EMISSION FACTOR DOCUMENTATION FOR AP-42 SECTION 3.2, NATURAL GAS-FIRED RECIPROCATING ENGINES

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1.0 Introduction

The revised AP-42 section described in this report replaces the section published in September 1996 as Supplement B to the Fifth Edition. This background report replaces the Emission Factor (EF) Documentation for AP-42 section 3.2, Heavy-Duty Natural Gas-Fired Pipeline Compressor Engines, issued February 1993 and amended in 1996 to support Supplement B of the Fifth Edition. The purpose of this background report is to provide technical documentation supporting the revisions to AP-42 section 3.2.

EPA publishes emission factors in its Compilation of Air Pollutant Emission Factors, Volume I, Stationary Point and Area Sources, EPA Publication No. AP-42 (AP-42). The document has been published since 1968 as the primary compilation of EPA's emission factor information. Federal, state, and local agencies, consultants, and industry use the document to identify major contributors of atmospheric pollutants, develop emission control strategies, determine applicability of permitting programs, and compile emission inventories for ambient air impact analyses and State Implementation Plans (SIPs). Volume 1, Stationary Sources is published by Emission Factor Inventory Group (EFIG) in EPA's Office of Air Quality Planning and Standards (OAQPS). The OAQPS is located in Research Triangle Park, NC.

1.1 Reasons For Updating

The Clean Air Act Amendments of 1990 added greatly to the number of air pollution sources for which emission factor development was required, and also called for the improvement of existing factors. There are several reasons for updating or revising AP-42 sections and emission factors.

- Contractor Expertise. A contractor or consultant may have gained expertise on a source category during previous work, either for EPA or for other clients, and may warrant consideration by EPA for a relatively low-expense update and expansion of available information.

- New Standard. After the proposal of a standard, the contractor reviews the available material to determine if sufficient information has been gathered to support the development of emission factors for the industry or process being studied. Often, the proposal or development of a new standard for a source or source category will trigger a re-evaluation of emission factors for a particular source. In the proposal of a standard, the proposal team gathers substantial amounts of data to support the standard, much more data than is typically gathered for AP-42. The proposal team may compare their new data with existing information used to develop AP-42 emission factors. If, in the comparison, the team discovers a deficiency in the existing information, they may turn their data over to EFIG, who in turn may use the information to improve emission factors.

- Outside Requests. EPA receives requests for better source and emission factor information. Requests may come from other OAQPS branches, EPA laboratories and regional offices, state agencies, trade associations, special interest groups, or private individuals. The requests may take the form of directives, letters, oral inquiries, or comments on published emission factors.

- Improve the National Inventory. The EPA may determine that a particular source category is a significant contributor to the National Inventory and that EPA should develop or improve emission factors.

- New Information. New information will be useful that may have been developed initially for Emission Standards Division (ESD) background documents involving New Source Performance Standards, Maximum Achievable Control Technologies (MACT), National Emission Standards For Hazardous Air Pollutants (NESHAP), and Control Techniques Guidelines (CTG), and reports by various EPA laboratories.

Section 3.2 has been updated to incorporate new available data on this source category. New information has been used to better characterize this source category, develop improved volatile organic compound (VOC) and particulate matter (PM) emission factors, and update criteria pollutant emission factors. In response to upcoming MACT standards for this source category, an expanded hazardous air pollutant (HAP) emission factors have also been provided.

This background report consists of four sections. This introduction provides background information on AP-42 and documents such as this one that are issued to update sections of AP-42. Section 2 presents the data search and screening steps, discusses the references used to revise Section 3.2, and defines the emissions data quality rating system. Section 3 discusses overall revisions to this section, provides details about the data base built for storing the available data, presents the calculations used to calculate emission factors, and defines the emission factor quality rating system. Section 4 presents the revised AP-42 section 3.2. Appendix A presents general information for the emissions test reports used in developing the emission factors.

1.2 REFERENCES FOR SECTION 1

1. *Procedures for Preparing Emission Factor Documents*, EPA-454/R-95-015, Office of Air Quality Planning and Standards, U.S. EPA, Research Triangle Park, NC 27711, November 1997.

2.0 Literature Search And Screening

Data used in this section were obtained from a number of sources within the OAQPS and from outside organizations. The AP-42 Background files were reviewed for information on these engines, demonstrated pollution control technologies, and emissions data. The Factor Information Retrieval System (FIRE) was searched for emissions data on natural gas-fired engines. The Source Test Information Retrieval System (STIRS) data set, compiled by EFIG, was reviewed and provided emissions data from several engine tests. The STIRS data set is a collection of emission test reports that have been scanned and stored on CD-ROM. Emissions tests on several engines were obtained from an industry report recently published by the Gas Research Institute (GRI).

