Stationary Reciprocating Internal Combustion Engines Technical Support Document for NOx SIP Call Proposal

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CONTENTS

Introduction

Large[1] natural gas-fired lean-burn IC engines are primarily used in pipeline transmission service and some are used in field storage pumping operations. Gas turbines are also used in these operations. On a capacity basis the IC engines and turbines in pipeline transmission service are about evenly divided.[2,3] The uncontrolled emission rate from IC engines is about ten times greater than the uncontrolled emission rate for gas turbines.[4] That is, uncontrolled NOx emissions from large IC engines are greater than 3.0 lbs/mmBtu while uncontrolled NOx emissions from gas turbines are about 0.3 lbs/mmBtu.

In the NOx SIP call, EPA determined that NOx emissions from large gas turbines (and large boilers) can be decreased by highly cost-effective controls to an average emission rate of 0.15-0.17 lbs/mmBtu[5]. As part of the NOx SIP call rulemaking, EPA proposed to find that highly cost-effective controls[6] are available to reduce emissions from large IC engines by 90% from uncontrolled levels (i.e.,

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[1]Large, as defined in the NOx SIP call (63 FR 57356, October 27, 1998), means an IC engine which emitted, on average, greater than 1.0 ton/day during the 1995 ozone season.

[2]Alternative Control Techniques (ACT) document, "NO_x Emissions from Stationary Reciprocating Internal Combustion Engines," (ACT document for IC engines) EPA-453/R-93-032, July 1993, page 3-15. The ACT documents were required by section 183(c) of the Clean Air Act Amendments of 1990 and subject to public review prior to publication.

[3]"Retrofit NOx Control Technologies for Natural Gas Prime Movers," Gas Research Institute, March 1994, GRI-94/0329, page 2-4, (1994 GRI report).

[4]See, for example, data from EPA's AP-42, Emission Factors document, Table 3.2-1, 10/96.

[5]See NOx SIP call final rule and support material (63 FR 57356, October 27, 1998).

[6]"Highly cost-effective controls" are defined in the NOx SIP call as controls which are less than $2000/ton of ozone season NOx reduction in 1990 dollars (63 FR 57356, October 27, 1998).

to about 0.3 lbs/mmBtu)[7]. In the proposed rulemaking associated with this TSD, EPA is proposing that highly cost-effective controls are available to reduce emissions from large IC engines by 82-91%.

In the October 27, 1998 final NOx SIP call rule, EPA identified about 300 large IC engines. Subsequently, EPA received information from commenters seeking to make changes to the emissions inventory. The EPA recently made corrections and now includes about 200 stationary reciprocating internal combustion engines in its final NOx SIP call budget[8]. The vast majority are natural gas-fired engines.

A recent report by the Pechan-Avanti Group estimates the control costs and NO_x emission reductions for large IC engines affected under the NO_x SIP Call re-proposal. The report provides information about the universe of potentially affected stationary IC engines, control cost modeling methods, scenario analyses, and caveats and uncertainties associated with this analysis.[9] For the control range of 82-91%, the report estimates the average cost per ton at $520-549 per ton.[10]

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[7]The discussion below uses “grams/brake horsepower-hour” or g/bhp-hr rather than lbs/mmBtu since the former is the convention for the industry. The uncontrolled estimate of 3.0 lbs/mmBtu (from AP-42, October 1996) corresponds to about 11.3 g/bhp-hr. The 1993 ACT document for IC engines estimates average uncontrolled emissions at 5.13 lb/mmBtu or 16.8 g/bhp-hr.

[8]Federal Register of March 2, 2000 (65 FR 11222).

[9]“NOx Emissions Control Costs for Stationary Reciprocating Internal Combustion Engines in the NOx SIP Call States” prepared by Pechan-Avanti Group for EPA, August 11, 2000 (Pechan IC engines report).

[10] Annual (capital and operating) costs in 1990 $ per ozone season tons reduced. For SCR and NSCR, the annual operating costs are for the ozone season only. LEC controls are assumed to operate year-round, thus, year-round operating costs are included. For comparison to other recent EPA rulemakings, the costs can be escalated to 1997 $ using a factor of 1.21, resulting in $629-664/ton.

