

The vendor calculated costs and cost effectiveness for two situations involving 2,600 bhp natural gas-fired SI engines: (1) three engines each operated 400 hours per year and (2) one engine operated 2,000 hours per year. For the first case, capital costs were calculated at $187,000, including catalyst, urea control, injectors, engine map, startup assistance, reagent tank, and installation. For the second case, with just one engine, these costs totaled $68,000.

Annual costs for the first case totaled $48,200 based on capital recovery (equipment life of 7 years and 10 percent interest rate) and reagent costs. The emission reduction at 90 percent efficiency totaled 27 tons of NO_X . In combination, this results in a cost effectiveness of about $1,800 per ton. Based on the same components (except for an equipment life of only 5 years) annual costs for the second case would total $35,680, the emission reduction would be 45 tons of NO_X, and the cost effectiveness would be under $800 per ton.

The vendor carried out a similar analysis for a 1,000 bhp diesel engine. For an engine operating 200 hours per year, the cost effectiveness was calculated at almost $4,000 per ton. For an engine operating 2,000 hours per year, the cost effectiveness dropped to less than $900 per ton.

These cost and cost effectiveness calculations do not include all the cost elements normally considered by the EPA. For example, no indirect installation costs are included in the capital costs. In addition, the annual costs do not include any operating or maintenance costs.

5.3 REFERENCES FOR CHAPTER 5

1. *Alternative Control Techniques Document–NO_X Emissions from Stationary Reciprocating Internal Combustion Engines*. U. S. Environmental Protection Agency, Research Triangle Park, NC. Publication No. EPA-453/R-93-032. July 1993. http://www.epa.gov/ttncatc1/products.html. (1993 ACT document) Pp. 6-30 - 6-39, 6-56, and 6-57.

2. U. S. Environmental Protection Agency. *OAQPS Control Cost Manual*. Fifth Edition. Office of Air Quality Planning and Standards, Research Triangle Park, NC. Publication No. EPA 453/B-96-001. 42pp.

3. Facsimile from J. Hibbard, Cooper Energy Systems to Bill Neuffer, U.S. EPA. March 15, 1999.

4. Facsimile from R. Faulkner, Diesel Supply Company, to Stephen Edgerton, EC/R Incorporated. April 17, 2000.

5. 1993 ACT document. Pg. 6-33.

6. Facsimile from G. Arney, Southern California Gas Company, to S. Edgerton, EC/R Incorporated. Information on Low Emission Combustion Engines. December 17, 1999. 2pp.

7. EC/R Incorporated. Final Site Visit Reports for Southern California Gas Company Facilities. Prepared for Ozone Policy and Strategies Group, U. S. Environmental Protection Agency, Research Triangle Park, NC. June 26, 2000. 12pp.

8. Facsimile from G. Arney, Southern California Gas Company, to S. Edgerton, EC/R Incorporated. Information on Low Emission Combustion Engines. August 3, 2000. 1p.

9. Telecon. R. Faulkner, Diesel Supply Company, with S. Edgerton, EC/R. Information on LEC retrofits. July 25, 2000.

10. Telecon. R. Faulkner, Diesel Supply Company, with S. Edgerton, EC/R. Information on LEC retrofits. July 25, 2000.

11. GRI-94/0329. *Retrofit NO_X Control Technologies for Natural Gas Prime Movers*. Final Report. March 1994. Prepared by Accurex Environmental Corporation, Mountain View, California.

12. U. S. EPA. OTAG data base of large IC engines. February 2000.

13. U. S. EPA. Data base of IC engines prepared for the Industrial Combustion Coordinated Rulemaking. 1997. http://www.epa.gov/ttn/iccr/engine/icengv4.exe.

14. Letter and attachments from Lisa Beal, INGAA, to Docket No. A-96-56. Comments on the final NO_X SIP call. June 25, 1998. Appendix B.

15. GRI-90/0215. *NO_X Reduction Technology for Natural Gas Industry Prime Movers*. Special Report, August 1990. Prepared by Carlo Castaldini, Acurex Corp., for GRI. Pg. 5.

16. GRI-94/0329. *Retrofit NO_X Control Technologies for Natural Gas Prime Movers*. Final Report. March 1994. Prepared by Accurex Environmental Corporation, Mountain View, California. Pp. A-40, A-42, and A-44.

17. *CAPCOA/ARB Proposed Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Internal Combustion Engines*. State of California Air Resources Board, December 3, 1997. Pp. 43, 45

18. Ajax Superior. Letter and attachments from L. Palmer to W. Neuffer, U. S. EPA. Information on Low Emission Combustion. Cooper Energy Services, Ajax Superior Division, Springfield, OH. March 20, 1999. 86pp. Attachment entitled “Economics of Cleanburn Technology and Conversions.”

19. EC/R Incorporated. Final Site Visit Reports for Southern California Gas Company Facilities. Prepared for Ozone Policy and Strategies Group, U. S. Environmental Protection Agency, Research Triangle Park, NC. June 26, 2000. 12pp.

20. Manufacturers of Emission Controls Association. *Urea SCR for Stationary IC Engines.* Slides from a presentation to the NESCAUM Stationary Source and Permits Committee. October 6, 1999.