In the review of available references, emissions data were accepted if:

- sufficient information about the engine and any pollution control devices was given.
- the test report identified if the emission tests were conducted before or after a pollution control device.
- emissions levels were measured by a current test method.
- emission test results were reported in units which could be converted into the reporting units selected for this section.
- sufficient data existed to characterize operating conditions.

2.1 Review Of Data Sets

Since Supplement B to the fifth edition was published, EPA has initiated several efforts towards gathering emissions data for combustion sources, including stationary reciprocating internal combustion engines. These efforts include the STIRS and the ICCR efforts. Under the STIRS program, EPA's EFIG group searched state files for emission test results from point sources. Under the ICCR program, industry representatives provided EPA with review of gathered emission reports and with additional emissions data for units in their operations. In addition, EPA with participation from industry and engine manufacturers, has conducted emissions testing on three lean burn engines (two gas-fired engines and one diesel-fired engine) at Colorado State University (CSU). The objective of this testing campaign were to determine the effect of potential control technologies and engine operating conditions on HAPs emissions. Simultaneous emissions measurements of before and after control devices were obtained. The control devices evaluated were CO oxidation catalysts, and the CSU engines were tested for HAPs and criteria pollutants. In addition to EPA's efforts, the Gas Research Institute (GRI) has completed several emission testing program and published the results of their efforts in comprehensive reports on criteria, non-criteria, and toxic pollutant emissions from natural gas-fired engines. These reports are entitled *Measurement of Air Toxic Emissions from Natural Gas-Fired Internal Combustion Engines at Natural Gas Transmission and Storage Facilities* and *Measurement of Air Toxic Emissions from Combustion Equipments at Natural Gas Processing Plants*, emissions database report ID numbers 29 and 31, respectively. These reports provides extensive process and emissions data from 68 tests on different engine types. The data from these reports provide emissions (NO_x, CO, TOC, PM, speciated VOCs, speciated PAHs) in units of ppmvd, ppmvw, *u*g/dscf, gr/dscf, with associated engine operating parameters (horsepower, rpm, fuel analysis, fuel flow, exhaust flow, exhaust O_2). Furthermore, several tests were conducted on engines operating with selective catalytic reduction (SCR), non-selective catalytic reduction (NSCR), and catalytic oxidation.

The background documents in the reference file assembled for the previous AP-42 version were also reviewed. Data from this source were accepted if the source tests were conducted recently (within the past 10 years) with currently approved test methods and if sufficient process data were available to characterize engine operation. Based on this review, no emissions data were incorporated into the data set for this version.

A total of 71 emissions test reports containing 469 emissions tests were gathered for stationary internal combustion engines. In most cases, the test reports included pooled testing efforts for several engines. Due to the large amount of gathered source tests, EPA decided to base the emission factors for Section 3.2 on original emissions data (actual source tests). The GRI testing efforts, References 1 and 2, were also included in the development of the emission factors due to the extensive amount of emissions and operating information that are included.

Detailed information for each test report used for developing the presented emission factors in Section 3.2 of the AP-42 Document is provided in the emissions data base for the section. Refer to Section 3.2.1 of this background report for instructions on how to obtain, use, and review the gathered emissions data for stationary reciprocating internal combustion engines.

A summary of the emission tests used to develop emission factors and their associated data base identification numbers is presented for each developed emission factor in Section 3.4, Tables 3.4-1 through 3.4-3. Nearly all of the emission test data used for developing the emission factors were assigned a rating of A due to the detailed information provided. These references are source test reports for natural gas-fired stationary reciprocating internal combustion engines used for electric generation, gas transmission and production, and industrial uses. A total of 71 test reports containing 469 emission tests were gathered for engines firing natural gas. Out of the 71 test reports, 61 test reports containing 324 emission tests included reference to the engine type (e.g., 2SLB, 4SLB, or 4SRB) and were used to develop the emission factors for this section. The breakdown of the number of test reports and tests used for developing the emission factors per engine category is as follows: for 2SLB engines, 18 test reports containing 120 emission tests; for 4SLB engines, 18 test reports containing 93 emission tests; and for 4SRB engines, 25 test reports containing 111 emission tests. Some of these test reports included controlled emissions data. The type of control devices tested include add-on catalysts; such as, selective catalytic reduction (SCR), non-selective catalytic reduction (NSCR), and CO-Catalyst; and combustion process modification; such as, pre-combustion chamber (PCC).

Only uncontrolled emission factors for both criteria and HAP emissions are presented in the revision of Section 3.2 of AP-42. Controlled emission factors can be obtained from the emissions database provided with this background documentation. Refer to Section 3.2.1 of this background report for instructions on how to obtain, use, and review the gathered emissions data for stationary reciprocating internal combustion engines.

2.2 Emission Data Quality Rating System

As part of the emission data analysis, the quality of the information contained in the set of reference documents was evaluated. Source test reports were considered to have sound methodology and adequate detail if they met the following criteria:

1. Source operation. The manner in which the source was operated is well documented in the report. The source was operating within typical parameters during the test.