Large IC Engines Except Natural Gas-Fired Lean-Burn

In the NOx SIP call budget calculation, EPA divided IC engines into 4 categories and assigned a 90 percent emissions decrease on average based on information in EPA's ACT document for IC engines to each category including the following: non-selective catalytic reduction (NSCR) for rich-burn engines and selective catalytic reduction (SCR) for diesel and dual-fuel engines. For all large IC engines, except natural gas-fired lean-burn engines (see discussion below), EPA believes that 90% control is achievable through NSCR or SCR and is highly cost-effective. This is demonstrated in the 1993 ACT document for IC engines and in a recent report which updates information on NOx emissions and control techniques for IC engines.[11] In addition, the following sources provide supporting information (see docket A-96-56):

* "NOx Reduction Technology for Natural Gas Industry Prime Movers,"Acurex Corporation for Gas Research Institute, August 1990.
* "Retrofit NOx Control Technologies for Natural Gas Prime Movers," section 4, Gas Research Institute, March 1994, GRI-94/0329.
* "Assessment of Control Technologies for Reducing Nitrogen Oxide Emissions from Non-Utility Point Sources and Major Area Sources," Final Ozone Transport Assessment Group (OTAG) Policy Paper, July 1996; Chapter 5, Appendix C, to the OTAG Final Report, http://www.epa.gov/ttn/rto/otag/index.html.
* "Emission Control Technology for Stationary Internal Combustion Engines," Status Report, Manufacturers of Emission Controls Association, July 1997.
* "CAPCOA/ARB Proposed Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Internal Combustion Engines," December 3, 1997.

Natural Gas-Fired Rich-Burn Engines

Non-selective catalytic reduction (NSCR) provides the greatest NO_x reduction of all the highly cost effective technologies considered in the ACT document and is capable of providing a 90 to 98 percent reduction in NO_x emissions.[12] The recent EC/R report on IC engines states that 95 percent control is generally achievable through the use of NSCR on rich-burn IC engines.[13] The time required

[11] "Stationary Reciprocating Internal Combustion Engines: Updated Information on NOx Emissions and Control Techniques," EC/R Incorporated, September 1, 2000 (EC/R report on IC engines).

[12] ACT document for IC engines, Tables 2-2 and 2-12.

[13] EC/R report on IC engines, section 4.3.4.

from cost proposal to field installation of NSCR is less than 11 months.[14]

Diesel and Dual Fuel Engines

For diesel and dual fuel engines, SCR provides the greatest NO_x reduction of all highly cost effective technologies considered in the 1993 ACT document and is reported to provide an 80-90 percent reduction in NO_x emissions.[15] More recent reports state that NOx emissions can be reduced by 90% or more by SCR.[16, 17, 18] Therefore, EPA estimates NOx reductions for these engines at 90% on average. The EPA estimates the diesel/dual fuel IC engines are a very small part of the large IC engines population in the NOx SIP call; there are only 5 large diesel IC engines identified in the SIP call jurisdictions, some of which may be capable of dual fuel operation.

[14]Telephone records by Bill Neuffer, EPA, dated 5-19-00 and 5-24-00; conversations with a regulatory agency representative, an operator of the control equipment and an equipment vendor.

[15]ACT document for IC engines, Tables 2-8, 2-14 and 2-15.

[16]"Emission Control Technology for Stationary Internal Combustion Engines," Status Report by Manufacturers of Emission Controls Association, July 1997, page 7 (1997 MECA report).

[17]"CAPCOA/ARB Proposed Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Internal Combustion Engines," December 3, 1997, page 29.

[18]EC/R report on IC engines, section 4.2.4.

