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Alternative Control Techniques Document -- NOx Emissions from Stationary Reciprocating Internal Combustion Engines

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Alternative Control Techniques Document-- NO_x Emissions from Stationary Reciprocating Internal Combustion Engines

Emission Standards Division

U. S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, NC 27711
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ALTERNATIVE CONTROL TECHNIQUES DOCUMENTS

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1.0 INTRODUCTION

Congress, in the Clean Air Act Amendments of 1990 (CAAA), amended Title I of the Clean Air Act (CAA) to address ozone nonattainment areas. A new Subpart 2 was added to Part D of Section 103. Section 183(c) of the new Subpart 2 provides that:

> [w]ithin 3 years after the date of the enactment of the CAAA, the Administrator shall issue technical documents which identify alternative controls for all categories of stationary sources of...oxides of nitrogen which emit or have the potential to emit 25 tons per year or more of such air pollutant.

These documents are to be subsequently revised and updated as determined by the Administrator.

Stationary reciprocating engines have been identified as a category that emits more than 25 tons of nitrogen oxide (NO_x) per year. This alternative control techniques (ACT) document provides technical information for use by State and local agencies to develop and implement regulatory programs to control NO_x emissions from stationary reciprocating engines. Additional ACT documents are being developed for other stationary source categories.

Reciprocating engines are used in a broad scope of applications. It must be recognized that the alternative control techniques and the corresponding achievable NO_x emission levels presented in this document may not be applicable for every reciprocating engine application. The size and design of the engine, the operating duty cycle, site conditions, and other site-specific factors must be taken into consideration, and the suitability of an alternative control technique must be determined on a case-by-case basis.

The information in this ACT document was generated through a literature search and from information provided by engine manufacturers, control equipment vendors, engine users, and regulatory agencies. Chapter 2.0 presents a summary of the findings of this study. Chapter 3.0 presents information on engine operation and industry applications. Chapter 4.0 contains a discussion of NO_x formation and uncontrolled NO_x emission factors. Alternative control techniques and achievable controlled emission levels are included in Chapter 5.0. The cost and cost effectiveness of each control technique are presented in Chapter 6.0. Chapter 7.0 describes environmental and energy impacts associated with implementing the NO_x control techniques.

2.0 SUMMARY

This chapter presents a summary of uncontrolled nitrogen oxide (NO_x) emissions factors, NO_x emission control techniques, achievable controlled NO_x emission levels, and the costs and cost effectiveness for NO_x control techniques applied to stationary reciprocating internal combustion (IC) engines. The extent of applicability and the effects of NO_x control techniques on engine operating parameters and carbon monoxide (CO) and hydrocarbon (HC) emissions are also summarized for each control technique.

In this document, emissions are stated in units of grams per horsepower-hour (g/hp-hr), parts per million by volume (ppmv), and pounds per million British thermal units (lb/MMBtu). All emission levels stated in units of ppmv are corrected to 15 percent oxygen (O_2), unless stated otherwise. Emission rates were requested from engine manufacturers in units of g/hp-hr. Published reports and test data often report emission levels in either g/hp-hr or ppmv. Conversion factors presented in Chapter 4 are used throughout this document to convert g/hp-hr to ppmv and vice-versa. Where HC emission levels are not speciated, it is expected that the emission levels presented correspond to nonmethane hydrocarbon (NMHC) levels rather than total hydrocarbon (THC) levels.

Information for both spark-ignition (SI) and compression-ignition (CI) engines are presented for operation on gaseous and oil fuels. Gasoline-fueled engines are not included in this document due to limited stationary applications and available information for these engines.

This document presents information by engine type (i.e., rich-burn SI, lean-burn SI, and diesel and dual-fuel engines). A rich-burn engine is classified as one with an air-to-fuel ratio (A/F) operating range that is near stoichiometric or fuel-rich of stoichiometric and can be adjusted to operate with an exhaust oxygen concentration of 1 percent or less. A lean-burn engine is classified as one with an A/F operating range that is fuel-lean of stoichiometric and cannot be adjusted to operate with an exhaust concentration of less than 1 percent. All naturally aspirated, four-cycle SI engines and some turbocharged, four-cycle SI engines are rich-burn engines. All other engines, including all two-cycle SI engines and all CI engines, are lean-burn engines.

Some control techniques discussed in this document require that additional equipment be installed on the engine or in the engine exhaust. Issues regarding the point of responsibility for potential engine mechanical malfunctions or safety concerns resulting from the use of the control techniques presented are not evaluated in this document.

Section 2.1 presents a summary of uncontrolled NO_x emissions. Section 2.2 presents a summary of the performance and achievable controlled NO_x emissions of each control technique. A summary of the total capital and annual costs and cost effectiveness of each control technique is presented in Section 2.3.

2.1 UNCONTROLLED NO_x EMISSIONS

The operating temperatures and pressures in IC engines produce NO_x emissions. Thermal NO_x is the predominant mechanism by which NO_x is formed in IC engines because most engines burn fuels that contain little or no nitrogen and, therefore, fuel NO_x formation is minimal.

Fuel rates and uncontrolled NO_x emission levels for SI and CI engines were provided by engine manufacturers. These fuel and emission rates were averaged for a range of engines sizes and are presented in Table 2-1. For rich-burn SI engines, average uncontrolled NO_x emission factors range from 13.1 to 16.4 g/hp-hr

TABLE 2-1. AVERAGE HEAT RATES AND UNCONTROLLED NO_x EMISSION FACTORS FOR RECIPROCATING ENGINES

Engine size, hp	No of engines	Average heat rate, Btu/hp-hr[a]	Average NO_x emissions, g/hp-hr[a]	Average NO_x emissions, ppmv @15% O_2[b]	Average NO_x emission factor, lb/MMBtu[c]	Weighted average for each engine type[d]		
						NO_x, g/hp-hr	NO_x, ppmv @15% O_2[b]	NO_x, lb/MMBtu
RICH-BURN SI ENGINES								
0-200	8	8140	13.1	880	3.54	15.8	1060	4.64
201-400	13	7820	16.4	1100	4.62			
401-1000	31	7540	16.3	1090	4.76			
1001-2000	19	7460	16.3	1090	4.81			
2001-4000	10	6780	15.0	1000	4.87			
4001 +	2	6680	14.0	940	4.62			
LEAN-BURN SI ENGINES								
0-400	7	8760	7.9	580	1.99	16.8	1230	5.13
401-1000	17	7660	18.6	1360	5.35			
1001-2000	43	7490	17.8	1300	5.23			
2001-4000	30	7020	17.2	1260	5.40			
4001 +	25	6660	16.5	1200	5.46			
DIESEL ENGINES								
0-200	12	6740	11.2	820	3.66	12.0	880	3.95
201-400	8	6600	11.8	860	3.94			
401-1000	22	6790	13.0	950	4.22			
1001-2000	14	6740	11.4	830	3.73			
2001-4000	6	6710	11.4	830	3.74			
4001 +	6	6200	12.0	880	4.26			
DUAL-FUEL ENGINES								
700-1200	5	6920	10.0	730	3.18	8.5	620	2.72
1201-2000	3	7220	10.7	780	3.26			
2001-4000	5	6810	8.4	610	2.72			
4001 +	4	6150	4.9	360	1.75			

[a]Calculated from figures corresponding to International Standards Organization (ISO) conditions, as provided by engine manufacturers.

[b]Calculated from g/hp-hr figures using the conversion factors from Chapter 4.

[c]lb/MMBtu = (g/hp-hr) x (lb/454g) x (1/Heat Rate) x (1,000,000).

[d]Weighted average is calculated by multiplying the average NO_x emission factor by the number of engines for each engine size and dividing by the total number of engines. For example, for dual-fuel engines, the weighted average is calculated as:

$$[(5 \times 10.0) + (3 \times 10.7) + (5 \times 8.4) + (4 \times 4.9)]/17 = 8.5 \text{ g/hp-hr}$$

(880 to 1,100 ppmv), or 3.54 to 4.87 lb/MMBtu. Lean-burn SI engine average NO_x emission levels range from 7.9 to 18.6 g/hp-hr (580 to 1,360 ppmv), or 1.99 to 5.46 lb/MMBtu. Average NO_x emission levels from diesel engines range from 11.2 to 13.0 g/hp-hr (820 to 950 ppmv), or 3.66 to 4.26 lb/MMBtu. Duel-fuel engine average NO_x emission levels range from 4.9 to 10.7 g/hp-hr (360 to 780 ppmv), or 1.75 to 3.26 lb/MMBtu.

Weighted averages were also calculated for NO_x emission levels from each engine type. These weighted averages show that SI engines have the highest NO_x emission rates, at 16.8 and 15.8 g/hp-hr (1,060 and 1,230 ppmv), or 5.13 and 4.64 lb/MMBtu for lean-burn and rich-burn engines, respectively. The weighted average for diesel engines is 12.0 g/hp-hr (880 ppmv), or 3.95 lb/MMBtu. Dual-fuel engines have the lowest weighted NO_x emission rate, at 8.5 g/hp-hr (620 ppmv), or 2.72 lb/MMBtu.

2.2 CONTROL TECHNIQUES AND ACHIEVABLE NO_x EMISSION REDUCTIONS

The control techniques included in this document for each engine type are listed below:

<u>Rich-burn SI engines</u>

A/F adjustment (AF)
Ignition timing retard (IR)
A/F adjustment plus ignition timing retard
Prestratified charge (PSC®)
Nonselective catalytic reduction (NSCR)
Low-emission combustion (L-E)

<u>Lean-burn SI engines</u>

A/F adjustment
Ignition timing retard
A/F adjustment plus ignition timing retard
Selective catalytic reduction (SCR)
Low-emission combustion

<u>Diesel engines</u>

Injection timing retard (IR)
Selective catalytic reduction

<u>Dual-fuel engines</u>

Injection timing retard
Selective catalytic reduction
Low-emission combustion

The performance of each control technique is summarized in this section, including applicability and the extent of application, achievable controlled NO_x emission levels, and the effect on engine performance and CO and HC emissions. Controls that apply to rich-burn SI engines are discussed in

Section 2.2.1; lean-burn SI engines in Section 2.2.2; and diesel and dual-fuel engines in Section 2.2.3. These control techniques are discussed in greater detail in Chapter 5.

2.2.1 Control Techniques for Rich-Burn SI Engines

A summary of the achievable NO_x emission reductions for rich-burn SI engines is presented in Tables 2-2 and 2-3. The effects of these control techniques on other emissions, fuel consumption, and power output are presented in Table 2-4.

2.2.1.1 AF. Adjusting the A/F toward fuel-rich operation reduces the oxygen available to combine with nitrogen, thereby inhibiting NO_x formation. The low-oxygen environment also contributes to incomplete combustion, which results in lower combustion temperatures and, therefore, lower NO_x formation rates. The incomplete combustion also increases CO emissions and, to a lesser extent, HC emissions. Combustion efficiency is also reduced, which increases brake-specific fuel consumption (BSFC). Excessively rich A/F's may result in combustion instability and unacceptable increases in CO emissions.

The A/F can be adjusted on all new or existing rich-burn engines. Sustained NO_x reduction with changes in ambient conditions and engine load, however, is best accomplished with an automatic A/F control system.

The achievable NO_x emission reduction ranges from approximately 10 to 40 percent from uncontrolled levels. Based on an average uncontrolled NO_x emission level of 15.8 g/hp-hr (1,060 ppmv), the expected range of controlled NO_x emissions is from 9.5 to 14.0 g/hp-hr (640 to 940 ppmv). Available data show that the achievable NO_x reduction using AF varies for each engine model and even among engines of the same model, which suggests that engine design and manufacturing tolerances influence the effect of AF on NO_x emission reductions.

2.2.1.2 IR. Ignition timing retard delays initiation of combustion to later in the power cycle, which increases the volume of the combustion chamber and reduces the residence time of the combustion products. This increased volume and reduced residence time offers the potential for reduced NO_x formation.

TABLE 2-2. EXPECTED RANGE OF NO_x EMISSION REDUCTIONS AND CONTROLLED EMISSION LEVELS FOR CONTROL TECHNIQUES APPLIED TO RICH-BURN SI ENGINES (NATURAL GAS FUEL)

Control technique	Average uncontrolled NO_x emission level[a]		Achievable NO_x reduction, %	Expected controlled NO_x emission levels	
	g/hp-hr	ppmv		g/hp-hr	ppmv
AF	15.8	1,060	10 - 40	9.5 - 14.0	640 - 940
IR	15.8	1,060	0 - 40	9.5 - 15.8	640 - 1,060
AF + IR	15.8	1,060	10 - 40	9.5 - 14.0	640 - 940
PSC	15.8	1,060	87	2.0[b]	135
NSCR	15.8	1,060	90 - 98[c]	0.3 - 1.6	20 - 110
L-E	15.8	1,060	87	2.0[b]	135

[a]The uncontrolled emission rate shown is a representative average for rich-burn SI engines. The actual uncontrolled emission rate will vary from engine to engine.
[b]Guaranteed controlled NO_x emission level offered by control equipment supplier.
[c]Guaranteed NO_x reduction efficiency offered by catalyst vendors.

TABLE 2-3. POTENTIAL NO_x REDUCTIONS FOR RICH-BURN SI ENGINES (NATURAL GAS FUEL)

RICH-BURN ENGINES						
Engine size, hp	Average uncontrolled NO_x emission level, g/hp-hr[a]	Average uncontrolled NO_x emission level, tons/yr	Potential NOx reduction, tons/yr[b]			
			Parametric adjustments[c]	PSC[d]	NSCR[e]	Low-emission combustion[d]
100	15.8	13.9	1.39 - 5.57	12.2	12.5	12.2
500		69.6	6.96 - 27.8	60.8	62.6	60.8
1,000		139	13.9 - 55.7	122	125	122
1,500		209	20.9 - 83.5	182	188	182
2,000		278	27.8 - 111	243	251	243
3,000		418	41.8 - 167	365	376	365
4,000		557	55.7 - 223	486	501	486
6,000		835	83.5 - 334	730	752	730
8,000		1,110	111 - 445	973	1,000	973

[a]The uncontrolled emission rate shown is a representative average for rich-burn SI engines. The actual uncontrolled emission rate will vary from engine to engine.

[b]Potential NO_x reductions correspond to 8,000 annual operating hours. NO_x reductions for other utilization rates can be estimated by multiplying the value in the table by the actual annual operating hours and dividing by 8,000.

[c]NO_x reductions for parametric adjustments (AF, IR, and AF + IR) correspond to a reduction efficiency range of 10 to 40 percent from uncontrolled levels.

[d]NO_x reductions for PSC and low-emission combustion correspond to a controlled emission level of 2 g/hp-hr.

[e]NO_x reductions for NSCR correspond to a reduction efficiency of 90 percent.

TABLE 2-4. EFFECTS OF NO_x CONTROL TECHNIQUES ON RICH-BURN SI ENGINES

RICH-BURN ENGINES				
Control technique	Effect on CO emissions	Effect on HC emissions	Effect on fuel consumption	Effect on power output[a]
AF	increase (1 to 33 g/hp-hr)	increase (0.2 to 0.3 g/hp-hr)	0 to 5 percent increase	none[b]
IR	minimal	minimal	0 to 7 percent increase	none[b]
AF and IR	increase[c]	increase[c]	0 to 7 percent increase	minimal[d]
PSC	increase ($\leq$3.0 g/hp-hr)	increase ($\leq$2.0 g/hp-hr)	2 percent increase	5 to 20 percent reduction
NSCR	increase ($\leq$37 g/hp-hr)[f]	minimal[e] ($\leq$3.3 g/hp-hr)	0 to 5 percent increase	1 to 2 percent reduction
L-E	increase ($\leq$3.5 g/hp-hr)	increase ($\leq$2.0 g/hp-hr)	variable[g]	none

[a]At rated load.
[b]Severe adjustment or retard may reduce power output.
[c]The increase is expected to be less than that shown for A/F adjustment.
[d]One source reported a 5 percent power reduction at rated load.
[e]According to a VCAPCD test report summary.
[f]From VCAPCD data base, consistent with 4,500 ppmv CO emission limit.
[g]In most engines the effect is a decrease in fuel consumption of 0-5 percent.

The extent to which the ignition timing can be retarded to reduce NO_x emissions varies for each engine, as IR increases exhaust temperatures, which may adversely impact exhaust valve life and turbocharger performance, and extreme levels of IR may result in combustion instability and a loss of power. Brake-specific fuel consumption increases. Limited data suggest that moderate levels of IR has little effect on CO and HC emission levels.

Ignition timing can be adjusted on all new or existing rich-burn engines. Sustained NO_x reduction with changes in ambient conditions and engine load, however, is best accomplished using an electronic ignition control system.

The achievable NO_x emission reduction ranges from virtually no reduction to as high as 40 percent. Based on an average uncontrolled NO_x emission level of 15.8 g/hp-hr (1,060 ppmv), the expected range of controlled NO_x emissions is from 9.5 to 15.8 g/hp-hr (640 to 1,060 ppmv). Available data and information provided by engine manufacturers show that, like AF, the achievable NO_x reductions using IR are engine-specific.

2.2.1.3 AF and IR. The combination of AF and IR can be used to reduce NO_x emissions. Available data and information from engine manufacturers suggest that the achievable NO_x emission reduction for the combination of control techniques is approximately the same as for AF alone (i.e., 10 to 40 percent) but offers some flexibility in achieving these reductions. Since parametric adjustments affect such operating characteristics as fuel consumption, response to load changes, and other emissions (especially CO), the combination of AF and IR offers the potential to reduce NO_x emissions while minimizing the impact on other operating parameters.

2.2.1.4 PSC®. This add-on control technique facilitates combustion of a leaner A/F. The increased air content acts as a heat sink, reducing combustion temperatures, thereby reducing NO_x formation rates. Because this control technique is installed upstream of the combustion process, PSC® is often used with engines fueled by sulfur-bearing gases or other gases (e.g., sewage or landfill gases) that may adversely affect some catalyst materials.

Prestratified charge applies only to four-cycle, carbureted engines. Pre-engineered, "off-the-shelf" kits are available for most new or existing candidate engines, regardless of age or size. According to the vendor, PSC® to date has been installed on engines ranging in size up to approximately 2,000 hp.

The vendor offers guaranteed controlled NO_x emission levels of 2 g/hp-hr (140 ppmv), and available test data show numerous controlled levels of 1 to 2 g/hp-hr (70 to 140 ppmv). The extent to which NO_x emissions can be reduced is determined by the extent to which the air content of the stratified charge can be increased without excessively compromising other operating parameters such as power output and CO and HC emissions. The leaner A/F effectively displaces a portion of the fuel with air, which may reduce power output from the engine. For naturally aspirated engines, the power reduction can be as high as 20 percent, according to the vendor. This power reduction can be at least partially offset by modifying an existing turbocharger or installing a turbocharger on naturally aspirated engines. In general, CO and HC emission levels increase with PSC®, but the degree of the increase is engine-specific. The effect on BSFC is a decrease for moderate controlled NO_x emission levels (4 to 7 g/hp-hr, or 290 to 500 ppmv), but an increase for controlled NO_x emission levels of 2 g/hp-hr (140 ppmv) or less.

2.2.1.5 NSCR. Nonselective catalytic reduction is essentially the same catalytic reduction technique used in automobile applications and is also referred to as a three-way catalyst system because the catalyst reactor simultaneously reduces NO_x, CO, and HC to water (H_2O), carbon dioxide (CO_2), and diatomic nitrogen (N_2). The chemical stoichiometry requires that O_2 concentration levels be kept at or below approximately 0.5 percent, and most NSCR systems require that the engine be operated at fuel-rich A/F's. As a result, CO and HC emissions typically increase, and BSFC also increases due to the fuel-rich operation and the increased backpressure on the engine from the catalyst reactor.

Nonselective catalytic reduction applies only to carbureted rich-burn engines and can be retrofit to existing installations. Sustained NO_x reductions are achieved with changes in ambient conditions and operating loads only with an automatic A/F control system, and a suitable A/F controller is not available for fuel-injected engines. In addition, there is limited experience with fuels other than natural gas (e.g., sewage gas, landfill gas, and gases containing hydrogen sulfide [H_2S]), as these fuels contain constituents that may mask or poison the catalyst.

Catalyst vendors quote NO_x emission reduction efficiencies of 90 to 98 percent. Based on an average uncontrolled NO_x emission level of 15.8 g/hp-hr (1,060 ppmv), the expected range of controlled NO_x emissions is from 0.3 to 1.6 g/hp-hr (20 to 110 ppmv). Numerous test reports support this NO_x reduction efficiency range, but the corresponding CO emission levels range up to 37 g/hp-hr (4,500 ppmv) in some cases. Where controlled NO_x emission levels result in unacceptable CO emission rates, an oxidation catalyst may be required to reduce these emissions.

The predominant catalyst material used in NSCR applications is a platinum-based metal catalyst. The spent catalyst material is not considered hazardous, and most catalyst vendors accept return of the material, often with a salvage value that can be credited toward purchase of replacement catalyst.

2.2.1.6 L-E. Engine manufacturers have developed low-emission combustion designs (often referred to as torch ignition, or jet cell combustion) that operate at much leaner A/F's than do conventional designs. These designs incorporate improved swirl patterns to promote thorough air/fuel mixing and may include a precombustion chamber (PCC). A PCC is an antechamber that ignites a relatively fuel-rich mixture that propagates to the main combustion chamber. The high exit velocity from the PCC promotes mixing and complete combustion of the lean A/F in the main chamber, effectively lowering combustion temperatures and, therefore, NO_x emission levels.

Low-emission combustion designs are available from engine manufacturers for most new SI engines, and retrofit kits are available for some existing engine models. For existing engines, the modifications required for retrofit are similar to a major engine overhaul, and include a turbocharger addition or upgrade and new intake manifolds, cylinder heads, pistons, and ignition system. The intake air and exhaust systems must also be modified or replaced due to the increased air flow requirements.

Controlled NO_x emission levels reported by manufacturers for L-E are generally in the 2 g/hp-hr (140 ppmv) range, although lower levels may be quoted on a case-by-case basis. Emission test reports show controlled emission levels ranging from 1.0 to 2.0 g/hp-hr (70 to 140 ppmv). Information provided by manufacturers shows that, in general, BSFC decreases slightly for L-E compared to rich-burn designs, although in some engines the BSFC increases. An engine's response to increases in load is adversely affected by L-E, which may make this control technique unsuitable for some installations, such as stand-alone power generation applications. The effect on CO and HC emissions is a slight increase in most engine designs.

2.2.2 Control Techniques for Lean-Burn SI Engines

The control techniques available for lean-burn SI engines are discussed in this section. A summary of the achievable NO_x emission reductions for lean-burn SI engines using these control techniques is presented in Tables 2-5 and 2-6. The effects of these control techniques on other emissions, fuel consumption, and power output are presented in Table 2-7.

2.2.2.1 AF. Adjusting the A/F toward fuel-lean operation increases the volume of air in the combustion process, which increases the heat capacity of the mixture, lowering combustion temperatures and reducing NO_x formation. Limited data suggest CO emissions increase slightly, and HC emissions also increase. Combustion efficiency is reduced, and BSFC increases.

TABLE 2-5. EXPECTED RANGE OF NO_x EMISSION REDUCTIONS AND CONTROLLED EMISSION LEVELS FOR CONTROL TECHNIQUES APPLIED TO LEAN-BURN SI ENGINES (NATURAL GAS FUEL)

Control technique	Average uncontrolled NO_x emission level[a]		Achievable NO_x reduction, %	Expected controlled NO_x emission levels	
	g/hp-hr	ppmv		g/hp-hr	ppmv
AF	16.8	1,230	5 - 30	11.8 - 16.0	860 - 1,170
IR	16.8	1,230	0 - 20	13.4 - 16.8	980 - 1,260
AF + IR	16.8	1,230	20 - 40	10.1 - 13.4	740 - 980
SCR	16.8	1,230	90[b]	1.7	125
L-E	16.8	1,230	87	2.0[c]	150

[a]The uncontrolled emission rate shown is a representative average for lean-burn SI engines. The actual uncontrolled emission rate will vary from engine to engine.
[b]Guaranteed NO_x reduction available from most catalyst vendors.
[c]Guaranteed controlled NO_x emission level available from engine manufacturers.

TABLE 2-6. POTENTIAL NO_x REDUCTIONS FOR LEAN-BURN SI ENGINES

LEAN-BURN ENGINES					
Engine size, hp	Average uncontrolled NO_x emission level, g/hp-hr[a]	Average uncontrolled NO_x emission level, tons/yr	Potential NOx reduction, tons/yr[b]		
			Parametric adjustments[c]	SCR[d]	Low-emission combustion[e]
100	16.8	14.8	0.74 - 5.18	13.3	13.0
500		74.0	3.70 - 25.9	66.6	65.2
1,000		148	7.40 - 51.8	133	130
1,500		222	11.1 - 77.7	200	196
2,000		296	14.8 - 104	266	261
3,000		444	22.2 - 155	400	391
4,000		592	29.6 - 207	533	522
6,000		888	44.4 - 311	799	782
8,000		1,184	59.2 - 414	1,070	1,040
10,000		1,480	74.0 - 518	1,330	1,300

[a]The uncontrolled emission rate shown is a representative average for lean-burn SI engines. The actual uncontrolled emission rate will vary from engine to engine.
[b]Potential NO_x reductions correspond to 8,000 annual operating hours. NO_x reductions for other utilization rates can be estimated by multiplying the value in the table by the actual annual operating hours and dividing by 8,000.
[c]NO_x reductions for parametric adjustments correspond to a reduction efficiency range of 5 to 35 percent from uncontrolled levels.
[d]NO_x reductions for SCR correspond to a reduction efficiency of 90 percent.
[e]NO_x reductions for low-emission combustion correspond to a controlled emission level of 2 g/hp-hr.

TABLE 2-7. EFFECTS OF NO_x CONTROL TECHNIQUES ON LEAN-BURN SI ENGINES

LEAN-BURN ENGINES				
Control technique	Effect on CO emissions	Effect on HC emissions	Fuel consumption	Effect on power output[a]
AF	minimal	slight increase	0 to 5 percent increase	none[b]
IR	minimal	minimal	0 to 5 percent increase	none[b]
AF and IR	minimal[c]	minimal[c]	0 to 5 percent increase	minimal[d]
SCR	minimal	minimal	0.5 percent increase	1 to 2 percent reduction
L-E	increase ($\leq$3.5 g/hp-hr)	increase ($\leq$2.0 g/hp-hr)	variable[e]	none

[a]At rated load.
[b]Severe adjustment or retard may reduce power output.
[c]The increase is expected to be less than that shown for A/F adjustment.
[d]One source reported a 5 percent power reduction at rated load.
[e]In most engines the effect is a decrease in fuel consumption of 0 to 5 percent.

Excessively lean A/F's may result in combustion instability and lean misfire.

The A/F can be adjusted in the field on most lean-burn engines. Pump- and blower-scavenged engines, however, have no provisions for AF. To supply the increased volume of air needed for AF, a turbocharger may be required for existing naturally aspirated engines, and modification or replacement of the turbocharger may be required for turbocharged engines. An automatic control system to regulate the delivered volume of air is also required for sustained NO_x reduction with changes in ambient conditions and engine loads.

The achievable NO_x emission reduction for AF ranges from approximately 5 to 30 percent. Based on an average uncontrolled NO_x emission level of 16.8 g/hp-hr (1,230 ppmv), the expected range of controlled NO_x emissions is from 11.8 to 16.0 g/hp-hr (860 to 1,170 ppmv). Available data show that the achievable NO_x reduction using AF varies for each engine model and even among engines of the same model, which suggests that engine design and manufacturing tolerances influence the effect of AF on NO_x emission reduction.

2.2.2.2 IR. Ignition timing retard in lean-burn SI engines has similar effects on NO_x formation and engine performance to those discussed for rich-burn engines in Section 2.2.1.2. Limited data for IR in lean-burn engines show no definite trend for CO emissions for moderate levels of IR and only a slight increase in HC emissions.

Like rich-burn engines, IR can be performed on all new or existing lean-burn engines. Sustained NO_x reductions, however, require an electronic ignition control system to automatically adjust the timing for changes in ambient conditions and engine load.

The achievable NO_x emission reduction using IR ranges from virtually no reduction to as high as 20 percent. Based on an average uncontrolled NO_x emission level of 16.8 g/hp-hr (1,230 ppmv), the expected range of controlled NO_x emissions is from 13.4 to 16.8 g/hp-hr (980 to 1,260 ppmv). Available data and information provided by engine manufacturers show that the achievable NO_x reductions using IR are engine-specific.

2.2.2.3 AF and IR. The combination of AF and IR can be used to reduce NO_x emissions. Limited data and information available on the combination of control techniques suggest that, as is the case for each control technique used independently, the achievable NO_x emission reduction is engine-specific. Based on available data and information from engine manufacturers, it is estimated that the achievable NO_x emission reduction for the combination of control techniques is 20 to 40 percent. Based on an average uncontrolled NO_x emission level of 16.8 g/hp-hr (1,230 ppmv), the expected range of controlled NO_x emissions is from 10.1 to 13.4 g/hp-hr (740 to 980 ppmv).

The effect of each control technique used independently is a slight increase in CO and HC emissions, and it is expected that the combination of controls would produce similar results. Since parametric adjustments affect such operating characteristics as fuel consumption, response to load changes, and other emissions, the combination of AF and IR offers the potential to reduce NO_x emissions while minimizing the impact on these operating parameters.

2.2.2.4 SCR. Selective catalytic reduction is an add-on control technique that injects ammonia (NH_3) into the exhaust, which reacts with NO_x to form N_2 and H_2O in the catalyst reactor. The two primary catalyst formulations are base-metal (usually vanadium pentoxide) and zeolite. Spent catalysts containing vanadium pentoxide may be considered a hazardous material in some areas, requiring special disposal considerations. Zeolite catalyst formulations do not contain hazardous materials.

Selective catalytic reduction applies to all lean-burn SI engines and can be retrofit to existing installations except where physical space constraints may exist. There is limited operating experience to date, however, with these engines. A total of 23 SCR installations with lean-burn SI engines were identified in the United States from information provided by catalyst vendors, in addition to over 40 overseas installations.

To date there is also little experience with SCR in variable load applications due to ammonia injection control limitations. Several vendors cite the availability of injection systems, however, designed to operate in variable load applications. Injection systems are available for either anhydrous or aqueous ammonia. As is the case for NSCR catalysts, fuels other than pipeline-quality natural gas may contain contaminants that mask or poison the catalyst, which can render the catalyst ineffective in reducing NO_x emissions. Catalyst vendors typically guarantee a 90 percent NO_x reduction efficiency for natural gas-fired applications, with an ammonia slip level of 10 ppmv or less. One vendor offers a NO_x reduction guarantee of 95 percent for gas-fired installations. Based on an average uncontrolled NO_x emission level of 16.8 g/hp-hr (1,230 ppmv), the expected controlled NO_x emission level is 1.7 g/hp-hr (125 ppmv). Emission test data show NO_x reduction efficiencies of approximately 65 to 95 percent for existing installations. Ammonia slip levels were available only for a limited number of installations for manually adjusted ammonia injection control systems and ranged from 20 to 30 ppmv. Carbon monoxide and HC emission levels are not affected by implementing SCR. The engine BSFC increases slightly due to the backpressure on the engine caused by the catalyst reactor.

2.2.2.5 L-E. Low-emission combustion designs are available from engine manufacturers for most new lean-burn SI engines. The required engine modifications, effect on engine performance, achievable controlled NO_x emission levels, and effect on CO and HC emissions are essentially the same as for rich-burn engines and are discussed in Section 2.2.1.6.

2.2.3 Control Techniques for Diesel and Dual-Fuel CI Engines

The control techniques available for CI engines are discussed in this section. A summary of the achievable NO_x emission reductions for diesel and dual-fuel engines using these control techniques is presented in Tables 2-8, 2-9, and 2-10. The effect of these control techniques on other emissions, fuel

TABLE 2-8. EXPECTED RANGE OF NO_x EMISSION REDUCTIONS AND CONTROLLED EMISSION LEVELS FOR CONTROL TECHNIQUES APPLIED TO DIESEL AND DUAL-FUEL ENGINES

Control technique	Average uncontrolled NO_x emission level[a]		Achievable NO_x reduction, %	Expected controlled NO_x emission levels	
	g/hp-hr	ppmv		g/hp-hr	ppmv
DIESEL ENGINES					
IR	12.0	875	20 - 30	8.4 - 9.6	610 - 700
SCR	12.0	875	80 - 90[b]	1.2 - 2.4	90 - 175
DUAL-FUEL ENGINES					
IR	8.5	620	20 - 30	6.0 - 6.8	430 - 500
SCR	8.5	620	80 - 90[b]	0.8 - 1.7	600 - 125
L-E	8.5	620	75	2.0[c]	150

[a]The uncontrolled emission rates shown are representative averages for diesel and dual-fuel engines. The actual uncontrolled emission rate varies from engine to engine.
[b]Guaranteed NO_x reduction available from most catalyst vendors.
[c]Guaranteed controlled NO_x emission level available from engine manufacturers.

TABLE 2-9. POTENTIAL NO_x REDUCTIONS FOR DIESEL ENGINES

DIESEL ENGINES				
Engine size, hp	Average uncontrolled NO_x emission level, g/hp-hr[a]	Average uncontrolled NO_x emission level, tons/yr	Potential NO_x reduction, tons/yr[b]	
			Injection retard[c]	SCR[d]
100	12.0	10.6	2.11 - 3.17	9.5
500		52.9	10.6 - 15.9	47.6
1,000		106	21.1 - 31.7	95
1,500		159	31.7 - 47.6	143
2,000		211	42.3 - 63.4	190
3,000		317	63.4 - 95.2	285
4,000		423	84.6 - 127	381
6,000		634	127 - 190	571
8,000		846	169 - 254	761

[a]The uncontrolled emission rate shown is a representative average for diesel engines. The actual uncontrolled emission rate will vary from engine to engine.
[b]Potential NO_x reductions correspond to 8,000 annual operating hours. NO_x reductions for other utilization rates can be estimated by multiplying the value in the table by the actual annual operating hours and dividing by 8,000.
[c]NO_x reductions for injection retard correspond to a reduction efficiency range of 20 to 30 percent from uncontrolled levels.
[d]NO_x reductions for SCR correspond to a reduction efficiency of 90 percent.

TABLE 2-10. POTENTIAL NO_x REDUCTIONS FOR DUAL-FUEL ENGINES

DUAL-FUEL ENGINES					
Engine size, hp	Average uncontrolled NO_x emission level, g/hp-hr[a]	Average uncontrolled NO_x emission level, tons/yr	Potential NO_x reduction, tons/yr[b]		
			Injection retard[c]	SCR[d]	Low-emission combustion[e]
700	8.5	52.4	10.5 - 15.7	47.2	40.1
1,000		74.9	15.0 - 22.5	67.4	57.3
1,500		112	22.5 - 33.7	101	85.9
2,000		150	30.0 - 44.9	135	115
3,000		225	44.9 - 67.4	202	172
4,000		300	59.9 - 89.9	270	229
6,000		449	89.9 - 135	404	344
8,000		599	120 - 180	539	458

[a]The uncontrolled emission rate shown is a representative average for dual-fuel engines. The actual uncontrolled emission rate will vary from engine to engine.
[b]Potential NO_x reductions correspond to 8,000 annual operating hours. NO_x reductions for other utilization rates can be estimated by multiplying the value in the table by the actual annual operating hours and dividing by 8,000.
[c]NO_x reductions for injection retard correspond to a reduction efficiency range of 20 to 30 percent from uncontrolled levels.
[d]NO_x reductions for SCR correspond to a reduction efficiency of 90 percent.
[e]NO_x reductions for low-emission combustion correspond to a controlled emission level of 2 g/hp-hr.

consumption, and power output is presented in Table 2-11 for diesel and dual-fuel engines.

2.2.3.1 IR. Injection timing retard in CI engines reduces NO_x emissions by the same principles as those for SI engines and is discussed in Section 2.2.1.2. Injection timing can be adjusted on all new or existing CI engines. Sustained NO_x reductions, however, require an electronic injection control system to automatically adjust the timing for changes in ambient conditions and engine load.

Available data and information provided by engine manufacturers show that the achievable NO_x reductions using IR is engine-specific but generally ranges from 20 to 30 percent. Based on an average uncontrolled NO_x emission level for diesel engines of 12.0 g/hp-hr (875 ppmv), the expected range of controlled NO_x emissions is from 8.4 to 9.6 g/hp-hr (610 to 700 ppmv). For dual-fuel engines, the average uncontrolled NO_x emission level is 8.5 g/hp-hr (620 ppmv) and the expected range of controlled NO_x emissions is from 6.0 to 6.8 g/hp-hr (430 to 500 ppmv).

Limited data for ignition retard show no definite trend for CO and HC emissions for moderate levels of ignition retard in diesel engines and a slight increase in these emissions in dual-fuel engines. The BSFC increases with increasing levels of IR for both diesel and dual-fuel engines. Excessive timing retard results in combustion instability and engine misfire.

2.2.3.2 SCR. Selective catalytic reduction applies to all CI engines and can be retrofit to existing installations except where physical space constraints may exist. As is the case with SI engines, however, there is limited operating experience to date with these engines. A total of 9 SCR installations with diesel engines and 27 installations with dual-fuel engines were identified in the United States by catalyst vendors. Approximately 10 overseas SCR installations with CI engines were identified, including one fueled with heavy oil. To date there is also little experience with SCR in variable load applications

TABLE 2-11. EFFECTS OF NO_x CONTROL TECHNIQUES ON DIESEL AND DUAL-FUEL ENGINES

Control technique	Effect on CO emissions	Effect on HC emissions	Effect on fuel consumption	Effect on power output[a]
DIESEL ENGINES				
IR	varied[b]	varied[c]	0 to 5 percent increase	none[d]
SCR	minimal	minimal	0.5 percent increase	1 to 2 percent reduction
DUAL-FUEL ENGINES				
IR	increase (13 to 23 percent)	increase (6 to 21 percent)	0 to 3 percent increase	none[d]
SCR	minimal	minimal	0.5 percent increase	1 to 2 percent reduction
L-E	varied[e]	varied[e]	0 to 3 percent increase	none

[a]At rated load.
[b]Ranged from a 13.2 percent decrease to a 10.8 percent increase for limited test results.
[c]Ranged from a 0 to 76.2 percent increase for limited test results.
[d]Severe adjustment or retard may reduce power output.
[e]May be slight increase or decrease, depending on engine model and manufacturer.

due to ammonia injection control limitations, as discussed in Section 2.2.2.4.

Some base-metal catalysts utilize a guard bed upstream of the catalyst to catch heavy hydrocarbons that would otherwise deposit on the catalyst and mask the active surface. In the past some catalysts were also susceptible to poisoning by sulfur (the maximum sulfur content of No. 2 diesel oil is 0.5 percent), but sulfur-resistant catalyst formulations are now available.

Zeolite catalyst vendors typically guarantee a NO_x reduction efficiency for CI engines of 90 percent or higher, with an ammonia slip of 10 ppmv or less. Base-metal catalyst vendors quote guarantees for CI engines of 80 to 90 percent NO_x reduction, with ammonia slip levels of 10 ppmv or less. Based on an average uncontrolled NO_x emission level of 12.0 g/hp-hr (875 ppmv) for diesel engines, the expected range of controlled NO_x emissions is from 1.2 to 2.4 g/hp-hr (90 to 175 ppmv). For dual-fuel engines, the average uncontrolled NO_x emission level is 8.5 g/hp-hr (620 ppmv) and the expected range of controlled NO_x emissions is from 0.8 to 1.7 g/hp-hr (60 to 125 ppmv).

Limited emission test data show NO_x reduction efficiencies of approximately 88 to 95 percent for existing installations, with ammonia slip levels ranging from 5 to 30 ppmv. Carbon monoxide and HC emission levels are not affected by implementing SCR. The engine BSFC increases approximately 1 to 2 percent due to the backpressure on the engine caused by the catalyst reactor.

2.2.3.3 L-E. No L-E designs were identified for diesel engines, but L-E is available from engine manufacturers for a limited number of dual-fuel engines. Where available, these designs generally apply to both new engines and retrofit applications. Like SI engines, the L-E designs use a PCC (see Section 2.2.1.6), which ignites a very lean mixture in the main chamber. The pilot diesel oil is reduced from 5 to 6 percent of the total fuel delivery of conventional designs to approximately 1 percent, and is injected into the PCC. Engine modifications required for retrofit applications are similar in scope to a major engine overhaul, and may also require modifications or replacement of the turbocharger and intake and exhaust systems to supply the increased volume of combustion air required for L-E.

Controlled NO_x emission levels for L-E reported by manufacturers are generally in the 2 g/hp-hr (140 ppmv) range, although lower levels may be quoted on a case-by-case basis. Emission test reports show controlled emission levels ranging from 1.0 to 2.0 g/hp-hr (70 to 140 ppmv). These controlled emission levels apply only to the dual-fuel operating mode; the emissions from the diesel operating mode are not reduced. Information provided by manufacturers shows that BSFC increases slightly for L-E compared to conventional engines. The effect of L-E on CO and HC emissions varies by engine manufacturer, and no definite trend could be established from the limited data available.

2.3 CONTROL TECHNIQUES COSTS AND COST EFFECTIVENESS

Total capital and annual costs and cost effectiveness for the control techniques are presented in this section, in 1993 dollars, for each engine type. Costs and cost effectiveness for rich-burn and lean-burn SI engine control techniques are presented in Sections 2.3.1 and 2.3.2, respectively. Sections 2.3.3 and 2.3.4 present costs and cost effectiveness for diesel and dual-fuel engines, respectively.

Total capital costs include the purchased equipment costs and direct and indirect installation costs. Total annual costs consist of direct operating costs (materials and labor for maintenance, operation, incremental fuel and utilities, and consumable material replacement and disposal) and indirect operating costs (plant overhead, general administration, and recovery of capital costs). These cost components are discussed in Chapter 6.

The total capital costs for parametric adjustment control techniques (i.e., AF, IR, or a combination of these controls) include the cost of installing automatic control systems. The necessary hardware and control equipment to implement these control techniques are described in Chapter 6. Some existing installations may already have provisions for automatic controls, and for these engines the capital and annual costs and cost effectiveness for parametric adjustments would be considerably lower than the figures presented in this chapter.

Cost effectiveness for each control technique is calculated by dividing the total annual cost by the annual NO_x reduction and is stated in units of dollars per ton of NO_x removed ($/ton). The cost-effectiveness figures presented in this chapter correspond to 8,000 annual operating hours. Lower utilization rates (i.e., fewer annual operating hours) result in higher cost effectiveness, and cost-effectiveness figures for other utilization rates are presented in Chapter 6. The controlled NO_x emission levels for each control technique used to calculate cost effectiveness are also included in Chapter 6.

2.3.1 Costs and Cost Effectiveness for Rich-Burn SI Engines

Total capital and annual costs and cost-effectiveness figures for control techniques applied to rich-burn SI engines are presented in Figures 2-1, 2-2, and 2-3, respectively, and are summarized in Table 2-12. Dual plots are used where necessary to expand the Y-axis to provide separation of curves with close proximity.

2.3.1.1 Capital Costs. Capital costs are presented in Figure 2-1 and are lowest for parametric adjustment controls, ranging from $11,500 to $50,000, followed by PSC® and NSCR, which range from $20,000 to $250,000.

When comparing the costs for PSC® and NSCR, the following should be noted:

1. No PSC® applications were identified for engines above approximately 2,000 hp.

2. Costs for PSC® were extrapolated for engines over 1,400 hp because costs were not available for larger engines.

3. Implementing PSC® may result in a derate in engine power output of up to 20 percent, according to the supplier. Power derate was not included in the economic analysis for this or any other control technique due to the potential variation in the extent of the derate and the difficulty in quantifying the value

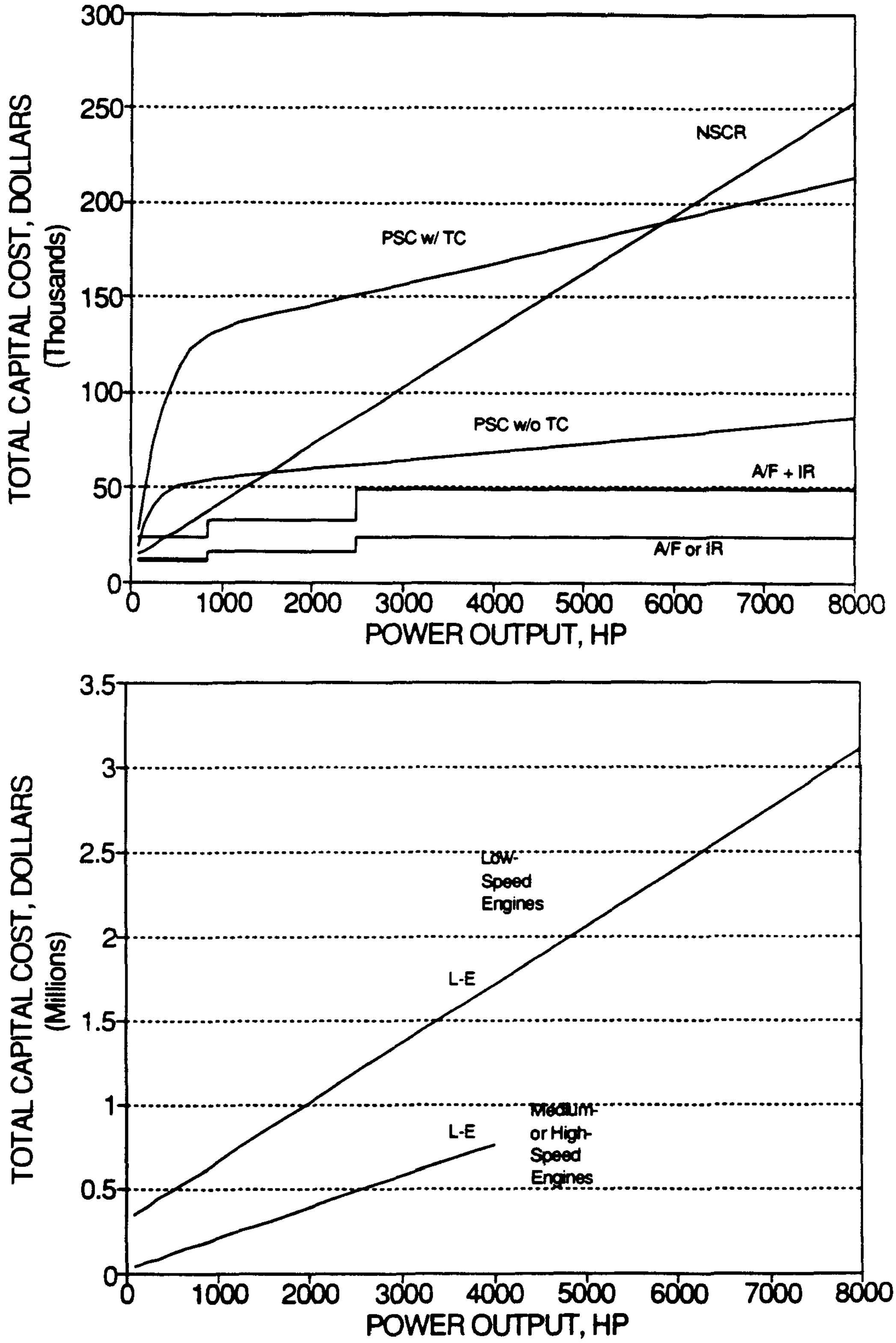
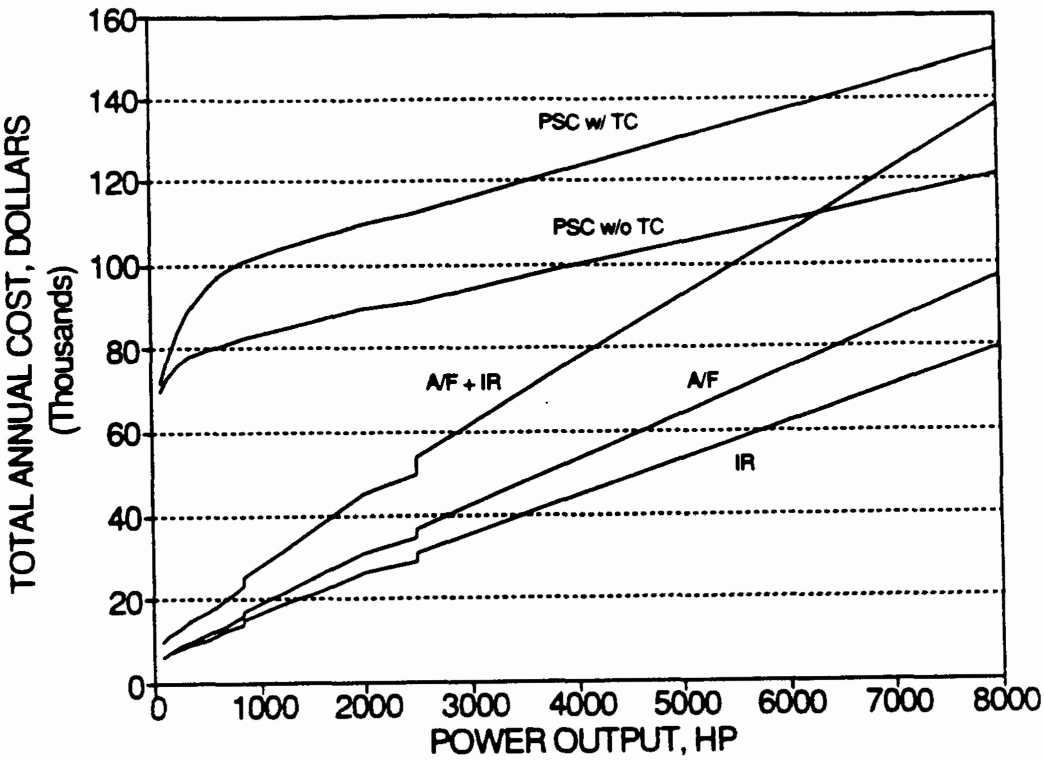


Figure 2-1. Total capital costs for NO_x control techniques applied to rich-burn SI engines.



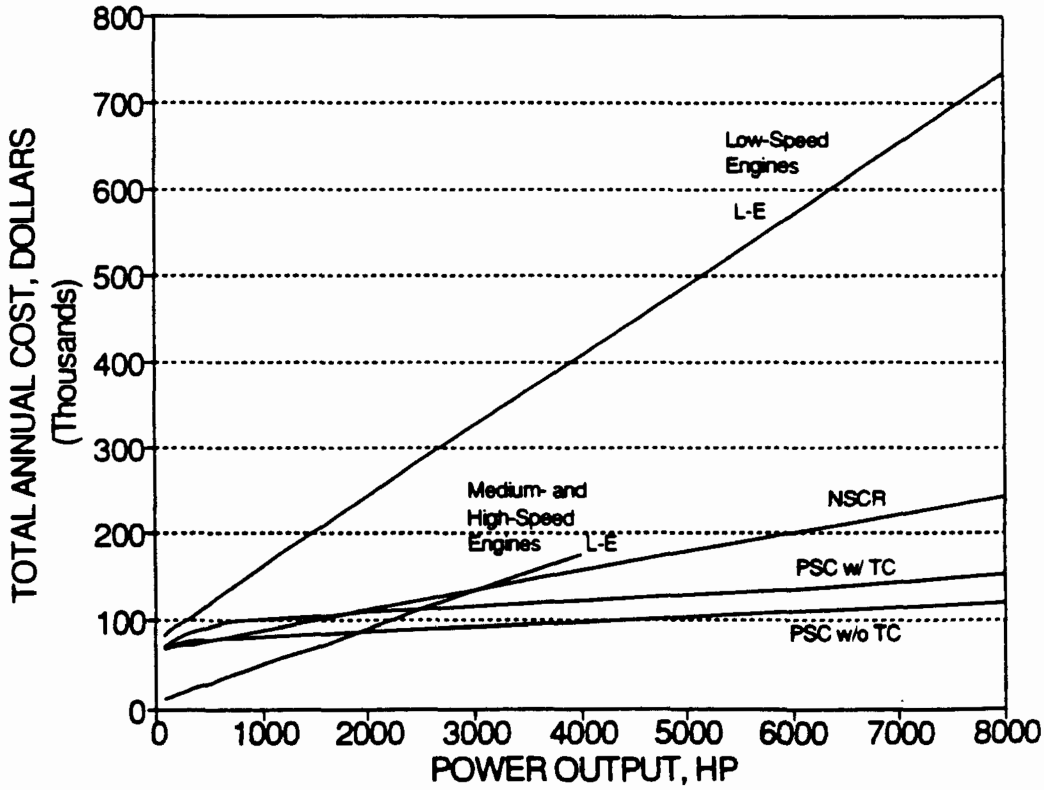


Figure 2-2. Total annual costs for NO_x control techniques applied to rich-burn SI engines (8,000 hr/yr).

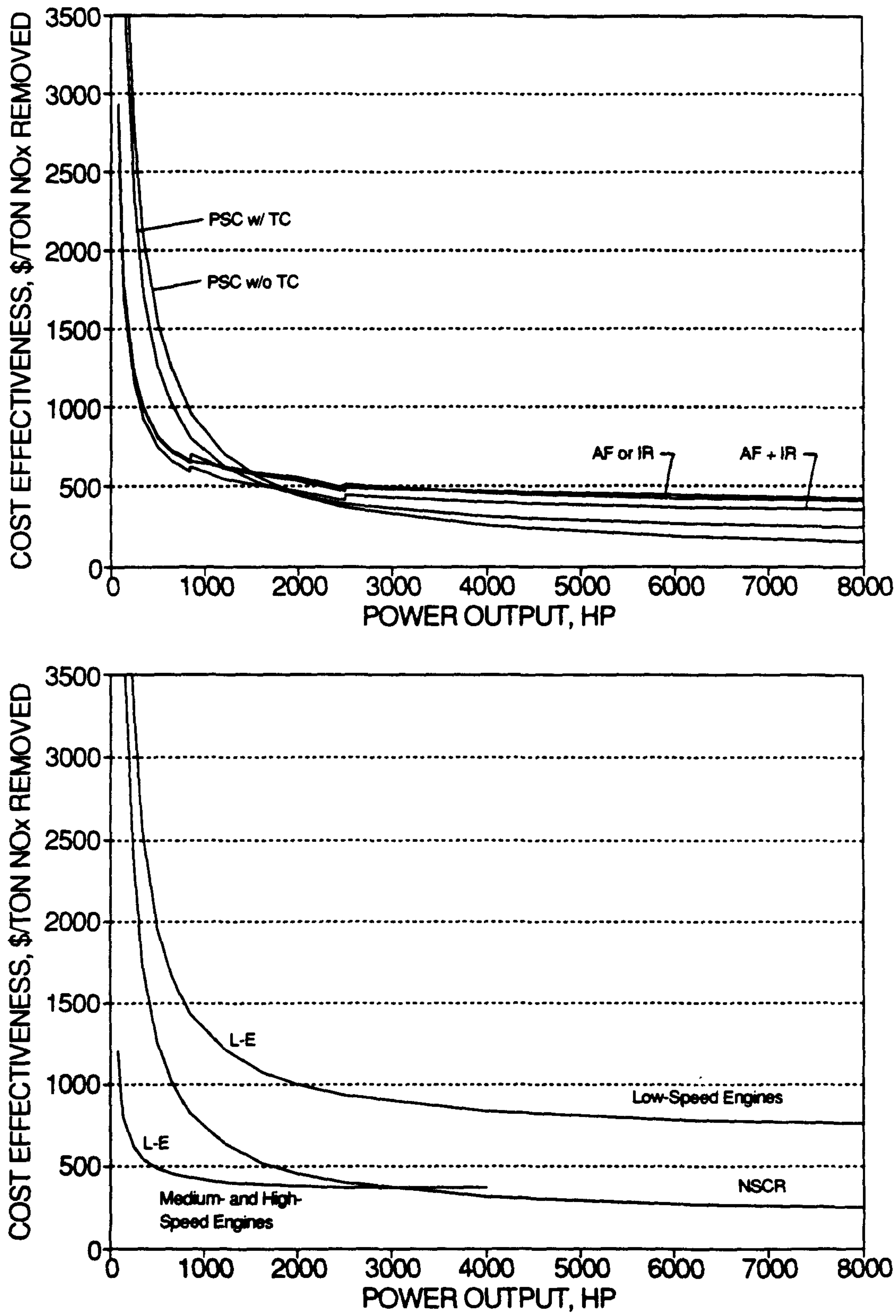


Figure 2-3. Cost effectiveness for NO_x control techniques applied to rich-burn engines (8,000 hr/yr).

TABLE 2-12. COSTS AND COST EFFECTIVENESS SUMMARY FOR NO_x CONTROL TECHNIQUES APPLIED TO RICH-BURN SI ENGINES

Engine size, hp	AF	IR	AF + IR	PSC w/o TC[a]	PSC w/TC[a]	NSCR	L-E, medium-speed engines	L-E, low speed engines
Total capital costs ($1,000)								
80-500	12	12	23	20-50	28-112	15-27	39-116	343-489
501-1,000	12-16	12-16	23-32	50-55	112-133	27-41	116-207	489-665
1,001-2,500	16	16	32	55-62	133-151	41-87	207-482	665-1,190
2,501-4,000	25	25	50	62-69	151-168	87-132	482-756	1,190-1,710
4,001-8,000	25	25	50	69-87	168-215	132-253	NA[b]	1,710-3,100
Total annual costs ($1,000)[c]								
80-500	6.3-11	6.3-11	9.8-17	70-80	72-94	69-79	12-23	85-120
501-1,000	11-18	11-16	17-27	80-83	94-101	79-90	23-50	120-161
1,001-2,500	18-36	16-31	27-50	83-91	101-112	90-124	50-114	161-284
2,501-4,000	36-53	31-44	50-77	91-100	112-123	124-158	114-177	284-408
4,001-8,000	53-97	44-80	77-138	100-121	123-152	158-244	NA[b]	408-737
Cost effectiveness ($/ton)[c]								
80-500	830-2,900	750-2,900	810-2,900	1,300-7,200	1,500-7,400	1,260-6,900	480-1,200	2,000-8,800
501-1,000	700-830	600-750	620-810	750-1,300	900-1,500	750-1,260	420-480	1,350-2,000
1,001-2,500	500-700	420-600	470-620	300-750	370-900	395-750	375-420	940-1,350
2,501-4,000	480-500	400-420	460-470	200-300	250-370	315-395	360-375	840-940
4,001-8,000	430-480	360-400	410-460	150-300	150-250	240-315	NA[b]	760-840

[a]PSC may result in significant engine power output deviation, as discussed in Chapter 5.
[b]NA - Medium-speed engines are not manufactured for this range of engines.
[c]8,000 hr/yr.

of lost product. The associated cost of any power derate should be considered on a case-by-case basis and added to the costs shown for PSC®.

The capital costs for L-E retrofit range from $39,000 to $756,000 for medium-speed engines ranging in size from 80 to 4,000 hp. For low-speed engines, the capital costs range from $343,000 to $3,100,000 for engines ranging in size from 80 to 8,000 hp.

2.3.1.2 Total Annual Costs for Rich-Burn SI Engines. Total annual costs are shown in Figure 2-2 and for parametric adjustments range from $6,300 to $138,000. Parametric adjustments have the lowest total annual costs, primarily because of their relatively low capital costs. The total annual costs for PSC® and NSCR are comparable, especially for engines rated at 2,000 hp or less, ranging from $70,000 to $111,000. For engines over 2,000 hp, the total annual costs for PSC® range from $90,000 to $150,000, and for NSCR range from $110,000 to $244,000. The total annual costs for L-E retrofit of medium-speed engines are comparable to or lower than either PSC® or NSCR for engines up to approximately 2,500 hp, ranging from $12,000 to $114,000. The total annual costs are higher for L-E retrofits for medium-speed engines over 2,500 hp, ranging to $177,000 for a 4,000 hp engine, but as noted above, these engines are generally rated at less than 2,800 hp. The highest total annual costs are for L-E retrofits for low-speed engines, ranging from $85,000 to $737,000.

2.3.1.3 Cost Effectiveness for Rich-Burn SI Engines. Cost effectiveness for control techniques applied to rich-burn SI engines is shown in Figure 2-3. Figure 2-3 shows that, despite the wide range of capital and annual costs for the control techniques, the range of cost effectiveness, in $/ton of NO_x removed, is comparable for all control techniques. In general, this is because the control techniques with the lowest capital and annual costs achieve the lowest NO_x reductions, and the control techniques with the highest capital and annual costs generally achieve the highest NO_x reductions.

For parametric adjustments, the cost effectiveness ranges from a high of $2,900/ton for the smallest engines (80 hp) to under $1,000/ton for engines larger than approximately 250 hp. For engines larger than 2,500 hp, the cost effectiveness for parametric adjustments is less than $500/ton. The cost effectiveness for NSCR and PSC® with and without turbocharger modifications is comparable, ranging from $1,300 to $7,400 per ton for engines up to 500 hp and less than $3,000/ton for engines larger than approximately 250 hp (the cost effectiveness axis in Figure 2-7 is limited to $3,500/ton for greater clarity in the 0 to $3,000/ton range). The cost effectiveness for either PSC® or NSCR is less than $1,000/ton for engines larger than 800 hp and decreases further to below $500/ton for engines above 1,800 hp. For L-E, the cost effectiveness for medium-speed engines ranges from a high of $1,200/ton for an 80 hp engine to $500/ton or less for engines greater than 500 hp. The cost effectiveness range for L-E retrofit is considerably higher for low-speed engines due to the higher capital costs involved and ranges from a high of $8,800/ton for an 80 hp engine to $2,000/ton for a 500 hp engine. The cost effectiveness is $2,000/ton or less for L-E retrofit for engines greater than 2,000 hp.

2.3.2 Costs and Cost Effectiveness for Lean-Burn SI Engines

Total capital and annual costs and cost-effectiveness figures for control techniques applied to lean-burn SI engines are presented in Figures 2-4, 2-5, and 2-6, respectively, and are summarized in Table 2-13. Dual plots are used where necessary to expand the Y-axis to separate curves with similar cost-effectiveness ranges.

2.3.2.1 Capital Costs. Capital costs are presented in Figure 2-4 and are lowest for parametric adjustment controls, ranging from $12,000 to $24,000 for IR and $74,000 to $130,000 for AF. The cost for AF applied to lean-burn engines includes turbocharger modifications and is considerably higher than AF for rich-burn engines. Where AF can be implemented for lean-burn engines without the requirement for turbocharger modifications,

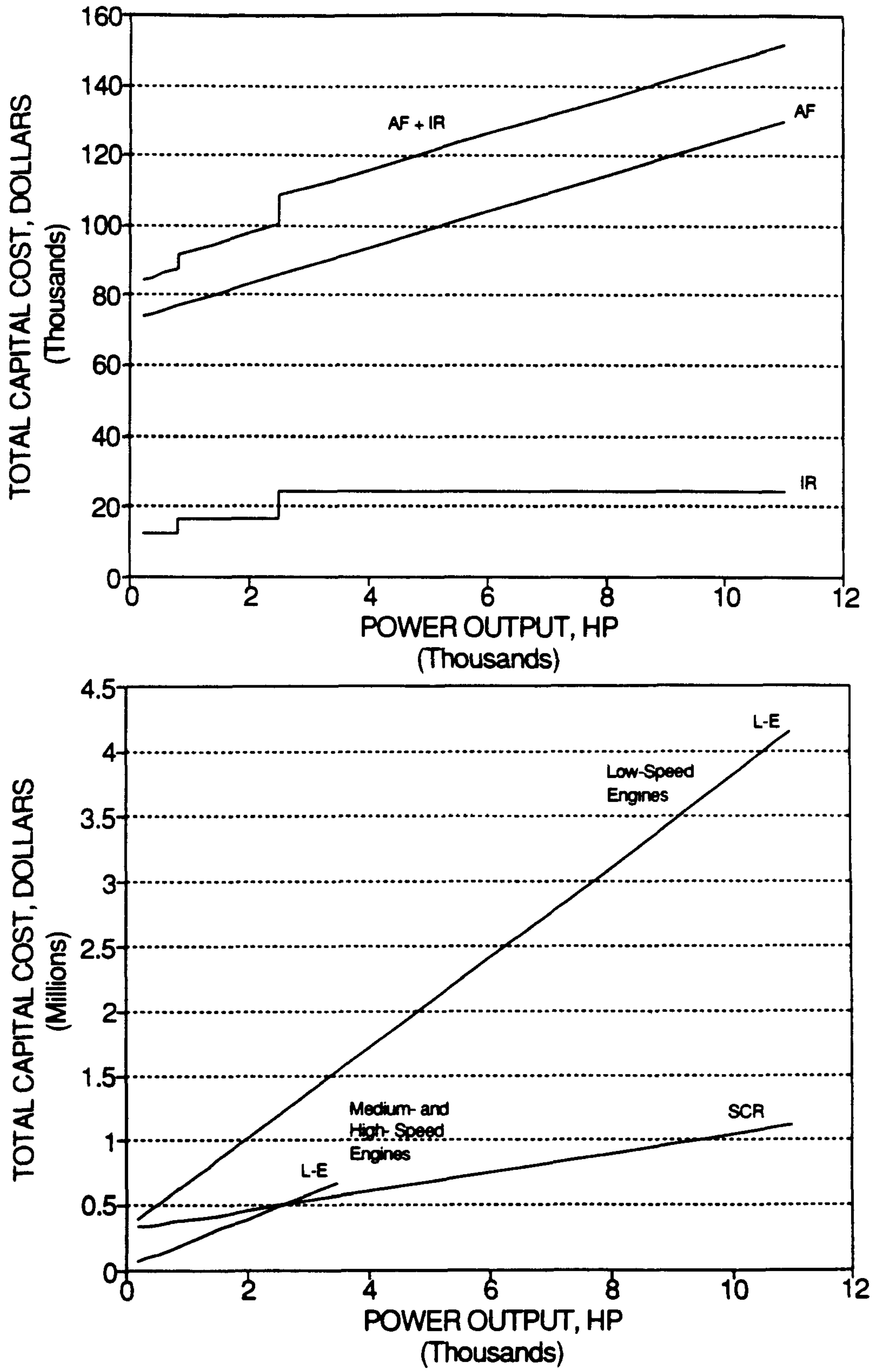


Figure 2-4. Total capital costs for NO_x control techniques applied to lean-burn SI engines.

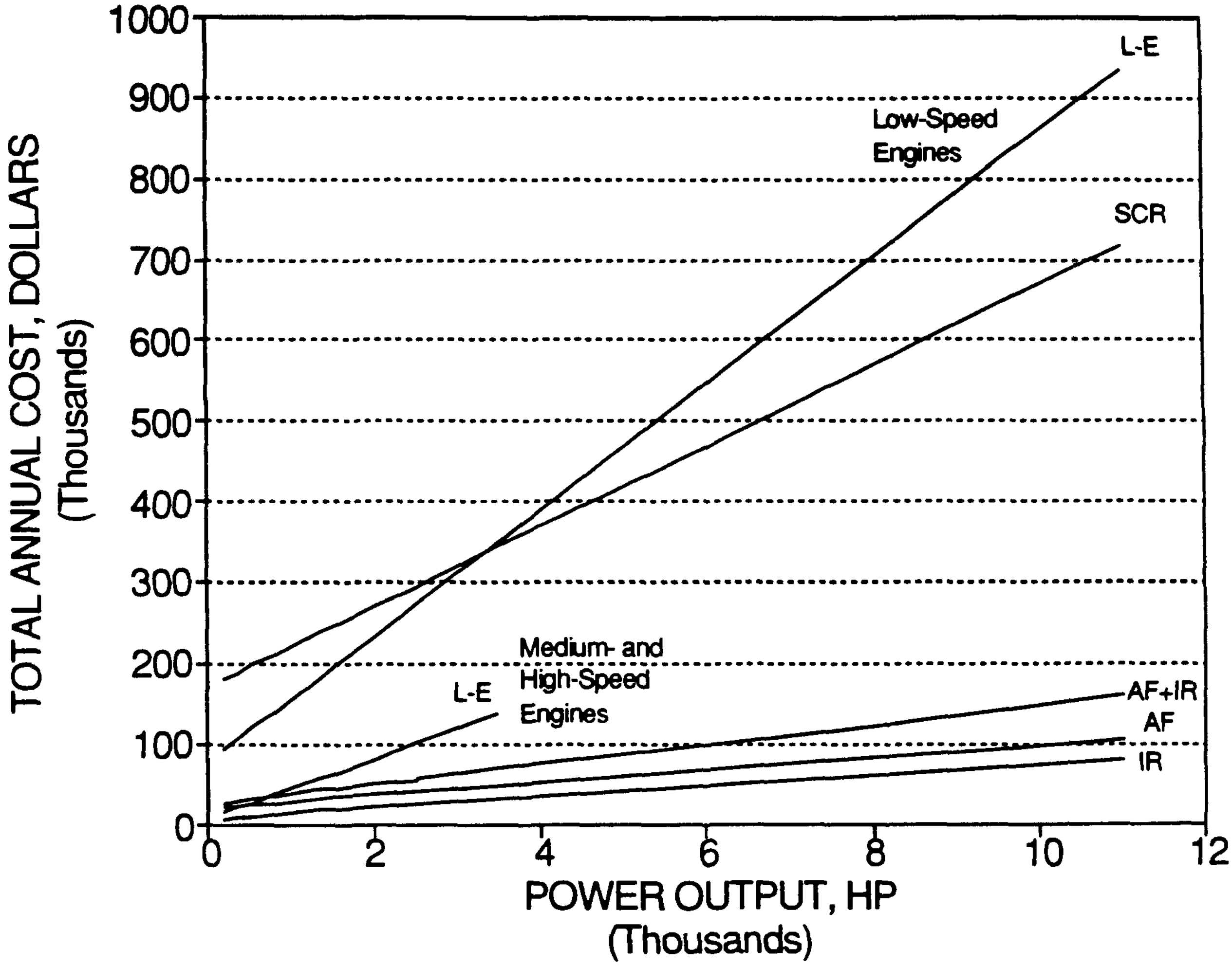


Figure 2-5. Total annual costs for NO_x control techniques applied to lean-burn SI engines (8,000 hr/yr).

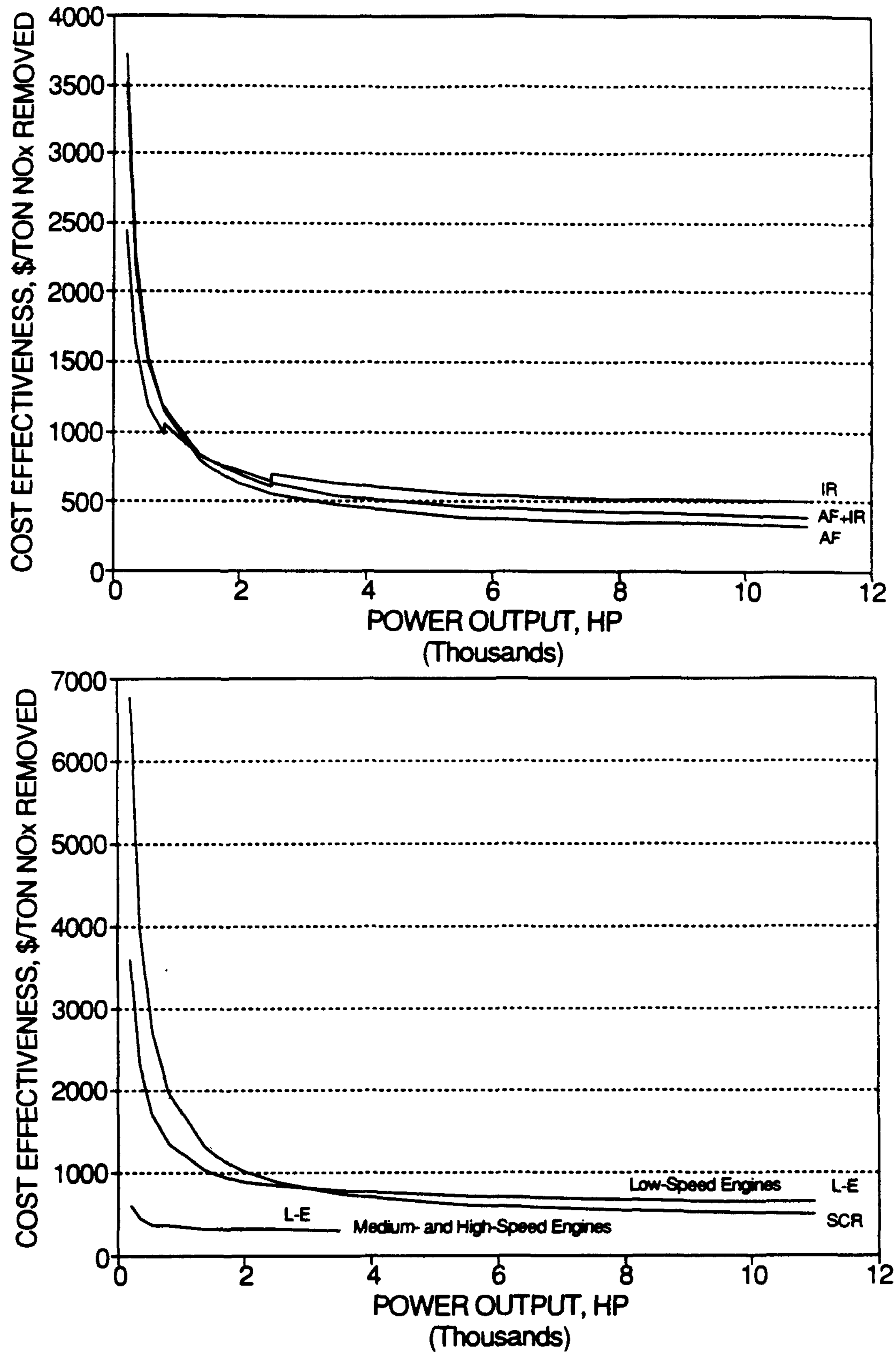


Figure 2-6. Cost effectiveness for NO_x control techniques applied to lean-burn SI engines (8,000 hr/yr).

TABLE 2-13. COSTS AND COST EFFECTIVENESS SUMMARY FOR NO_x CONTROL TECHNIQUES APPLIED TO LEAN-BURN SI ENGINES

Engine size, hp	AF	IR	AF & IR	SCR	L-E, medium-speed engines	L-E, low-speed engines
Total capital costs ($1,000)						
200-500	74-75	12	84-86	324-346	61-116	385-489
501-1,000	75-78	12-16	86-92	346-382	116-207	489-665
1,001-2,500	78-86	16	92-100	382-491	207-482	665-1,190
2,501-4,000	86-94	16-24	100-116	491-600	482-756	1,190-1,710
4,001-11,000	94-130	24	116-151	600-1,110	NA[a]	1,710-4,150
Total annual costs ($1,000)[b]						
200-500	22-24	7.2-9.3	26-30	180-196	15-27	94-117
501-1,000	24-29	9.3-14	30-37	196-220	27-45	117-156
1,001-2,500	29-41	14-24	37-55	220-295	45-102	156-272
2,501-4,000	41-53	24-36	55-77	295-370	102-158	272-389
4,001-11,000	53-106	36-81	77-160	370-717	NA[a]	389-935
Cost effectiveness ($/ton)[b]						
200-500	1,700-3,700	1,300-2,400	1,500-3,500	2,900-6,800	410-590	1,800-3,600
501-1,000	980-1,700	950-1,300	750-1,500	1,700-2,900	350-410	1,200-1,800
1,001-2,500	550-980	650-950	630-750	890-1,700	310-350	840-1,200
2,501-4,000	510-550	610-700	600-630	700-890	300-310	750-840
4,001-11,000	330-510	500-610	400-600	490-700	NA[a]	650-750

[a]NA - Medium-speed engines are not manufactured for this range of engines.
[b]8,000 hr/yr.

the costs would be comparable to those shown for rich-burn AF in Section 2.3.1.1.

The total capital costs for SCR range from $324,000 to $1,110,000. The total capital costs for L-E retrofit range from $61,000 to $756,000 for medium-speed engines ranging in size from 200 to 4,000 hp. For low-speed engines, the capital costs range from $385,000 to $4,150,000 for engines ranging in size from 200 to 11,000 hp.

2.3.2.2 Total Annual Costs for Lean-Burn SI Engines. Total annual costs are shown in Figure 2-5. Annual costs for IR range from $7,200 to $81,000 and for AF range from $22,000 to $106,000. For SCR, the annual costs range from $180,000 to $717,000. The annual costs for L-E applied to medium-speed engines range from $15,000 to $158,000 for engines up to 4,000 hp and for low-speed engines range from $94,000 to $935,000 for engines up to 11,000 hp.

2.3.2.3 Cost Effectiveness for Lean-Burn SI Engines. Cost effectiveness for control techniques applied to lean-burn SI engines is shown in Figure 2-6. As is the case for rich-burn engines, despite the wide range of capital and annual costs for the control techniques, the range of cost effectiveness, in $/ton of NO_x removed, is generally comparable for all control techniques. For parametric adjustments, the cost effectiveness ranges from a high of $3,700/ton for the smallest engines (200 hp) to under $1,000/ton for engines larger than approximately 1,000 hp. For L-E applied to medium-speed engines, the cost effectiveness ranges from a high of $590/ton for a 200 hp engine to $500/ton or less for engines larger than 500 hp. The cost effectiveness for SCR ranges from $490 to $6,800 per ton and for L-E retrofit to low-speed engines ranges from $650 to $3,600 per ton. The cost effectiveness for SCR and L-E retrofit to low-speed engines is comparable for engines above approximately 2,000 hp and is less than $1,000/ton for either control technique for engines in this size range.

2.3.3 Costs and Cost Effectiveness for Diesel Engines

Total capital and annual costs and cost-effectiveness figures for control techniques applied to diesel engines are presented in Figures 2-7, 2-8, and 2-9, respectively, and are summarized in Table 2-14.

2.3.3.1 Capital Costs. Capital costs are presented in Figure 2-7 and range from $12,000 to $24,000 for IR and from $195,000 to $967,000 for SCR.

2.3.3.2 Total Annual Costs for Diesel Engines. Total annual costs are shown in Figure 2-8. Annual costs for IR range from $6,200 to $78,000 and for SCR range from $145,000 to $523,000.

2.3.3.3 Cost Effectiveness for Diesel Engines. Cost effectiveness for NO_x control techniques applied to diesel engines is shown in Figure 2-9. For IR, cost effectiveness ranges from a high of $2,900/ton for an 80 hp engine to $370/ton for an 8,000 hp engine and is under $1,000/ton for engines larger than approximately 400 hp. The cost effectiveness for SCR ranges from $690 to $19,000 per ton (the cost effectiveness axis in Figure 2-9 is limited to $8,000 for greater clarity in the 0 to $3,000 range). For engines larger than 750 hp, the cost effectiveness for SCR is $3,000/ton or less and is less than $1,000/ton for engines larger than 3,200 hp.

2.3.4 Costs and Cost Effectiveness for Dual-Fuel Engines

Total capital and annual costs and cost-effectiveness figures for control techniques applied to duel-fuel engines are presented in Figures 2-10, 2-11, and 2-12, respectively, and are summarized in Table 2-15. Dual plots are used where necessary to expand the Y-axis to separate curves with similar cost-effectiveness ranges.

2.3.4.1 Capital Costs. Total capital costs are presented in Figure 2-10 and are lowest for IR, ranging from $12,000 to $24,000. The total capital costs for SCR range from $255,000 to $967,000. The capital costs for L-E retrofit for dual-fuel engines range from $720,000 to $4,000,000 for engines ranging in size from 700 to 8,000 hp.

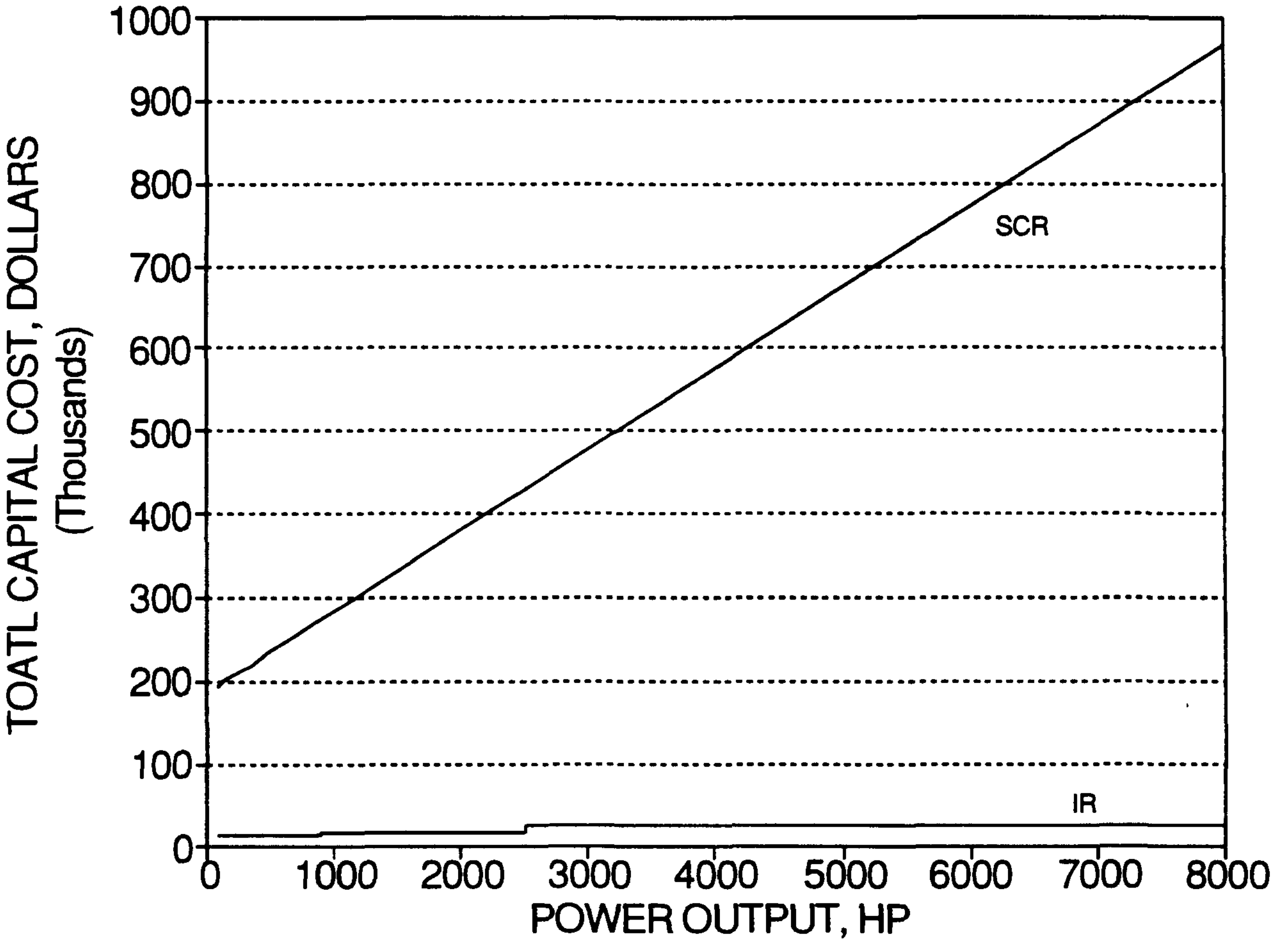


Figure 2-7. Total capital costs for NO_x control techniques applied to diesel engines.