2. Sampling procedures. The sampling procedures conformed to a generally acceptable methodology. The emission tests were conducted using a current measurement method. If actual procedures deviated from accepted methods, the deviations are well documented. When this occurred, an evaluation was made of the extent to which such alternative procedures could influence the test results.

3. Sampling and process data. Adequate sampling and process data are documented in the report, and any variations in the sampling and process operation are noted. If a large range between test results cannot be explained by information contained in the test report, the data are suspect and are given a lower rating.

4. Analysis and calculations. The test reports contain original raw data sheets. The nomenclature and equations used were compared to those (if any) specified by EPA to establish equivalency. The depth of review of the calculations was dictated by the reviewer's confidence in the ability and conscientiousness of the tester, which in turn was based on factors such as consistency of results and completeness of other areas of the test report.

After the source test reports were deemed acceptable based on the aforementioned criteria, data contained in these reports that were used to calculate emission factors were assigned a quality rating. The rating system used was that specified by OAQPS for preparing AP-42 sections.[1] The data were rated as follows:

A- Multiple tests that were performed on the same source using sound methodology and reported in enough detail for adequate validation. These tests do not necessarily conform to the methodology specified in EPA reference test methods, although these methods were used as a guide for the methodology actually used.

B - Tests that were performed by a generally sound methodology, but lack enough detail for adequate validation.

C - Tests that were based on an untested or new methodology or that lacked a significant amount of background data.

D - Tests that were based on a generally unacceptable method but may provide an order-of-magnitude value for the source.

2.3 REFERENCES FOR SECTION 2

1. *Procedures for Preparing Emission Factor Documents*, EPA-454/R-95-015, Office of Air Quality Planning and Standards, U.S. EPA, Research Triangle Park, NC 27711, November 1997.

3.0 AP-42 Section Development

3.1 Revisions to Section Narrative

The main change to Section 3.2 in AP-42 was to move turbines to Section 3.1 of AP-42. The EPA decided that a more effective method of presenting data for engines and turbines was to give each of these source categories an individual section. In this revised version of Section 3.2, only reciprocating, natural gas-fired, internal combustion engines are addressed. All combustion turbines have been combined into Section 3.1.

Overall, the technical discussion in this section was appropriate. There were no significant technological changes in this source category identified since the last publication. Some of the discussion on pollutant formation was revised to better characterize emissions from this source category. For example, discussions on particulate matter (PM) from these engines were revised to reflect improvements in measurement technologies. In previous versions, PM from these engines were considered below measurement detection levels. However, PM emissions from these engines can be measured using newer techniques and the text required revision to characterize these pollutants.

As for emissions information, the most significant change to the previous section is the amount of emissions data used for developing the e missions data, and the inclusion of an emissions database summarizing the gathered information. EPA has gathered 71 source test reports containing 469 emissions tests for HAPs and criteria pollutants for stationary reciprocating internal combustion engines, of which 61 test reports and 324 emissions tests were used in the development of the emission factors presented in Section 3.2. The remaining test reports were not used due to lack of essential information regarding the engine family during testing. A further discussion of the emissions data is presented in Section 3.2.2.

3.2 Pollutant Emission Factor Development

3.2.1 Data Base Design

The emission data assembled for the development of engine emission factors was stored in a Microsoft Access data base, Access 97. A data base approach was chosen to easily access and manipulate the large amount of data collected for this section and to facilitate data transfer within other concurrent projects at EPA. The design of this data base was accomplished in conjunction with the former Industrial Combustion Coordinated Rulemaking (ICCR) effort ongoing within the Emission Standards Division (ESD). Data entered under either of these projects was easily transferred between data bases. Furthermore, the common design of the data base will allow for future additions to the data base and simple recalculation of engine emission factors.

Within the data base, data was stored in two tables to reduce repetitive entry of data. These tables, and the data fields associated with each table are as follows:

Facilities Table

- Facility name
- Location
- Testing Company
- Date of Test

- Engine Manufacturer
- Engine Model
- Engine Family (2-stroke lean-burn, 4-stroke rich-burn, etc.)
- Air Supply (turbocharged, naturally aspirated, etc.)
- Number of Cylinders
- Rated Horsepower
- Test Horsepower
- Load
- Fuel Type
- Fuel Higher Heating Value
- Post-combustion Emission Controls

Test Data Table

- Pollutant
- Test Method
- Pollutant Concentration (as reported)
- Detection Limit
- Exhaust Oxygen Percentage
- Data Rating
- Fuel Exhaust Factor (F-Factor)
- Exhaust Flow Rate
- Fuel Flow Rate
- Exhaust Moisture Fraction
- Molecular Weight of Pollutant

The data base was programmed to merge the data in the two tables and calculate emission factors for the available pollutants in units of part per billion at 15 percent O_2 (ppb), pounds per million British thermal units (lb/MMBtu), pounds per hour (lb/hr), and pounds per horsepower-hour (lb/hp-hr). To ensure consistent calculation of emission factors, the data base was programmed to use the emission concentration data and process data taken during the testing period to calculate the emission factors. Emission factors provided in test reports were not used. The EPA concluded that this method of calculation would provide the highest quality emission factors. This method of calculating emission factors was chosen because different methods of calculating emission factors were used in some of the references and in some cases, the method of calculating emission factors was not given. Equations used to calculate emission factors for this section rely on the pollutant concentration units and on the desired emission factor.