Natural Gas-Fired Lean-Burn IC Engines

Information received by EPA from the natural gas transmission industry after publication of the NOx SIP Call final rule indicate that most, if not all, large natural gas-fired lean-burn IC engines in the SIP Call region are in natural gas distribution and storage service and that these engines experience frequently changing load conditions which make application of SCR infeasible. The industry also states that low emission combustion (LEC) technology is a proven technology for natural gas-fired lean-burn engines, while SCR is not.[19] Regarding variable load operations, EPA's ACT document states that little data exist with which to evaluate application of SCR for the lean burn, variable load operations. More recent information indicates that application of SCR on variable load engines experienced problems in earlier applications but that vendors of SCR systems believe they have corrected the earlier problems with a new generation of the SCR technology.[20] However, SCR still remains to be widely demonstrated in the United States on lean burn IC engines in variable load operation. With the understanding that these large IC engines are in variable load operations, EPA believes there is an insufficient basis currently to conclude that SCR is an appropriate technology for the large lean-burn engines. Therefore, EPA is no longer proposing that SCR is a highly cost-effective control technology for the natural gas- fired lean-burn IC engines.

Lean burn engines can reduce NOx emissions by adjusting the air/fuel ratio to a leaner mode of operation. The increased volume of air in the combustion process increases the heat capacity of the mixture, lowering combustion temperatures and reducing NOx formation. LEC technology involves a large increase in the air/fuel ratio compared to conventional designs.

As described in various documents, including, for example, a 1994 Gas Research Institute study,[21] emissions of NOx from lean burn engines can vary widely due, largely, to the specific air/fuel ratio at which the engine is designed to operate. For naturally aspirated engines (which operate at near stoichiometric air/fuel ratios), emissions can be as high as 26 g/bhp-hr. Turbocharged engines can reduce emissions of NOx up to 40 percent by air/fuel ratio increases. Further, engines designed to operate at very high air/fuel ratios and with advanced ignition technology can reduce emissions to about 1 g/bhp-hr.

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[19] For example, December 1, 1998 letter from Lisa Beal, INGAA, to docket A-98-12 (docket # III-D-53) and February 16, 1999 memo from Lisa Beal, INGAA, to Tom Helms, EPA.

[20] EC/R report on IC engines, section 4.2.

[21] "Retrofit NOx Control Technologies for Natural Gas Prime Movers," section 4, Gas Research Institute, March 1994, GRI-94/0329 (1994 GRI report).

The ACT for IC engines and other documents indicate that LEC technology is appropriate for lean-burn engines, continuous or variable load, and is highly cost effective. The EPA believes application of LEC would achieve average NO_x emission levels in the range of 1.5-3.0 g/bhp-hr. This is an 82-91 percent reduction from the average uncontrolled emission levels reported in the ACT document. An EPA memorandum summarizing 269 tests shows that 96 percent of IC engines with installed LEC technology achieved emission rates of less than 2.0 g/bhp-hr.[22] The more recent EC/R report on IC engines summarizes 476 tests and shows that 97% of the IC engines with installed LEC technology achieve emission rates of 2.0 g/bhp-hr or less.[23]

Because there are many types of existing lean burn engines (e.g., some turbocharged, some not), the retrofit of LEC technology would require different modifications depending on the particular engine. Application of components of LEC technology and their degree (i.e., the resultant air/fuel ratio) will yield incremental emissions reductions. Therefore, it is important to carefully define LEC technology.

For natural gas-fired lean-burn engines, EPA proposes that an 82-91% emissions decrease is highly cost-effective; i.e., less than $2000/ton. This is demonstrated in the ACT document for IC engines and in the EC/R report on IC engines. Based on additional analysis of available data regarding demonstrated costs, effectiveness, availability, and feasibility of LEC technology, and consideration of comments received in response to the proposal, EPA intends to determine a percent reduction number to use in calculating this portion of the NOx SIP call budget decrease; the reduction is likely to be within the 82-91% range.

The EPA believes that LEC retrofit kits are available for all affected lean-burn engines. This is based on the EC/R report on IC engines and information recently received from engine manufacturers.[24, 25] Consistent with the ACT document, LEC technology for lean-burn IC engines means:

> The modification of a natural gas fueled, spark ignited, reciprocating internal combustion engine to reduce emissions of NOx by utilizing ultra-lean air-fuel ratios, high energy ignition systems and/or pre-combustion chambers, increased turbocharging or adding a turbocharger, and increased cooling and/or adding an intercooler or aftercooler, resulting in an engine that is

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[22]Data summarized from May 19, 2000 memo from David Sanders, EPA, to the files.