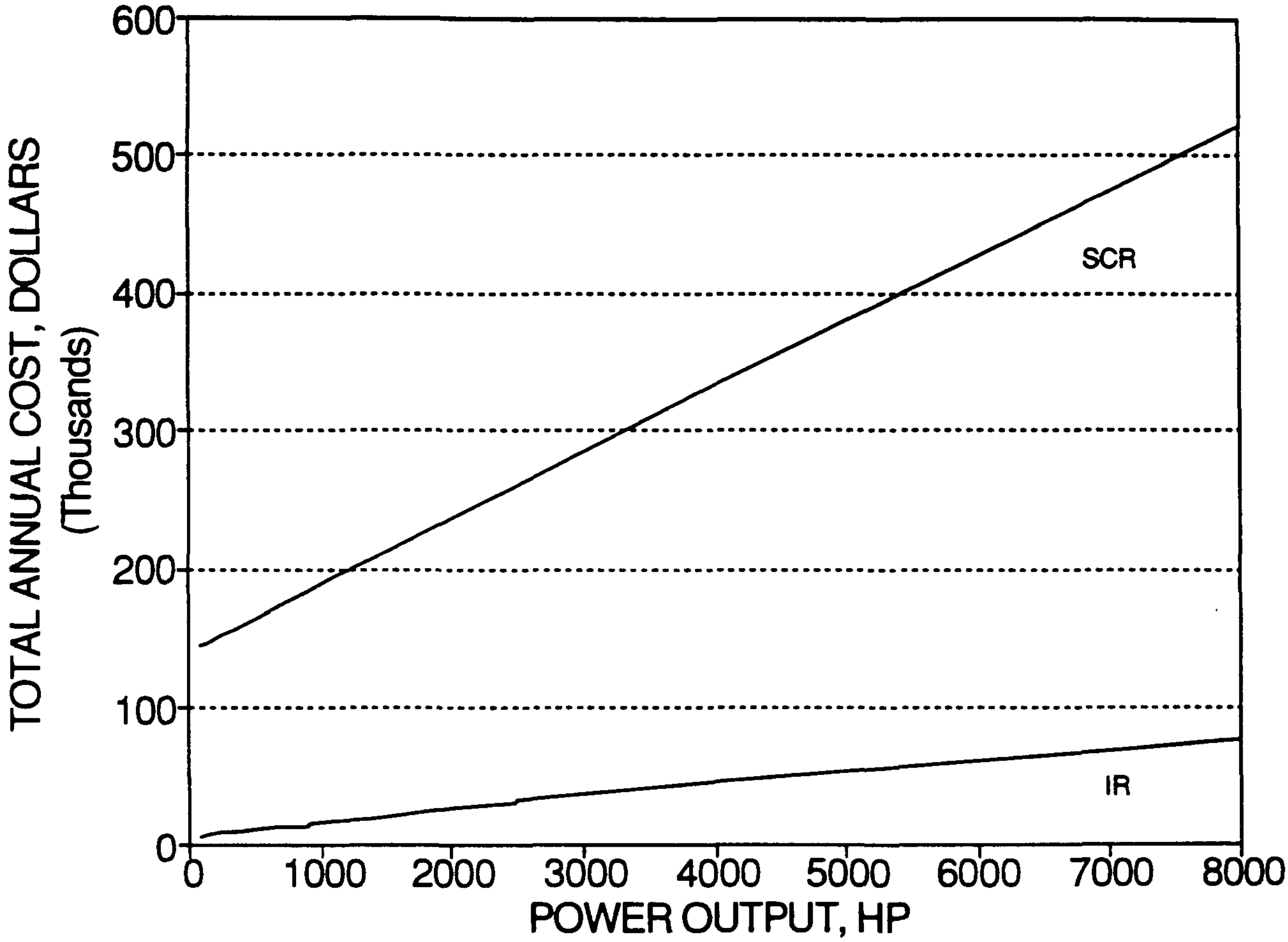


Figure 2-8. Total annual costs for NO_x control techniques applied to diesel engines (8,000 hr/yr).

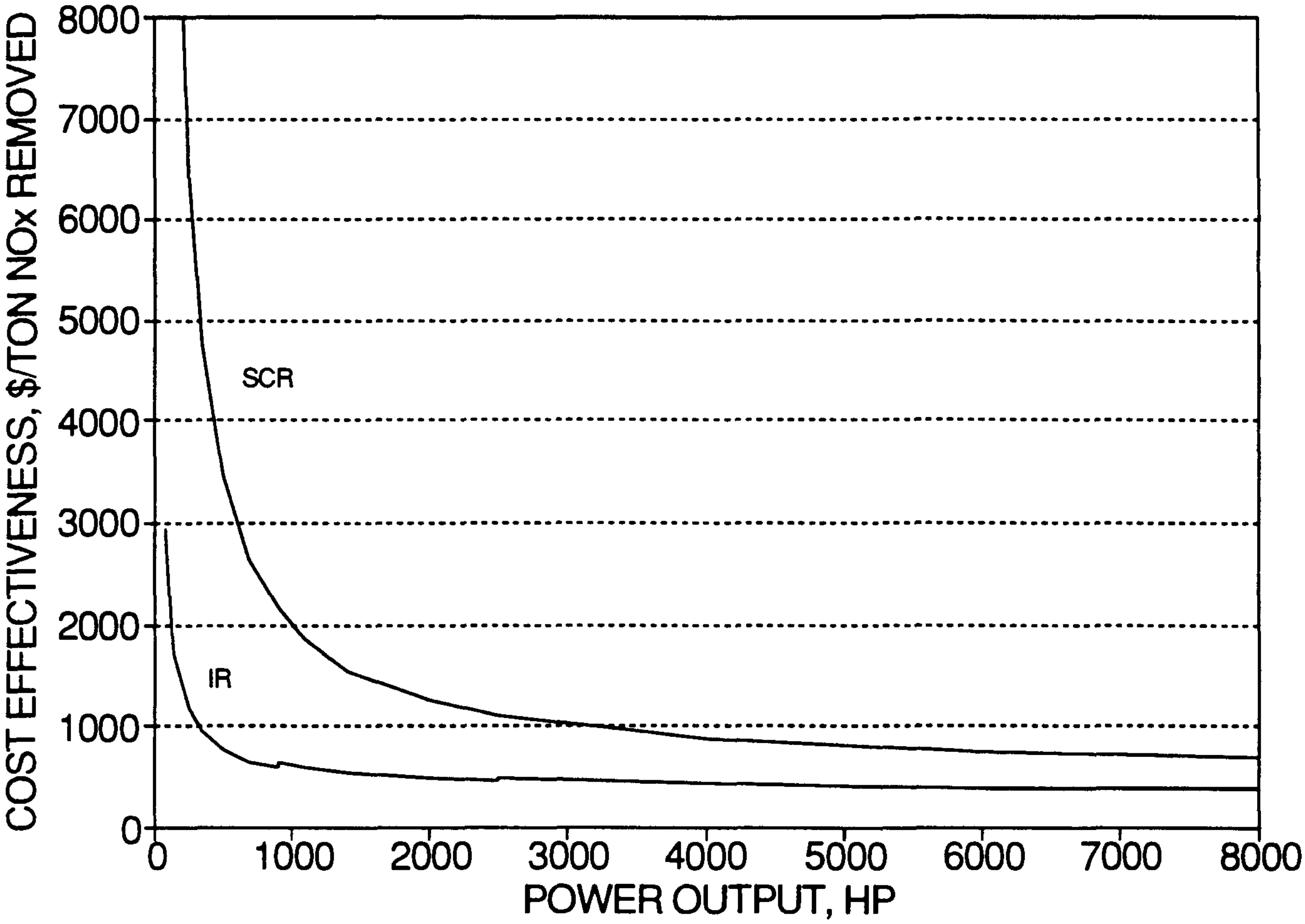


Figure 2-9. Cost effectiveness for NO_x control techniques applied to diesel engines (8,000 hr/yr).

TABLE 2-14. COSTS AND COST EFFECTIVENESS SUMMARY FOR NO_x CONTROL TECHNIQUES APPLIED TO DIESEL ENGINES

Total capital costs ($1,000)		
Engine size, hp	IR	SCR
80-500	12	195-236
501-1,000	12-16	236-285
1,001-2,500	16-24	285-431
2,501-4,000	24	431-577
4,001-8,000	24	577-967
Total annual costs ($1,000)[a]		
80-500	6.2-10	145-165
501-1,000	10-16	165-184
1,001-2,500	16-32	184-261
2,501-4,000	32-46	261-332
4,001-8,000	46-78	332-523
Cost effectiveness ($/ton)[a]		
80-500	770-2,900	3,500-19,000
501-1,000	590-770	2,000-3,500
1,001-2,500	450-590	1,100-2,000
2,501-4,000	440-450	880-1,100
4,001-8,000	370-440	690-880

[a]8,000 hr/yr.

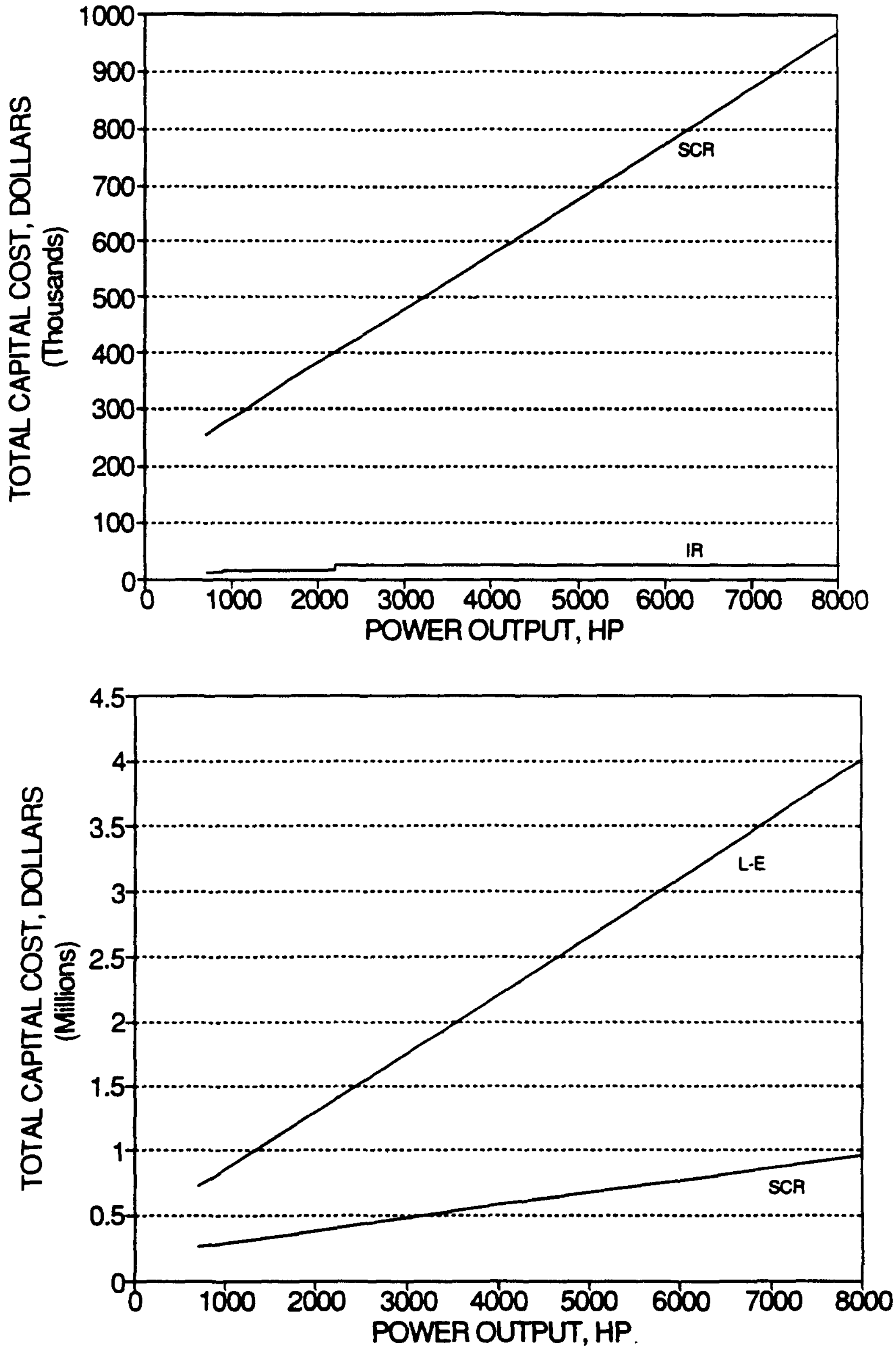


Figure 2-10. Total capital costs for NO_x control techniques applied to dual-fuel engines.

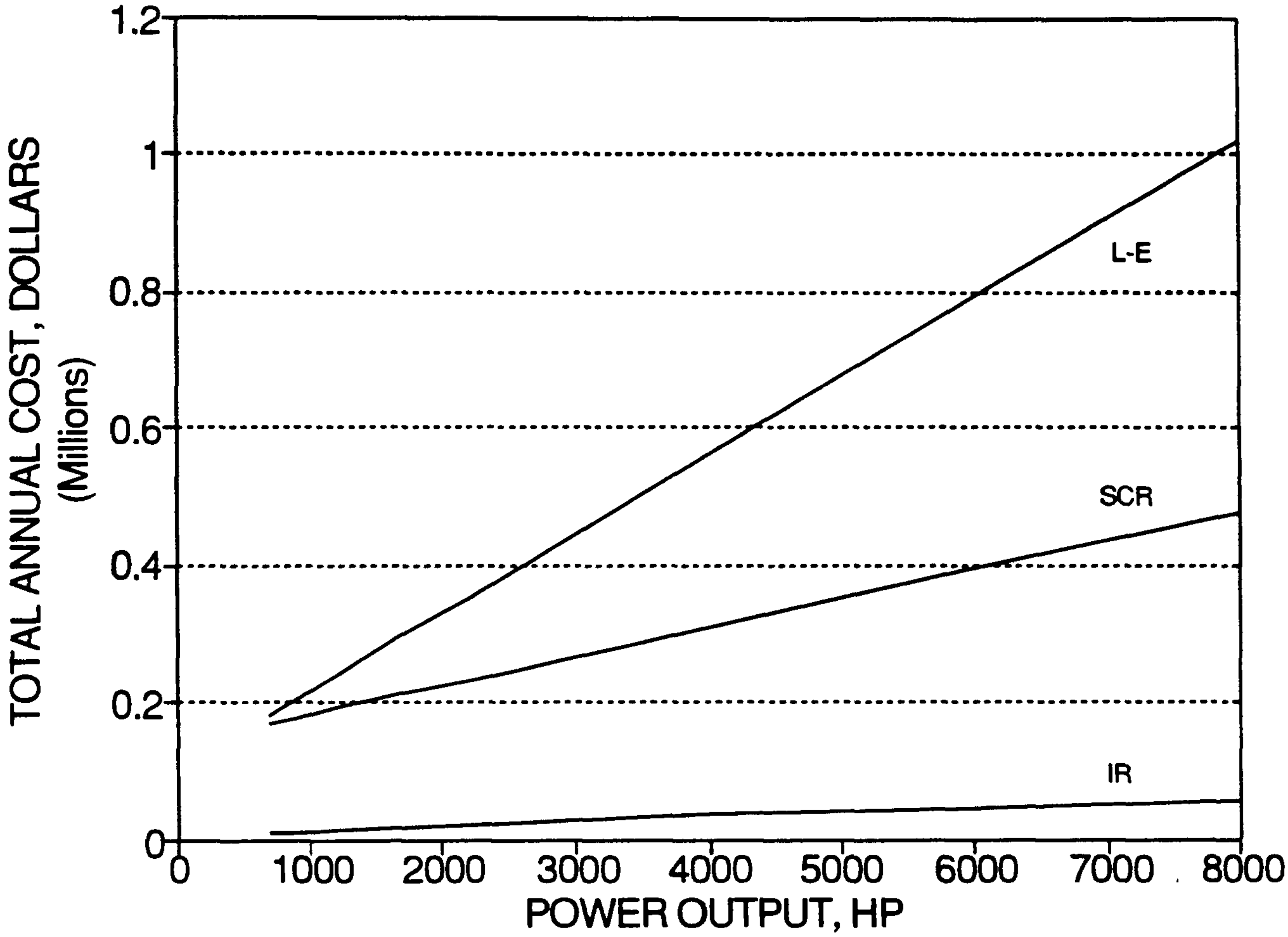


Figure 2-11. Total annual costs for NO_x control techniques applied to dual-fuel engines (8,000 hr/yr).

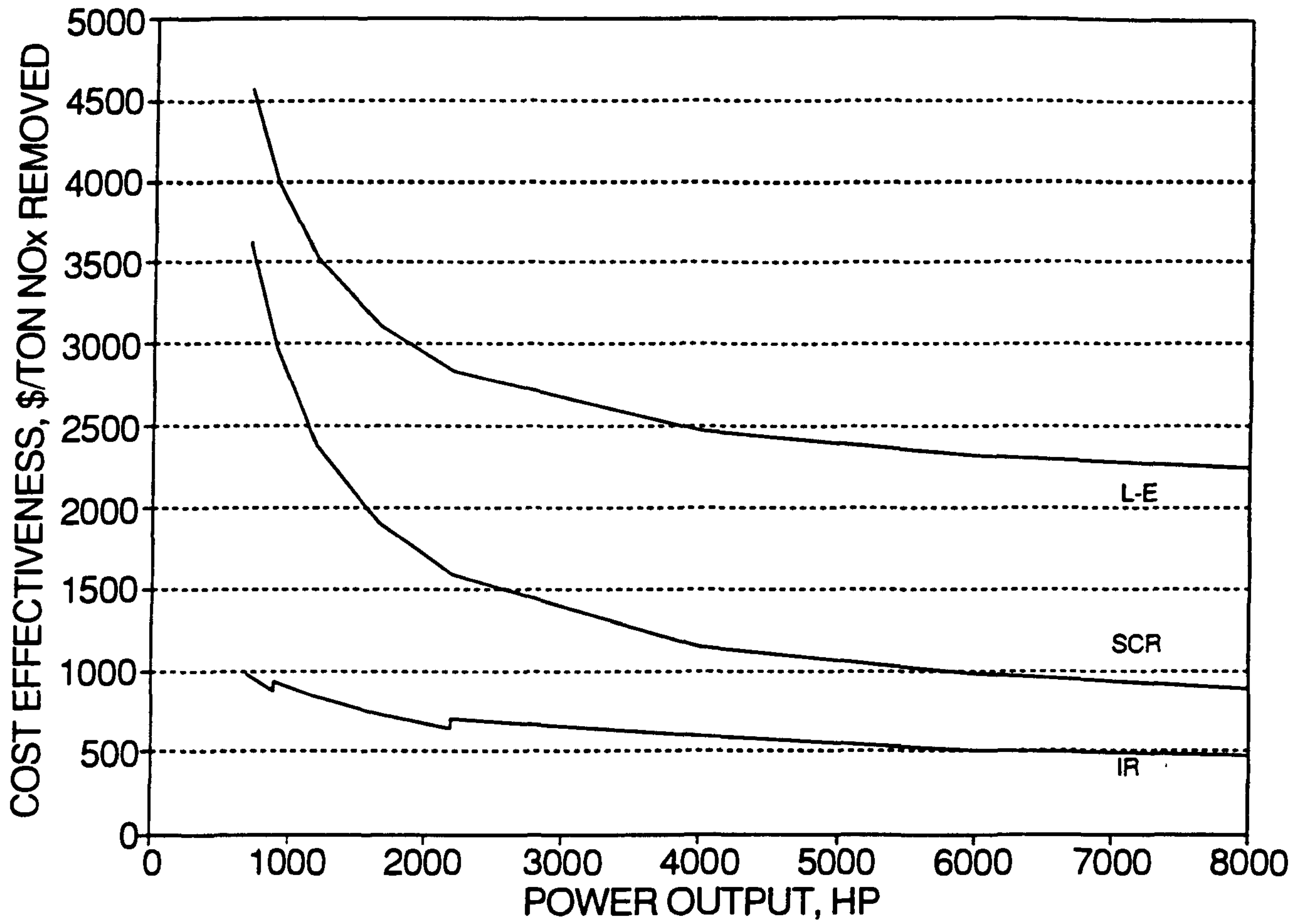


Figure 2-12. Cost effectiveness for NO_x control techniques applied to dual-fuel engines (8,000 hr/yr).

TABLE 2-15. COSTS AND COST EFFECTIVENESS SUMMARY FOR NO_x CONTROL TECHNIQUES APPLIED TO DUAL-FUEL ENGINES

Engine size, hp	IR	SCR	L-E
Total capital costs ($1,000)			
700-1,000	12-16	255-284	720-855
1,001-2,500	16-24	284-431	855-1,530
2,501-4,000	24	431-577	1,530-2,200
4,001-8,000	24	577-967	2,200-4,000
Total annual costs ($1,000)[a]			
700-1,000	10-13	170-183	182-216
1,001-2,500	13-25	183-247	216-390
2,501-4,000	25-35	247-310	390-563
4,001-8,000	35-57	310-478	563-1,020
Cost effectiveness ($/ton)[a]			
700-1,000	900-990	2,700-3,600	3,800-4,600
1,001-2,500	680-900	1,500-2,700	2,700-3,800
2,501-4,000	600-680	1,200-1,500	2,500-2,700
4,001-8,000	480-600	890-1,200	2,200-2,500

[a]8,000 hr/yr.

2.3.4.2 Total Annual Costs for Dual-Fuel Engines. Total annual costs are shown in Figure 2-11 and for IR range from $10,000 to $57,000 for engines rated from 700 to 8,000 hp. Total annual costs for SCR range from $170,000 to $478,000 and for L-E retrofit range from $182,000 to $1,020,000.

2.3.4.3 Cost Effectiveness for Dual-Fuel Engines. Cost effectiveness for control techniques applied to dual-fuel engines is shown in Figure 2-12. For IR, the cost effectiveness is less than $1,000/ton for all engines sizes, ranging from a high of $990/ton for the smallest engine (700 hp) to $480/ton for an 8,000 hp engine. The cost effectiveness for SCR ranges from $890 to $3,600 per ton and is less than $3,000/ton for engines larger than approximately 800 hp. For L-E, the cost effectiveness ranges from $2,200 to $4,600 per ton and is less than $3,000/ton for engines greater than approximately 2,000 hp.

3.0 DESCRIPTION OF INTERNAL COMBUSTION ENGINES AND INDUSTRY APPLICATIONS

Stationary reciprocating internal combustion (IC) engines are used in a wide variety of applications where mechanical work is performed using shaft power. These engines operate on the same principles as common automotive IC engines. They can be fueled with gasoline, diesel oil, natural gas, sewage (digester) gas, or landfill gases. In some engines certain mixtures of these fuels may be used. They can be built to meet a wide range of speed and load requirements, installed rapidly, and instrumented for remote operation if desired. The size of IC engine ranges from approximately 1 horsepower (hp, <1 kilowatt [kW]) to over 10,000 hp (7.5 megawatt [MW]). The smallest of these engines are typically mobile engines converted for stationary application at construction sites, farms, and households. The use of larger engines ranges from large municipal electrical generators to industrial and agricultural applications for mechanical and electric power production.[1]

This chapter describes the physical components and operating designs of IC engines, the types of fuel used, and the applications of these engines in industry and agriculture. Section 3.1 describes the operating design considerations, including ignition methods, operating cycles, and fuel charging methods. Section 3.2 discusses and compares spark-ignited and compression-ignited engines. Section 3.3 reviews available information on the applications of stationary IC engines in the oil and gas industry, in other industries and agriculture, and for electrical power generation. References are given in Section 3.4.

3.1 OPERATING DESIGN CONSIDERATIONS

All reciprocating IC engines use the same basic process. A combustible fuel-air mixture is compressed between a movable piston and its surrounding cylinder and head and is then ignited. The energy generated by the combustion process drives the piston downward. The piston's linear motion is converted via a crankshaft to rotary power. The piston returns (reciprocates), forcing out the spent combustion (exhaust) gases, and the cycle is repeated.

Reciprocating IC engines are classified primarily by the method of ignition and the type of fuel used, secondarily by the combustion cycle and the fuel-charging method, and finally by the horsepower produced. These parameters are discussed below.

3.1.1 Ignition Methods

Two methods of igniting the fuel-air mixture are used in IC engines: spark ignition (SI) and compression ignition (CI). The ignition method is closely related to the type of fuel used and the thermodynamic cycle involved.

All gasoline or natural gas engines (Otto Cycle) are SI engines. The fuel is usually premixed with air in a carburetor (for gasoline) or in the power cylinder (for gaseous fuels), then ignited in the cylinder by a spark (electrical discharge) across a spark plug.

All diesel-fueled engines (Diesel Cycle) are CI engines. Air is introduced into the cylinder and compressed. High-pressure compression raises the air temperature to the ignition temperature of the diesel fuel. The diesel fuel is then injected into the hot air and spontaneous ignition occurs.

There are variations of each of these two basic types of engines. Some CI engines are designed to use both diesel oil and gas. Injection of diesel oil into a compressed air-gas mixture initiates combustion. Such dual-fueled engines are usually designed to burn any diesel oil-gas mixture from 100 percent to 6 percent oil, based on heating values. Various methods of carburetion or fuel injection are used in SI engine designs to mix gasoline or natural gas with combustion air, which is ignited with a spark in the cylinder.[2]

The CI engines usually operate at a higher compression ratio (the ratio of the cylinder volume when the piston is at the bottom of its stroke to the volume when it is at the top) than SI engines because fuel is not present during compression; hence there is no danger of premature autoignition. Since engine thermal efficiency rises with increasing pressure ratio, CI engines are more efficient than SI engines.

3.1.2 Operating Cycles

For reciprocating IC engines, the combustion process may be accomplished with either a two-stroke or four-stroke cycle of the piston, a stroke being a movement of the piston from one end of the cylinder to the other end. Two-stroke and four-stroke operating cycles are described below.

A two-stroke cycle completes the power cycle in one revolution of the crankshaft, as shown in Figure 3-1. In the first stroke, air or an air and fuel mixture is drawn or forced into the cylinder by a low-pressure blower as the piston moves away from the bottom of the cylinder and toward the top. As the piston nears the top of the cylinder, the charge is compressed and ignited. In the second stroke, the piston delivers power to the crankshaft as it is forced downward through the cylinder by the high gas pressure produced following ignition and combustion. Eventually, the piston passes and uncovers exhaust ports (or exhaust valves open), and the combustion gases exit. As the piston begins the next cycle, exhaust gas continues to be purged from the cylinder, partially by the upward motion of the piston and partially by the scavenging action of the incoming fresh air. Finally, all ports are covered again (and/or valves closed), and the next charge of air or air and fuel is compressed in the next cycle.

Two-stroke engines have the advantage of a higher horsepower-to-weight ratio compared to four-stroke engines when both operate at the same speed. In addition, when ports are used instead of valves, the mechanical design of the engine is

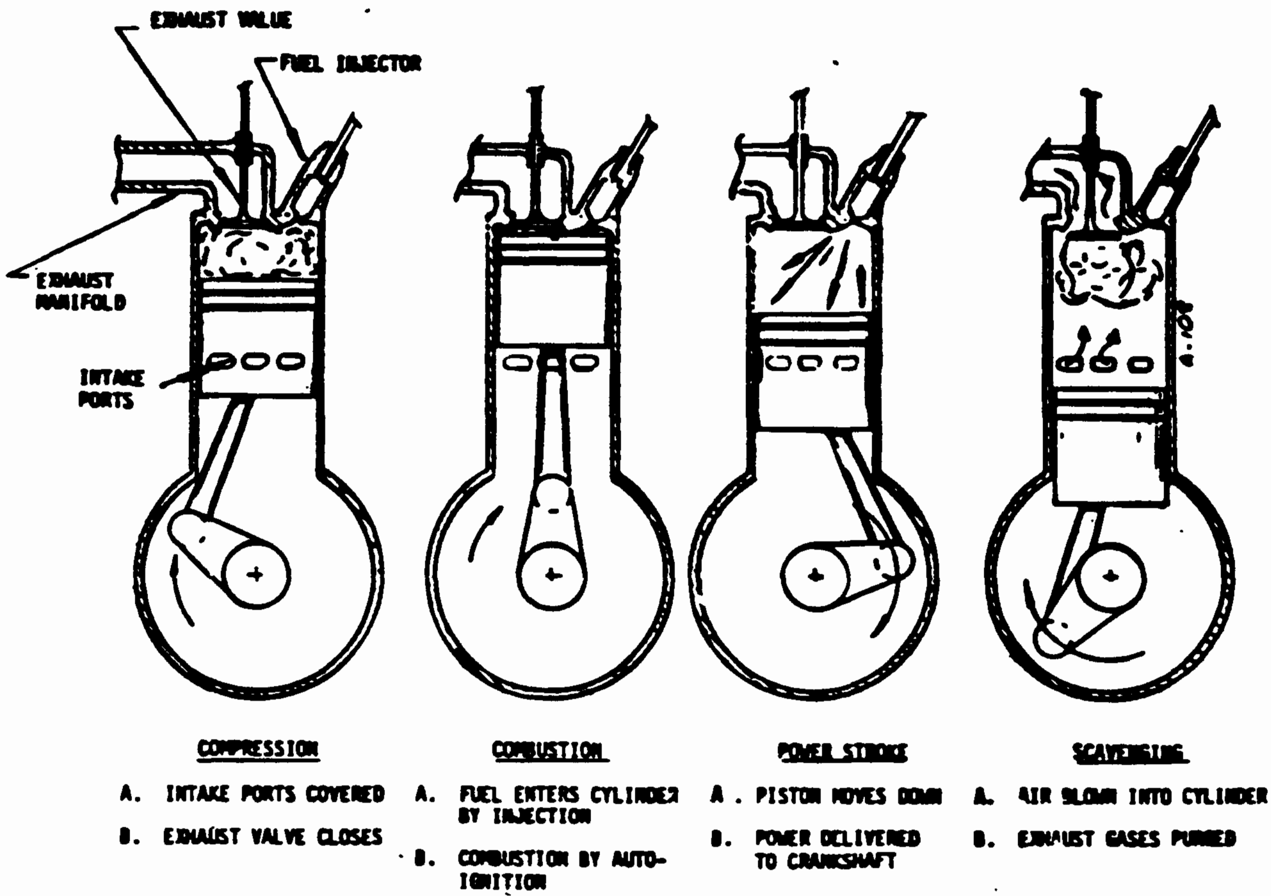


Figure 3-1. Two-stroke, compression ignition (blower-scavenged) IC engine cycle. Two strokes of 180° each of crankshaft rotation, or 360° rotation per cycle.[4]

simplified. However, combustion can be better controlled in a four-stroke engine, and excess air ratios to purge the cylinder are not as great as in a two-stroke engine. Therefore, four-stroke engines tend to be slightly more efficient and may emit less pollutants (primarily unburned hydrocarbons) than two-stroke engines.[5]

A four-stroke cycle completes the power cycle in two revolutions of the crankshaft, as shown in Figure 3-2. The sequence of events can be summarized as follows:

1. Intake stroke--The downward motion of the piston through the cylinder in a naturally aspirated engine or an exhaust-driven blower in a turbocharged engine draws or forces air or an air and fuel mixture into the cylinder.

2. Compression stroke--An upward motion of the piston compresses the air or air and fuel mixture, reducing its volume and thereby raising its temperature. Compression ratios range from 11:1 to 18:1 for a diesel engine and 7:1 to 10:1 for gasoline and natural gas engines.

3. Ignition and power (expansion) stroke--Combustion of the air-fuel mixture increases the temperature and pressure in the cylinder, driving the piston downward and delivering power to the crankshaft.

4. Exhaust stroke--An upward movement of the piston expels the exhaust gases from the cylinder.

3.1.3 Charging Methods

Three methods are commonly used to introduce or charge the air or air-fuel mixture into the cylinder(s) of an IC engine. These charging methods are natural aspiration, blower-scavenging, and turbocharging or supercharging. These charging methods are discussed below.

3.1.3.1 Natural Aspiration. A naturally aspirated engine uses the reduced pressure created behind the moving piston during the intake stroke to induct the fresh air charge, and two-stroke engines subsequently use the fresh air to assist in purging the exhaust gases by a scavenging action. This process tends to be somewhat inefficient, however, on both counts. In particular,

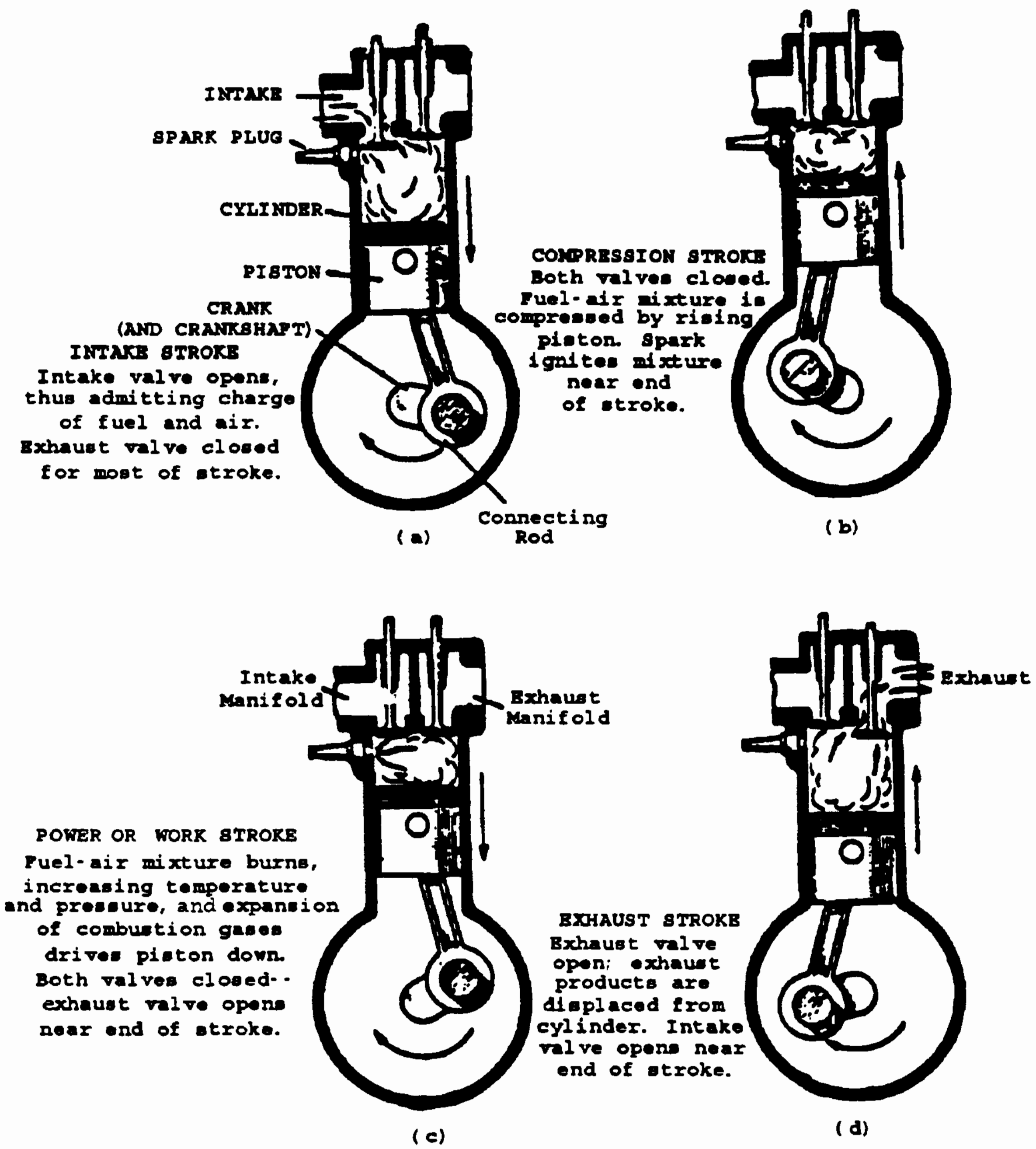


Figure 3-2. The four-stroke, spark ignition IC engine cycle. Four strokes of 180° each of crankshaft rotation, or 720° of rotation per cycle.[6]

the volume of air drawn into the cylinder by natural aspiration is usually equal to only 50 to 75 percent of the displaced volume.[7] For two-stroke engines, a more efficient method of charging the cylinder is to pressurize the air (or air and fuel) with a blower, turbocharger, or a supercharger, as described below.

3.1.3.2 <u>Blower-Scavenging.</u> Low-pressure air blowers are often used to charge two-stroke engines. Such systems are usually called blower-scavenged rather than blower-charged, however, because the high volumetric flow rates achieved are quite effective in purging the cylinder of exhaust gases, while the relatively small increase in pressure produced by the blower does not increase the overall engine efficiency nearly as much as does supercharging or turbocharging.[8]

3.1.3.3 <u>Supercharging/Turbocharging</u>. Supercharging refers to any method used to increase the charge density of the combustion air. This air charging is accomplished by placing a compressor wheel upstream of the intake air manifold. The charge compressor is driven by either the engine crankshaft (mechanical supercharging) or by energy recovered from the engine exhaust (turbocharging). Turbocharging is accomplished by placing a turbine wheel in the exhaust stream, which drives the compressor wheel. This turbine/compressor rotor is called a turbocharger. Turbocharging was originally introduced to overcome performance problems incurred with engine operation at high altitudes, where air pressure is low. The air pressurization allows a higher mass of air to be introduced into a given cylinder. For a constant air-to-fuel ratio, this increase in air mass allows a corresponding increase in fuel, so the power output for a given cylinder is increased.

Turbochargers are normally designed to increase an engine's output to approximately 1.5 times its original power. However, if the engine is constructed to withstand the higher internal pressures, turbocharging can be used to raise the engine's charging capacity, and therefore its power output, to two to three times its naturally aspirated value.[9] Turbocharging is generally offered as an option to many current naturally aspirated or blower-scavenged SI and CI engines. Turbocharging was noted to be the most common method of air pressurization for stationary diesel-fueled engines in a recent study in southern California.[10]

The large increase in air pressure achieved by turbochargers and superchargers is accompanied by an increase in temperature that, if uncontrolled, would adversely limit the amount of air that could be charged to the cylinder at a given pressure. Therefore, an intercooler or aftercooler (heat exchanger) is normally used on most larger pressure-charged IC engines to lower the temperature of the intake air, and one is always used on high-power, turbocharged SI engines fueled with natural gas to prevent premature autoignition of the fuel-air mixture. The heat exchanger is located between the turbocharger and the intake manifold, as shown in Figure 3-3. Decreasing the temperature of the air increases its density, allowing a greater mass of air and higher fuel flow rates to enter the cylinder at a given pressure, thereby increasing power output.

3.1.3.4 Fuel Delivery. In SI engines, fuel may be delivered by either a carburetor or a fuel injection system. A carburetor mixes the fuel with air upstream of the intake manifold, and this fuel/air mixture is then distributed to each cylinder by the intake manifold. Fuel injection is a more precise delivery system. With fuel injection, the fuel is injected at each cylinder, either into the intake manifold just upstream of each cylinder or directly into the cylinder itself.

All CI engines use fuel injection. Two methods of fuel injection are commonly used. Direct injection places the fuel directly into the cylinder and the principal combustion chamber. These units are also called open chamber engines because combustion takes place in the open volume bounded by the top of the piston, the cylinder walls, and the head. Indirect injection, in contrast, places the fuel into a small antechamber where combustion begins in a fuel-rich (oxygen-deficient) atmosphere and then progresses into the cooler, excess-air region

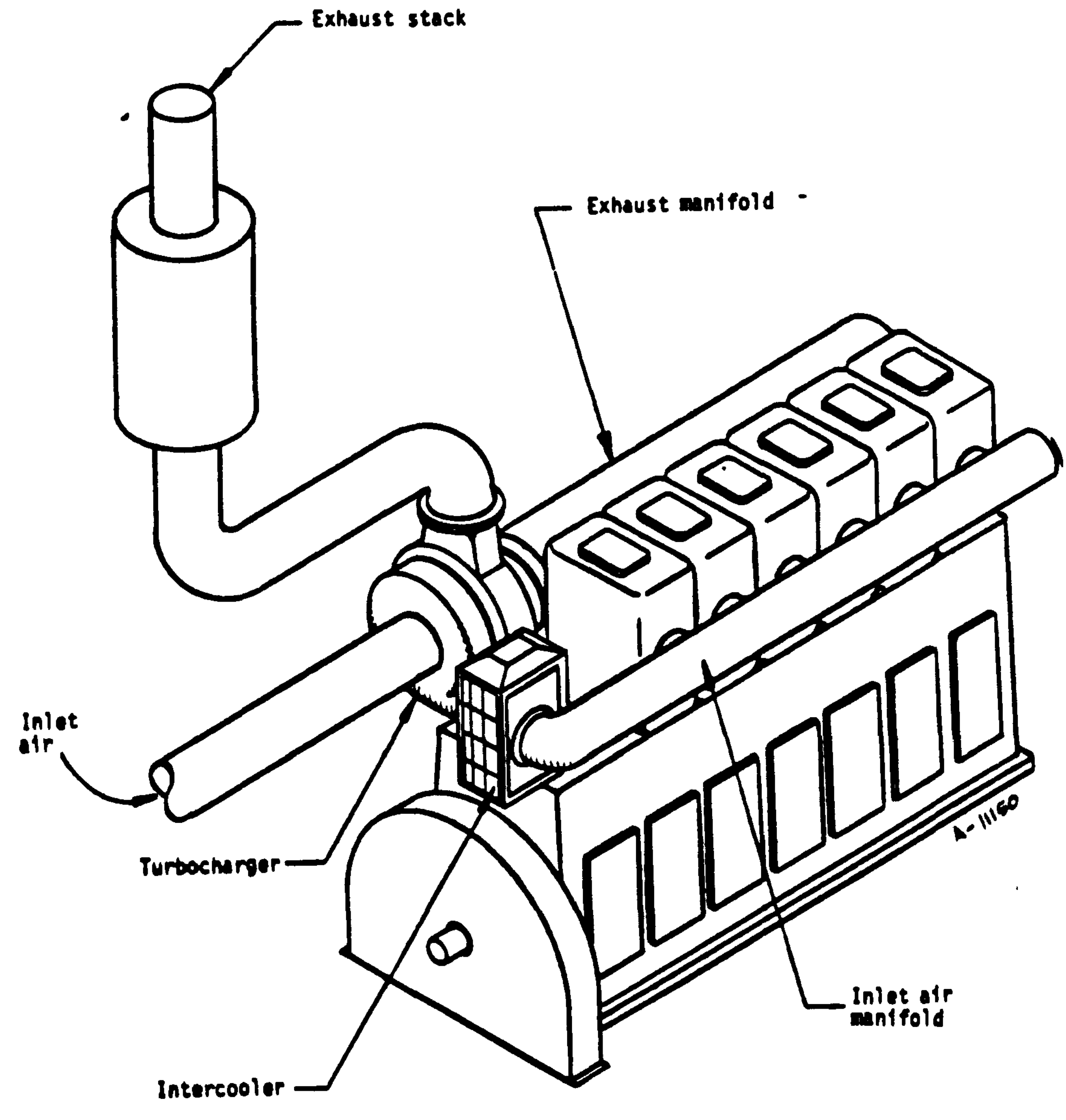


Figure 3-3. Turbocharged, intercooled, large bore IC engine.[11]

of the main chamber. These latter engines are also called divided or precombustion chamber systems.

3.2 TYPES OF FUEL

Internal combustion engines can burn a variety of fuels. The primary fuels for SI engines are natural gas or gasoline. Spark-ignited engines can be modified to burn other gaseous fuels such as digester gas, landfill gas, or coal-derived gases. For CI engines, the primary fuel is diesel oil for diesel engines and a mixture of diesel oil and natural gas for duel-fuel engines. Other fuels such as heavy fuel oil can be burned in some CI engines, but their use is limited.[12]

3.2.1 Spark-Ignited Engines

Gasoline is used primarily for mobile and portable SI engines. For stationary applications at construction sites, farms, and households, converted mobile engines typically are used because their cost is often less than an engine designed specifically for stationary purposes.[13] In addition, mobile engine parts and service are readily available, and gasoline is easily transported to the site. Thus, gasoline engines are used in some small and medium-size stationary engines applications.

Natural gas is used more than any other fuel for large stationary IC engines.[2] Natural gas-fueled engines are used to power pumps or compressors in gas processing plants and pipeline transmission stations because natural gas is available in large volumes and at low cost at such sites.

Gaseous fuels such as sewage (digester) gas and landfill gas can be used at wastewater treatment plants or landfills where the gas is available. These gaseous fuels can generally be used in the same engines as natural gas.

3.2.2 Compression-Ignited Engines

Diesel fuel, like gasoline, is easily transported and therefore is also used in small and medium-size CI engines. The generally higher efficiencies exhibited by diesel engines make diesel oil the most practical fuel for large engines where operating costs must be minimized. Natural gas, however, is often less expensive than diesel fuel and may be the primary fuel constituent in a dual-fuel CI engine.

3.3 INDUSTRY APPLICATIONS

A wide variety of applications exists for stationary reciprocating IC engines, and several types of engines are used. While IC engines are categorized by type of fuel used, air-fuel charging method, ignition method, and number of strokes per cycle (as discussed in Sections 3.1 and 3.2), their classification by size is also important when considering specific applications. The following sections describe the characteristics of engines of various sizes and the applications of stationary IC engines in four broad categories: (1) oil and gas industry, (2) general industrial and municipal usage, (3) agricultural usage, and (4) electrical power generation.

Estimates of the engine populations, where available, are provided for each industry category. These data are circa 1975 to 1978. Data from a limited number of engine manufacturers were available for engine populations sold from 1985 to 1990.[14-21] These data showed that for SI engines approximately 5,660,000 total hp (4,220 MW) was sold during this period for stationary applications. The limited data provided suggest that over 75 percent of these engines were installed in continuous-duty applications for oil and gas production, transmission, and power generation installations.

For CI engines, definitive data were not available to determine the installed horsepower sold from 1985 to 1990. The limited data provided suggest that the largest market for diesel engines under 300 hp (225 kW) is standby power generation applications, followed by agricultural and industrial applications. Less than 5 percent of diesel engines under 300 hp are used in continuous power generation. Installations for diesel engines above 300 hp are primarily power generation and are nearly evenly divided between continuous duty and standby applications. The data for duel-fuel engines, although limited, suggest that these engines are used almost exclusively for power generation, in either continuous duty or standby applications.

3.3.1 Engine Sizes

Four size classes are commonly used for stationary IC engines: (1) very small engines, (2) small engines and generators, (3) medium-bore engines, and (4) large-bore engines. Although there is some overlap between the classes, the differences tend to be more distinct when viewed on a horsepower, power-per-cylinder, or displacement-per-cylinder basis.

Very small engines typically have single cylinders with a bore (diameter) of 1 to 3 inches (in.), power ranges of 2 to 16 hp (1 to 12 kW), and very high crankshaft operating speeds in the range of 3,000 to 4,000 rpm. These are typically air-cooled gasoline engines of the type used in nonstationary applications such as lawn and garden equipment, chain saws, recreational vehicles, etc., but some are also used for operating small stationary equipment, such as appliances, air compressors, etc., where electricity is not available.[22]

Small-bore engines and generators typically have one or two cylinders of 3 to 5 in. bore each (a few have four cylinders), 3 to 50 hp (2 to 35 kW) output (3 to 15 hp [2 to 11 kW]/cylinder), and 1,000 to 4,000 rpm operation. These are sometimes called low-power, high-speed engines for industrial applications. Most of these are diesel- or gasoline-fueled four-stroke engines. Electrical power generation in remote locations is a major application. Refrigeration compressors in trucks and railroad cars and hydraulic pumps for trash compactors and tractor-trailer dump trucks are other applications.[22]

Medium-bore engines typically have multiple cylinders of 3.5 to 9 in. bore, 50 to 1,200 hp (35 to 900 kW) output (10 to 100 hp [7 to 75 kW]/cylinder), and 1,000 to 4,000 rpm operation. These are regarded as medium-power, high-speed engines. Medium-power engines are usually fueled with either diesel oil or gasoline, occasionally with natural gas. They have a lower power output per cylinder than do large-bore engines and therefore require more cylinders to achieve a given engine horsepower. The high rotary speeds and the wide range of horsepower available make medium-bore engines desirable for many uses, including agricultural, nonpropulsive marine, commercial, and miscellaneous industrial applications.[22]

Large-bore engines typically have multiple cylinders of 8 to 18 in. bore, 400 to 13,000 hp (300 to 9,700 kW) output (80 to 700 hp [60 to 520 kW]/cylinder), and 250 to 1,200 rpm operation, generally considered low- to medium-speed. Large-bore, high-power CI engines are usually four-cycle designs that can operate on either diesel oil or a duel-fuel mixture of diesel oil and natural gas. Large-bore SI engines are split about equally between two- and four-cycle designs and usually operate on natural gas. In addition, a few engines in this size class are designed to operate interchangeably as either CI or SI depending on fuel availability. The large-bore, low-speed engines, with their high power output per cylinder, are more economical to operate than medium-bore engines because of their lower fuel consumption and longer service life. Therefore, they tend to be used in applications requiring continuous operation, such as municipal electrical power generation, oil and gas pipeline transmission, and oil and gas production.[22]

3.3.2 Oil and Gas Industry

Stationary IC engines are widely used in the oil and gas industry, both in production and in transport by pipeline. Usage tends to be concentrated in the oil- and gas-producing States in the lower Midwest and the Gulf Coast and along the pipeline distribution network toward the Northeast. Most of these engines are fueled with either natural gas or diesel oil. Some dual-fueled but few gasoline engines are used in applications in this industry segment. Table 3-1 summarizes the use of stationary engines in the oil and gas industry.

The transmission of natural gas relies heavily on stationary gas-fueled engines as prime movers at pumping stations, mostly in remote locations. This use, in turn, is currently the major application for natural gas engines.[24] Nearly 7,700 prime mover engines of 350 hp (260 kW) capacity or greater were estimated in 1989 to be in operation at compressor stations. About 83 percent of these engines were reciprocating IC engines, while 17 percent

TABLE 3-1. OIL AND GAS INDUSTRY APPLICATIONS OF STATIONARY IC ENGINES CIRCA 1979[23]

Fuel	Application	Number in use	Average size, hp	Average operation, hr/yr
Natural gas	Production			
	Well drilling	3,050	350	2,000
	Well pumps	266,000	15	3,500
	Secondary recovery	5,600	200	6,000
	Plant processing	4,000	750	8,000
Natural gas	Utility compression	4,500	2,000	6,000
		4,000	750	6,000
Diesel oil	Production			
	On-land drilling	3,050	350	2,000
	Off-shore drilling	675	350	2,000
Diesel oil	Transmission	500	2,000	6,000
Dual-fueled	Transmission	a	b	6,000

Number in use was calculated from annual engine production data and estimated average service for each type of engine.

[a]Included with diesel data.
[b]Not available.

were gas turbines, which because of their larger size (1,000 to 30,000 hp [0.75 to 22.4 MW] turbines vs. 50 to 10,000 hp [0.04 to 7.5 MW] reciprocating engines) contributed about one-half of the total capacity. Nearly 350 models of reciprocating engines are in use in this application. Thirty percent of the engines in gas transmission service are more than 30 years old, and 50 years' service is not uncommon.[25]

Diesel engines are used extensively in on-land and off-shore drilling and in oil pipeline pumping. In 1979, 3,050 stationary diesel (or dual-fueled) engines were in use in on-land drilling and 675 in off-shore drilling. These engines had an average power rating of 350 hp (260 kW).[23]

3.3.3 General Industrial and Municipal Usage

The largest population of stationary reciprocating IC engines, in terms of numbers of units, is found in the general industrial category, which includes construction and some municipal water services uses. The available data showing usage by fuel type and application as of 1979 are given in Table 3-2. The data for diesel engines also include some unspecified agricultural uses; presumably these might include some compressors, pumps, standby generators, welders, etc. Small gasoline engines (<15 hp [11 kW]) are used most frequently in this category. Gasoline- and diesel-fueled standby electrical generators constitute another widely used application in this category, but these data do not include the natural gas and diesel/dual-fueled engines used for electric power generation summarized later in Section 3.3.5. Gas-fueled engines for commercial shaft power have the highest power output (2,000 hp [1,500 kW] average) in use in this category, while large diesel engines (200 to 750 hp [150-560 kW] average) are used in electric power generation, construction, industrial shaft power, and waste treatment applications.[26]

3.3.4 Agricultural Usage

Available data on the use of stationary IC engines in agriculture as of 1979 are given in Table 3-3. These data lack

TABLE 3-2. GENERAL INDUSTRIAL AND MUNICIPAL APPLICATIONS OF STATIONARY IC ENGINES CIRCA 1979[23]

Fuel	Application	No. in use[a]	Average size, hp	Average operation, hr/yr
Natural gas	Air conditioning	3,760	80	2,000
	Municipal water supply	2,100	120	3,000
	Municipal waste treatment	1,740	400	4,000
	Plant air	750	100	4,000
	Shaft power, commercial	600	2,000	1,000
	Shaft power, industrial	2,900	200	5,000
Diesel oil[b]	Construction, small	50,000	50	500
	Construction, large	50,000	240	500
	Compressor, portable[c]	90,000	75	500
	Generator sets, standby			
	<50 kw	70,000	75	500
	50-400 kw	160,000	250	250
	400-1000 kw	30,000	750	100
	Marine, nonpropulsive	15,000	100	3,500
	Miscellaneous, large[d]	30,000	750	100
	Municipal water supply	2,100	120	3,000
	Pumps	25,000	100	1,000
	Welders	80,000	100	500
Gasoline	Compressors	70,000	55	400
	Construction	40,000	150	500
	Generator sets, >5 kw	350,000	55	400
	Miscellaneous	50,000	55	400
	Small, <15 hp	63,000,000	4	50
	Welders	180,000	55	400

[a]Number in use was calculated from annual engine production data and estimated average service for each type of engine.

[b]Includes some agricultural uses.

[c]Does not include mobile refrigeration units.

[d]Includes pumps, snow blowers, aircraft turbine starters, etc.

TABLE 3-3. AGRICULTURAL APPLICATIONS OF STATIONARY IC ENGINES CIRCA 1979[23]

Fuel	Application	Number in use[a]	Average size, hp	Average operation, hr/yr
Natural gas	All	91,000	100	2,500
Diesel oil	Compressors, pumps, standby generators, welders, etc.	b	b	b
Gasoline	Irrigation Misc. machinery[c]	10,000 400,000	100 30	2,000 200

[a]Number in use was calculated from annual engine production data and estimated average service for each type of engine.

[b]Data were included in general industrial category, Table 3-2.

[c]Includes some mobile equipment such as combines, balers, sprayers, dusters, etc.

the degree of detail available for the oil and gas industry and general industrial categories.

Small to medium-size gasoline engines (30 hp [22 kW] average) for "miscellaneous machinery" constitutes the largest use class, while those used in pumping service for irrigation are larger (100 hp [75 kW] average). Other uses would include frost and pest control, harvester-mounted auxiliary power, and some remote and standby electricity generation where electric motors do not meet the need.[26]

Some natural gas- and diesel-fueled engines are also used, but data for the latter are not available separate from those given in Table 3-2 for general industrial applications.

3.3.5 Electric Power Generation

Electric power generation is one area in which stationary reciprocating IC engines do not compete with electric motors. The available installation data as of 1979 for electric power generation by natural gas, diesel, and dual-fuel engines is shown in Table 3-4. These data do not include smaller generators used to supply power locally for industrial and agricultural equipment or for standby/emergency needs in those industries. In some cases, the demarcation between categories cannot be discerned with certainty from the available data.

The data in Table 3-4 indicate that gas-fueled engines used to operate emergency/standby generators were the largest application, in terms of units in service (2,000) in this category in 1979. Information provided by diesel engine manufacturers suggests that many small diesel engines have been installed in standby power generation applications. One manufacturer reported total sales of approximately 1 million hp between 1985 and 1990 for diesel engines of 300 hp (225 KW) or less for standby power generation. The South Coast Air Quality Management District has permitted more than 400 diesel engines for standby power generation.[10] The engine/generator sets are installed at hospitals, banks, insurance companies, and other facilities where continuity of electrical power is critical. This reference states that these are typically medium-power

TABLE 3-4. ELECTRICAL POWER GENERATION BY STATIONARY IC ENGINES CIRCA 1979[23]

Fuel	Application	No. in use[a]	Average Size, hp	Average operation, hr/yr	Output, million hp-hr/yr x 10^6
Natural gas	Emergency/standby	2,000	100	50	9
	Industrial on-site	1,500	300	4,000	1,080
	Commercial/institutional	450	200	4,000	162
	Private/public utility	b	b	b	166
Diesel oil[b]	All	400	2,500	2,600	2,160
Dual-fueled	All	d	b	b	6,000
Gasoline	e	e	e	e	e

[a]Number in use was calculated from annual engine production data and estimated average service for each type of engine.
[b]Not available.
[c]Does not include generators counted in general industrial usage, Table 3-2.
[d]Included with diesel data.
[e]See general industrial (Table 3-2) and agricultural (Table 3-3) applications.

(100 hp [75 kW]/cylinder), high-speed (1,000 rpm), four-cycle engines that are turbocharged and after-cooled.

The data in Table 3-4 show that the diesel and dual-fueled engines are by far the largest (2,000 hp [1,500 kW] average) used for electrical generation, but they do not provide details of specific applications. Dual-fuel, large-bore CI engines are used almost exclusively for prime electrical power generation in order to take advantage of the economy of natural gas and the efficiency of the diesel engine.[27]

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4.0 CHARACTERIZATION OF NO_x EMISSIONS

This chapter discusses the formation of NO_x emissions in reciprocating internal combustion (IC) engines. Section 4.1 describes how NO_x and other emissions are formed during the combustion process. Factors that influence the rate of formation of NO_x and other emission are discussed in Section 4.2. Uncontrolled emission factors are presented in Section 4.3. References for this chapter are listed in Section 4.4.

4.1 FORMATION OF EMISSIONS

The primary focus of this document is NO_x emissions, and the formation of NO_x is discussed in Section 4.1.1. Efforts to reduce NO_x emissions can affect the formation of carbon monoxide (CO) and hydrocarbons (HC), however, and the formation of these emissions is briefly presented in Section 4.1.2.

4.1.1 The Formation of NO_x

The combustion of an air/fuel mixture in the cylinder of an IC engine results in the dissociation of nitrogen (N_2) and oxygen (O_2) into N and O, respectively. Reactions following this dissociation result in seven known oxides of nitrogen: NO, NO_2, NO_3, N_2O, N_2O_3, N_2O_4, and N_2O_5. Of these, nitric oxide (NO) and nitrogen dioxide (NO_2) are formed in sufficient quantities to be significant in atmospheric pollution.[1] In this document, "NO_x" refers to either or both of these gaseous oxides of nitrogen.

Virtually all NO_x emissions originate as NO. This NO is further oxidized in the exhaust system or later in the atmosphere to form the more stable NO_2 molecule.[2] There are two mechanisms by which NO_x is formed in an IC engine: (1) the oxidation of atmospheric nitrogen found in the combustion air (thermal NO_x) and (2) the conversion of nitrogen chemically bound in the fuel

(fuel NO_x, or organic NO_x). These mechanisms are discussed below.

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

$$O_2 \rightarrow 2O$$
$$O + N_2 \rightarrow NO + N$$
$$N + O_2 \rightarrow NO + O$$

The reaction rate toward NO formation increases exponentially with temperature. The NO further oxidizes to NO_2 and other NO_x compounds downstream of the combustion chamber.

4.1.1.2 Formation of Fuel NO_x. Fuel NO_x (also known as organic NO_x) is formed when fuels containing nitrogen are burned. Nitrogen compounds are present in coal and petroleum fuels as pyridine-like (C_5H_5N) structures that tend to concentrate in the heavy resin and asphalt fractions upon distillation. Some low-British thermal unit (Btu) synthetic fuels contain nitrogen in the form of ammonia (NH_3), and other low-Btu fuels such as sewage and process waste-stream gases also contain nitrogen. When these fuels are burned, the nitrogen bonds break and some of the resulting free nitrogen oxidizes to form NO_x.[3] With excess air, the degree of fuel NO_x formation is primarily a function of the nitrogen content in the fuel. The fraction of fuel-bound nitrogen (FBN) converted to fuel NO_x decreases with increasing nitrogen content, although the absolute magnitude of fuel NO_x increases. For example, a fuel with 0.01 percent nitrogen may have 100 percent of its FBN converted to fuel NO_x, whereas a fuel with a 1.0 percent FBN may have only a 40 percent fuel NO_x conversion rate. While the low-percentage-FBN fuel has a 100 percent conversion rate, its overall NO_x emission level would be lower than that of the high-percentage FBN fuel with a 40 percent conversion rate.[4]

Nitrogen content varies from 0.1 to 0.5 percent in most residual oils and from 0.5 to 2 percent for most U.S. coals.[5]

Traditionally, most light distillate oils have had less than 0.015 percent nitrogen content by weight. However, today many distillate oils are produced from poorer-quality crudes, especially in the northeastern United States, and these distillate oils may contain percentages of nitrogen exceeding the 0.015 threshold. These higher nitrogen contents increase fuel NO_x formation.[6]

Most IC engines are presently fueled by natural gas or light distillate oil that typically contains little or no FBN. As a result, when compared to thermal NO_x, fuel NO_x is not currently a major contributor to overall NO_x emissions from most IC engines.

4.1.2 Formation of Other Emissions

The formation of CO and HC is briefly discussed in this section.

4.1.2.1 Carbon Monoxide (CO). Carbon monoxide is an intermediate combustion product that forms when the oxidation of CO to CO_2 cannot proceed to completion. This situation occurs if there is a lack of available oxygen, if the combustion temperature is too low, or if the residence time in the cylinder is too short.[7]

4.1.2.2 Hydrocarbons (HC). The pollutants commonly classified as hydrocarbons are composed of a wide variety of organic compounds. They are discharged into the atmosphere when some of the fuel remains unburned or is only partially burned during the combustion process. This incomplete burning usually occurs as a result of inadequate mixing of fuel and air, incorrect air/fuel ratios, or "quenching" of the combustion products by the combustion chamber surfaces.[4]

Nonmethane hydrocarbons (NMHC) are sometimes categorized separately from methane HC's because NMHC's react with NO_x in the lower atmosphere, contributing to the formation of photochemical smog. Methane does not readily react with NO_x in the lower atmosphere, so methane HC emissions are not a major concern in some regulated areas.[8]

4.2 FACTORS THAT INFLUENCE NO_x EMISSIONS

Engine design and operating parameters, type of fuel, and ambient conditions all have an impact on NO_x emissions from IC engines. These factors are discussed in this section.

4.2.1 Engine Design and Operating Parameters

Variations in engine design or operating parameters will affect emissions. These parameters may be divided into five classes: (1) air-to-fuel ratio (A/F) and charging method; (2) ignition timing; (3) combustion chamber valve design; (4) engine combustion cycle; and (5) operating load and speed.

4.2.1.1 Air-to-Fuel Ratio and Charging Method. The formation rate of NO_x increases with increases in combustion temperature. Maximum temperatures occur when the A/F is just above stoichiometric. The relationship between A/F and NO_x formation is shown in Figure 4-1. This figure shows that maximum NO_x formation rates occur in the region of stoichiometric A/F's due to the high combustion temperatures. In any engine, as the A/F decreases from stoichiometric, NO_x formation decreases due to a lack of excess oxygen. As the A/F increases from stoichiometric, NO_x formation first increases with the presence of additional oxygen, then steadily decreases as the A/F increases beyond stoichiometric.[9]

Emissions of CO increase sharply, as shown in Figure 4-1, at fuel-rich A/F's due to the lack of oxygen to fully oxidize the carbon. As the A/F is increased toward fuel-lean conditions, excess oxygen is available and CO emissions decrease as essentially all carbon is oxidized to CO_2. Emissions of HC increase at fuel-rich A/F's because insufficient oxygen levels inhibit complete combustion. At fuel-lean A/F's, HC emissions increase slightly as excess oxygen cools combustion temperatures and inhibits complete combustion.

The operational range of lean A/F's is often restricted by the charging method. Turbocharged, fuel-injected engines have precise A/F control at each cylinder and can operate at A/F's approaching lean flammability limits. Naturally aspirated engines have imprecise carbureted A/F control and must operate at

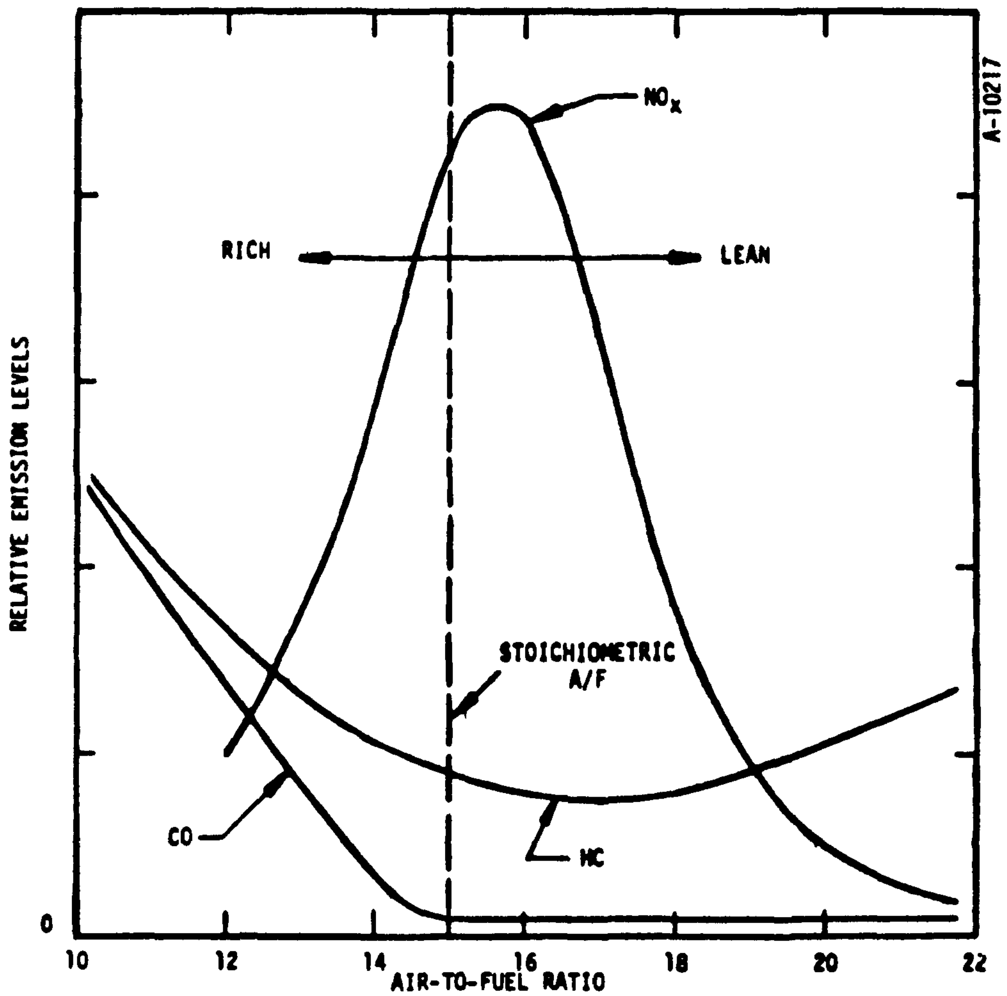

Figure 4-1. Effect of air/fuel ratio on NO_x, CO, and HC emissions.[9]

richer A/F's to avoid excessively lean mixtures at individual cylinders, which can result in incomplete combustion or misfiring.[10]

4.2.1.2 Ignition Timing. As discussed in Chapter 3, combustion is initiated by the injection of fuel oil in compression-ignited engines and by a spark in spark-ignited engines. By delaying, or retarding, the timing of ignition, the combustion process occurs later in the power cycle. Ignition retard, therefore, effectively increases the combustion chamber volume, which reduces pressures in the cylinder and may lower combustion temperatures. These changes in combustion conditions result in lower NO_x emission levels in most engines.[10,11] Emissions of CO and HC are not significantly affected by timing retard except in extreme cases where misfiring can occur.

Timing retard lowers NO_x levels significantly, but the lower combustion pressures result in reduced cycle efficiency and, therefore, increased engine fuel consumption. Excessive smoke may also result from moderate to high degrees of ignition retard in diesel engines.[12] Increased exhaust smoke from ignition timing retard may result in increased soot levels in the lube oil, which requires more frequent oil changes.[11]

4.2.1.3 Combustion Chamber and Valve Design. Almost any variation in cylinder or valve design will affect emissions. Unfortunately, the effects cannot be quantified since each engine is different and changing some design variables may cancel any beneficial effects of others. However, some generalizations can be made. Design variables that improve mixing within the cylinder tend to decrease emissions. Improvements in mixing may be accomplished through swirling the air or fuel-air mixture within the cylinder, improving the fuel atomization, and optimizing the fuel injection locations. Decreasing the cylinder compression ratio may reduce NO_x emissions, especially in older engine designs.[11]

The vintage and accumulated operating hours of an engine may affect emission rates. Engine manufacturers may implement changes to the combustion chamber and valve designs over the production life of an engine model, making emission rates dependent upon the date of manufacture. Also, maintenance practices can affect long-term engine performance, resulting in changes in emission rates among otherwise identical engines.

4.2.1.4 Engine Combustion Cycle. As discussed in Chapter 3, reciprocating IC engines may be either two- or four-stroke cycle. During combustion, emissions from either type are similar.[13] However, several events during the charging of a two-cycle engine may affect emission levels. On noninjected engines, the scavenge air, which purges the cylinder of exhaust gases and provides the combustion air, can also sweep out part of the fuel charge. Thus, carbureted two-cycle engines often have higher HC emissions in the form of unburned fuel.

If the cylinder of a two-stroke engine is not completely purged of exhaust gases, the result is internal exhaust gas recirculation (EGR). The remaining inert exhaust gases absorb energy from combustion, lowering peak temperatures and thereby lowering NO_x.

4.2.1.5 Effects of Load and Speed. The effect of operating load and engine speed on emissions varies from engine to engine. One manufacturer states that for SI engines the total NO_x emissions on a mass basis (e.g., lb/hr) increase with increasing power output. On a power-specific (also referred to as brake-specific, e.g., g/hp-hr) basis, however, NO_x emissions decrease with increasing power levels.[11] Test data for a second manufacturer's SI engine shows that NO_x emissions decrease with increases in load if the engine speed decreases with decreasing load. If the engine speed is held constant, however, brake-specific NO_x emission levels decrease with decreasing engine load.[14] In general, diesel compression ignition engines exhibit decreasing brake-specific NO_x emissions with increasing load at constant speed. This is partly caused by changes in the A/F ratio. Some turbocharged engines show the opposite effect of increasing brake-specific NO_x emissions as load increases.

In diesel engines, carbon monoxide emissions first decrease with increasing load (equivalent to increasing temperature) and then increase as maximum load is approached. Brake-specific HC emissions decrease with increasing load as a result of increasing temperature. For naturally aspirated engines, smoke emissions generally reach their maximum at full load. Turbocharged engines, however, offer the potential to optimize the engine at full load and minimize smoke emissions at full load. Natural gas engines follow the same trends as diesel engines for HC and CO.[10] As this discussion indicates, the effect of engine load and speed on NO_x, CO, and HC emissions is engine-specific.

4.2.2 Fuel Effects

As discussed in Section 4.1.1, overall NO_x emissions are the sum of fuel NO_x and thermal NO_x. Fuel NO_x emissions increase with increases in FBN content, and using residual or crude oil increases fuel NO_x and hence total NO_x emissions. Similarly, using gaseous fuels with significant FBN contents such as coal gas or waste stream gases increases NO_x emissions when compared to natural gas fuel. Quantitative effects were not available.

Thermal NO_x levels are also influenced by the type of fuel. Landfill and digester (or sewage) gases and propane are examples of alternate fuels for SI engines, and the relative emission levels for landfill gas, propane, and natural gas are shown in Figure 4-2. Landfill and digester gases have relatively low Btu contents compared to those of natural gas and propane and therefore have lower flame temperatures, which result in lower NO_x emissions. Because the stoichiometric A/F is different for each gas, emissions are shown in Figure 4-2 as a function of the excess air ratio rather than A/F. The excess air ratio is defined as:

$$\textit{Excess air ratio } (\lambda) = \frac{A/F \textit{ actual}}{A/F \textit{ stoichiometric}}$$

Figure 4-2 shows that the effect of alternative fuels is greatest at A/F's from near-stoichiometric to approximately 1.4, which is within the operating range of rich-burn and lean-burn SI engine designs. The effect of alternate fuels on emissions is minimal for low-emission engine designs that operate at higher

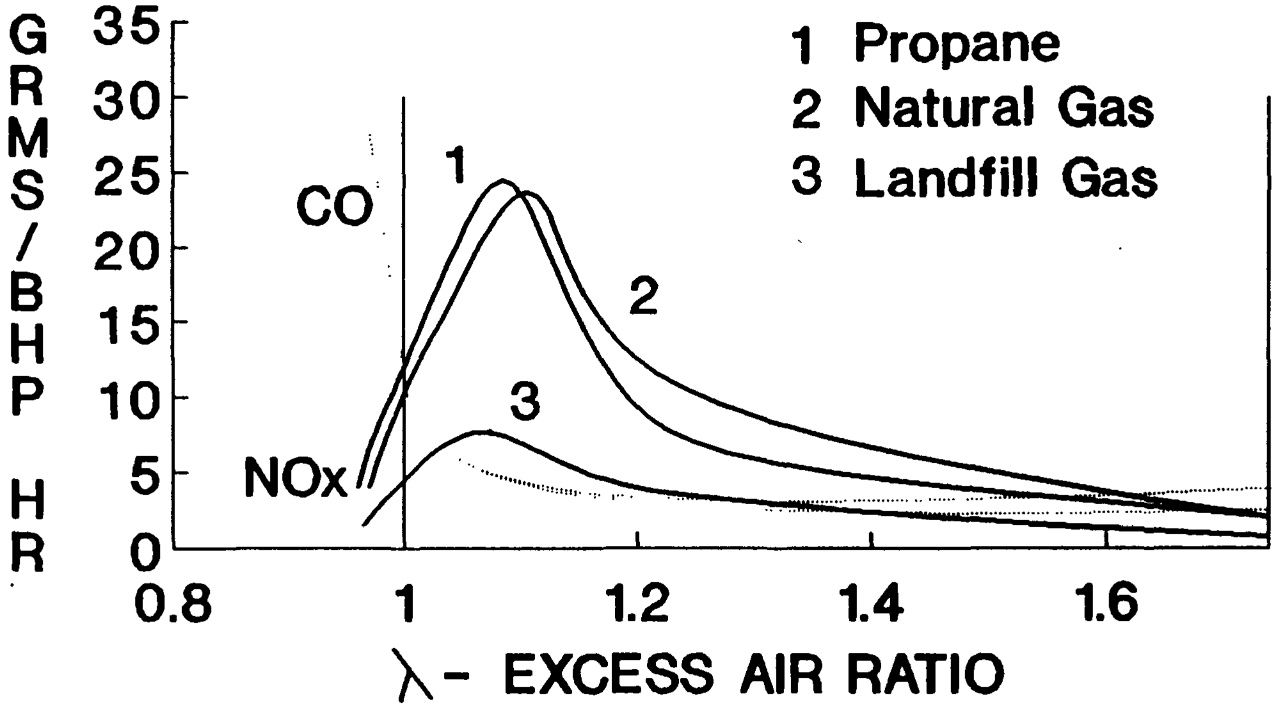

Figure 4-2. Impact of different fuels on NO_x and CO emissions[15]

A/F's and relatively low combustion temperatures. Fuel effects on CO emissions, as shown in Figure 4-2, are minimal.[15]

4.2.3 Ambient Conditions.

The effects of atmospheric conditions on NO_x emissions have been evaluated by several sources, predominately by or for automotive engine manufacturers. These test results indicate changes in NO_x of up to 25 percent caused by ambient temperature changes and up to 40 percent caused by ambient pressure changes.[16] Most of these effects are caused by changes in the A/F as the density of the combustion air changes. Humidity has an additional effect on lowering NO_x in that high-moisture conditions reduce the peak temperatures within the engine cylinders, decreasing NO_x emissions by up to 25 percent.[17]

The design A/F varies for different IC engines, so engines respond differently to changes in atmospheric conditions. Thus it is quite difficult to quantify atmospheric effects on engine emissions. However, the following general effects have been observed for engines operating close to stoichiometric conditions:[17]

1. Increases in humidity decrease NO_x emissions;
2. Increases in intake manifold air temperature may increase HC and CO emissions; and
3. Decreases in atmospheric pressure increase HC and CO emissions.

4.3 UNCONTROLLED EMISSION LEVELS

Stationary IC engine sizes vary widely, so comparisons of emissions among a group of engines require that emissions be presented on a brake-specific, mass-per-unit-power-output basis. In this document emissions are expressed in units of grams per horsepower-hour (g/hp-hr). For conversion to parts per million by volume (ppmv) at 15 percent O_2, the following approximate conversion factors are used in this document:[18]

<u>NO_x emissions</u>:

rich-burn engines: 1 g/hp-hr = 67 ppmv

lean-burn engines: 1 g/hp-hr = 73 ppmv

<u>CO emissions</u>:

rich-burn engines: 1 g/hp-hr = 110 ppmv

lean-burn engines: 1 g/hp-hr = 120 ppmv

<u>HC emissions</u>:

rich-burn engines: 1 g/hp-hr = 194 ppmv

lean-burn engines: 1 g/hp-hr = 212 ppmv

Uncontrolled emission levels were provided by several engine manufacturers. These emissions levels were tabulated and averaged for engines with similar power ratings. The range of NO_x emissions and the average for engine size categories from 0 to 4,000+ hp are shown in Table 4-1. Most manufacturers provided emission data only for current production engines, but some included older engine lines as well. For rich-burn engines, the average NO_x emission level ranges from 13.1 to 16.4 g/hp-hr (3.54 to 4.87 pounds/million Btu's [lb/MMBtu]). For lean-burn engines, the average ranges from 7.9 to 18.6 g/hp-hr (1.99 to 5.46 lb/MMBtu). The 7.9 g/hp-hr shown for the smallest lean-burn engine category is considerably lower than for the other lean-burn engines. This figure reflects unusually low NO_x emissions reported for one manufacturer's line of engines. Excluding this engine line yields emission levels similar to those shown for other lean-burn engine categories (i.e., 17.0 to 17.5 g/hp-hr). For diesel engines, NO_x emissions range from 11.2 to 13.0 g/hp-hr (3.66 to 4.26 lb/MMBtu). Dual-fuel engines have the lowest NO_x emission rates, ranging from 4.9 to 10.7 g/hp-hr (1.75 to 3.26 MMBtu).

TABLE 4-1. AVERAGE NO_x EMISSIONS FOR IC ENGINES[18-25]

Size category, hp	Number of engines in data base	Average heat rate, Btu/hp-hr[a]	Uncontrolled NO_x emissions			
			Highest	Lowest	Average	
			g/hp-hr	g/hp-hr	g/hp-hr[a]	lb/MMBtu[b]
Rich-Burn SI Engines[c]						
0-200	8	8,140	15.8	9.1	13.1	3.54
201-400	13	7,820	23.5	9.1	16.4	4.62
401-1000	31	7,540	22.4	10.4	16.3	4.76
1001-2000	19	7,460	25.0	13.0	16.3	4.81
2001-4000	10	6,780	18.0	13.0	15.0	4.87
4001+	2	6,680	14.0	14.0	14.0	4.62
Lean-Burn SI Engines[c]						
0-400	7	8,760	17.5	3.0	7.9	1.99
401-1000	17	7,660	27.0	15.5	18.6	5.35
1001-2000	43	7,490	27.0	14.0	17.8	5.23
2001-4000	30	7,020	27.0	10.0	17.2	5.40
4001+	25	6,660	17.5	10.0	16.5	5.46
Diesel CI Engines[d]						
0-200	12	6,740	17.1	10.0	11.2	3.66
201-400	8	6,600	19.0	7.6	11.8	3.94
401-1000	22	6,790	19.0	9.0	13.0	4.22
1001-2000	14	6,740	19.0	8.5	11.4	3.73
2001-4000	6	6,710	14.0	9.3	11.4	3.74
4000+	6	6,300	12.0	12.0	12.0	4.20
Dual Fuel CI Engines[e]						
700-1200	5	6,920	13.0	9.3	10.0	3.18
1201-2000	3	7,220	13.0	6.2	10.7	3.26
2001-4000	5	6,810	13.0	5.0	8.4	2.72
4000+	4	6,150	5.0	4.5	4.9	1.75

[a]Calculated from figures corresponding to International Standards Organization (ISO) conditions, as provided by engine manufacturers.
[b]lb/MMBtu = (g/hp-hr)*(lb/454 g)*(1/heat rate)*10^6.
[c]Natural gas fuel.
[d]No. 2 diesel oil fuel.
[e]Natural gas and No. 2 diesel oil fuel.

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21. Letter and attachment from Iocco, D. E., Dresser-Rand, to Snyder, R. B., Midwest Research Institute. October 1, 1991. Internal combustion engines.

22. Letter and attachment from McCormick, W. M., Cooper Industries--Ajax Superior Division, to Snyder, R. B., Midwest Research Institute. September 16, 1991. Internal combustion engines.

23. Letter and attachment from Axness, J., Deere Power Systems Group, to Snyder, R. B., Midwest Research Institute. August 30, 1991. Internal combustion engines.

24. Letter and attachment from Fisher, J., Detroit Diesel Corporation, to Jordan, B. C., EPA/ESD . June 10, 1992. Internal combustion engines.