The following equations were used to convert concentration data to the selected emission factors used in this section.

For concentration in parts per million by volume - dry (ppmvd), the following equations were used:

(1) $$EF_{lb/MMBtu} = \frac{(C_{ppmvd} \times F \times MW)}{(10^6 \times 385.5)} \times \text{temperature correction} \times \text{oxygen correction}$$

$$(2) \qquad EF_{lb/MMscf} = \frac{(C_{ppmvd} \times F \times 1020 \times MW)}{(10^6 \times 385.5)} \times \text{temperature correction} \times \text{oxygen correction}$$

$$(3) \qquad EF_{lb/hr} = \frac{(C_{ppmvd} \times Q_{out} \times 60 \times MW)}{(10^6 \times 385.5)} \times \text{temperature correction}$$

$$(4) \qquad EF_{lb/hp-hr} = \frac{(C_{ppmvd} \times Q_{out} \times 60 \times MW)}{(hp \times 10^6 \times 385.5)} \times \text{temperature correction}$$

For concentration in parts per million by volume - wet (ppmvw), the following equations were used:

$$(5) \qquad EF_{lb/MMBtu} = \frac{(C_{ppmvw} \times F \times MW)}{(10^6 \times 385.5) \times (1 - W_c)} \times \text{temperature correction} \times \text{oxygen correction}$$

$$(6) \qquad EF_{lb/MMscf} = \frac{(C_{ppmvw} \times F \times 1020 \times MW)}{(10^6 \times 385.5) \times (1 - W_c)} \times \text{temperature correction} \times \text{oxygen correction}$$

$$(7) \qquad EF_{lb/hr} = \frac{(C_{ppmvw} \times Q_{out} \times 60 \times MW)}{(10^6 \times (1 - Wc) \times 385.5)} \times \text{temperature correction}$$

$$(8) \qquad EF_{lb/hp-hr} = \frac{(C_{ppmvw} \times Q_{out} \times 60 \times MW)}{(hp \times 10^6 \times (1 - Wc) \times 385.5)} \times \text{temperature correction}$$

For concentration in micrograms per dry standard cubic feet, the following equations were used:

$$(9) \qquad EF_{lb/MMBtu} = \frac{(C_{ugf} \times F)}{(10^6 \times 453.6)} \times \text{oxygen correction}$$

(10) $$EF_{lb/MMscf} = \frac{(C_{ugf} \times F \times 1020)}{(10^6 \times 453.6)} \times \text{oxygen correction}$$

(11) $$EF_{lb/hr} = \frac{(C_{ugf} \times Q_{out} \times 60)}{(10^6 \times 453.6)}$$

(12) $$EF_{lb/hp\text{-}hr} = \frac{(C_{ugf} \times Q_{out} \times 60)}{(hp \times 10^6 \times 453.6)}$$

For concentration in parts per billion by volume - dry, the following equations were used:

(13) $$EF_{lb/MMBtu} = \frac{(Cppbvd \times F \times MW)}{(10^9 \times 385.5)} \times \text{temperature correction} \times \text{oxygen correction}$$

(14) $$EF_{lb/hr} = \frac{(C_{ppbvd} \times Qout \times 60)}{(10^9 \times 385.5)} \times \text{temperature correction}$$

(15) $$EF_{lb/hp\text{-}hr} = \frac{(C_{ppbvd} \times Qout \times 60)}{(hp \times 10^9 \times 385.5)} \times \text{temperature correction}$$

For concentration in volume percent, the following equations were used:

(16) $$EF_{lb/MMBtu} = \frac{(C_{\%} \times F \times MW)}{(100 \times 385.5)} \times \text{temperature correction} \times \text{oxygen correction}$$

(17) $$EF_{lb/hp\text{-}hr} = \frac{(C_{\%} \times Q_{out} \times 60 \times MW)}{(hp \times 100 \times 385.5)} \times \text{temperature correction}$$

For concentration in nanograms per dry standard cubic feet, the following equations were used:

(18) $$EF_{lb/MMBtu} = \frac{(C_{ngf} \times F)}{(10^{9} \times 453.6)} \times \text{oxygen correction}$$