[23]EC/R report on IC engines, Table 2-1.

[24]EC/R report on IC engines, section 4.1.2.

[25]March 3, 1999 letter from J. W. Hibbard, Cooper Energy Services, to Bill Neuffer, EPA; March 4, 1999 telecon summary of call between Joe Hibbard, Cooper Energy Services and Bill Neuffer, EPA; and letter of May 7, 1999 from Charles Wilke, Dresser-Rand Company, to Bill Neuffer.

designed to achieve a consistent NO_x emission rate of not more than 1.5-3.0 g/bhp-hr at full capacity (usually 100 percent speed and 100 percent load).

The average cost effectiveness for large IC engines using LEC technology was recently estimated in the Pechan IC engines report to be $532/ton (ozone season).[26] The EC/R report on IC engines estimates the average cost effectiveness for IC engines using LEC technology to range from $420-840/ton (ozone season) for engines in the 2,000-8,000 bhp range.[27] The key variables in determining average cost effectiveness for LEC technology are the average uncontrolled emissions at the existing source, the projected level of controlled emissions, annualized costs of the controls, and number of hours of operation in the ozone season. The ACT document uses an average uncontrolled level of 16.8 g/bhp-hr, a controlled level of 2.0 g/bhp-hr (87% decrease), and nearly continuous operation in the ozone season. The EPA believes the ACT document provides a reasonable approach to calculating cost effectiveness for LEC technology (see discussion in EC/R report on IC engines). Further, EPA believes the cost-effectiveness analysis should use updated annualized cost data as described later in this TSD.

The EPA acknowledges that specific values will vary from engine to engine. For additional information, we have included sensitivity analyses in this TSD regarding the key variables for cost effectiveness: uncontrolled and controlled levels, hours of operation, and annualized costs. The sensitivity analyses are summarized later in this TSD and indicate a range of cost effectiveness for large IC engines using LEC technology of $540-890/ton (ozone season).

[26]Pechan IC engines report. Annual costs in 1990 $ per ozone season tons reduced. Note: 1990 $ are used in order to easily compare with the NOx SIP call's "highly cost effective" value of $2000/ton (in 1990 $).

[27]EC/R report on IC engines, section 2.2. Annual costs in 1990 $ per ozone season tons reduced. ($460-910 in 1997 dollars).

Other Cost and Analysis Factors

Monitoring costs

In the NOx SIP call rulemaking, EPA assumed continuous emissions monitoring systems (CEMS) might be required by States that chose to regulate IC engines. The EPA now believes that CEMS may not be necessary unless an engine is participating in a trading program. Alternate monitoring approaches, such as parametric monitoring and/or annual testing, are less costly and may be sufficient to assure compliance. Monitoring of pressure, which may be correlated with temperature and, thus, NOx emissions, is a form or parametric monitoring that may be successfully applied at a cost of less than $1000/year.[28] Annual testing would add about $3,000/year.[29]

Time to Implement Controls for IC Engines

Based on information primarily from manufacturers of control equipment, and from a regulatory agency and operator of the control equipment, EPA believes the time between a request for cost proposal and field installation is less than 11 months.[30]

Increased Power Output and Fuel Savings

Implementation of LEC may yield additional benefits of fuel economy and power output. Up to 5% fuel economy improvement is reported in the ACT document (pg 7-12). The 1990 GRI report describes “cost credit due to improved engine performance”and states that fuel economy can be improved up to15% and power output 65% (p10). The 1994 GRI report indicates increases in power output but slight losses in fuel economy associated with controls that achieve 80-90% NOx reduction. The 1996 AP-42 indicates improved power output and fuel efficiency with LEC (sect. 3.2.4.2). In the Pechan IC engines report cited earlier in this TSD, a 1% fuel savings is included in the cost analysis.

Types of IC Engines

Data from the Industrial Combustion Coordinated Rulemaking reciprocating internal combustion engines database indicate that the population of rich and lean burn IC engines in pipeline operation are divided with about 37% rich burn and 63% lean burn; data from GRI indicate a

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[28]EC/R report on IC engines, section 5.1.4.