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5.0 NO_x CONTROL TECHNIQUES

This chapter describes NO_x emission control techniques for reciprocating engines. For each control technique, the process description, extent of applicability, factors that affect the performance, and achievable controlled emission levels are presented. The effect of NO_x reduction on carbon monoxide (CO) and unburned hydrocarbon (HC) emissions is also discussed. Some regulatory agencies speciate nonmethane hydrocarbon (NMHC) emissions from total hydrocarbon (THC) emissions. Where HC emission levels presented in this chapter are not speciated, it is expected that the emission levels correspond to NMHC rather than THC emissions. Emissions are stated in units of grams per horsepower-hour (g/hp-hr) and parts per million by volume (ppmv). The first units reported are those reported in the referenced source; the corresponding units given in parentheses were calculated using the conversion factors shown in Section 4.3.. It should be noted that these conversion factors are approximate only, and the calculated emission levels shown in parentheses using these conversion factors are provided for information only. Unless noted otherwise, all emission levels reported in units of ppmv are referenced to 15 percent oxygen.

Some control techniques discussed in this chapter require that additional equipment be installed on the engine or downstream of the engine in the exhaust system. Issues regarding the point of responsibility for potential engine mechanical malfunctions or safety concerns resulting from use of the control techniques presented are not evaluated in this document.

All IC engines can be classified as either rich-burn or lean-burn. A rich-burn engine is classified as one with an air-to-fuel ratio (A/F) operating range that is near stoichiometric or fuel-rich of stoichiometric, and can be adjusted to operate with an exhaust oxygen (O_2) concentration of 1 percent or less. A lean-burn engine is classified as one with an A/F operating range that is fuel-lean of stoichiometric, and cannot be adjusted to operate with an exhaust concentration of less than 1 percent. All naturally aspirated, spark-ignition (SI) four-cycle engines and some turbocharged SI four-cycle engines are rich-burn engines. All other engines, including all two-cycle SI engines and all compression-ignition (CI) engines (diesel and dual-fuel), are lean-burn engines.

This chapter presents NO_x control techniques by engine type (i.e., rich-burn or lean-burn) to enable the reader to identify available NO_x control techniques for a particular engine type. Section 5.1 describes NO_x control techniques for rich-burn engines. Lean-burn SI engine NO_x control techniques are presented in Section 5.2. Lean-burn CI engine NO_x control techniques are presented in Section 5.3. Section 5.4 describes NO_x control techniques including exhaust gas return (EGR), engine derate, water injection, and alternate fuels that are not considered viable at this time because of marginal NO_x reduction efficiencies and/or lack of commercial availability. References for Chapter 5 are listed in Section 5.5.

The discussion of each control technique is organized to include:

1. Process description;
2. Applicability to new and/or existing IC engines;
3. Factors that affect NO_x reduction performance; and
4. Achievable emission levels and test data.

The annual emission reduction based on the achievable controlled NO_x emissions levels is quantified and presented in Chapter 7 for each control technology.

5.1 NO_x CONTROL TECHNIQUES FOR RICH-BURN ENGINES

Rich-burn engines operate at A/F's near or fuel-rich of stoichiometric levels, which results in low excess O_2 levels and therefore low exhaust O_2 concentrations. The rich-burn engine classification is given in the introduction of this chapter. Four-cycle, naturally aspirated SI engines and some four-cycle, turbocharged SI engines are classified as rich-burn engines.

The control technologies available for rich-burn engines are:

1. Adjustments to A/F;
2. Ignition timing retard;
3. Combination of A/F adjustment and ignition timing retard;
4. Prestratified charge (PSC®);
5. Nonselective catalytic reduction (NSCR); and
6. Low-emission combustion.

5.1.1 Adjustment of A/F in Rich-Burn Engines

5.1.1.1 Process Description. Rich-burn engines can operate over a range of A/F's. The A/F can be adjusted to a richer setting to reduce NO_x emissions. As shown in Figure 5-1, small variations in the A/F for rich-burn engines have a significant impact on emissions of NO_x as well as on those of carbon monoxide (CO) and hydrocarbons (HC).[1] In the fuel-rich environment at substoichiometric A/F's, NO_x formation is inhibited due to reduced O_2 availability and consequent lower combustion temperatures. Incomplete combustion in this fuel-rich environment, however, raises CO and HC emission levels.[2]

5.1.1.2 Applicability. Adjustment of the A/F can be performed in the field on all rich-burn engines. For effective NO_x reductions, most engines require that an automatic A/F feedback controller be installed on the engine to ensure that NO_x reductions are sustained with changes in operating parameters such as speed, load, and ambient conditions.[3] For some turbocharged engines, A/F adjustments may require that an exhaust bypass system with a regulator valve be installed to regulate the airflow delivered by the turbocharger.[3] In addition to maintaining effective emissions control, an automatic A/F controller also avoids detonation (knock) or lean misfire with changes in engine operating parameters.

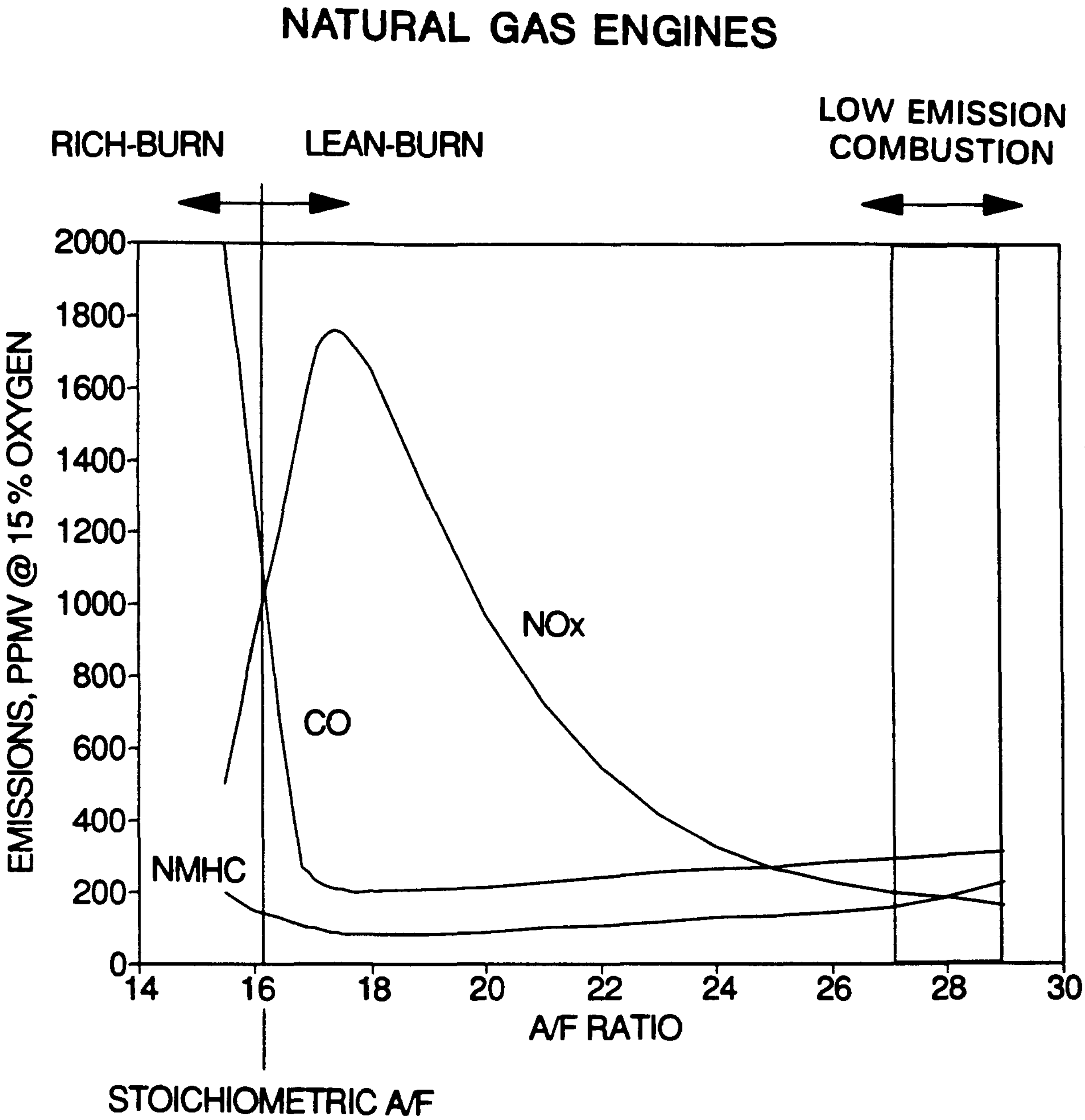


Figure 5-1. The effect of air-to-fuel ratio on NO_x, CO, and HC emissions.[1]

5.1.1.3 Factors that Affect Performance. As shown in Figure 5-1, A/F adjustment toward fuel-rich operation to reduce NO_x results in rapid increases in CO and, to a lesser extent, HC emissions. The extent to which the A/F can be adjusted to reduce NO_x emissions may be limited by offsetting increases in CO emissions. As discussed in Section 5.1.1.2, an automatic A/F controller may be required to maintain the A/F in the relatively narrow band that yields acceptable NO_x emission levels without allowing simultaneous CO emission levels to become excessive.

Adjusting the A/F also results in changes in fuel efficiency and response to load characteristics. Adjusting the A/F to a richer setting reduces NO_x emissions, but increases the brake-specific fuel consumption (BSFC) while improving the engine's response to load changes. Conversely, adjusting the A/F to a leaner setting increases NO_x emissions, decreases BSFC, and decreases the engine's ability to respond to load changes.[4,5]

5.1.1.4 Achievable Emission Reduction. Table 5-1 shows estimated emissions for adjusting the A/F for one manufacturer's rich-burn, medium-speed engines.[4] These engines are rated at 2,000 hp or lower. As this table shows, adjusting the A/F ratio from the leanest to the richest setting can reduce NO_x emissions from an average of 19.2 to 8.0 g/hp-hr. The corresponding increases in average CO and HC emissions are 1.0 to 33.0 g/hp-hr and 0.2 to 0.3 g/hp-hr, respectively. As Table 5-1 indicates, NO_x reductions at the richest A/F's are accompanied by substantial increases in CO emissions of 24 g/hp-hr or more; increases in HC emissions are relatively minor.

A summary of emission test results from A/F adjustments performed on seven rich-burn, medium-speed engines is shown in Table 5-2.[6] Controlled NO_x emissions ranged from 1.52 to 5.70 g/hp-hr, which represents reductions from uncontrolled levels ranging from 10 to 72 percent. Emissions of CO and HC were not reported. The average controlled NO_x emission level for the seven engines was 3.89 g/hp-hr, an average reduction of 45 percent from the average uncontrolled NO_x emission level of 7.22 g/hp-hr. The uncontrolled NO_x emissions from these engines

TABLE 5-1. RANGE OF EMISSIONS RESULTING FROM A/F ADJUSTMENT FOR ONE MANUFACTURER'S RICH-BURN, MEDIUM-SPEED ENGINES[4]

Model series	Emissions, g/hp-hr[a]						Air-to-fuel, mass basis	
	Richest A/F			Leanest A/F				
	NO_x	CO	HC[b]	NO_x	CO	HC[b]	Richest A/F	Leanest A/F
1	7.0	28	0.3	18	1	0.2	15.5:1	17:1
2	10	25	0.3	25	0.5	0.2	15.5:1	18:1
3	8.3	34	0.4	20.7	0.8	0.3	15.5:1	17.4:1
4	8.0	30.5	0.2	24	0.6	0.1	15.5:1	18:1
5	8.5	35	0.4	20	1.0	0.2	15.5:1	17:1
6	7.0	34	0.3	16	1.0	0.3	15.5:1	17:1
7	7.5	45	0.4	11	2.0	0.3	15.15:1	17:1
Average	8.0	33	0.3	19.2	1.0	0.2		

[a]Based on natural gas fuel, hydrogen/carbon ratio of 3.85.
[b]Nonmethane hydrocarbons only.

TABLE 5-2. ACHIEVABLE CONTROLLED EMISSION LEVELS USING A/F ADJUSTMENT[6]

Engine No.	Rated power output, hp	Uncontrolled emissions		Controlled emissions		Percent reduction
		NO_x, g/hp-hr	ppmv	NO_x, g/hp-hr	ppmv	
1	620	10.5	3,060	5.38	1,560	49
2	620	10.7	1,560	5.70	830	47
3	450	7.9	1,970	3.76	1,050	47
4	620	5.4	814	1.52	228	72
5	620	5.4	857	3.71	591	31
6	620	5.4	805	2.30	346	57
7	620	5.4	901	4.84	812	10
AVERAGES		7.2		3.89		45

Notes:

1. Emission levels were reported in g/hp-hr and ppmv. Units of ppmv were not referenced to any oxygen level.
2. CO and HC emissions were not reported.

are considerably lower than the 13 to 27 g/hp-hr range for uncontrolled NO_x emissions shown in Table 4-1 for rich-burn engines in this range of engine power output. The A/F corresponding to the uncontrolled and controlled emission levels was not reported, so the extent to which the A/F was adjusted is not known. The engines shown in Tables 5-1 and 5-2 are all medium-speed engines rated at 2,000 hp or less. For low-speed engines, one manufacturer reports that A/F adjustment for these rich-burn engines results in potential NO_x emission reductions ranging to 45 percent.[7]

All available sources indicate that the achievable NO_x reductions using A/F adjustment are highly variable, even among identical engine models. Based on the available data, it is estimated that NO_x emissions can be reduced between 10 and 40 percent using A/F adjustment. A reduction of 20 percent is used to calculate controlled NO_x emission levels and cost effectiveness in Chapter 6.

Adjusting the A/F to a richer setting improves the engine's response to load changes but results in an increase in BSFC. One engine manufacturer estimates the increase in BSFC to be 1 to 5 percent.[7]

5.1.2 Adjustment of Ignition Timing in Rich-Burn Engines

5.1.2.1 Process Description. Adjusting the ignition timing in the power cycle affects the operating pressures and temperatures in the combustion chamber. Advancing the timing so that ignition occurs earlier in the power cycle results in peak combustion when the piston is near the top of the cylinder, when the combustion chamber volume is at a minimum. This timing adjustment results in maximum pressures and temperatures and has the potential to increase NO_x emissions. Conversely, retarding the ignition timing causes the combustion process to occur later in the power stroke when the piston is in its downward motion and combustion chamber volume is increasing. Ignition timing retard reduces operating pressures, temperatures, and residence time and has the potential to reduce NO_x formation.

5.1.2.2 Applicability. Adjustment of the ignition timing can be performed in the field on all rich-burn engines. Sustained NO_x reduction and satisfactory engine operation, however, typically require replacement of the ignition system with an electronic ignition control system.[8] The electronic control system automatically adjusts the ignition timing to maintain satisfactory engine performance with changes in operating parameters and ambient conditions.

5.1.2.3 Factors That Affect Performance. Adjustment to retard the ignition timing from the standard setting may reduce NO_x emissions, but it also affects other engine parameters. Shifting the combustion process to later in the power cycle increases the engine exhaust temperature, which may affect turbocharger speed (if the engine is so equipped) and may have detrimental effects on the engine exhaust valves. Brake-specific fuel consumption also increases, as does the potential for misfire. Engine speed stability, power output, and response to load changes may also be adversely affected. These effects on engine parameters occur continuously and proportionately with increases in timing retard and generally limit ignition retard to 4° to 6° from the standard setting.[9]

5.1.2.4 Achievable Emission Reduction. Ignition timing can typically be adjusted in a range of up to approximately 4° to 6° from the standard timing setting to reduce NO_x emissions. The extent of ignition retard required to achieve a given NO_x reduction differs for each engine model and operating speed. For example, 2° to 4° of retard is likely to achieve a greater NO_x reduction on an engine with an operating speed of 500 to 1,000 rpm than an engine with an operating speed of 2,000 to 3,000 rpm.[3] Data to quantify the effect of ignition retard on rich-burn engines were available from three engine manufacturers. The first manufacturer indicates that, in general, NO_x emission reductions of up to 10 percent can be achieved by retarding ignition timing.[7] The second manufacturer provided emission data for an engine operated at three ignition timing settings.[9] These data, plotted in Figure 5-2, suggest that the NO_x reduction achieved by ignition retard in rich-burn engines largely depends upon the A/F. For operation near and rich of stoichiometric, timing retard has only a small effect on NO_x levels. According to the manufacturer, this minimal effect is thought to be because the lack of oxygen and lower temperatures in this A/F range substantially mitigate the effect of any further peak temperature and pressure reduction achieved by retarding the ignition timing. For above-stoichiometric A/F's, ignition retard reduces NO_x emissions, but Figure 5-2 shows that these reductions are realized only at near-peak NO_x emission levels. A third manufacturer provided data, presented in Figure 5-3, for a rich-burn engine that indicates potential NO_x reductions for a 5° retard ranging from 10 to 40 percent, depending upon the A/F.[10] Unlike the plot shown in Figure 5-2, potential NO_x reductions increase at richer A/F's.

The available data suggest that the effect of ignition timing on NO_x reduction is engine-specific, and also depends on the A/F. The achievable NO_x reduction ranges from essentially no reduction to as high was 40 percent, depending on the engine model and the A/F. A reduction of 20 percent is used to calculate controlled NO_x emission levels and cost effectiveness in Chapter 6.

Timing retard greater than approximately 4° to 6° results in marginal incremental NO_x reduction and negative engine performance as described in Section 5.1.2.3. The increase in BSFC corresponding to increases in timing retard was estimated by one manufacturer to range up to approximately 7 percent.[7]

Emissions of CO and HC are largely insensitive to changes in ignition timing.[5,10] The higher exhaust temperatures resulting from ignition retard tend to oxidize any unburned fuel or CO, offsetting the effects of reduced combustion chamber residence time.

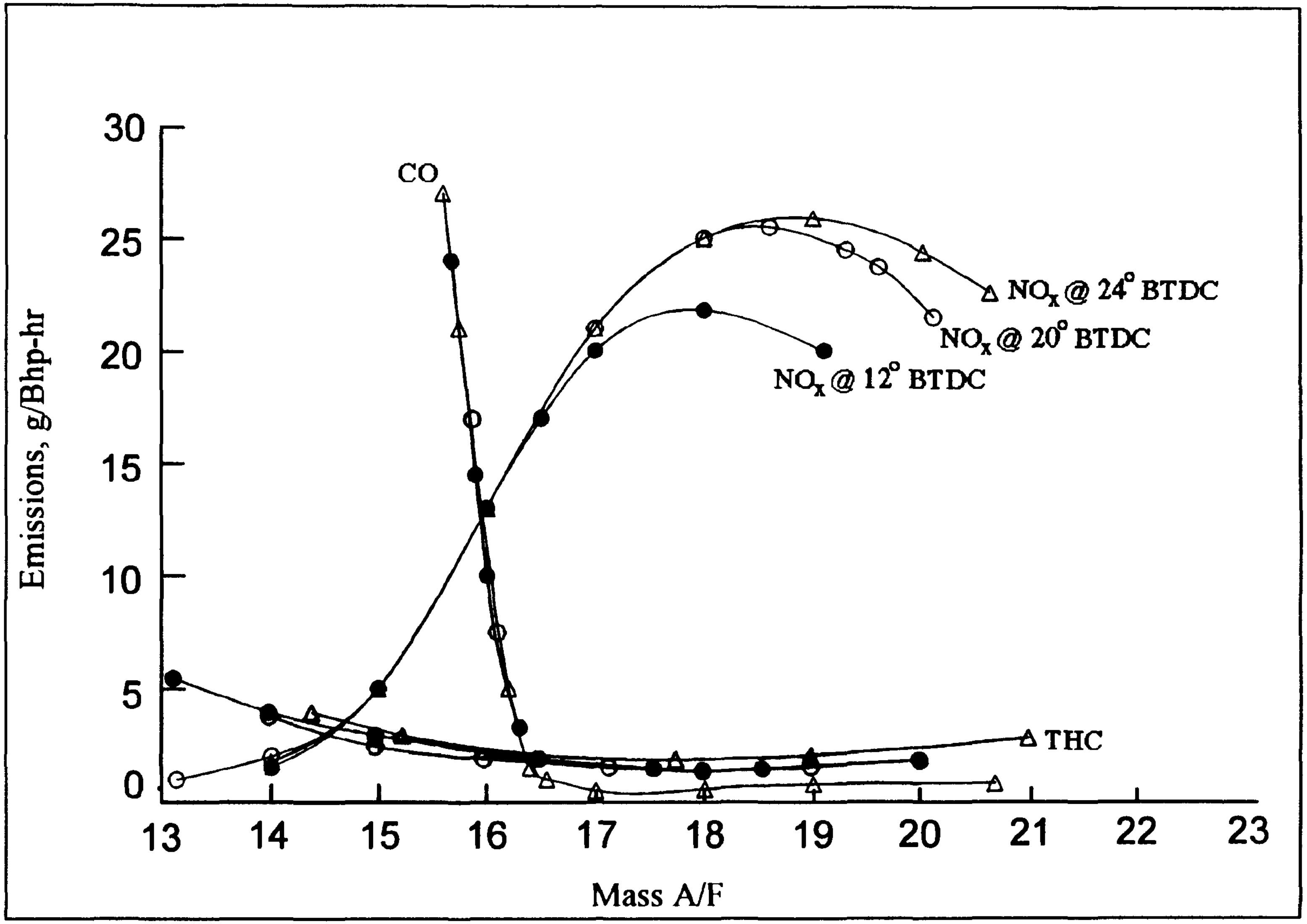


Figure 5-2. Parametric adjustments and the effect of ignition timing retard for a rich-burn engine model.[9]

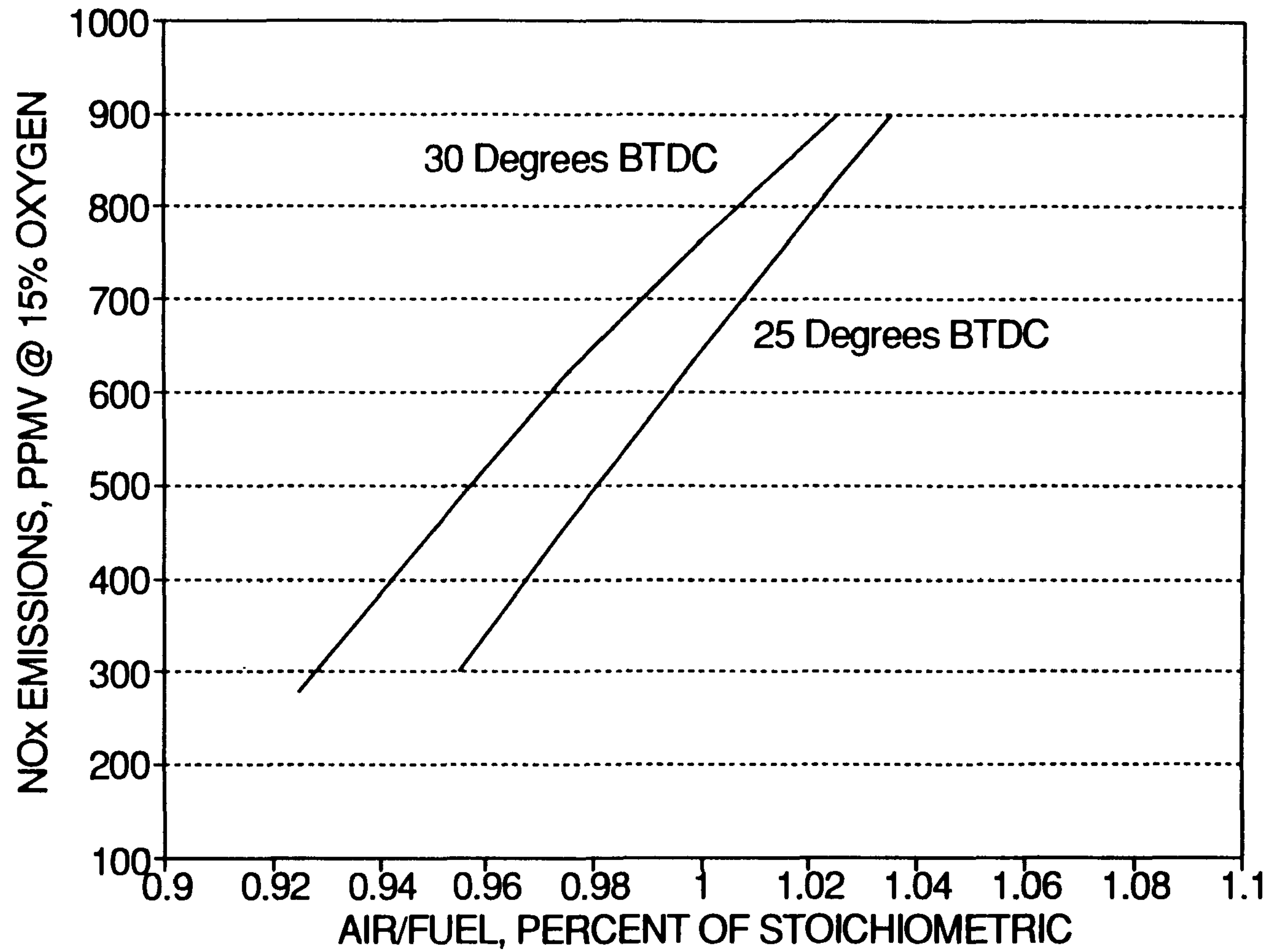


Figure 5-3. Parametric adjustments and the effect of ignition timing retard for a second rich-burn engine model.[10]

5.1.3 Combination of A/F Adjustment and Ignition Timing Retard

Either A/F adjustment or ignition timing retard can be used independently to reduce NO_x emissions from rich-burn engines. These control techniques can also be applied in combination. Automated controls for both A/F and ignition timing are required for sustained NO_x reductions with changes in engine operating conditions. As is the case with either control technique used independently, potential NO_x reductions for the combination of control techniques are engine-specific. As previously shown for one manufacturer's engines in Figure 5-2, A/F adjustment to a richer setting achieves the greatest NO_x reductions, and at these sub-stoichiometric A/F's, ignition timing retard achieves little or no further NO_x reduction. A manufacturer of low-speed engines also reports that the range of achievable NO_x reductions is the same for the combination of A/F adjustment and ignition timing retard as for A/F adjustment alone.[7] The data presented in Figure 5-3 also support this conclusion. The minimum controlled NO_x emission level using A/F adjustment is not further reduced with a 5° ignition timing retard from the 30° setting.

Figure 5-3, however, does show that the combination of A/F and timing retard offers some flexibility in achieving NO_x reductions. For example, a controlled NO_x emission level of 400 ppmv (5.3 g/hp-hr) represents a NO_x reduction of over 50 percent from maximum emission levels for the engine shown in Figure 5-3. While Figure 5-3 shows that this controlled NO_x emission level can be achieved by A/F adjustment alone, using a 5° ignition timing retard in combination with A/F adjustment achieves the 400 ppmv controlled NO_x level at a higher (leaner) A/F. Since parametric adjustments affect such operating characteristics as fuel consumption, response to load changes, and other emissions, the combination of parametric adjustments offers the potential to reduce NO_x emissions while minimizing the impact on other operating parameters. In particular, CO emissions rise sharply as the A/F is reduced but are largely insensitive to ignition timing retard. Using timing retard in combination with A/F adjustment may allow the engine to achieve a given NO_x reduction at a higher A/F, thereby minimizing the increase in CO emissions.

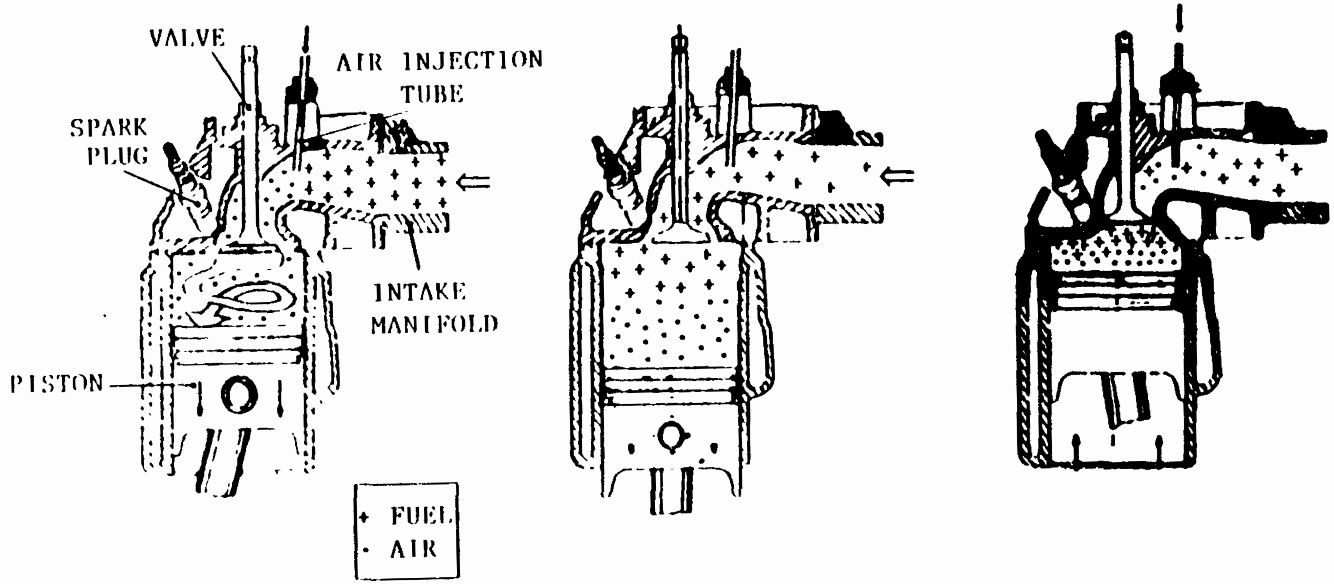
Based on the available data, it is expected that NO_x reductions of 10 to 40 percent can be achieved using a combination of A/F adjustment and ignition timing retard. While this is the same range expected for A/F adjustment alone, the combination of control techniques offers the potential in some engines to achieve NO_x reductions at the upper end of this range with reduced impacts on CO emissions or other operating characteristics. A reduction of 30 percent is used to calculate controlled NO_x emission levels and cost effectiveness in Chapter 6.

5.1.4 Prestratified Charge (PSC®)

5.1.4.1 Process Description. Prestratified charge injects air into the intake manifold in a layered, or stratified, charge arrangement. As shown in Figure 5-4, the resulting stratification of the air/fuel mixture remains relatively intact when drawn into the combustion chamber and provides a readily ignitable mixture in the vicinity of the spark plug while maintaining an overall fuel-lean mixture in the combustion chamber.[11] This stratified charge allows a leaner A/F to be burned without increasing the possibility of misfire due to lean flammability limits. This leaner combustion charge results in lower combustion temperatures, which in turn lower NO_x formation.[12]

A PSC® kit consists of new intake manifolds, air hoses, air filters, control valve(s), and either a direct mechanical linkage to the carburetor or a microprocessor-based control system.[11] A typical PSC® system schematic is shown in Figure 5-5.

5.1.4.2 Applicability. The PSC® system is available as an add-on control device for rich-burn, naturally aspirated or turbocharged, carbureted, four-cycle engines. These engines represent approximately 20 to 30 percent of all natural gas-fired engines and 30 to 40 percent of natural gas-fired engines over 300 hp.[13] Fuel-injected engines and blower-scavenged engines cannot use PSC®. Kits are available on an off-the-shelf basis to



INTAKE STROKE (early)

INTAKE STROKE (late)

COMPRESSION STROKE AND IGNITION

Figure 5-4. Stratification of the air/fuel charge using a prestratified charge control system.[11]

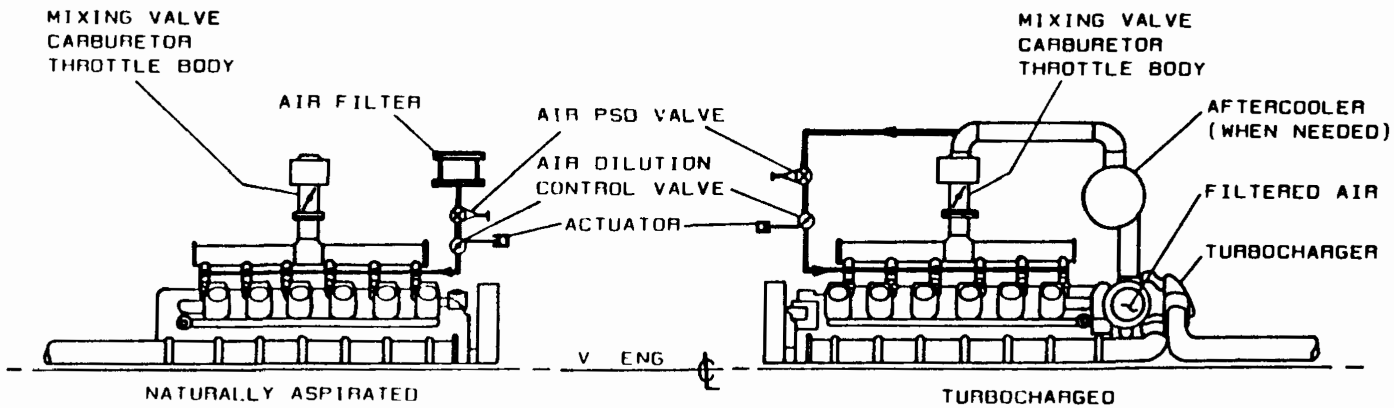


Figure 5-5. Schematic of a prestratified charge system.[11]

retrofit virtually all candidate engines with a rated power output of 100 hp (75 kW) or higher, regardless of the age of the engine.[14] Experience with PSC® systems to date has been primarily those engines operating at a steady power output and ranging in size up to approximately 2,000 hp. A limited number of PSC® systems have been used in cyclical load applications.[14]

Prestratified charge systems have been successfully applied to engines fueled with natural gas as well as to engines using sulfur-bearing fuels such as digester gas and landfill gas.[12,14]

5.1.4.3 Factors That Affect Performance. The NO_x reduction efficiency for PSC® is determined by the extent to which the air content of the stratified charge can be increased without excessively affecting other operating parameters. These parameters are engine power derate, increased CO emissions, and to a lesser extent, HC emissions. The effects on engine power output and CO and HC emissions are quantified in Section 5.1.4.4.

5.1.4.4 Achievable NO_x Emissions Levels Using PSC®. The achievable NO_x emission reductions using PSC® are limited by the quantity of air that can be induced by the intake manifold vacuum, the acceptable level of engine power derate, and the acceptable increase in the level of CO emissions.

Information provided by the vendor for PSC® states that the achievable controlled emission levels for natural gas-fueled engines equipped with PSC® are:[14]

Emissions	g/hp-hr	ppmv @ 15% O_2[a]
NO_x	2	146
CO	3	360
NMHC	<2	<425

[a]Conversion factors from g/hp-hr to ppmv at 15 percent O_2 are from Section 4.3 for lean-burn engines. Lean-burn conversion factors are used because PSC® typically raises the exhaust O_2 levels above 4 percent.

Emission data from several sources suggest that controlled NO_x emission levels for PSC® can meet the levels shown above and, where necessary, can achieve even lower levels. South Coast Air Quality Management District (SCAQMD) Rule 1110.2 requires that engines equipped with PSC® achieve an 80 percent NO_x reduction at 90 percent of rated load. A total of 11 test reports were available for SCAQMD installations, and are presented in Table 5-3.[15-23] All of these installations achieved NO_x reductions of 79 percent or higher. Emission levels were reported only in units of ppmv; units of g/hp-hr were calculated using the correction factors from Section 4.3. Controlled NO_x emission levels range from 83 to 351 ppmv (1.1 to 4.8 g/hp-hr). In all but one case CO emissions increased as a result of PSC®, ranging from 137 to 231 ppmv (1.1 to 1.9 g/hp-hr), an increase of 25 to 171 percent over uncontrolled CO levels. Hydrocarbon emissions were not reported.

An emission data base was provided by the Ventura County Air Pollution Control District (VCAPCD).[24] Engines operating with PSC® in VCAPCD must achieve a NO_x emission level of 50 ppmv (0.75 g/hp-hr), or a 90 percent NO_x reduction, in accordance with Rule 74.9. Emission data for a total of 79 emission tests, performed at 16 engine installations, are presented in Table A-1 in Appendix A. Table A-1 shows that 68 of these emission tests report NO_x levels consistent with the VCAPCD requirements. The data base provided incomplete information to confirm compliance for the 11 remaining tests. In all cases, however, the controlled NO_x emission levels were less than 100 ppmv (1.4 g/hp-hr), and in some cases were 25 ppmv (0.35 g/hp-hr) or less. Of the 79 test summaries, all but 5 reported controlled CO emissions below 300 ppmv (2.5 g/hp-hr), and all but 6 reported controlled NMHC emission levels below 100 ppmv (0.5 g/hp-hr). Uncontrolled CO and NMHC emission levels prior to installation of the PSC® system were not reported, so no assessment of the increases in these emissions as a result of PSC® could be made for these installations.

In general, CO and HC emission levels increase as NO_x emission levels are reduced using PSC®.[12] The increase is due to incomplete combustion that occurs in the larger quench zone

TABLE 5-3. CONTROLLED EMISSION LEVELS FOR PSC INSTALLATIONS IN THE SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT[15-23]

Engine No.	Engine (hp)	Test No.	Test date	NO_x emissions[a]				CO emissions[a]				Percent Change	
				PSC off[b]		PSC on[c]		PSC off[b]		PSC on[c]			
				ppmv	g/hp-hr	ppmv	g/hp-hr	ppmv	g/hp-hr	ppmv	g/hp-hr	NO_x	CO
1	670[c]	1	1987	1820	27.2	228	3.1	94	0.9	187	1.6	-87	99
1	670[c]	2	1987	1760	26.3	237	3.2	94	0.9	199	1.7	-87	112
2	670[c]	1	1986	1970	29.4	229	3.1	97	0.9	200	1.7	-88	106
3	670[c]	1	1987	1630	24.3	157	2.2	103	0.9	195	1.6	-90	89
4	670[c]	1	1986	1730	25.9	277	3.8	105	1.0	190	1.6	-84	81
4	670[c]	2	1987	1840	27.5	351	4.8	76	0.7	206	1.7	-81	171
5	870[c]	1	1988	1030	15.3	115	1.6	163	1.5	231	1.9	-89	42
5	870[c]	2	1990	1660	24.7	157	2.2	113	1.0	184	1.5	-91	63
6	420[d]	1	1991	1490	22.2	234	3.2	96	0.9	169	1.4	-84	76
7	NA[e]	1	1991	1160	17.3	243	3.3	139	1.3	174	1.5	-79	25
8	420[d]	1	1991	961	14.3	179	2.5	136	1.2	184	1.5	-81	35
9	141[d]	1	1991	930	13.9	101	1.4	99	0.9	139	1.2	-89	40
10	141[d]	1	1991	888	13.3	83	1.1	92	0.8	155	1.3	-91	68
11	NA[e]	1	1991	783	11.7	116	1.6	691	6.3	137	1.1	-85	-80

[a]Emission tests conducted to verify compliance with SCAQMD requirement for 80 percent NO_x reduction. Emission levels were reported in ppmv, referenced to 15 percent oxygen. HC emissions were not reported.

[b]Units of g/hp-hr were calculated using the following emission conversion factors (rich-burn engines):

NO_x: 1 g/hp-hr = 67 ppmv @ 15 percent oxygen
CO: 1 g/hp-hr = 110 ppmv @ 15 percent oxygen

[c]Units of g/hp-hr were calculated using the following emission conversion factors (lean-burn engines):

NO_x: 1 g/hp-hr = 73 ppmv @ 15 percent oxygen
CO: 1 g/hp-hr = 120 ppmv @ 15 percent oxygen

[c]Site-rated power output listed in the test report.

[d]International Standards Organization (ISO) power rating provided by the manufacturer, without site losses. Site-rated power output is usually less than the ISO rating.

[e]NA--information not available from the test reports.

associated with PSC® near the combustion chamber walls and the lower exhaust temperatures resulting from the leaner A/F's. The extent to which these emission levels increase, however, is highly variable for various engine models and even among engines of the same model, as shown in Tables 5-3 and A-1.

For fuels with relatively high levels of CO_2, such as digester gas and landfill gas, the impact of PSC® on CO emissions is a minimal increase or in some cases a decrease in CO emissions. Controlled CO emission levels using PSC® for high-CO_2-content fuels typically range from 200 to 500 ppmv (1.67 to 4.17 g/hp-hr). Test reports for PSC® operation on two digester gas-fired units show CO levels ranging from 140 to 278 ppmv, corrected to 15 percent O_2 (1.17 to 2.32 g/hp-hr).[12]

Using PSC® to reduce NO_x emissions typically results in a reduction in the rated power output of the engine. According to the vendor, the power derate for PSC® ranges from 15 to 20 percent for naturally aspirated engines and from zero to 5 percent for turbocharged engines. The controlled NO_x level of 2 g/hp-hr (150 ppm) at rated load can be further reduced as low as 1.0 to 1.2 g/hp-hr (73 to 88 ppmv), but engine power output derate increases to 25 percent for naturally aspirated engines and to 10 percent for turbocharged engines.[14] This engine derate results from displacing with air a portion of the carburetor-delivered combustion charge in the intake manifold; the resulting leaner combustion charge yields a lower power output. Where the design of an existing naturally aspirated engine will accommodate the addition of a turbocharger, or an existing turbocharger can be replaced with a larger unit, these equipment changes can be included with the PSC® retrofit kit and the power derate can be reduced to 5 to 10 percent.[14] This type of installation is similar to the altitude kits installed on integral engines (engines with both power cylinders and gas compression cylinders) to develop full sea level ratings at higher elevations. The horsepower loading on the engine frame is limited when adding a turbocharger so as not to exceed the original naturally aspirated engine rating.

The power derate associated with PSC® applies only to the rated power output at a given installation. For applications where an engine operates below rated power output, no power deration occurs. For example, if a naturally aspirated engine with a rated power output of 100 hp is used in an application that requires 80 hp or less, no power deration will result from the installation of a PSC® system.[14]

The emission test summaries shown in Tables 5-3 and A-1 do not include power output data to assess the power derate associated with the emission levels shown. Data were available, however, for a limited number of installations that correlate power output with controlled NO_x emission levels. These installations are summarized in Table 5-4.[25] In all cases the controlled NO_x levels are less than 2 g/hp-hr (150 ppmv). The percent power derate was determined by the PSC® supplier by comparing the calculated power output at the time of testing with the manufacturer's published power rating, which was adjusted for site elevation and fuel composition. Engine No. 5 is a naturally aspirated engine, and the PSC® installation did not include the addition of a turbocharger. For this engine, the power derate for a total of four tests averages 12 percent. The power derate is also 12 percent (averaged for three tests) for engine No. 8, a turbocharged engine for which the PSC® installation included no modifications to the turbocharger. For turbocharged engines for which the PSC® installation included modification or replacement of the turbocharger to increase the turbo boost (engine Nos. 1, 2, 6, and 7), the power derate ranges from 0 to 32 percent. The 32 percent figure corresponds to an engine tested while process capacity demand was low, and the engine operated below the maximum available power output. As a result, the 32 percent figure overstates the required derate to some extent. Excluding this case, the power and rate for the turbocharged engines with turbocharger modifications ranges from 0 to 5 percent. These power derates are consistent with those stated by the PSC® vendor for controlled NO_x emission levels of 2 g/hp-hr.

TABLE 5-4. CONTROLLED EMISSION LEVELS AND CORRESPONDING ENGINE POWER DERATE FOR PSC® INSTALLATIONS[25]

Engine No.	Engine (hp)[b]	No. of tests[c]	Test date	NO_x emissions[a]			CO emissions[a]			NMHC emissions[a]			Percent power derate from site rating[d]
				PSC® off	PSC® on		PSC® off	PSC® on		PSC® off	PSC® on		
					ppmv	g/hp-hr		ppmv	g/hp-hr		ppmv	g/hp-hr	
1	1550	1	1992	NA[e]	105	1.44	NA	163	1.36	NA	25	0.12	32[f]
2	1550	1	1992	NA	133	1.82	NA	152	1.27	NA	78	0.37	0[f]
3	800	1	1992	NA	42	0.58	NA	523	4.36	NA	21	0.10	8[g]
4	800	1	1992	NA	120	1.65	NA	666	5.55	NA	21	0.10	1.4[g]
5	660	4	1992	NA	118	1.62	NA	95	0.79	NA	21	0.10	12[h]
6	1200	5	1992	NA	138	1.89	NA	283	2.36	NA	21	0.10	2[i]
7	1200	6	1992	NA	105	1.44	NA	259	2.16	NA	21	0.10	5[i]
8	800	3	1992	NA	60	0.82	NA	130	1.08	NA	142	0.67	12[j]

[a]Emission levels were reported in g/hp-hr. Units of ppmv, referenced to 15 percent oxygen, were calculated using the following conversion factors:
NOx: 1 g/hp-hr = 73 ppmv @ 15 percent oxygen
CO: 1 g/hp-hr = 120 ppmv @ 15 percent oxygen
NMHC: 1 g/hp-hr = 212 ppmv @ 15 percent oxygen

[b]International Standards Organization (ISO) power rating provided by the manufacturer, without site losses. Site-rated power output is usually less than the ISO rating.

[c]Where more than one test is indicated, the emissions and power derate presented reflect an average of all tests.

[d]Power derate is calculated by comparing calculated power level during test to manufacturer's published rating. Power outputs during tests were based on process conditions and do not necessarily reflect maximum engine power capability. The power derate at these sites may therefore be less in some cases than shown here.

[e]NA = information not available from the test summaries.

[f]PSC installation included replacement of turbochargers with larger units to increase turbo boost. Engine No. 1 power output was limited by process conditions; the actual derate is expected to be less.

[g]No information available regarding addition/modification of turbocharger for this PSC installation.

[h]No changes were made to the charge capacity for PSC installation on this naturally aspirated engine.

[i]PSC installation included the addition of a turbocharger to these naturally aspirated engines.

[j]No changes were made to the turbocharger for PSC installation on this engine.

It is important to note that the power derate associated with PSC® depends on site-specific conditions, including the controlled NO_x emission level, engine model, and operating parameters. Several sources have indicated that the power derate associated with PSC® may be greater in some cases than the levels presented in this section. A determination of the power derate associated with a potential PSC® installation should be made on a case-by-case basis.

Based on the available data presented in this section, it is estimated that a controlled NO_x emission level of 2.0 g/hp-hr (150 ppmv) or less is achievable in rich-burn engines using PSC®, and this 2.0 g/hp-hr figure is used in Chapter 6 to calculate controlled NO_x emission levels and cost effectiveness.

Moderate NO_x reductions to approximately 4 to 7 g/hp-hr reduce BSFC by approximately 5 to 7 percent. Further NO_x reductions below the 4 to 7 g/hp-hr level, however, increase BSFC by as much as 2 percent over uncontrolled levels.[14]

5.1.5 <u>Nonselective Catalytic Reduction</u>

5.1.5.1 <u>Process Description</u>. Nonselective catalytic reduction is achieved by placing a catalyst in the exhaust stream of the engine. This control technique is essentially the same as the catalytic reduction systems that are used in automobile applications and is often referred to as a three-way catalyst because it simultaneously reduces NO_x, CO, and HC to water, CO_2, and N_2. This conversion occurs in two discrete and sequential steps, shown in simplified form by the following equations:[26]

Step 1 Reactions:

$$2CO + O_2 \rightarrow 2CO_2$$
$$2H_2 + O_2 \rightarrow 2H_2O$$
$$HC + O_2 \rightarrow CO_2 + H_2O$$

Step 2 Reactions:

$$NO_x + CO \rightarrow CO_2 + N_2$$
$$NO_x + H_2 \rightarrow H_2O + N_2$$
$$NO_x + HC \rightarrow CO_2 + H_2O + N_2$$

The Step 1 reactions remove excess oxygen from the exhaust gas because CO and HC will more readily react with O_2 than with NO_x. For this reason the O_2 content of the exhaust must be kept below approximately 0.5 percent to ensure adequate NO_x reduction. Therefore, NSCR is applicable only to rich-burn engines.

A schematic for a typical NSCR system is shown in Figure 5-6. An O_2 sensor is placed in the exhaust, and the A/F is adjusted in the fuel-rich direction from stoichiometric as necessary to maintain suitable exhaust O_2 and CO levels for adequate NO_x reduction through the catalyst reactor. Manual and automatic A/F controllers are available. With a manual A/F control system, the signal from the exhaust O_2 sensor is typically connected to a bank of status lights. When indicated by these status lights, the operator must manually adjust the A/F to return the O_2 content of the exhaust to its proper range. With an automatic A/F control system, the exhaust O_2 sensor is connected to a control system that uses this signal to automatically position an actuator installed on the engine carburetor so the exhaust O_2 concentration is maintained at the proper level.[27]

One manufacturer uses natural gas as the reducing agent in the NSCR system to reduce NO_x. The natural gas is injected into the exhaust stream ahead of the catalyst reactor and acts as a reducing agent for NO_x in the low (<2 percent) O_2 environment.[28] A second proprietary NSCR system that injects natural gas into the exhaust stream uses an afterburner downstream of the engine and two catalyst reactors. A schematic of this system is shown in Figure 5-7. This system injects natural gas into the afterburner to achieve a 925°C (1700°F) minimum exhaust temperature to maximize destruction of unburned HC. The exhaust is then cooled in the first heat exchanger to approximately 425°C (800°F) prior to entering the reduction catalyst, where CO and NO_x are reduced. Excess CO emissions exiting the reduction catalyst are maintained at approximately 1,000 ppmv to minimize ammonia and cyanide formation. A second heat exchanger further cools the exhaust to approximately 230°C (450°F) prior to entering the oxidation catalyst to minimize the reformation of NO_x across the oxidation catalyst. The oxidation catalyst is used to reduce CO emissions.[29] According to the vendor, this

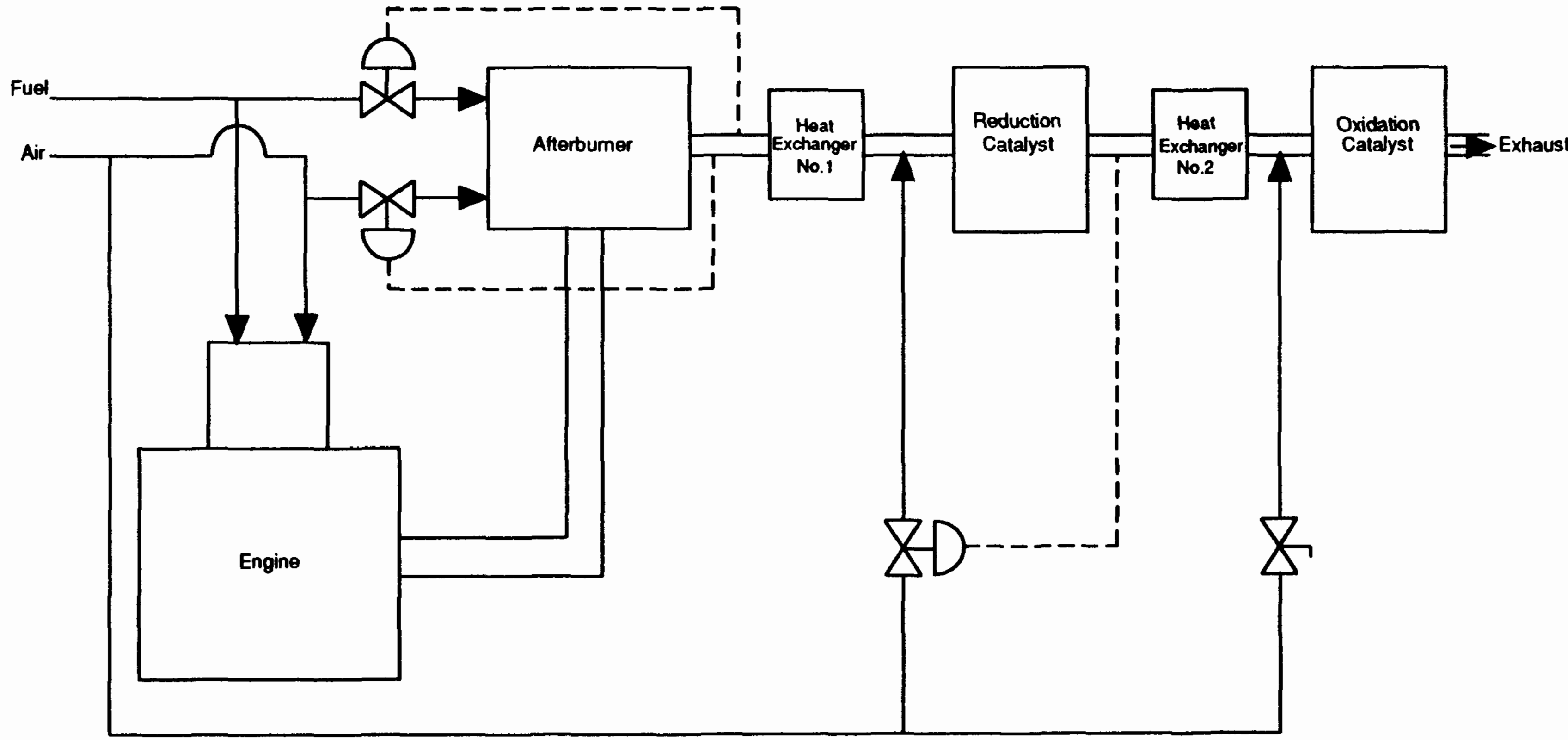


Figure 5-7. Schematic of a nonselective catalytic reduction system design with two catalytic reactors.

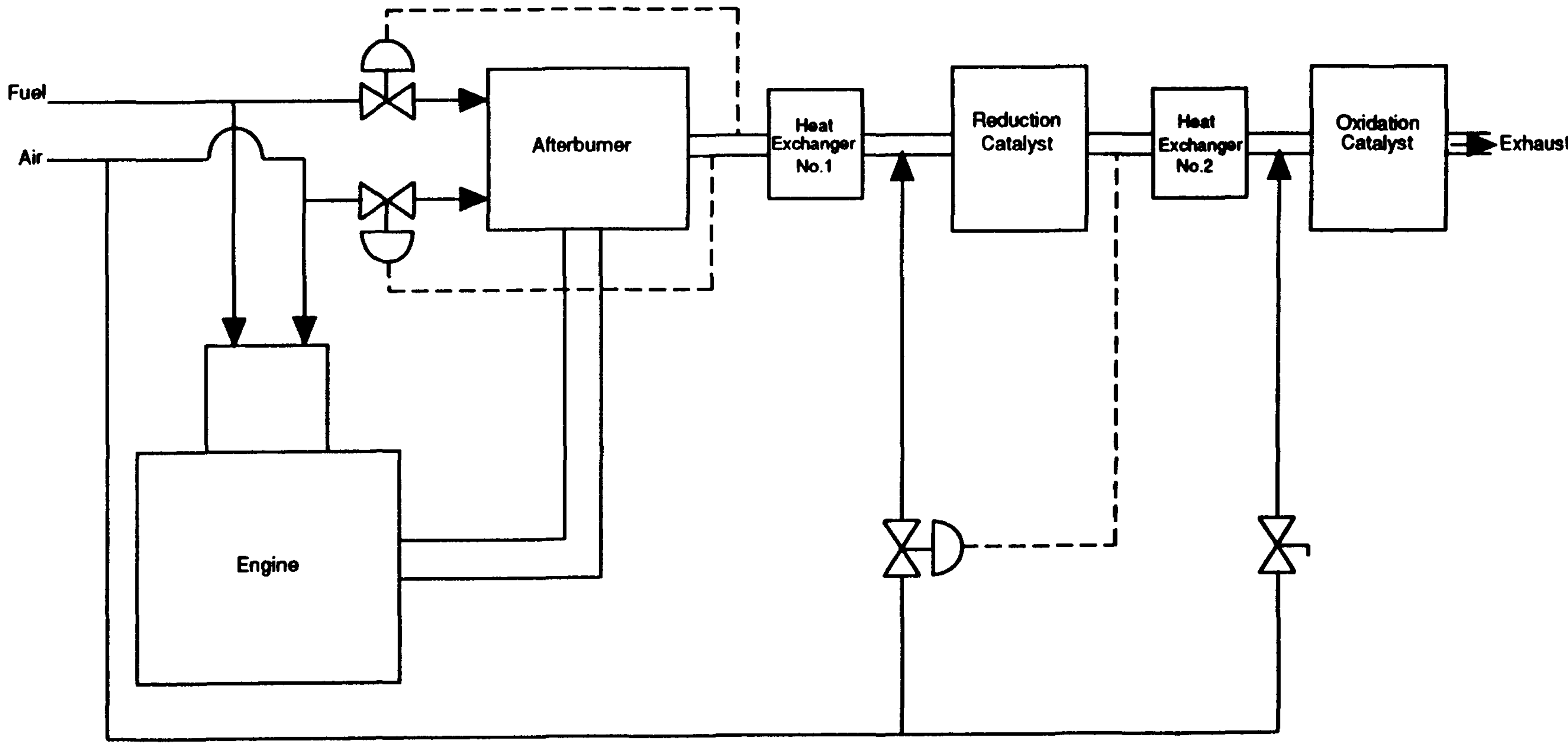


Figure 5-7. Schematic of a nonselective catalytic reduction system design with two catalytic reactors.

catalytic system can also be used with lean-burn SI and CI engines in lieu of SCR.

5.1.5.2 Applicability for NSCR. Nonselective catalytic reduction applies to all carbureted rich-burn engines. The limitation to carbureted engines results from the inability to install a suitable A/F controller on fuel-injected units. This control technique can be installed on new engines or retrofit to existing units. For vintage engines, after-market carburetors are available to replace primitive carburetors, where necessary, to achieve the necessary A/F control for NSCR operation.[26]

Another factor that limits the applicability of NSCR is the type of fuel used. Landfill and digester gas fuels may contain masking or poisoning agents, as described in Section 5.1.5.3, that can chemically alter the active catalyst material and render the catalyst ineffective in reducing NO_x emissions. One catalyst vendor cited NSCR experience in landfill gas-fueled applications where the fuel gas is treated to remove contaminants.[30]

There is limited experience with NSCR applications on cyclically loaded engines. Changes in engine load cause variations in the exhaust gas temperature as well as NO_x and O_2 exhaust concentrations. An A/F controller is not commercially available to maintain the exhaust O_2 level within the narrow range required for consistent NO_x reduction for cyclically loaded engines such as those used to power rod pumps.[27] One vendor offers an NSCR system that uses an oversized exhaust piping system and incorporates the catalyst into the muffler design. The increased volume of this exhaust system acts to increase the residence time in the catalyst, which compensates for the adverse impacts of other operating parameters. This vendor has installed this catalyst/muffler NSCR system in both base-load and cyclical-load applications.[31]

5.1.5.3 Factors That Affect Performance. The primary factors that affect the performance of NSCR are control of the engine A/F, the exhaust temperature, and masking or poisoning agents in the exhaust stream. To achieve the desired chemical reactions to reduce NO_x emissions (see Section 5.1.4.1) and minimize CO emissions from the catalyst, the exhaust O_2 concentration must be maintained at approximately 0.5 percent by volume. This O_2 level is accomplished by maintaining the A/F in a narrow band, between 16.95 and 17.05 according to one catalyst vendor.[27, 18] An automatic A/F controller offers the most effective control of NO_x and CO emissions since it continually monitors the O_2 exhaust content and can maintain the A/F in a narrow range over the entire range of operating and ambient conditions.

The operating temperature range for various NSCR catalysts is from approximately 375° to 825°C (700° to 1500°F). For NO_x reductions of 90 percent or greater, the temperature window narrows to approximately 425° to 650°C (800° to 1200°F). This temperature window coincides with the normal exhaust temperatures for rich-burn engines.[13] This temperature range is a compilation of all available catalyst formulations. Individual catalyst formulations will have a narrower operating temperature range, and maximum reduction efficiencies may not be achievable over the entire spectrum of exhaust temperatures for an engine operating in a variable load application. Abnormal operating conditions such as backfiring can result in excessive temperatures that damage the highly porous catalyst surface, permanently reducing the emission reduction capability of the catalyst.

Masking or poisoning of the catalyst occurs when materials deposit on the catalyst surface and either cover the active areas (mask) or chemically react with the active areas and reduce the catalyst's reduction capacity (poison). Masking agents include sulfur, calcium, fine silica particles, and hydrocarbons. Poisoning agents include phosphorus, lead, and chlorides. These masking and poisoning agents are found in the fuel and/or lubricating oils. The effects of masking can be reversed by cleaning the catalyst (except for fine silica particles that cannot be dislodged from the porous catalyst surface); the effects of poisoning are permanent and cannot be reversed.[27, 18]

5.1.5.4 <u>Achievable Emission Reductions Using NSCR</u>. Information provided for the proprietary NSCR system that uses both a reducing catalyst and an oxidation catalyst states controlled NO_x emission levels of less than 25 ppmv (0.37 g/hp-hr) are achievable. Corresponding CO emissions are expected to be less than 100 ppmv.[29] No test data were available for this system design.

For NSCR systems that use a single catalyst reactor, the ratio of CO to NO_x entering the catalyst unit in a properly tuned system is approximately 2:1. According to one NSCR vendor, the A/F is adjusted to achieve an approximate CO level of 6,000 ppmv and a NO_x level of 3,000 ppmv entering the catalyst. At these emission levels, the typical controlled emissions levels exiting the catalyst are:[27]

Emissions	g/hp-hr	Approximate ppmv at 15 percent O_2[a]
NO_x	2	134
CO	2	220
HC	0.5	97

[a]Conversion factors from g/hp-hr to ppmv at 15 percent O_2 are from Section 4.3 for rich-burn engines.

Compliance requirements in several local regulatory districts in California require considerably lower NO_x emission levels than those shown above. The SCAQMD Rule 1110.2 requires an 80 percent NO_x reduction, with a maximum CO emission limit of 2,000 ppmv. Four test summaries of SCAQMD engine installations using NSCR are presented below:[32]

Test No.	NO_x reduction (percent)	CO emissions (ppmv)
1	92	118
2	99	258
3	99	364
4	82	1,803

Actual NO_x ppmv levels were not included in the available test summary. These data suggest that CO emission levels do not necessarily increase with increased NO_x reduction. No HC emission levels were reported.

The VCAPCD emission data base includes over 250 emission test summaries from 49 engine installations operating in continuous-duty applications.[24] These emission summaries are shown in Table A-2 in Appendix A. Of the approximately 275 tests, only 2 did not achieve compliance with the VCAPCD Rule 74.9 NO_x requirement of 50 ppmv or 90 percent reduction. One additional test summary showed a NO_x emission level higher than 50 ppmv, but no reduction figure was listed. Every test achieved a NO_x emission level of less than 100 ppmv (1.5 g/hp-hr). Levels of CO emissions vary greatly, ranging from less than 100 to over 19,000 ppmv (0.9 to 173 g/hp-hr). Prior to 1989, there was no CO emission limit in VCAPCD; in 1989, a limit of 4,500 ppmv was added to VCAPCD Rule 74.9. Evaluation of the 275 continuous-duty installations shows the following average annual emission levels:

Year(s)	Controlled emission averages (ppmv)		
	NO_x	CO	NMHC
86-88	26.9	4691	27.5
89	18.5	6404	39.0
90-92	22.7	2424	73.6

These data indicate that controlled CO emission levels decreased between 48 and 62 percent following implementation of the CO emission limit, with little or no effect on controlled NO_x emission levels. The data base included only a limited number of NMHC emission levels, which range from 1 to 694 ppmv (0 to 3.3 g/hp-hr).

These emission averages and the emission levels presented in Table A-2 suggest that controlled CO and NMHC emission levels vary widely for NSCR applications and are not necessarily inversely proportional to controlled NO_x emission levels. An oxidation catalyst can be installed downstream of the NSCR catalyst, where necessary, to further reduce CO emissions. Air injection would be required upstream of the oxidation catalyst to introduce O_2 into exhaust stream.

The VCAPCD emission data base shows NSCR installations that have been in operation for 5 years or longer. The maintenance requirements and the catalyst replacement schedules were not available. Catalyst vendors will guarantee NO_x reduction efficiencies as high as 98 percent and typically guarantee catalyst life and system performance for 2 or 3 years.[33] Precious metal catalysts are used in NSCR systems, so the spent catalyst does not contain potentially hazardous materials. Most catalyst vendors offer a credit toward the purchase of new catalyst for return of these spent catalysts.[33]

Based on the data presented in this section, it is estimated that a NO_x reduction of 90 percent or higher is achievable using NSCR with rich-burn engines. A 90 percent reduction is used in Chapter 6 to calculate controlled NO_x emission levels and cost effectiveness.

The fuel-rich A/F setting and the increased back pressure on the engine caused by the catalyst reactor may reduce power output and increase the BSFC. The back pressure created by an NSCR system was not provided, but the estimate for an SCR system is 2 to 4 inches of water (in. w.c.).[34] For a 4-in. back pressure, one engine manufacturer estimated a power loss of 1 percent for naturally aspirated engines and 2 percent for turbocharged engines. The increase in BSFC was estimated at 0.5 percent for either naturally aspirated or turbocharged engines.[3] As stated in Section 5.1.1.1, rich-burn engines can be operated over a range of A/F's, so the incremental change between the A/F setting required for NSCR and the A/F used prior to installation of the NSCR is also site-specific. The increase in BSFC estimated by NSCR vendors ranged from 0 to 5 percent. Another source provided information showing that the BSFC increase could potentially be greater than 10 percent for some engines.[35]

5.1.6 Low-Emission Combustion

5.1.6.1 Process Description. Rich-burn engines operate at near-stoichiometric A/F's. As shown in Figure 5-1, NO_x emissions can be greatly reduced by increasing the A/F so that the engine operates at very lean A/F's, as depicted in the region at the right side of this figure where NO_x formation is low. Extensive retrofit of the engine and ancillary systems is required to operate at the higher A/F's. These low-emission combustion designs are also referred to as torch ignition, jet cell, and CleanBurn® by various manufacturers. (CleanBurn® is a registered trademark of Cooper Industries.)

The increased air requirements for low-emission engines can range up to nearly twice the levels required for rich-burn operation according to information provided by one engine manufacturer.[1] This increased airflow is provided by adding a turbocharger and intercooler or aftercooler to naturally aspirated engines or by replacing an existing turbocharger and inter/aftercooler with a larger-capacity unit. The air intake and filtration system, carburetor(s), and exhaust system must also be replaced to accommodate the increased flows.

The very lean mixture also requires substantial modification of the combustion chamber to ensure ignition and stable combustion. For engines that have a relatively small cylinder bore, the combustion chamber can use an open cylinder design, which is similar to a conventional combustion chamber but incorporates improved swirl patterns to promote thorough mixing. Larger cylinder bores cannot reliably ignite and sustain combustion with an open-cylinder design and a precombustion chamber (PCC) is used. These low-emission combustion designs vary somewhat with each manufacturer, but representative sketches are shown in Figure 5-8.[1] One manufacturer's low-emission combustion chamber with a PCC design is shown in Figure 5-9.[36] The PCC is an antechamber that has a volume of 5 to 10 percent of the main chamber and ignites a fuel-rich mixture, which propagates into the main cylinder and ignites the very lean combustion charge.[11] The high exit velocity of the combustion

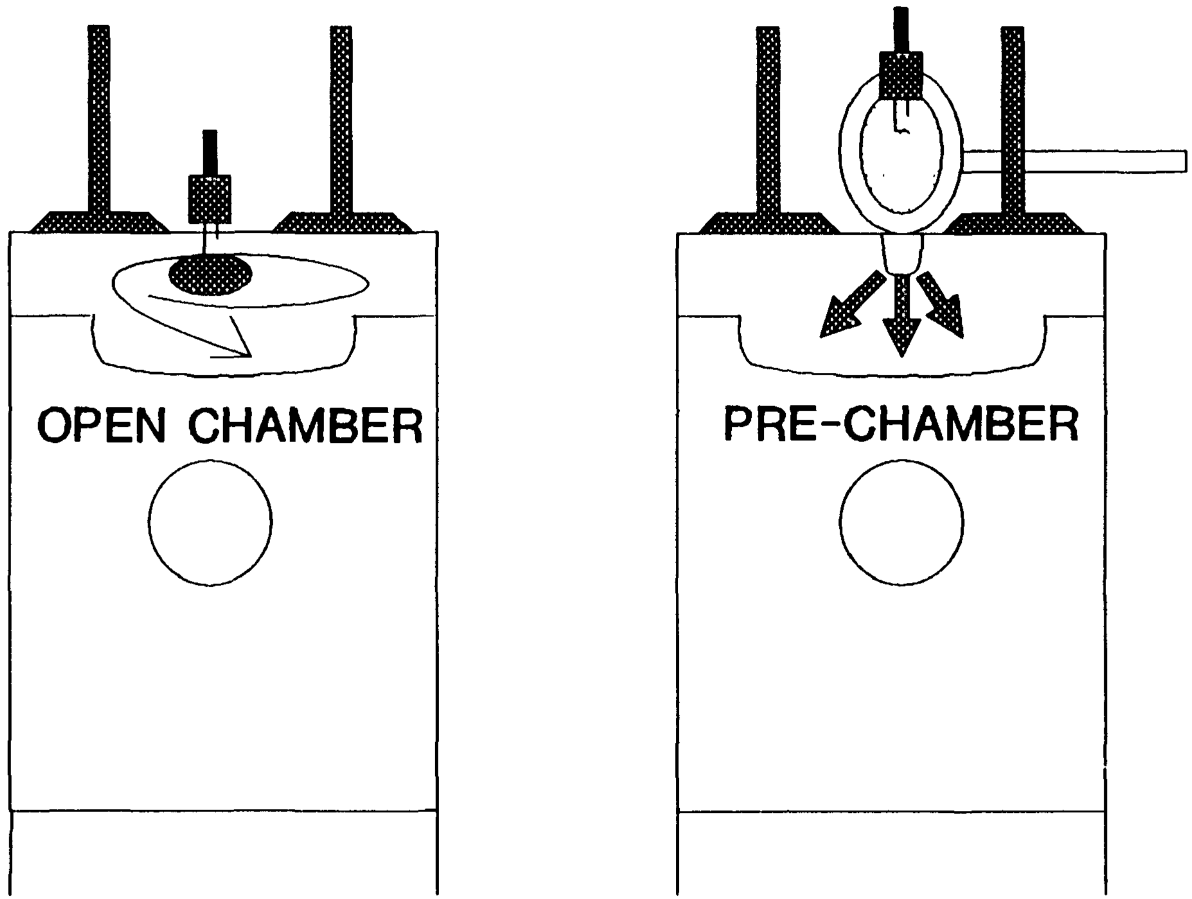


Figure 5-8. Low-emission engine combustion chamber configurations.[1]

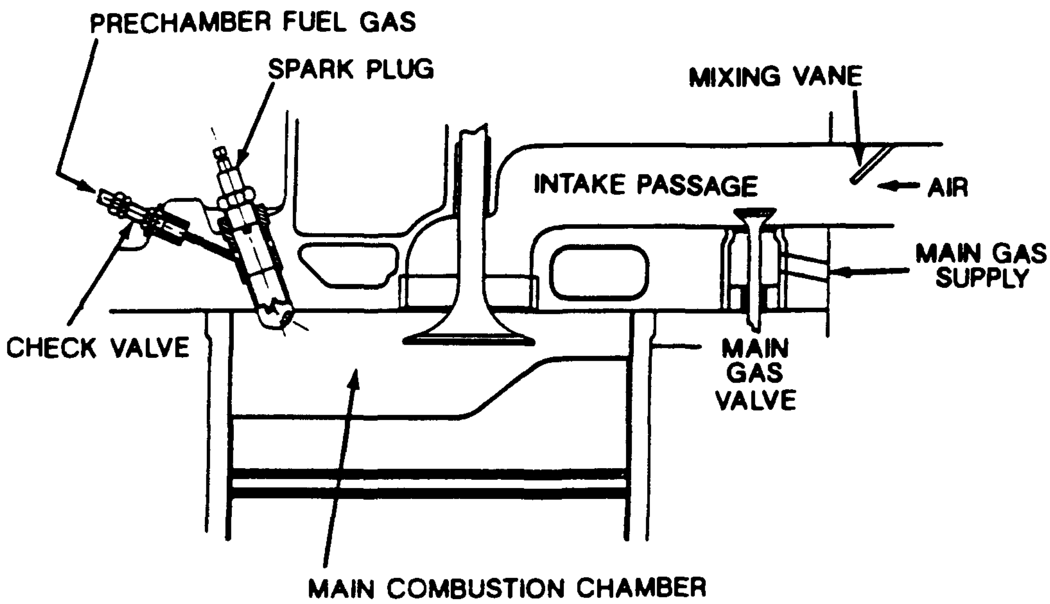


Figure 5-9. Low-emission engine combustion chamber with a precombustion chamber.[36]

products from the PCC has a torch-like effect in the main chamber and results in improved mixing and combustion characteristics. As a result, leaner A/F's can be used in a main combustion chamber with a PCC design, and NO_x emissions are lower than those from open-chamber designs. Redesigning the combustion chamber in the case of either an open or a PCC design usually requires replacing the intake manifolds, cylinder heads, pistons, and the ignition system.

5.1.6.2 Applicability of Low-Emission Combustion. The applicability of combustion modifications to rich-burn engines is limited only by the availability of a conversion kit from the manufacturer and application considerations. Since the low-emission conversion essentially requires a rebuild of the engine, the hardware must be available from the engine manufacturer. Responses received from engine manufacturers show that the availability of retrofit kits varies by manufacturer, from only a few models to virtually all models.[37-42]

When considering a low-emission conversion for a rich-burn engine, the duty cycle of the engine must be taken into consideration. Conversion to a low-emission design may adversely affect an engine's response to load characteristics. According to one manufacturer, a low-emission engine can accept a load increase up to 50 percent of rated load and requires approximately 15 seconds to recover to rated speed. A turbocharged rich-burn engine is limited to this same 50 percent load increase but will recover to rated speed in 7 seconds. A naturally aspirated rich-burn engine can accept a load of up to 100 percent of rated load and will stabilize at rated speed in 3.5 seconds.[43] Applications that have substantial load swings, such as power generation applications that are not tied to the utility grid or cyclically loaded engines, may not be able to use a low-emission design due to reduced load acceptance capability.

An additional consideration is that the fuel delivery pressure requirement may be higher for a low-emission engine due to the addition of the turbocharger. This higher fuel pressure requirement may require the addition of a fuel gas booster compressor.

5.1.6.3 Factors That Affect Performance. The factors that most affect the emission reduction performance of a rich-burn engine that has been converted to low-emission combustion are the design of the new combustion chamber and the volume of air that can be delivered. The new combustion chamber design determines the highest A/F that can be used, and as shown in Figure 5-1, higher A/F's will result in lower NO_x emissions. In general, lower NO_x emissions can be achieved using a PCC than with an open chamber design because of the leaner A/F's that can be reliably combusted in the main combustion chamber with a PCC design.

The turbocharger necessary to supply the additional intake air for clean-burn operation results in increased working pressures in the engine. Existing rich-burn engine designs may limit the turbocharger size that can be retrofit due to either strength limitations of the existing engine frame or space constraints of the existing air intake configuration. Any limitation in the availability of combustion air may effectively limit the operating A/F below optimum levels and therefore limit potential NO_x reductions.

5.1.6.4 Achievable Emission Levels Using Low-Emission Combustion. The nominal emission levels provided by engine manufacturers for low-emission open chamber designs are:[37-42]

Emissions, g/hp-hr			Emissions, ppmv at 15% O_2		
NO_x	CO	HC	NO_x	CO	HC
3.8-11.7	0.9-3.6	1.0-4.6	280-865	110-440	250-990

The nominal emission levels provided by engine manufacturers for PCC designs are:[37-42]

Emissions, g/hp-hr			Emissions, ppmv at 15% O_2		
NO_x	CO	HC	NO_x	CO	HC
1.5-2.5	1.3-3.5	0.6-4.9	110-185	160-425	130-1,055

As can be seen from the above tables, NO_x emissions are substantially lower for engines that use a PCC design. Since an open chamber design is generally used in smaller, high-speed engines, these engines typically emit higher controlled NO_x emissions than do larger, low-speed engines. These figures show that the levels of CO and HC, however, are not substantially influenced by the combustion chamber geometry.

Reductions in NO_x emissions using combustion modifications generally result in higher CO and HC emission levels. For this reason, it is not likely that the low end of each range for NO_x, CO, and HC in the figure listed above can be achieved simultaneously.

The percent reduction that is achievable by converting a rich-burn engine to a low-emission design can be misleading because the uncontrolled emission levels can vary widely with slight adjustments in the A/F, as shown in Figure 5-1. For example, average NO_x emission levels from rich-burn engines can range from 8.0 to 19.2 g/hp-hr with adjustments to the A/F (see Table 5-1). Conversion to low-emission combustion can achieve controlled NO_x emission levels of 1.5 to 2.5 g/hp-hr. The percent reduction could therefore range from 69 to 92 percent, depending upon the uncontrolled and controlled NO_x levels used to calculate the percent reduction.

Test results for five engines that were converted from rich-burn to low-emission combustion are presented in Table 5-5.[6,44] This table shows that controlled NO_x emissions range from 0.37 to 2.0 g/hp-hr (29 to 146 ppmv at 15 percent O_2) and average 1.02 g/hp-hr (75.6 ppmv at 15 percent O_2). Carbon monoxide emissions range from 1.6 to 2.6 g/hp-hr (192 to 323 ppmv at 15 percent O_2) and average 2.19 g/hp-hr (265 ppmv at 15 percent O_2). Levels of HC emissions range from 0.26 to 0.6 g/hp-hr (55 to 127 ppmv at 15 percent O_2) and average 0.39 g/hp-hr (83.7 ppmv at 15 percent O_2). These engines all use a PCC design. The NO_x emissions are lower than those provided by engine manufacturers, but CO and HC emissions fall within the ranges provided by the manufacturers.

TABLE 5-5. EMISSION SUMMARY OF RICH-BURN ENGINES FOLLOWING RETROFIT TO LOW-EMISSION COMBUSTION USING A PRECOMBUSTION CHAMBER[6,44]

Engine No.	Manufacturer	Model	Power output, hp	Emissions, g/hp-hr			Emissions, ppmv at 15% O_2		
				NO_x	CO	HC	NO_x	CO	HC
1	Waukesha	L-7042GL	1,200	0.37	2.6	0.31	29	323	69
2	Waukesha	L-7042GL	1,200	0.61	2.3	0.26	45	279	55
3	Superior	12GTLA	1,650	2.0	1.6	0.6	146[a]	192[a]	127[a]
4	Dresser-Rand	412-KSV	2,000	1.00	NA[b]	NA	75[a]	NA	NA
5	Dresser-Rand	412-KSV	2,000	1.10	NA	NA	83[a]	NA	NA
Averages				1.02	2.19	0.39	75.6	265	83.7

[a]Calculated using conversion factors listed below:

NO_x: 1g/hp-hr = 75 ppmv @ 15 percent O_2
CO: 1g/hp-hr = 120 ppmv @ 15 percent O_2
HC: 1g/hp-hr = 212 ppmv @ 15 percent O_2

[b]NA - Data not available.

Table 5-6 presents achievable emissions levels for new low-emission engines that were developed by engine manufacturers from rich-burn designs.[6] For a total of eight engines NO_x emissions range from 0.73 to 2.00 g/hp-hr (55 to 150 ppmv at 15 percent O_2) and average 1.50 g/hp-hr (112 ppmv at 15 percent O_2). Emission levels for CO range from 1.20 to 3.10 g/hp-hr (144 to 372 ppmv at 15 percent O_2) and average 2.19 g/hp-hr (263 ppmv at 15 percent O_2). Hydrocarbon emissions range from 0.13 to 2.20 g/hp-hr (28 to 466 ppmv at 15 percent O_2) and average 0.95 g/hp-hr (200 ppmv at 15 percent O_2). These emission levels all fall within the ranges quoted by the manufacturers.

Test data for low-emission engines developed from rich-burn engine designs were also available from the VCAPCD data base.[24] These data are presented in Table A-3 in Appendix A, and include a total of 124 emission tests performed on 15 engines, representing 4 engine models from 2 manufacturers. Controlled NO_x emission limits for these engines in VCAPCD are 125 ppmv or 80 percent NO_x reduction. Controlled CO and NMHC emission limits are 4500 and 750 ppmv, respectively. The data base indicates that all engines met these compliance limits. Controlled NO_x emission levels in Table A-3 range from 11 to 173 ppmv (0.15 to 2.3 g/hp-hr). Corresponding CO emission levels vary widely, from 3 to 3,327 ppmv (0 to 27 g/hp-hr). The range for NMHC emissions is 74 to 364 ppmv (0.4 to 1.7 g/hp-hr). To some extent, the data show an inverse relationship between NO_x and CO emissions, as the three highest CO emission levels correspond to NO_x emission levels of 35 ppmv or less, and the highest NMHC emission level corresponds to the lowest NO_x emission level (11 ppmv). This relationship does not hold true for all cases, however, as many of the emission tests show relatively low controlled levels for all three emissions. The data also show that controlled emission levels are sustained over time, as compliance limits have been maintained at all installations, dating back to when the data base was developed in 1986.

No information was available to determine whether the low-emission engines in Table A-3 were purchased as new equipment

TABLE 5-6. ACHIEVABLE CONTROLLED EMISSION LEVELS FOR NEW LOW-EMISSION ENGINES DEVELOPED FROM RICH-BURN ENGINE DESIGNS[6]

Engine No.	Manufacturer	Model	Power output, hp	Emissions, g/hp-hr			Emissions, ppmv at 15% O_2[a]		
				NO_x	CO	HC	NO_x	CO	HC
1	Waukesha	9390GL	1,500	2.00	2.00	0.87	150	240	184
2	Superior	12SGTA	2,000	2.00	1.20	0.26	150	144	55
3	Dresser-Rand	412-KVSR	2,850	1.45	2.75	1.50	109	330	318
4	Dresser-Rand	412-KVSR	2,700	1.00	3.10	2.20	75	372	466
5	Superior	8GTLB	1,100	0.73	1.96	0.13	55	235	28
6	Superior	12GTLA	1,650	2.00	1.60	0.60	150	192	127
7	Waukesha	7042GL	1,320	1.40	2.50	1.00	105	300	212
8	Waukesha	7042GL	1,320	1.40	2.40	1.00	105	288	212
Averages				1.50	2.19	0.95	112	263	200

[a]Emissions were reported in g/hp-hr. Units of ppmv were calculated using the following conversion factors:

NO_x: 1 g/hp-hr = 75 ppmv @ 15 percent oxygen
CO: 1 g/hp-hr = 120 ppmv @ 15 percent oxygen
HC: 1 g/hp-hr = 212 ppmv @ 15 percent oxygen

or were retrofit from existing rich-burn engines. Based on the information provided by engine manufacturers and the data presented in Tables 5-5, 5-6, and A-3, it is estimated that a controlled NO_x emission level of 1.0 to 2.0 g/hp-hr is achievable for rich-burn engines that have been converted to low-emission combustion. A 2.0 g/hp-hr figure is used in Chapter 6 to calculate controlled NO_x emission levels and cost effectiveness.