(19) $$EF_{lb/hp-hr} = \frac{(C_{ngf} \times Q_{out} \times 60)}{(hp \times 10^{9} \times 453.6)}$$

For concentration in grains/dscf, the following equations were used:

(20) $$EF_{lb/MMBtu} = (C_{grf} \times F \times 1.43 \times 10^{-4}) \times \text{oxygen correction}$$

(21) $$EF_{lb/hp-hr} = \frac{(C_{grf} \times Q_{out} \times 60 \times 1.43 \times 10^{-4})}{(hp)} \times \text{oxygen correction}$$

For concentration in micrograms per dry standard cubic meter, the following equations were used:

(22) $$EF_{lb/MMBtu} = \frac{(C_{ugm} \times F)}{(10^{6} \times 453.6 \times 35.31)} \times \text{oxygen correction}$$

(23) $$EF_{lb/hp-hr} = \frac{(C_{ugm} \times Q_{out} \times 60 \times\ )}{(hp \times 10^{6} \times 453.6 \times 35.31)}$$

Where:

EF_{MMBtu} = Emission factor (pounds per million Btu)
EF_{hp} = Emission factor (pounds per horsepower-hour)
EF_{MMscf} = Emission factor (pounds per million standard cubic feet or fuel input)
C_{ppmvd} = Concentration (parts per million by volume, dry)

C_{ppmvw}	=	Concentration (parts per million by volume, wet)
C_{ugf}	=	Concentration (micrograms per dry standard cubic foot)
C_{ppbvd}	=	Concentration (parts per billion by volume, dry)
$C_{\%}$	=	Concentration (percent by volume)
C_{ngf}	=	Concentration (nanograms per dry standard cubic foot)
C_{grf}	=	Concentration (grains per dry standard cubic foot)
C_{ugm}	=	Concentration (micrograms per dry standard cubic meter)
Q_{out}	=	Stack exhaust flow rate (dry standard cubic feet per minute)
F	=	F-Factor (dry standard cubic feet per million Btu as referenced in the test report Default values obtained from 40 CFR 60, App. A, Table 19-1)
MW	=	Molecular weight (pounds per pound-mole)
hp	=	Power output (break horsepower)
T_{test}	=	Test temperature (EF)
$\%O_2$	=	Percent of oxygen is exhaust, by volume
1020	=	Natural gas heating value (MMBtu per MMscf)
385.5	=	Volume occupied by 1 lb-mole at 68EF and 14.7 psia (standard cubic feet per lb-mole)
60	=	Conversion factor (minutes per hour)
W_c	=	Water vapor volume fraction in exhaust
453.6	=	Conversion factor (grams per pound)
$1.43*10^{-4}$	=	Conversion factor (pounds per grain)
35.31	=	Conversion factor (dry standard cubic feet per dry standard cubic meter)

$$\begin{matrix}\text{Temperature correction}\\ \text{(to 68EF)}\end{matrix} \;,\; \left(\frac{528ER_{std}}{460ER_{t} \;\%\; T_{test}\; EF}\right)$$

$$\begin{matrix}\text{Oxygen correction}\\ \text{(to 0\% } O_2\text{)}\end{matrix} \;,\; \left(\frac{20.9}{20.9 \;\&\; \%O_2}\right)$$

Detection Limits

For cases where the concentration of a specific pollutant was below the test method detection limit and a detection limit was provided, one half of the detection limit was used to calculate an emission factor. If no detection limit was provided, then the results from that test were not used. Furthermore, if an emission factor for an individual engine was developed from a detection limit and the resulting emission factor was higher than the emission factors generated from detected concentrations, then the emission factor based on a detection limit was removed from the average. The goal of this decision was to prevent unusually high detection limit from artificially increasing an average emission factor. If an average emission factor was generated entirely from detection limits and not on measured values, a “less than” indicator was printed beside the emission factor presented in AP-42. Furthermore, it is noted as an emission factor based on detection limits and that expected emissions are lower than the emission factor. These methods for addressing detection level issues were provided in the Procedures For Preparing Emission Factor Documents.[1]

Calculation of Average Emission Factors

To provide average emission factors for each engine group, the emission factors from all tests in a specific group were averaged to generate the engine group emission factor. The averaging method used in the data base was an arithmetic average. For tests that consisted of multiple runs, the arithmetic average of the runs was used to develop the emission factor of that test. Tests from the same engine (same unit and location, such as CSU tests) and same operating conditions, such as load, are grouped and averaged as one test. For such cases, the average factor presented in the emissions data base will not match the factor presented in the AP-42 section. Individual tests were given equal weight in the calculation of average emission factors for each engine group. If the data used to generate an emission factor were from non-detect results where one half of the detection limit was used, then the average emission factor was noted to be made up of mostly detection limit estimates. The EPA intends for average emission factors generated from detection limits to provide an order of magnitude estimate of emissions levels. This type of emission factor is given a low quality rating.