[29]The 1993 ACT document for IC engines uses a cost of $2,440 for annual testing, page 6-5. In “CAPCOA/ARB Proposed Determination of Reasonably Available Control Technology and Best Available Retrofit Control Technology for Stationary Internal Combustion Engines,” December 3, 1997 the document estimates testing costs at $3,000 per engine (pg.52).

[30]Telephone records by Bill Neuffer dated 5-18-00, (two) 5-19-00, and 5-24-00.

population of 24% rich burn and 76% lean burn.[31]

The percentages of rich and lean burn IC engines estimated in the NOx SIP call final rule were 33% and 67%, respectively. In the related cost analysis, however, it was assumed that all engines were lean burn.[32] This likely resulted in the control costs being overstated because the lower costs associated with NSCR for rich-burn engines were not applied.

Information from GRI and INGAA indicates that engines in natural gas transmission and storage should be considered in variable load operation.[33] The EPA believes the vast majority of lean burn engines affected by the NOx SIP call are in natural gas transmission operation.

In the final rulemaking, if EPA chooses to use different control levels for any of the types of IC engines, it will be necessary to estimate the amount of controlled and uncontrolled emissions from each of these types of engines in order to calculate the budget emissions reductions. The EPA proposes to assume that two thirds of the natural gas-fired IC engines are in lean burn operation and one third is in rich burn.

[31] ICCR and GRI data contained in facsimile transmittal from Alpha-Gamma Technologies, Inc., March 22, 2000.

[32] "Ozone Transport Rulemaking Non-Electricity Generating Unit Cost Analysis" prepared by the Pechan-Avanti Group for EPA, September 17, 1998, [document VI-B-09 (vvv) in docket A-96-56].

[33] 1994 GRI report and February 16, 1999 fax from Lisa Beal, INGAA, to Tom Helms, EPA.

Results of Cost and Sensitivity Analyses

A recent report by the Pechan-Avanti Group estimates the control costs and NO_x emission reductions for large IC engines affected under the NO_x SIP Call re-proposal. The report provides information about the universe of potentially affected stationary IC engines, control cost modeling methods, scenario analyses, and caveats and uncertainties associated with this analysis.[34] The results of the analyses are summarized below.

The average cost per ton (ozone season) for the main analysis, Scenario A, is $532 per ton. This ozone season cost per ton is affected mostly by the natural gas-fired engine control costs. Oil-fired engines are about 3 percent of the population of large IC engines. While oil-fired engine costs are just above $1,000 per ton, they have a negligible influence on regionwide costs.

In Scenario B, the control efficiency for low emission combustion applied to lean burn natural gas-fired engines is reduced to 82 percent. This increases the average cost per ton by $17 per ton. The tons of NO_x decreased drops by 2,004 ozone season tons in Scenario A, compared to the 87% reduction in the main analysis.

Scenario C increases the NO_x control efficiency for lean burn engines to 91 percent. This additional emission reduction reduces the average cost per ton to about $520 per ton, which is $12 per ton less than in the main analysis.

Scenario D changes the uncontrolled NO_x emission level for lean burn gas-fired engines to 13.7 g/bhp-hr from 16.8 g/bhp-hr. With fewer NO_x tons being reduced, this raises the cost per ton to $603 per ton.

A control level of 1.2 g/bhp-hr (93% decrease) in Scenario E produces the lowest average cost per ton of $513 (and the largest emission reduction).

Scenario F reduces annual operating hours to 6,500. This changes both the emission reductions and the costs. Compared with other scenarios, there are fewer emission reductions but lower costs, resulting in a cost per ton $49 higher than that in the main analysis.

Scenario G retains the capital cost estimates that were used in the September 1998 Non-Electricity Generating Unit (EGU) cost analysis for the NO_x SIP Call. The scenario has the same emission reductions as the main analysis, but with $334 per ton higher estimated costs.

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[34] Pechan IC engines report.