The operating characteristics of low-emission designs, including substantially leaner A/F and increased operating pressures from turbocharging, suggest improved fuel economy. Information provided by engine manufacturers shows that, in general, engine heat rates range from no change to improved fuel efficiency as high as 21 percent. For a few engines, however, the fuel efficiency actually declined as much as 2 percent.[37-42]

5.2 NO_x CONTROL TECHNIQUES FOR LEAN-BURN SI ENGINES

As discussed at the beginning of this chapter, a lean-burn engine is classified as one with an A/F operating range that is lean of stoichiometric and cannot be adjusted to operate with an exhaust O_2 concentration of less than one percent. For SI engines, this includes all two-cycle engines and most four-cycle engines that are turbocharged.

The combustion control technologies available for lean-burn engines are:

1. Adjustments to the A/F;
2. Ignition timing retard;
3. Combination of A/F adjustment and ignition timing retard;
4. Selective catalytic reduction; and
5. Low-emission combustion.

5.2.1 <u>Adjustments to the A/F for Lean-Burn Engines</u>

5.2.1.1 <u>Process Description</u>. As shown previously in Figure 5-1, increasing the A/F in lean-burn engines results in lower NO_x formation. The higher air content increases the heat capacity of the mixture in the combustion chamber, which lowers combustion temperatures and reduces NO_x formation. To increase the A/F, the airflow must be increased or the fuel flow must be decreased. Decreasing the fuel flow results in a derate in the available power output from the engine, and so higher A/F's are achieved by increasing the air flow (charge capacity) of the engine. An increase in air charge capacity may require the addition of a turbocharger to naturally aspirated engines and modification or replacement of an existing turbocharger for turbocharged engines.

5.2.1.2 Applicability. The A/F can be adjusted in the field for most lean-burn engines. Pump-scavenged and blower-scavenged two-cycle engines typically have no provisions for A/F adjustment.[8] To increase the air charge capacity, A/F adjustment may require turbocharger modification or replacement and the addition of a regulator system to control the air charge capacity from the turbocharger if the engine is not already so equipped.

For effective NO_x reductions, the addition of an automatic A/F feedback controller may also be required to ensure sustained NO_x reductions with changes in engine operating parameters such as speed, load, and ambient conditions. This automatic A/F controller also maintains the proper A/F to avoid lean misfire with changes in operating parameters.

5.2.1.3 Factors That Affect Performance. The degree to which the A/F can be increased without exceeding the lean flammability limit of the engine is the primary factor that determines the potential NO_x reduction that can be achieved with this control technique. As this limit is approached, combustion instability and engine misfire begin to occur. The extent to which the A/F can be increased before the onset of combustion instability is specific to each engine design and is influenced by the air and fuel charging system.

To deliver the higher volume of air required to increase the A/F, the turbocharger must either be able to deliver a higher capacity or be replaced with a larger turbocharger. Some engine designs may limit the extent to which the turbocharger capacity can be increased due to physical space constraints on the air intake system or power output limitations on the existing engine frame.

For engines that are fuel injected, the A/F for each cylinder can be adjusted and so the A/F can be optimized in each cylinder. Carbureted engines, however, can have significant variations in the A/F from cylinder to cylinder due to less than ideal distribution of air and fuel in the intake manifold. This A/F variation requires that carbureted engines operate with a richer A/F to ensure that the lean misfire limit is not exceeded in any individual cylinder. Therefore, the extent that the A/F can be increased is higher for fuel-injected engines than for carbureted engines.[78]

An additional consideration is the duty cycle of the engine. An engine's ability to respond to load changes decreases with increases in the A/F.

5.2.1.2 Achievable Emission Reduction Using A/F Adjustment. The achievable NO_x emission reduction by A/F adjustment is specific to each engine model. To understand the potential effect of A/F adjustments on emissions for lean-burn engines, the ratios at which the engine normally operates must be examined. All two-cycle engines are classified as lean-burn because the scavenge air used to purge the exhaust gases from the cylinder results in exhaust O_2 concentrations greater than 1 percent. Figure 5-10 illustrates, however, that some two-cycle engines are designed to operate at near-stoichiometric A/F's and therefore respond to A/F adjustments in a manner similar to rich-burn engines.

The four engines shown in Figure 5-10 are all two-cycle designs, so they are classified as lean-burn. All four are from the same manufacturer. Engines 1, 2, and 3 are the same engine model and are rated at approximately 1,400 hp. Engine 4 is a different model and is rated at approximately 3,500 hp.[45] This figure shows that each engine has a discrete operating A/F range and corresponding NO_x emission rate. The measured A/F is referenced to the exhaust flow and includes both the combustion A/F and the scavenge air flow. The emission rates indicate that

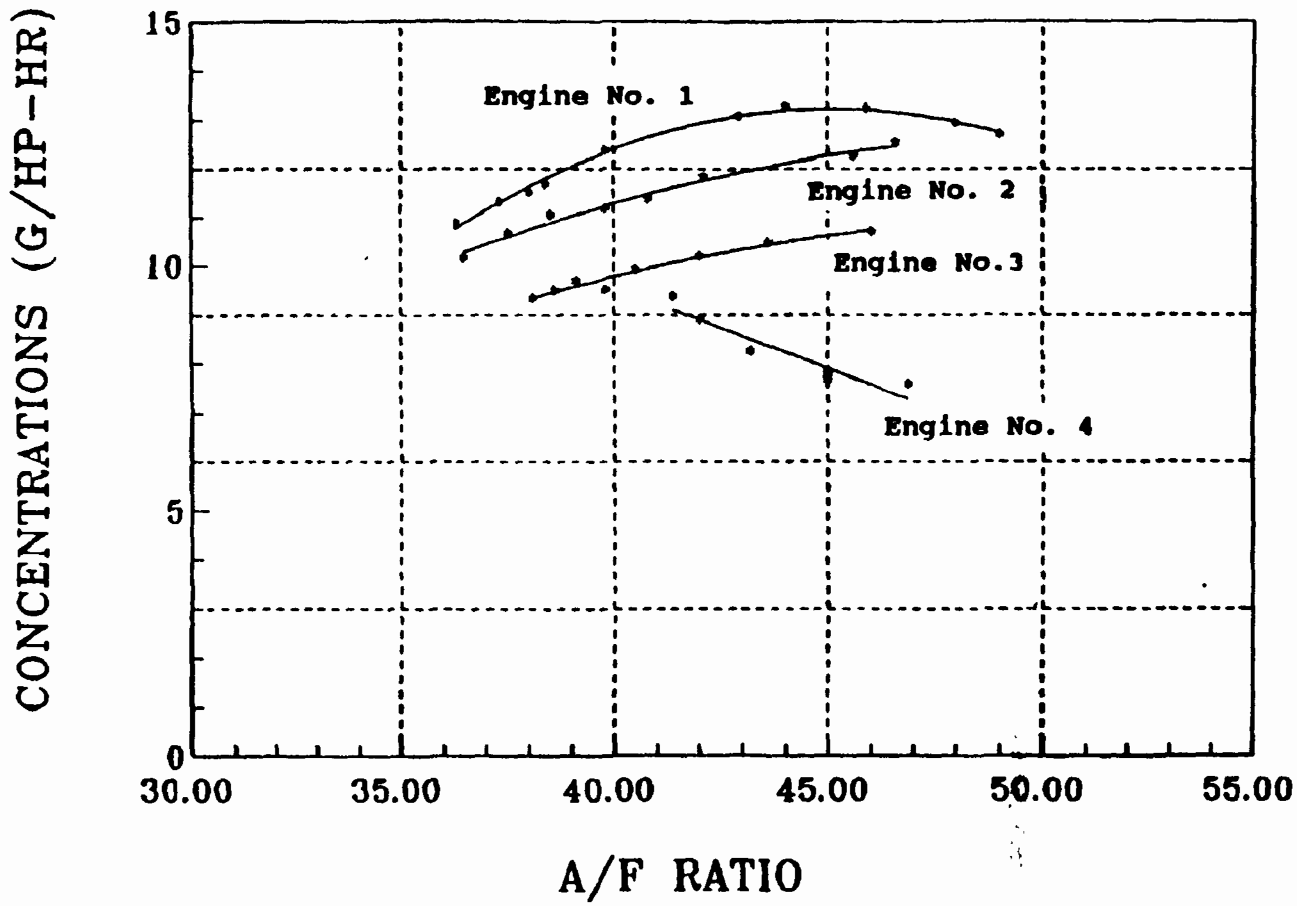


Figure 5-10. The effect of A/F adjustment on NO_x emissions for two lean-burn engine models.[45]

Engines 1 through 3 operate at combustion A/F's that fall to the left of the knee of the NO_x curve (see Figure 5-1), and increases in the A/F initially result in increases in NO_x emissions. Of these three engines, only Engine 1 achieves NO_x reductions at the upper limit of increases in the A/F.

Engine No. 4 operates at a higher combustion A/F range to the right of the knee of the NO_x curve shown in Figure 5-1, and NO_x reductions occur continuously with increases in A/F. Emission test results for a similar lean-burn engine model are shown in Figure 5-11.[46] This figure shows emission rates for four identical engines that operate at combustion A/F's to the right of the knee of the NO_x curve in Figure 5-1, and increases in the A/F result in NO_x emission reductions. (The composite plot of filled dots in Figure 5-10 is based on empirical data and does not necessarily reflect an achievable operating A/F range or NO_x emission signature for these engines.)

Figures 5-10 and 5-11 illustrate that while all two-cycle engines are lean-burn, the effect of A/F adjustment on NO_x emission levels varies depending upon whether the engine is designed to operate at A/F's that fall to the right or left of the knee in the curve shown in Figure 5-1.

Using the midpoint of the A/F range as the baseline, the potential NO_x emission reductions were estimated for the engines shown in Figure 5-10. Decreasing the A/F in Engines 1 through 3 results in NO_x reductions ranging from approximately 10 to 15 percent. Increasing the A/F in Engine 4 results in a NO_x reduction of less than 10 percent. For the four engines shown in Figure 5-11, increasing the A/F from baseline levels results in NO_x reductions ranging from approximately 20 to 33 percent.

Another report was available to quantify the achievable NO_x emission reductions using A/F adjustment for two lean-burn, two-cycle, turbocharged engines.[47] These engines are from two different manufacturers, and each is rated at 3,400 hp. The effect of increasing the A/F for one of these engines from an established baseline exhaust A/F on emissions and BSFC is shown in Figure 5-12. For this engine, NO_x emissions decreased with

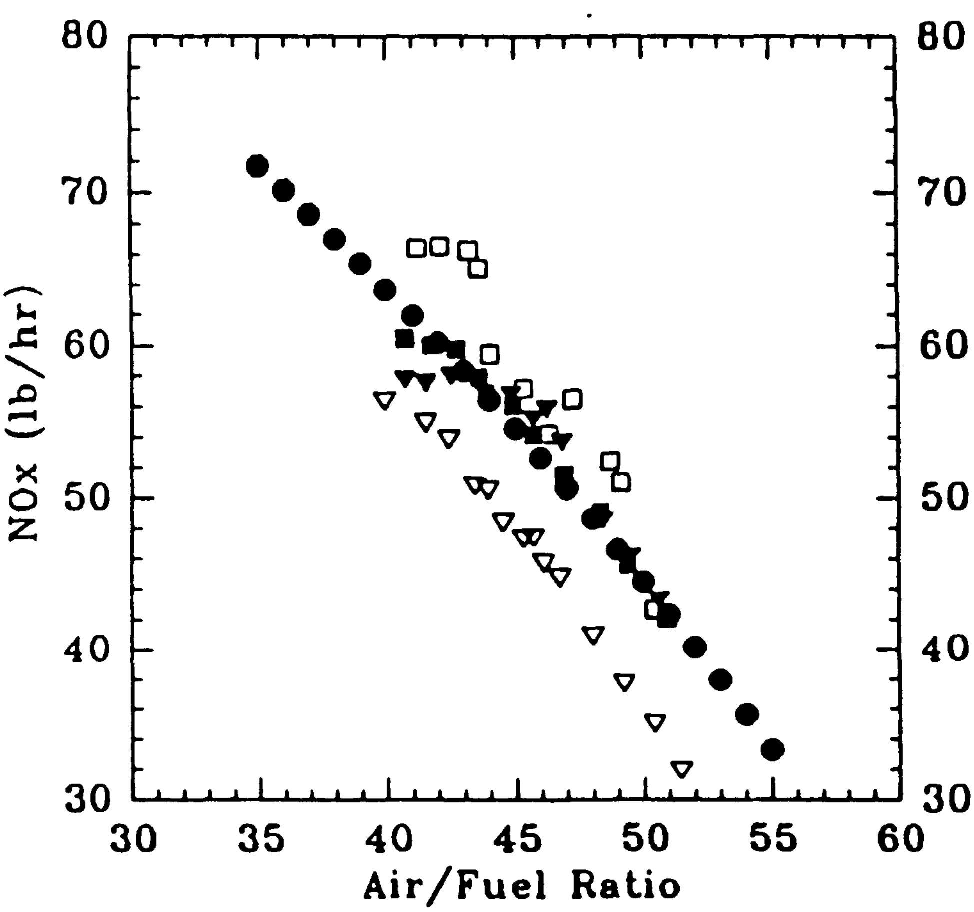


Figure 5-11. The effect of A/F adjustment on NO_x emissions for four identical lean-burn engines.[46]

increasing A/F's, from 13.6 to 9.4 g/hp-hr, a reduction of 31 percent. There was little or no effect on CO emission levels; HC emissions steadily increased from approximately 4 to 7 g/hp-hr, an increase of 75 percent. The initial effect on BSFC was minimal, but at the highest acceptable (no engine misfire) A/F, the BSFC was approximately 2.5 percent higher than at the baseline level. A corresponding plot of the results of A/F adjustment for the second engine was not presented, but the report states that A/F adjustment was limited to a 5 percent increase before the onset of lean misfire, and the NO_x emission reduction was limited to 2 percent. Brake-specific fuel consumption increased 1 percent. The manufacturer of this second engine reports that, in general, A/F adjustment for its line of engines has the potential to reduce NO_x emissions up to approximately 12 percent, with a resulting increase in BSFC of less than 2 percent.[7]

Figures 5-10, 5-11, and 5-12 illustrate that the effect of A/F adjustment on NO_x emissions is engine model-specific. Among engines of the same model, the effect of A/F adjustment is similar, but the range of operating A/F's, and therefore the achievable controlled emission levels, are engine-specific. These figures also illustrate that because these engines can be operated over a range of A/F's, the extent to which NO_x emissions can be reduced depends on where the engine is operating in this range prior to adjustment of the A/F. For example, if Engine 4 in Figure 5-10 is operating at an A/F of approximately 42 prior to adjustment, increasing the A/F to 45 or 46 reduces NO_x emissions by about 1.5 g/hp-hr, a reduction of approximately 15 to 20 percent. However, if the engine is operating at an A/F of 45 or higher, little or no further adjustment to a higher setting can be made, and little or no NO_x reduction is possible from this A/F set point.

Based on the data presented, it is estimated that A/F adjustment for lean-burn engines achieves NO_x emission reductions ranging from 5 to 30 percent. A 25 percent reduction was used to calculate controlled NO_x emission levels and cost effectiveness

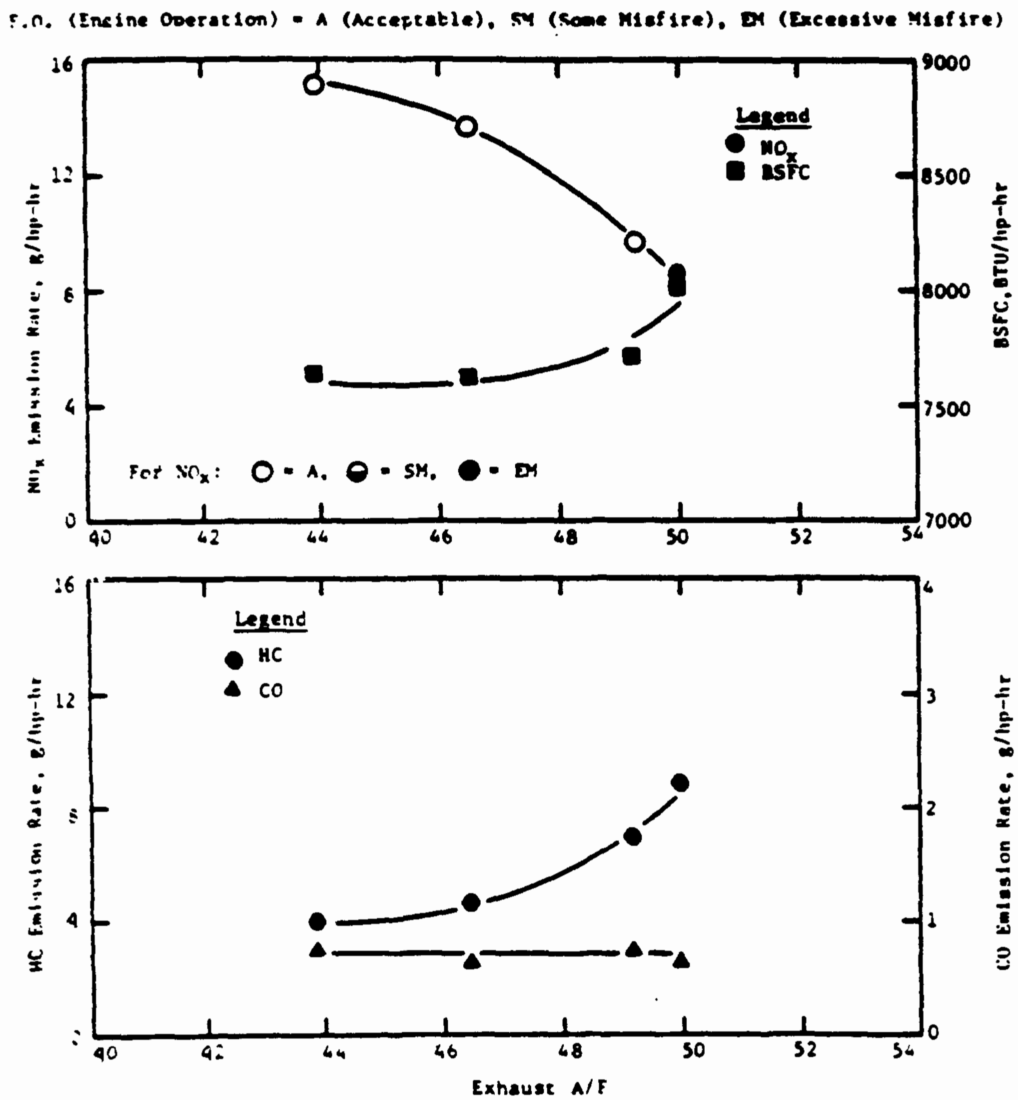


Figure 5-12. The effect of A/F adjustment on emissions and fuel efficiency for a lean-burn engine.[47]

in Chapter 6. The data available to estimate the effect on CO and HC emissions were limited, but based on the general emission curves shown in Figure 5-1 and the data plotted in Figure 5-12, the effect on CO emissions is minimal and HC emissions generally increase. These effects on CO and HC are supported by conclusions drawn from parametric testing of two other lean-burn engines, which cited increases in HC emissions but found no definite trends for CO emissions.[48] The increase in BSFC is estimated to be less than 5 percent, based on the data presented in this section and the conclusions drawn in Reference 48.

5.2.2 Ignition Timing Retard

5.2.2.1 Process Description. Retarding the ignition timing, as described in Section 5.1.2.1, initiates the combustion process at a later point in the power stroke, which results in reduced operating pressures and temperatures in the combustion chamber. These lower pressures and temperatures offer the potential for reduced NO_x formation.

5.2.2.2 Applicability. Ignition timing can be adjusted in the field on all lean-burn engines. As discussed in Section 5.1.2.2, however, the existing ignition system usually must be replaced with an electronic ignition and control system to achieve sustained NO_x reduction and satisfactory engine operation with changes in operating conditions.

5.2.2.3 Factors That Affect Performance. Delaying the combustion by ignition retard results in higher exhaust temperatures, decreased speed stability, and potential for engine misfire and decreased engine power output. These factors are discussed in Section 5.1.2.3. These effects occur continuously and proportionately with increases in timing retard, and limit the extent to which the timing can be adjusted to reduce NO_x emissions.

5.2.2.4 Achievable Emission Reduction. As with A/F adjustment, the achievable NO_x emission reduction using ignition timing retard is engine-specific. The effect of ignition timing retard is shown in Figure 5-13 for four identical lean-burn engines.[46] (The composite plot of filled dots is based on

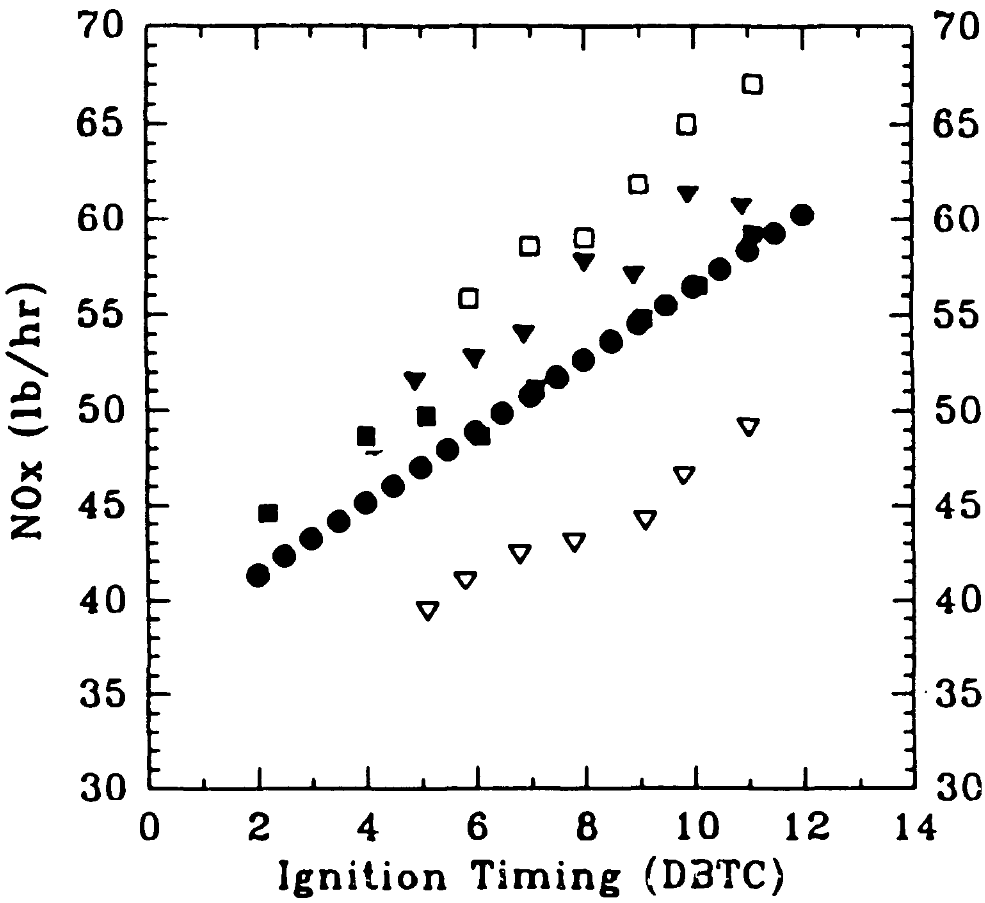


Figure 5-13. The effect of ignition timing retard on NO_x emissions for four identical lean-burn engines.[46]

empirical data and does not necessarily represent the extent to which the ignition timing can be adjusted or the NO_x emission level for these engines.) This figure shows NO_x emission reductions ranging from approximately 3 to 15 percent for ignition retard of up to 6° from the baseline setting of 8° before top dead center (BTDC). The source does not indicate whether engine misfire occurred at the extremes of this 6° range of timing retard.

The effect of timing retard on emissions and fuel consumption is shown for another lean-burn engine in Figure 5-14.[47] A NO_x reduction of less than 10 percent was achievable before the onset of engine misfire with a timing retard of between 3° to 6° from the baseline setting of 8° BTDC. For moderate levels of timing retard, the effect on CO and HC emissions is minimal for this engine. As the timing is further retarded, CO emissions increase with the onset of engine misfire; HC emissions decrease. The effect on BSFC is a continual increase with increasing levels of retard. The increase is approximately five percent for 4° of retard. The manufacturer of this engine states that, in general, timing retard has the potential to reduce NO_x emissions for its line of engines by up to approximately 25 percent. The corresponding increase in BSFC ranges up to 2 percent.[7] For the other lean-burn engine in this study, supplied by a different manufacturer, a 4° retard reduced NO_x emissions by 21 percent, with a minimal increase in BSFC.[47] Further timing retard beyond 4° resulted in engine misfire.

The data suggest that NO_x emission reductions are engine-specific and range up to approximately 20 percent for ignition timing retard levels of from 2° to 6° from the standard setting. Attempts to further reduce NO_x emission levels with further timing retard results in engine performance deterioration and misfire. A 10 percent reduction is used to calculate controlled NO_x emission levels and cost effectiveness in Chapter 6. The impact on CO and HC emissions is minimal, a conclusion supported in a report of parametric testing for two additional lean-burn engines, which cites no definite trend for

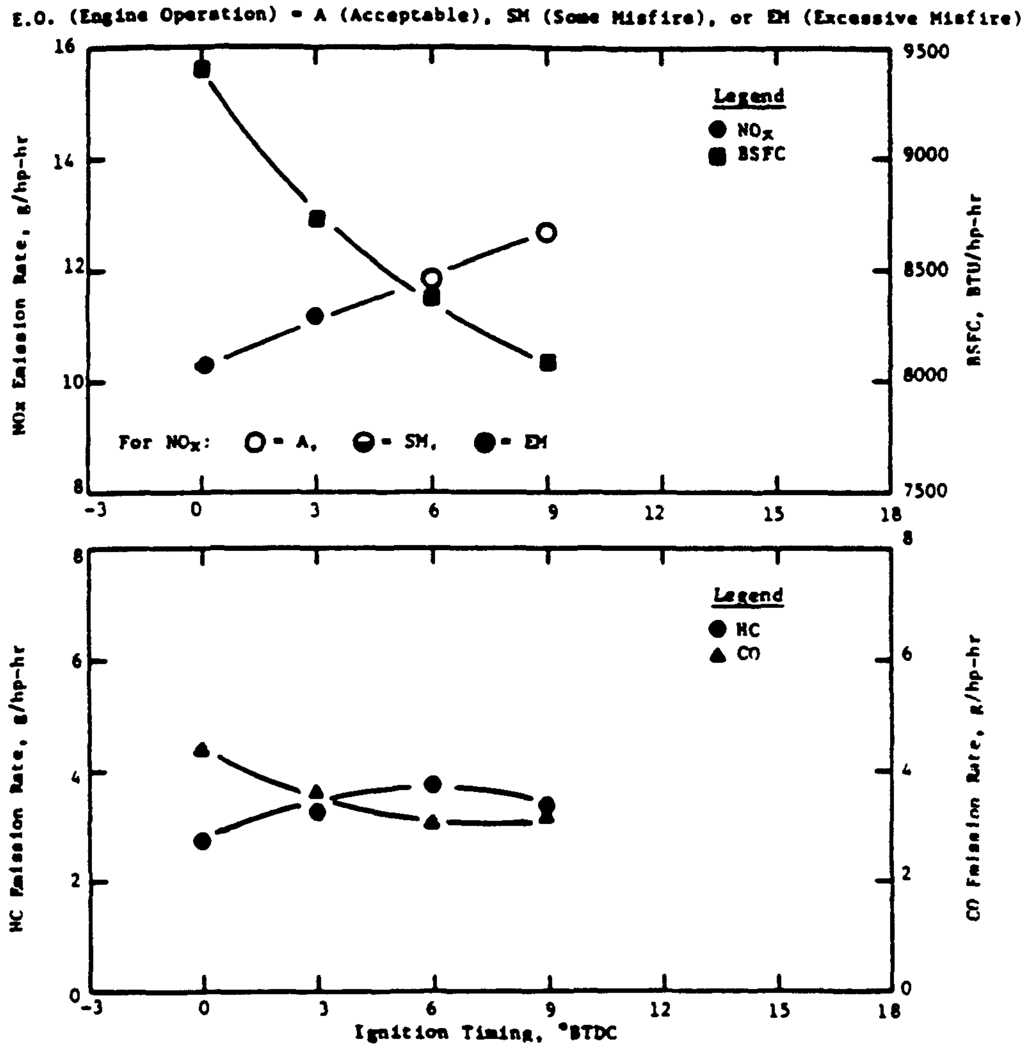


Figure 5-14. The effect of ignition timing on emissions and fuel efficiency for a lean-burn engine.[47]

CO and only slight increases in HC levels.[48] The effect on BSFC is an increase of up to 5 percent, based on the data presented and the conclusions drawn in Reference 48.

5.2.3 Combination of A/F and Ignition Retard

A combination of A/F adjustment and ignition timing retard can be used to reduce NO_x emissions. The potential NO_x reduction for this combination is expected to be greater than for either control technique used by itself but less than the sum of each technique. A summary of emission tests performed before and after adjustment of A/F and ignition timing for seven naturally aspirated lean-burn engines is presented in Table 5-7.[49] Engines 1 through 6 are the same engine model. The engines range in size from 300 to 600 hp and were manufactured in the 1940's. The NO_x reductions resulting from the combination of control techniques ranged from 2.7 to 48 percent and averaged 25 percent. These data reflect the wide variation in achievable NO_x reductions, even for engines of the same model. The engine manufacturer for Engines 1 through 6 estimates a potential NO_x reduction of approximately 20 to 35 percent for the combination of these control techniques, with a corresponding increase in BSFC of less than 5 percent.[7] For either control technique used independently, this manufacturer estimates a maximum achievable NO_x emission reduction of 12 and 25 percent for A/F and ignition timing retard, respectively. Another source estimated that NO_x reductions of up to 22 percent were possible without engine performance deterioration and engine misfire for the engines shown in Figures 5-12 and 5-14.[47]

Based on the limited information available, potential NO_x reductions using a combination of A/F adjustment and ignition timing retard are estimated to range from 20 to 40 percent. This is slightly higher than the estimated reductions of 5 to 30 percent for A/F adjustment and 0 to 20 percent for ignition timing retard used independently. Again, the actual achievable NO_x emission reductions for the combination of these control techniques are engine-specific. A reduction of 25 percent is

TABLE 5-7. ACHIEVABLE NO_x EMISSION REDUCTIONS FOR LEAN-BURN ENGINES USING A COMBINATION OF A/F ADJUSTMENT AND IGNITION TIMING RETARD[49]

Engine No.	Manufacturer	Model	Output (hp)	NO_x reduction, percent
1	Dresser-Rand	RA32	300	25
2	Dresser-Rand	RA32	300	2.7
3	Dresser-Rand	RA32	300	48
4	Dresser-Rand	RA32	300	27
5	Dresser-Rand	RA32	300	26
6	Dresser-Rand	RA32	300	39
7	Cooper-Bessemer	NA	600	8.4
Average				25

used to calculate controlled NO_x emission levels and cost effectiveness in Chapter 6.

Data were not available to quantify the effect of the combination of A/F adjustment and ignition timing retard on CO and HC emissions. Because the effect on CO and HC emissions is minimal or a slight increase when these control techniques are used independently, it is expected that the combination of control techniques produces similar results.

5.2.4 Selective Catalytic Reduction

5.2.4.1 Process Description. Selective catalytic reduction (SCR) is an add-on NO_x control technology that is placed in the exhaust stream following the engine. The SCR process reduces NO_x emissions by injecting ammonia into the flue gas. A simplified schematic of a SCR system is shown in Figure 5-15. The ammonia reacts with NO_x in the presence of a catalyst to form water and nitrogen. In the catalyst unit, the ammonia reacts with NO_x primarily by the following equations:[50]

$4\ NH_3 + 6\ NO \rightarrow 5\ N_2 + 6\ H_2O$; and

$8\ NH_3 + 6\ NO_2 \rightarrow 7\ N_2 + 12\ H_2O$.

The catalyst reactor is usually a honeycomb configuration, as shown in Figure 5-16.[51] Several methods of construction and active material formulations are available. Base-metal (vanadium or titanium) oxide or precious metal catalysts typically are constructed with a ceramic or metal substrate, over which the active material is placed as a wash coat. Zeolite catalysts are extruded as a homogeneous material in which the active material is distributed throughout the zeolite crystalline structure. The geometric configuration of the substrate is designed for maximum surface area and minimum obstruction of the flue gas flow path to maximize conversion efficiency and minimize back-pressure on the engine.

An ammonia injection grid is located upstream of the catalyst body and is designed to disperse the ammonia uniformly throughout the exhaust flow prior to its entry into the catalyst unit. In a typical ammonia injection system, anhydrous ammonia is drawn from a storage tank and evaporated using a steam-heated

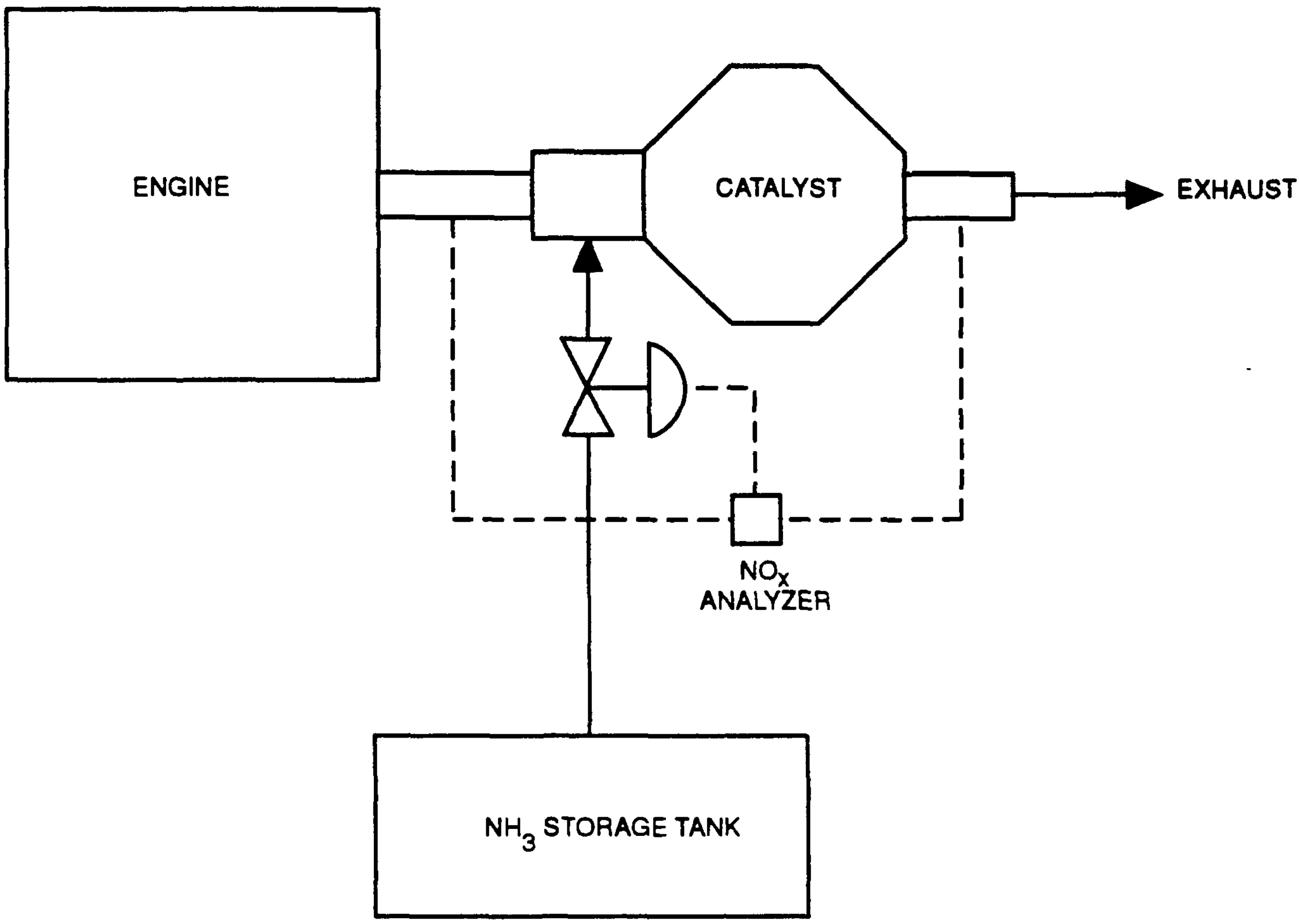


Figure 5-15. Schematic of a selective catalytic reduction system.

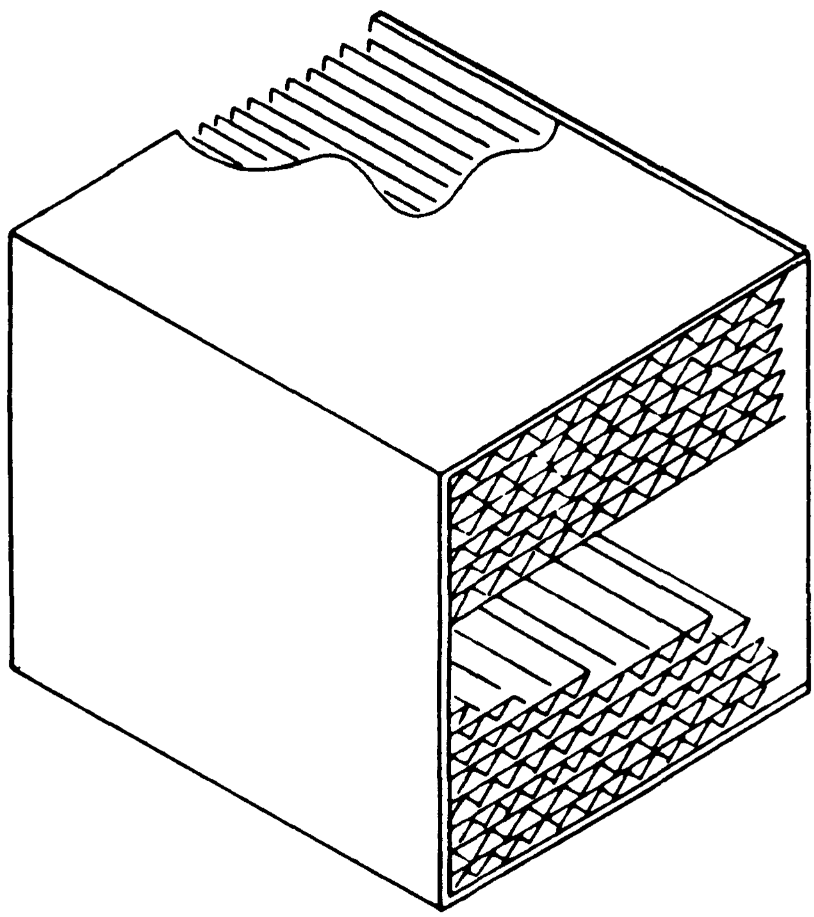


Figure 5-16. Cutaway view of a honeycomb catalyst configuration.[51]

or electrically heated vaporizer. The vapor is mixed with a pressurized carrier gas to provide both sufficient momentum through the injection nozzles and effective mixing of the ammonia with the flue gases. The carrier gas is usually compressed air or steam, and the ammonia concentration in the carrier gas is about 5 percent.[52]

An alternative to using anhydrous ammonia is to use an aqueous ammonia system. The diluted ammonia concentration in an aqueous solution reduces the potential safety concerns associated with transporting and storing anhydrous ammonia.

5.2.4.2 Applicability. The exhaust O_2 level of lean-burn engines makes SCR applicable to all of these engines, but several operating factors may limit the use of SCR. These factors are fuel type and engine duty cycle. Contaminants in the fuel can poison or mask the catalyst surface and reduce or terminate catalyst activity. Examples of these contaminants are sulfur, chlorine, and chloride, which are found in such fuels as digester gas and landfill gas.[27] Natural gas is free of these contaminants, but fuels such as refinery gas, coal gas, and oil fuels may have significant levels of one or more contaminants. Phosphorus and ash in the engine lubricating oil also act as catalyst masking and poisoning agents.

Sulfur-bearing fuels require special consideration when used in SCR applications. Sulfur dioxide (SO_2), formed in the combustion process, oxidizes to SO_3 in some catalysts. Unreacted ammonia reacts with SO_3 to form ammonium bisulfate (NH_4HSO_4) and ammonium sulfate ($(NH_4)_2SO_4$)) in the low-temperature section of the catalyst or waste heat recovery system. Ammonium bisulfate is a sticky substance that causes corrosion of the affected surfaces. Additionally, the deposits lead to fouling and plugging of these surfaces and increase the back pressure on the engine. This requires that the catalyst and any waste heat recovery equipment be removed from service periodically to water-wash the affected surfaces. Ammonium sulfate is not corrosive, but like ammonium bisulfate, these deposits contribute to plugging and fouling of the affected surfaces.

Formation of ammonium salts can be minimized by limiting the sulfur content of the fuel and/or limiting the ammonia slip. The detrimental effects of catalyst masking, poisoning, and ammonium salt formation can also be minimized by using a zeolite catalyst, according to one catalyst vendor. Zeolite is a highly porous crystalline structure; 1 gram of zeolite can contain up to 3,000 square feet of catalyst surface. The catalytic reaction does not take place on the surface of the catalyst but rather in the molecular sieve of the crystalline structure. The NO_x and NH_3 diffuse into the molecular-sized cavities of the crystalline structure, and the exothermic reduction reaction forcefully expels the products of the reaction from the cavities in a self-cleansing action. Because the reducing reaction takes place within the molecular sieve, effects of masking and poisoning that occur on the surface of the catalyst have a minimal effect on the catalyst reduction efficiency.[53,54] The catalyst vendor cites experience with natural gas-fired two-cycle engines with lube oil consumption rates three times greater than those usually seen from this type of engine. An independent lab test performed on samples of the catalyst after 1,000 operating hours showed that concentration levels of phosphorus, sulfur, and zinc found on the surface of the catalyst rapidly diminished from the catalyst surface to the center of the channel wall. The original catalysts at this installation have operated for over 6 years with a NO_x reduction efficiency loss of less than 5 percent. In addition, zeolite has an inherent SO_2 to SO_3 conversion rate of less than 0.1 percent, so ammonium salt formation is minimized.[55]

The duty cycle of the engine should also be considered in determining the applicability of SCR. Exhaust temperature and NO_x emission levels depend upon engine power output, and variable load applications may cause exhaust temperature and NO_x concentration swings that pose problems for the SCR system. The lower exhaust temperature at reduced power output may result in a reduced NO_x reduction efficiency from the catalyst. It should be noted, however, that exhaust NO_x concentrations are lower at reduced power output, and residence time in the catalyst is higher, which would offset to some extent the lower catalyst reduction efficiency at reduced temperatures. The variation in NO_x concentrations in the exhaust caused by changes in power output requires that the ammonia flow be adjusted to maintain the proper NH_3/NO_x ratio. As the exhaust flow rate and NO_x concentration level vary, the NH_3 injection rate must change accordingly to avoid increased levels of unreacted NH_3 emissions (ammonia slip) and maintain NO_x reduction efficiency. At least three catalyst vendors offer an NH_3 injection control system for use in variable load applications. These systems are discussed in Section 5.2.4.4.

5.2.4.3 Factors That Affect Performance. The factors that affect the performance of SCR are catalyst material, exhaust gas temperature, space velocity, the NH_3/NO_x ratio, and the presence of catalyst contaminants in the exhaust gas stream.

Several catalyst materials are available, and each has an optimum NO_x removal efficiency range corresponding to a specific temperature range. Proprietary formulations containing titanium oxide, vanadium pentoxide, platinum, or zeolite offer wide operating temperature ranges and are the most common catalyst materials. The NO_x removal efficiencies for these catalysts are typically between 80 and 90 percent when new; over time, the NO_x removal efficiency may drop as the catalyst deteriorates due to surface deposits, poisoning, or sintering.[51]

The space velocity (volumetric flue gas flow rate divided by the catalyst volume) is essentially the inverse of residence time in the catalyst unit. The lower the space velocity, the higher the residence time, and the higher the potential for increased NO_x emission reductions. Since the exhaust gas flow is dictated by the engine, the space velocity is largely dependent upon the size of the catalyst body. Lower space velocities require larger catalyst bodies.

The NH_3/NO_x ratio can be varied to achieve the desired level of NO_x reduction. The SCR systems generally operate with a molar NH_3/NO_x ratio of approximately 1.0.[51] Increasing this ratio will further reduce NO_x emissions but will also result in increased ammonia slip.

Contaminants in the exhaust gas stream will mask or poison the surface of the catalyst reactor. Masking agents, such as sulfur and ash, deposit on the catalyst surface and require that the catalyst be mechanically cleaned to restore lost catalyst activity. Poisoning agents such as chlorine and phosphorus chemically alter the catalyst material, and any resulting loss of catalyst activity is permanent. The source of most contaminants is gaseous fuels other than natural gas; ash and phosphorus are found in lubricating oils. Low-ash and low-phosphorus lubricating oils are available and are recommended for use with catalyst systems.[27] The use of low-ash oils may have a detrimental effect on the valve life of some four-cycle engines. Past experience has shown that the exhaust valve life of some engines may be reduced be as much as 50 percent, doubling the frequency of top-end overhaul maintenance requirements of the engine.[56]

5.2.4.4 Achievable Emission Reduction Using SCR. Based on information provided by catalyst vendors, a total of 23 gas-fired, lean-burn engine SCR applications have been installed or will be installed in the United States by the end of 1993. Of these installations, three are used in digester gas applications, and the rest are natural gas-fueled. From the information provided it was not possible to confirm that this list includes all SCR installations in the United States or whether any of these installations have been decommissioned.

Operating experience and emission test summaries for 16 engines at 9 installations in California were provided by one catalyst vendor and are shown in Table 5-8.[57] For these installations, NO_x reduction levels range from 75 to 90 percent, with corresponding NH_3 slip levels of 20 to 30 ppmv. All but one of these installations uses a manually adjusted NH_3 injection control system. The controlled NO_x emission and ammonia slip levels for the two digester gas-fired applications are similar to those for the natural gas-fired engines shown in this table.

TABLE 5-8. GAS-FUELED SCR APPLICATIONS AND OPERATING EXPERIENCE FOR ONE CATALYST VENDOR[57]

Installation date	Engine manufacturer	Engine model	Fuel	Power	Speed	Load	Ammonia control	Performance test results		Catalyst changes and operating hours[a]
								NO_x reduction	Ammonia slip	
06/86	Dresser-Rand	RA-6 (3)	Natural gas	660 HP	325 RPM	Constant	Manual	80%	NA[b]	8-88/18,720 hr, 8-92/35,040 hr
04/90	Waukesha	L7042GL	Digester gas	800 HP	700 RPM	Constant	Manual	90%	30 PPM	None, 7,800 hr
05/85	Dresser-Rand	KVG10	Digester gas	800 HP	700 RPM	Constant	Manual	80%	20 PPM	None, 16,000 hr
05/85	Dresser-Rand	RA-6(2)	Natural gas	600 HP	325 RPM	Constant	Manual	90%	NA[b]	3-88, 24,090 hr
07/83	Dresser-Rand	RA-8(2)	Natural gas	200 HP	325 RPM	Constant	Manual	90%	20 PPM	3-92, 75,920 hr
05/82	Cooper Bessemer	GMV-6	Natural gas	660 HP	400 RPM	Constant	Manual	80%	20 PPM	2-86, 32,850 hr
04/83	Dresser-Rand	HRA-6	Natural gas	600 HP	325 RPM	Constant	Manual	75%	20 PPM	None
09/86	Cooper Bessemer	GMV-8(2)	Natural gas	800 HP	300 RPM	Constant	Load following	80%	20 PPM	3-89/21,900 hr, 6-91/19,710 hrs
12/87	Dresser-Rand	RA-6(3)	Natural gas	600 HP	325 RPM	Constant	Manual	80%	20 PPM	None

[a]Hours between catalyst changes are estimated.
[b]Data not available.

Emission compliance test summaries were also reported in the VCAPCD emission data base for six SCR installations. These test summaries are shown in Table A-5 in Appendix A.[24] For a total of 34 test summaries, only 1 did not achieve compliance with the controlled NO_x requirement of 125 ppmv or 80 percent reduction, and the data base reports that this engine was removed from service. Of the five remaining SCR installations, two other engines were in compliance, but were removed from service and replaced by electrification. Controlled NO_x emission levels for those engines in compliance range from 10 to 222 ppmv (0.14 to 3.1 g/hp-hr), with corresponding reduction efficiencies of 65 to 97 percent. The data base shows that two of these SCR installations have been operating within compliance limits for over 5 years. Information regarding catalyst maintenance requirements and replacement schedules for these engines was not available. Ammonia slip levels were not reported in the data base. (Rule 74.9 for VCAPCD and Rule 1110.2 for SCAQMD do not include ammonia emissions limits.)

In addition to the experience described above for U.S. installations, one zeolite catalyst vendor also provided SCR operating experience for engine installations worldwide. The installation list shows over 40 gas-fired engine applications using natural gas, landfill and digester gases, and mining gases. Applications include power generation and cogeneration, natural gas pipeline compression, and district heating. Seven of these installations have been in service since 1985, and one of these installations has operated for over 6 years with only a 5 percent loss in NO_x reduction efficiency. The two-cycle engines in this installation consume three times more lubrication oil than is considered normal by the catalyst vendor. The guaranteed minimum NO_x reduction at this site is 85 percent.[53,54]

Catalyst vendors typically offer NO_x reduction efficiency guarantees of 90 percent, with an ammonia slip level of 10 ppmv or less. The performance is guaranteed by most vendors for 3 years for natural gas-fired applications.[34] One zeolite catalyst vendor offers a guarantee of up to 95 percent NO_x

reduction with an ammonia slip limit of 10 ppmv or less for 2 years.[54]

As discussed in Section 5.2.4.2, NO_x emission levels and exhaust flow vary with changes in engine load, and the NH_3 injection rate must follow these changes. Several catalyst vendors state that NH_3 injection system controls are available for variable load applications. One vendor's design has been in use since 1988, but system design details were not available.[55] Another vendor offers a load-following ammonia injection control system design for the installations shown in Table 5-8, dating back to 1989. These installations have achieved NO_x emission reductions of 75 to 90 percent with NH_3 emission slip levels of 20 to 30 ppmv, based on 15 minute emission averaging.[57] Information regarding the extent and frequency of the engine load changes, however, were not available. Information for a microprocessor-based, feedforward/feedback NH_3 injection control system was provided by a third vendor. This system is available with provisions to predict NO_x emissions based on engine operating parameters. The predictive emission maps are developed either by the engine manufacturer or by the catalyst vendor during the start-up/commissioning phase of the project, and these maps can be automatically updated periodically by the microprocessor system, based on historical operating data. The feedforward control regulates the NH_3 injection rate consistent with the anticipated NO_x emissions, and the injection rate is trimmed by the feedback controller, which monitors emission levels downstream of the catalyst reactor. A deadtime compensation routine is incorporated into the control scheme to compensate for the difference between the catalyst reactor reduction rate and the controller response time. This control scheme is operating in Europe and at a demonstration site in the United States, and typical deviations from the target NO_x emission setpoint are within 4 percent.[58]

Based on the available information and the emission test data presented in Tables 5-8 and A-5, it is estimated that the achievable NO_x emission reduction for SCR in gas-fired applications is 80 to 90+ percent for baseload applications, with an NH_3 slip level of 10 ppmv or less. A 90 percent NO_x reduction is used in Chapter 6 to calculate controlled NO_x emission levels and cost effectiveness. The available data are not sufficient to assess the achievable continuous NO_x reductions and ammonia slip levels for SCR used in variable load applications. Emissions of CO and HC are not significantly affected by the use of SCR.[11]

The backpressure on the engine increases by approximately 2 to 4 in. w.c. with the installation of an SCR system. The resultant BSFC increase from a backpressure of 4 in. w.c. is estimated at 0.5 percent.[3] This backpressure also is estimated to decrease the power output by 1 percent in naturally aspirated engines and 2 percent in turbocharged engines.[3]

5.2.5 Low-Emission Combustion

5.2.5.1 Process Description. Lean-burn engine NO_x emissions can be reduced by increasing the A/F so that the engine operates in the region depicted on the right side of Figure 5-1. These low-emission combustion designs are also referred to as torch ignition, jet cell, and CleanBurn® by various manufacturers. (CleanBurn® is a registered trademark of Cooper Industries.) The increase in the air content serves to raise the heat capacity of the mixture and results in lower combustion temperatures, which lowers NO_x formation. This increased airflow is provided by adding a turbocharger and intercooler or aftercooler to naturally aspirated engines or by replacing an existing turbocharger and inter/aftercooler with a larger-capacity unit. The air intake and filtration system, carburetor(s), and exhaust system must also be replaced to accommodate the increased flows.

Substantial modification of the combustion chamber is required to ensure ignition and stable combustion of the higher A/F mixture. For engines that have a relatively small cylinder bore, the combustion chamber may use an open cylinder design, which is similar to a conventional combustion chamber but incorporates improved swirl patterns to promote thorough mixing. Larger cylinder bores cannot reliably ignite and sustain combustion with an open-cylinder design and a PCC. These clean-burn combustion designs vary somewhat with each manufacturer, but descriptions and representative sketches are presented in Section 5.1.6.1. The redesigned combustion chamber in the case of either an open or PCC design usually requires replacement of the intake manifolds, cylinder heads, pistons, and the ignition system.

5.2.5.2 Applicability of Low-Emission Combustion. The applicability of combustion modifications for lean-burn, low-emission engines is limited only by the availability of a conversion kit from the manufacturer. The application considerations discussed for rich-burn engines in Section 5.1.6.2 also apply to lean-burn engines.

5.2.5.3 Factors That Affect Performance. The factors that most affect the emissions reduction performance of a lean-burn engine that has been converted to low-emission combustion are the design of the new combustion chamber and the volume of air that can be delivered. The factors described in Section 5.1.6.3 for rich-burn engines also apply to lean-burn engines.

5.2.5.4 Achievable Emission Levels Using Low-Emission Combustion. The nominal emission levels provided by engine manufacturers for both 2-cycle and 4-cycle PCC designs are:[37-42]

Emissions, g/hp-hr			Emissions, ppmv at 15% O_2		
NO_x	CO	HC	NO_x	CO	HC
1.5-3.0	0.6-3.5	1.0-9.0	110-225	72-425	217-1,950

Reductions in NO_x emissions using combustion modifications generally result in higher CO and HC emission levels. For this reason, it is not likely that the low end of each range for NO_x, CO, and HC in the figure listed above can be achieved simultaneously.

There was no discernable difference in achievable emissions levels between applying combustion controls to 2-cycle versus 4-cycle engines. (Two low-emission engine models from one manufacturer that have controlled NO_x emissions of 6.5 g/hp-hr

[475 ppmv] were not included in the above table. These models will soon be updated, and controlled NO_x emissions will be within the range shown above.)

The percent NO_x reduction that is achievable by converting a lean-burn engine to a low-emission design varies depending upon the uncontrolled and controlled NO_x levels used to calculate the percent reduction. Uncontrolled emission levels typically range from 15 to 20 g/hp-hr for lean-burn engines.[37-42] Conversion to clean-burn operation can achieve controlled NO_x emission levels of 1.5 to 3.0 g/hp-hr. The percent reduction, therefore, ranges from 80 to 93 percent.

Test results for nine low-emission engines that were developed from lean-burn engine designs are presented in Table 5-9.[59-62] Four of these engines are retrofit installations; the other five were installed as new equipment. This table shows that controlled NO_x emission levels range from 0.53 to 6.0 g/hp-hr (40 to 450 ppmv), and average 2.0 g/hp-hr (154 ppmv). The 6.0 g/hp-hr level for engine No. 7 is not considered to be representative of the achievable controlled NO_x emission level, since engine Nos. 6 and 7 are the same engine model and engine No. 7 achieved a 1.5 g/hp-hr emission level. The average NO_x emission level drops from 2.0 to 1.6 g/hp-hr (154 ppmv) if engine No. 6 is not included. Carbon monoxide emission levels range from 1.05 to 2.2 g/hp-hr (126 to 264 ppmv) and average 1.6 g/hp-hr (192 ppmv). Hydrocarbon emissions range from 0.3 to 4.4 g/hp-hr (53 to 933 ppmv) and average 1.2 g/hp-hr (262 ppmv). All of these engines use a PCC design, and the controlled emission levels are within or below the achievable ranges stated by the engine manufacturers.

Emission test results for several low-emission engines were also included in the VCAPCD emission data base.[24] These emission summaries are presented in Table A-4 in Appendix A. For a total of 64 emission tests performed on six engines, all but 5 of the tests show controlled NO_x emission levels of less than 100 ppmv (1.34 g/hp-hr), and average the 75 ppmv (1.0 g/hp-hr), with average controlled CO and HC emission levels of 500 ppmv

TABLE 5-9. ACHIEVABLE EMISSION LEVELS FOR NEW AND RETROFIT LOW-EMISSION ENGINES DEVELOPED FROM LEAN-BURN DESIGNS[59-62]

Engine No.	Manufacturer	Model	Power (hp)	New/retrofit	Emissions (g/hp-hr)			Emissions (ppmv @ 15% oxygen)[a]		
					NO_x	CO	HC	NO_x	CO	HC
1	DeLaval	HVA-16-C6	5,500	R	1.1	1.5	NA[b]	83	180	NA[b]
2	DeLaval	HVA-16-C6	5,500	R	0.53	1.05	NA[b]	40	126	NA[b]
3	DeLaval	HVA-16-C4	4,000	R	1.01	1.88	4.4	76	226	933
4	Cooper-Bessemer	10V-250	3,400	R	1.3	NA[b]	NA[b]	98	NA[b]	NA[b]
5	Cooper-Bessemer	16Q155HC	6,960	N	1.8	1.1	0.3	135	128	53
6	Cooper-Bessemer	GMVH-10	2,250	N	6.0	1.4	1.5	450	168	322
7	Cooper-Bessemer	GMVH-12	2,700	N	1.5	2.2	0.5	113	264	106
8	Dresser-Rand	TCV-10	4,200	N	2.6	1.9	0.4	191	233	78
9	Dresser-Rand	TCV-10	4,200	N	2.6	1.7	0.4	197	209	78
Averages					2.0	1.6	1.2	154	192	262

[a]Emissions were reported in g/hp-hr. Units of ppmv were calculated using the following conversion factors:

NO_x: 1 g/hp-hr = 75 ppmv @ 15 percent oxygen
CO: 1 g/hp-hr = 120 ppmv @ 15 percent oxygen
HC: 1 g/hp-hr = 212 ppmv @ 15 percent oxygen

[b]NA - Data not provided.

(4.17 g/hp-hr) and 127 (0.60 g/hp-hr), respectively. The NO_x and HC emission levels are consistent with those stated by engine manufacturers, but the CO emission levels are generally higher. No information was available to explain these relatively elevated CO emission levels, but the range shown in Table A-4 is well within the VCAPCD CO limit of 4,500 ppmv.

The data presented suggest that achievable controlled NO_x emission levels of 1.0 to 2.0 g/hp-hr (75 to 150 ppmv) can be achieved with combustion modifications for either new or retrofit lean-burn engine installations. A 2.0 g/hp-hr controlled NO_x emission level is used in Chapter 6 for cost effectiveness calculations. This is also the controlled NO_x emission range for combustion modifications for rich-burn engines. Emission levels for CO and HC vary for different engine models and even among engines of a given model, but most range from approximately 1.0 to 5.0 g/hp-hr (120 to 600 ppmv) for CO and 0.5 to 4.0 g/hp-hr (110 to 500 ppmv) for HC.

The operating characteristics of low-emission combustion, including a substantially leaner A/F and the potential increase in operating pressures from turbocharging, suggest improved fuel economy. Information for four manufacturers' engines for which comparable heat rates were provided shows that the effect of the combustion modification on engine heat rates was mixed. The effect ranged from an increase in heat rate of as much as 3.5 percent to a decrease of as much as 12.4 percent.[37,38,40,42]

5.3 NO_x CONTROL TECHNIQUES FOR CI ENGINES

Both diesel and dual-fuel engines operate with significant excess O_2 levels in the exhaust gas stream. Although classified as lean-burn, the effect of control techniques applied to these CI engines is in many cases different from those for SI engines. Therefore, the discussion of control techniques applied to CI engines is presented separately.

The control technologies available for CI engines are:

1. Injection timing retard;
2. Selective catalytic reduction; and

3. Low-emission combustion (dual-fuel engines only). Section 5.3.1 describes the performance of NO_x control techniques for diesel engines. The performance of NO_x control techniques for dual-fuel engines is discussed in Section 5.3.2.

5.3.1 <u>Diesel Engines</u>

5.3.1.1 <u>Injection Timing Retard for Diesel Engines</u>. In a CI engine, the injection of the fuel into the cylinder initiates the combustion process. Retarding the timing of the fuel injection initiates the combustion process later in the power stroke when the piston is in its downward motion and the combustion chamber volume is increasing. This increasing volume lowers combustion temperatures and pressures, thereby lowering NO_x formation. Along with NO_x reductions, injection timing retard increases both black smoke and cold smoke (white smoke during start-up) emissions, increases exhaust temperatures, and can make starting the engine at cold temperatures more difficult. Brake-specific fuel consumption also increases with timing retard.[63,64] Two sources report that power output decreases by roughly the same amount as BSFC increases.[64,65] Another engine manufacturer, however, reports that injection timing retard does not reduce power output for its line of engines.[63] The increase in exhaust temperatures affects turbocharger performance and may be detrimental to exhaust valve life.[63,65] Excessive timing retard causes engine misfire.[67] These performance impacts generally limit the extent of injection timing retard to less than 8° from the standard setting.[63]

Injection timing to retard the ignition can be adjusted in the field on all diesel engines. For maximum NO_x reduction, an electronic injection timing system is required, which temporarily advances the timing during start-up and under acceleration in response to load changes.[63,65]

Injection timing retard reduces NO_x emissions from all diesel engines, but the magnitude of the reductions is specific to each engine model. The effectiveness of injection retard on decreasing NO_x formation diminishes with increasing levels of retard. Data to quantify the effects of injection timing retard were available from only one manufacturer for retard levels between 3° and 5°. These data are shown in Table 5-10.[66] The results from three different engines show that injection retard reduced NO_x emissions in all three engines by greater than 20 percent, but the magnitude of the reduction varied for each engine. Another manufacturer estimated achievable NO_x reduction potential for injection timing retard ranges up to 50 percent.[63] Data from Reference 5 indicate that NO_x reductions range from 20 to 34 percent. Based on the available data and estimates by manufacturers, the expected range for NO_x reductions using injection timing retard in diesel engines is 20 to 30 percent. A 25 percent reduction is used to calculate controlled NO_x emission levels and cost effectiveness in Chapter 6. The actual NO_x reduction, however, is engine-specific and may be higher or lower than the expected range.

The effect on CO emissions shown in Table 5-10 is an increase for two of the engines and a decrease for the third engine. The overall impact on CO emissions, whether an increase or a decrease, is a change of less than 15 percent for these engines. The effect on HC emissions also varies among engines, ranging from no change to an increase of 76.2 percent. The BSFC increases for all three engines. The magnitude of the fuel increase grows with the degree of retard, ranging from 0.9 percent for a 3° retard to 4.5 percent for a 5° retard.[66] In general, the effect of reducing NO_x emissions by fuel injection retard on CO and HC emissions is estimated to range from a 10 percent decrease up to 30 percent increase for CO and +/- 30 percent change for HC, according to one manufacturer. The increase in BSFC is a maximum of 5 percent.[63] The effect on CO and HC emissions and BSFC for the engines shown in Table 5-10, although produced by another manufacturer, is generally consistent with these estimates.

5.3.1.2 <u>Selective Catalytic Reduction</u>. The process description for SCR discussed in Section 5.2.4.1 applies to diesel engine applications. Selective catalytic reduction applies to all diesel engines, and the application considerations

TABLE 5-10. EFFECT OF FUEL INJECTION TIMING RETARD ON EMISSIONS AND FUEL CONSUMPTION FOR DIESEL ENGINES[66]

Engine No.	Power output, hp	Retard, degrees	Emission, pre/post timing retard, g/hp-hr			Percent change			
			NO_x	CO	HC	NO_x	CO	HC	BSFC[a]
1	1800	3	8.03/6.24	2.65/2.84	0.21/0.26	-22.3	+7.2	+23.8	+0.9
2	2518	4.25	8.74/6.16	2.78/3.08	0.21/0.37	-29.5	+10.8	+76.2	+2.9
3	1615	5	35.5/26.5	15.2/13.2	0.3/0.3	-25.4	-13.2	-0-	+4.5

[a]BSFC - brake-specific fuel consumption.

discussed in Section 5.2.4.2 for SI engines also apply to diesel engines. The factors that affect the performance of SCR for diesel engines are the same as those discussed in Section 5.2.4.3. Fuel specifications for No. 2 diesel fuel limit the sulfur content to 0.5 percent. Heavier diesel fuels may have higher sulfur contents, however, that may result in increased formation of ammonia salts (see Section 5.2.4.2).

The potential NO_x emission reductions for SCR applications with diesel engines are similar to those for natural gas applications. Catalyst vendors that offer zeolite catalysts quote NO_x reduction efficiencies for diesel engine applications of 90 percent or higher, with corresponding NH_3 slip levels of 10 ppmv or less.[54,68]

According to one of these vendors, the crystalline molecular structure of zeolite, combined with the exothermic characteristics of the NO_x and NH_3 reducing reaction, minimizes the masking and poisoning problems that have been experienced with base metal catalysts. Zeolite also has a SO_2 to SO_3 conversion rate of less than 0.1 percent, so ammonia salt formation is minimal.[55] The two zeolite vendors contacted for this study have diesel engine installations using SCR outside of the United States for which these 90 percent NO_x reduction efficiencies are guaranteed for 3 years, but to date they have no installations in the United States. A total of nine oil-fired zeolite installations were identified.[54,69] All of these installations are overseas, mostly in Europe. Of these installations, eight engines are diesel-fired; the other is fueled with heavy oil. These installations date back as far as 1985, and the catalyst vendors guarantee a 90 percent NO_x reduction or higher, with an ammonia slip level of 10 ppmv or less, for 3 years. One of these diesel-fired installations has a 3-year guarantee of 95 percent NO_x reduction with an maximum ammonia slip level of 5 ppmv. The heavy oil-fired installation was installed in 1985.

To date there are no zeolite SCR installations in diesel-fired applications in the United States, but a U.S. SCR installation with a 6,700 hp dual-fuel engine achieved over 30,000 hours before one quarter of the original catalyst was replaced. This engine operates up to 25 percent of the time in a diesel mode, firing 100 diesel oil, and it is estimated that the original catalyst operated up to 7,500 of the 30,000+ total hours on diesel fuel, maintaining a guaranteed NO_x reduction of 93 percent or higher with an ammonia slip level of less than 10 ppmv. The only catalyst maintenance requirement at this site is periodic vacuuming of the catalyst face to remove particulate matter, which is attributed to engine lube oil consumption. This accumulation of particulate matter is manifested by an increase in pressure drop across the catalyst from a design 3.5 in. w.c. to 5+ in. w.c. No notable decrease in catalyst reduction performance accompanies this pressure drop.[70]

The NO_x reduction efficiency quoted by vendors offering base-metal catalysts for diesel applications is typically 80 to 90 percent.[57,71] The exhaust from diesel engines has a higher level of heavy hydrocarbons than natural gas-fueled engines, and these hydrocarbons lead to soot formation on the catalyst surface, which can mask the catalyst and reduce the NO_x reduction activity.[50] A guard bed, having the same structural makeup as the catalyst material, is usually installed upstream of the catalyst body in diesel applications to collect the heavy hydrocarbons that would otherwise mask the base-metal catalyst. This guard bed is replaced approximately every 2,000 hours of operation.[72]

Only two vendors offering base metal catalysts contacted for this study have SCR installations operating with diesel engines. The majority of these installations are in emergency power generation service and have accumulated relatively few operating hours. One base-metal catalyst vendor's diesel-fired SCR experience is presented in Table 5-11 and shows six U.S. installations with a total of nine engines.[57] All of these SCR applications are load-following, but details of the duty cycle and the ammonia injection control scheme were not provided. The reported NO_x emission reductions range from 88 to 95 percent,

TABLE 5-11. DIESEL-FUELED SCR APPLICATIONS FOR ONE CATALYST VENDOR[57]

Installation date	Engine manufacturer	Engine model	Fuel	Power, hp	Speed, rpm	Load	Ammonia control	Performance test results: NO_x reduction, %	Performance test results: Ammonia slip, ppmv	Catalyst changes and operating hours
02/93	CATERPILLAR	3408	Diesel	475	1,800	Variable	Load following	90	5	None
01/91	CATERPILLAR	3412	Diesel	750	1,800	Variable	Load following	95	20	None, 4500 hrs
12/91	CUMMINS	KTA 19-G1	Diesel	560	1,800	Variable	Load following	90	20	None, 400 hrs
09/89	CATERPILLAR	3306	Diesel	270	2,100	Constant	Manual	90	30	None
01/90	COOPER	LSV16	Diesel	2,500	700	Variable	Load following	94	30	None, 12000 hrs
03/90	CATERPILLAR	3516 (3)	Diesel	2,850	1,800	Variable	Load following	95	20	None, 600 hrs
02/90	DETROIT	16V149 (2)	Diesel	2,350	1,800	Variable	Load following	88	30	None, 600 hrs

with corresponding ammonia slip levels of 5 to 30 ppmv. The tests were performed in accordance with State-approved methods for California, with emissions reported on a 15-minute averaging basis. The first of these installations was installed in 1989, and one installation has operated over 12,000 hours to date.

The available data show diesel-fired SCR applications using either zeolite or base-metal catalysts achieve NO_x reduction efficiencies of 90+ percent, with ammonia slip levels of 5 to 30 ppmv. These installations include both constant- and variable-load applications. Experience to date, however, especially in the United States, is limited in terms of both the number of installations and the operating hours. A 90 percent reduction is used in Chapter 6 to calculate controlled NO_x emission levels and cost effectiveness.

As discussed in Section 5.2.4.4, the effect of SCR on CO and HC emissions is minimal. The engine BSFC increases with the use of SCR due to the increased exhaust backpressure created by the catalyst reactor.

5.3.2 Dual-Fuel Engines

5.3.2.1 Injection Timing Retard for Dual-Fuel Engines. Fuel injection timing retard reduces NO_x emissions from dual-fuel engines. The process description, extent of applicability, and the factors that affect performance are the same as for diesel engines and are discussed in Section 5.3.1.1.

The achievable NO_x emission reductions range from 20 to 30 percent for a timing retard of 4°, based on information and data in Reference 5. The actual reduction is specific to each engine. Additional data were available only for one engine and are presented in Table 5-12.[65] This table shows that a timing retard of 3° results in a NO_x reduction of 14 percent. An additional retard of 3° yields an additional 5 percent NO_x reduction. The nominal NO_x emission rate for this engine is 5 g/hp-hr.[38] Reductions of 14 and 19 percent result in controlled NO_x emissions of 4.3 and 4.1 g/hp-hr, respectively. The total NO_x reduction figure of 19 percent for a 6° timing retard is slightly lower than the 20 to 30 percent reduction

TABLE 5-12. RESULTS OF RETARDING THE INJECTION TIMING FOR ONE DUAL-FUEL ENGINE MODEL[65]

Affected parameter	Percent change due to retarding from 21° to 18° BTDC	Percent change due to retarding from 18° to 15° BTDC
NO_x emissions	-14	-5
CO emissions	+13	+10
HC emissions	+6	+15
Fuel consumption	+0.7	+2.5

range stated in Reference 5. A 20 percent reduction was used in Chapter 6 to calculate controlled NO_x emission levels and cost effectiveness.

Timing retard increases emissions of CO and HC as well as BSFC. Table 5-12 shows that the initial 3° timing retard increases CO and HC emissions 13 and 6 percent, respectively. The BSFC increased 0.7 percent. This table also shows the diminishing NO_x reduction benefit and the rise in the rate of increase of other emissions and fuel consumption with incremental increases in timing retard. The increase in timing retard from 3° to 6° yielded an additional NO_x reduction of 5 percent, while CO and HC emissions increased an additional 10 and 15 percent, respectively, and fuel consumption increased an additional 2.5 percent.

5.3.2.2 Selective Catalytic Reduction for Dual-Fuel Engines. The process description, extent of applicability, and the factors that affect the performance of SCR for dual-fuel engines is the same as for CI engines and is discussed in Section 5.3.1.

Catalyst vendors report a total of 27 U.S. SCR systems installed to date with dual-fuel engines.[58,70] The achievable NO_x emission reduction using SCR with dual-fuel engines ranges from 80 to 90+ percent. Two vendors with SCR installations in the United States using zeolite catalysts have guaranteed 90 percent or higher NO_x reduction efficiencies with a 10 ppmv or less ammonia slip for a 3-year period.[54,68] The first SCR installation in the United States was installed downstream of a 6,700 hp dual-fuel engine in 1988. The NO_x reduction guaranteed at this site is 93 percent, with an ammonia slip level of less than 10 ppmv. The results of an emission test performed during commissioning in 1989 at this site are presented in Table 5-13.[73] Controlled NO_x emission levels averaged 0.38 and 0.22 g/hp-hr (48.3 and 27.1 ppmv) for operation on diesel and dual-fuel, respectively. Ammonia slip levels were not reported in the test results. Catalyst life was guaranteed for 3 years or 20,000 hours. The SCR system achieved over 30,000 operating

TABLE 5-13. EMISSIONS COMPLIANCE TEST RESULTS FOR A DUAL-FUEL ENGINE USING SCR[73]

Run No.	Power output, hp	Uncontrolled NO_x emissions				Controlled NO_x emissions				Percent reduction	
		Diesel		Dual fuel		Diesel		Dual fuel		Diesel	Dual fuel
		g/hp-hr	ppmv[a]	g/hp-hr	ppmv	g/hp-hr	ppmv[a]	g/hp-hr	ppmv[a]		
0	6500	5.4	NA[b]	3.2	--	--	--	--	--	--	--
1	6500	--	--	--	--	0.38	52.3	--	--	92.8	--
2	6500	--	--	--	--	0.38	47.0	--	--	93.0	--
3	6500	--	--	--	--	--	--	0.22	25.9	--	93.2
4	6500	--	--	--	--	--	--	0.22	27.3	--	93.0
5	6500	--	--	--	--	--	--	0.22	28.1	--	93.0
6	6500	--	--	--	--	--	--	0.22	28.1	--	93.0
Avg	6500	5.4	NA[b]	3.2	NA[b]	0.38	48.3	0.22	27.1	92.9	93.1

[a]Referenced to 15 percent O_2.
[b]NA - not available.

hours before one of the four sections of the original catalyst was replaced. This engine operates up to 25 percent of the time in a diesel mode, and on this basis it is estimated that the catalyst has operated up to 7,500 of the 30,000+ total hours on diesel fuel. The only catalyst maintenance requirement at this site is periodic vacuuming of the catalyst face to remove particulate matter, which is attributed to engine lube oil consumption. This accumulation of particulate matter is manifested by an increase in pressure drop across the catalyst from a design 3.5 to 5+ in. w.c. No notable decrease in catalyst reduction performance accompanies this pressure drop. No other site-specific emission data were available for dual-fuel SCR applications.

The limited data suggest that a NO_x emission reduction of 80 to 90 percent is achievable using SCR with dual-fuel engines. The experience with this control technique to date is limited, however, especially in the United States. A 90 percent reduction was used in Chapter 6 to calculate controlled NO_x emission levels and cost effectiveness.

As discussed in Section 5.2.4.4, the effect of SCR on CO and HC emissions is minimal. The engine BSFC increases with the use of SCR due to the increased exhaust backpressure created by the catalyst reactor.

5.3.2.3 Low-Emission Combustion for Dual-Fuel Engines. Engine manufacturers have applied some of the design features used in SI low-emission engines to dual-fuel engines. Information was available from two manufacturers for low-emission dual-fuel engines that use a PCC design similar to that used for SI engines.[74,75] The PCC makes it possible to reduce the injection rate of oil pilot fuel used for ignition from the conventional 5 to 6 percent level down to approximately 1 percent while maintaining acceptable combustion stability. In addition to the PCC, the low-emission engines also use a higher A/F in the main combustion chamber and ignition retard to reduce NO_x emission levels. In addition to reduced NO_x emission levels, the reduced pilot oil injection rate also reduces the yellow plume associated with dual-fuel engine exhaust, according to one manufacturer.[75]

The manufacturers report that emission reductions using the low-emission PCC designs are achieved only in the dual-fuel operating mode. Emission levels for the diesel operating mode (100 percent diesel fuel) are essentially unchanged.

These low-emission designs are available for both new and retrofit installations, although information was not available to determine the extent of availability for retrofit applications, especially those engines that are no longer in production. Minimum retrofit requirements include modification or replacement of the engine heads, fuel system and controls, and turbocharger.[75]

Nominal emission levels for two manufacturers' low-emission dual-fuel engines are presented in Table 5-14 and are compared to corresponding emission levels for conventional open-chamber designs.[38,41,74,75] Achievable controlled NO_x emission levels range from 1.0 to 2.0 g/hp-hr (75 to 150 ppmv), a reduction of 60 to 78 percent from open-chamber combustion NO_x levels. The effect on CO and HC emissions appears to be engine-specific, as one manufacturer reports increases in both CO and HC while the other reports no change in CO and a decrease in HC emissions. Fuel consumption increases for the low-emission engines in both designs, with increases ranging from 1.6 to 3.1 percent.

Emission test results for retrofit application of a low-emission PCC design were available only for one manufacturer's engines and are presented in Table 5-15. The first engine was retrofit and tested in-house by the manufacturer.[75] The second engine was retrofit and tested in the field.[76] These tests show that NO_x emissions from the first engine were reduced with the PCC design by over 90 percent, and the engine achieved a controlled NO_x emission level of 0.9 g/hp-hr (68 ppmv). Carbon monoxide emissions were not recorded. Total HC emission levels increased by nearly 400 percent, but uncontrolled HC levels prior to installation of the PCC design were very low. The controlled HC level of

TABLE 5-14. NOMINAL EMISSION LEVELS COMPARING OPEN-CHAMBER AND PRECOMBUSTION CHAMBER DESIGNS FOR DUAL FUEL ENGINES[38,41,74,75]

	Emissions, g/hp-hr			BSFC
	NO_x	CO	THC[a]	Btu/hp-hr
E-Series Turbocharged Engine (dual-fuel mode)				
Open-chamber[b]	4.5	1.3	2.0	6,100
Enviro-Design®[b]	1.0	2.0	2.5	6,290
Percent change	-78	+54	+25	+3.1
LSVB Engine (dual-fuel mode)				
Open chamber	5.0	2.0	7.0	6,200
CleanBurn®	2.0	2.0	5.0	6,300
Percent change	-60	NC[c]	-29	+1.6

[a]Total hydrocarbon emissions.
[b]900 rpm engine speed.
[c]NC - no change.

TABLE 5-15. EMISSION TEST RESULTS FOR A LOW-EMISSION DUAL-FUEL ENGINE RETROFIT WITH A PRECOMBUSTION CHAMBER[75,76]

	Emissions, g/hp-hr			BSFC	Smoke
	NO_x	CO	THC[a]	(Btu/hp-hr)	(Opacity, percent)
LSB-6 Engine (dual-fuel mode, in-house tests)					
Open-chamber	11.5	NA[b]	1.0	6,230	NA[b]
CleanBurn®	0.9	NA[b]	4.9	6,330	NA[b]
Percent change	0.92	NA[b]	+390	+1.6	NA[b]
LSVB-20 engine (dual-fuel mode, average of 3 tests at site)					
CleanBurn®	1.27	1.60	3.48	NA[b]	0-5

[a]Total hydrocarbon emissions.
[b]NA - data not available.

4.9 g/hp-hr (1,040 ppmv) for this engine is within the expected range of 5.0 g/hp-hr stated by the manufacturer and shown in Table 5-14. Fuel consumption increased for the low-emission design by 1.6 percent.

The test results in Table 5-15 for the second engine are for an existing 6.0 MW (8,000 hp) dual-fuel engine installation that was retrofit with the PCC design in 1990.[76] Emission test results following this retrofit show that controlled NO_x emission levels at full-load conditions average 1.27 g/hp-hr (95 ppmv). Pre-retrofit emission levels were not reported, but the operator reports that this controlled NO_x level represents a reduction of 68 percent from average pre-retrofit levels of greater than 4.0 g/hp-hr (300 ppmv). Controlled CO and HC emissions average 1.60 and 3.48 g/hp-hr (190 and 740 ppmv), respectively. The operator reports controlled HC levels are lower than pre-retrofit levels; the effect of the retrofit on CO emission levels was not clearly stated in the reference. The effect of the retrofit on BSFC also could not be determined. The manufacturer of this engine reports that exhaust opacity is reduced with the PCC design and virtually eliminates the yellow plume associated with dual-fuel engines.[75] The test results show that opacity was reduced to 0 to 5 percent, compared to 10 to 20 percent prior to the retrofit.[76]

Based on the limited data presented in this section, it is estimated that controlled NO_x emission levels of 1.0 to 2.0 g/hp-hr (75 to 150 ppmv) can be achieved with low-emission, dual-fuel engine designs for either new or retrofit installations, where these designs are available from the engine manufacturer. A 2.0 g/hp-hr controlled emission level is used in Chapter 6 to calculate cost-effectiveness.

The effect on CO and HC emissions varies, depending upon the engine model and manufacturer. Brake-specific fuel consumption increases by up to 3 percent. The potential NO_x emission reductions apply only to operation in a dual-fuel mode; emission levels are unchanged with low-emission engine designs for 100 percent diesel fuel operation.

5.4 OTHER NO_x CONTROL TECHNIQUES

The control techniques presented in this section are given limited discussion due to a lack of available information or demonstrated effectiveness in commercial applications to date. These techniques are intake air cooling, EGR, engine derate, water injection and water/fuel emissions, and alternate fuels. These techniques are discussed briefly in this section.