Presentation of Data

Due to the size of the data base, a printout of all test data used to generate the engine emission factors in Section 3.2 is not presented. Instead, EPA is providing an electronic copy of the data base in Microsoft Access format on the EPA Technology Transfer Network (TTN). This has substantially decreased the volume of this background information document and will provide users with a more detailed background data set for this section. Furthermore, by providing the data base to the public, anyone may use or augment the data base for their individual needs, providing a substantial building block to there interested in compiling an extensive data base on natural gas-fired reciprocating engines. An electronic copy of the data base can be downloaded from the TTN at http://www.epa.gov/ttn/chief. In this website, follow the main menu options to locate the file and then download it.

To view the tests used to calculate the emission factors calculated for theses sources, open the data base file which will automatically open the MAIN FORM view (in case where the MAIN FORM does not open, open the file and choose the FORMS selection on the main data base screen, then under the FORMS selection, choose MAIN FORM). This will activate a macro which will provide a pollutant list, fuel type, and control device type available for these sources. This provides the option to view the input data, source information, or the emission tests used to calculate the emission factor for a specific pollutant (based on fuel type and control information) by simply clicking on the desired button: To view the data used to calculate the average emission factor for each test, click the EF INPUTS button; to view the individual source information, click the VIEW FACILITIES button; to view the data used for calculating the emission factor, click the EF REPORT button.

Several test reports did not include sufficient information necessary for characterizing the engine family. These reports were not used in developing the presented emission factors for Section 3.2. To view a summary of these reports, please refer to the Report Section in the emissions database and select the report entitled, “Reports Not Used in EF Development.”

3.2.2 Results Of Data Analysis

Source Category Selection

An important step in emission factor development is to determine which emission sources are similar enough to be grouped together and be represented by a single emission factor. This is accomplished by investigating which factors influence emissions and should be used to establish engine categories. The emission factors for each test contained in the data base were analyzed to determine appropriate categories.

When the emission levels of NO_x, CO, total hydrocarbons, and formaldehyde were compared against the different engine types (i.e., 2-stroke lean-burn, 4-stroke lean-burn, and 4-stroke rich-burn) emission profiles exhibited noticeable differences between the different types. The differences in emission profiles across these engine types are due to the different combustion parameters (i.e., temperature, oxygen concentration, residence time) that are specific to these engine types. For example, lean-burn engines operate with exhaust oxygen levels around 8 percent. These levels of excess air are effective in reducing NO_x emissions because the increased nitrogen and oxygen content in the fuel/air mixture acts as diluent to lower overall combustion temperatures, thus suppressing the thermal NO_x formation temperature. However, the cooler combustion temperatures lead to increased CO and hydrocarbon emissions.

Emission levels of NO_x, CO, total hydrocarbons, and formaldehyde were also compared against engine size and operating load. These parameters were studied to evaluate their effect on emissions and to determine if further segregation of engine categories was needed. Within the scatter of the data, size showed no consistent effect on the emission levels of NO_x, CO, total hydrocarbons, or formaldehyde for any of the engine types. Load showed the highest effect on NO_x and CO emissions. However, the EPA was not able to develop an algorithm that relates NO_x or CO to load. Therefore, emission factors based on two sets of load conditions (90-105 percent and less than 90 percent) are presented for NO_x and CO. For all other pollutants, load showed some effect on emission levels; however, the trends were not consistent nor were they significant compared to the data scatter. Therefore, the source categories were not further segregated by size or load because no clear effect in emission factors resulting from either of these parameters was observed for all pollutants within the scatter of the data.

In addition, for VOC emissions, the scatter of data did not warrant further categorization based on combustion control techniques previously used for NO_x control, such as PSC and PCC. Therefore, the uncontrolled emission factors for all pollutants, with the exception of NO_X, CO, and PM-10, are for no oxidation control; the data set may include units with control techniques used for NOx control, such as PCC and SCR for lean burn engines, and PSC for rich burn engines. The uncontrolled emission factors for NO_X and CO do not represent any combustion or add-on controls; however, the factors may include turbocharged units. The uncontrolled PM-10 emission factors for 2SLB engines and 4SLB engines also do not represent any combustion or add-on controls.

In summary, the three engine categories identified for stationary natural gas-fired reciprocating engines are 2-stroke lean-burn, 4-stroke lean-burn, and 4-stroke rich-burn. Average uncontrolled emission factors for these three engine categories are presented in Tables 3.4-1 through 3.4-3 at the end of this section. These tables include the average emission factor in units of lb/MMscf and lb/MMBtu, the number of data points used to generate each factor, the relative standard deviation for each emission factor, and the test IDs used for developing this factor. The relative standard deviation is presented to indicate the variability of the data used to calculate each emission factor. The data set used to develop each individual emission factor in these tables can be reviewed in the pollutant specific EF REPORT contained in the data base.