Selection of Values for Cost and Sensitivity Analyses

Data available for each of the key variables is described below. This data were used by EPA to select the values for the above main and sensitivity analyses.[35]

1. Uncontrolled Emissions from Lean Burn IC Engines

Using the 16.8 g/bhp-hr uncontrolled level from ACT document

Uncontrolled emissions data for lean burn IC engines are available from several sources, including: the ACT document, EPA's 10-96 AP-42, EPA's draft 1997 AP-42, recent manufacturers data, and individual test data. In addition to the information in the ACT document itself, the following points support use of the ACT document's uncontrolled level.

1. Using the applicable ACT document rather than AP-42 is consistent with how EPA treated other non-EGU source categories, including glass, process heaters, iron & steel, etc. in the NOx SIP call rulemaking.
2. The ACT document is the most comprehensive look at the IC engine class and has the advantage of using a consistent data set for uncontrolled emissions, costs, and controls.
3. AP-42 numbers are being revised and the final AP-42 numbers are unknown.
4. If we used AP-42 uncontrolled numbers, it would be logical to use the AP-42 controlled numbers. However, the AP-42 controlled data set is limited in terms of technologies considered, costs, and expected decreases in emissions. LEC is reported to achieve between 0.55 and 2.3 g/bhp-hr (including both the 1996 and 1997 draft AP-42).
5. The ACT document's 122 tests make a large data set from which to draw conclusions.
6. More test data are available (122 in ACT compared to 56 in AP-42 draft).
7. ACT test data are available in several horsepower size categories; this could be important since EPA chose to not calculate emission reductions from the smaller IC engines.
8. AP-42 may have included some tests at relatively low torque and/or speed; compliance testing would likely be at 100% torque and speed.
9. The updated AP-42 section does not differentiate between uncontrolled lean-burn engines and "clean burn" engines (essentially LEC)[36]; thus, the average "uncontrolled" emissions may include some engines with LEC.

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[35]The EC/R report on IC engines provides additional support for the values selected in the cost and sensitivity analyses in the Pechan IC engines report. The EC/R report was not used to select these values, however, because it was completed after the Pechan analysis.

[36]March 29, 2000 memo from Stephen Edgerton, EC/R, to David Sanders and Doug Grano, EPA regarding IC engine ACT update.

10. The 16.8 g/bhp-hr appears to be more representative of larger engines, which are the engines affected by the NOx SIP call.

Using Alternative Uncontrolled Levels

As described in the 1994 GRI report, emissions of NOx from lean burn engines can vary widely due, largely, to the specific air/fuel ratio at which the engine is designed to operate. For naturally aspirated engines (which operate at near stoichiometric air/fuel ratios), emissions can be as high as 26 g/bhp-hr. Turbocharged engines can reduce emissions of NOx up to 40% by air/fuel ratio increases. Engines designed to operate at very high air/fuel ratios and with advanced ignition technology can reduce emissions to about 1 g/bhp-hr.

Uncontrolled emissions data for lean burn IC engines are available from several sources, including those listed below (g/bhp-hr). These are roughly organized into two groups. Data from group 1 generally supports the 16.8 level used in the ACT document while data in group 2 indicate a lower value may be appropriate. Therefore, for purposes of sensitivity analysis, EPA will also analyze the most recent AP-42 uncontrolled value: 13.7 g/bhp-hr.

1. Group 1 (g/bhp-hr)
    * 25-29 from older engines (1994 GRI report)
    * 18.0 (1997 MECA report)
    * 10-20 (1992 Cooper Industries paper[37])
    * 7-26 (1990 GRI report[38], p3)
    * 24 (1998 GRI report[39], figure 1-1)

2. Group 2 (g/bhp-hr)
    * 13.7 (draft AP-42, 1997)
    * 11.3 (AP-42, 10-96)
    * 13 all engines (controlled and uncontrolled) > 2000 hp (1994 GRI report)

2. Controlled Emissions from Lean Burn IC Engines with LEC

The ACT document indicates LEC technology is appropriate for lean-burn engines and is

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[37]"An Overview of Exhaust Emissions Regulatory Requirements and Control Technology for Stationary Natural Gas Engines" H.N. Ballard, S. C. Hay, and W.N. Shade Jr, Cooper Industries, presented to Society of Petroleum Engineers April 1992).