5.4.1 Intake Air Cooling

Cooling the intake air prior to induction into the cylinder has the potential to reduce NO_x emissions. The reduced air temperature theoretically lowers peak combustion temperatures, thereby reducing NO_x formation. Cooler intake air temperatures also offer the potential for increased power output and improved fuel economy.

Naturally aspirated engines induce air at ambient temperatures. Turbocharged engines have a heat exchanger located downstream of the turbocharger (aftercooler) that removes some of the heat generated by compression of the intake air through the turbocharger. In naturally aspirated engines, a separate-circuit cooling system connected to a heat exchanger in the intake air system would be required to cool the intake air to below ambient temperatures. A larger, more efficient aftercooler would potentially reduce intake air temperatures in turbocharged engines, but substantial air cooling would require a separate-circuit cooling system.

This control technique is used in combination with other parametric adjustments in emission tests reported in several references to reduce NO_x emissions from both SI and CI engines. Data were not available, however, to indicate achievable NO_x reductions using air intake cooling independently.

5.4.2 Exhaust Gas Recirculation

This control technique replaces a portion of the incoming combustion air with exhaust gas. The exhaust gas has a low O_2 content and acts as a heat sink during the combustion process, lowering combustion temperatures and, hence, NO_x formation. In SI engines EGR may require cooling and filtering of the recirculated exhaust gases and a complex control system.[77] For CI engines, EGR results in fouled air intake systems, combustion chamber deposits, and increased engine wear rates.[63] All manufacturers contacted for this study indicated that this technique is not offered for production SI and CI engines.

5.4.3 Power Output Derate

Engine derate is accomplished by reducing the fuel input to the engine, thereby reducing power output. This reduced fuel input results in lower combustion temperatures and pressures, thereby reducing NO_x. Emission data in Reference 5 show only marginal brake-specific NO_x reductions ranging from 0.2 to 6.2 percent. In CI engines, brake-specific NO_x emissions may actually increase at reduced power levels.

5.4.4 Water Injection

Direct water injection into IC engines does not appear to be a viable control technique. Internal combustion engines have a lubricating oil film on the walls of the cylinders that minimizes mechanical wearing of reciprocating parts, and water injection adversely impacts this oil film, accelerating engine wear. This control technique is not available from any engine manufacturers contacted for this report.

5.4.5 Water/Fuel Emulsions

No documentation of this control technique has been found to suggest it has been demonstrated in stationary IC engines. All engine manufacturers contacted stated that water/fuel emulsions are not an option for their engines.

5.4.6 Alternate Fuels

Coal/water slurries (CWS) and methanol have been fired in IC engines in limited testing to date. For CWS, several reports include test data indicating reduced NO_x emissions. Methanol produces lower combustion temperatures than natural gas and diesel and therefore would theoretically produce lower NO_x emissions. No data for methanol firing were found. Neither CWS nor methanol is currently being used in any identified commercial engine installation in the United States.

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6.0 CONTROL COSTS

This chapter presents cost and cost effectiveness estimates for the NO_x control techniques discussed in Chapter 5. Section 6.1 presents the cost evaluation methodology used to develop capital and annual costs for these techniques. Sections 6.2 and 6.3 present the costs and cost effectiveness for rich-burn and lean-burn spark-ignition (SI) engine controls, respectively. Control costs and cost effectiveness for diesel and dual-fuel engines are given in Section 6.4. References for the chapter are listed in Section 6.5. Summary tables for capital and annual costs and cost effectiveness for each control technique are included in Appendix B. All costs presented in this chapter and Appendix B are in 1993 dollars.

6.1 COST EVALUATION METHODOLOGY

Three cost considerations are presented in this chapter: total capital costs, total annual costs, and cost effectiveness. The components that make up these costs and the methodology used to determine each cost component are presented in this section.

Implementing some control techniques results in a reduction in the engine power output caused either by altered combustion conditions or increased backpressure on the engine. The potential power deration, where applicable, is identified for each control technique in this chapter and in Chapter 5. Any costs associated with the power reduction penalty, however, depend upon site-specific factors (e.g., value of lost product or capital and annual costs for equipment required to make up for the power loss) and cannot be quantified in this document. As a result, the cost associated with the power reduction should be identified on a site-specific basis and added to the costs presented in this chapter for each control technique for which a potential power reduction is identified. For example, if a compressor engine is derated by 200 horsepower (hp) as a result of installing a control technique, the owner could incur the cost of a 200 hp motor, compressor, drive coupling, ancillary equipment, and installation, operation, and maintenance of the equipment to make up the power loss. For a pipeline application, a capacity reduction of as little as 0.4 percent could require the installation of an additional compressor engine, complete with ancillary equipment, interconnecting piping and controls, buildings, permitting, and potential emission offset requirements.[1]

6.1.1 Capital Cost Estimation

As shown in Table 6-1, the total capital cost is the sum of the purchased equipment costs, direct installation costs, indirect installation costs, and contingency costs. The purchased equipment cost (PEC) used in this chapter for each control technique is based on cost information provided by engine manufacturers or control system vendors. Where capital cost estimates provided by equipment suppliers did not include installation costs, these costs were estimated using the approach in the EPA Office of Air Quality and Planning Standards (OAQPS) Control Cost Manual, which recommends estimating direct installation costs as 45 percent of PEC and indirect installation costs as 33 percent of PEC.[2] Where installation costs were included in the capital cost estimate provided by equipment suppliers, it was assumed that these cost estimates did not include such items as the purchaser's engineering and project management costs, field connections, painting, and training. Therefore, reduced direct and indirect installation factors were applied to the capital cost estimates provided by the supplier to cover these costs. The direct and indirect installation factors used in each case are defined in the appropriate sections of this chapter. In each case a contingency factor of 20 percent was

TABLE 6-1. TOTAL CAPITAL COST COMPONENTS AND FACTORS[2]

Capital cost elements
<u>Direct costs (DC)</u> Purchased equipment costs (PEC): · Control device and auxiliary equipment · Instrumentation · Sales taxes (3 percent of PEC) · Freight (5 percent of PEC) Direct installation costs (DIC): · Foundations and supports · Handling and erection · Electrical · Piping · Insulation for ductwork · Painting
Total direct cost (DC) = PEC + DIC
<u>Indirect costs (IC)</u> Indirect installation costs (IIC): · Engineering · Construction and field expenses · Contractor fees · Start-up · Performance test · Model study · Training Contingencies (C): · Equipment redesign and modifications · Cost escalations · Delays in start-up
Total indirect cost (IC) = IIC + C
TOTAL CAPITAL COST (TCC) = DC + IC

added to the vendor costs, as recommended in the OAQPS cost manual, to cover contingencies as listed in Table 6-1.

6.1.2 Annual Costs

Annual costs consist of the direct operating costs of materials and labor for maintenance, operation, utilities, and material replacement and disposal (e.g., spent catalyst material) and the indirect operating charges, including plant overhead, general administration, and capital recovery charges. Table 6-2 lists these costs and includes the values used for these costs.

A brief description is provided below for each component of the direct and indirect annual operating costs used in the cost evaluation. Additional discussions, where necessary, are provided in the appropriate section for each control technique.

6.1.2.1 Utilities. Utility requirements for IC engine control techniques are limited to electricity and/or compressed air to power control instrumentation and auxiliary equipment and the energy requirements for vaporization and injection of ammonia for SCR systems. The cost for electricity and compressed air, where required, is considered to be negligible relative to the other operating costs. The cost for ammonia vaporization and injection was calculated using steam for ammonia dilution and vaporization. A cost of $6/1,000 pounds (lb) was used for steam.

6.1.2.2 Operating and Supervisory Labor. Operating and supervisory labor may be required for some control techniques, depending on the complexity of the system involved and the extent to which the control system is automated. The addition of control equipment at remote, unmanned engine installations could require a part- or full-time operator, plus travel time and expenses in some cases for coverage of multiple sites. For this cost methodology, an operating labor requirement of 2 hours (hr) per 8-hr shift is estimated for prestratified charge and nonselective catalytic reduction. For selective catalytic reduction, the operator requirement is increased to 3 hours per 8-hr shift to include operation of the ammonia injection and continuous emission monitoring systems (CEMS). For parametric adjustment (e.g., air/fuel ratio adjustment and ignition/

TABLE 6-2. TOTAL ANNUAL COST ELEMENTS AND FACTORS

Direct annual costs (DC)	
1. Utilities:	
Electricity[a]	\$0.06/kWh
Compressed air[a]	\$0.16/1,000 scfm
Natural gas[b,c]	\$3.88/1,000 ft^3 19,820 Btu/lb (LHV) 940 Btu/ft^3 (LHV) 0.0473 lb/ft^3
Diesel fuel[b,c]	\$0.77/gallon 18,330 Btu/lb (LHV) 7.21 lb/gallon
Steam[d]	\$6/1,000 lb.
2. Operating labor[e] Operator labor	\$27.00 per hour
Supervising labor	15% of operator labor
3. Maintenance	10% of purchased equipment costs
4. Annual compliance test	\$2,440[f]
5. Catalyst replacement	\$10/hp[g]
6. Catalyst disposal	\$15/ft^3 [h]
Indirect annual costs (IC)[i]	
Overhead	60% of maintenance cost
Property tax	1% of total capital cost
Insurance	1% of total capital cost
Administrative charges	2% of total capital cost
Capital recovery	CRF x total capital investment
TOTAL ANNUAL COST	DC + IC

LHV = lower heating value
CRF = capital recovery factor

[a]Reference 2, Table 5.10.
[b]Average costs for 1990 from Reference 3.
[c]Fuel properties from Reference 4.
[d]From Reference 2, Table 4.5.
[e]Reference 5.
[f]Reference 6, escalated at 5 percent annually.
[g]Reference 7.
[h]Reference 8.
[i]Reference 2, p. 2-29.

injection timing retard) and low-emission combustion modification, no additional operating labor requirements are expected over that required for current operation. The operating labor rate, shown in Table 6-2, is estimated at $27/hr. Supervisory labor costs are calculated as 15 percent of the annual operating labor costs.

6.1.2.3 Maintenance. Specific maintenance costs were not available from the control system vendors and manufacturers. The guidelines for maintenance costs in Reference 2 suggest a maintenance labor cost of 0.5 hour per 8 hr shift, and a maintenance material cost equal to this labor cost. However, this approach, using a maintenance labor cost of $34.40/hr, results in maintenance costs that approach or exceed the PEC for some control techniques. This approach also results in maintenance costs that are constant for each control technique, regardless of engine size or control system complexity. For these reasons, the total annual maintenance cost, including labor and materials, is calculated for continuous-duty applications to be equal to 10 percent of the purchased equipment cost for each control technique. For intermittent- and standby-duty applications, the maintenance cost is prorated based on the operating hours.

6.1.2.4 Fuel Penalty. Implementing most of the control techniques changes the brake-specific fuel consumption of the engine, due either to a change in combustion conditions or increased backpressure on the engine. A fuel penalty is assessed, where applicable, to compensate for increased fuel consumption. Engine power output and fuel consumption rate (heat rate) were provided by engine manufacturers.[9-15] This information was used to establish a range of engine sizes within each engine category (i.e., rich-burn spark-ignited [SI], lean-burn SI, diesel, and dual-fuel) and to calculate an average heat rate for each range, as shown in Table 6-3. For example, as shown in Table 6-3, rich-burn SI engines up to 200 hp in size are assigned a heat rate of 8,140 Btu/hp-hr. The fuel penalty is assessed as a percentage of the annual fuel cost, which is

TABLE 6-3. UNCONTROLLED NO_x EMISSION FACTORS FOR COST EFFECTIVENESS CALCULATIONS

Engine size, hp	No of engines	Heat rate, Btu/hp-hr	Average NO_x emisson factor, g/hp-hr	Average NO_x emission factor, lb/MMBtu	Weighted average for each engine type[a]	
					NO_x, g/hp-hr	NO_x, lb/MMBtu
RICH-BURN SI ENGINES						
0-200	8	8140	13.1	3.54		
201-400	13	7820	16.4	4.62		
401-1000	31	7540	16.3	4.76		
1001-2000	19	7460	16.3	4.81	15.8	4.64
2001-4000	10	6780	15	4.87		
4001 +	2	6680	14	4.62		
LEAN-BURN SI ENGINES						
0-400	7	8760	7.9	1.99		
401-1000	7	7660	18.6	5.35		
1001-2000	43	7490	17.8	5.23	16.8	5.13
2001-4000	30	7020	17.2	5.40		
4001 +	25	6660	16.5	5.46		
DIESEL ENGINES						
0-200	12	6740	11.2	3.66		
201-400	8	6600	11.8	3.94		
401-1000	22	6790	13.0	4.22		
1001-2000	14	6740	11.4	3.73	12.0	3.95
2001-4000	6	6710	11.4	3.74		
4001 +	6	6200	12.0	4.26		
DUAL-FUEL ENGINES						
700-1200	5	6920	10.0	3.18		
1201-2000	3	7220	10.7	3.26		
2001-4000	5	6810	8.4	2.72	8.5	2.72
4001 +	4	6150	4.9	1.75		

Note: lb/MMBtu = (g/hp-hr) x (lb/454g) x (1/Heat Rate) x (1,000,000).

[a]Weighted average is calculated by multiplying the average NO_x emission factor by the number of engines for each engine size and dividing by the total number of engines. For example, for dual-fuel engines, the weighted average is calculated as:

$$[(5 \times 10.0) + (3 \times 10.7) + (5 \times 8.4) + (4 \times 4.9)]/17 = 8.5 \text{ g/hp-hr}$$

calculated using the assigned heat rate from Table 6-3 and the fuel cost from Table 6-2.

6.1.2.5 Catalyst Replacement and Disposal. Most catalyst vendors guarantee that the catalyst material will meet the site-specified emissions reduction requirements for a period of 2 or 3 years. A catalyst life of 3 years (24,000 hr) was used in this analysis for both selective catalytic reduction (SCR) and nonselective catalytic reduction (NSCR).

6.1.2.6 Overhead. An annual overhead charge of 60 percent of the total maintenance cost was used, consistent with guidelines in Reference 2.

6.1.2.7 Property Taxes. The property taxes were calculated as 1 percent of the total capital cost of the control system, consistent with guidelines in Reference 2.

6.1.2.8 Insurance. The cost of insurance was calculated as 1 percent of the total capital cost of the control system, consistent with guidelines in Reference 2.

6.1.2.9 Administrative Charges. The administrative charges were calculated as 2 percent of the total capital cost of the control system, consistent with guidelines in Reference 2.

6.1.2.10 Emission Compliance Test. It is anticipated that an emission compliance test would be required at least annually at sites where emission limits are established and control techniques are implemented. An annual cost for emission testing of $2,440 is used, based on information from Reference 6, escalated at 5 percent per year.

6.1.2.11 Capital Recovery. In this cost analysis the capital recovery factor (CRF) is defined as:[2]

$$CRF = \frac{i\,(1+i)^n}{(i+1)^n - 1} = 0.1098$$

where: i = the annual interest rate, 7 percent, and
n = the equipment life, 15 years.

The CRF is used as a multiplier for the total capital cost to calculate equal annual payments over the equipment life.

6.1.3 Cost Effectiveness

Cost effectiveness, in \$/ton of NO_x removed, is calculated for each control technique by dividing the total annual cost by the annual tons of NO_x removed. Uncontrolled emission factors were developed using information provided by engine manufacturers.[9-15] This information was used to establish a range of engine sizes within each engine category (i.e., rich-burn SI, lean-burn SI, diesel, and dual-fuel) and to calculate an average uncontrolled emission factor for each range, as shown in Table 6-3. To simplify NO_x emission calculations, a single emission factor was developed for each engine category, calculated as the weighted average for all engines in each category. For example, as shown in Table 6-3, rich-burn SI engines are assigned a NO_x emission factor of 15.8 grams per horsepower-hour (g/hp-hr) (4.64 pounds per million British thermal units [lb/MMBtu]).

In general, cost effectiveness is highest for small engines because capital costs, on a per-horsepower basis, are highest for these engines while the per-horsepower NO_x removal rate remains constant regardless of engine size. Cost effectiveness also increases as operating hours decrease because capital costs remain unchanged while annual NO_x reductions decrease with operating hours.

6.2 CONTROL COSTS FOR RICH-BURN SI ENGINES

The applicable control techniques for rich-burn SI engines are air/fuel ratio (A/F) adjustment, ignition timing retard, a combination of A/F adjustment and ignition timing retard, prestratified charge (PSC®), NSCR, and low-emission combustion. The costs for these control techniques as applied to rich-burn SI engines are presented in this section.

6.2.1 Control Costs for A/F Adjustment

6.2.1.1 Capital Costs. The capital costs for A/F adjustment are based on installing an automatic A/F ratio controller on the engine to achieve sustained NO_x emission reductions with changes in operating loads and ambient conditions and to minimize engine misfire with these changes. The A/F controls typically consist of an oxygen (O_2) sensor installed in the exhaust, which directs a signal to a regulator that modifies fuel or air delivery pressure. For carbureted, naturally aspirated engines, the control system adjusts a bypass around the carburetor or a pressure regulator. For turbocharged engines, the control adjusts the wastegate valve to bypass exhaust around the turbocharger turbine.

Some engine manufacturers provide these A/F controls as standard equipment on their engines, especially in newer engine designs, and A/F can be adjusted on these engines with no requirement for purchased equipment. In this case, the total capital cost for A/F control is expected to be less than $4,000 for all engines, regardless of size. This cost includes approximately 16 labor hours, associated direct/indirect and contingency factors to perform the adjustments on the engine, and an emission compliance test.

For engines that are not equipped with provisions for automatic A/F adjustment, the capital costs for hardware and software are estimated by engine manufacturers to range from approximately $7,000 to $18,000.[16,17] A cost of $7,000 was used for engines up to 1,000 hp, $10,000 for engines from 1,001 hp to 2,500 hp, and $15,000 for engines above 2,500 hp. Sales tax and freight charges total 8 percent of the PEC. These costs are for retrofit kits provided by the engine manufacturer, so the direct and indirect installation factors are reduced from 45 and 33 to 15 and 20 percent of the PEC, respectively. These factors are chosen because this control system mounts directly on the engine and is pre-engineered, thereby reducing the engineering and installation efforts required by the purchaser. The contingency factor is 20 percent of PEC.

Based on the above methodology, the total capital costs for A/F adjustment for rich-burn engines are:

Engines to 1,000 hp:	$11,400

Engines 1,001 to 2,500 hp:	$16,300
Engines over 2,500 hp:	$24,500

These total capital costs are presented in Figure 6-1.

6.2.1.2 Annual Costs. The anticipated annual costs associated with A/F adjustment include an increase in maintenance due to the addition of the automatic A/F system, an increase in brake-specific fuel consumption (BSFC), emission compliance testing, and capital recovery. The increased maintenance cost is estimated as 10 percent of the PEC, plus an overhead cost equal to 60 percent of the maintenance cost. Based on information presented in Chapter 5, a fuel penalty of 5 percent is assessed. Taxes, insurance, and administrative costs are charged as shown in Table 6-2. The cost of a compliance test is estimated at $2,440. The capital recovery is calculated as discussed in Section 6.1.2.11.

Based on the above methodology, the total annual costs for A/F adjustment for rich-burn engines are presented in Figure 6-1. As Figure 6-1 shows, the costs are essentially linear and can be approximated using the following equations:

Operating hours	Total annual cost
8,000	$6,340 + ($11.4 x hp)
6,000	$5,790 + ($8.70 x hp)
2,000	$4,710 + ($3.10 x hp)
500	$4,300 + ($1.00 x hp)

For an 80 hp engine, the total annual costs range from $4,290 for 500 hr/yr to $6,340 for 8,000 hr/yr. For an 8,000 hp engine, the total annual costs range from $11,800 for 500 hr/yr to $96,700 for 8,000 hr/yr.

6.2.1.3 Cost Effectiveness. As discussed in Chapter 5, the expected range of NO_x reduction for A/F adjustment for rich-burn engines is 10 to 40 percent, and the cost effectiveness varies according to the actual site-specific NO_x reduction. The cost effectiveness presented in this section is calculated using a NO_x

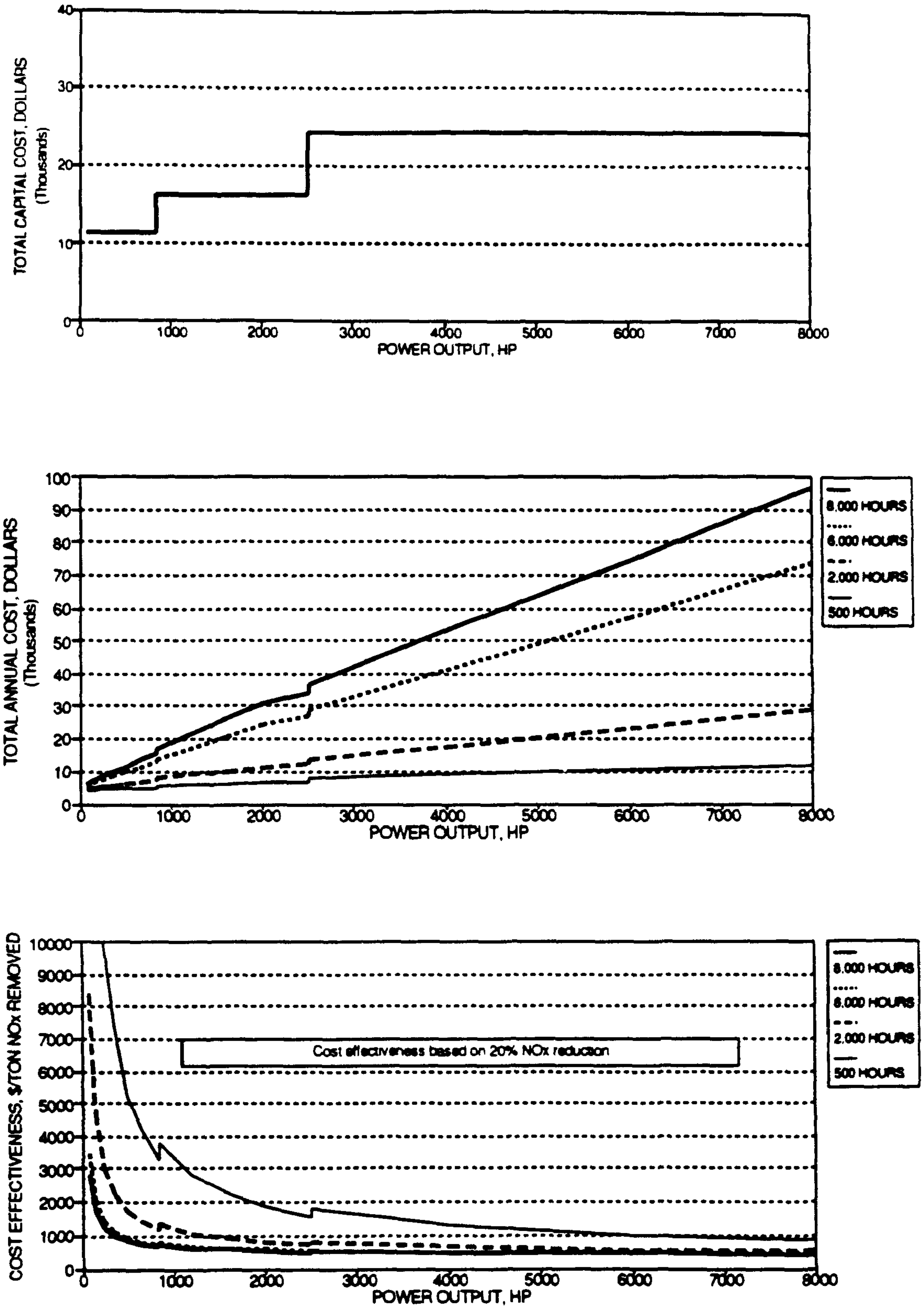


Figure 6-1. Total capital and annual costs and cost effectiveness for A/F adjustment in rich-burn engines, based on installation of an automatic A/F adjustment system and controls.

reduction efficiency of 20 percent. For engine installations already equipped with automatic A/F control, no additional equipment purchase is necessary, and cost effectiveness is estimated to be less than $1,000/ton for all but the smallest engines operating in stand-by applications.

For those engines that require installation of automatic A/F control equipment, the cost effectiveness is presented in Figure 6-1.

For continuous-duty engines, the cost effectiveness for A/F adjustment in rich-burn engines is over $2,800/ton for engines less than 100 hp but decreases rapidly as engine size increases. For engines above 1,000 hp, the cost-effectiveness curve is relatively flat at approximately $600/ton or less. A similar cost-effectiveness trend applies to engines that operate less than 8,000 hr/yr, but the cost effectiveness increases to a high of $31,000/ton for the smallest engines and decreases to approximately $3,000/ton or less for engines above 1,000 hp operating 500 hr/yr. The cost-effectiveness range from $10,000 to $31,000 per ton is not shown on the plot in Figure 6-1 in order to more clearly present the range of $0 to $10,000 per ton.

6.2.2 Control Costs for Ignition Timing Retard

6.2.2.1 Capital Costs. Effective and sustained NO_x reduction with changes in engine load and ambient conditions requires that the engine be fitted with an electronic ignition control system to automatically adjust the ignition timing. This ignition system is standard equipment on some engines, and in this case no purchased equipment is required. For this case, capital costs are expected to be approximately $4,000 or less to cover the cost of labor (16 hr) for the initial adjustment by the operator and subsequent emission testing.

For those engines not equipped with an electronic ignition system, the cost for the ignition system is estimated for low-speed, large-bore engines to be $10,000, plus $5,000 for the electronic control system.[18] This cost varies according to engine size and the number of power cylinders, and for this study the PEC for an electronic ignition system is estimated to be:

Engines to 1,000 hp:	$ 7,500
Engines 1,001 to 2,500 hp:	$10,000
Engines above 2,500 hp:	$15,000

Sales taxes and freight are added as 8 percent of the PEC. As is the case for A/F adjustment, direct and indirect installation activities are expected to be relatively straightforward, as this system is offered as a fully engineered package from the manufacturer and mounts directly on the engine. For these reasons, direct and indirect installation factors of 15 and 20 percent, respectively, of the PEC are used. The contingency factor is 20 percent of the PEC.

The total capital costs for ignition timing retard using this methodology are:

Engines to 1,000 hp:	$12,200
Engines 1,001 to 2,500 hp:	$16,300
Engines over 2,500 hp:	$24,500

These costs are shown in Figure 6-2.

6.2.2.2 Annual Costs. The anticipated annual costs associated with ignition timing retard are an increase in maintenance due to the addition of the electronic ignition control system, an increase in BSFC, emission compliance testing, and capital recovery. The increased maintenance cost is estimated as 10 percent of the PEC, plus an overhead cost equal to 60 percent of the maintenance cost. Based on information presented in Chapter 5, a fuel penalty of 4 percent is assessed. Taxes, insurance, and administrative costs are charged as shown in Table 6-2, and the compliance test cost is $2,440. The capital recovery is calculated as discussed in Section 6.1.2.11.

Based on the above methodology, the total annual costs for ignition timing retard for rich-burn engines are presented in Figure 6-2. As this figure shows, the costs are essentially linear and can be approximated using the following equations:

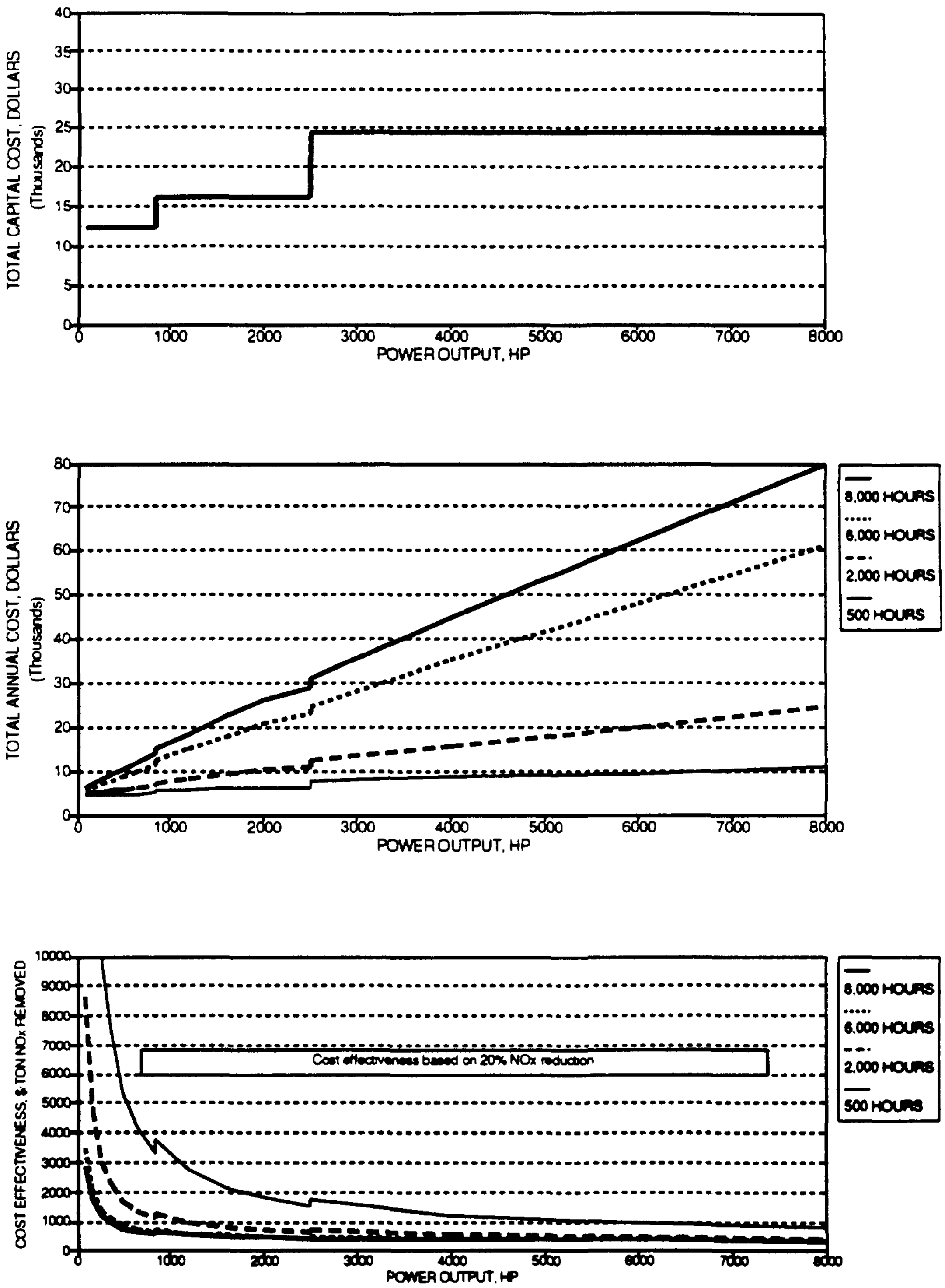


Figure 6-2. Total capital and annual costs and cost effectiveness for ignition timing retard in rich-burn engines, based on installation of an electronic ignition system.

Operating hours	Total annual cost
8,000	\$6,300 + (\$9.30 x hp)
6,000	\$5,790 + (\$7.10 x hp)
2,000	\$4,770 + (\$2.50 x hp)
500	\$4,390 + (\$0.85 x hp)

For an 80 hp engine, the total annual costs range from \$4,400 for 500 hr/yr to \$6,340 for 8,000 hr/yr. For an 8,000 hp engine, the total annual costs range from \$10,700 for 500 hr/yr to \$79,800 for 8,000 hr/yr.

6.2.2.3 Cost Effectiveness. As discussed in Chapter 5, the expected range of NO_x reduction for ignition timing retard for rich-burn engines is 0 to 40 percent, and the cost effectiveness will vary according to the actual site-specific NO_x reduction. The cost effectiveness presented in this section is calculated using a NO_x reduction efficiency of 20 percent. For engine installations already equipped with an electronic ignition control system, no additional equipment purchase is necessary, and the cost effectiveness is estimated to be less than \$1,000/ton for all but the smallest engines operating in stand-by applications.

For those engines which require installation of an electronic ignition system, the cost effectiveness is presented in Figure 6-2. For continuous-duty engines, the cost effectiveness for ignition timing retard in rich-burn engines is over \$2,800/ton for engines less than 100 hp, but decreases rapidly as engine size increases. For engines above 1,000 hp, the cost-effectiveness curve is relatively flat at approximately \$600/ton or less. A similar cost-effectiveness trend applies to engines that operate less than 8,000 hours per year, but the cost effectiveness increases to a high of over \$31,000/ton for the smallest engines operating 500 hours annually, decreasing to approximately \$3,000/ton or less for engines above 1,000 hp operating 500 hours annually. The cost-effectiveness range from

$10,000 to $31,000 per ton is not shown on the plot in Figure 6-2 in order to more clearly present the range of $0 to $10,000 per ton.

6.2.3 Control Costs For Combination of A/F Adjustment and Ignition Timing Retard

6.2.3.1 Capital Costs. The capital costs for a combination of A/F adjustment and ignition timing retard are based on installing an automatic A/F ratio controller and an electronic ignition system on the engine. Some engines include these systems and controls as standard equipment, especially newer engine designs, and no additional equipment is required for these engines. In this case, capital costs are expected to be approximately $4,000 or less. This cost includes approximately 25 labor hours and associated direct/indirect and contingency factors to perform the adjustments on the engine and an emission compliance test.

For engines that require the installation of A/F control and electronic ignition systems, the capital costs are estimated to be equal to the sum of the costs for each system. A combined PEC of $14,500 is used for engines up to 1,000 hp; $20,000 for 1,001 hp to 2,500 hp engines; and $30,000 for engines above 2,500 hp. Sales taxes and freight are added as 8 percent of the PEC. Because these systems are available from engine manufacturers as fully engineered kits, direct and indirect labor factors for installation are estimated at 15 and 20 percent, respectively, of the combined PEC. These factors are chosen because this control system mounts directly on the engine and is pre-engineered, thereby reducing the engineering and installation efforts required by the purchaser. The contingency factor is 20 percent of the PEC.

Based on the above methodology, the total capital costs for the combustion of A/F adjustment and ignition timing retard for rich-burn engines are:

Engines to 1,000 hp:	$23,600
Engines 1,001 to 2,500 hp:	$32,600
Engines over 2,500 hp:	$48,900

These capital costs are presented in Figure 6-3.

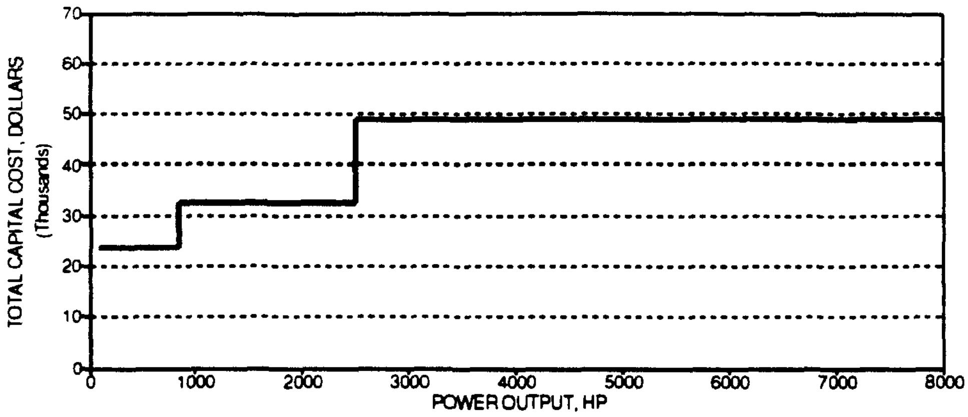
6.2.3.2 Annual Costs. The anticipated annual costs associated with the combination of A/F adjustment and ignition timing retard include an increase in maintenance due to the addition of the A/F adjustment and electronic ignition control systems, an increase in BSFC, emission compliance testing, and capital recovery. The increased maintenance cost is estimated as 10 percent of the PEC, plus an overhead cost equal to 60 percent of the maintenance cost. Based on information presented in Chapter 5, a fuel penalty of 7 percent is assessed. Taxes, insurance, and administrative costs are charged as shown in Table 6-2, and the emission test cost is $2,440. The capital recovery is calculated as discussed in Section 6.1.2.11.

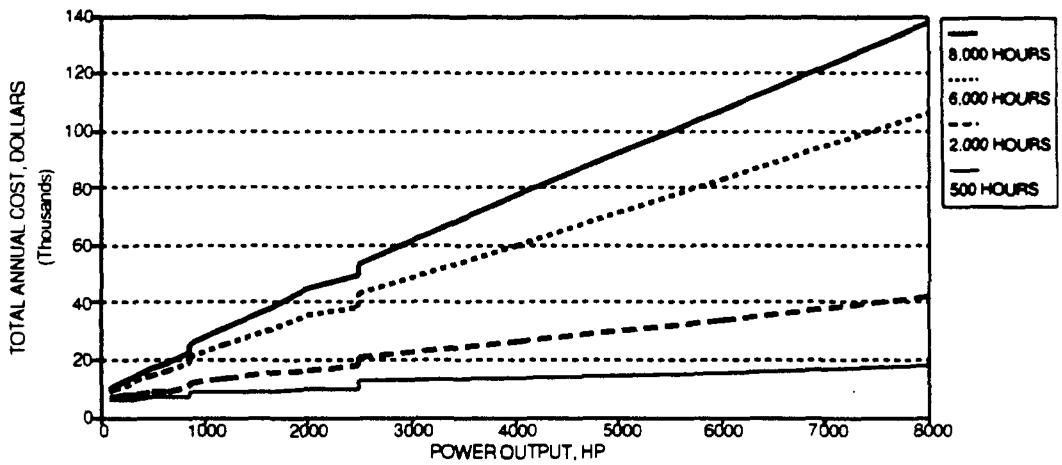
Based on the above methodology, the total annual costs for the combination of A/F adjustment and ignition timing retard for rich-burn engines is presented in Figure 6-3. As Figure 6-3 shows, the costs are essentially linear and can be approximated using the following equations:

Operating hours	Total annual cost
8,000	$9,770 + ($16.3 x hp)
6,000	$8,830 + ($12.4 x hp)
2,000	$6,940 + ($4.50 x hp)
500	$6,230 + ($1.60 x hp)

For an 80 hp engine, the total annual costs range from $6,220 for 500 hr/yr to $9,800 for 8,000 hr/yr. For an 8,000 hp engine, the total annual costs range from $17,800 for 500 hr/yr to $138,000 for 8,000 hr/yr.

6.2.3.3 Cost Effectiveness. As discussed in Chapter 5, the expected range of NO_x reduction for the combination of A/F adjustment and ignition retard for rich-burn engines is 10 to





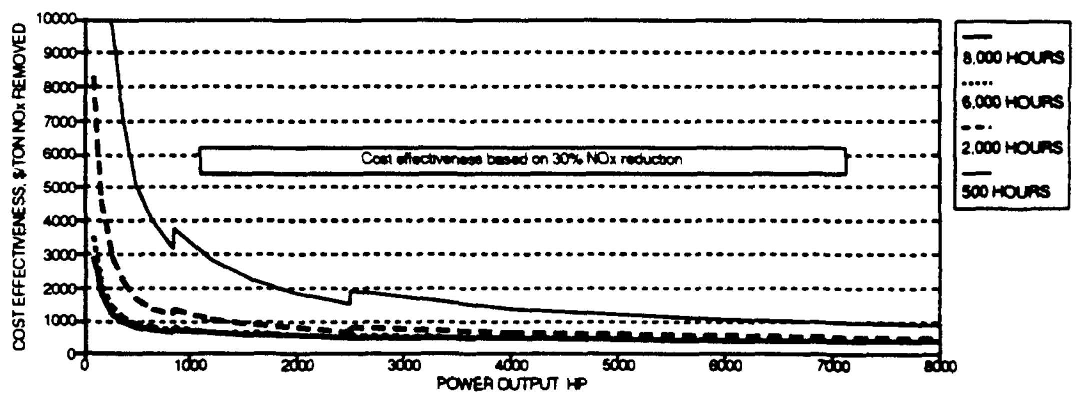


Figure 6-3. Total capital and annual costs and cost effectiveness for A/F adjustment and ignition timing retard in rich-burn engines, based on installation of automatic A/F adjustment system and controls and an electronic ignition system.

40 percent, and the cost effectiveness varies according to the actual site-specific NO_x reduction. The cost effectiveness presented in this section is calculated using a NO_x reduction efficiency of 30 percent. For engine installations already equipped with both automatic A/F and electronic ignition control systems, no additional equipment purchase is necessary, and the cost effectiveness is estimated to be less than $1,000/ton for all but the smallest engines operating in stand-by applications. For those engines equipped with provisions for one but not both control systems, the second control system must be purchased and installed. The cost effectiveness in this case is approximately the same as that shown in Figure 6-1 or 6-2 for either control used independently.

For installations where both control systems are added to the engine, the cost effectiveness is presented in Figure 6-3. For continuous-duty engines, the cost effectiveness for the combination of A/F adjustment and ignition timing retard in rich-burn engines is approximately $3,000/ton for engines less than 100 hp but decreases rapidly as engine size increases. For engines above 1,000 hp, the cost-effectiveness curve is relatively flat at less than $1,000/ton, decreasing slightly with increasing engine size. A similar cost-effectiveness trend applies to engines that operate less than 8,000 hr/yr, but the cost effectiveness increases to a high of $30,000/ton for the smallest engines operating 500 hr/yr and decreases to approximately $3,000/ton or less for engines above 1,000 hp operating 500 hr/yr. The cost-effectiveness range from $10,000 to $31,000 per ton is not shown on the plot in Figure 6-3 in order to more clearly present the range of $0 to $10,000 per ton.

6.2.4 Control Costs for Prestratified Charge (PSC®)

As discussed in Section 5.1.3, a PSC® system can be installed on carbureted, four-cycle engines. This control technique can be applied with or without the addition of a turbocharger to naturally aspirated engines or modification of the existing turbocharger on turbocharged engines. The turbocharger upgrade/addition is typically performed to minimize or eliminate the power output deration associated with PSC®. The costs for PSC® are presented with and without the cost for turbocharger upgrade/addition.

6.2.4.1 Capital Costs. Purchased equipment cost estimates were provided for a limited number of candidate engines by the licensed PSC® vendor.[19] The costs provided include typical installation costs, based on the vendor's experience. These costs are approximate and vary according to site-specific factors such as engine model and number of cylinders, hardware and software modifications required for the turbocharger, complexities of control and shutdown devices, and field installation requirements.[19] A control system cost of $7,700 was added to the estimated PSC® system cost, which is the average of the control costs housed in a weatherproof enclosure versus a National Electrical Manufacturers Association Class 7 (NEMA 7) enclosure.[19] The costs, calculated on a per-horsepower basis, are presented in Figure 6-4 and represent the PEC for PSC®, including controls and installation by the vendor. The costs for engines larger than 1,200 hp were extrapolated because data were not available for PSC® installated on larger engines.

The total capital costs were calculated by multiplying the PEC presented in Figure 6-4 by 1.08 to include sales taxes and freight, and by direct and indirect installation factors of 15 and 20 percent, respectively, for installations without turbocharger modifications. For installations with turbocharger modifications, the direct installation factor is increased to 25 percent. A 20 percent contingency factor is included.

Based on the above methodology, the total capital costs for PSC®, with and without turbocharger modification/addition, are presented in Figures 6-5 and 6-6, respectively. The costs for engines larger than 1,200 hp were extrapolated because estimates were not available for these engine sizes. For PSC® installations without turbocharger modification/addition, the total capital costs begin at approximately $20,000 for 100 hp engines and rise to over $55,000 for engines at approximately 800 to 1,000 hp. The cost estimates provided showed that capital

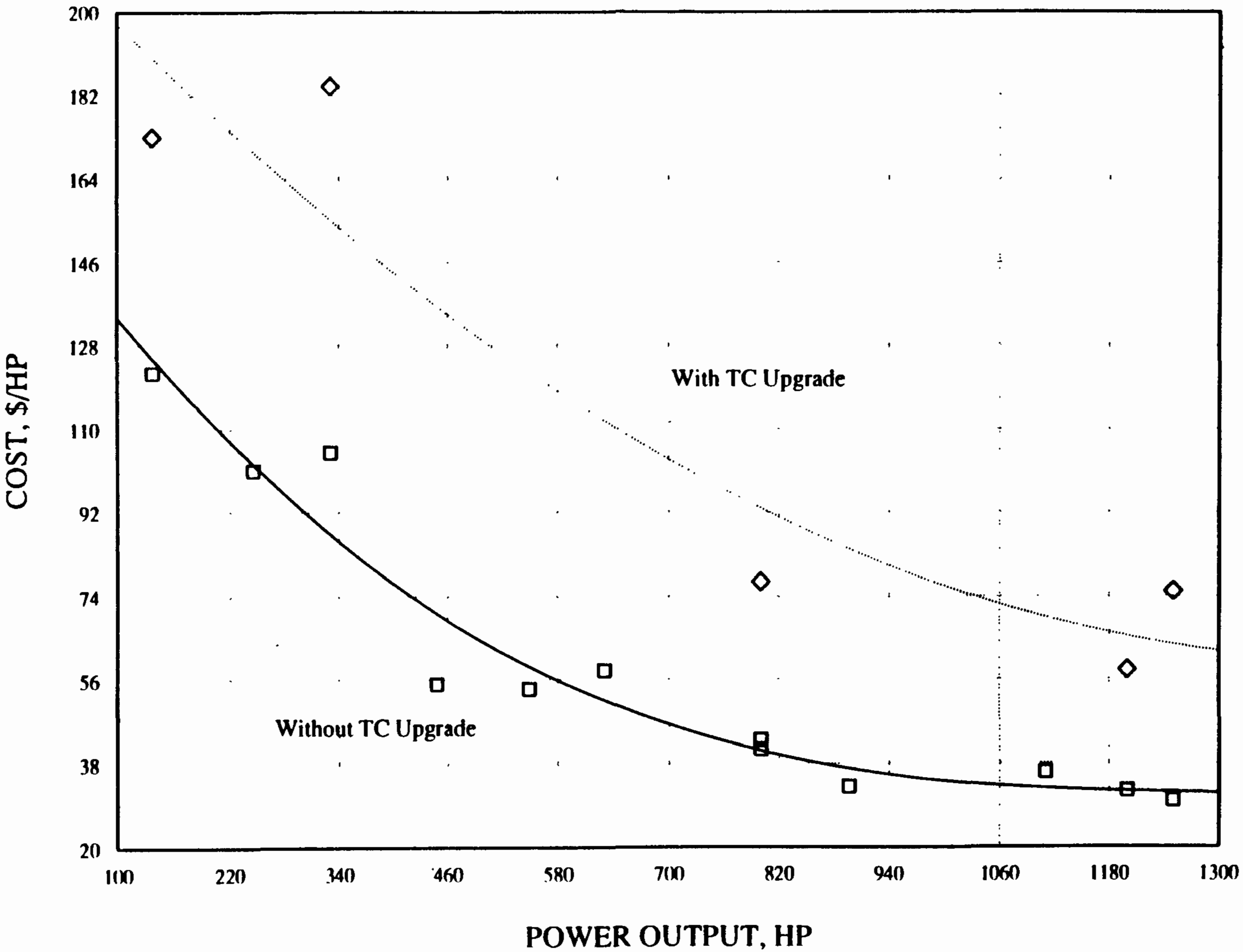


Figure 6-4. Purchased equipment costs (including controls and installation) estimated by vendor for PSC® installations, with and without turbocharger modification/addition.[19]

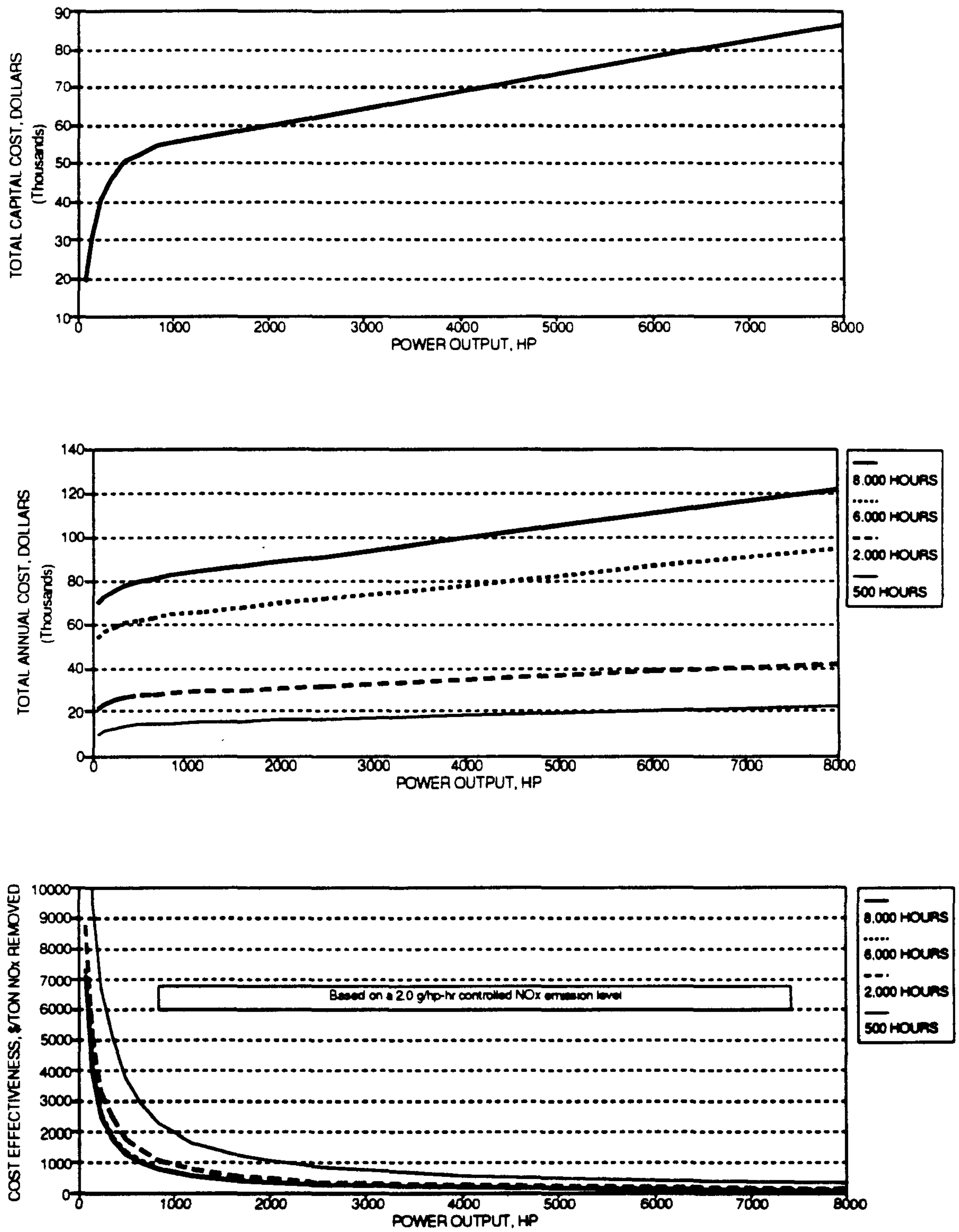
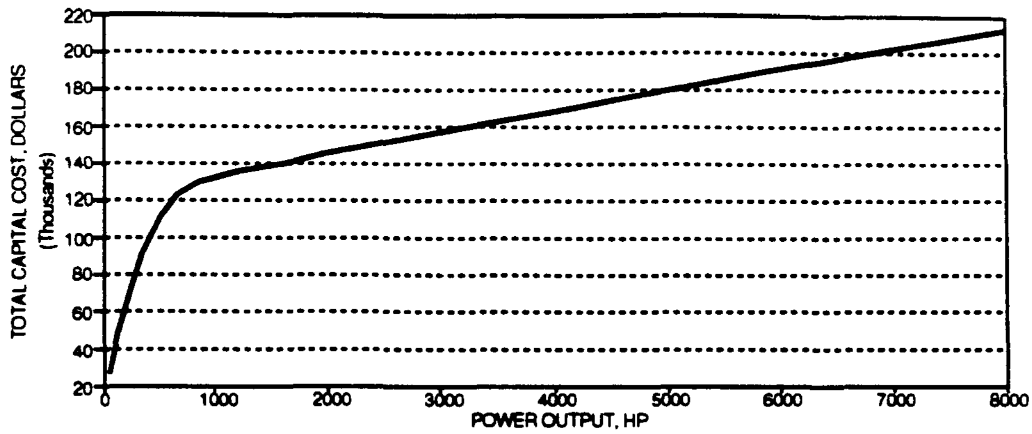
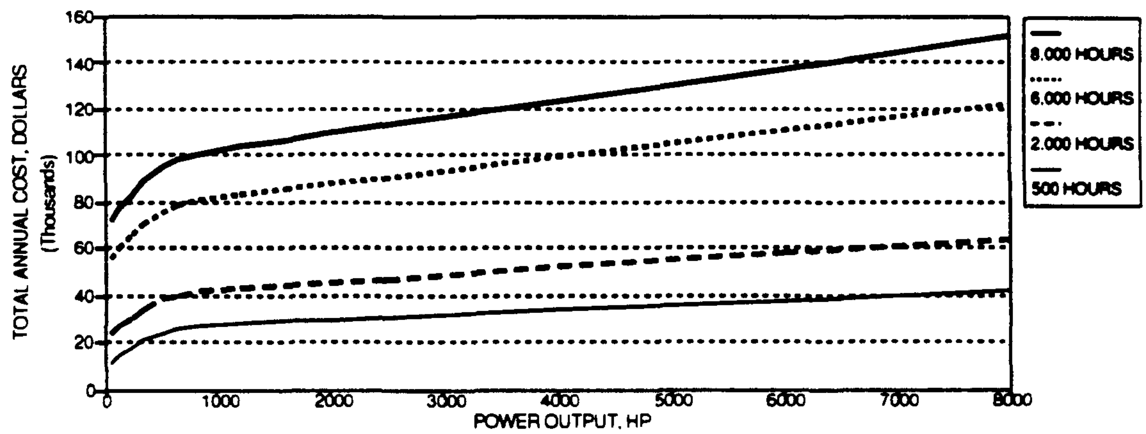


Figure 6-5. Total capital and annual costs and cost effectiveness for PSC® in rich-burn engines, without turbocharger installation or modification.





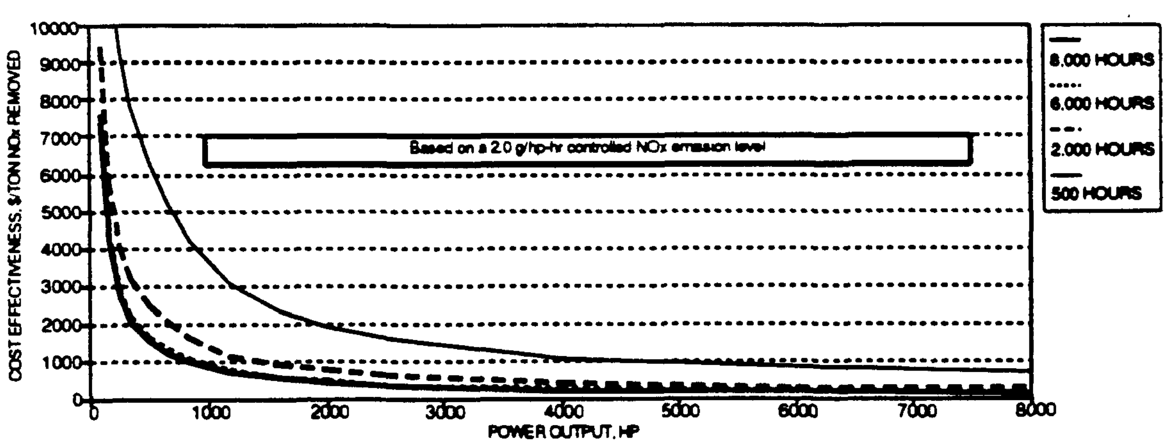


Figure 6-6. Total capital and annual costs and cost effectiveness for PSC® in rich-burn engines, with turbocharger installation or modification.

costs began to level off for engines in the range of 1,000 to 1,200 hp, and above 1,200 hp the costs were extrapolated linearly, resulting in an estimated total capital cost for an 8,000 hp engine of $87,000.

The available cost estimates for turbocharger modifications were limited to only five engines. Because the extent of engine modifications required to install or modify a turbocharger can vary widely for different engine models, the total capital costs for PSC® installations that include turbocharger modifications may vary widely from the costs shown in Figure 6-6. The capital costs curve for PSC® installations that include turbocharger modification/addition include the costs described above plus the capital costs for the turbocharger rework. The costs begin at approximately $28,000 for engines rated at 100 hp or less and climb steeply to over $130,000 for engines rated at 800 to 1,000 hp. The cost estimates provided show that capital costs began to level off for engines in the range of 1,000 to 1,200 hp, and above 1,200 hp the costs were extrapolated linearly, resulting in an estimated total capital cost for an 8,000 hp engine of $215,000.

6.2.4.2 Annual Costs. The annual costs associated with PSC® include operating and supervisory labor, maintenance and overhead, fuel penalty, taxes, insurance, administrative costs, and capital recovery. No power reduction penalty is assessed, consistent with Section 6.1. However, implementing PSC® results in a potential power reduction of up to 20 percent, according to the vendor, and any penalty associated with the potential power reduction is an additional cost that should be considered on a case-by-case basis.

Operating labor requirements are estimated to be 2 hr per 8-hr shift, and supervisory labor is calculated as 15 percent of operating labor. The increased maintenance cost is estimated as 10 percent of the PEC, plus an overhead cost equal to 60 percent of the maintenance cost. Based on information presented in Chapter 5, a fuel penalty of 2 percent is assessed. Taxes, insurance, and administrative costs are charged as shown in

Table 6-2. An emission test cost of $2,440 is included. The capital recovery is calculated as discussed in Section 6.1.2.11.

The total annual costs for PSC®, with and without turbocharger modification/addition, are presented in Figures 6-5 and 6-6, respectively. For continuous-duty PSC® installations without turbocharger modification/addition, the total annual costs are approximately $70,000 for 100 hp engines and rise to over $80,000 for engines at approximately 800 to 1,000 hp. Above 1,200 hp, the costs are extrapolated and increase linearly with engine size, from an estimated total annual cost of $85,000 for a 1,200 hp engine to $120,000 for an 8,000 hp engine. The additional costs associated with PSC® installations with turbocharger modification/addition increase the total annual costs for continuous-duty applications to over $70,000 for the smallest engines, rising to approximately $100,000 for 1,200 hp engines. The annual costs for engines above 1,200 hp are estimated to increase linearly with engine size and total $150,000 for an 8,000 hp engine.

6.2.4.3 Cost Effectiveness. As discussed in Chapter 5, the achievable controlled NO_x emission level for PSC® is 2 g/hp-hr or less. The cost effectiveness presented in this section is calculated using a controlled NO_x emission level of 2 g/hp-hr.

For PSC® installations that do not include the addition or modification of a turbocharger, the cost effectiveness is presented in Figure 6-5. For continuous-duty engines (8,000 hr/yr), the cost effectiveness is approximately $7,700/ton for engines rated at 100 hp or less and decreases rapidly with increasing engine size to approximately $700/ton for a 1,000 hp engine. The cost effectiveness is relatively constant for engines rated above 1,000 hp and is less than $600/ton. For engines operating less than 8,000 hr/yr, cost effectiveness increases with decreasing operating hours. The increase is relatively small for larger engines but increases rapidly for smaller engines, especially engines less than 1,000 hp. The cost effectiveness for these smaller engines operating 6,000 hr/yr or less ranges from approximately $400 to over $15,000/ton, increasing as engine size and annual operating hours decrease. The cost-effectiveness range from $10,000 to $15,000 per ton is not shown on the plot in Figure 6-5 in order to more clearly present the range of $0 to $10,000 per ton.

For PSC® installations that include turbocharger modification/addition, cost effectiveness is presented in Figure 6-6. The cost-effectiveness figures are higher than those shown in Figure 6-5 due to the higher total annual costs associated with the turbocharger. The increase in cost effectiveness is relatively small: less than $300/ton for continuous-duty engines, increasing to a maximum of $2,000/ton for the smallest engine operating 500 hr/yr. The cost effectiveness for an 80 hp engine operating 500 hr/yr is $17,400/ton. The cost-effectiveness range above $10,000/ton is not shown on the plot in Figure 6-6 in order to more clearly present the range of $0 to $10,000 per ton.

6.2.5 Control Costs for Nonselective Catalytic Reduction (NSCR)

6.2.5.1 Capital Costs. The PEC for NSCR includes the cost of the catalyst system and an automatic A/F controller. These costs are estimated at $15/hp for the catalyst and $6,000 for the A/F controller.[7,20] Sales taxes and freight are included as 8 percent of the PEC. The PEC is multiplied by factors of 45, 33, and 20 percent, respectively, for direct and indirect installation costs and contingencies. Using this methodology, the total capital costs for NSCR are presented in Figure 6-7. The costs are essentially linear and can be estimated by the following formula:

$$\text{Total capital cost} = \$12{,}100 + (\$30.1 \times \text{hp})$$

The total capital costs range from $14,800 for an 80 hp engine to $253,000 for an 8,000 hp engine.

6.2.5.2 Annual Costs. The annual costs associated with NSCR include operating and supervisory labor, maintenance and overhead, fuel penalty, catalyst cleaning and replacement, taxes, insurance, administrative costs, emission compliance testing, and

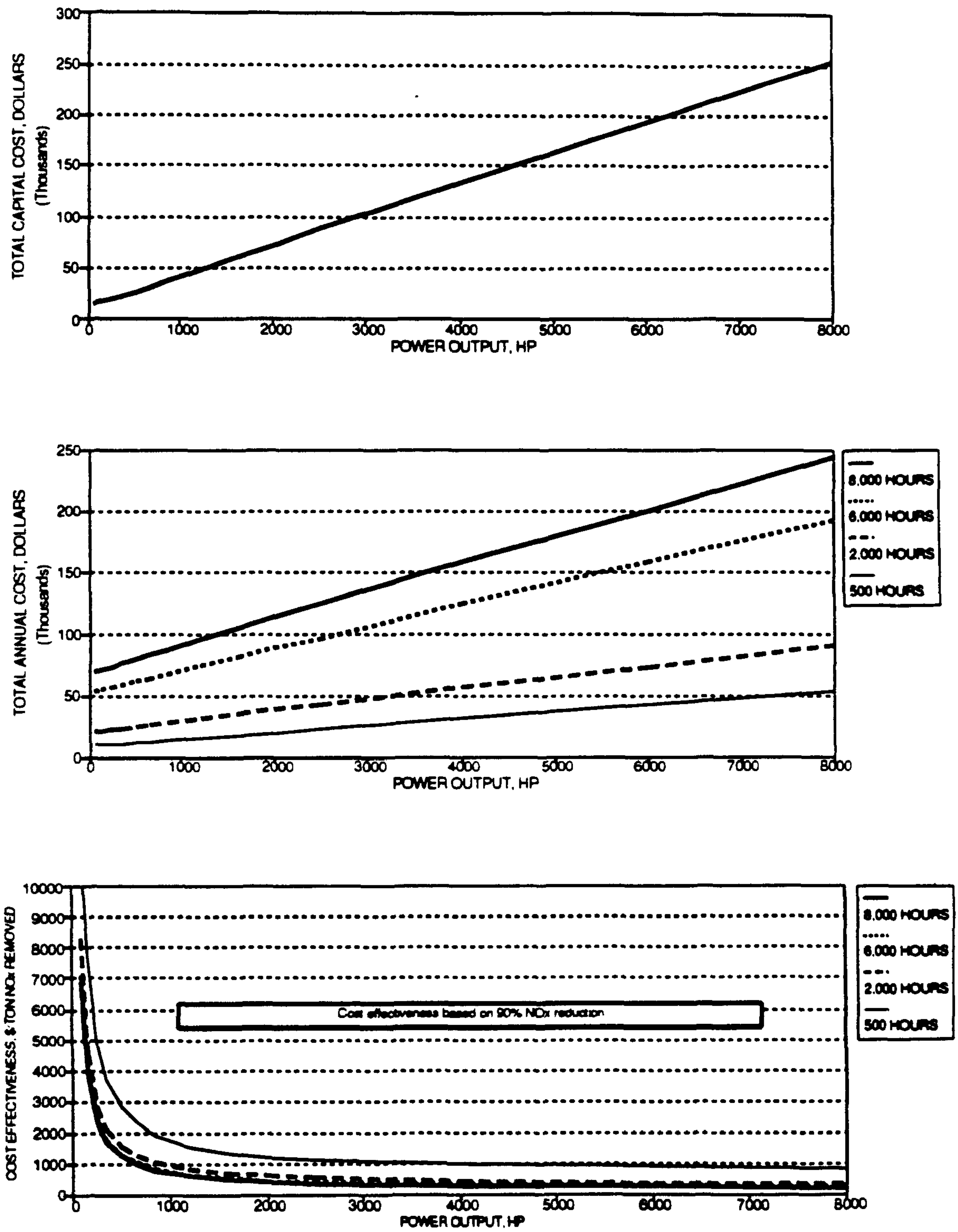


Figure 6-7. Total capital and annual costs and cost effectiveness for nonselective catalytic reduction for rich-burn engines.

capital recovery. No power reduction penalty is assessed, consistent with Section 6.1. The expected power reduction resulting from a backpressure of 4 inches of water column (in. w.c.) caused by the catalyst system is expected to be 1 percent for naturally aspirated engines and 2 percent for turbocharged engines. Any penalty associated with the potential power reduction is an additional cost that should be considered on a case-by-case basis.

Operating labor requirements are estimated to be 2 hr per 8-hr shift, and supervisory labor is calculated as 15 percent of operating labor. Maintenance costs are calculated as 10 percent of the PEC, plus an overhead cost equal to 60 percent of the maintenance cost. A fuel penalty of 5 percent is assessed.

Catalyst cleaning is scheduled every 12,000 hr, and a catalyst life of 3 yr (24,000 hr) is used in this methodology consistent with the guaranteed period available from most catalyst vendors. The cost of cleaning is estimated at $0.75/hp plus 10 percent for freight and is based on shipping the catalyst to an offsite facility for cleaning.[20] Based on this schedule, the annual cost for catalyst cleaning is calculated as $0.25/hp plus 10 percent for freight for continuous-duty applications (8,000 hr). The catalyst replacement cost is estimated to be $10/hp.[7] The annual cost for catalyst replacement is calculated to be $3.67/hp plus 10 percent for freight for continuous-duty applications. No disposal cost was assessed for NSCR applications because precious metal catalysts are most commonly used in NSCR systems, and most catalyst vendors offer a credit for return of spent catalyst reactors of $0.80/hp toward the purchase of new catalyst. For this methodology, the credit was not considered because it could not be confirmed that all catalyst vendors offer this credit.

Plant overhead, taxes, insurance, and administrative costs are calculated as described in Section 6.1, and an emission test cost of $2,440 is included. The capital recovery is calculated as discussed in Section 6.1.2.11.

The resultant total annual costs for NSCR are presented in Figure 6-7 and can be estimated using the following equations:

Operating hours	Total annual cost
8,000	\$68,300 + (\$22.0 x hp)
6,000	\$52,300 + (\$17.7 x hp)
2,000	\$20,200 + (\$8.9 x hp)
500	\$8,260 + (\$5.6 x hp)

For an 80 hp engine, the total annual costs range from \$8,700 for 500 hr/yr to \$69,300 for 8,000 hr/yr. For an 8,000 hp engine, the total annual costs range from \$53,100 for 500 hr/yr to \$244,000 for 8,000 hr/yr.

6.2.5.3 Cost Effectiveness. As discussed in Chapter 5, the potential NO_x emission reduction using NSCR ranges to a maximum of 98 percent. The cost effectiveness presented in this section is calculated using a 90 percent NO_x emission reduction, consistent with most of the emissions data presented in Chapter 5.

The cost effectiveness is presented in Figure 6-7. For continuous-duty engines, the cost effectiveness for NSCR approaches \$7,000/ton for engines less than 100 hp but decreases rapidly for larger engines. For engines above 1,000 hp, the cost-effectiveness curve is relatively flat at \$800/ton or less, decreasing slightly with increasing engine size. A similar cost-effectiveness trend applies to engines that operate less than 8,000 hr/yr, but the cost effectiveness increases to a high of over \$13,000/ton for the smallest engines operating 500 hr/yr and decreases to approximately \$1,700/ton or less for engines above 1,000 hp operating 500 hr/yr. The cost-effectiveness range from \$10,000 to \$14,000 per ton is not shown on the plot in Figure 6-7 in order to more clearly present the range of \$0 to \$10,000 per ton.

6.2.6 Control Costs for Conversion to Low-Emission Combustion

The costs presented in this section reflect the cost to retrofit an existing engine to low-emission combustion. Because the hardware requirements, and therefore the installation requirements, are similar for either rich- or lean-burn engines, the capital costs presented in this section apply to either engine type. For new engine installations, the costs would be considerably less than those presented here. The capital cost premium for new, low-emission, medium-speed engines is estimated by one manufacturer to range from approximately $11 to $15 per hp for one line of engines rated at 100 to 700 hp. For another engine line rated at 800 to 2,700 hp, the premium ranges from approximately $10 to $33 per hp.[16] Another medium-speed engine manufacturer estimated that the incremental cost for low-emission engines is approximately 5 percent over that of conventional engines.[21] Similar new-equipment costs were not available for low-speed engines.

The hardware and labor requirements to retrofit low-emission combustion to an existing engine are similar in scope to a major engine overhaul. If the low-emission combustion retrofit is scheduled to coincide with a scheduled major engine overhaul, the capital costs and cost effectiveness figures will be less than those shown in this section. One SI engine manufacturer estimates that retrofit to low-emission combustion, performed in conjunction with a major overhaul on medium-speed SI engines (approximately 800 to 2,700 hp) results in a reduction in cost effectiveness of approximately $40 to $50 per ton of NO_x.[16]

6.2.6.1 Capital Costs. Cost estimates from three engine manufacturers were used to develop the capital costs for the hardware required to retrofit existing engines to low-emission combustion.[9,10,16] An analysis of these costs showed that the costs for medium-speed, large-bore engines, provided by two manufacturers, is considerably less than those for low-speed large-bore engines provided by the third manufacturer. For this reason, the costs are presented separately for low- and medium-speed engines.

The hardware costs for medium-speed engines, ranging in size from 100 to 2,700 hp, are presented in Figure 6-8. The costs, although scattered, are approximated using the line plotted on

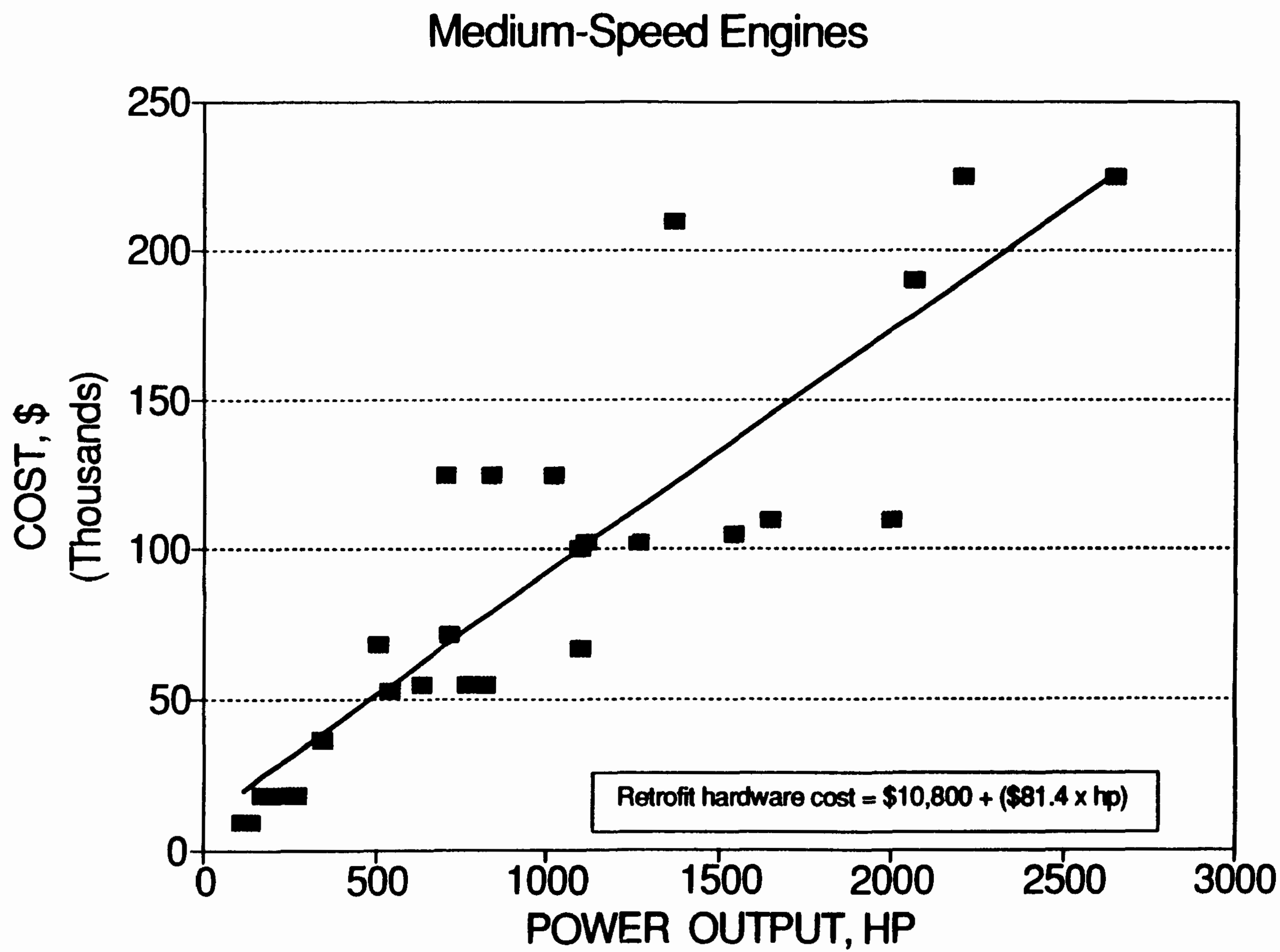


Figure 6-8. Hardware costs estimated by engine manufacturers for retrofit to low-emission combustion for medium-speed, SI engines.[9,16]

this figure. The equation of this line results in a capital cost for the retrofit hardware for medium-speed engines of:

Medium-speed engine hardware cost = \$10,800 + (\$81.4 x hp)

Similar costs for low-speed engines, ranging in size from 200 to 11,000 hp, are presented in Figure 6-9. Again, the costs, although scattered, are approximated by the line plotted on this figure. The equation of the line gives a capital cost for the retrofit hardware for low-speed engines of:

Low-speed engine hardware cost = \$140,000 + (\$155 x hp)

These equations were used to estimate the hardware costs for low-emission retrofits.

The increased air flows required for low-emission combustion typically require purchase of new inlet air filtration and ductwork, exhaust silencers and ductwork, and aerial coolers. The cost of this equipment is estimated to be 30 percent of the hardware costs.[1] The PEC is therefore calculated as 1.3 times the hardware cost.

Direct and indirect installation factors are calculated as 25 and 20 percent of the PEC, respectively. The contingency factor is 20 percent. Adding sales taxes and freight yields total capital costs as presented in Figures 6-10 and 6-11 for medium-speed and low-speed engines, respectively. The costs are linear and can be estimated using the equations listed below:

Medium-speed engines:

Total capital costs = \$24,300 + (\$183 x hp)

Low-speed engines:

Total capital costs = \$315,000 + (\$350 x hp)

The total capital costs for medium-speed engines range from \$38,900 for an 80 hp engine to \$757,000 for a 4,000 hp engine. The total capital costs for low-speed engines are considerably

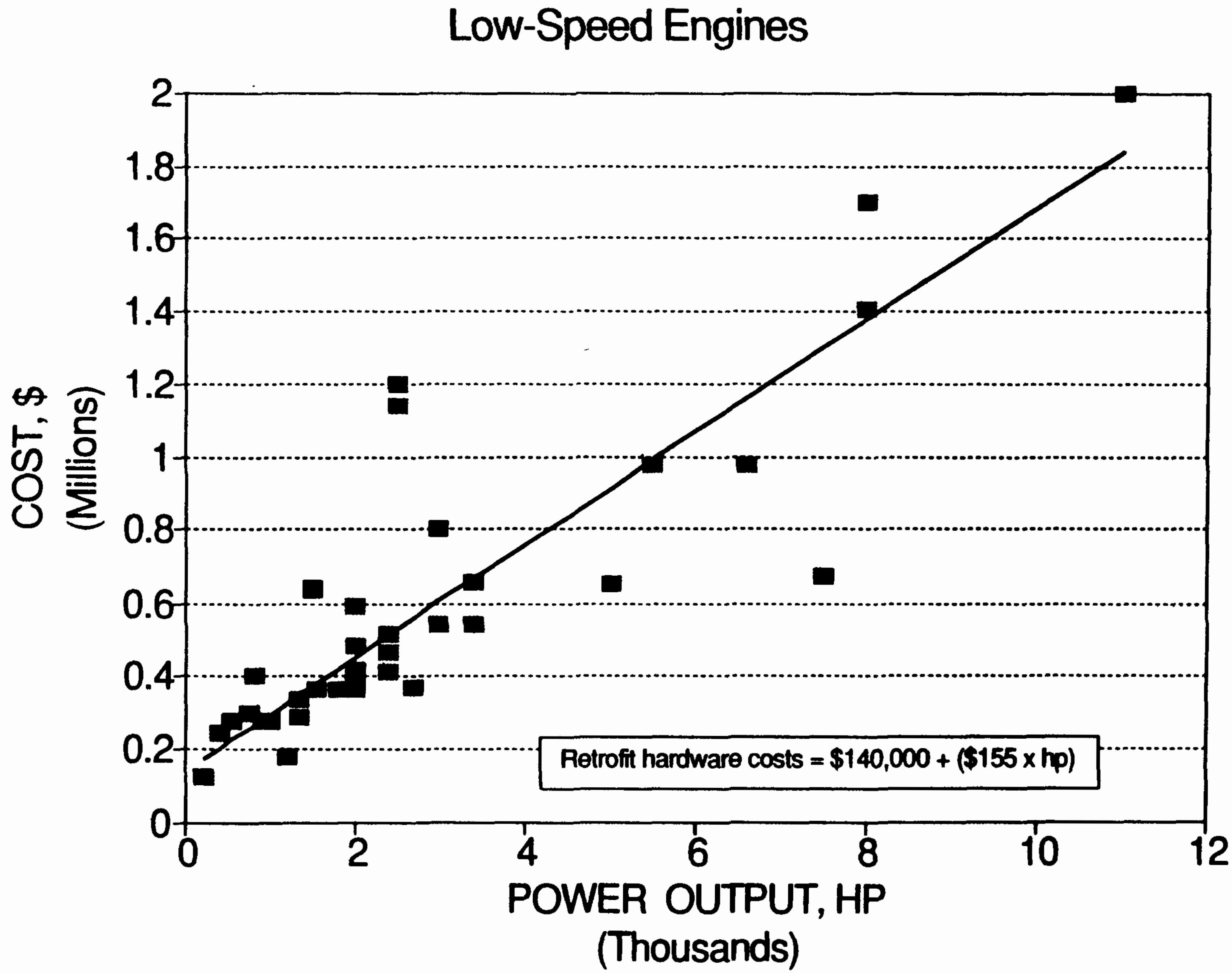


Figure 6-9. Hardware costs estimated by one engine manufacturer for retrofit to low-emission combustion for low-speed engines.[10]

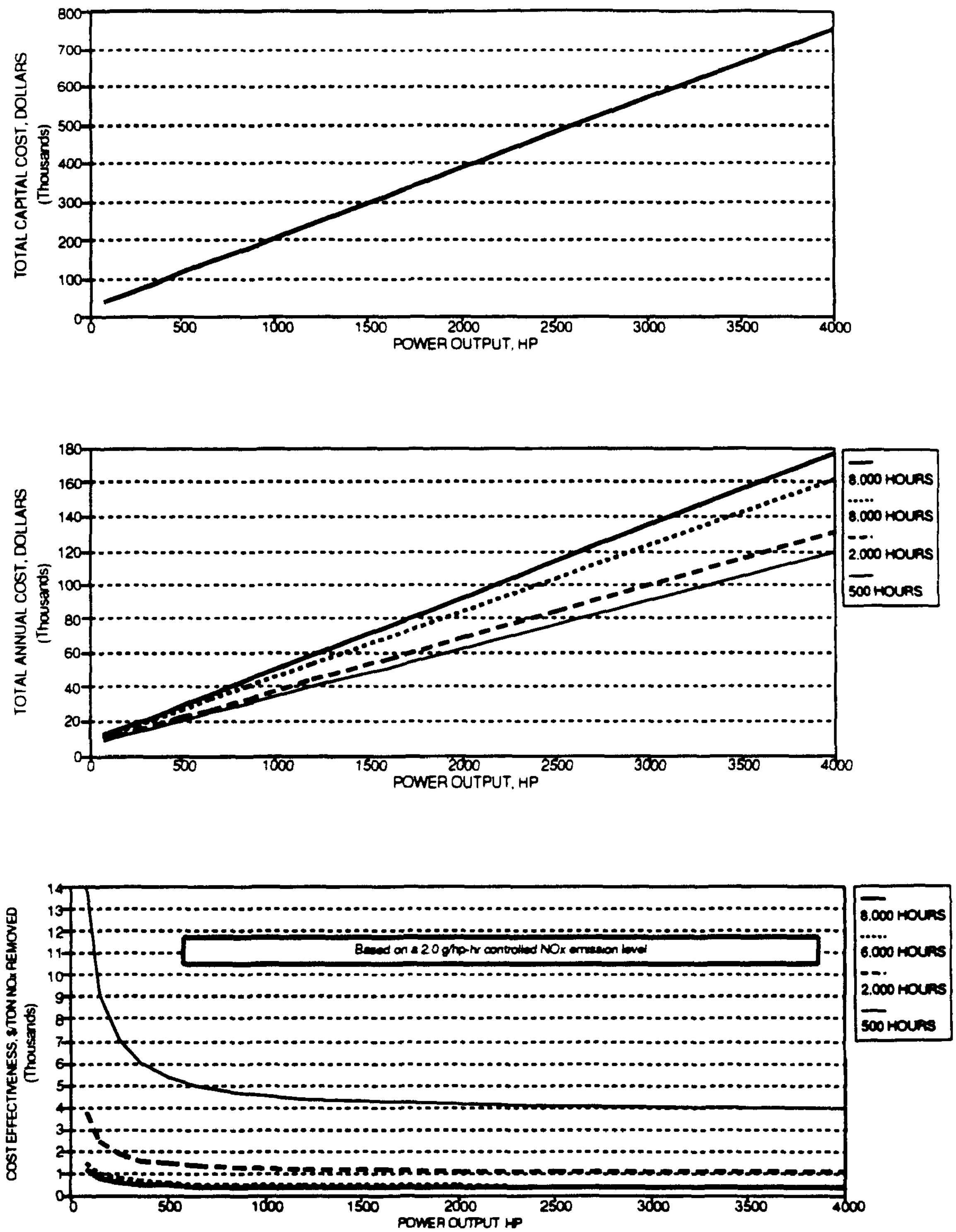


Figure 6-10. Total capital and annual costs and cost effectiveness for retrofit to low-emission combustion for medium-speed engines.