A summary of the reference and the contained information for each source test report in the emissions database is presented in Appendix A. This table presents general information for each test including the database ID, facility name, location, unit tested, engine model, engine size, and pollutants tested. The same information can also be viewed using the emissions database by selecting the VIEW FACILITIES from the MAIN FORM.

VOC Emission Factors

VOC emission factors for these engines were calculated to correspond with EPA's definition of VOC as total organic compounds excluding methane, ethane, and several chlorinated and fluorinated compounds.[1] Since VOCs cannot be measured directly, VOC emission factors must be calculated from other organic measurements. One option for calculating VOC was to subtract methane and ethane emission factors from the TOC emission factor. However, methane emission factors were only available for two of the three engine categories. The other option was to add up the available speciated VOCs in the data base to provide a total VOC emission factor. For this section, VOC was calculated by summing the emission factors of all speciated VOCs. The EPA concluded that this approach was valid since the most prevalent VOC compounds in exhaust from these engines, C_3+ alkanes along with formaldehyde, were included in the summation.

Methane Emission Factors

As previously mentioned, methane emission factors were not available for one of the three engine categories, therefore, methane emission factors needed to be calculated. The approach taken to calculate methane emission factors was to subtract the VOC and ethane emission factors from the TOC emission factor. For consistency, all methane emission factors were calculated in this fashion, even in the two cases where a methane emission factor was measured. To determine if this approach for calculating methane was acceptable, the calculated methane emission factors were compared to the measured methane emission factors in the two cases where methane data was available. For 2 stroke lean-burn engines, the calculated methane emission factors and the measured emission factors compared well, 1.45 lb/MMBtu vs. 1.48 lb/MMBtu, respectively.

C (2-stroke lean-burn) Calculated methane = 1.45 lb/MMBtu
Measured methane = 1.48 lb/MMBtu

C (4-stroke lean-burn) Calculated methane = 1.25 lb/MMBtu
Measured methane = 1.31 lb/MMBtu

PM Emission Factors

For a limited number of tests, PM measurements were conducted. For 4SLB engines, these PM measurements include filterable PM-10, inorganic condensable PM, and organic condensable PM. To provide a total PM-10 emission factor, these three PM fractions were added together. For 2SLB and 4SRB engines, only total PM-10 were measured. Although the condensable PM values are not presented as a certain size, EPA has assumed that all condensable PM are $\leq$1 Fm in diameter.[1] To provide a total PM-2.5 emission factor, EPA assumed that filterable PM-10 is less than 2.5 Fm in diameter. Therefore, the total PM-10 and total PM-2.5 are equal. The EPA believes that this assumption for filterable PM-2.5 is valid since natural gas does not contain ash and the nucleation of PM from combustion products will not yield particles larger than 1 to 2 Fm.

CO_2 and SO_2

As outlined in the Procedures for Preparing Emission Factor Documents,[1] emission factors for

CO_2 were calculated by mass balance. This approach was also taken for calculating SO_2. Since the carbon and sulfur content in pipeline-quality natural gas is fairly consistent, EPA believes this is the best method for calculating CO_2 and SO_2 emission factors. For CO_2, it was assumed that 99.5 percent of the fuel carbon was converted to CO_2. For SO_2, a 100 percent conversion of fuel sulfur was assumed. The CO_2 emission factor was based on a carbon weight percent in natural gas of 75 percent and the SO_2 emission factor was based on a sulfur concentration in natural gas of 2,000 grains per million standard cubic feet.

Aldehydes Emission Factors

The EPA has identified that for lean-burn engines, the California Air Resource Board (CARB) 430 measurement method for quantifying aldehyde emissions may have interference problems with the 2, 4-dinitrophenylhydrazine (DNPH) solution. This is due to the expected high concentrations of N_2 and O_2 percent in the engine exhaust stream. In such cases, the reported aldehyde measurements may be biased low. Emission factors based only on FTIR are presented in the AP-42 section for lean burn engines. Separate factors for FTIR and CARB 430 are presented in this document. However, the EPA recommends aldehyde emission factors that are based on FTIR measurements for lean-burn engines. The FTIR is a real-time measurement method approved by the EPA and is capable of monitoring aldehyde emissions.

For rich-burn engines, no interference problems are expected with the CARB 430 method. This is due to the low amount of O_2 percent expected in the engine exhaust stream. Therefore, the aldehyde emission factors for rich-burn engines are based on the average of all gathered emission tests, regardless whether the measurements are based on CARB 430 or FTIR.

Controlled Emission Factors

Controlled emission factors for criteria pollutants are not presented due to the limited number of available emissions data that included corresponding measurements of before and after controls. Controlled emission factors for HAPs are not presented because none of the available control devices are specifically designed for HAP control. The emissions database includes controlled emission factors for criteria pollutants and HAPs; however, it is important to indicate these factors, with exception of the CSU data, do not correspond to and are not based on simultaneous before and after controls measurements. Also note that the CSU data were in draft from as of the publication of this document. Therefore, the controlled emission factors should be used for references purposes only and not as a representation of the control device effectiveness.