[38]"NOx Reduction Technology for Natural Gas Industry Prime Movers" Acurex Corporation for Gas Research Institute, August 1990 (1990 GRI report). Attached to June 25, 1998 letter from INGAA to Docket No. A-96-56; included as docket item V-H-157.

[39]"NOx Control for Two-Cycle Pipeline Reciprocating Engines" prepared by Arthur D. Little, Inc. for GRI, December 1998.

expected to achieve NO_x emission levels in the range of 1.5 - 3.0 g/bhp-hr. The precise emissions decrease for each engine depends on the specific engine and operating conditions, such that some would be above and some below the average 2.0 g/bhp-hr reduction used in the ACT document analyses. That is, engines equipped with LEC designed to meet a 1.5 - 3.0 g/bhp-hr standard will generally meet the design goal, although a few engines would be expected to attain levels below and a few to exceed that range. The selection of an appropriate controlled emissions level takes into consideration a number of large IC engines and the average emissions level from that group. For the lean burn IC engines, EPA believes the 2.0 g/bhp-hr level is appropriate to use in the cost and effectiveness analyses as the average controlled level.

Using 2 g/bhp-hr

Controlled emissions data for lean burn IC engines are available from several sources, including the ACT document. In addition to the information in the ACT document itself, the following information supports use of the ACT document's controlled level.

1. Controlled level of 2.3 grams (clean burn 2-cycle) in AP-42 (1996).
2. 1990 GRI report assumes meeting a 2 g/bhp-hr limit (p10).
3. 1994 GRI report indicates LEC retrofits can average less than 2 g/bhp-hr (p4-20).
4. 1998 GRI report indicates clean burn achieves 2 gram or lower (p2-2).
5. Urban, et al 1989 paper states that low-emission engines (e.g., clean burn) generally produce NOx emissions below 2.5 g/bhp-hr.[40]

Using Alternative Controlled Levels

The OTAG Final Report, Chapter 5, Appendix C, indicates that LEC is expected to achieve 80-93% emission reduction. Information from INGAA suggests a 4.0 g/bhp-hr level, and, in some cases, 7.0 g/bhp-hr;[41] since little supporting data were provided, however, no further analysis is warranted at this time. Controlled emissions data for lean burn IC engines applying LEC are available from several sources, and are summarized in the table below. The comprehensive test data listed below support average control levels below 2.0 g/bhp-hr. Therefore, for purposes of sensitivity analysis, EPA will also analyze the controlled level at 1.2 g/bhp-hr.

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[40]"Emission Control Technology for Stationary Natural Gas Engines" C.W. Urban, H.E. Dietzmann, and E.R. Fanick, Southwest Research Institute, Journal of Engineering for Gas Turbines and Power, July 1989, Vol. 111/369.

[41]February 16, 1999 memo from Lisa Beal, INGAA, to Tom Helms, EPA.

Low Emission Combustion Test Data Summary[42]

269 total tests (49 engines)

Control level* (g/bhp-hr)	95% (1.0)	93% (1.2)	91% (1.5)	90% (1.7)	87% (2.0)	82% (3.0)	76% (4.0)
# tests below cutpoint	192	231	246	253	258	266	268
% tests below cutpoint	71%	86%	91%	94%	96%	99.0%	99.6%

*Using 16.8 g/bhp-hr as the uncontrolled level

3. Hours of Operation

Using nearly continuous operation in the ozone season

Hours of operation data for lean burn IC engines are available from several sources. The ACT document for IC engines uses 8000 hours operation per year, leaving 760 hours maintenance or other downtime per year. Similarly, the 9-17-98 cost analysis by the Pechan-Avanti Group in support of the NOx SIP call used (5/12)*760 hours = 317 hours downtime for the ozone season. In addition to the information in the ACT document itself, the following information provides support for use of the ACT document's hours of operation.