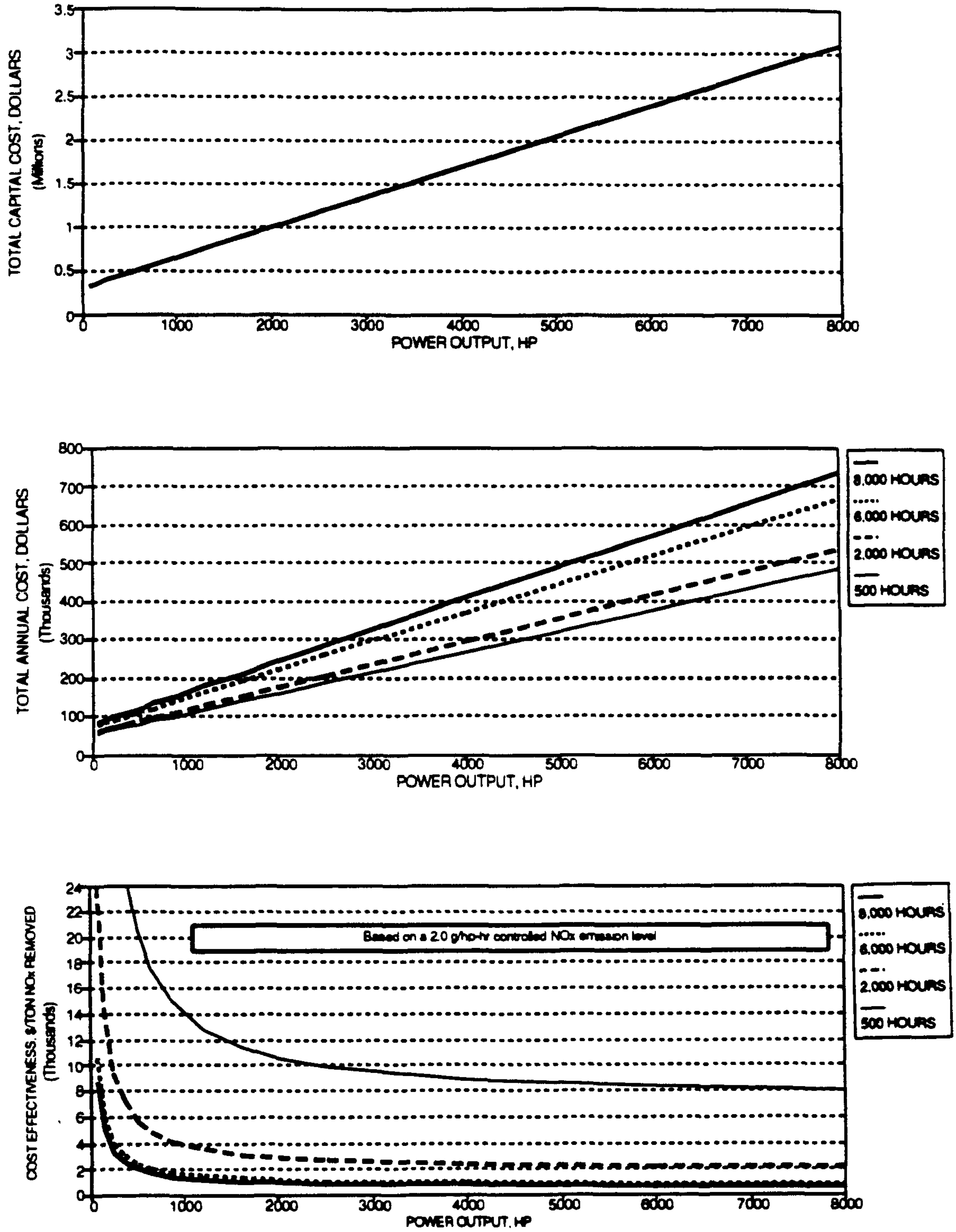


Figure 6-11. Total capital and annual costs and cost effectiveness for retrofit to low-emission combustion for low-speed engines.

higher, ranging from $343,000 for an 80 hp engine to $3,100,000 for a 8,000 hp engine. Because retrofit requirements are highly variable, depending upon the engine model and installation-specific factors, the actual costs for low-emission engine conversion may vary considerably from those calculated using the equations shown above.

6.2.6.2 Annual Costs. The annual costs associated with low-emission combustion include maintenance and overhead, fuel consumption, taxes, insurance, administrative costs, emission compliance testing, and capital recovery. No power reduction results from low-emission combustion; in fact, the addition of the turbocharger in some cases may increase the power output of engines that were previously naturally aspirated.

No increase in operating labor requirements is expected with low-emission combustion engines. Maintenance activities increase, however, due to potential decreased spark plug life, precombustion chamber admission valves maintenance requirements, and increased turbocharger inspections. Maintenance costs are calculated as 10 percent of the PEC, plus an overhead cost equal to 60 percent of the maintenance cost. Based on a comparison of heat rates for rich-burn engines and low-emission engines, a 1 percent fuel credit is used in the annual cost calculations.

Plant overhead, taxes, insurance, and administrative costs are calculated as described in Section 6.1. A cost of $2,440 is added for emission testing. The capital recovery is calculated as discussed in Section 6.1.2.11.

The resultant total annual costs for medium- and low-speed engines for low-emission combustion are presented in Figures 6-10 and 6-11, respectively. The costs are essentially linear and can be approximated by the following equations:

Medium-speed engines:

Operating hours	Total annual cost
8,000	$8,100 + ($42.2 x hp)
6,000	$7,600 + ($38.5 x hp)
2,000	$6,600 + ($31.1 x hp)
500	$6,200 + ($28.3 x hp)

Low-speed engines:

Operating hours	Total annual cost
8,000	$78,500 + ($82.3 x hp)
6,000	$71,300 + ($74.8 x hp)
2,000	$56,800 + ($59.7 x hp)
500	$51,400 + ($54.1 x hp)

The total annual costs for an 80 hp, medium-speed engine range from $8,480 for 500 hr/yr to $11,700 for 8,000 hr/yr. For a 4,000 hp, medium-speed engine, the total annual costs range from $120,000 for 500 hr/yr to $177,000 for 8,000 hr/yr. The total annual costs for an 80 hp low-speed engine range from $55,800 for 500 hr/yr to $85,300 for 8,000 hr/yr. For an 8,000 hp, low-speed engine, the total annual costs range from $484,000 for 500 hr/yr to $737,000 for 8,000 hr/yr. The higher range of annual costs for low-speed engines is attributable to the higher capital costs for these engines relative to medium-speed engines.

6.2.6.3 Cost Effectiveness. The cost effectiveness presented in this section is calculated using a controlled NO_x emission rate of 2 g/hp-hr (150 ppmv), consistent with most of the emissions data presented in Chapter 5. The cost effectiveness for medium-speed engines is presented in Figure 6-10. For continuous-duty engines (8,000 hr/yr), the cost effectiveness is approximately $1,200/ton for engines rated at 100 hp or less and decreases rapidly with increasing engine size to less than $400/ton for a 1,000 hp engine. The cost-effectiveness curve is relatively flat for engines rated above

1,000 hp, decreasing slightly from $400/ton for a 1,200 hp engine to $350/ton for an 8,000 hp engine.

For medium-speed engines operating less than 8,000 hr/yr, cost effectiveness increases with decreasing operating hours. The increase is relatively small for larger engines but increases rapidly for smaller engines, especially engines less than 1,000 hp. The cost effectiveness for these smaller engines ranges from approximately $4,000 to $14,000 per ton, increasing as engine size and annual operating hours decrease.

As shown in Figure 6-11, for continuous-duty low-speed engines, cost effectiveness for low-emission retrofit approaches $8,800/ton for engines less than 100 hp but decreases rapidly for larger engines. For engines above 1,000 hp, the cost-effectiveness curve is relatively flat at less than $1,300/ton, decreasing slightly with increasing engine size to a low of approximately $750/ton for an 8,000 hp engine. A similar cost-effectiveness trend applies to low-speed engines that operate less than 8,000 hr/yr, but the cost effectiveness increases to a high of over $90,000/ton for the smallest engines operating 500 hr/yr and decreases to approximately $15,000/ton or less for engines above 1,000 hp operating 500 hr/yr. The cost-effectiveness range from $24,000 to $92,000 per ton is not shown on the plot in Figure 6-11 in order to more clearly present the range of $0 to $10,000 per ton.

6.3 CONTROL COSTS FOR LEAN-BURN SI ENGINES

The applicable control techniques for lean-burn SI engines are A/F adjustment, ignition timing retard, a combination of A/F adjustment and ignition timing retard, SCR, and low-emission combustion. The costs for these control techniques as applied to lean-burn SI engines are presented in this section.

6.3.1 Control Costs for A/F Adjustment

6.3.1.1 Capital Costs. Adjusting the A/F to a leaner setting requires a higher volume of air. For naturally aspirated engines, this usually requires the addition of a turbocharger. For turbocharged engines, either modifications to the existing turbocharger or replacement with a larger unit may be required. Some manufacturers size the turbocharger to provide adequate airflow at minimum engine speed and full torque, and at higher engine speeds the output from the turbocharger is throttled or regulated with a bypass arrangement to maintain the desired A/F. For these engines, A/F adjustment to reduce NO_x emission levels may be possible by changing the control settings for the turbocharger. Changing the turbocharger control setting, however, reduces the operating speed range for the engine, as the turbocharger capacity would not be adequate at lower engine speeds. The lower speed range would limit the operating flexibility for variable-speed applications (e.g., compressor and pump) and increase BSFC and carbon monoxide (CO) emissions. The airflow capacity in some engines can be increased by changing the turbine nozzle ring in the existing turbocharger. Modifications to the existing turbocharger would also require replacement of the air manifold valves with an exhaust waste gate valve and readjustment of the A/F control setpoint. According to information provided by an engine manufacturer, the capital costs for either scenario discussed above are expected to be similar to or less than the costs shown in Section 6.2.1 for A/F adjustment for rich-burn engines.[16]

Naturally aspirated engines that cannot achieve a sufficient increase in the A/F to reduce NO_x emission levels would require installation of a new turbocharger, and turbocharged engines would require replacement of the existing turbocharger with a larger unit. The capital costs presented in this section apply to the addition/replacement of a turbocharger. Not all existing engine designs will accommodate this retrofit.

The hardware costs associated with a new turbocharger were estimated by an engine manufacturer to be \$43,000 for engines up 1,100 hp, and \$47,500 for engines between 1,100 and 2,650; the associated labor cost were estimated to be 76 hr for either engine size.[16] Assuming a linear relationship between hardware costs and engine size yields the following equation:

$$\text{Hardware costs} = \$40{,}000 + (\$3 \times \text{hp})$$

The PEC was calculated as the hardware cost plus labor costs (76 hr x \$27/hr). Direct and indirect installation factors of 25 and 20 percent of the PEC, respectively, were applied. The contingency factor is 20 percent of the PEC, and sales taxes and freight total 8 percent of the PEC.

Based on the above methodology, the total capital cost for A/F adjustment for lean-burn engines that require a new turbocharger are presented in Figure 6-12. The costs are linear and can be estimated by the equation shown below:

$$\text{Total capital costs} = \$73{,}000 + (\$5.2 \times \text{hp})$$

The total capital costs range from \$73,800 for a 200 hp engine to \$130,000 for an 11,000 hp engine.

6.3.1.2 Annual Costs. For engines that do not require a new turbocharger, the annual costs are expected to be similar to or less than those shown for A/F adjustment for rich-burn engines in Section 6.2.1. For engines that require a new turbocharger, the anticipated annual costs associated with A/F adjustment include an increase in maintenance due to the addition of a new or larger turbocharger, an increase in BSFC, an emission compliance test, and capital recovery. The increased maintenance cost is estimated as 10 percent of the PEC, plus an overhead cost equal to 60 percent of the maintenance cost. Based on information presented in Chapter 5, a fuel penalty of 3 percent is assessed. Taxes, insurance, and administrative costs are charged as shown in Table 6-2. The cost of a compliance test is estimated at \$2,440. The capital recovery is calculated as discussed in Section 6.1.2.11.

Based on the above methodology, the total annual costs for A/F adjustment for lean-burn engines retrofit with a new turbocharger are presented in Figure 6-12. As Figure 6-12 shows,

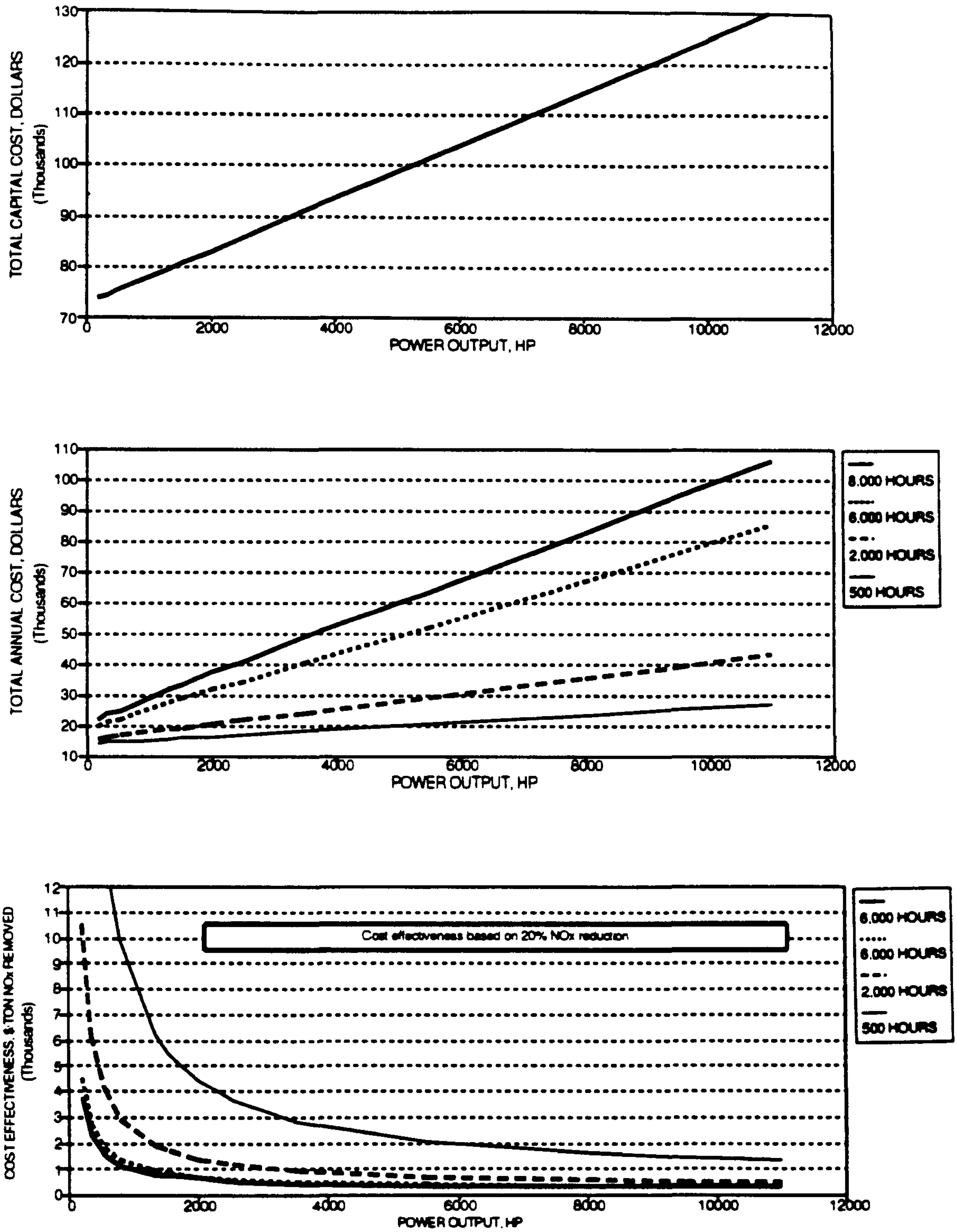


Figure 6-12. Total capital and annual costs and cost effectiveness for A/F adjustment in lean-burn engines, based on the addition of a new turbocharger to the existing engine.

the costs are essentially linear and can be approximated using the following equations:

Operating hours	Total annual cost
8,000	\$21,100 + (\$7.8 x hp)
6,000	\$19,200 + (\$6.0 x hp)
2,000	\$15,300 + (\$2.5 x hp)
500	\$13,800 + (\$1.2 x hp)

For a 200 hp engine, the total annual costs range from \$14,000 for 500 hr/yr to \$22,100 for 8,000 hr/yr. For an 11,000 hp engine, the total annual costs range from \$27,200 for 500 hr/yr to \$106,000 for 8,000 hr/yr.

6.3.1.3 Cost Effectiveness. As discussed in Chapter 5, the expected range of NO_x reduction for A/F adjustment for lean-burn engines is 5 to 30 percent, and the cost effectiveness varies according to the actual site-specific NO_x reduction. The cost effectiveness presented in this section is calculated using a NO_x reduction efficiency of 20 percent. For engines that do not require turbocharger replacement, the cost effectiveness is estimated to be similar to or less than those shown for A/F adjustment for rich-burn engines in Section 6.2.1.

For those engines that require a new turbocharger, the cost effectiveness is presented in Figure 6-12. For continuous-duty (8,000 hr/yr) engines, the cost effectiveness ranges from a high of approximately \$3,700/ton for engines rated at 200 hp or less and decreases rapidly as engine size increases, to \$1,000/ton or less for 1,000+ hp engines.

Cost effectiveness is higher for engines operating less than 8,000 hr/yr, especially for engines less than 1,000 hp. For these smaller engines the cost effectiveness increases rapidly, especially for engines that operate 2,000 hr/yr or less. The cost effectiveness for these engines ranges from approximately \$2,400 to \$7,500 per ton for 1,000 hp engines and from \$10,500 to \$38,000 per ton for 200 hp engines. The cost-effectiveness range from \$12,000 to \$38,000 per ton is not shown on the plot in

Figure 6-12 in order to more clearly present the range of \$0 to \$10,000 per ton.

6.3.2 Control Costs for Ignition Timing Retard

6.3.2.1 Capital Costs. For effective and sustained NO_x reduction with changes in engine load and ambient conditions, the engine must be fitted with an electronic ignition control system to automatically adjust the ignition timing. The total capital costs for ignition timing retard applied to lean-burn SI engines are expected to be the same as for rich-burn engines, presented in Section 6.2.2.1 and shown in Figure 6-13.

6.3.2.2 Annual Costs. The anticipated annual costs associated with ignition timing retard include an increase in maintenance due to the addition of the electronic ignition control system, an increase in BSFC, an emission compliance test, and capital recovery. The increased maintenance cost is estimated as 10 percent of the PEC, plus an overhead cost equal to 60 percent of the maintenance cost. Based on information presented in Chapter 5, a fuel penalty of 3 percent is assessed. Taxes, insurance, and administrative costs are charged as shown in Table 6-2, and a cost of \$2,440 is included for emissions testing. The capital recovery is calculated as discussed in Section 6.1.2.11.

Based on the above methodology, the total annual costs for ignition timing retard for lean-burn engines are presented in Figure 6-13. As Figure 6-13 shows, the costs are essentially linear and can be approximated using the following equations:

Operating hours	Total annual cost
8,000	\$6,840 + (\$6.8 x hp)
6,000	\$6,250 + (\$5.2 x hp)
2,000	\$5,070 + (\$1.8 x hp)
500	\$4,620 + (\$0.6 x hp)

For a 200 hp engine, the total annual costs range from \$4,460 for 500 hr/yr to \$7,210 for 8,000 hr/yr. For an 11,000 hp engine,

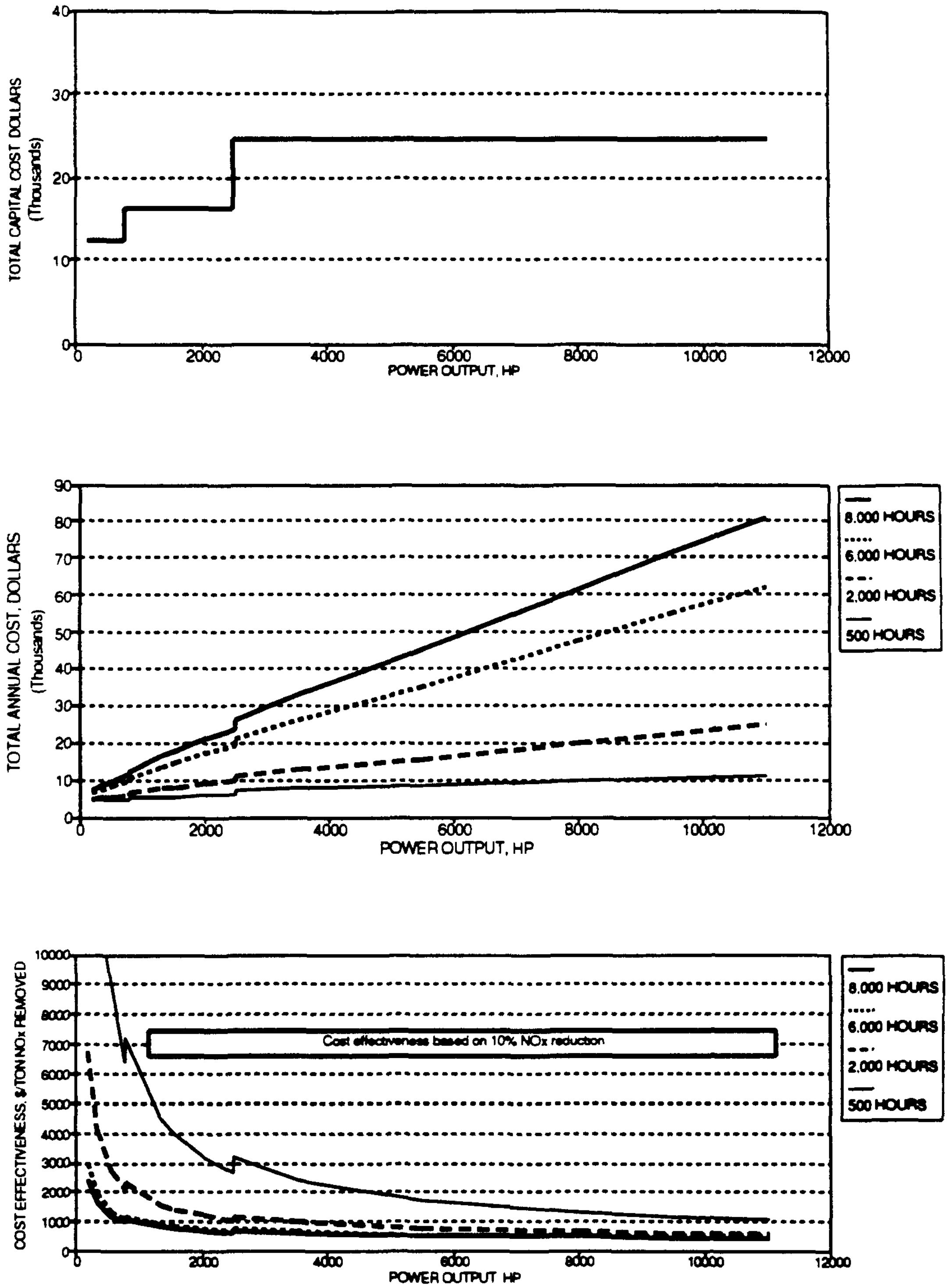


Figure 6-13. Total capital and annual costs and cost effectiveness for ignition timing retard in lean-burn SI engines, based on installation of an electronic ignition system.

the total annual costs range from $10,800 for 500 hr/yr to $81,100 for 8,000 hr/yr.

6.3.2.3 Cost Effectiveness. As discussed in Chapter 5, the expected range of NO_x reduction for the ignition retard for lean-burn engines is 0 to 20 percent, and the cost effectiveness varies according to the actual site-specific NO_x reduction. The cost effectiveness presented in this section is calculated using a NO_x reduction efficiency of 10 percent. For engine installations already equipped with an electronic ignition control system, no additional equipment purchase is necessary, and the cost effectiveness is estimated to be less than $1,000/ton for all but the smallest engines operating in stand-by applications.

For those engines which require installation of an electronic ignition system, the cost effectiveness is presented in Figure 6-13. For continuous-duty engines (8,000 hr/yr), the cost effectiveness ranges from a high of approximately $2,400/ton for engines rated at 200 hp or less down to less than $1,800/ton for engines rated at 1,000+ hp.

Cost effectiveness is higher for engines operating at less than 8,000 hr/yr, especially for engines less than 1,000 hp. For these smaller engines the cost effectiveness increases rapidly, especially for engines less than 1,000 hp that operate 2,000 hr/yr or less. The cost effectiveness for these engines ranges from approximately $1,800 to $5,000 per ton for 1,000 hp engines to $6,800 to over $24,000 per ton for 200 hp engines. The cost-effectiveness range from $10,000 to $24,000 per ton is not shown on the plot in Figure 6-13 in order to more clearly present the range of $0 to $10,000 per ton.

6.3.3 Control Costs for A/F Adjustment and Ignition Timing Retard

6.3.3.1 Capital Costs. The capital costs presented in this section apply to installing both a new turbocharger and an electronic ignition system on the engine. Where an existing engine does not require modification (i.e., the turbocharger capacity is adequate for A/F adjustment and the engine is equipped with an electronic ignition system), no additional equipment is required. In this case, capital costs are expected to be approximately $4,000 or less. This cost includes an emission compliance test and approximately 25 labor hours and associated direct/indirect and contingency factors to perform the adjustments on the engine. Where an existing engine requires only one of the control system modifications (i.e., turbocharger modification/replacement or electronic ignition system), the capital costs are presented in Sections 6.3.1 and 6.3.2.

For engines that require installation of a new turbocharger and an electronic ignition system, the capital costs are estimated to be equal to the sum of the costs for each system. The combined PEC for these systems can be approximated by the following equations:

Engines to 1,000 hp: PEC = $49,600 + ($3 x hp)
Engines to 1,001 to 2,500 hp: PEC = $52,100 + ($3 x hp)
Engines over 2,500 hp: PEC = $57,100 + ($3 x hp)

Direct and indirect installation factors are each estimated at 20 percent of the combined PEC. The contingency factor is 20 percent of the PEC, and sales taxes and freight are 8 percent of the PEC.

Based on the above methodology, the total capital costs for the combination of A/F adjustment and ignition timing retard for lean-burn engines requiring both a new turbocharger and electronic ignition system are presented in Figure 6-14. The costs can be approximated by the following equations:

Engines to 1,000 hp: TCC = $83,200 + ($5.0 x hp)
Engines to 2,500 hp: TCC = $87,500 + ($5.0 x hp)
Engines above 2,500 hp: TCC = $95,800 + ($5.0 x hp)

The total capital costs range from $85,700 for a 200 hp engine to $151,000 for an 11,000 hp engine.

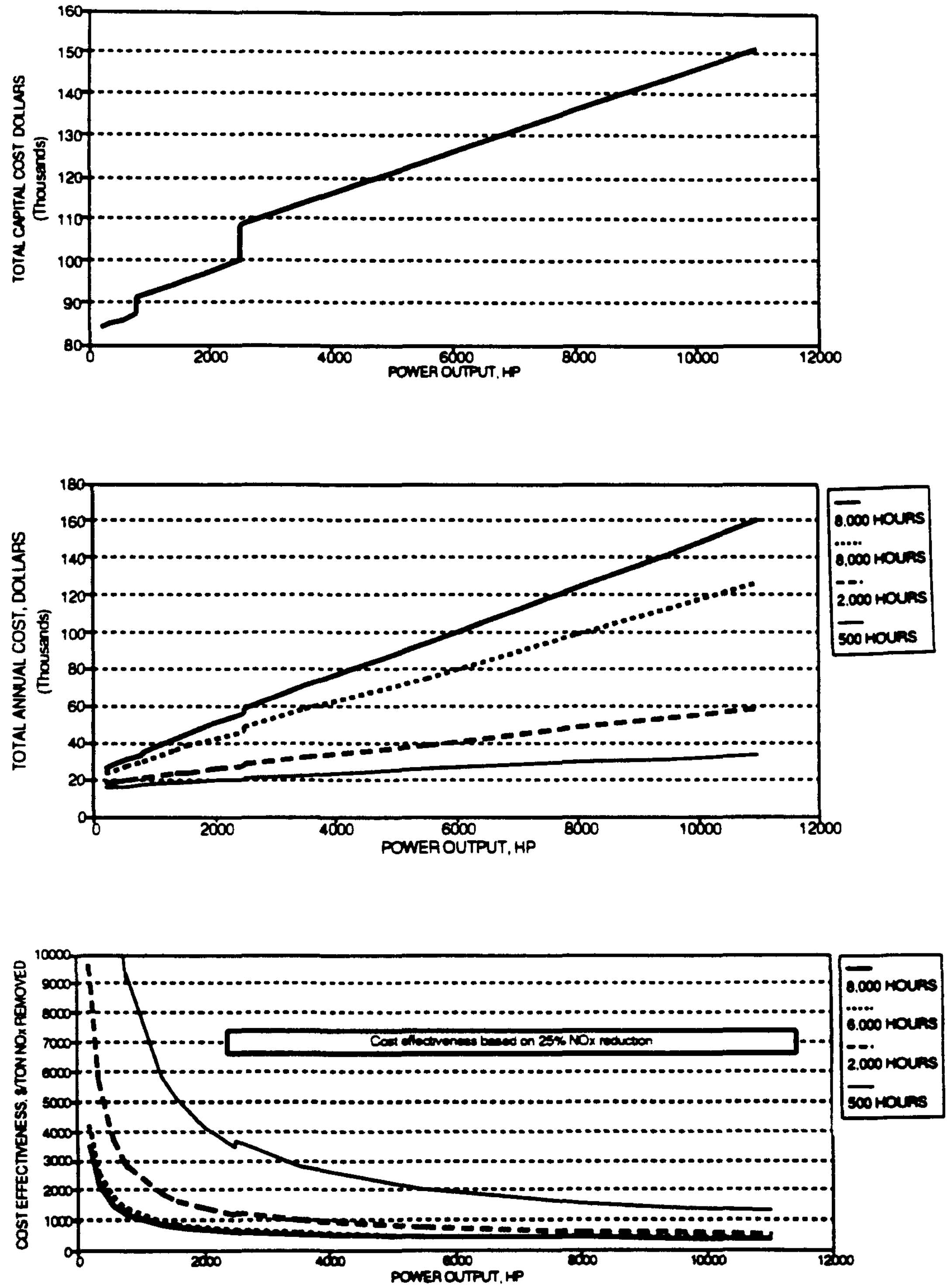


Figure 6-14. Total capital and annual costs and cost effectiveness for A/F adjustment and ignition timing retard in lean-burn SI engines, based on addition of a new turbocharger and an electronic ignition system.

6.3.3.2 Annual Costs. The anticipated annual costs associated with the combination of A/F adjustment and ignition timing retard include an increase in maintenance due to the installation of a new turbocharger and electronic ignition control systems, an increase in BSFC, an emission compliance test, and capital recovery. The increased maintenance cost is estimated as 10 percent of the PEC, plus an overhead cost equal to 60 percent of the maintenance cost. Based on information presented in Chapter 5, a fuel penalty of 5 percent is assessed. Taxes, insurance, and administrative costs are charged as shown in Table 6-2, and the compliance test cost is estimated at $2,440. The capital recovery is calculated as discussed in Section 6.1.2.11.

Based on the above methodology, the total annual costs for the combination of A/F adjustment and ignition timing retard for lean-burn engines are presented in Figure 6-14. As Figure 6-14 shows, the costs are essentially linear and can be approximated using the following equations:

Operating hours	Total annual cost
8,000	$24,900 + ($12.4 x hp)
6,000	$22,500 + ($9.5 x hp)
2,000	$17,600 + ($3.8 x hp)
500	$15,700 + ($1.7 x hp)

For a 200 hp engine, the total annual costs range from $15,700 for 500 hr/yr to $26,000 for 8,000 hr/yr. For an 11,000 hp engine, the total annual costs range from $33,600 for 500 hr/yr to $160,000 for 8,000 hr/yr.

6.3.3.3 Cost Effectiveness. As discussed in Chapter 5, the expected range of NO_x reduction for the combination of A/F adjustment and ignition retard for lean-burn engines is 20 to 40 percent, and the cost effectiveness varies according to the actual site-specific NO_x reduction. The cost effectiveness presented in this section is calculated using a NO_x reduction efficiency of 25 percent. For engine installations already equipped with both automatic A/F and electronic ignition control systems, no additional equipment purchase is necessary, and the cost effectiveness is estimated to be less than $1,000/ton for all but the smallest engines operating in stand-by applications. For those engines equipped with provisions for one but not both control systems, the second control system must be purchased and installed. The cost effectiveness in this case is less than that shown in Figure 6-12 or 6-13 for either control used independently, because the 25 percent NO_x reduction efficiency is higher than that used in either of these figures.

For continuous-duty engines, the cost effectiveness for A/F adjustment plus ignition timing retard in lean-burn engines is over $3,500/ton for a 200 hp engine but decreases rapidly as engine size increases. For engines above 1,000 hp, the cost-effectiveness curve is relatively flat at approximately $1,000/ton for a 1,000 hp engine and decreases to approximately $400/ton for an 11,000 hp engine.

A similar cost-effectiveness trend applies for engines that operate less than 8,000 hr/yr, but the cost effectiveness increases to a high of $34,000/ton for the smallest engines operating 500 hr/yr and decreases to less than $9,000/ton for 1,000 hp engines and less than $2,000/ton above 5,000 hp. The cost-effectiveness range from $10,000 to $34,000 per ton is not shown on the plot in Figure 6-14 in order to more clearly present the range of $0 to $10,000 per ton.

6.3.4 Control Costs for SCR Applied to Lean-Burn SI Engines

6.3.4.1 Capital Costs. Capital costs for SCR are estimated using installed cost estimates available from three sources.[5,22,23] These cost estimates are presented in Figure 6-15 and include the catalyst, reactor housing and ductwork, ammonia injection system, controls, and engineering and installation of the equipment. The line drawn on Figure 6-15 was used to develop the capital costs for SCR systems, and the equation of this line is given below:

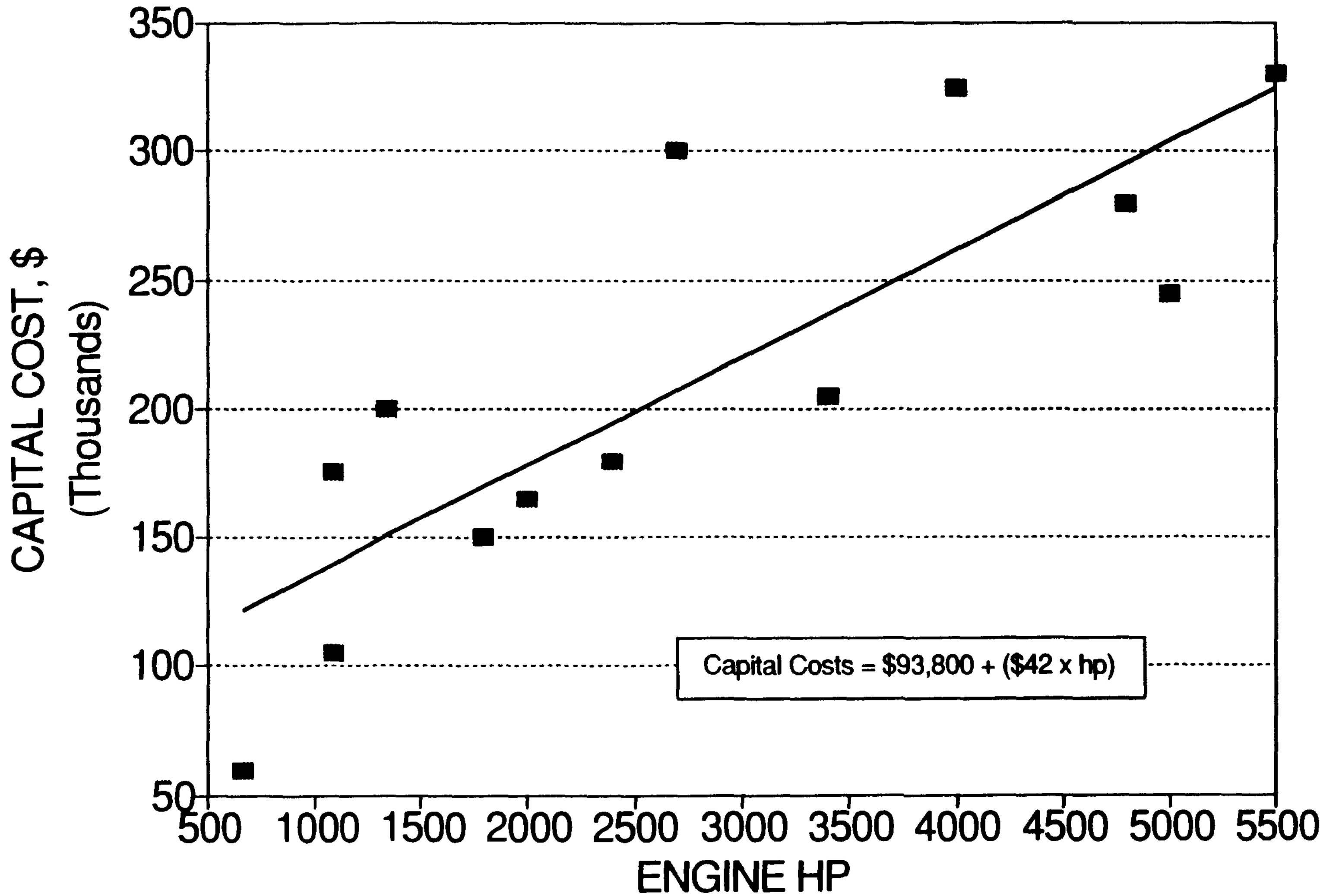


Figure 6-15. Installed costs for selective catalytic reduction estimated by catalyst vendors for gas-fired, lean-burn engines.[22,23]

Installed vendor cost estimates = \$93,800 + (\$42 x hp)

It is expected that most SCR installations would require a CEMS, and the additional cost for this is estimated at \$85,000, regardless of engine size.[5] The total PEC for SCR with a CEMS can be approximated using the following equation:

Purchased equipment cost = \$179,000 + (\$42 x hp)

This equation includes installation costs, so the direct and indirect installation factors are reduced to 25 and 20 percent of the PEC, respectively. The contingency factor is 20 percent of the PEC. Sales taxes and freight are assessed as shown in Table 6-1.

Based on the above methodology, the total capital costs for SCR for lean-burn SI engines are presented in Figure 6-16. These costs are essentially linear and can be estimated by the following equation:

Total capital costs = \$310,000 + (\$72.7 x hp)

The total capital costs range from \$324,000 for a 200 hp engine to \$1,110,000 for an 11,000 hp engine.

6.3.4.2 Annual Costs. The anticipated annual costs associated with SCR include an increase in operating labor and maintenance due to the addition of the ammonia injection and CEMS; an increase in BSFC; catalyst cleaning, replacement, and disposal; an emission compliance test; and capital recovery. The increased operating labor is calculated as 3 hr per 8-hr shift, with supervisory labor as an additional 15 percent of operating labor. Maintenance costs are estimated as 10 percent of the PEC, plus an overhead cost equal to 60 percent of the maintenance cost. Based on information presented in Chapter 5, a fuel penalty of 0.5 percent is assessed.

Based on information provided in References 8 and 20, the volume of catalyst for SCR applications is approximately twice

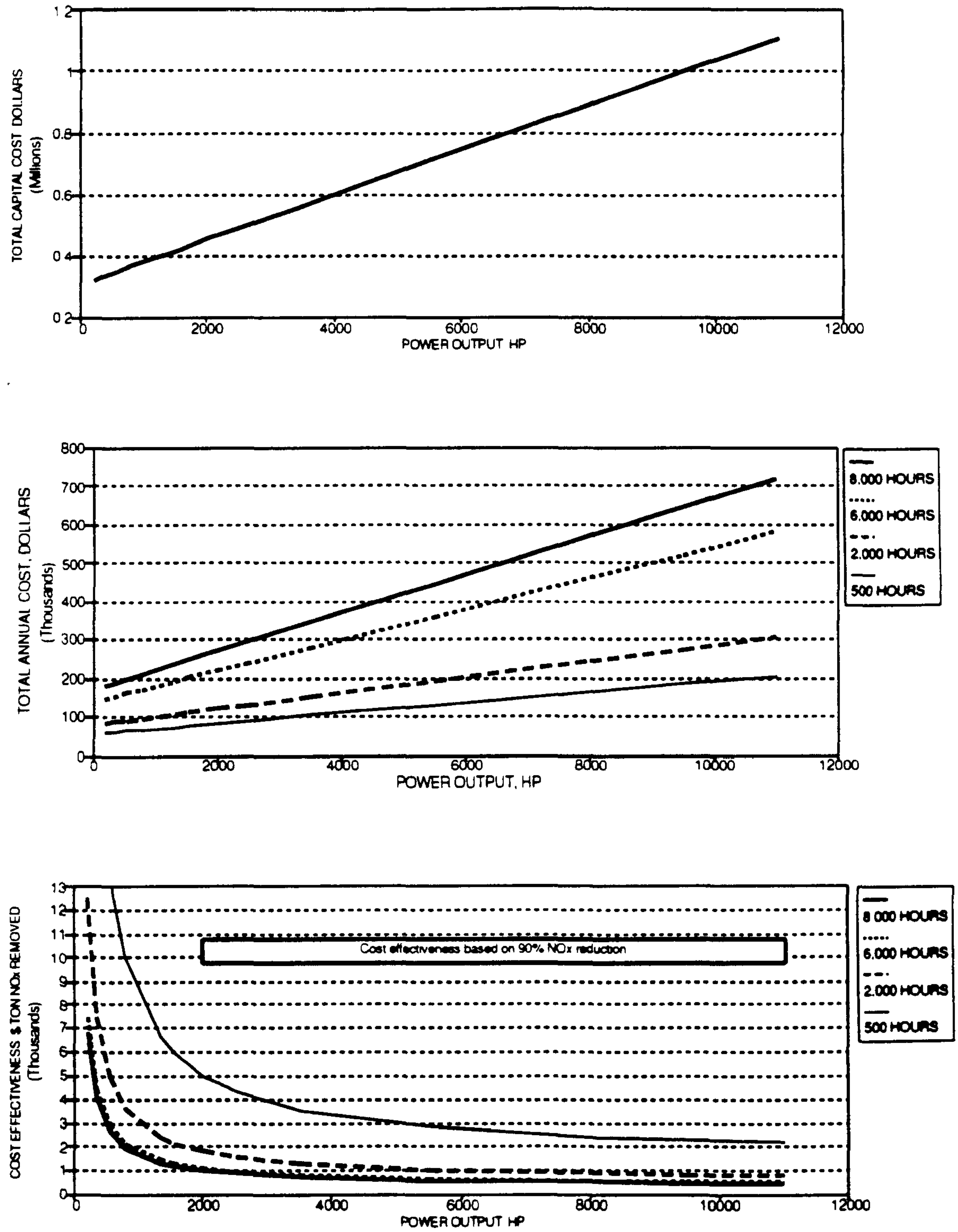


Figure 6-16. Total capital and annual costs and cost effectiveness for selective catalytic reduction for lean-burn SI engines, including a continuous emission monitoring system.

that required for NSCR applications. This is due in part to the higher airflows associated with the scavenge requirements for 2-cycle engines; other factors were not discussed in the references. The cleaning cost used for NSCR in Section 6.2.5 was therefore doubled to $1.50/hp for SCR catalyst cleaning, plus 10 percent for freight. A cleaning schedule of once every 1.5 yr (12,000 hr) is used for SCR, consistent with that for NSCR. A catalyst life of 3 yr (24,000 hr), consistent with guarantees offered by most catalyst vendors, is used. This results in one catalyst cleaning operation prior to catalyst replacement, or the requirement of one cleaning operation every 3 yr (36,000 hr). The annual cost for cleaning based on this schedule is calculated as $0.50/hp plus 10 percent for freight.

A catalyst replacement cost of $10/hp is estimated based on cost information from Reference 5. Using a catalyst replacement schedule of every 3 yr, the annual cost is calculated as $3.33/hp, plus 10 percent for freight.

To date, very little cost information is available for disposal of spent catalyst material because most catalyst applications have not yet replaced existing catalyst material. Most catalyst vendors accept return of spent catalysts, but details of these return policies and associated costs, if any, were not provided. Catalyst disposal costs were estimated at \$15 per cubic foot (\$15/ft^3) by one catalyst vendor for spent zeolite catalyst material. Based on a cost of \$15/ft^3 and an estimated catalyst volume of 0.002 ft^3/hp, the catalyst disposal cost is $0.03/hp.[8,20] The annual cost for disposal, using a 3-yr catalyst life, is $0.01/hp. This cost applies to nonhazardous material disposal, and disposal costs are expected to be higher for spent catalyst material that contains vanadium pentoxide, where this material has been classified as a hazardous waste by State or local agencies.

The operating cost for the ammonia system includes the cost for the ammonia (NH_3) and the energy required for ammonia vaporization and injection. Costs for anhydrous ammonia were used because it is the most common ammonia system. Steam is selected for ammonia vaporization and dilution to a 5 percent ammonia solution by volume for injection. The cost of anhydrous ammonia was estimated at $250/ton.[24] Steam costs were estimated at $6/1,000 lb.[2] Using a NO_x/NH_3 molar ratio of 1.0, the annual costs for ammonia and steam consumption are:

$$\begin{aligned}
\text{Ammonia} &= N \times hp \times hours \times (NH_3\ MW/NO_x\ MW) \times (1\ lb/454\ g) \times \\
&\quad (1\ ton/2000\ lb) \times \$250/ton \\
&= N \times hp \times hours \times 1.01 \times 10^{-4} \text{ and} \\
\text{Steam} &= N \times hp \times hours \times (NH_3\ MW/NO_x\ MW) \times (1\ lb/454\ g) \times \\
&\quad (H_2O\ MW/NH_3\ MW) \times (95/5) \times \$6/1,000\ lb \\
&= N \times hp \times hours \times 9.83 \times 10^{-5}
\end{aligned}$$

where:

N = uncontrolled NO_x emissions, g/hp-hr;
hp = engine horsepower;
hours = annual operating hours;
NH_3 MW = molecular weight of NH_3 = 17.0;
NO_x MW = molecular weight of NO_x = 46.0; and
H_2O MW = molecular weight of H_2O = 18.0.

Taxes, insurance, and administrative costs are charged as shown in Table 6-2, and an emission test cost of $2,440 is included. The capital recovery is calculated as discussed in Section 6.1.2.11.

Based on the above methodology, the total annual costs for SCR are presented in Figure 6-16. As this figure shows, the costs are essentially linear and can be approximated using the following equations:

Operating hours	Total annual cost
8,000	$171,000 + ($49.7 x hp)
6,000	$140,000 + ($40.0 x hp)
2,000	$79,300 + ($20.6 x hp)
500	$56,400 + ($13.3 x hp)

For a 200 hp engine, the total annual costs range from $59,100 for 500 hr/yr to $181,000 for 8,000 hr/yr. For an 11,000 hp engine, the total annual costs range from $203,000 for 500 hr/yr to $717,000 for 8,000 hr/yr.

6.3.4.3 Cost Effectiveness. As discussed in Chapter 5, the achievable NO_x reduction efficiency for SCR is 90 percent, and this figure is used to calculate the effectiveness presented in Figure 6-16. For continuous-duty (8,000 hr/yr) engines, the cost effectiveness ranges from a high of approximately $6,800/ton for engines rated at 200 hp or less and decreases rapidly as engine size increases, to approximately $1,600/ton at 1,000 hp and $500/ton at 11,000 hp.

Cost effectiveness is higher for engines operating less than 8,000 hr/yr, especially for engines under 1,000 hp. For these smaller engines, the cost effectiveness increases rapidly as engine size decreases, especially for engines operating 2,000 hr/yr or less. The cost effectiveness for these engines ranges from approximately $3,000 to $8,500 per ton for 1,000 hp engines and increases to $12,000 to over $35,000 per ton for 200 hp engines. The portion of the cost-effectiveness range from $13,000 to $35,000 per ton is not shown on the plot in Figure 6-16 in order to more clearly present the range of $0 to $10,000 per ton.

6.3.5 Control Costs for Conversion to Low-Emission Combustion

Because the hardware and installation requirements for conversion to low-emission combustion are essentially the same for either rich-burn or lean-burn engines, the capital costs are considered to be same for either engine type. Annual costs are also essentially the same, except that a fuel credit of 3 percent is expected for lean-burn engine conversions, compared to

1 percent for rich-burn engines. This difference in fuel costs is a very minor portion of the total annual costs, and the costs and cost effectiveness presented in Section 6.2.6 are considered to apply for low-emission conversion of either rich-burn or lean-burn engines.

6.4 CONTROL COSTS FOR COMPRESSION IGNITION (CI) ENGINES

The control techniques for diesel and dual-fuel engines are injection timing retard and SCR. For dual-fuel engines, low-emission combustion engine designs are also available from some manufacturers. The cost methodologies for control techniques applied to CI engines are presented in this section.

6.4.1 Control Costs For Injection Timing Retard

6.4.1.1 Capital Costs. It is expected that injection timing retard for a CI engine requires an automated electronic control system similar to ignition timing adjustment for an SI engine. Capital costs, therefore, are estimated on the same basis as ignition retard costs for SI engines, presented in Section 6.2.2.1. The total capital costs for injection timing retard are shown in Figures 6-17 and 6-18 for diesel and dual-fuel engines, respectively.

6.4.1.2 Annual Costs. Annual costs for injection timing retard are calculated using the same methodology as that used for ignition timing retard for SI engines in Section 6.2.2.2. A 3 percent fuel penalty is used for both diesel and dual-fuel engines. The total annual costs for injection timing retard in CI engines are presented in Figures 6-17 and 6-18 for diesel and dual-fuel engines, respectively. The costs are essentially linear and can be estimated by the following equations:

Diesel engines:

Operating hours	Total annual costs
8,000	\$6,150 + (\$9.2 x hp)
6,000	\$5,680 + (\$6.9 x hp)
2,000	\$4,740 + (\$2.5 x hp)
500	\$4,390 + (\$0.8 x hp)

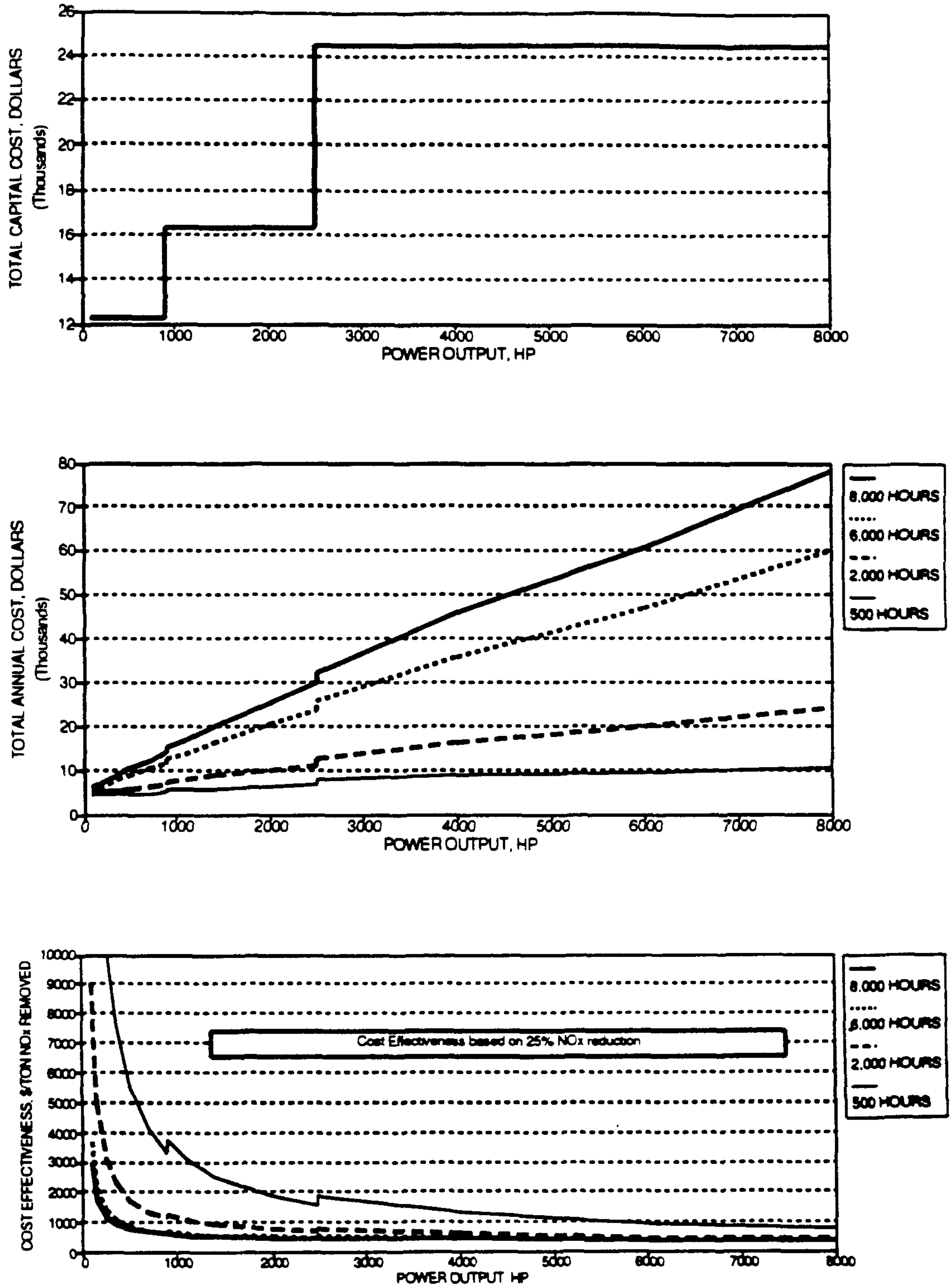


Figure 6-17. Total capital and annual costs and cost effectiveness for injection timing retard in diesel engines, based on installation of an electronic ignition system.

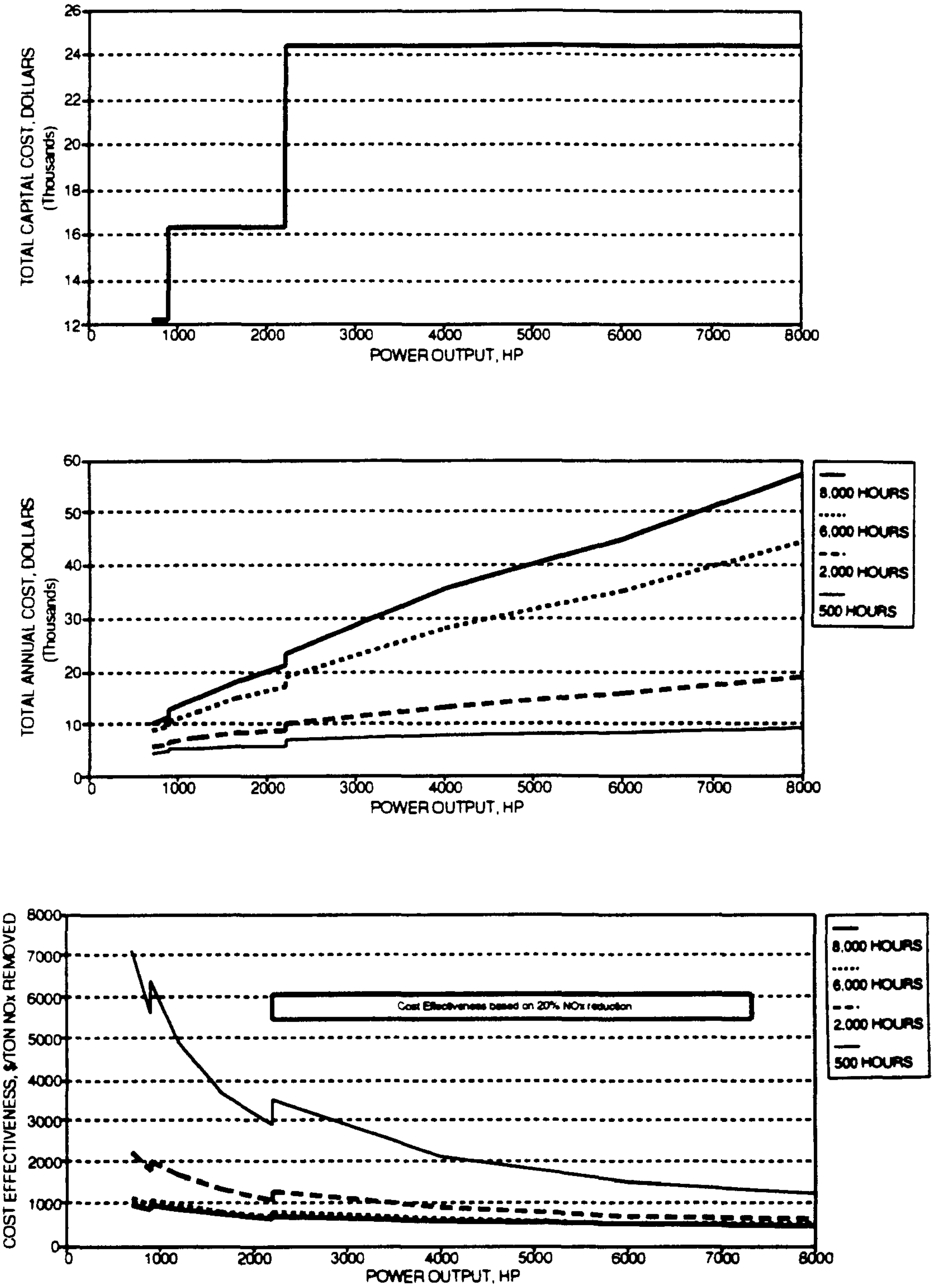


Figure 6-18. Total capital and annual costs and cost effectiveness for injection timing retard in dual-fuel engines, based on installation of an electronic ignition system.

Dual-fuel engines:

Operating hours	Total annual costs
8,000	$7,060 + ($6.4 x hp)
6,000	$6,380 + ($4.9 x hp)
2,000	$5,040 + ($1.8 x hp)
500	$4,530 + ($0.7 x hp)

The total annual costs for an 80 hp diesel engine range from $4,390 for 500 hr/yr to $6,230 for 8,000 hr/yr. For an 8,000 hp diesel engine, the total annual costs range from $10,600 for 500 hr/yr to $77,900 for 8,000 hr/yr. The total annual costs for a 700 hp dual-fuel engine range from $4,650 for 500 hr/yr to $10,300 for 8,000 hr/yr. For an 8,000 hp dual-fuel engine, the total annual costs range from $9,300 for 500 hr/yr to $57,200 for 8,000 hr/yr.

6.4.1.3 Cost Effectiveness. Based on information in Chapter 5, cost effectiveness is calculated for diesel and dual-fuel engines using a NO_x reduction efficiency of 25 and 20 percent, respectively. For diesel engines the cost effectiveness is presented in Figure 6-17 and for continuous-duty diesel engines ranges from a high of approximately $3,000/ton for an 80 hp engine to $375/ton for an 8,000 hp engine. The cost effectiveness drops rapidly and is less than $1,000/ton for continuous-duty diesel engines larger than 300 hp. Cost-effectiveness figures increase as annual operating hours decrease, and for diesel engines operating 500 hr/yr range from over $33,000/ton for an 80 hp engine to as low as $802/ton for an 8,000 hp engine. The cost-effectiveness range from $10,000 to $33,000 per ton is not shown on the plot in Figure 6-17 in order to more clearly present the range of $0 to $10,000 per ton.

For dual-fuel engines, the cost effectiveness is presented in Figure 6-18. For continuous-duty dual-fuel engines, cost effectiveness is $1,000/ton or less for all engines in this study, ranging from a high of approximately $1,000/ton for a 700 hp engine to $500/ton for an 8,000 hp engine. Cost-effectiveness figures increase as annual operating hours decrease, and for diesel engines operating 500 hr/yr range from over $7,100/ton for an 80 hp engine to a low of $1,250/ton for an 8,000 hp engine.

6.4.1.4 Control Costs for Diesel and Dual-Fuel SCR Applications.

6.4.1.5 Capital Costs. Capital cost estimates for diesel and dual-fuel engine SCR applications were provided by two SCR vendors.[23,25] These cost estimates are presented in Figure 6-19. One vendor provided an equation to estimate costs for base-metal catalyst systems; the other vendor's cost estimates are for zeolite catalyst systems and were given as a range, in $/hp. Both vendors said that the costs are for systems that achieve a NO_x reduction efficiency of 90 percent. The capital costs shown in Figure 6-19 include the catalyst, reactor housing and ductwork, ammonia injection system, controls, and engineering and installation of this equipment. The line in this figure is used to represent the installed cost for SCR for either a base-metal or zeolite catalyst, and the equation of this line is given below:

$$\text{Capital costs} = \$22{,}800 + (\$56.4 \times \text{hp})$$

This equation is similar to that for SI engine SCR applications; the lower capital costs for CI engines are expected to be the result of lower exhaust flows and NO_x emission rates for CI engines. It is expected that most SCR installations would require a CEMS, and the additional cost for this is estimated at $85,000, regardless of engine size.[25] The total PEC for SCR with a CEMS can be estimated using the following equation:

$$\text{Purchased equipment cost} = \$108{,}000 + (\$56.4 \times \text{hp})$$

This equation includes installation costs, so the direct and indirect installation factors are reduced to 25 and 20 percent of the PEC, respectively. The contingency factor is 20 percent of

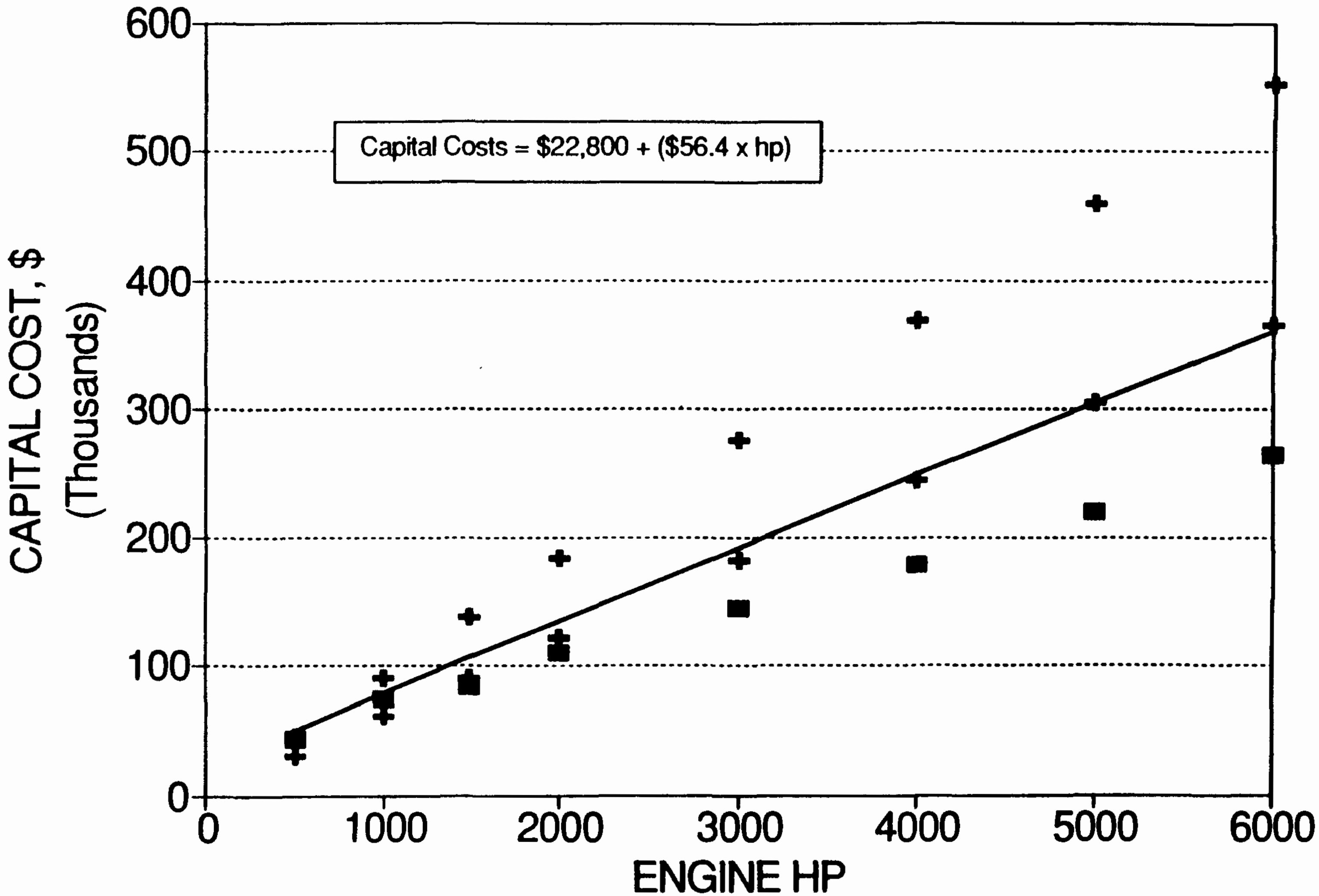


Figure 6-19. Installed capital costs for selective catalytic reduction estimated by catalyst vendors for diesel and dual-fuel engines.[23,25]

the PEC. Sales taxes and freight are assessed as shown in Table 6-1.

Based on the above methodology, the total capital costs for SCR for diesel and dual-fuel engines are presented in Figures 6-20 and 6-21, respectively, and can be estimated by the following equation:

$$\text{Total capital costs} = \$187{,}000 + (\$98 \times \text{hp})$$

The total capital costs for diesel engines range from $195,000 for an 80 hp engine to $967,000 for a 8,000 hp engine. The total capital costs for dual-fuel engines range from $255,000 for a 700 hp engine to $967,000 for a 8,000 hp engine.

6.4.1.6 Annual Costs. The anticipated annual costs associated with SCR include an increase in operating labor and maintenance due to the addition of the ammonia injection and CEMS; an increase in BSFC; catalyst cleaning, replacement, and disposal; an emission compliance test; and capital recovery. The cost methodology used to estimate the costs for operating/supervisory labor, maintenance, ammonia, steam diluent, and fuel penalty are the same as those for SI engines presented in Section 6.3.4.2.

The costs associated with catalyst cleaning, replacement, and disposal are estimated using the same methodology as that presented in Section 6.3.4.2, but the annual costs are reduced to 75 percent of those used for SI engines. The 75 percent figure is approximately the ratio of the capital cost estimate factors of $42/hp to $56/hp used in the purchased equipment equations, and this 75 percent figure is expected to compensate for the reduced catalyst volume required for CI engines. Some base-metal catalyst vendors said that cleaning requirements are more frequent for diesel-fueled applications, and so the cleaning schedule is adjusted from every 12,000 hr used for SI engines to every 8,000 hr. The annual costs for catalyst cleaning, replacement, and disposal for continuous-duty applications were estimated at $0.76/hp, $2.50/hp, and $0.01/hp, respectively, plus

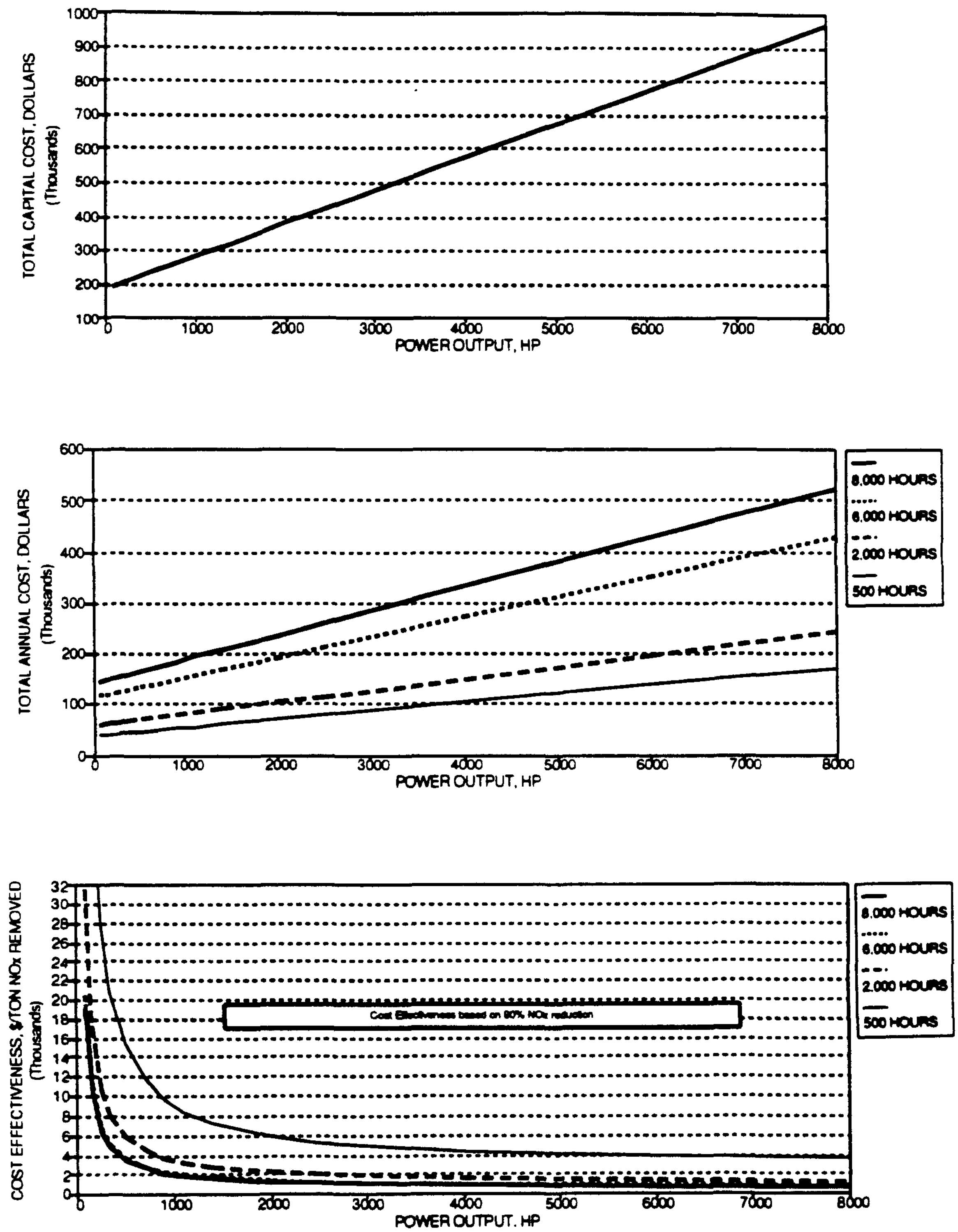


Figure 6-20. Total capital and annual costs and cost effectiveness for selective catalytic reduction for diesel engines, including a continuous emission monitoring system.

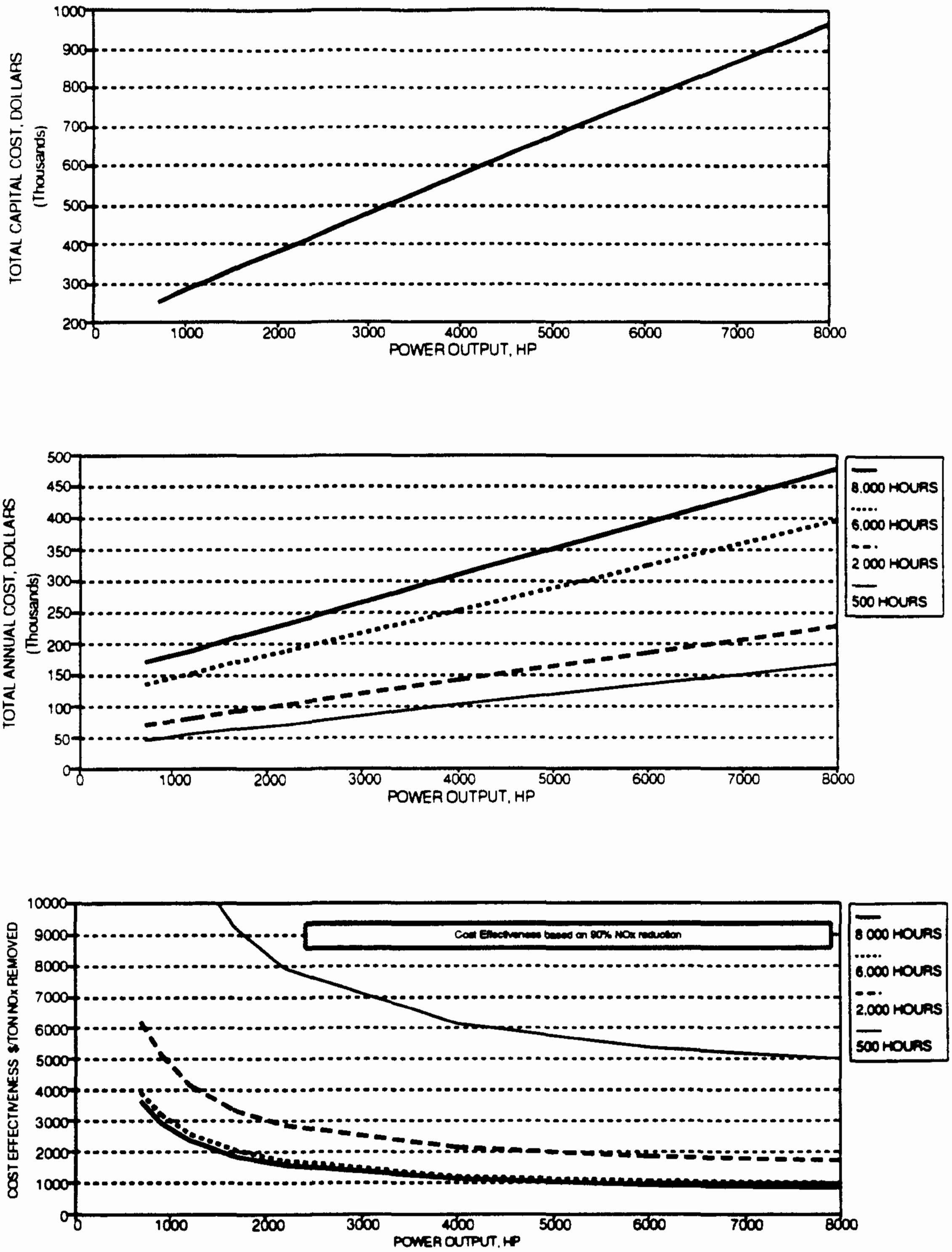


Figure 6-21. Total capital and annual costs and cost effectiveness for selective catalytic reduction for dual-fuel engines, including a continuous emission monitoring system.

10 percent for freight. The disposal cost applies to nonhazardous material disposal, and disposal costs are expected to be higher for spent catalyst material that contains vanadium pentoxide where this material has been classified as a hazardous waste by State or local agencies.

Plant overhead, taxes, insurance, and administrative costs are calculated as described in Section 6.1.3. A cost of $2,440 is included for emission testing, and capital recovery is calculated as discussed in Section 6.1.2.11.

Using this methodology, the total annual costs for diesel engine SCR applications are presented in Figure 6-20 and can be estimated using the following equations:

Operating hours	Total annual cost
8,000	$141,000 + ($47.8 x hp)
6,000	$113,000 + ($39.5 x hp)
2,000	$58,100 + ($22.9 x hp)
500	$37,300 + ($16.7 x hp)

For dual-fuel engines, the total annual costs for SCR applications are presented in Figure 6-21 and can be estimated using the following equations:

Operating hours	Total annual cost
8,000	$141,000 + ($42.1 x hp)
6,000	$113,000 + ($35.2 x hp)
2,000	$58,100 + ($21.5 x hp)
500	$37,300 + ($16.3 x hp)

The total annual costs for an 80 hp diesel engine range from $38,700 for 500 hr/yr to $145,000 for 8,000 hr/yr. For an 8,000 hp diesel engine the total annual costs range from $171,000 for 500 hr/yr to $523,000 for 8,000 hr/yr. The total annual costs for a 700 hp dual-fuel engine range from $48,800 for 500 hr/yr to $170,000 for 8,000 hr/yr. For an 8,000 hp dual-fuel engine, the total annual costs range from $168,000 for 500 hr/yr to $478,000 for 8,000 hr/yr.

6.4.1.7 Cost Effectiveness. Zeolite catalyst vendors guarantee a 90 percent NO_x reduction efficiency for diesel and dual-fuel SCR applications. Base-metal catalyst vendors also offer a 90 percent NO_x reduction efficiency, although some vendors said that cleaning requirements increase for this reduction efficiency over that required for an 80 percent reduction level. A 90 percent NO_x reduction efficiency is used to calculate cost effectiveness in this section.

The cost effectiveness for diesel engines is presented in Figure 6-20 and for continuous-duty diesel engines ranges from a high of over $19,000/ton for an 80 hp engine to less than $700/ton for an 8,000 hp engine. The cost effectiveness drops rapidly and is less than $3,000/ton for continuous-duty diesel engines larger than 600 hp. Cost-effectiveness figures increase as annual operating hours decrease, and for diesel engines operating 500 hr/yr range from over $80,000/ton for an 80 hp engine a low of $3,900/ton for an 8,000 hp engine. The cost-effectiveness range from $32,000 to $82,000 per ton is not shown on the plot in Figure 6-20 in order to more clearly present the range of $0 to $10,000 per ton.

For dual-fuel engines, the cost effectiveness is presented in Figure 6-21. For continuous-duty dual-fuel engines, cost effectiveness ranges from a high of approximately $3,600/ton for a 700 hp engine to approximately $900/ton for an 8,000 hp engine. Cost-effectiveness figures increase as annual operating hours decrease, and for dual-fuel engines operating 500 hr/yr range from over $16,000/ton for an 80 hp engine to a low of $5,000/ton for an 8,000 hp engine. The cost-effectiveness range from $10,000 to $16,000 per ton is not shown on the plot in Figure 6-21 in order to more clearly present the range of $0 to $10,000 per ton.

6.4.2 Control Costs for Conversion to Low-Emission Combustion

Dual-fuel engine manufacturers have developed low-emission engine designs for some dual-fuel engines. These engine designs are relatively new, and limited cost information was available to develop the costs presented in this section.

The hardware and labor requirements to retrofit low-emission combustion to an existing engine are similar in scope to a major engine overhaul. If the low-emission combustion retrofit is scheduled to coincide with a scheduled major engine overhaul, the capital costs and cost-effectiveness figures will be less than those shown in this section.

6.4.2.1 Capital Costs. Capital costs for the hardware to retrofit existing dual-fuel engines to low-emission combustion were available from only one engine manufacturer for one line of engines.[10] No incremental costs for low-emission designs compared to conventional engine costs were available for new installations. The retrofit hardware costs were approximately 30 percent higher than for retrofit of a comparable low-speed, large-bore SI engine. Applying this 30 percent factor to the costs shown in Section 6.2.6.1 results in the following equation:

Retrofit hardware costs = $182,000 + ($200 x hp)

The low-emission design requires higher combustion airflows and an upgraded turbocharger, similar to SI designs. Consistent with the SI engine cost methodology, the retrofit hardware cost is multiplied by 1.3 to cover the cost of replacing the inlet and exhaust systems and aerial cooler. Taxes and freight are assessed as shown in Table 6-1. Direct and indirect installation factors of 25 and 20 percent, respectively, are included, along with a contingency factor of 20 percent. Based on this methodology, the total capital costs for retrofit of existing dual-fuel engines to low-emission combustion are presented in Figure 6-22 and can be estimated by the following equation:

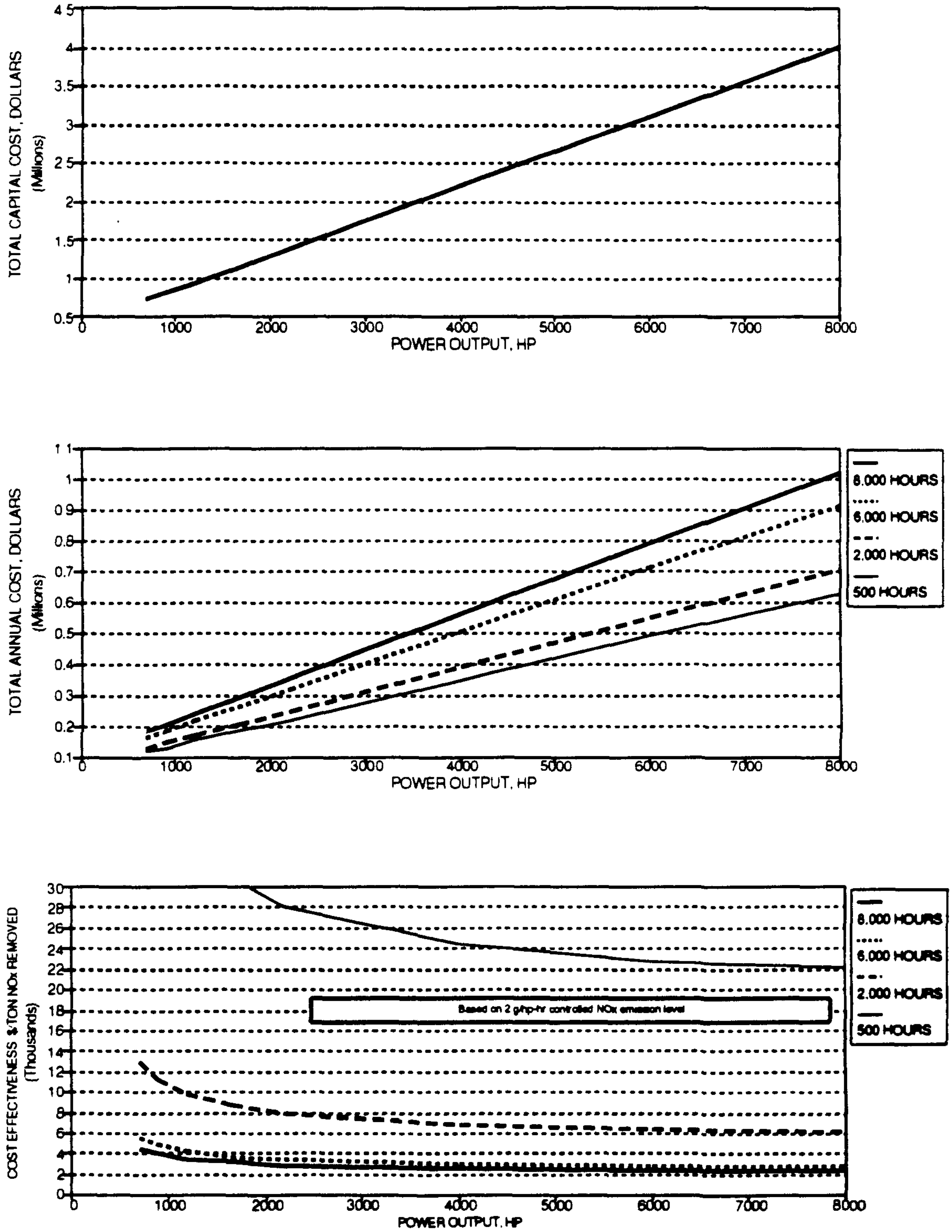


Figure 6-22. Total capital and annual costs and cost effectiveness for retrofit to low-emission combustion for dual-fuel engines.

$$\text{Total capital cost} = \$405{,}000 + (\$450 \times \text{hp})$$

The total capital costs range from $720,000 for a 700 hp engine to $4,000,000 for an 8,000 hp engine.

6.4.2.2 Annual Costs. Annual costs associated with low-emission combustion include maintenance and overhead, fuel consumption, taxes, insurance, administrative costs, and capital recovery. No power reduction results from low-emission combustion, and no increase in operating labor is expected.

Maintenance costs are calculated as 10 percent of the PEC, plus overhead equal to 60 percent of maintenance costs. A fuel penalty of 3 percent is assessed and is calculated based on 100 percent natural gas fuel to simplify the calculation. (Diesel fuel represents only 1 percent of the total fuel consumption.) Plant overhead, taxes, insurance, administrative costs, and capital recovery are calculated as discussed in Section 6.1. An emission test cost of $2,440 is also included. The capital recovery cost is included as discussed in Section 6.1.2.11.

The resultant total annual costs for low-emission combustion for dual-fuel engines are presented in Figure 6-22, and can be estimated by the following equations:

Operating hours	Total annual cost
8,000	$102,000 + ($115 x hp)
6,000	$92,200 + ($103 x hp)
2,000	$72,800 + ($79.3 x hp)
500	$65,500 + ($70.4 x hp)

The total annual costs for a 700 hp dual-fuel engine range from $115,000 for 500 hr/yr to $182,000 for 8,000 hr/yr. For an 8,000 hp dual-fuel engine, the total annual costs range from $628,000 for 500 hr/yr to $1,020,000 for 8,000 hr/yr.

6.4.2.3 Cost Effectiveness. Data presented in Chapter 5 suggests that controlled NO_x emission levels for low-emission dual-fuel engine designs range from 1.0 to 2.0 g/hp-hr. A

2.0 g/hp-hr controlled NO_x emission level is used to calculate cost effectiveness, as presented in Figure 6-22.

For continuous-duty engines (8,000 hr/yr), the cost effectiveness is approximately $4,560/ton for a 700 hp engine and decreases to $2,250/ton for an 8,000 hp engine. The cost effectiveness increases for engines operating less than 8,000 hr/yr, and is $46,100/ton for a 700 hp engine operating 500 hr/yr and $22,100/ton for an 8,000 hp engine operating 500 hr/yr. The cost-effectiveness range from $30,000 to $46,000 per ton is not shown on the plot in Figure 6-22 in order to more clearly present the range of $0 to $10,000 per ton.

6.5 REFERENCES FOR CHAPTER 6

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8. Letter and attachments from Henegan, D., Norton Company, to Snyder, R. B., Midwest Research Institute. March 28, 1991. Catalytic controls for internal combustion engines.

9. Letter and attachments from Stachowicz, R. W., Waukesha Engine Division of Dresser Industries, Inc., to Snyder, R. B., Midwest Research Institute. September 16, 1991. Internal combustion engines.

10. Letter and attachments from Miklos, R. A., Cooper-Bessemer Reciprocating Products Division, to Jordan, B. C., EPA. January 21, 1992. Internal combustion engines.

11. Letter and attachments from Dowdall, D. C., Caterpillar Inc., to Jordan, B. C., EPA. March 25, 1992. Internal combustion engines.

12. Letter and attachments from Iocco, D. E., Dresser-Rand, to Snyder, R. B., Midwest Research Institute. October 1, 1991. Internal combustion engines.

13. Letter and attachments from McCormick, W. M., Cooper Industries - Ajax Superior Division, to Snyder, R. B., Midwest Research Institute. September 16, 1991. Internal combustion engines.

14. Letter and attachments from Fisher, J., Detroit Diesel Corporation, to Neuffer, W., EPA. June 10, 1992. Internal combustion engines.

15. Letter and attachments from Axness, J., Deere Power Systems Group, to Snyder, R., Midwest Research Institute. August 30, 1991. Internal combustion engines.

16. Letter and attachment from Shade, W. N., Ajax-Superior Division of Cooper Industries, to Snyder, R. B., Midwest Research Institute. March 19, 1993. Control techniques and costs for reciprocating engines.

17. Letter and attachment from Dowdall, D. C., Caterpillar Incorporated, to Snyder, R. B., Midwest Research Institute. April 16, 1993. Effect of parametric adjustments on reciprocating engines.

18. Minutes from meeting dated March 4, 1993 with representatives from the Interstate Natural Gas Association of America, U. S. Environmental Protection Agency, and Midwest Research Institute. March 9, 1993. Review of draft reciprocating engine ACT document.

19. Letter and attachments from Mikkelsen, B. L., Emissions Plus, Inc., to Snyder, R. B., Midwest Research Institute. April 8, 1992. Prestratified charge systems for IC engines.

20. Letter from Weeks, M. D., Emission Control Systems, Inc., to Neuffer, W. J., EPA/ISB. November 2, 1992. Review of draft reciprocating engine ACT document.

21. Letter and attachments from Stachowicz, R. W., Waukesha Engine Division of Dresser Industries, Inc., to Cassidy, M. A., Midwest Research Institute. June 14, 1991. Internal combustion engine emissions control.

22. Letter from Wax, M. J., Institute of Clean Air Companies, to Snyder, R. B., Midwest Research Institute. March 16, 1993. Costs for SCR systems applied to reciprocating engines.

23. Letter and attachments from Becquet, J., Kleenaire Division of Encore Environmental Consulting and Remediation, to Snyder, R. B., Midwest Research Institute. March 25, 1993.

24. Minutes of meeting dated February 5, 1992 with representatives of the Industrial Gas Cleaning Institute, U. S. Environmental Protection Agency, and Midwest Research Institute. December 18, 1991. Selective catalytic reduction.

25. Letter from Sparks, J. S., Atlas-Steuler Division of Atlas Minerals and Chemicals, Incorporated, to Snyder, R. B., Midwest Research Institute. March 30, 1993. SCR system information for reciprocating engines.

7.0 ENVIRONMENTAL AND ENERGY IMPACTS

This chapter presents environmental and energy impacts for the NO_x emission control techniques described in Chapter 5. These control techniques are air-to-fuel ratio (A/F) adjustment, ignition timing retard, a combination of A/F adjustment and ignition timing retard, prestratified charge (PSC®), nonselective catalytic reduction (NSCR), selective catalytic reduction (SCR), and conversion to low-emission combustion. The impacts of the control techniques on air pollution, solid waste disposal, and energy consumption are discussed in this chapter.

This chapter is organized in three sections. Section 7.1 presents air pollution impacts; Section 7.2 presents solid waste impacts; and Section 7.3 presents energy consumption impacts.

7.1 AIR POLLUTION

Applying the control techniques discussed in Chapter 5 reduces NO_x emissions from spark-ignited (SI) and compression-ignited (CI) engines. The tables in this section present uncontrolled NO_x emissions, percent NO_x reduction, controlled NO_x emissions, and annual NO_x removed for each control technique. Since the applicable control techniques vary by type of engine, tables in this section are organized by engine type. Furthermore, the tables presented in this section are for continuous-duty engines operating at 8,000 hours per year (hr/yr). Nitrogen oxide emission reductions for engines operating at reduced annual capacity levels would be calculated by prorating the NO_x reductions shown in these tables.

7.1.1 <u>NO_x Emission Reductions for Rich-Burn SI Engines</u>

The available control techniques for rich-burn SI engines (discussed in Section 5.1) are A/F adjustment, ignition timing retard, a combination of A/F adjustment and ignition timing retard, PSC®, NSCR, and low-emission combustion. The achievable NO_x emission reductions for these control techniques are shown in Table 7-1 for rich-burn engines with power outputs ranging from 80 to 8,000 hp. Air-to-fuel ratio adjustment or ignition timing retard results in the lowest (20 percent) NO_x emission reductions, each achieving a reduction in NO_x emissions for engines operating in continuous-duty applications from 2.23 tons/yr for the smallest engine (80 hp) to 222 tons/yr for the largest engine (8,000 hp). The greatest NO_x emission reductions are achieved by NSCR. For a 90 percent NO_x reduction efficiency, NSCR achieves NO_x reductions ranging from 10 tons/yr for the smallest continuous-duty engine (80 hp) to 1,000 tons/yr for the largest continuous-duty engine (8,000 hp).

7.1.2 NO_x Emission Reductions for Lean-Burn SI Engines

The available control techniques for lean-burn SI engines (discussed in Section 5.2) are A/F adjustment, ignition timing retard, a combination of A/F adjustment and ignition timing retard, SCR, and low-emission combustion. Table 7-2 presents the achievable NO_x emission reductions for these control techniques. For lean-burn engines, ignition timing retard results in the lowest (20 percent) NO_x emission reductions. For continuous-duty engines, NO_x reductions range from 3.0 tons/yr for the smallest engine (200 hp) to 118 tons/yr for the largest engine (8,000 hp). For a 90 percent NO_x reduction efficiency, SCR achieves the highest NO_x reductions, ranging from 26.6 tons/yr for the smallest continuous-duty engine (200 hp) to 1,060 tons/yr for the largest continuous-duty engine (8,000 hp).

7.1.3 NO_x Emission Reductions for Diesel CI Engines

The available control techniques for diesel CI engines are ignition timing retard and SCR. These control techniques are discussed in Section 5.3.1. The achievable NO_x reductions are presented in Table 7-3. Ignition timing retard has the lowest NO_x reduction efficiency (25 percent), removing 2.11 tons/yr for the smallest continuous-duty engine (80 hp) to 211 tons/yr for the largest continuous-duty engine (8,000 hp). Selective catalytic reduction provides the greatest NO_x reduction

TABLE 7-1. RICH-BURN SI ENGINES

Power output, HP	Uncontrolled NO_x, tons/yr	Control technique	Percent NO_x reduction	Controlled NO_x, tons/yr	NO_x removed, tons/yr
80	11.1	A/F Adjustment	20	8.9	2.2
80	11.1	IT Retard	20	8.9	2.2
80	11.1	A/F & IT Adjustment	30	7.8	3.3
80	11.1	PSC®	87	1.4	9.7
80	11.1	NSCR	90	1.1	10
80	11.1	Low-Emission Combustion	87	1.4	9.7
150	20.9	IT Retard	20	16.7	4.2
150	20.9	A/F & IT Adjustment	30	14.6	6.3
150	20.9	PSC®	87	2.6	18.2
150	20.9	NSCR	90	2.1	18.8
150	20.9	Low-Emission Combustion	87	2.6	18.2
250	34.8	A/F Adjustment	20	27.8	7.0
250	34.8	IT Retard	20	27.8	7.0
250	34.8	A/F & IT Adjustment	30	24.4	10.4
250	34.8	PSC®	87	4.4	30.4
250	34.8	NSCR	90	3.5	31.3
250	34.8	Low-Emission Combustion	87	4.4	30.4
350	48.7	A/F Adjustment	20	39.0	9.7
350	48.7	IT Retard	20	39.0	9.7
350	48.7	A/F & IT Adjustment	30	34.1	14.6
350	48.7	PSC®	87	6.2	42.6
350	48.7	NSCR	90	4.9	43.9
350	48.7	Low-Emission Combustion	87	6.2	42.6
500	69.6	A/F Adjustment	20	55.7	13.9
500	69.6	IT Retard	20	55.7	13.9
500	69.6	A/F & IT Adjustment	30	48.7	20.9
500	69.6	PSC®	87	8.8	60.8
500	69.6	NSCR	90	7.0	62.6
500	69.6	Low-Emission Combustion	87	8.81	60.8
650	90.5	A/F Adjustment	20	72.4	18.1
650	90.5	IT Retard	20	72.4	18.1
650	90.5	A/F & IT Adjustment	30	63.3	27.1
650	90.5	PSC®	87	11.5	79.0
650	90.5	NSCR	90	9.1	81.4
650	90.5	Low-Emission Combustion	87	11.5	79.0
850	118	A/F Adjustment	20	94.7	23.7
850	118	IT Retard	20	94.7	23.7
850	118	A/F & IT Adjustment	30	82.8	35.5
850	118	PSC®	87	15.0	103
850	118	NSCR	90	11.8	106
850	118	Low-Emission Combustion	87	15.0	103
1200	167	A/F Adjustment	20	134	33.4
1200	167	IT Retard	20	134	33.4
1200	167	A/F & IT Adjustment	30	117	50.1
1200	167	PSC®	87	21.1	146
1200	167	NSCR	90	16.7	150
1200	167	Low-Emission Combustion	87	21.1	146
1600	223	A/F Adjustment	20	178	44.5
1600	223	IT Retard	20	178	44.5
1600	223	A/F & IT Adjustment	30	156	66.8
1600	223	PSC®	87	28.2	195
1600	223	NSCR	90	22.3	200
1600	223	Low-Emission Combustion	87	28.2	195

TABLE 7-1. (continued)

Power output, HP	Uncontrolled NO_x, tons/yr	Control technique	Percent NO_x reduction	Controlled NO_x, tons/yr	NO_x removed, tons/yr
2000	278	A/F Adjustment	20	223	55.7
2000	278	IT Retard	20	223	55.7
2000	278	A/F & IT Adjustment	30	195	83.5
2000	278	PSC®	87	35.2	243
2000	278	NSCR	90	27.8	251
2000	278	Low-Emission Combustion	87	35.2	243
2500	348	A/F Adjustment	20	278	69.6
2500	348	IT Retard	20	278	69.6
2500	348	A/F & IT Adjustment	30	244	104
2500	348	PSC®	87	44.1	304
2500	348	NSCR	90	34.8	313
2500	348	Low-Emission Combustion	87	44.1	304
4000	557	A/F Adjustment	20	445	111
4000	557	IT Retard	20	445	111
4000	557	A/F & IT Adjustment	30	390	167
4000	557	PSC®	87	70.5	486
4000	557	NSCR	90	55.7	501
4000	557	Low-Emission Combustion	87	70.5	486
6000	835	A/F Adjustment	20	668	167
6000	835	IT Retard	20	668	167
6000	835	A/F & IT Adjustment	30	585	251
6000	835	PSC®	87	106	730
6000	835	NSCR	90	83.5	752
6000	835	Low-Emission Combustion	87	106	730
8000	1,110	A/F Adjustment	20	888	222
8000	1,110	IT Retard	20	888	222
8000	1,110	A/F & IT Adjustment	30	777	333
8000	1,110	PSC®	87	141	969
8000	1,110	NSCR	90	111	999
8000	1,110	Low-Emission Combustion	87	141	969

TABLE 7-2. LEAN-BURN SI ENGINES

Power output, HP	Uncontrolled NO_x, tons/yr	Control technique	Percent NO_x reduction	Controlled NO_x, tons/yr	NO_x removed, tons/yr
200	29.6	A/F Adjustment	20	23.7	5.9
200	29.6	IT Retard	10	26.6	3.0
200	29.6	A/F & IT Adjustment	25	22.2	7.4
200	29.6	SCR	90	3.0	26.6
200	29.6	Low-Emission Combustion	88	3.5	26.1
350	51.8	A/F Adjustment	20	41.4	10.4
350	51.8	IT Retard	10	46.6	5.2
350	51.8	A/F & IT Adjustment	25	38.9	13.0
350	51.8	SCR	90	5.2	46.6
350	51.8	Low-Emission Combustion	88	6.2	45.6
550	81.4	A/F Adjustment	20	65.1	16.3
550	81.4	IT Retard	10	73.3	8.1
550	81.4	A/F & IT Adjustment	25	61.1	20.4
550	81.4	SCR	90	8.1	73.3
550	81.4	Low-Emission Combustion	88	9.69	71.7
800	118	A/F Adjustment	20	94.7	23.7
800	118	IT Retard	10	107	11.8
800	118	A/F & IT Adjustment	25	88.8	29.6
800	118	SCR	90	11.8	107
800	118	Low-Emission Combustion	88	14.1	104
1350	200	A/F Adjustment	20	160	40.0
1350	200	IT Retard	10	180	20.0
1350	200	A/F & IT Adjustment	25	150	50.0
1350	200	SCR	90	20.0	180
1350	200	Low-Emission Combustion	88	23.8	176
1550	229	A/F Adjustment	20	184	45.9
1550	229	IT Retard	10	206	22.9
1550	229	A/F & IT Adjustment	25	172	57.4
1550	229	SCR	90	22.9	206
1550	229	Low-Emission Combustion	88	27.3	202
2000	296	A/F Adjustment	20	237	59.2
2000	296	IT Retard	10	266	29.6
2000	296	A/F & IT Adjustment	25	222	74.0
2000	296	SCR	90	29.6	266
2000	296	Low-Emission Combustion	88	35.2	261
2500	370	A/F Adjustment	20	296	74.0
2500	370	IT Retard	10	333	37.0
2500	370	A/F & IT Adjustment	25	278	92.5
2500	370	SCR	90	37.0	333
2500	370	Low-Emission Combustion	88	44.1	326
3500	518	A/F Adjustment	20	414	104
3500	518	IT Retard	10	466	51.8
3500	518	A/F & IT Adjustment	25	389	130
3500	518	SCR	90	51.8	466
3500	518	Low-Emission Combustion	88	61.7	456
5500	814	A/F Adjustment	20	651	163
5500	814	IT Retard	10	733	81.4
5500	814	A/F & IT Adjustment	25	611	204
5500	814	SCR	90	81.4	733
5500	814	Low-Emission Combustion	88	96.9	717
8000	1,180	A/F Adjustment	20	944	236
8000	1,180	IT Retard	10	1,060	118
8000	1,180	A/F & IT Adjustment	25	885	295
8000	1,180	SCR	90	120	1,060
8000	1,180	Low-Emission Combustion	88	141	1,040

TABLE 7-3. NO_x EMISSION REDUCTIONS FOR DIESEL CI ENGINES

Power output, HP	Uncontrolled NO_x, tons/yr	Control technique	Percent NO_x reduction	Controlled NO_x, tons/yr	NO_x removed, tons/yr
80	8.46	IT Retard	25	6.3	2.1
80	8.46	SCR (base metal)	80	1.7	6.8
80	8.46	SCR (zeolite)	90	0.85	7.6
150	15.9	IT Retard	25	11.9	4.0
150	15.9	SCR (base metal)	80	3.2	12.7
150	15.9	SCR (zeolite)	90	1.6	14.3
250	26.4	IT Retard	25	19.8	6.6
250	26.4	SCR (base metal)	80	5.3	21.1
250	26.4	SCR (zeolite)	90	2.6	23.8
350	37.0	IT Retard	25	27.8	9.3
350	37.0	SCR (base metal)	80	7.4	29.6
350	37.0	SCR (zeolite)	90	3.7	33.3
500	52.9	IT Retard	25	39.6	13.2
500	52.9	SCR (base metal)	80	10.6	42.3
500	52.9	SCR (zeolite)	90	5.3	47.6
700	74.0	IT Retard	25	55.5	18.5
700	74.0	SCR (base metal)	80	14.8	59.2
700	74.0	SCR (zeolite)	90	7.4	66.6
900	95.2	IT Retard	25	71.4	23.8
900	95.2	SCR (base metal)	80	19.0	76.1
900	95.2	SCR (zeolite)	90	9.5	85.6
1100	116	IT Retard	25	87.2	29.1
1100	116	SCR (base metal)	80	23.3	93.0
1100	116	SCR (zeolite)	90	11.6	105
1400	148	IT Retard	25	111	37.0
1400	148	SCR (base metal)	80	29.6	118
1400	148	SCR (zeolite)	90	14.8	133
2000	211	IT Retard	25	159	52.9
2000	211	SCR (base metal)	80	42.3	169
2000	211	SCR (zeolite)	90	21.1	190
2500	264	IT Retard	25	198	66.1
2500	264	SCR (base metal)	80	52.9	211
2500	264	SCR (zeolite)	90	26.4	238
4000	423	IT Retard	25	317	106
4000	423	SCR (base metal)	80	84.6	338
4000	423	SCR (zeolite)	90	42.3	381
6000	634	IT Retard	25	476	159
6000	634	SCR (base metal)	80	127	507
6000	634	SCR (zeolite)	90	63.4	571
8000	846	IT Retard	25	634	211
8000	846	SCR (base metal)	80	169	677
8000	846	SCR (zeolite)	90	84.6	761

efficiency (90 percent) for continuous-duty engines and removes from 7.61 tons/yr (for the smallest engine [80 hp]) to 761 tons/yr (for the largest engine [8,000 hp]) of NO_x emissions. Zeolite catalyst vendors quote a 90 percent NO_x reduction efficiency; base-metal catalyst vendors quote either 80 or 90 percent. For this reason, NO_x reduction levels are shown for both 80 and 90 percent in Table 7-3.

7.1.4 NO_x Emission Reductions for Dual-Fuel CI Engines

The available control techniques for dual-fuel engines are ignition timing retard, SCR, and low-emission combustion. These controls are discussed in Section 5.3.2 and are shown in Table 7-4. Ignition timing retard has the lowest NO_x reduction efficiency (20 percent), removing 10.5 tons/yr for the smallest continuous-duty engine (700 hp) to 120 tons/yr for the largest continuous-duty engine (8,000 hp). Selective catalytic reduction has the highest reduction efficiency (90 percent), removing 47.2 tons/yr for the smallest continuous-duty engine (700 hp) to 539 tons/yr for the largest continuous-duty engine (8,000 hp).

7.1.5 Emissions Trade-offs

Control techniques that modify combustion conditions to reduce the amount of NO_x formed may also increase the amounts of CO and unburned HC emissions produced. Also, SCR produces ammonia emissions. These air pollution impacts are discussed in the following two sections.

7.1.5.1 Impacts of Combustion Controls on CO and HC Emissions. As discussed in Chapter 5, reducing NO_x emission levels may increase CO and HC emissions. Table 7-5 shows the effect on CO and HC emissions of various control techniques on all engine types. For rich-burn engines, CO and HC emissions increase for most control techniques used. Emissions of CO increase sharply at fuel-rich A/F's due to the lack of oxygen to fully oxidize the carbon. As the A/F increases toward fuel-lean conditions, excess oxygen is available and CO emissions decrease as essentially all carbon is oxidized to CO_2. Emissions of HC increase at fuel-rich A/F's because insufficient oxygen levels inhibit complete combustion.

TABLE 7-4. DUAL-FUEL CI ENGINES

Power output, HP	Uncontrolled NO_x, tons/yr	Control technique	Percent NO_x reduction	Controlled NO_x, tons/yr	NO_x removed, tons/yr
700	52.4	IT Retard	20	41.9	10.5
700	52.4	SCR	90	5.2	47.2
700	52.4	Low-Emission Combustion	76	12.3	40.1
900	67.4	IT Retard	20	53.9	13.5
900	67.4	SCR	90	6.7	60.7
900	67.4	Low-Emission Combustion	76	15.9	51.5
1650	124	IT Retard	20	98.9	24.7
1650	124	SCR	90	12.4	111
1650	124	Low-Emission Combustion	76	29.1	94.5
2200	165	IT Retard	20	132	33.0
2200	165	SCR	90	16.5	148
2200	165	Low-Emission Combustion	76	38.8	126
3000	225	IT Retard	20	180	44.9
3000	225	SCR	90	22.5	202
3000	225	Low-Emission Combustion	76	52.9	172
5000	374	IT Retard	20	300	74.9
5000	374	SCR	90	37.4	337
5000	374	Low-Emission Combustion	76	88.1	286
8000	599	IT Retard	20	479	120
8000	599	SCR	90	60.0	539
8000	599	Low-Emission Combustion	76	141	458

TABLE 7-5. EFFECTS OF NO_x CONTROL TECHNIQUES ON CO AND HC EMISSIONS

Engine type	Control technique	Effect on CO emissions	Effect on HC emissions
Rich-Burn SI	A/F Adjustment	increase (1 to 33 g/hp-hr)	increase (0.2 to 0.3 g/hp-hr)
	IR Retard	minimal	minimal
	A/F and IR Adjustments	increase[a]	increase[a]
	PSC	increase ($\leq$3.0 g/hp-hr)	increase ($\leq$2.0 g/hp-hr)
	NSCR	increase ($\leq$37 g/hp-hr)[b]	minimal[c] ($\leq$3.3 g/hp-hr)
	Low-Emission Combustion	increase ($\leq$3.5 g/hp-hr)	increase ($\leq$2.0 g/hp-hr)
Lean-Burn SI	A/F Adjustment	minimal	slight increase
	IR Retard	minimal	minimal
	A/F and IR Adjustments	minimal[a]	minimal[a]
	SCR	minimal	minimal
	Low-Emission Combustion	increase ($\leq$3.5 g/hp-hr)	increase ($\leq$2.0 g/hp-hr)
Diesel CI	IR Retard	varied[d]	varied[e]
	SCR	minimal	minimal
Dual-Fuel CI	IR Retard	increase (13 to 23 percent)	increase (6 to 21 percent)
	SCR	minimal	minimal
	Low-Emission Combustion	varied[f]	varied[f]

[a]The increase is expected to be less than that shown for A/F adjustment.
[b]From VCAPCD data base, consistent with 4,500 ppmv CO emission limit.
[c]According to a VCAPCD test report summary.
[d]Ranged from a 13.2 percent decrease to a 10.8 percent increase for limited test results.
[e]Ranged from a 0 to 76.2 percent increase for limited test results.
[f]May be slight increase or decrease, depending on engine model and manufacturer.

Control techniques used on lean-burn engines to reduce NO_x generally have less effect on CO and HC emissions. At fuel-lean A/F's, CO and HC emissions increase slightly as excess oxygen cools combustion temperatures and inhibits complete combustion. While it is unclear what effect ignition timing retard has on CO and HC emissions for diesel engines (see Section 5.3.1.1), SCR has a minimal effect on these emissions. For dual-fuel engines, ignition timing retard increases CO and HC emissions, while SCR has little effect on CO and HC emissions.

As NO_x control techniques increase CO and HC emissions to unacceptable levels, an oxidation catalyst can be used to reduce these emissions. The oxidation catalyst is an add-on control device that reduces CO and HC emissions to CO_2 and H_2O. This reaction is spontaneous in the presence of the catalyst but requires excess oxygen in the exhaust. For this reason, air may need to be injected into the exhaust upstream of the oxidation catalyst for rich-burn engines, especially for rich-burn engines operating with an NSCR system to reduce NO_x emission.

7.1.5.2 <u>Ammonia Emissions from SCR.</u> The SCR process reduces NO_x emissions by injecting ammonia (NH_3) into the flue gas. The ammonia reacts with NO_x in the presence of a catalyst to form water and nitrogen. The NO_x removal efficiency of this process is partially dependent on the NH_3/NO_x ratio. Increasing this ratio reduces NO_x emissions but increases the probability of passing unreacted ammonia through the catalyst unit into the atmosphere (known as ammonia "slip"). Although some ammonia slip is unavoidable because of ammonia injection control limitations and imperfect distribution of the reacting gases, a properly designed SCR system will limit ammonia slip to less than 10 ppmv for base-load applications. Ammonia injection controls for variable-load applications have limited experience to date, and ammonia slip levels may be higher for variable or cyclical-load applications.[1]

7.2 SOLID WASTE DISPOSAL

Catalytic materials used in SCR and NSCR systems have a finite life, and the spent catalyst material must be disposed of or recycled. Most catalyst suppliers accept return of spent catalyst materials.[1]

While spent precious metal and zeolite catalysts are not considered hazardous waste, it has been argued that vanadium- and titanium-based catalysts are classified as hazardous waste and therefore must be handled and disposed of in accordance with hazardous waste regulations. According to the Best Demonstrated Available Technology (BDAT) Treatment Standards for Vanadium P119 and P120, spent catalysts containing vanadium pentoxide are not classified as hazardous waste.[2]

State and local agencies are authorized to establish their own hazardous waste classification criteria, however, and spent catalyst material may be classified as a hazardous material in some areas. For example, the State of California has reportedly classified spent catalyst material containing vanadium pentoxide as a hazardous waste.[3]

7.3 ENERGY CONSUMPTION

Fuel consumption increases as a result of some control techniques used to reduce NO_x emissions. In particular, those techniques that adjust operating or combustion parameters often increase BSFC. These increased fuel consumptions, where applicable, are discussed in Chapter 5 and are summarized in Table 7-6.

Some control techniques may reduce the power engine output due to lower fuel input to the engine caused by lean A/F's, or increased backpressure on the engine caused by placement of a catalyst in the exhaust. Although this reduction in power output produces lower NO_x emissions for the plant, the lost power must be produced by another source, such as a utility. Increased NO_x emissions may result at these alternative power sources. These reductions in power output, where applicable, are discussed in Chapter 5 and are summarized in Table 7-6.

TABLE 7-6. EFFECTS OF NO_x CONTROL TECHNIQUES ON FUEL CONSUMPTION AND POWER OUTPUT

Engine type	Control technique	Fuel consumption	Effect on power output[a]
Rich-burn SI	A/F Adjustment	0-5 percent increase	none[b]
	IR Retard	0-7 percent increase	none[b]
	A/F and IR Adjustments	0-7 percent increase	minimal[c]
	PSC	2 percent increase	5-20 percent reduction
	NSCR	0-5 percent increase	1-2 percent reduction[d]
	Low-Emission Combustion	variable[e]	none
Lean-burn SI	A/F Adjustment	0-5 percent increase	none[b]
	IR Retard	0-5 percent increase	none[b]
	A/F and IR Adjustments	0-5 percent increase	minimal[c]
	SCR	0.5 percent increase	1-2 percent reduction
	Low-Emission Combustion	variable[e]	none
Diesel CI	IR Retard	0-5 percent increase	none[b]
	SCR	0.5 percent increase	1-2 percent reduction
Dual Fuel CI	IR Retard	0-3 percent increase	none[b]
	SCR	0.5 percent increase	1-2 percent reduction
	Low-Emission Combustion	0-3 percent increase	none

[a]At rated load.
[b]Severe adjustment or retard may reduce power output.
[c]One source reported a 5 percent power reduction at rated load (Reference 4).
[d]Power reduction associated with backpressure on the engine created by a catalyst. Fuel-rich adjustment for NSCR operation may offset this power reduction.
[e]In most engines, the effect is a decrease in fuel consumption of 0-5 percent.

Furthermore, for SCR units, additional electrical energy is required to operate ammonia pumps and ventilation fans. This energy requirement, however, is believed to be small and is not included in this analysis.

7.4 REFERENCES FOR CHAPTER 7

1. Letter and attachments from Smith, J. C., Institute of Clean Air Companies, to Neuffer, W. J., EPA/ISB. May 14, 1992. Use of catalyst systems with stationary combustion sources.

2. 55 FR 22576. June 1, 1990.

3. M. Schorr. NO_x Control for Gas Turbines: Regulations and Technology. General Electric Company, Schenectady, NY. Presented at the Council of Industrial Boiler Owners NO_x Control IV Conference, February 11-12, 1991. pp. 3-5.

4. Letter from Eichamer, P. D., Exxon Chemical Company, Baytown, TX, to Snyder, R. B., Midwest Research Institute. June 24, 1992. Engine adjustments for NO_x control.

APPENDIX A

This appendix contains a summary of emission tests conducted on reciprocating engines in Ventura County, California. The summary was compiled from a data base provided by the Ventura County Air Pollution Control District (VCAPCD).[1] The data are tabled by control technique as follows:

Table A-1:	Prestratified charge (PSC®);
Table A-2:	Nonselective catalytic reduction (NSCR);
Table A-3:	Low-emission combustion, rich-burn engines;
Table A-4:	Low-emission combustion, lean-burn engines; and
Table A-5:	Selective catalytic reduction (SCR).

An explanation of the table entries and abbreviations is given below:

Engine No.:	Each engine is given a specific number, assigned by VCAPCD.
Test No.:	For those tables in which this column appears, this number corresponds to the number of emission tests performed on the engine. This number was added to the data base provided by VCAPCD.
Manufacturer:	The engine manufacturer as listed in the data base.
Model:	The engine model as listed in the data base.
Test date:	Date of the test as listed in the data base.
Status:	The status of the engine, as listed in the data base. The key for this column is:

c- controlled and currently operating (at the time the database was received)

d- deleted, removed from service

e- exempt from Rule 74.9

m- deleted, but electrified in Southern California Edison's incentive program

s- standby

Emissions: Emission levels, as reported in the database in ppmv, referenced to 15 percent oxygen.

TABLE A-1 VENTURA COUNTY APCD EMISSION DATABASE FOR PSC CONTROL FOR IC ENGINES.

						Emissions, ppmv at 15 percent oxygen						
						NOx		Percent	CO		NMHC	
Engine No	Manufacturer	Model	Power (hp)	Test date	Status	PSC Off	PSC On	reduction	PSC Off	PSC On	PSC Off	PSC On
1	Waukesha	140GZ	116	12/21/86		840	24	97	NA	77	NA	89
2	Caterpillar	G379	330	06/27/89	c	0	24	0	NA	135	NA	40
2	Caterpillar	G379	330	07/29/92	c	0	37	0	NA	197	NA	204
2	Caterpillar	G379	330	12/12/91	c	954	63	93	NA	122	NA	9
3	Caterpillar	G379	330	03/23/87	c	14	14	0	NA	231	NA	56
3	Caterpillar	G379	330	07/29/92	c	0	29	0	NA	212	NA	180
3	Caterpillar	G379	330	06/27/89	c	0	42	0	NA	192	NA	64
3	Caterpillar	G379	330	11/24/86	c	44	44	0	NA	193	NA	102
4	Caterpillar	G379	330	06/27/89	c	0	43	0	NA	139	NA	26
4	Caterpillar	G379	330	07/29/92	c	0	33	0	NA	161	NA	325
4	Caterpillar	G379	330	05/15/90	c	0	39	0	NA	179	NA	0
4	Caterpillar	G379	330	12/12/91	c	852	66	92	NA	108	NA	4
4	Caterpillar	G379	330	03/03/88	c	14	14	0	NA	166	NA	63
4	Caterpillar	G379	330	03/23/87	c	23	23	0	NA	172	NA	22
5	Waukesha	P9390G	800	06/27/89	c	0	43	0	NA	63	NA	76
5	Waukesha	P9390G	800	10/20/87	c	44	44	0	NA	114	NA	18
5	Waukesha	P9390G	800	07/30/92	c	0	23	0	NA	143	NA	11
6	Waukesha	P9390G	800	06/27/89	c	0	19	0	NA	89	NA	18
6	Waukesha	P9390G	800	07/30/92	c	0	33	0	NA	145	NA	15
7	Waukesha	P9390G	800	05/15/90	c	0	20	0	NA	118	NA	0
7	Waukesha	P9390G	800	06/27/89	c	0	22	0	NA	84	NA	13
7	Waukesha	P9390G	796	12/29/87	c	39	39	0	NA	180	NA	21
7	Waukesha	P9390G	800	07/30/92	c	0	29	0	NA	133	NA	9
7	Waukesha	P9390G	796	03/24/87	c	845	50	94	NA	141	NA	17
8	Ingersoll-Rand	XVG	300	09/20/89	c	814	45	94	NA	77	NA	0
8	Ingersoll-Rand	XVG	300	07/17/90	c	814	52	94	NA	96	NA	0
8	Ingersoll-Rand	XVG	300	12/21/88	c	67	67	0	NA	96	NA	24
8	Ingersoll-Rand	XVG	300	03/20/90	c	814	31	96	NA	128	NA	0
8	Ingersoll-Rand	XVG	300	09/14/88	c	26	26	0	NA	62	NA	0
8	Ingersoll-Rand	XVG	300	12/13/89	c	814	67	92	NA	76	NA	0
8	Ingersoll-Rand	XVG	300	09/24/91	c	814	14	98	NA	96	NA	0
8	Ingersoll-Rand	XVG	300	12/03/91	c	814	72	91	NA	86	NA	0
8	Ingersoll-Rand	XVG	300	04/18/88	c	79	79	0	NA	28	NA	0
8	Ingersoll-Rand	XVG	300	05/24/88	c	17	17	0	NA	72	NA	0
8	Ingersoll-Rand	XVG	300	05/17/89	c	814	44	95	NA	0	NA	0
8	Ingersoll-Rand	XVG	300	02/22/89	c	814	20	98	NA	0	NA	0
9	Ingersoll-Rand	XVG	300	07/17/90	c	1429	45	97	NA	129	NA	0
9	Ingersoll-Rand	XVG	300	12/21/88	c	53	53	0	NA	100	NA	7
9	Ingersoll-Rand	XVG	300	09/20/89	c	1429	37	97	NA	120	NA	0
9	Ingersoll-Rand	XVG	300	04/15/88	c	79	79	0	NA	43	NA	0
9	Ingersoll-Rand	XVG	300	02/22/89	c	1429	34	98	NA	0	NA	0
9	Ingersoll-Rand	XVG	300	05/17/89	c	1429	58	96	NA	0	NA	0
9	Ingersoll-Rand	XVG	300	12/03/91	c	1429	97	93	NA	279	NA	0
9	Ingersoll-Rand	XVG	300	09/24/91	c	1429	46	97	NA	191	NA	0
9	Ingersoll-Rand	XVG	300	05/24/88	c	41	41	0	NA	47	NA	0
9	Ingersoll-Rand	XVG	300	12/13/89	c	1429	77	95	NA	82	NA	0
9	Ingersoll-Rand	XVG	300	09/14/88	c	10	10	0	NA	70	NA	0
10	Ingersoll-Rand	XVG	300	09/14/88	c	21	21	0	NA	70	NA	0
10	Ingersoll-Rand	XVG	300	12/21/88	c	34	34	0	NA	87	NA	14
10	Ingersoll-Rand	XVG	300	04/18/88	c	68	68	0	NA	49	NA	0
10	Ingersoll-Rand	XVG	300	05/17/89	c	1090	22	98	NA	0	NA	0
10	Ingersoll-Rand	XVG	300	05/24/88	c	81	81	0	NA	43	NA	0
10	Ingersoll-Rand	XVG	300	02/22/89	c	1090	26	98	NA	0	NA	0
10	Ingersoll-Rand	XVG	300	09/20/89	c	1090	66	94	NA	66	NA	0
11	Ingersoll-Rand	XVG	300	07/17/90	c	991	93	90	NA	116	NA	0
11	Ingersoll-Rand	XVG	300	03/19/90	c	991	19	98	NA	106	NA	0
11	Ingersoll-Rand	XVG	300	12/03/91	c	991	50	95	NA	170	NA	0
11	Ingersoll-Rand	XVG	300	09/24/91	c	991	62	94	NA	109	NA	0
12	Ingersoll-Rand	SVG-8	440	05/24/88	c	69	69	0	NA	69	NA	0
12	Ingersoll-Rand	SVG-8	440	12/21/88	c	78	78	0	NA	80	NA	36
12	Ingersoll-Rand	SVG-8	440	02/22/89	c	1261	67	95	NA	0	NA	0
12	Ingersoll-Rand	SVG-8	440	09/20/89	c	1261	87	93	NA	63	NA	0
12	Ingersoll-Rand	SVG-8	440	05/18/89	c	1261	94	93	NA	0	NA	0
12	Ingersoll-Rand	SVG-8	440	04/15/88	c	86	86	0	NA	76	NA	0
12	Ingersoll-Rand	SVG-8	440	09/14/88	c	70	70	0	NA	89	NA	0
13	Caterpillar	G398	412	06/17/90	c	0	74	0	NA	1087	NA	229
13	Caterpillar	G398	412	03/03/89	c	677	43	94	NA	307	NA	66
13	Caterpillar	G398	412	10/19/90	c	0	21	0	NA	405	NA	33
13	Caterpillar	G398	412	12/19/91	c	0	40	0	NA	1566	NA	15
13	Caterpillar	G398	412	01/30/89	c	787	46	94	NA	197	NA	0
13	Caterpillar	G398	412	12/28/87	c	492	45	91	NA	293	NA	385
14	Waukesha	F817GU	190	12/01/88	c	30	30	0	NA	209	NA	14
14	Waukesha	F817GU	190	12/10/87	c	27	27	0	NA	164	NA	51
14	Waukesha	F817GU	190	01/09/92	c	0	25	0	NA	176	NA	4
14	Waukesha	F817GU	190	12/13/89	c	0	39	0	NA	238	NA	16
15	Waukesha	F817GU	190	12/13/89	c	0	45	0	NA	247	NA	16
15	Waukesha	F817GU	190	01/09/92	c	0	37	0	NA	224	NA	5
15	Waukesha	F817GU	190	12/01/88	c	41	41	0	NA	189	NA	9
16	Waukesha	145GZU	100	10/14/88		24	24	0	NA	18774	NA	98

TABLE A-2. VENTURA COUNTY APCD EMISSION DATABASE FOR NSCR CONTROL FOR IC ENGINES.

Engine No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at to 15 percent oxygen NOx Uncontr.	Contr.	Percent reduction	CO	NMHC
2	Ingersoll-Rand	JVG-6	165	03/04/88	c	457	29	94	2087	28
3	Ingersoll-Rand	JVG-8	225	12/10/87	c	564	32	94	2455	24
5	Caterpillar	G379	295	12/10/87	c	786	31	96	1061	53
15	Caterpillar	G3306	67	12/11/89	c	393	23	94	5241	22
16	Waukesha	F3521G	391	06/11/90	c	495	22	96	3402	23
16	Waukesha	F3521G	391	12/11/89	c	174	4	98	11045	30
39	Caterpillar	G353	250	03/27/92	c	0	29	0	65	0
81	Waukesha	L7042G	858	02/04/87	c	1074	16	99	2819	4
81	Waukesha	L7042G	858	05/27/87	c	691	18	97	433	0
81	Waukesha	L7042G	775	10/19/87	c	635	1	100	3469	0
81	Waukesha	L7042G	775	12/08/87	c	769	16	98	132	0
81	Waukesha	L7042G	775	03/22/88	c	2563	56	98	201	0
81	Waukesha	L7042G	858	06/29/88	c	1231	61	95	1359	0
81	Waukesha	L7042G	775	03/30/89	c	591	16	99	1574	0
81	Waukesha	L7042G	775	06/05/89	c	448	8	96	2712	0
81	Waukesha	L7042G	775	09/13/89	c	458	21	95	3269	0
81	Waukesha	L7042G	775	12/12/89	c	513	5	99	2848	0
81	Waukesha	L7042G	775	03/05/90	c	565	38	93	1796	0
81	Waukesha	L7042G	775	04/09/90	c	425	6	99	3906	0
83	Waukesha	L7042G	858	03/10/87	c	618	43	93	2079	0
83	Waukesha	L7042G	858	05/27/87	c	583	45	92	886	0
83	Waukesha	L7042G	775	09/22/87	c	630	53	92	2158	0
83	Waukesha	L7042G	775	12/08/87	c	764	50	94	859	0
83	Waukesha	L7042G	775	03/22/88	c	2417	166	93	158	0
83	Waukesha	L7042G	858	06/29/88	c	2257	197	91	617	0
83	Waukesha	L7042G	775	03/30/89	c	71	10	87	11834	0
83	Waukesha	L7042G	775	06/05/89	c	52	4	92	11589	0
83	Waukesha	L7042G	775	09/13/89	c	626	5	99	403	0
83	Waukesha	L7042G	775	12/12/89	c	619	67	89	993	0
83	Waukesha	L7042G	775	03/09/90	c	640	46	93	1045	0
83	Waukesha	L7042G	775	06/19/92	c	0	3	0	2003	185
84	Waukesha	L7042G	513	02/24/87	c	970	8	99	4165	12
84	Waukesha	L7042G	858	05/29/87	c	839	3	100	57	0
84	Waukesha	L7042G	775	09/22/87	c	620	20	97	1347	0
84	Waukesha	L7042G	775	12/08/87	c	694	22	97	777	0
84	Waukesha	L7042G	775	03/22/88	c	2147	43	98	1838	0
84	Waukesha	L7042G	775	06/29/88	c	2338	45	98	2143	0
84	Waukesha	L7042G	775	03/31/89	c	495	21	96	492	0
84	Waukesha	L7042G	775	06/05/89	c	337	11	97	5968	0
84	Waukesha	L7042G	775	09/14/89	c	363	12	97	4946	0
84	Waukesha	L7042G	775	12/28/89	c	372	17	96	4797	0
84	Waukesha	L7042G	775	03/05/90	c	442	9	98	5282	0
84	Waukesha	L7042G	775	04/09/90	c	360	20	94	4359	0
84	Waukesha	L7042G	775	06/06/90	c	407	13	97	1412	0
85	Waukesha	L7042G	858	02/09/87	c	1204	5	100	3247	21
85	Waukesha	L7042G	858	05/29/87	c	691	11	98	1080	0
85	Waukesha	L7042G	775	09/22/87	c	576	15	97	1141	0
85	Waukesha	L7042G	775	12/08/87	c	714	6	99	111	0
85	Waukesha	L7042G	775	03/22/88	c	2432	150	94	1135	0
85	Waukesha	L7042G	775	06/29/88	c	2189	28	99	2517	0
85	Waukesha	L7042G	775	03/31/89	c	252	12	95	6411	0
85	Waukesha	L7042G	775	06/05/89	c	210	5	97	8113	0
85	Waukesha	L7042G	775	09/14/89	c	185	2	99	8453	0
85	Waukesha	L7042G	775	12/28/89	c	254	4	98	7240	0
85	Waukesha	L7042G	775	03/05/90	c	243	15	94	9624	0
85	Waukesha	L7042G	775	04/09/90	c	565	44	91	734	0
85	Waukesha	L7042G	775	06/19/92	c	0	19	0	1988	694
87	Waukesha	L7042G	775	03/31/89	c	144	3	98	9772	0
87	Waukesha	L7042G	775	06/19/92	c	0	32	0	2922	341
87	Waukesha	L7042G	858	05/29/87	c	333	27	92	6085	0
87	Waukesha	L7042G	775	06/06/90	c	0	15	92	1412	0

TABLE A-2. VENTURA COUNTY APCD EMISSION DATABASE FOR NSCR CONTROL FOR IC ENGINES.

Engine No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at to 15 percent oxygen NOx Uncontr.	Contr.	Percent reduction	CO	NMHC
87	Waukesha	L7042G	858	06/29/88	c	780	37	95	8396	0
87	Waukesha	L7042G	775	06/05/89	c	116	6	95	11607	0
87	Waukesha	L7042G	775	09/14/89	c	103	5	95	10784	0
87	Waukesha	L7042G	775	12/28/89	c	127	11	91	12472	0
87	Waukesha	L7042G	775	03/22/88	c	717	57	92	7517	0
87	Waukesha	L7042G	775	09/22/87	c	280	18	94	10825	0
87	Waukesha	L7042G	775	03/09/90	c	560	47	91	2124	0
87	Waukesha	L7042G	858	03/10/87	c	235	11	95	9662	0
87	Waukesha	L7042G	775	12/08/87	c	255	23	91	7488	0
87	Waukesha	L7042G	775	04/09/90	c	498	21	96	3098	0
87	Waukesha	L7042G	775	06/29/88	c	780	37	95	8396	0
90	Waukesha	L7042G	775	12/08/87	c	766	17	98	224	0
90	Waukesha	L7042G	775	06/29/88	c	2114	30	99	703	0
90	Waukesha	L7042G	775	03/22/88	c	2094	35	98	1085	0
90	Waukesha	L7042G	775	09/22/87	c	531	8	99	2822	0
90	Waukesha	L7042G	775	06/19/92	c	0	10	0	795	308
90	Waukesha	L7042G	858	03/10/87	c	345	38	89	6686	0
90	Waukesha	L7042G	775	06/05/89	c	380	7	98	5764	0
90	Waukesha	L7042G	775	03/09/90	c	410	11	97	6253	0
90	Waukesha	L7042G	775	03/09/90	c	699	17	97	713	0
90	Waukesha	L7042G	858	05/28/87	c	677	2	100	606	0
90	Waukesha	L7042G	775	09/13/89	c	285	10	96	5342	0
90	Waukesha	L7042G	775	03/31/89	c	394	6	98	5503	0
90	Waukesha	L7042G	858	06/29/88	c	2114	30	99	703	0
90	Waukesha	L7042G	775	12/12/89	c	439	7	99	2549	0
122	Minneapolis-Mol	800-6A	80	07/13/92	c	0	13	0	56	29
123	Minneapolis-Mol	800-6A	80	06/23/92	c	0	6	0	565	1
130	Caterpillar	G342	225	07/28/92	c	395	1	100	3183	31
130	Caterpillar	G342	225	12/19/87	c	436	2	100	4991	26
130	Caterpillar	G342	225	08/09/90	c	566	15	97	2114	11
130	Caterpillar	G342	225	10/04/89	c	618	17	97	910	0
130	Caterpillar	G342	225	08/03/88	c	443	13	97	0	0
153	White Superior	G-8258	625	12/04/86	c	497	22	96	3883	6
153	White	G-8258	625	03/23/89	c	268	8	97	6708	0
153	White Superior	G-8258	625	08/03/88	c	248	2	99	0	0
153	White	G-8258	625	08/09/90	c	1765	2	100	1458	9
153	White Superior	G-8258	625	10/19/87	c	108	12	89	0	0
153	White	G-8258	625	07/28/92	c	362	12	97	2588	7
153	White	G-8258	625	08/15/90	c	1052	1	100	2599	8
153	White	G-8258	625	10/02/89	c	451	46	90	4057	5
156	White Superior	G-8258	625	08/03/88	c	507	36	93	0	0
156	White Superior	G-8258	625	10/19/87	c	324	38	88	0	0
156	White	G-8258	625	08/09/90	c	333	35	89	2250	10
156	White	G-8258	625	07/28/92	c	666	18	97	3682	4
156	White	G-8258	625	10/02/89	c	390	39	90	3799	6
156	White Superior	G-8258	625	12/04/86	c	478	19	96	3954	5
206	Waukesha	L7042G	1250	12/01/87	c	572	39	93	3566	37
206	Waukesha	L7042G	1250	02/22/88	c	2005	114	94	0	0
206	Waukesha	L7042G	1250	08/06/90	c	554	31	94	2244	22
206	Waukesha	L7042G	1250	07/29/92	c	694	44	94	748	24
206	Waukesha	L7042G	1250	10/06/89	c	613	44	93	3681	29
206	Waukesha	L7042G	1250	08/02/88	c	318	26	92	0	0
206	Waukesha	L7042G	1250	03/22/89	c	215	40	81	0	0
207	Waukesha	L7042G	1250	07/29/92	c	497	18	96	902	33
207	Waukesha	L7042G	1250	08/06/90	c	676	62	91	3980	38
207	Waukesha	L7042G	1250	08/01/88	c	426	28	93	0	0
207	Waukesha	L7042G	1250	10/07/89	c	564	42	93	3808	21
207	Waukesha	L7042G	1250	12/11/87	c	711	23	97	3118	38
207	Waukesha	L7042G	1250	02/22/88	c	1799	84	95	0	0
208	Waukesha	L7042G	1250	02/22/88	c	635	56	91	0	0
208	Waukesha	L7042G	1250	03/23/89	c	845	49	94	1260	0

TABLE A-2. VENTURA COUNTY APCD EMISSION DATABASE FOR NSCR CONTROL FOR IC ENGINES.

Engine No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at to 15 percent oxygen NOx Uncontr.	Contr.	Percent reduction	CO	NMHC
208	Waukesha	L7042G	1250	08/02/88	c	841	12	99	0	0
208	Waukesha	L7042G	1250	12/01/87	c	67	7	90	10669	87
208	Waukesha	L7042G	1250	07/29/92	c	598	30	95	3544	30
208	Waukesha	L7042G	1250	08/06/90	c	793	18	98	712	22
233	Waukesha	F1197G	186	05/22/90	c	684	45	93	408	105
233	Waukesha	H2476G	186	09/19/89	c	655	38	94	1357	167
233	Waukesha	F1197G	186	03/10/92	c	660	41	94	948	0
234	Waukesha	F1197G	186	05/22/90	c	647	17	97	1224	122
234	Waukesha	F1197G	186	03/11/92	c	612	37	94	862	0
234	Waukesha	H2476G	186	09/19/89	c	714	46	94	537	137
239	Caterpillar	G398	412	07/06/89	c	0	8	0	585	13
239	Caterpillar	G398	412	05/11/90	c	0	25	0	1375	0
240	Caterpillar	G398	412	04/26/88	c	475	31	94	4398	64
240	Caterpillar	G398	412	12/19/91	c	591	26	96	2238	48
240	Caterpillar	G398	412	05/11/90	c	0	37	0	232	0
240	Caterpillar	G398	412	12/07/90	c	0	24	0	1063	17
241	Caterpillar	G398	412	04/26/88	c	271	37	86	8662	0
241	Caterpillar	G398	412	12/19/91	c	617	39	94	988	31
241	Caterpillar	G398	412	10/19/90	c	0	20	0	3038	89
241	Caterpillar	G398	412	05/11/90	c	0	18	0	836	0
241	Caterpillar	G398	412	07/27/88	c	628	17	97	2273	0
294	Waukesha	L5790G	738	11/14/88	c	164	3	98	5111	0
294	Waukesha	L5790G	738	06/20/90	c	224	6	98	5504	0
294	Waukesha	L5790G	738	09/18/87	c	183	3	98	2199	3
294	Waukesha	L5790G	738	11/17/89	c	415	2	100	2879	0
294	Waukesha	L5790G	738	08/31/89	c	328	12	97	2677	14
294	Waukesha	L5790G	738	06/23/88	c	245	1	100	1074	0
294	Waukesha	L5790G	738	01/15/88	c	479	1	100	6976	0
294	Waukesha	L5790G	738	12/02/91	c	0	17	0	1954	0
294	Waukesha	L5790G	738	03/11/92	c	0	65	0	1892	50
294	Waukesha	L5790G	738	09/09/88	c	102	1	99	5187	0
294	Waukesha	L5790G	738	06/21/89	c	592	3	99	8998	0
303	Waukesha	F1197G	150	06/19/89	c	102	11	87	5542	0
303	Waukesha	F1197G	150	06/05/92	c	0	27	0	809	142
303	Waukesha	F1197G	150	12/10/91	c	0	18	0	1797	9
303	Waukesha	F1197G	150	11/30/89	c	271	15	94	3946	26
303	Waukesha	F1197G	150	05/21/90	c	201	31	85	4435	0
303	Waukesha	F1197G	150	10/28/86	c	351	17	95	2740	7
303	Waukesha	F1197G	150	02/19/87	c	35	20	43	14333	0
303	Waukesha	F1197G	150	09/30/87	c	221	13	94	1629	0
303	Waukesha	F1197G	150	02/14/89	c	168	7	96	12305	0
303	Waukesha	F1197G	150	06/29/90	c	194	31	84	3535	0
303	Waukesha	F1197G	150	09/08/88	c	76	35	54	14102	0
303	Waukesha	F1197G	150	03/18/88	c	141	13	91	9970	0
303	Waukesha	F1197G	150	09/08/89	c	205	5	98	3450	0
303	Waukesha	F1197G	150	02/28/90	c	0	41	0	4095	0
303	Waukesha	F1197G	150	01/19/88	c	62	20	68	1994	3
304	Waukesha	F1197G	150	06/05/92	c	0	45	0	831	226
304	Waukesha	F1197G	150	06/19/89	c	247	28	89	8641	0
304	Waukesha	F1197G	150	12/10/91	c	0	14	0	480	0
304	Waukesha	F1197G	150	11/30/89	c	101	12	88	8518	0
304	Waukesha	F1197G	150	09/08/88	c	142	30	79	11969	0
304	Waukesha	F1197G	150	05/21/90	c	304	14	96	4401	0
304	Waukesha	F1197G	150	01/19/88	c	265	5	98	5829	7
304	Waukesha	F1197G	150	03/30/88	c	236	35	85	7924	0
304	Waukesha	F1197G	150	08/29/90	c	303	16	95	2436	0
304	Waukesha	F1197G	150	02/28/90	c	0	10	0	1343	6
304	Waukesha	F1197G	150	02/14/89	c	486	19	96	2825	0
305	Waukesha	F1197G	150	09/30/87	c	107	23	79	2397	0
305	Waukesha	F1197G	150	09/08/88	c	117	12	90	7706	0
305	Waukesha	F1197G	150	08/29/90	c	88	7	92	2263	28

TABLE A-2. VENTURA COUNTY APCD EMISSION DATABASE FOR NSCR CONTROL FOR IC ENGINES.

Engine No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at to 15 percent oxygen NOx Uncontr.	Contr.	Percent reduction	CO	NMHC
305	Waukesha	F1197G	150	03/18/88	c	119	32	73	12827	0
305	Waukesha	F1197G	150	12/13/91	c	36	9	76	2696	3
305	Waukesha	F1197G	150	05/21/90	c	106	5	95	4505	0
305	Waukesha	F1197G	150	02/19/87	c	64	34	47	9250	0
305	Waukesha	F1197G	150	02/17/89	c	120	16	87	9130	6
305	Waukesha	F1197G	150	06/05/92	c	0	35	0	309	133
305	Waukesha	F1197G	150	06/19/89	c	79	19	77	2801	0
305	Waukesha	F1197G	150	09/08/89	c	75	12	85	10014	0
305	Waukesha	F1197G	150	01/19/88	c	87	35	80	6721	39
305	Waukesha	F1197G	150	10/28/86	c	572	29	95	2259	7
320	Waukesha	F1197G	150	02/20/90	c	154	29	81	10369	0
320	Waukesha	F1197G	150	09/07/89	c	95	3	97	12230	34
320	Waukesha	F1197G	150	11/10/87	c	747	39	95	1105	11
320	Waukesha	F1197G	98	02/17/88	c	146	44	70	10849	0
320	Waukesha	F1197G	150	12/13/91	c	190	47	75	3911	38
320	Waukesha	F1197G	150	08/22/88	c	90	33	63	13722	45
320	Waukesha	F1197G	150	06/04/92	c	0	4	0	332	194
320	Waukesha	F1197G	150	06/08/89	c	104	23	79	11684	0
320	Waukesha	F1197G	150	01/31/89	c	102	7	93	9699	0
320	Waukesha	F1197G	150	11/16/89	c	177	25	86	11779	0
320	Waukesha	F1197G	150	12/10/91	c	0	2	0	453	4
320	Waukesha	F1197G	150	10/03/90	c	489	11	98	393	3
320	Waukesha	F1187G	150	05/15/90	c	225	15	93	4288	0
321	Waukesha	F1197G	150	09/07/89	c	39	11	71	12874	41
321	Waukesha	F1197G	150	02/20/90	c	117	36	70	5499	0
321	Waukesha	F1197G	150	01/31/89	c	98	3	97	7077	0
321	Waukesha	F1197G	150	08/22/88	c	33	18	45	12391	78
321	Waukesha	F1197G	150	11/16/89	c	40	18	55	18210	0
321	Waukesha	F1197G	98	02/17/88	c	211	34	84	7103	0
321	Waukesha	F1197G	150	10/11/90	c	565	35	94	2002	8
321	Waukesha	F1197G	150	05/14/90	c	62	38	38	10033	0
321	Waukesha	F1197G	150	06/08/89	c	31	9	68	12008	0
322	Waukesha	F1197G	150	06/08/89	c	355	6	98	2874	0
322	Waukesha	F1197G	150	11/16/89	c	90	33	64	15666	0
322	Waukesha	F1197G	150	10/11/90	c	481	18	96	770	14
322	Waukesha	F1197G	150	08/22/88	c	231	14	94	8927	39
322	Waukesha	F1197G	98	02/17/88	c	488	8	98	1578	0
322	Waukesha	F1197G	150	02/20/90	c	68	48	30	10722	0
322	Waukesha	F1197G	150	05/15/90	c	190	8	96	3785	0
322	Waukesha	F1197G	150	02/14/89	c	436	27	94	2553	0
322	Waukesha	F1197G	150	09/07/89	c	90	17	81	11463	92
330	Enterprise	GSG-6	465	10/26/89	c	93	1	99	19411	20
330	Enterprise	GSG-6	465	03/13/92	c	0	17	0	2213	0
330	Enterprise	GSG-6	465	11/21/90	c	361	5	99	3868	7
330	Enterprise	GSG-6	465	06/15/88	c	39	1	97	12840	0
330	Enterprise	GSG-6	465	04/15/87	c	29	2	93	11133	43
331	Enterprise	GSG-6	520	11/20/90	c	457	22	95	2232	19
331	Enterprise	GSG-6	520	10/25/89	c	625	29	95	1043	9
331	Enterprise	GSG-6	520	01/14/87	c	561	3	100	1804	9
331	Enterprise	GSG-6	520	12/27/88	c	728	11	98	1423	13
332	Enterprise	GSG-6	520	03/28/89	c	317	16	95	4386	32
332	Enterprise	GSG-6	520	10/25/89	c	325	22	93	4822	30
332	Enterprise	GSG-6	520	12/30/86	c	237	2	99	9474	23
332	Enterprise	GSG-6	520	11/27/90	c	611	19	97	1662	1
333	Enterprise	GSM-8	300	10/27/89	c	428	35	92	11700	57
333	Enterprise	GSM-8	300	04/22/87	c	131	2	99	11070	29
333	Enterprise	GSM-8	300	12/11/90	c	367	1	100	3155	51
333	Enterprise	GSM-8	300	06/16/88	c	33	7	79	14265	0
333	Enterprise	GSM-8	300	05/01/92	c	0	36	0	1398	41
334	Caterpillar	G398	420	06/10/92	c	0	2	0	1174	0
334	Caterpillar	G398	420	12/27/89	c	606	29	95	2745	0

TABLE A-2. VENTURA COUNTY APCD EMISSION DATABASE FOR NSCR CONTROL FOR IC ENGINES.

Engine No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at to 15 percent oxygen NOx Uncontr.	Contr.	Percent reduction	CO	NMHC
334	Caterpillar	G398	420	03/30/87	c	152	1	99	10117	23
334	Caterpillar	G398	420	04/07/92	c	0	3	0	165	0
334	Caterpillar	G398	420	09/06/90	c	603	7	99	1154	17
335	Caterpillar	G398	420	05/11/89	c	315	10	97	5421	32
335	Caterpillar	G398	420	03/30/87	c	402	13	97	5914	17
335	Caterpillar	G398	420	05/04/90	c	312	45	86	6090	31
335	Caterpillar	G398	420	04/14/88	c	331	18	95	6764	34
335	Caterpillar	G398	420	12/27/89	c	300	41	86	7274	0
335	Caterpillar	G398	420	06/10/92	c	0	13	0	1039	0
336	Caterpillar	G398	420	06/10/92	c	0	33	0	2282	0
336	Caterpillar	G398	420	05/11/89	c	121	11	91	10132	54
336	Caterpillar	G398	420	07/26/90	c	874	21	98	1098	12
336	Caterpillar	G398	420	04/14/88	c	277	16	94	6855	43
339	Caterpillar	G398	420	09/06/90	c	592	11	98	1825	8
339	Waukesha	F2895	420	06/10/92	c	0	5	0	1459	0
345	Minneapolis-Mol	800-6A	160	12/05/91	c	561	5	99	5969	64
345	Minneapolis-Mol	800-6A	160	03/11/92	c	0	7	0	1100	22
353	Tecogen	CM-75	108	03/30/89	c	606	64	90	1445	6
359	Tecogen	CM-60	85	09/18/92	c	0	10	0	0	0
367	Tecogen Cogen	CM-75	108	06/18/92	c	0	39	0	481	0
368	Tecogen	CM-60	87	06/18/90	c	7452	10	99	1459	2
368	Tecogen Cogen	CM-60	87	06/18/92	c	0	9	0	164	0
378	Tecogen	CM-60	87	06/18/90	c	732	1	100	753	3
378	Tecogen Cogen	CM-60	87	06/18/92	c	0	1	0	377	0
379	Waukesha	H2476G	186	09/20/89	c	749	47	94	678	113
379	Waukesha	F1197G	186	05/23/90	c	992	53	95	381	75
379	Waukesha	F1197G	186	03/10/92	c	575	23	96	1232	0
382	Waukesha	L5790G	748	07/27/92	c	571	46	92	2818	20
382	Waukesha	L5790G	748	08/09/90	c	322	28	91	2236	24
382	Waukesha	L5790G	748	10/06/89	c	391	49	87	4116	15
383	Waukesha	L5790G	748	10/02/89	c	588	31	95	2442	2
383	Waukesha	L5790G	748	07/27/92	c	782	65	92	2836	12
383	Waukesha	L5790G	748	08/09/90	c	622	52	93	4013	24
256	Ingersoll-Rand	XVG-8	300	06/07/89	s	520	84	84	8746	20
256	Ingersoll-Rand	XVG	300	09/14/88	s	39	28	28	14142	0
256	Ingersoll-Rand	XVG	300	12/23/87	s	404	3	99	3353	12
256	Ingersoll-Rand	XVG	300	11/08/89	s	100	40	60	11214	0
256	Ingersoll-Rand	XVG	300	06/13/88	s	139	32	77	8770	0
256	Ingersoll-Rand	XVG	300	12/14/88	s	43	1	98	21939	0
256	Ingersoll-Rand	XVG	300	03/01/88	s	359	4	99	2543	0
258	Ingersoll-Rand	XVG	300	03/17/88	s	277	10	96	6308	0
258	Ingersoll-Rand	XVG	300	09/16/88	s	92	18	80	12092	0
258	Ingersoll-Rand	XVG	300	06/13/88	s	129	41	68	8716	0
258	Ingersoll-Rand	XVG	300	12/23/87	s	306	1	100	5583	18
271	Ingersoll-Rand	XVG	300	12/06/88	s	242	14	94	5968	0
271	Ingersoll-Rand	XVG	300	06/17/88	s	127	1	99	8607	0
271	Ingersoll-Rand	XVG	300	09/01/89	s	217	43	80	7400	0
271	Ingersoll-Rand	XVG	300	12/30/87	s	407	2	100	3642	12
271	Ingersoll-Rand	XVG	300	02/26/88	s	260	6	98	5452	0
271	Ingersoll-Rand	XVG	300	11/09/89	s	276	22	92	6111	0
278	Ingersoll-Rand	XVG	300	09/14/88	s	226	6	97	6046	0
278	Ingersoll-Rand	XVG	300	11/09/89	s	369	25	93	4398	11
278	Ingersoll-Rand	XVG	300	12/06/88	s	103	3	97	10612	13
278	Ingersoll-Rand	XVG	300	12/31/87	s	259	5	98	5528	9
278	Ingersoll-Rand	XVG-8	300	06/23/89	s	746	61	92	7915	0
278	Ingersoll-Rand	XVG	300	09/01/89	s	79	22	73	11306	0
278	Ingersoll-Rand	XVG	300	03/17/88	s	357	6	98	3349	0
278	Ingersoll-Rand	XVG	300	06/17/88	s	216	4	96	5888	0
278	Ingersoll-Rand	XVG-8	300	12/05/91	s	0	30	0	476	13
290	Ingersoll-Rand	XVG	550	09/06/89	s	103	1	99	11331	0
290	Ingersoll-Rand	SVG-10	550	06/18/86	s	153	2	99	6706	0

TABLE A-2. VENTURA COUNTY APCD EMISSION DATABASE FOR NSCR CONTROL FOR IC ENGINES.

Engine No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at to 15 percent oxygen NOx Uncontr.	Contr.	Percent reduction	CO	NMHC
290	Ingersoll-Rand	SVG-10	550	12/09/86	s	65	1	99	13909	37
290	Ingersoll-Rand	SVG-10	550	12/16/91	s	0	3	0	40	2
290	Ingersoll-Rand	SVG-10	550	02/18/87	s	344	13	96	10209	0
290	Ingersoll-Rand	SVG-10	550	02/26/88	s	67	12	82	12378	0
290	Ingersoll-Rand	XVG	300	12/06/88	s	58	25	57	13469	33
290	Ingersoll-Rand	SVG-10	550	09/14/88	s	69	23	67	13961	0
290	Ingersoll-Rand	SVG-10	550	06/23/89	s	365	1	99	9268	0
290	Ingersoll-Rand	SVG-10	550	06/09/87	s	91	7	92	6043	0
290	Ingersoll-Rand	SVG-10	550	12/29/87	s	283	30	89	4766	20
290	Ingersoll-Rand	SVG-10	550	03/19/86	s	189	5	97	21119	12
290	Ingersoll-Rand	SVG-10	550	09/11/86	s	272	1	100	6694	0
290	Ingersoll-Rand	XVG	550	11/09/89	s	390	1	99	3546	10
290	Ingersoll-Rand	SVG-10	550	06/13/88	s	69	20	71	13686	0
290	Ingersoll-Rand	SVG-10	550	09/18/87	s	142	9	94	7014	0
33	Caterpillar	G398	500	07/30/92	d	0	26	0	311	244
34	Caterpillar	G398	500	07/30/92	d	0	26	0	227	47
142	Ingersoll-Rand	SVG-12	660	10/04/89	d	715	28	96	725	0
142	Ingersoll-Rand	SVG-12	660	10/20/87	d	981	10	99	0	0
142	Ingersoll-Rand	SVG-12	660	08/05/88	d	406	38	91	0	0
143	Ingersoll-Rand	SVG-12	660	08/12/88	d	321	18	94	0	0
143	Ingersoll-Rand	SVG-12	660	10/05/89	d	389	48	88	3125	11
143	Ingersoll-Rand	SVG-12	660	10/23/87	d	73	4	95	0	0
143	Ingersoll-Rand	SVG-12	660	12/03/86	d	514	19	96	2650	9
144	Ingersoll-Rand	SVG-12	660	12/02/86	d	501	4	99	3066	6
144	Ingersoll-Rand	SVG-12	660	08/04/88	d	162	3	98	0	0
144	Ingersoll-Rand	SVG-12	660	10/05/89	d	546	29	95	2096	7
144	Ingersoll-Rand	SVG-12	660	10/22/87	d	260	16	94	0	0
145	Ingersoll-Rand	SVG-12	660	12/02/86	d	461	0	1	3753	6
145	Ingersoll-Rand	SVG-12	660	10/05/89	d	512	19	96	2415	7
145	Ingersoll-Rand	SVG-12	660	10/20/87	d	626	42	93	0	0
145	Ingersoll-Rand	SVG-12	660	08/04/88	d	182	10	95	0	0
146	Ingersoll-Rand	SVG-12	660	10/23/87	d	778	10	99	0	0
146	Ingersoll-Rand	SVG-12	660	12/03/86	d	393	4	99	5174	7
146	Ingersoll-Rand	SVG-12	660	08/09/88	d	278	13	95	0	0
147	Ingersoll-Rand	SVG-12	660	08/04/88	d	116	7	94	0	0
147	Ingersoll-Rand	SVG-12	660	10/04/89	d	587	25	96	2040	1
147	Ingersoll-Rand	SVG-12	660	12/03/86	d	443	1	100	3384	5
148	Ingersoll-Rand	SVG-12	660	08/05/88	d	157	6	96	0	0
148	Ingersoll-Rand	SVG-12	660	10/05/89	d	503	40	92	1349	8
148	Ingersoll-Rand	SVG-12	660	12/01/86	d	426	19	96	4475	6
152	White Superior	G-8258	625	08/05/88	d	326	29	91	0	0
152	White Superior	G-8258	625	10/21/87	d	117	22	81	0	0
152	White Superior	G-8258	625	12/05/86	d	369	24	94	4807	5
154	White Superior	G-8258	625	08/05/88	d	303	23	92	0	0
154	White Superior	G-8258	625	10/21/87	d	154	39	75	0	0
154	White Superior	G-8258	625	12/05/86	d	585	47	92	3333	5
155	White Superior	G-8258	625	12/05/86	d	306	27	91	5375	6
155	White Superior	G-8258	625	10/21/87	d	165	27	84	0	0
155	White Superior	G-8258	625	08/05/88	d	596	50	92	0	0
260	Ingersoll-Rand	XVG-8	300	06/07/89	d	479	100	79	8055	0
260	Ingersoll-Rand	XVG	300	09/14/88	d	304	13	96	3556	0
260	Ingersoll-Rand	XVG	300	02/26/88	d	196	3	98	5633	0
260	Ingersoll-Rand	XVG	300	06/13/88	d	431	9	98	1677	0
260	Ingersoll-Rand	XVG	300	12/07/88	d	245	5	98	4593	16
260	Ingersoll-Rand	XVG	300	12/23/87	d	298	7	98	4723	11
272	Ingersoll-Rand	XVG-8	300	09/30/87	d	337	16	95	2874	0
272	Ingersoll-Rand	XVG	300	11/08/89	d	334	1	100	2279	374
272	Ingersoll-Rand	XVG-8	300	12/10/86	d	149	2	99	9461	7
272	Ingersoll-Rand	XVG-8	300	06/16/86	d	26	15	42	14342	0
272	Ingersoll-Rand	XVG-8	300	01/08/88	d	277	35	87	4725	9

TABLE A-2. VENTURA COUNTY APCD EMISSION DATABASE FOR NSCR CONTROL FOR IC ENGINES.

Engine No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at to 15 percent oxygen NOx Uncontr.	Contr.	Percent reduction	CO	NMHC
272	Ingersoll-Rand	XVG	300	09/16/88	d	109	5	95	9906	0
272	Ingersoll-Rand	XVG-8	300	03/04/87	d	412	2	100	3886	0
272	Ingersoll-Rand	XVG-8	300	09/25/86	d	77	1	99	9502	0
272	Ingersoll-Rand	XVG-8	300	03/19/86	d	64	17	73	22439	18
272	Ingersoll-Rand	XVG	300	06/17/88	d	105	27	74	10643	0
272	Ingersoll-Rand	XVG	300	03/18/88	d	90	39	57	10868	0
318	Waukesha	145GKU	65	02/18/88	d	389	1	100	1487	0
318	Waukesha	145GKU	90	11/12/87	d	312	2	99	2587	18
318	Waukesha	145GKU	90	06/15/89	d	517	5	99	1554	0
318	Waukesha	145GKU	90	10/03/90	d	143	3	98	1510	0
318	Waukesha	145GKU	90	05/14/90	d	174	8	95	3241	0
318	Waukesha	145GKU	90	09/07/89	d	99	5	95	8647	42
319	Waukesha	145GKU	90	06/15/89	d	404	28	93	4384	0
319	Waukesha	145GKU	90	09/15/89	d	465	26	95	2943	0
319	Waukesha	145GKU	90	06/23/88	d	421	9	98	560	0
319	Waukesha	145GKU	90	02/22/90	d	561	42	93	1603	8
319	Waukesha	145GKU	65	02/18/88	d	457	19	96	389	0
319	Waukesha	145GKU	90	11/12/87	d	386	6	96	150	2
319	Waukesha	145GKU	90	12/01/89	d	430	16	96	4316	0
319	Waukesha	145GKU	90	02/17/89	d	515	31	94	2067	14
358	Tecogen	CM-75	108	08/24/89	d	670	115	83	6652	36
358	Tecogen	CM-75	108	03/30/89	d	572	99	83	3120	8
61	Ingersoll-Rand	XVG	350	08/25/88	m	81	48	41	6286	314
61	Ingersoll-Rand	XVG	350	01/07/88	m	195	2	99	6490	33
82	Waukesha	L7042G	775	03/30/89	m	513	12	97	2406	0
82	Waukesha	L7042G	775	03/05/90	m	452	37	91	3812	0
82	Waukesha	L7042G	775	09/13/89	m	669	14	98	477	0
82	Waukesha	L7042G	775	03/22/88	m	2014	227	89	2523	0
82	Waukesha	L7042G	775	12/08/87	m	571	29	95	3098	0
82	Waukesha	L7042G	858	05/27/87	m	597	55	91	1503	0
82	Waukesha	L7042G	775	12/12/89	m	690	18	97	794	0
82	Waukesha	L7042G	775	06/29/88	m	2248	53	98	787	0
82	Waukesha	L7042G	775	09/22/87	m	641	18	97	1621	0
82	Waukesha	L7042G	775	03/09/90	m	171	5	97	12607	0
82	Waukesha	L7042G	775	04/09/90	m	532	44	92	2641	0
82	Waukesha	L7042G	858	06/29/88	m	2248	53	98	787	0
82	Waukesha	L7042G	775	06/30/89	m	629	31	95	1553	0
82	Waukesha	L7042G	858	03/10/87	m	596	18	97	2541	0
86	Waukesha	L7042G	775	12/08/87	m	660	10	99	1730	0
86	Waukesha	L7042G	775	03/05/90	m	497	27	95	3163	0
86	Waukesha	L7042G	775	06/05/89	m	213	12	94	8084	0
86	Waukesha	L7042G	775	09/14/89	m	865	14	94	7687	0
86	Waukesha	L7042G	775	03/22/88	m	2206	59	97	1169	0
86	Waukesha	L7042G	858	06/29/88	m	1922	42	98	3798	0
86	Waukesha	L7042G	775	04/09/90	m	505	32	94	3084	0
86	Waukesha	L7042G	775	09/22/87	m	668	21	97	193	0
86	Waukesha	L7042G	775	06/29/88	m	1922	42	98	3798	0
86	Waukesha	L7042G	775	03/31/89	m	464	32	93	3418	0
86	Waukesha	L7042G	858	02/10/87	m	950	3	100	2848	49
86	Waukesha	L7042G	775	12/28/89	m	472	15	97	1862	0
89	Waukesha	L7042G	775	03/22/88	m	720	7	99	9020	0
89	Waukesha	L7042G	858	06/29/88	m	913	1	100	8789	0
89	Waukesha	L7042G	775	09/13/89	m	179	2	99	7928	0
89	Waukesha	L7042G	858	03/10/87	m	475	0	1	4262	0
89	Waukesha	L7042G	775	12/08/87	m	353	0	1	6040	0
89	Waukesha	L7042G	775	09/22/87	m	357	3	99	5997	0
89	Waukesha	L7042G	775	03/30/89	m	202	1	99	9701	0
89	Waukesha	L7042G	775	06/29/88	m	913	1	100	8789	0
89	Waukesha	L7042G	858	05/27/87	m	338	3	99	3900	0
89	Waukesha	L7042G	775	12/12/89	m	191	2	99	9885	0

TABLE A-2. VENTURA COUNTY APCD EMISSION DATABASE FOR NSCR CONTROL FOR IC ENGINES.

Engine No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at to 15 percent oxygen NOx Uncontr.	Contr.	Percent reduction	CO	NMHC
89	Waukesha	L7042G	775	06/05/89	m	157	1	99	10676	0
91	Waukesha	L7042G	775	03/05/90	m	674	33	94	867	0
91	Waukesha	L7042G	775	12/12/89	m	154	4	98	6651	0
91	Waukesha	L7042G	775	03/30/89	m	144	3	97	10138	0
91	Waukesha	L7042G	775	09/13/89	m	163	4	98	8651	0
91	Waukesha	L7042G	775	09/22/87	m	335	6	98	5997	0
91	Waukesha	L7042G	858	06/29/88	m	879	4	100	9019	0
91	Waukesha	L7042G	775	03/22/88	m	1342	24	98	4780	0
91	Waukesha	L7042G	775	12/08/87	m	283	1	100	6608	0
91	Waukesha	L7042G	775	06/29/88	m	879	4	100	9019	0
91	Waukesha	L7042G	775	06/05/89	m	135	1	99	11318	0
91	Waukesha	L7042G	858	03/10/87	m	180	0	1	9631	0
91	Waukesha	L7042G	858	05/28/87	m	512	8	98	1900	0
92	Waukesha	L7042G	775	03/31/89	m	489	1	99	5326	0
92	Waukesha	L7042G	775	12/08/87	m	539	1	100	4102	0
92	Waukesha	L7042G	775	09/22/87	m	494	2	100	10825	0
92	Waukesha	L7042G	775	12/12/89	m	409	13	97	7867	0
92	Waukesha	L7042G	858	05/29/87	m	773	1	100	60	0
92	Waukesha	L7042G	858	06/29/88	m	2562	16	99	1231	0
92	Waukesha	L7042G	775	09/14/89	m	385	3	99	5733	0
92	Waukesha	L7042G	775	06/30/89	m	493	6	99	7233	0
92	Waukesha	L7042G	858	02/06/87	m	1614	2	100	4534	18
92	Waukesha	L7042G	775	06/29/88	m	2562	16	99	1231	0
92	Waukesha	L7042G	775	03/09/90	m	477	1	99	85	0
92	Waukesha	L7042G	775	03/09/90	m	559	1	99	8336	0
92	Waukesha	L7042G	775	03/22/88	m	2589	3	100	5829	0
316	Ingersoll-Rand	SVG-6	330	05/15/90	m	245	10	96	3400	7
316	Ingersoll-Rand	SVG-6	330	03/20/86	m	266	20	93	5672	8
316	Ingersoll-Rand	SVG-6	330	06/10/87	m	201	5	98	3460	0
316	Ingersoll-Rand	SVG-6	330	06/09/86	m	236	10	96	4768	0
316	Ingersoll-Rand	SVG-6	330	09/07/89	m	168	10	94	6211	0
316	Ingersoll-Rand	SVG-6	330	12/10/86	m	242	4	98	4971	6
316	Ingersoll-Rand	SVG-6	330	10/19/90	m	319	6	98	2268	8
316	Ingersoll-Rand	SVG-6	330	08/23/88	m	326	20	94	7677	0
316	Ingersoll-Rand	SVG-6	330	12/15/87	m	562	10	98	790	6
316	Ingersoll-Rand	SVG-6	330	02/26/87	m	227	5	98	4978	0
316	Ingersoll-Rand	SVG-6	330	02/22/90	m	417	11	97	484	0
316	Ingersoll-Rand	SVG-6	330	02/14/89	m	332	7	98	3305	0
316	Ingersoll-Rand	SVG-6	330	08/27/86	m	176	8	96	7275	0
316	Ingersoll-Rand	SVG-6	330	09/29/87	m	412	13	97	2524	0
316	Ingersoll-Rand	SVG-6	330	02/18/88	m	318	16	95	4083	0
317	Ingersoll-Rand	SVG-6	330	11/30/89	m	322	15	98	4596	0
317	Ingersoll-Rand	SVG-6	330	08/23/88	m	207	2	99	5421	0
317	Ingersoll-Rand	SVG-6	330	06/10/87	m	342	6	98	1294	0
317	Ingersoll-Rand	SVG-6	330	03/19/87	m	433	2	100	2650	6
317	Ingersoll-Rand	SVG-6	330	02/17/89	m	263	3	99	2408	4
317	Ingersoll-Rand	SVG-6	330	06/09/86	m	355	7	98	2385	0
317	Ingersoll-Rand	SVG-6	330	04/07/86	m	372	19	95	368	1
317	Ingersoll-Rand	SVG-6	330	12/17/86	m	372	1	100	3347	0
317	Ingersoll-Rand	SVG-6	330	08/28/86	m	251	2	99	5758	0
317	Ingersoll-Rand	SVG-6	330	09/29/87	m	177	3	98	2678	0
317	Ingersoll-Rand	SVG-6	330	10/03/90	m	307	11	97	2579	0
317	Ingersoll-Rand	SVG-6	330	02/18/88	m	358	4	99	2554	7
317	Ingersoll-Rand	SVG-6	330	06/15/89	m	142	10	93	7133	0
317	Ingersoll-Rand	SVG-6	330	12/15/87	m	373	21	94	295	0
327	Ingersoll-Rand	SVG-8	440	02/06/89	m	519	30	94	865	10
327	Ingersoll-Rand	SVG-8	440	09/18/89	m	240	1	100	4602	16
0	Ingersoll-Rand	SVG-10	550	08/28/86		42	1	98	14722	0
0	Ingersoll-Rand	SVG-12	660	11/24/86		519	4	99	2580	6
0	Ingersoll-Rand	SVG-12	660	12/01/86		461	4	99	3805	5

TABLE A-2. VENTURA COUNTY APCD EMISSION DATABASE FOR NSCR CONTROL FOR IC ENGINES.