1. NOx SIP call emissions inventory data for large IC engines indicates operation rates of 23-4 hours per day, 6-7 days per week.[43]
2. Typically larger size IC engines are operated continuously at full load due to operation efficiency. Smaller IC engines are used for peaking demands and backup purposes.[44]

Using Alternative Hours of Operation

Hours of operation data are available from several sources. The data listed below from comprehensive studies by GRI, the ICCR group, and EPA provide support for analysis of 6,000-7,000 hours of operation per year or greater. IC engines at storage facilities may operate fewer hours than those in pipeline transmission; however, EPA believes most of the large IC engines in the NOx SIP call emissions inventory are in pipeline transmission. Therefore, for purposes of sensitivity analysis, EPA

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[42]Data summarized from May 19, 2000 memo from David Sanders, EPA, to the files.

[43]Data on 177 large IC engines taken from the NOx SIP call database (3-2-00).

[44]December 9, 1998 memorandum from Brahim Richani and Jennifer Snyder, Alpha-Gamma Technologies, Inc. to Amanda Agnew, EPA, page 2.

will also analyze the hours of operation at an average of 6500 hours per year (5/12 * 2260 hours = 942 hours downtime for the ozone season).

a. 1994 GRI report uses 7000 hours/year

b. ICCR database indicates 6500 hours/year[45] (Alpha-Gamma 4-00 note)

c. EPA 1979 report referenced in the ACT document for IC engines (pg 3-14) estimates 6,000 hours (EPA 450/2-78-125a).

d. INGAA comment letter 6-24-98, app. B (App. F, p5-8)

-- Lean burn 2-stroke > 10,000 hp: 31% over Q2 & 3

-- Lean burn 4-stroke 4,332 hp: 36% over Q2 & 3

-- Lean burn 2-stroke > 5,113 hp: 37% Q2 & 3

4. Annualized Costs

Using recent manufacturers data

Annualized cost data for lean burn IC engines are available from several sources. The EPA believes that costs have decreased since the ACT document was written. Therefore, EPA believes the more recent cost data from manufacturers of the control equipment[46] should be used. The detailed cost factors are listed in a separate report;[47] the approximate annualized costs are summarized below.

1. $80,500 for 2000 hp
2. $115,000 for 4000 hp
3. $130,000 for 8000 hp

Using Alternative Annualized Costs

Annualized cost data for lean burn IC engines applying LEC are available from several sources, including those listed below. Costs will vary depending on each engine; e.g., the retrofit of older engines with naturally aspirated systems will require considerably more extensive modifications than more recent turbocharged engines. For purposes of sensitivity analysis, EPA used annualized costs developed from the control cost estimates by source size contained in the ACT for IC engines; these are the same costs that were used in the NOx SIP call final rule, which generally encompass the other estimates noted below.

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[45] April 5, 2000 memorandum from Brahim Richani, Alpha-Gamma Technologies, Inc., to Sims Roy, EPA.

[46] Including March 3 and 15, 1999 memos from Joe Hibbard, Cooper Energy Services, to Bill Neuffer, EPA; March 22, 1999 letter from R.W. Stachowicz, Waukesha Engine Division to Bill Neuffer, EPA; April 17, 2000 letter from Bob Faulkner, Diesel Supply Company, USA, to Stephen Edgerton, EC/R; and May 18, 2000 record of phone call between Bill Neuffer, EPA, and Chuck Wilkie, Dresser Rand.

[47] Pechan IC engines report, Table A-1.

1. NOx SIP call levels[48]
   * $170,000 for 2500 hp
   * $240,000 for 4000 hp
   * $520,000 for 11000 hp
2. 1990 GRI report estimates (1989 $) for LEC on typical gas transmission prime movers (about 2000 hp; for 2 & 4 cycle lean):
   -- less than $700/ton (p5 & 17)
   -- $150-200/hp installed cost (p17)
3. Urban et al July 1989 paper (JEGTP, vol. 111/371) for pre-1988 retrofits
   -- $20,000 + $70 x HP (1987 $)
4. 1994 GRI report
   -- total annualized cost estimate of $153,000 (1100 hp) (p A-40)
   -- total annualized cost estimate of $259,000 (1800 hp) (p A-42
   -- total annualized cost estimate of $297,000 (2000 hp) (p A-44))
   -- $680-730/hp capital cost (p 6-12)

[48]Pechan IC engines report, Table A-7.