Engine No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at to 15 percent oxygen NOx Uncontr.	Contr.	Percent reduction	CO	NMHC
0	Minneapolis-Mol	800-6A	80	07/13/92		0	6	0	164	4
0	Ingersoll-Rand	SVG-10	550	06/16/86		260	17	94	5387	0
0	Ingersoll-Rand	XVG	300	12/07/88		57	22	61	13606	30
0	White Superior	G-8258	625	12/17/82		0	0	0	60	47
0	Waukesha	F1197G	150	11/10/87		449	17	96	3217	5
0	Waukesha	F1197G	150	11/10/87		479	3	99	3575	3
0	Ingersoll-Rand	SVG-12	660	02/09/82		537	6	99	1021	31
0	White Superior	G-8258	625	12/17/82		572	5	99	1695	73
0	Ingersoll-Rand	SVG-12	660	11/24/86		758	3	100	2834	6
0	Ingersoll-Rand	SVG-12	660	12/12/86		315	8	98	5933	6
0	White Superior	G-8258	625	12/17/82		2	2	0	3191	76
0	Ingersoll-Rand	SVG-12	660	10/20/87		747	23	97	0	0
0	Waukesha	F1197G	150	06/11/87		63	27	57	5220	0
0	Waukesha	F1197G	150	06/11/87		39	20	49	7665	0
0	Ingersoll-Rand	SVG-12	660	10/22/87		565	4	99	0	0
0	Ingersoll-Rand	SVG-10	500	04/02/82		432	61	86	2638	0
0	Ingersoll-Rand	SVG-10	550	12/09/86		180	1	99	4652	0
0	Ingersoll-Rand	SVG-12	660	02/09/82		449	3	99	1146	101
0	Ingersoll-Rand	XVG	300	12/31/85		311	3	99	8056	5
76	Waukesha	GMVA-8	165	06/15/87		174	19	89	8894	117
76	Waukesha	GMVA-8	165	07/02/86		384	23	94	2752	0
323	Ingersoll-Rand	SVG-8	440	12/18/87		358	1	100	705	5

TABLE A-3. VENTURA COUNTY APCD EMISSION DATABASE FOR LOW-EMISSION ENGINES DEVELOPED FROM RICH-BURN DESIGNS

Engine No.	Test No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at 15 percent oxygen NOx	CO	NMHC
74	1	Superior	16SGTA	2650	08/14/86	e	42	0	0
74	2	Superior	16SGTA	2650	08/25/87	e	52	0	152
74	3	Superior	16SGTA	2650	01/26/88	e	30	0	168
74	4	Superior	16SGTA	2650	04/26/88	e	24	0	160
74	5	Superior	16SGTA	2650	08/18/88	e	49	0	179
74	6	Superior	16SGTA	2650	09/06/88	e	35	32	182
74	7	Superior	16SGTA	2650	10/06/88	e	35	23	132
74	8	Superior	16SGTA	2650	12/20/88	e	45	0	177
74	9	Superior	16SGTA	2650	06/16/89	e	79	0	0
74	10	Superior	16SGTA	2650	06/01/90	e	44	9	108
75	1	Superior	16SGTA	2650	08/14/86	e	43	0	0
75	2	Superior	16SGTA	2650	08/25/87	e	39	0	164
75	3	Superior	16SGTA	2650	01/26/88	e	76	0	177
75	4	Superior	16SGTA	2650	04/26/88	e	75	0	187
75	5	Superior	16SGTA	2650	08/18/88	e	89	0	215
75	6	Superior	16SGTA	2650	09/07/88	e	77	3	200
75	7	Superior	16SGTA	2650	10/07/88	e	77	4	238
75	8	Superior	16SGTA	2650	12/20/88	e	71	0	125
75	9	Superior	16SGTA	2650	06/16/89	e	82	0	0
75	10	Superior	16SGTA	2650	06/01/90	e	78	10	166
295	1	Waukesha	L7042GL	1100	06/17/87	c	46	95	278
295	2	Waukesha	L7042GL	1108	09/17/87	c	47	0	264
295	3	Waukesha	L7042GL	990	01/20/88	c	47	0	279
295	4	Waukesha	L7042GL	995	03/31/88	c	79	0	330
295	5	Waukesha	L7042GL	1117	07/13/88	c	58	0	336
295	6	Waukesha	L7042GL	1100	09/15/88	c	49	0	326
295	7	Waukesha	L7042GL	1100	02/10/89	c	59	0	301
295	8	Waukesha	L7042GL	1100	02/15/90	c	90	0	341
295	9	Waukesha	L7042GL	1108	08/22/90	c	29	0	344
295	10	Waukesha	L7042GL	1100	11/15/89	c	36	113	235
296	1	Waukesha	L7042GL	1100	08/17/87	c	44	97	289
296	2	Waukesha	L7042GL	1129	09/17/87	c	22	0	270
296	3	Waukesha	L7042GL	937	01/20/88	c	131	0	315
296	4	Waukesha	L7042GL	1012	03/31/88	c	50	0	256
296	5	Waukesha	L7042GL	1051	07/13/88	c	50	0	295
296	6	Waukesha	L7042GL	1100	09/15/88	c	52	0	333
296	7	Waukesha	L7042GL	1100	02/10/89	c	58	0	282
296	8	Waukesha	L7042GL	1100	09/21/89	c	46	106	259
296	9	Waukesha	L7042GL	1100	11/15/89	c	61	0	280
296	11	Waukesha	L7042GL	1100	02/15/90	c	92	0	292
296	12	Waukesha	L7042GL	1108	05/22/90	c	38	0	297
296	13	Waukesha	L7042GL	1108	08/22/90	c	46	99	330
296	14	Waukesha	L7042GL	1108	12/05/91	c	117	85	253
297	1	Waukesha	L7042GL	1100	03/16/87	c	73	92	313
297	2	Waukesha	L7042GL	1100	03/27/87	c	56	41	313
297	2	Waukesha	L7042GL	1100	03/27/87	c	45	70	292
297	2	Waukesha	L7042GL	1100	03/27/87	c	41	81	282
297	3	Waukesha	L7042GL	1100	06/16/87	c	47	0	231
297	4	Waukesha	L7042GL	1164	09/28/87	c	125	0	262
297	5	Waukesha	L7042GL	959	01/15/88	c	87	0	311
297	6	Waukesha	L7042GL	984	03/31/88	c	98	109	313
297	7	Waukesha	L7042GL	1100	07/14/88	c	77	0	337
297	8	Waukesha	L7042GL	1100	09/21/88	c	63	0	317
297	9	Waukesha	L7042GL	1100	03/13/89	c	45	128	285
297	10	Waukesha	L7042GL	1100	06/14/89	c	60	0	313
297	11	Waukesha	L7042GL	1100	09/20/89	c	53	0	259
297	12	Waukesha	L7042GL	1100	11/29/89	c	56	0	241
297	13	Waukesha	L7042GL	1100	02/27/90	c	46	117	302
298	1	Waukesha	L7042GL	1100	03/18/87	c	54	106	308
298	2	Waukesha	L7042GL	1100	06/16/87	c	40	0	261
298	3	Waukesha	L7042GL	1120	10/08/87	c	45	0	264
298	4	Waukesha	L7042GL	1067	01/18/88	c	98	0	303
298	5	Waukesha	L7042GL	987	03/31/88	c	84	94	283

TABLE A-3. VENTURA COUNTY APCD EMISSION DATABASE FOR LOW-EMISSION ENGINES DEVELOPED FROM RICH-BURN DESIGNS

Engine No.	Test No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at 15 percent oxygen NOx	CO	NMHC
298	6	Waukesha	L7042GL	1062	07/14/88	c	63	0	323
298	7	Waukesha	L7042GL	1100	09/21/88	c	61	0	313
298	8	Waukesha	L7042GL	1100	03/13/89	c	72	102	270
298	9	Waukesha	L7042GL	1100	06/14/89	c	52	0	279
298	10	Waukesha	L7042GL	1100	09/20/89	c	85	0	285
298	11	Waukesha	L7042GL	1100	11/29/89	c	93	0	256
298	12	Waukesha	L7042GL	1108	06/05/90	c	119	0	299
298	13	Waukesha	L7042GL	1108	09/05/90	c	31	0	288
298	14	Waukesha	L7042GL	1108	12/02/91	c	69	56	309
299	1	Waukesha	L7042GL	1100	03/18/87	c	44	133	289
299	2	Waukesha	L7042GL	1100	06/16/87	c	47	0	279
299	3	Waukesha	L7042GL	1058	10/08/87	c	84	0	268
299	4	Waukesha	L7042GL	979	01/18/88	c	173	0	331
299	5	Waukesha	L7042GL	964	03/31/88	c	88	92	277
299	6	Waukesha	L7042GL	1100	03/13/89	c	90	0	311
299	7	Waukesha	L7042GL	1100	09/20/89	c	52	0	255
299	8	Waukesha	L7042GL	1100	11/29/89	c	115	109	285
299	9	Waukesha	L7042GL	1100	02/27/90	c	48	0	301
299	10	Waukesha	L7042GL	1108	06/05/90	c	28	0	74
299	11	Waukesha	L7042GL	1108	09/05/90	c	57	0	331
300	1	Waukesha	L7042GL	1100	06/17/87	c	26	101	282
300	2	Waukesha	L7042GL	1138	09/17/87	c	71	0	255
300	3	Waukesha	L7042GL	929	12/17/87	c	77	0	241
300	4	Waukesha	L7042GL	1007	03/31/88	c	72	0	251
300	5	Waukesha	L7042GL	1048	07/13/88	c	71	0	259
300	6	Waukesha	L7042GL	1100	09/15/88	c	47	0	242
300	7	Waukesha	L7042GL	1100	02/10/89	c	126	0	292
300	8	Waukesha	L7042GL	1100	09/21/89	c	37	0	277
300	9	Waukesha	L7042GL	1100	03/02/90	c	16	0	273
300	10	Waukesha	L7042GL	1108	05/22/90	c	80	0	313
300	11	Waukesha	L7042GL	1108	08/22/90	c	34	0	291
301	1	Waukesha	L7042GL	1100	03/16/87	c	45	159	289
301	2	Waukesha	L7042GL	1100	06/16/87	c	67	0	282
301	3	Waukesha	L7042GL	1235	09/28/87	c	55	0	269
301	4	Waukesha	L7042GL	1005	01/15/88	c	104	0	298
301	5	Waukesha	L7042GL	941	03/31/88	c	92	105	284
301	6	Waukesha	L7042GL	1100	09/21/88	c	136	0	364
301	7	Waukesha	L7042GL	1100	03/13/89	c	60	0	276
301	8	Waukesha	L7042GL	1100	06/14/89	c	42	0	264
301	9	Waukesha	L7042GL	1100	09/20/89	c	48	124	219
301	10	Waukesha	L7042GL	1100	11/29/89	c	104	0	257
301	11	Waukesha	L7042GL	1108	09/05/90	c	36	0	267
302	1	Waukesha	L7042GL	1100	06/17/87	c	36	94	268
302	2	Waukesha	L7042GL	1077	09/17/87	c	56	0	246
302	3	Waukesha	L7042GL	1029	12/17/87	c	90	0	278
302	4	Waukesha	L7042GL	941	03/31/88	c	57	0	259
302	5	Waukesha	L7042GL	1081	07/13/88	c	36	0	305
302	6	Waukesha	L7042GL	1100	02/10/89	c	77	0	269
302	7	Waukesha	L7042GL	1100	09/21/89	c	39	0	245
302	8	Waukesha	L7042GL	1100	11/15/89	c	68	109	274
302	9	Waukesha	L7042GL	1100	02/27/90	c	50	0	297
302	10	Waukesha	L7042GU	1108	05/22/90	c	42	0	289
354	1	Superior	8GTLB	1100	05/24/90	c	13	3327	356
354	2	Superior	8GTLB	1100	03/12/92	c	11	0	431
355	1	Superior	8GTLB	1100	05/24/90	c	32	1980	264
355	2	Superior	8GTLB	1100	03/12/92	c	19	0	275
356	1	Superior	8GTLB	1100	05/23/90	c	23	1545	254
356	2	Superior	8GTLB	1100	03/12/92	c	17	0	245
362	1	Waukesha	F3521GL	616	05/07/90	c	34	136	289
363	1	Waukesha	F3521GL	616	05/07/90	c	35	118	279

TABLE A-4. VENTURA COUNTY APCD EMISSION DATABASE FOR LOW-EMISSION IC ENGINES DEVELOPED FROM LEAN-BURN DESIGNS

Engine No.	Test No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at 15 percent oxygen NOx	CO	NMHC
67	1	Cooper Bessemer	GMVA-8	1100	02/06/86	c	64	40	178
67	2	Cooper Bessemer	GMVA-8	1100	05/05/86	c	65	68	173
67	3	Cooper Bessemer	GMVA-8	1100	08/22/86	c	218	0	165
67	4	Cooper Bessemer	GMVA-8	1110	10/31/86	c	71	0	189
67	5	Cooper Bessemer	GMVA-8	1100	02/06/87	c	238	0	109
67	6	Cooper Bessemer	GMVA-8	1100	05/08/87	c	97	0	0
67	7	Cooper Bessemer	GMVA-8	1100	01/08/88	c	248	0	0
67	8	Cooper Bessemer	GMVA-8	1100	10/30/89	c	1096	0	0
68	1	Cooper Bessemer	GMVA-8	1100	01/13/89	c	302	53	72
116	1	Ajax	DCP-180	180	08/07/87	c	51	1284	82
116	2	Ajax	DCP-180	180	05/17/89	c	60	0	0
116	3	Ajax	DCP-180	180	09/19/89	c	38	0	89
116	4	Ajax	DCP-180	180	12/12/89	c	38	0	98
116	5	Ajax	DCP-180	180	03/20/90	c	42	0	0
116	6	Ajax	DCP-180	180	06/14/90	c	33	528	86
116	7	Ajax	DCP-180	180	09/23/91	c	40	235	95
117	1	Ajax	DCP-180	180	07/03/86	c	78	0	127
117	2	Ajax	DCP-180	180	10/02/86	c	51	0	108
117	3	Ajax	DCP-180	180	02/09/87	c	35	0	132
117	4	Ajax	DCP-180	180	04/23/87	c	56	0	112
117	5	Ajax	DCP-180	180	08/06/87	c	55	739	98
117	6	Ajax	DCP-180	180	04/18/88	c	50	0	128
117	7	Ajax	DCP-180	180	06/10/88	c	44	0	0
117	8	Ajax	DCP-180	180	09/13/88	c	25	0	110
117	9	Ajax	DCP-180	180	12/01/88	c	84	74	155
117	10	Ajax	DCP-180	180	02/21/89	c	57	0	0
117	11	Ajax	DCP-180	180	05/17/89	c	60	0	0
117	12	Ajax	DCP-180	180	09/19/89	c	38	0	87
117	13	Ajax	DCP-180	180	12/12/89	c	71	0	113
117	14	Ajax	DCP-180	180	03/20/90	c	37	0	0
117	15	Ajax	DCP-180	180	06/14/90	c	38	682	118
117	16	Ajax	DCP-180	180	09/23/91	c	25	225	93
118	1	Ajax	DCP-180	180	07/02/86	c	49	0	227
118	2	Ajax	DCP-180	180	10/02/86	c	28	0	195
118	3	Ajax	DCP-180	180	01/09/87	c	39	0	113
118	4	Ajax	DCP-180	180	04/22/87	c	28	0	155
118	5	Ajax	DCP-180	180	08/06/87	c	53	759	114
118	6	Ajax	DCP-180	180	04/18/88	c	76	0	159
118	7	Ajax	DCP-180	180	06/10/88	c	80	0	0
118	8	Ajax	DCP-180	180	09/13/88	c	18	0	133
118	9	Ajax	DCP-180	180	12/01/88	c	44	138	165
118	10	Ajax	DCP-180	180	02/21/89	c	61	0	0
118	11	Ajax	DCP-180	180	05/17/89	c	55	0	0
118	12	Ajax	DCP-180	180	09/19/89	c	32	0	143
118	13	Ajax	DCP-180	180	12/12/89	c	38	0	126
118	14	Ajax	DCP-180	180	03/20/90	c	41	0	0
118	15	Ajax	DCP-180	180	06/14/90	c	45	976	148
118	16	Ajax	DCP-180	180	09/23/91	c	45	510	133
119	1	Ajax	DCP-180	180	07/02/86	c	30	0	91
119	2	Ajax	DCP-180	180	10/02/86	c	18	0	88
119	3	Ajax	DCP-180	180	01/09/87	c	46	0	102
119	4	Ajax	DCP-180	180	04/22/87	c	30	0	102
119	5	Ajax	DCP-180	180	08/07/87	c	80	719	103
119	6	Ajax	DCP-180	180	04/18/88	c	35	0	141
119	7	Ajax	DCP-180	180	06/10/88	c	28	0	0
119	8	Ajax	DCP-180	180	09/13/88	c	21	0	80
119	9	Ajax	DCP-180	180	12/01/88	c	45	25	174
119	10	Ajax	DCP-180	180	02/21/89	c	28	0	0
119	11	Ajax	DCP-180	180	05/17/89	c	38	0	0
119	12	Ajax	DCP-180	180	09/19/89	c	45	0	104
119	13	Ajax	DCP-180	180	12/12/89	c	38	0	128
119	14	Ajax	DCP-180	180	03/20/90	c	27	0	0
119	15	Ajax	DCP-180	180	06/14/90	c	81	1380	143
119	16	Ajax	DCP-180	180	09/23/91	c	30	556	179

TABLE A-5. VENTURA COUNTY APCD EMISSION DATABASE FOR SCR USED WITH LEAN-BURN RECIPROCATING ENGINES

Engine No.	Test No.	Manufacturer	Model	Power (hp)	Test date	Status	Emissions, ppmv at 15 percent oxygen NOx in	NOx out	Percent reduction	CO out	NMHC out
45	1	Clark	HRA-6	660	12/22/86	c	1094	180	84	217	305
45	2	Clark	HRA-6	660	05/06/88	c	885	104	88	243	132
45	3	Clark	HRA-6	660	05/02/89	c	636	55	91	364	197
45	4	Clark	HRA-6	660	04/23/90	c	1312	166	87	181	0
45	5	Clark	HRA-6	660	06/12/92	c	582	64	89	152	272
47	1	Clark	HRA-6	660	03/26/87	c	672	82	88	246	197
47	2	Clark	HRA-6	660	08/26/88	c	1159	155	87	231	160
47	3	Clark	HRA-6	660	05/23/89	c	619	72	88	225	95
47	4	Clark	HRA-6	660	04/23/90	c	1237	222	82	191	0
47	5	Clark	HRA-6	660	06/12/92	c	679	83	88	416	401
139	1	Cooper Bessemer	GMV	660	10/23/87	d	304	151	50	0	0
139	2	Cooper Bessemer	GMV	660	08/04/88	d	170	170	0	0	0
248	1	Cooper Bessemer	GMV-8	800	03/13/87	m	609	77	87	215	1203
248	2	Cooper Bessemer	GMV-8	800	08/03/87	m	1100	83	93	177	256
248	3	Cooper Bessemer	GMV-8	800	06/10/87	m	818	108	87	429	0
248	4	Cooper Bessemer	GMV-8	800	08/26/87	m	779	132	83	559	1617
248	5	Cooper Bessemer	GMV-8	800	01/08/88	m	660	98	85	420	0
248	6	Cooper Bessemer	GMV-8	800	06/23/88	m	638	46	93	680	0
248	7	Cooper Bessemer	GMV-8	800	09/09/88	m	576	38	93	1443	0
248	8	Cooper Bessemer	GMV-8	800	06/22/89	m	972	95	90	984	382
248	9	Cooper Bessemer	GMV-8	800	03/02/90	m	532	58	89	324	552
248	10	Cooper Bessemer	GMV-8	800	06/20/90	m	0	45	0	403	0
309	1	Clark	HRA-32	350	04/28/86	m	220	67	70	485	0
309	2	Clark	HRA-32	350	08/27/86	m	259	90	65	460	0
309	3	Clark	HRA-32	350	12/17/86	m	238	39	84	310	204
309	4	Clark	HRA-32	350	02/26/87	m	211	50	76	289	0
309	5	Clark	HRA-32	350	06/11/87	m	293	52	82	208	0
309	6	Clark	HRA-32	350	10/08/87	m	556	111	80	214	0
309	7	Clark	HRA-32	350	12/15/87	m	373	111	70	396	473
309	8	Clark	HRA-32	350	03/30/88	m	303	63	79	273	0
309	9	Clark	HRA-32	350	09/09/88	m	314	75	76	359	0
309	10	Clark	HRA-32	350	03/15/89	m	199	61	69	362	0
309	11	Clark	HRA-32	350	06/16/89	m	161	55	67	167	0
309	12	Clark	HRA-32	350	10/30/89	m	336	100	70	325	0
357	1	Tecogen	CM-200	291	12/07/89	c	354	10	97	7574	14
357	2	Tecogen	CM-200	291	04/13/90	c	646	36	95	406	4

REFERENCE FOR APPENDIX A

1. Diskette from Price, D. R., Ventura County Air Pollution Control District, to Snyder, R. B., Midwest Research Institute. Received March 22, 1993. Data base of reciprocating engine emission test summaries (ENGTESTM.DBF).

APPENDIX B.

This appendix contains tables of the cost and cost-effectiveness figures presented in Chapter 6. The methodologies used to calculate the values shown in these tables are discussed in Chapter 6.

TABLE B-1. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF AN AUTOMATIC A/F CONTROL SYSTEM TO A RICH-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
80	8,140	8,000	7,000	560	3,850	11,400
150	8,140	8,000	7,000	560	3,850	11,400
250	7,820	8,000	7,000	560	3,850	11,400
350	7,820	8,000	7,000	560	3,850	11,400
500	7,540	8,000	7,000	560	3,850	11,400
650	7,540	8,000	7,000	560	3,850	11,400
850	7,540	8,000	7,000	560	3,850	11,400
1,200	7,460	8,000	10,000	800	5,500	16,300
1,600	7,460	8,000	10,000	800	5,500	16,300
2,000	7,460	8,000	10,000	800	5,500	16,300
2,500	6,780	8,000	10,000	800	5,500	16,300
4,000	6,780	8,000	15,000	1,200	8,250	24,500
6,000	6,680	8,000	15,000	1,200	8,250	24,500
8,000	6,680	8,000	15,000	1,200	8,250	24,500

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
80	8,140	8,000	700	420	1,080	456	2,440	1,250	6,340
150	8,140	8,000	700	420	2,020	456	2,440	1,250	7,290
250	7,820	8,000	700	420	3,230	456	2,440	1,250	8,500
350	7,820	8,000	700	420	4,520	456	2,440	1,250	9,790
500	7,540	8,000	700	420	6,220	456	2,440	1,250	11,500
650	7,540	8,000	700	420	8,090	456	2,440	1,250	13,400
850	7,540	8,000	700	420	10,600	456	2,440	1,250	15,900
1,200	7,460	8,000	1,000	600	14,800	652	2,440	1,790	21,300
1,600	7,460	8,000	1,000	600	19,700	652	2,440	1,790	26,200
2,000	7,460	8,000	1,000	600	24,600	652	2,440	1,790	31,100
2,500	6,780	8,000	1,000	600	28,000	652	2,440	1,790	34,500
4,000	6,780	8,000	1,500	900	44,800	978	2,440	2,680	53,300
6,000	6,680	8,000	1,500	900	66,200	978	2,440	2,680	74,700
8,000	6,680	8,000	1,500	900	88,200	978	2,440	2,680	96,700

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	NOx reduction, %	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
80	8,140	8,000	11.1	20	8.91	2.23	6,340	2,850
150	8,140	8,000	20.9	20	16.7	4.17	7,290	1,740
250	7,820	8,000	34.8	20	27.8	6.96	8,500	1,220
350	7,820	8,000	48.7	20	39.0	9.74	9,790	1,000
500	7,540	8,000	69.6	20	55.7	13.9	11,500	826
650	7,540	8,000	90.5	20	72.4	18.1	13,400	739
850	7,540	8,000	118	20	94.6	23.7	15,900	670
1,200	7,460	8,000	167	20	134	33.4	21,300	637
1,600	7,460	8,000	223	20	178	44.5	26,200	588
2,000	7,460	8,000	278	20	223	55.7	31,100	559
2,500	6,780	8,000	348	20	278	69.6	34,500	495
4,000	6,780	8,000	557	20	445	111	53,300	479
6,000	6,680	8,000	835	20	668	167	74,700	447
8,000	6,680	8,000	1,110	20	891	223	96,700	434

TABLE B-2. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF AN ELECTRONIC IGNITION SYSTEM TO A RICH-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
80	8,140	8,000	7,500	600	4,130	12,200
150	8,140	8,000	7,500	600	4,130	12,200
250	7,820	8,000	7,500	600	4,130	12,200
350	7,820	8,000	7,500	600	4,130	12,200
500	7,540	8,000	7,500	600	4,130	12,200
650	7,540	8,000	7,500	600	4,130	12,200
850	7,540	8,000	7,500	600	4,130	12,200
1,200	7,460	8,000	10,000	800	5,500	16,300
1,600	7,460	8,000	10,000	800	5,500	16,300
2,000	7,460	8,000	10,000	800	5,500	16,300
2,500	6,780	8,000	10,000	800	5,500	16,300
4,000	6,780	8,000	15,000	1,200	8,250	24,500
6,000	6,680	8,000	15,000	1,200	8,250	24,500
8,000	6,680	8,000	15,000	1,200	8,250	24,500

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
80	8,140	8,000	750	450	869	489	2,440	1,340	6,340
150	8,140	8,000	750	450	1,630	489	2,440	1,340	7,100
250	7,820	8,000	750	450	2,610	489	2,440	1,340	8,080
350	7,820	8,000	750	450	3,650	489	2,440	1,340	9,130
500	7,540	8,000	750	450	5,030	489	2,440	1,340	10,500
650	7,540	8,000	750	450	6,540	489	2,440	1,340	12,000
850	7,540	8,000	750	450	8,560	489	2,440	1,340	14,000
1,200	7,460	8,000	1,000	600	12,000	652	2,440	1,790	18,400
1,600	7,460	8,000	1,000	600	15,900	652	2,440	1,790	22,400
2,000	7,460	8,000	1,000	600	19,900	652	2,440	1,790	26,400
2,500	6,780	8,000	1,000	600	22,600	652	2,440	1,790	29,100
4,000	6,780	8,000	1,500	900	36,200	978	2,440	2,680	44,700
6,000	6,680	8,000	1,500	900	53,500	978	2,440	2,680	62,000
8,000	6,680	8,000	1,500	900	71,300	978	2,440	2,680	79,800

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	NOx reduction, %	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
80	8,140	8,000	11.1	20	8.91	2.23	6,340	2,850
150	8,140	8,000	20.9	20	16.7	4.17	7,100	1,700
250	7,820	8,000	34.8	20	27.8	6.96	8,080	1,160
350	7,820	8,000	48.7	20	39.0	9.74	9,130	937
500	7,540	8,000	69.6	20	55.7	13.9	10,500	755
650	7,540	8,000	90.5	20	72.4	18.1	12,000	664
850	7,540	8,000	118	20	94.6	23.7	14,000	593
1,200	7,460	8,000	167	20	134	33.4	18,400	552
1,600	7,460	8,000	223	20	178	44.5	22,400	503
2,000	7,460	8,000	278	20	223	55.7	26,400	474
2,500	6,780	8,000	348	20	278	69.6	29,100	418
4,000	6,780	8,000	557	20	445	111	44,700	402
6,000	6,680	8,000	835	20	668	167	62,000	371
8,000	6,680	8,000	1110	20	891	223	79,800	359

TABLE B-3. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF AUTOMATIC A/F CONTROL AND ELECTRONIC IGNITION SYSTEMS TO A RICH-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
80	8,140	8,000	14,500	1,160	7,980	23,600
150	8,140	8,000	14,500	1,160	7,980	23,600
250	7,820	8,000	14,500	1,160	7,980	23,600
350	7,820	8,000	14,500	1,160	7,980	23,600
500	7,540	8,000	14,500	1,160	7,980	23,600
650	7,540	8,000	14,500	1,160	7,980	23,600
850	7,540	8,000	14,500	1,160	7,980	23,600
1,200	7,460	8,000	20,000	1,600	11,000	32,600
1,600	7,460	8,000	20,000	1,600	11,000	32,600
2,000	7,460	8,000	20,000	1,600	11,000	32,600
2,500	6,780	8,000	20,000	1,600	11,000	32,600
4,000	6,780	8,000	30,000	2,400	16,500	48,900
6,000	6,680	8,000	30,000	2,400	16,500	48,900
8,000	6,680	8,000	30,000	2,400	16,500	48,900

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
80	8,140	8,000	1,450	870	1,510	945	2,440	2,590	9,810
150	8,140	8,000	1,450	870	2,820	945	2,440	2,590	11,100
250	7,820	8,000	1,450	870	4,520	945	2,440	2,590	12,800
350	7,820	8,000	1,450	870	6,330	945	2,440	2,590	14,600
500	7,540	8,000	1,450	870	8,710	945	2,440	2,590	17,000
650	7,540	8,000	1,450	870	11,300	945	2,440	2,590	19,600
850	7,540	8,000	1,450	870	14,800	945	2,440	2,590	23,100
1,200	7,460	8,000	2,000	1,200	20,700	1,300	2,440	3,580	31,200
1,600	7,460	8,000	2,000	1,200	27,600	1,300	2,440	3,580	38,100
2,000	7,460	8,000	2,000	1,200	34,500	1,300	2,440	3,580	45,000
2,500	6,780	8,000	2,000	1,200	39,200	1,300	2,440	3,580	49,700
4,000	6,780	8,000	3,000	1,800	62,700	1,960	2,440	5,370	77,300
6,000	6,680	8,000	3,000	1,800	92,600	1,960	2,440	5,370	107,000
8,000	6,680	8,000	3,000	1,800	124,000	1,960	2,440	5,370	138,000

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	NOx reduction, %	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
80	8,140	8,000	11.1	30	7.79	3.34	9,810	2,940
150	8,140	8,000	20.9	30	14.6	6.26	11,100	1,780
250	7,820	8,000	34.8	30	24.4	10.4	12,800	1,230
350	7,820	8,000	48.7	30	34.1	14.6	14,600	1,000
500	7,540	8,000	69.6	30	48.7	20.9	17,000	815
650	7,540	8,000	90.5	30	63.3	27.1	19,600	723
850	7,540	8,000	118	30	82.8	35.5	23,100	651
1,200	7,460	8,000	167	30	117	50.1	31,200	623
1,600	7,460	8,000	223	30	156	66.8	38,100	571
2,000	7,460	8,000	278	30	195	83.5	45,000	539
2,500	6,780	8,000	348	30	244	104	49,700	476
4,000	6,780	8,000	557	30	390	167	77,300	463
6,000	6,680	8,000	835	30	584	250	107,000	428
8,000	6,680	8,000	1110	30	779	334	138,000	413

TABLE B-4. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF A PRESTRATIFIED CHARGE (PSC®) SYSTEM, WITHOUT TURBOCHARGER MODIFICATION OR ADDITION, TO A RICH-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
80	8,140	8,000	11,800	948	6,520	19,300
150	8,140	8,000	18,800	1,500	10,300	30,600
250	7,820	8,000	24,900	2,000	13,700	40,700
350	7,820	8,000	28,400	2,280	15,600	46,400
500	7,540	8,000	31,000	2,480	17,000	50,500
650	7,540	8,000	32,100	2,570	17,700	52,400
850	7,540	8,000	33,300	2,670	18,300	54,300
1,200	7,460	8,000	34,600	2,770	19,000	56,400
1,600	7,460	8,000	35,700	2,860	19,600	58,200
2,000	7,460	8,000	36,800	2,940	20,200	60,000
2,500	6,780	8,000	38,200	3,050	21,000	62,200
4,000	6,780	8,000	42,300	3,380	23,300	68,900
6,000	6,680	8,000	47,800	3,820	26,300	77,900
8,000	6,680	8,000	53,300	4,260	29,300	86,800

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Operating Labor, $	Supervisory Labor, $	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
80	8,140	8,000	54,000	8,100	1,180	711	430	772	2,440	2,120	69,800
150	8,140	8,000	54,000	8,100	1,880	1,130	806	1,220	2,440	3,360	72,900
250	7,820	8,000	54,000	8,100	2,490	1,500	1,290	1,630	2,440	4,460	75,900
350	7,820	8,000	54,000	8,100	2,840	1,710	1,810	1,850	2,440	5,090	77,800
500	7,540	8,000	54,000	8,100	3,100	1,860	2,490	2,020	2,440	5,550	79,600
650	7,540	8,000	54,000	8,100	3,210	1,930	3,240	2,100	2,440	5,750	80,800
850	7,540	8,000	54,000	8,100	3,330	2,000	4,230	2,170	2,440	5,970	82,200
1,200	7,460	8,000	54,000	8,100	3,460	2,080	5,910	2,260	2,440	6,190	84,400
1,600	7,460	8,000	54,000	8,100	3,570	2,140	7,880	2,330	2,440	6,390	86,800
2,000	7,460	8,000	54,000	8,100	3,680	2,210	9,850	2,400	2,440	6,580	89,300
2,500	6,780	8,000	54,000	8,100	3,820	2,290	11,200	2,490	2,440	6,830	91,200
4,000	6,780	8,000	54,000	8,100	4,230	2,540	17,900	2,760	2,440	7,570	99,500
6,000	6,680	8,000	54,000	8,100	4,780	2,870	26,500	3,110	2,440	8,550	110,000
8,000	6,680	8,000	54,000	8,100	5,330	3,200	35,300	3,470	2,440	9,530	121,000

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	Controlled NOx, g/hp-hr	Controlled NOx, tons/yr	NOx removed tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
80	8,140	8,000	11.1	2.0	1.41	9.72	69,800	7,170
150	8,140	8,000	20.9	2.0	2.64	18.2	72,900	4,000
250	7,820	8,000	34.8	2.0	4.41	30.4	75,900	2,500
350	7,820	8,000	48.7	2.0	6.17	42.5	77,800	1,830
500	7,540	8,000	69.6	2.0	8.81	60.8	79,600	1,310
650	7,540	8,000	90.5	2.0	11.5	79.0	80,800	1,020
850	7,540	8,000	118	2.0	15.0	103	82,200	796
1,200	7,460	8,000	167	2.0	21.1	146	84,400	579
1,600	7,460	8,000	223	2.0	28.2	194	86,800	447
2,000	7,460	8,000	278	2.0	35.2	243	89,300	367
2,500	6,780	8,000	348	2.0	44.1	304	91,200	300
4,000	6,780	8,000	557	2.0	70.5	486	99,500	205
6,000	6,680	8,000	835	2.0	106	729	110,000	151
8,000	6,680	8,000	1110	2.0	141	972	121,000	125

TABLE B-5. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF A PRESTRATIFIED CHARGE (PSC®) SYSTEM, WITH TURBOCHARGER MODIFICATION OR ADDITION, TO A RICH-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
80	8,140	8,000	16,100	1,290	10,500	27,900
150	8,140	8,000	28,100	2,250	18,300	48,700
250	7,820	8,000	42,300	3,380	27,500	73,100
350	7,820	8,000	53,200	4,250	34,600	92,000
500	7,540	8,000	64,500	5,160	41,900	112,000
650	7,540	8,000	71,100	5,690	46,200	123,000
850	7,540	8,000	75,100	6,010	48,800	130,000
1,200	7,460	8,000	78,800	6,300	51,200	136,000
1,600	7,460	8,000	81,500	6,520	53,000	141,000
2,000	7,460	8,000	84,100	6,730	54,700	146,000
2,500	6,780	8,000	87,400	6,990	56,800	151,000
4,000	6,780	8,000	97,300	7,780	63,200	168,000
6,000	6,680	8,000	110,000	8,830	71,700	191,000
8,000	6,680	8,000	124,000	9,880	80,300	214,000

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Operating Labor, $	Supervisory Labor, $	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Annual Cost, $
80	8,140	8,000	54,000	8,100	1,610	967	430	1,120	2,440	3,060	71,700
150	8,140	8,000	54,000	8,100	2,810	1,690	806	1,950	2,440	5,350	77,100
250	7,820	8,000	54,000	8,100	4,230	2,540	1,290	2,920	2,440	8,030	83,500
350	7,820	8,000	54,000	8,100	5,320	3,190	1,810	3,680	2,440	10,100	88,600
500	7,540	8,000	54,000	8,100	6,450	3,870	2,490	4,460	2,440	12,300	94,100
650	7,540	8,000	54,000	8,100	7,110	4,270	3,240	4,920	2,440	13,500	97,600
850	7,540	8,000	54,000	8,100	7,510	4,510	4,230	5,200	2,440	14,300	100,000
1,200	7,460	8,000	54,000	8,100	7,880	4,730	5,910	5,450	2,440	15,000	103,000
1,600	7,460	8,000	54,000	8,100	8,150	4,890	7,880	5,640	2,440	15,500	107,000
2,000	7,460	8,000	54,000	8,100	8,410	5,050	9,850	5,820	2,440	16,000	110,000
2,500	6,780	8,000	54,000	8,100	8,740	5,240	11,200	6,050	2,440	16,600	112,000
4,000	6,780	8,000	54,000	8,100	9,730	5,840	17,900	6,730	2,440	18,500	123,000
6,000	6,680	8,000	54,000	8,100	11,000	6,620	26,500	7,640	2,440	21,000	137,000
8,000	6,680	8,000	54,000	8,100	12,400	7,410	35,300	8,550	2,440	23,500	152,000

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	Controlled NOx, g/hp-hr	Controlled NOx, tons/yr	NOx removed tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
80	8,140	8,000	11.1	2.0	1.41	9.72	71,700	7,380
150	8,140	8,000	20.9	2.0	2.64	18.2	77,100	4,230
250	7,820	8,000	34.8	2.0	4.41	30.4	83,500	2,750
350	7,820	8,000	48.7	2.0	6.17	42.5	88,600	2,080
500	7,540	8,000	69.6	2.0	8.81	60.8	94,100	1,550
650	7,540	8,000	90.5	2.0	11.5	79.0	97,600	1,240
850	7,540	8,000	118	2.0	15.0	103	100,000	970
1,200	7,460	8,000	167	2.0	21.1	146	103,000	709
1,600	7,460	8,000	223	2.0	28.2	194	107,000	548
2,000	7,460	8,000	278	2.0	35.2	243	110,000	451
2,500	6,780	8,000	348	2.0	44.1	304	112,000	370
4,000	6,780	8,000	557	2.0	70.5	486	123,000	253
6,000	6,680	8,000	835	2.0	106	729	137,000	188
8,000	6,680	8,000	1110	2.0	141	972	152,000	156

TABLE B-6. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF NONSELECTIVE CATALYTIC REDUCTION (NSCR) TO A RICH-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
80	8,050	8,000	7,200	576	7,060	14,800
150	8,050	8,000	8,250	248	8,090	16,600
250	7,830	8,000	9,750	293	9,560	19,600
350	7,830	8,000	11,300	338	11,000	22,600
500	7,700	8,000	13,500	405	13,200	27,100
650	7,700	8,000	15,800	473	15,400	31,700
850	7,470	8,000	18,800	563	18,400	37,700
1,200	7,470	8,000	24,000	720	23,500	48,200
1,600	7,440	8,000	30,000	900	29,400	60,300
2,000	7,440	8,000	36,000	1,080	35,300	72,400
2,500	7,110	8,000	43,500	1,310	42,600	87,400
4,000	7,110	8,000	66,000	1,980	64,700	133,000
6,000	6,800	8,000	96,000	2,880	94,100	193,000
8,000	6,800	8,000	126,000	3,780	123,000	253,000

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Operating Labor, $	Supervisory Labor, $	Maintenance, $	Overhead, $	Fuel Penalty, $	Catalyst Cleaning, $	Catalyst Replacement, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
80	8,050	8,000	54,000	8,100	720	432	1,060	22.0	293	593	2,440	1,630	69,300
150	8,050	8,000	54,000	8,100	825	495	1,990	41.3	550	663	2,440	1,820	70,900
250	7,830	8,000	54,000	8,100	975	585	3,230	68 8	917	784	2,440	2,150	73,300
350	7,830	8,000	54,000	8,100	1,130	675	4,530	96.3	1,280	905	2,440	2,480	75,600
500	7,700	8,000	54,000	8,100	1,350	810	6,360	138	1,830	1,090	2,440	2,980	79,100
650	7,700	8,000	54,000	8,100	1,580	945	8,270	179	2,380	1,270	2,440	3,480	82,600
850	7,470	8,000	54,000	8,100	1,880	1,130	10,500	234	3,120	1,510	2,440	4,140	87,000
1,200	7,470	8,000	54,000	8,100	2,400	1,440	14,800	330	4,400	1,930	2,440	5,300	95,100
1,600	7,440	8,000	54,000	8,100	3,000	1,800	19,700	440	5,870	2,410	2,440	6,620	104,000
2,000	7,440	8,000	54,000	8,100	3,600	2,160	24,600	550	7,330	2,890	2,440	7,940	114,000
2,500	7,110	8,000	54,000	8,100	4,350	2,610	29,300	688	9,170	3,500	2,440	9,600	124,000
4,000	7,110	8,000	54,000	8,100	6,600	3,960	46,900	1,100	14,700	5,310	2,440	14,600	158,000
6,000	6,800	8,000	54,000	8,100	9,600	5,760	67,400	1,650	22,000	7,720	2,440	21,200	200,000
8,000	6,800	8,000	54,000	8,100	12,600	7,560	89,800	2,200	29,300	10,100	2,440	27,800	244,000

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	NOx Reduction, %	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
80	8,050	8,000	11.1	90	1.11	10.0	69,300	6,920
150	8,050	8,000	20.9	90	2.09	18.8	70,900	3,780
250	7,830	8,000	34.8	90	3.48	31.3	73,300	2,340
350	7,830	8,000	48.7	90	4.87	43 8	75,600	1,730
500	7,700	8,000	69.6	90	6.96	62.6	79,100	1,260
650	7,700	8,000	90.5	90	9.05	81 4	82,600	1,010
850	7,470	8,000	118	90	11.8	106	87,000	817
1,200	7,470	8,000	167	90	16.7	150	95,100	633
1,600	7,440	8,000	223	90	22.3	200	104,000	521
2,000	7,440	8,000	278	90	27.8	250	114,000	454
2,500	7,110	8,000	348	90	34.8	313	124,000	395
4,000	7,110	8,000	557	90	55.7	501	158,000	315
6,000	6,800	8,000	835	90	83 5	751	200,000	266
8,000	6,800	8,000	1110	90	111	1,000	244,000	244

TABLE B-7. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF LOW-EMISSION COMBUSTION TO A MEDIUM-SPEED, RICH-BURN OR LEAN-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
80	8,140	8,000	22,500	1,800	14,600	38,900
150	8,140	8,000	29,900	2,390	19,400	51,700
250	7,820	8,000	40,500	3,240	26,300	70,100
350	7,820	8,000	51,100	4,090	33,200	88,400
500	7,540	8,000	67,000	5,360	43,500	116,000
650	7,540	8,000	82,800	6,630	53,800	143,000
850	7,540	8,000	104,000	8,320	67,600	180,000
1,200	7,460	8,000	141,000	11,300	91,700	244,000
1,600	7,460	8,000	183,000	14,700	119,000	317,000
2,000	7,460	8,000	226,000	18,100	147,000	390,000
2,500	6,780	8,000	279,000	22,300	181,000	482,000
4,000	6,780	8,000	437,000	35,000	284,000	757,000
6,000	6,680	8,000	649,000	51,900	422,000	1,120,000
8,000	6,680	8,000	861,000	68,800	559,000	1,490,000

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
80	8,140	8,000	2,250	1,350	(215)	1,560	2,440	4,270	11,700
150	8,140	8,000	2,990	1,790	(403)	2,070	2,440	5,680	14,600
250	7,820	8,000	4,050	2,430	(646)	2,800	2,440	7,690	18,800
350	7,820	8,000	5,110	3,060	(904)	3,530	2,440	9,700	22,900
500	7,540	8,000	6,700	4,020	(1,240)	4,630	2,440	12,700	29,300
650	7,540	8,000	8,280	4,970	(1,620)	5,730	2,440	15,700	35,500
850	7,540	8,000	10,400	6,240	(2,120)	7,200	2,440	19,800	43,900
1,200	7,460	8,000	14,100	8,460	(2,960)	9,760	2,440	26,800	58,600
1,600	7,460	8,000	18,300	11,000	(3,940)	12,700	2,440	34,800	75,300
2,000	7,460	8,000	22,600	13,500	(4,930)	15,600	2,440	42,900	92,100
2,500	6,780	8,000	27,900	16,700	(5,600)	19,300	2,440	52,900	114,000
4,000	6,780	8,000	43,700	26,200	(8,960)	30,300	2,440	83,100	177,000
6,000	6,680	8,000	64,900	38,900	(13,200)	44,900	2,440	123,000	261,000
8,000	6,680	8,000	86,100	51,600	(17,650)	59,600	2,440	163,000	346,000

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	Controlled NOx, g/hp-hr	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
80	8,140	8,000	11.1	2.0	1.41	9.72	11,700	1,200
150	8,140	8,000	20.9	2.0	2.64	18.2	14,600	799
250	7,820	8,000	34.8	2.0	4.41	30.4	18,800	618
350	7,820	8,000	48.7	2.0	6.17	42.5	22,900	539
500	7,540	8,000	69.6	2.0	8.81	60.8	29,300	481
650	7,540	8,000	90.5	2.0	11.5	79.0	35,500	450
850	7,540	8,000	118	2.0	15.0	103	43,900	425
1,200	7,460	8,000	167	2.0	21.1	146	58,600	402
1,600	7,460	8,000	223	2.0	28.2	194	75,300	387
2,000	7,460	8,000	278	2.0	35.2	243	92,100	379
2,500	6,780	8,000	348	2.0	44.1	304	114,000	374
4,000	6,780	8,000	557	2.0	70.5	486	177,000	364
6,000	6,680	8,000	835	2.0	106	729	261,000	358
8,000	6,680	8,000	1110	2.0	141	972	346,000	355

TABLE B-8. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF LOW-EMISSION COMBUSTION TO A LOW-SPEED, RICH-BURN OR LEAN-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
80	8,140	8,000	198,000	15,800	129,000	343,000
150	8,140	8,000	212,000	17,000	138,000	367,000
250	7,820	8,000	232,000	18,600	151,000	402,000
350	7,820	8,000	253,000	20,200	164,000	437,000
500	7,540	8,000	283,000	22,600	184,000	489,000
650	7,540	8,000	313,000	25,000	203,000	541,000
850	7,540	8,000	353,000	28,300	230,000	611,000
1,200	7,460	8,000	424,000	33,900	275,000	733,000
1,600	7,460	8,000	504,000	40,400	328,000	873,000
2,000	7,460	8,000	585,000	46,800	380,000	1,010,000
2,500	6,780	8,000	686,000	54,900	446,000	1,190,000
4,000	6,780	8,000	988,000	79,000	642,000	1,710,000
6,000	6,680	8,000	1,390,000	111,000	904,000	2,410,000
8,000	6,680	8,000	1,790,000	144,000	1,170,000	3,100,000

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
80	8,140	8,000	19,800	11,900	(215)	13,700	2,440	37,600	85,300
150	8,140	8,000	21,200	12,700	(403)	14,700	2,440	40,300	91,000
250	7,820	8,000	23,200	13,900	(646)	16,100	2,440	44,100	99,200
350	7,820	8,000	25,300	15,200	(904)	17,500	2,440	48,000	107,000
500	7,540	8,000	28,300	17,000	(1,240)	19,600	2,440	53,700	120,000
650	7,540	8,000	31,300	18,800	(1,620)	21,700	2,440	59,400	132,000
850	7,540	8,000	35,300	21,200	(2,120)	24,400	2,440	67,100	148,000
1,200	7,460	8,000	42,400	25,400	(2,960)	29,300	2,440	80,500	177,000
1,600	7,460	8,000	50,400	30,300	(3,940)	34,900	2,440	95,800	210,000
2,000	7,460	8,000	58,500	35,100	(4,930)	40,500	2,440	111,000	243,000
2,500	6,780	8,000	68,600	41,100	(5,600)	47,500	2,440	130,000	284,000
4,000	6,780	8,000	98,800	59,300	(8,960)	68,400	2,440	188,000	408,000
6,000	6,680	8,000	139,000	83,500	(13,200)	96,300	2,440	264,000	572,000
8,000	6,680	8,000	179,000	108,000	(17,600)	124,000	2,440	341,000	737,000

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	Controlled NOx, g/hp-hr	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
80	8,140	8,000	11.1	2.0	1.41	9.72	85,300	8,770
150	8,140	8,000	20.9	2.0	2.64	18.2	91,000	4,990
250	7,820	8,000	34.8	2.0	4.41	30.4	99,200	3,260
350	7,820	8,000	48.7	2.0	6.17	42.5	107,000	2,520
500	7,540	8,000	69.6	2.0	8.81	60.8	120,000	1,970
650	7,540	8,000	90.5	2.0	11.5	79.0	132,000	1,670
850	7,540	8,000	118	2.0	15.0	103	148,000	1,440
1,200	7,460	8,000	167	2.0	21.1	146	177,000	1,210
1,600	7,460	8,000	223	2.0	28.2	194	210,000	1,080
2,000	7,460	8,000	278	2.0	35.2	243	243,000	998
2,500	6,780	8,000	348	2.0	44.1	304	284,000	936
4,000	6,780	8,000	557	2.0	70.5	486	408,000	838
6,000	6,680	8,000	835	2.0	106	729	572,000	785
8,000	6,680	8,000	1110	2.0	141	972	737,000	758

TABLE B-9. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF AN AUTOMATIC A/F CONTROL SYSTEM TO A LEAN-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
200	8,760	8,000	42,700	3,410	27,700	73,800
350	8,760	8,000	43,100	3,450	28,000	74,600
550	7,660	8,000	43,700	3,500	28,400	75,600
800	7,660	8,000	44,500	3,560	28,900	76,900
1,350	7,490	8,000	46,100	3,690	30,000	79,800
1,550	7,490	8,000	46,700	3,740	30,400	80,800
2,000	7,490	8,000	48,100	3,840	31,200	83,100
2,500	7,020	8,000	49,600	3,960	32,200	85,700
3,500	7,020	8,000	52,600	4,200	34,200	90,900
5,500	6,660	8,000	58,600	4,680	38,100	101,000
8,000	6,660	8,000	66,100	5,280	42,900	114,000
9,500	6,660	8,000	70,600	5,640	45,900	122,000
11,000	6,660	8,000	75,100	6,000	48,800	130,000

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
200	8,760	8,000	4,270	2,560	1,740	2,950	2,440	8,100	22,100
350	8,760	8,000	4,310	2,590	3,040	2,980	2,440	8,190	23,500
550	7,660	8,000	4,370	2,620	4,170	3,020	2,440	8,300	24,900
800	7,660	8,000	4,450	2,670	6,070	3,080	2,440	8,440	27,100
1,350	7,490	8,000	4,610	2,770	10,000	3,190	2,440	8,760	31,800
1,550	7,490	8,000	4,670	2,800	11,500	3,230	2,440	8,870	33,500
2,000	7,490	8,000	4,810	2,880	14,800	3,330	2,440	9,130	37,400
2,500	7,020	8,000	4,960	2,970	17,400	3,430	2,440	9,410	40,600
3,500	7,020	8,000	5,260	3,150	24,300	3,640	2,440	9,980	48,800
5,500	6,660	8,000	5,860	3,510	36,300	4,050	2,440	11,100	63,300
8,000	6,660	8,000	6,610	3,960	52,800	4,570	2,440	12,500	82,900
9,500	6,660	8,000	7,060	4,230	62,700	4,880	2,440	13,400	94,700
11,000	6,660	8,000	7,510	4,500	72,600	5,190	2,440	14,300	106,000

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	NOx reduction, %	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
200	8,760	8,000	29.6	20	23.7	5.91	22,100	3,730
350	8,760	8,000	51.7	20	41.4	10.3	23,500	2,270
550	7,660	8,000	81.3	20	65.1	16.3	24,900	1,530
800	7,660	8,000	118	20	94.6	23.7	27,100	1,150
1,350	7,490	8,000	200	20	160	39.9	31,800	796
1,550	7,490	8,000	229	20	183	45.8	33,500	731
2,000	7,490	8,000	296	20	237	59.1	37,400	633
2,500	7,020	8,000	370	20	296	73.9	40,600	549
3,500	7,020	8,000	517	20	414	103	48,800	472
5,500	6,660	8,000	813	20	651	163	63,300	389
8,000	6,660	8,000	1180	20	946	237	82,900	350
9,500	6,660	8,000	1400	20	1120	281	94,700	337
11,000	6,660	8,000	1630	20	1300	325	106,000	327

TABLE B-10. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF AN ELECTRONIC IGNITION SYSTEM TO A LEAN-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
200	8,760	8,000	7,500	600	4,130	12,200
350	8,760	8,000	7,500	600	4,130	12,200
550	7,660	8,000	7,500	600	4,130	12,200
800	7,660	8,000	7,500	600	4,130	12,200
800	7,660	8,000	10,000	800	5,500	16,300
1,350	7,490	8,000	10,000	800	5,500	16,300
1,550	7,490	8,000	10,000	800	5,500	16,300
2,000	7,490	8,000	10,000	800	5,500	16,300
2,500	7,020	8,000	10,000	800	5,500	16,300
2,500	7,020	8,000	15,000	1,200	8,250	24,500
3,500	7,020	8,000	15,000	1,200	8,250	24,500
5,500	6,660	8,000	15,000	1,200	8,250	24,500
8,000	6,660	8,000	15,000	1,200	8,250	24,500
9,500	6,660	8,000	15,000	1,200	8,250	24,500
11,000	6,660	8,000	15,000	1,200	8,250	24,500

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
200	8,760	8,000	750	450	1,740	489	2,440	1,340	7,210
350	8,760	8,000	750	450	3,040	489	2,440	1,340	8,510
550	7,660	8,000	750	450	4,170	489	2,440	1,340	9,640
800	7,660	8,000	750	450	6,070	489	2,440	1,340	11,500
800	7,660	8,000	1,000	600	6,070	652	2,440	1,790	12,600
1,350	7,490	8,000	1,000	600	10,000	652	2,440	1,790	16,500
1,550	7,490	8,000	1,000	600	11,500	652	2,440	1,790	18,000
2,000	7,490	8,000	1,000	600	14,800	652	2,440	1,790	21,300
2,500	7,020	8,000	1,000	600	17,400	652	2,440	1,790	23,900
2,500	7,020	8,000	1,500	900	17,400	978	2,440	2,680	25,900
3,500	7,020	8,000	1,500	900	24,300	978	2,440	2,680	32,800
5,500	6,660	8,000	1,500	900	36,300	978	2,440	2,680	44,800
8,000	6,660	8,000	1,500	900	52,800	978	2,440	2,680	61,300
9,500	6,660	8,000	1,500	900	62,700	978	2,440	2,680	71,200
11,000	6,660	8,000	1,500	900	72,600	978	2,440	2,680	81,100

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	NOx reduction, %	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
200	8,760	8,000	29.6	10	26.6	2.96	7,210	2,440
350	8,760	8,000	51.7	10	46.6	5.17	8,510	1,640
550	7,660	8,000	81.3	10	73.2	8.13	9,640	1,190
800	7,660	8,000	118	10	106	11.8	11,500	976
800	7,660	8,000	118	10	106	11.8	12,600	1,060
1,350	7,490	8,000	200	10	180	20.0	16,500	827
1,550	7,490	8,000	229	10	206	22.9	18,000	785
2,000	7,490	8,000	296	10	266	29.6	21,300	721
2,500	7,020	8,000	370	10	333	37.0	23,900	646
2,500	7,020	8,000	370	10	333	37.0	25,900	700
3,500	7,020	8,000	517	10	466	51.7	32,800	635
5,500	6,660	8,000	813	10	732	81.3	44,800	551
8,000	6,660	8,000	1180	10	1060	118	61,300	518
9,500	6,660	8,000	1400	10	1260	140	71,200	507
11,000	6,660	8,000	1630	10	1460	163	81,100	499

TABLE B-11. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF AUTOMATIC A/F CONTROL AND ELECTRONIC IGNITION SYSTEMS TO A LEAN-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
200	8,760	8,000	50,200	4,010	30,100	84,300
350	8,760	8,000	50,600	4,050	30,400	85,000
550	7,660	8,000	51,200	4,100	30,700	86,000
800	7,660	8,000	52,000	4,160	31,200	87,300
800	7,660	8,000	54,500	4,360	32,700	91,500
1,350	7,490	8,000	56,100	4,490	33,700	94,300
1,550	7,490	8,000	56,700	4,540	34,000	95,300
2,000	7,490	8,000	58,100	4,640	34,800	97,500
2,500	7,020	8,000	59,600	4,760	35,700	100,000
2,500	7,020	8,000	64,600	5,160	38,700	108,000
3,500	7,020	8,000	67,600	5,400	40,500	113,000
5,500	6,660	8,000	73,600	5,880	44,100	124,000
8,000	6,660	8,000	81,100	6,480	48,600	136,000
9,500	6,660	8,000	85,600	6,840	51,300	144,000
11,000	6,660	8,000	90,100	7,200	54,000	151,000

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
200	8,760	8,000	5,020	3,010	2,890	3,370	2,440	9,250	26,000
350	8,760	8,000	5,060	3,040	5,060	3,400	2,440	9,330	28,300
550	7,660	8,000	5,120	3,070	6,960	3,440	2,440	9,440	30,500
800	7,660	8,000	5,200	3,120	10,100	3,490	2,440	9,580	33,900
800	7,660	8,000	5,450	3,270	10,100	3,660	2,440	10,000	35,000
1,350	7,490	8,000	5,610	3,370	16,700	3,770	2,440	10,300	42,200
1,550	7,490	8,000	5,670	3,400	19,200	3,810	2,440	10,500	44,900
2,000	7,490	8,000	5,810	3,480	24,700	3,900	2,440	10,700	51,100
2,500	7,020	8,000	5,960	3,570	29,000	4,000	2,440	11,000	55,900
2,500	7,020	8,000	6,460	3,870	29,000	4,340	2,440	11,900	58,000
3,500	7,020	8,000	6,760	4,050	40,600	4,540	2,440	12,500	70,800
5,500	6,660	8,000	7,360	4,410	60,500	4,940	2,440	13,600	93,200
8,000	6,660	8,000	8,110	4,860	88,000	5,450	2,440	15,000	124,000
9,500	6,660	8,000	8,560	5,130	104,000	5,750	2,440	15,800	142,000
11,000	6,660	8,000	9,010	5,400	121,000	6,050	2,440	16,600	160,000

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NO_x, tons/yr	NO_x reduction, %	Controlled NO_x, tons/yr	NO_x removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NO_x removed
200	8,760	8,000	29.6	25	22.2	7.39	26,000	3,510
350	8,760	8,000	51.7	25	38.8	12.9	28,300	2,190
550	7,660	8,000	81.3	25	61.0	20.3	30,500	1,500
800	7,660	8,000	118	25	88.7	29.6	33,900	1,150
800	7,660	8,000	118	25	88.7	29.6	35,000	1,180
1,350	7,490	8,000	200	25	150	49.9	42,200	846
1,550	7,490	8,000	229	25	172	57.3	44,900	785
2,000	7,490	8,000	296	25	222	73.9	51,100	691
2,500	7,020	8,000	370	25	277	92.4	55,900	605
2,500	7,020	8,000	370	25	277	92.4	58,000	628
3,500	7,020	8,000	517	25	388	129	70,800	547
5,500	6,660	8,000	813	25	610	203	93,200	458
8,000	6,660	8,000	1180	25	887	296	124,000	419
9,500	6,660	8,000	1400	25	1050	351	142,000	405
11,000	6,660	8,000	1630	25	1220	407	160,000	395

TABLE B-12. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF SELECTIVE CATALYTIC REDUCTION (SCR) TO A LEAN-BURN SI ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
200	8,760	8,000	187,000	15,000	122,000	324,000
350	8,760	8,000	194,000	15,500	126,000	335,000
550	7,660	8,000	202,000	16,200	131,000	350,000
800	7,660	8,000	213,000	17,000	138,000	368,000
1,350	7,490	8,000	236,000	18,900	153,000	408,000
1,550	7,490	8,000	244,000	19,500	159,000	422,000
2,000	7,490	8,000	263,000	21,000	171,000	455,000
2,500	7,020	8,000	284,000	22,700	185,000	491,000
3,500	7,020	8,000	326,000	26,100	212,000	564,000
5,500	6,660	8,000	410,000	32,800	267,000	709,000
8,000	6,660	8,000	515,000	41,200	335,000	891,000
9,500	6,660	8,000	578,000	46,200	376,000	1,000,000
11,000	6,660	8,000	641,000	51,300	417,000	1,110,000

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Operating Labor, $	Supervisory Labor, $	Maintenance, $	Overhead, $	Fuel Penalty, $	Catalyst Cleaning, $	Catalyst Replacement & Disposal, $	Ammonia & Steam Consumption $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
200	8,760	8,000	81,000	12,200	18,700	11,200	289	110	735	5350	13,000	2,440	35,600	181,000
350	8,760	8,000	81,000	12,200	19,400	11,600	506	193	1,290	9360	13,400	2,440	36,800	188,000
550	7,660	8,000	81,000	12,200	20,200	12,100	696	303	2,020	14700	14,000	2,440	38,400	198,000
800	7,660	8,000	81,000	12,200	21,300	12,800	1,010	440	2,940	21400	14,700	2,440	40,400	210,000
1,350	7,490	8,000	81,000	12,200	23,600	14,100	1,670	743	4,960	36100	16,300	2,440	44,800	238,000
1,550	7,490	8,000	81,000	12,200	24,400	14,600	1,920	853	5,700	41500	16,900	2,440	46,400	248,000
2,000	7,490	8,000	81,000	12,200	26,300	15,800	2,470	1,100	7,350	53500	18,200	2,440	50,000	270,000
2,500	7,020	8,000	81,000	12,200	28,400	17,000	2,900	1,380	9,190	66900	19,700	2,440	53,900	295,000
3,500	7,020	8,000	81,000	12,200	32,600	19,600	4,060	1,930	12,900	93600	22,600	2,440	61,900	345,000
5,500	6,660	8,000	81,000	12,200	41,000	24,600	6,050	3,030	20,200	147000	28,400	2,440	77,900	444,000
8,000	6,660	8,000	81,000	12,200	51,500	30,900	8,800	4,400	29,400	214000	35,600	2,440	97,800	568,000
9,500	6,660	8,000	81,000	12,200	57,800	34,700	10,400	5,230	34,900	254000	40,000	2,440	110,000	643,000
11,000	6,660	8,000	81,000	12,200	64,100	38,500	12,100	6,050	40,400	294000	44,400	2,440	122,000	717,000

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NO_x, tons/yr	NO_x reduction, %	Controlled NO_x, tons/yr	NO_x removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NO_x removed
200	8,760	8,000	29.6	90	3 0	26 6	181,000	6,790
350	8,760	8,000	51.7	90	5 2	46.6	188,000	4,040
550	7,660	8,000	81.3	90	8 1	73 2	198,000	2,710
800	7,660	8,000	118	90	11 8	106	210,000	1,980
1,350	7,490	8,000	200	90	20 0	180	238,000	1,320
1,550	7,490	8,000	229	90	22 9	206	248,000	1,200
2,000	7,490	8,000	296	90	29 6	266	270,000	1,020
2,500	7,020	8,000	370	90	37.0	333	295,000	887
3,500	7,020	8,000	517	90	51 7	466	345,000	740
5,500	6,660	8,000	813	90	81.3	732	444,000	607
8,000	6,660	8,000	1183	90	118	1060	568,000	534
9,500	6,660	8,000	1405	90	140	1260	643,000	508
11,000	6,660	8,000	1626	90	163	1460	717,000	490

TABLE B-13. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF AN ELECTRONIC INJECTION CONTROL SYSTEM TO A DIESEL ENGINE

CAPITAL COSTS

Power Output hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
80	6,740	8,000	7,500	600	4,130	12,200
150	6,740	8,000	7,500	600	4,130	12,200
250	6,600	8,000	7,500	600	4,130	12,200
350	6,600	8,000	7,500	600	4,130	12,200
500	6,790	8,000	7,500	600	4,130	12,200
700	6,790	8,000	7,500	600	4,130	12,200
900	6,790	8,000	7,500	600	4,130	12,200
900	6,790	8,000	10,000	800	5,500	16,300
1,100	6,740	8,000	10,000	800	5,500	16,300
1,400	6,740	8,000	10,000	800	5,500	16,300
2,000	6,740	8,000	10,000	800	5,500	16,300
2,500	6,710	8,000	10,000	800	5,500	16,300
2,500	6,710	8,000	15,000	1,200	8,250	24,500
4,000	6,710	8,000	15,000	1,200	8,250	24,500
6,000	6,200	8,000	15,000	1,200	8,250	24,500
8,000	6,200	8,000	15,000	1,200	8,250	24,500

ANNUAL COSTS

Power Output hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
80	6,740	8,000	750	450	754	489	2,440	1,340	6,230
150	6,740	8,000	750	450	1,410	489	2,440	1,340	6,880
250	6,600	8,000	750	450	2,310	489	2,440	1,340	7,780
350	6,600	8,000	750	450	3,230	489	2,440	1,340	8,700
500	6,790	8,000	750	450	4,750	489	2,440	1,340	10,200
700	6,790	8,000	750	450	6,650	489	2,440	1,340	12,100
900	6,790	8,000	750	450	8,550	489	2,440	1,340	14,000
900	6,790	8,000	1,000	600	8,550	652	2,440	1,790	15,000
1,100	6,740	8,000	1,000	600	10,400	652	2,440	1,790	16,800
1,400	6,740	8,000	1,000	600	13,200	652	2,440	1,790	19,700
2,000	6,740	8,000	1,000	600	18,800	652	2,440	1,790	25,300
2,500	6,710	8,000	1,000	600	23,500	652	2,440	1,790	29,900
2,500	6,710	8,000	1,500	900	23,500	978	2,440	2,680	32,000
4,000	6,710	8,000	1,500	900	37,500	978	2,440	2,680	46,000
6,000	6,200	8,000	1,500	900	52,000	978	2,440	2,680	60,500
8,000	6,200	8,000	1,500	900	69,400	978	2,440	2,680	77,900

COST EFFECTIVENESS

Power Output hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	NOx reduction, %	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
80	6,740	8,000	8.45	25	6.33	2.11	6,230	2,950
150	6,740	8,000	15.8	25	11.9	3.96	6,880	1,740
250	6,600	8,000	26.4	25	19.8	6.60	7,780	1,180
350	6,600	8,000	36.9	25	27.7	9.24	8,700	942
500	6,790	8,000	52.8	25	39.6	13.2	10,200	774
700	6,790	8,000	73.9	25	55.4	18.5	12,100	656
900	6,790	8,000	95.0	25	71.3	23.8	14,000	590
900	6,790	8,000	95.0	25	71.3	23.8	15,000	633
1,100	6,740	8,000	116	25	87.1	29.0	16,800	580
1,400	6,740	8,000	148	25	111	36.9	19,700	533
2,000	6,740	8,000	211	25	158	52.8	25,300	480
2,500	6,710	8,000	264	25	198	66.0	29,900	454
2,500	6,710	8,000	264	25	198	66.0	32,000	484
4,000	6,710	8,000	422	25	317	106	46,000	436
6,000	6,200	8,000	633	25	475	158	60,500	382
8,000	6,200	8,000	845	25	633	211	77,900	369

TABLE B-14. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF SELECTIVE CATALYTIC REDUCTION (SCR) TO A DIESEL ENGINE

CAPITAL COSTS

Power Output hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
80	6,740	8,000	113,000	9,000	73,100	195,000
150	6,740	8,000	116,000	9,320	75,700	201,000
250	6,600	8,000	122,000	9,770	79,400	211,000
350	6,600	8,000	128,000	10,200	83,000	221,000
500	6,790	8,000	136,000	10,900	88,500	236,000
700	6,790	8,000	147,000	11,800	95,900	255,000
900	6,790	8,000	159,000	12,700	103,000	275,000
1,100	6,740	8,000	170,000	13,600	111,000	294,000
1,400	6,740	8,000	187,000	15,000	122,000	323,000
2,000	6,740	8,000	221,000	17,700	144,000	382,000
2,500	6,710	8,000	249,000	19,900	162,000	431,000
4,000	6,710	8,000	334,000	26,700	217,000	577,000
6,000	6,200	8,000	446,000	35,700	290,000	772,000
8,000	6,200	8,000	559,000	44,700	363,000	967,000

ANNUAL COSTS

Power Output hp	Heat Rate, Btu/hp-hr	Hours Per Year	Operating Labor, $	Supervisory Labor, $	Maintenance, $	Overhead, $	Fuel Penalty, $	Catalyst Cleaning, $	Catalyst Replacement & Disposal, $	Ammonia & Steam Consumption, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
80	6,740	8,000	81,000	12,200	11,300	6,750	126	66.0	221	1530	7,790	2,440	21,400	145,000
150	6,740	8,000	81,000	12,200	11,600	6,990	236	124	414	2870	8,060	2,440	22,100	148,000
250	6,600	8,000	81,000	12,200	12,200	7,330	385	206	689	4780	8,450	2,440	23,200	153,000
350	6,600	8,000	81,000	12,200	12,800	7,660	538	289	965	6690	8,840	2,440	24,300	158,000
500	6,790	8,000	81,000	12,200	13,600	8,170	791	413	1,380	9550	9,430	2,440	25,900	165,000
700	6,790	8,000	81,000	12,200	14,700	8,850	1,110	578	1,930	13400	10,200	2,440	28,000	174,000
900	6,790	8,000	81,000	12,200	15,900	9,530	1,420	743	2,480	17200	11,000	2,440	30,200	184,000
1,100	6,740	8,000	81,000	12,200	17,000	10,200	1,730	908	3,030	21000	11,800	2,440	32,300	194,000
1,400	6,740	8,000	81,000	12,200	18,700	11,200	2,200	1,160	3,860	26700	12,900	2,440	35,500	208,000
2,000	6,740	8,000	81,000	12,200	22,100	13,200	3,140	1,650	5,520	38200	15,300	2,440	41,900	237,000
2,500	6,710	8,000	81,000	12,200	24,900	14,900	3,910	2,060	6,890	47800	17,200	2,440	47,300	261,000
4,000	6,710	8,000	81,000	12,200	33,400	20,000	6,260	3,300	11,000	76400	23,100	2,440	63,400	332,000
6,000	6,200	8,000	81,000	12,200	44,600	26,800	8,670	4,950	16,500	115000	30,900	2,440	84,800	427,000
8,000	6,200	8,000	81,000	12,200	55,900	33,600	11,600	6,600	22,100	153000	38,700	2,440	106,000	523,000

COST EFFECTIVENESS

Power Output hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	NOx reduction, %	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
80	6,740	8,000	8.4	90	0.8	7.6	145,000	19,000
150	6,740	8,000	15.8	90	1.6	14.3	148,000	10,400
250	6,600	8,000	26.4	90	2.6	23.8	153,000	6,430
350	6,600	8,000	36.9	90	3.7	33.3	158,000	4,740
500	6,790	8,000	52.8	90	5.3	47.5	165,000	3,470
700	6,790	8,000	73.9	90	7.4	66.5	174,000	2,620
900	6,790	8,000	95.0	90	9.5	85.5	184,000	2,150
1,100	6,740	8,000	116	90	11.6	105	194,000	1,850
1,400	6,740	8,000	148	90	14.8	133	208,000	1,560
2,000	6,740	8,000	211	90	21.1	190	237,000	1,250
2,500	6,710	8,000	264	90	26.4	238	261,000	1,100
4,000	6,710	8,000	422	90	42.2	380	332,000	875
6,000	6,200	8,000	633	90	63.3	570	427,000	750
8,000	6,200	8,000	845	90	84.5	760	523,000	688

TABLE B-15. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF AN ELECTRONIC INJECTION CONTROL SYSTEM TO A DUAL-FUEL ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
700	6,920	8,000	7,500	600	4,130	12,200
900	6,920	8,000	7,500	600	4,130	12,200
900	6,920	8,000	10,000	800	5,500	16,300
1,200	7,220	8,000	10,000	800	5,500	16,300
1,650	7,220	8,000	10,000	800	5,500	16,300
2,200	6,810	8,000	10,000	800	5,500	16,300
2,200	6,810	8,000	15,000	1,200	8,250	24,500
4,000	6,810	8,000	15,000	1,200	8,250	24,500
6,000	6,150	8,000	15,000	1,200	8,250	24,500
8,000	6,150	8,000	15,000	1,200	8,250	24,500

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
700	6,920	8,000	750	450	4,800	489	2,440	1,340	10,300
900	6,920	8,000	750	450	6,170	489	2,440	1,340	11,600
900	6,920	8,000	1,000	600	6,170	652	2,440	1,790	12,700
1,200	7,220	8,000	1,000	600	8,580	652	2,440	1,790	15,100
1,650	7,220	8,000	1,000	600	11,800	652	2,440	1,790	18,300
2,200	6,810	8,000	1,000	600	14,800	652	2,440	1,790	21,300
2,200	6,810	8,000	1,500	900	14,800	978	2,440	2,680	23,300
4,000	6,810	8,000	1,500	900	27,000	978	2,440	2,680	35,500
6,000	6,150	8,000	1,500	900	36,600	978	2,440	2,680	45,100
8,000	6,150	8,000	1,500	900	48,700	978	2,440	2,680	57,200

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	NOx reduction, %	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
700	6,920	8,000	52.1	20	41.7	10.4	10,300	985
900	6,920	8,000	67.0	20	53.6	13.4	11,600	868
900	6,920	8,000	67.0	20	53.6	13.4	12,700	944
1,200	7,220	8,000	89.4	20	71.5	17.9	15,100	843
1,650	7,220	8,000	123	20	98.3	24.6	18,300	744
2,200	6,810	8,000	164	20	131	32.8	21,300	651
2,200	6,810	8,000	164	20	131	32.8	23,300	712
4,000	6,810	8,000	298	20	238	59.6	35,500	596
6,000	6,150	8,000	447	20	357	89.4	45,100	504
8,000	6,150	8,000	596	20	477	119	57,200	480

TABLE B-16. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF SELECTIVE CATALYTIC REDUCTION (SCR) TO A DUAL-FUEL ENGINE

CAPITAL COSTS

Power Output hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
700	6,920	8,000	147,000	11,800	95,900	255,000
900	6,920	8,000	159,000	12,700	103,000	275,000
1,200	7,220	8,000	176,000	14,100	114,000	304,000
1,650	7,220	8,000	201,000	16,100	131,000	348,000
2,200	6,810	8,000	232,000	18,600	151,000	401,000
4,000	6,810	8,000	334,000	26,700	217,000	577,000
6,000	6,150	8,000	446,000	35,700	290,000	772,000
8,000	6,150	8,000	559,000	44,700	363,000	967,000

ANNUAL COSTS

Power Output hp	Heat Rate, Btu/hp-hr	Hours Per Year	Operating Labor, $	Supervisory Labor, $	Maintenance, $	Overhead $	Fuel Penalty, $	Catalyst Cleaning, $	Catalyst Replacement & Disposal, $	Ammonia & Steam Consumption $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
700	6,920	8,000	81,000	12,200	14,700	8,850	1,130	578	1,930	9430	10,200	2,440	28,000	170,000
900	6,920	8,000	81,000	12,200	15,900	9,530	1,450	743	2,480	12100	11,000	2,440	30,200	179,000
1,200	7,220	8,000	81,000	12,200	17,600	10,500	2,020	990	3,310	16200	12,200	2,440	33,400	192,000
1,650	7,220	8,000	81,000	12,200	20,100	12,100	2,780	1,360	4,550	22200	13,900	2,440	38,200	211,000
2,200	6,810	8,000	81,000	12,200	23,200	13,900	3,490	1,820	6,070	29700	16,100	2,440	44,100	234,000
4,000	6,810	8,000	81,000	12,200	33,400	20,000	6,350	3,300	11,000	53900	23,100	2,440	63,400	310,000
6,000	6,150	8,000	81,000	12,200	44,600	26,800	8,600	4,950	16,500	80900	30,900	2,440	84,800	394,000
8,000	6,150	8,000	81,000	12,200	55,900	33,600	11,500	6,600	22,100	108000	38,700	2,440	106,000	478,000

COST EFFECTIVENESS

Power Output hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	NOx reduction, %	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
700	6,920	8,000	52.1	90	5.2	46.9	170,000	3,630
900	6,920	8,000	67.0	90	6.7	60 3	179,000	2,970
1,200	7,220	8,000	89.4	90	8.9	80.4	192,000	2,380
1,650	7,220	8,000	123	90	12.3	111	211,000	1,910
2,200	6,810	8,000	164	90	16.4	147	234,000	1,590
4,000	6,810	8,000	298	90	29.8	268	310,000	1,160
6,000	6,150	8,000	447	90	44.7	402	394,000	979
8,000	6,150	8,000	596	90	59.6	536	478,000	891

TABLE B-17. COSTS AND COST EFFECTIVENESS FOR RETROFIT OF LOW-EMISSION COMBUSTION TO A DUAL-FUEL ENGINE

CAPITAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Capital Equipment Cost, $	Sales Tax & Freight, $	Direct and Indirect Installation, Contingency, $	Total Capital Cost, $
700	6,920	8,000	416,000	33,300	270,000	720,000
900	6,920	8,000	468,000	37,400	304,000	810,000
1,200	7,220	8,000	546,000	43,700	355,000	945,000
1,650	7,220	8,000	663,000	53,000	431,000	1,150,000
2,200	6,810	8,000	806,000	64,500	524,000	1,390,000
4,000	6,810	8,000	1,270,000	102,000	828,000	2,200,000
6,000	6,150	8,000	1,790,000	144,000	1,170,000	3,100,000
8,000	6,150	8,000	2,310,000	185,000	1,500,000	4,000,000

ANNUAL COSTS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Maintenance, $	Overhead, $	Fuel Penalty, $	Taxes, Insurance, Admin., $	Compliance Test, $	Capital Recovery, $	Total Annual Cost, $
700	6,920	8,000	41,600	25,000	4,800	28,800	2,440	79,000	182,000
900	6,920	8,000	46,800	28,100	6,170	32,400	2,440	88,900	205,000
1,200	7,220	8,000	54,600	32,800	8,580	37,800	2,440	104,000	240,000
1,650	7,220	8,000	66,300	39,800	11,800	45,900	2,440	126,000	292,000
2,200	6,810	8,000	80,600	48,400	14,800	55,800	2,440	153,000	355,000
4,000	6,810	8,000	127,000	76,400	27,000	88,200	2,440	242,000	563,000
6,000	6,150	8,000	179,000	108,000	36,600	124,000	2,440	341,000	791,000
8,000	6,150	8,000	231,000	139,000	48,700	160,000	2,440	440,000	1,020,000

COST EFFECTIVENESS

Power Output, hp	Heat Rate, Btu/hp-hr	Hours Per Year	Uncontrolled NOx, tons/yr	Controlled NOx, g/hp-hr	Controlled NOx, tons/yr	NOx removed, tons/yr	Total annual cost, $	Cost effectiveness, $/ton NOx removed
700	6,920	8,000	52.1	2.0	12.3	39.8	182,000	4,560
900	6,920	8,000	67.0	2.0	15.9	51.2	205,000	4,000
1,200	7,220	8,000	89.4	2.0	21.1	68.2	240,000	3,520
1,650	7,220	8,000	123	2.0	29.1	93.8	292,000	3,110
2,200	6,810	8,000	164	2.0	38.8	125	355,000	2,840
4,000	6,810	8,000	298	2.0	70.5	227	563,000	2,480
6,000	6,150	8,000	447	2.0	106	341	791,000	2,320
8,000	6,150	8,000	596	2.0	141	455	1,020,000	2,240

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-453/R-93-032	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Alternative Control Techniques Document- NO_x Emissions from Stationary Reciprocating Internal Combustion Engines		5. REPORT DATE July 1993
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6. ABSTRACT

This alternative control techniques (ACT) document describes available control techniques for reducing NO_x emission levels from rich-burn and lean-burn natural gas-fired, diesel, and dual-fuel stationary reciprocating internal combustion engines. A discussion of the formation of NO_x and uncontrolled emission levels is included. Control techniques include parameter adjustments, prestratified charge, selective and nonselective catalytic reduction, and low-emission combustion. Achievable controlled NO_x emission levels, costs and cost effectiveness, and environmental impacts are presented, and the applicability of these control techniques to new equipment and retrofit applications is discussed.

7 KEY WORDS AND DOCUMENT ANALYSIS

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