Emission reduction levels (in percent reduction) are presented for most types of post-combustion control technologies. These reduction levels are based on the review of the limited available data which provided corresponding measurements of before and after controls. Post-combustion control technologies applicable to these sources include selective catalytic reduction (SCR), non-selective catalytic reduction (NSCR), and catalytic oxidation (CO oxidation catalyst). The approaches used to evaluate the pollution control efficiency of the SCR, NSCR, and the CO oxidation catalyst controls are presented in the following paragraphs. Due to the methods used to evaluate post-combustion control efficiency, the data base does not provide controlled emission levels. In all cases, pollution control efficiency was based on tests conducted upstream and downstream of the control device.

SCR Control

Two sets of upstream and downstream tests on SCR performance were presented in one reference.[2] These tests were conducted on one 4-stroke lean-burn engine. The average NO_x reduction efficiency across the SCR unit was 77 percent (Table 3.2-1). This reduction efficiency compared well with the results of the SCR analysis conducted by GRI, which reported average NO_x reductions across SCR units for natural gas-fired reciprocating engines of 80 percent.[3]

Table 3.2-1. SCR TEST RESULTS (NO_x)

Data Base I.D.	Uncontrolled Emission Factor (lb/hp-hr)	Controlled Emission Factor (lb/hp-hr)	Percent Reduction (%)
29.41x/29.43x	4.9 E-02	1.2 E-02	76
29.40x/29.42x	4.7 E-02	1.0 E-02	79
		Average	77

NSCR Control

Two sets of upstream and downstream tests on NSCR performance tests were extracted from Reference 2. These tests were conducted on a 4-stroke rich-burn engine. The average NO_x reduction efficiency across the NSCR units is 99 percent, (Table 3.2-2), which represents high level of achievable NO_x reduction. Previously published NO_x reductions achieved with NSCR range from 82 to 99 percent.[4]

The average CO reduction efficiency across the NSCR units is 98 percent. Again, this level of CO reduction is high compared to published CO reductions achieved with NSCR of 90 to 95 percent.

The EPA believes that these levels of emissions reduction may be attributed to fresh or green catalyst conditions. Catalyst performance has been observed to decrease over time due to catalyst decay. Catalyst decaying may result from metals in the exhaust which deposit on the catalysts thus blocking available reaction sites.

Table 3.2-2. NSCR TEST RESULTS (NO_x)

Data Base I.D.	Pollutant	Uncontrolled Emission Factor (lb/hp-hr)	Controlled Emission Factor (lb/hp-hr)	Percent Reduction (%)
29.29x/29.32x	NO_x	1.8 E-02	2.6 E-04	99
29.28x/29.31x	NO_x	1.9 E-02	5.2 E-05	99
			Average	99
29.29x/29.32x	CO	1.2 E-02	1.6 E-04	99
29.28x/29.31x	CO	1.5 E-02	2.6 E-04	98
			Average	98

Catalytic Oxidation Control

Limited emissions data were available for simultaneous measurements of uncontrolled and controlled emissions from engines equipped with oxidation catalysts (CO oxidation catalyst). CO oxidation catalyst performance increases with increased engine exhaust temperatures. For natural gas-fired engines, 2-stroke engines typically have lower exhaust temperatures than 4-stroke engines. Therefore, it is expected that higher CO emission reductions would be achieved from 4-stroke engines as compared to 2-stroke engines. From the gathered emissions data and catalyst manufacturers information, CO catalyst performance for 2SLB natural gas-fired engines is expected to be higher than 80% reduction. As for 4SLB natural gas-fired engines, the CO catalyst performance is expected to be higher than 90% reduction. CO oxidation catalysts can also be used for 4SRB engines; however, current practices favor the use of NSCR (3-way catalyst) for rich burn engines. The gathered emissions data for engines equipped with CO oxidation catalysts are discussed below and presented in Tables 3.2.3 and 3.2.4 for reference purposes.

One 2-stroke lean-burn engine (operating at clean-burn settings) tested under the GRI testing program employed an oxidation catalyst to control CO emissions.[2] Two sets of tests were conducted on this engine. The average CO reduction across the catalytic oxidation catalyst was 92 percent (Table 4.2-3). This level of emission reduction is high when compared to current installations for 2SLB engines.

The EPA testing at CSU also included testing of a CO catalyst on a 2SLB engine equipped with a pre-combustion chamber. The average CO percent reduction achieved during testing was 64 percent. The poor performance of the catalyst system was later contributed to masking/poisoning of the catalyst elements. This was validated by the catalyst manufacturer which provided laboratory analysis to EPA of the catalyst element condition. Only tests with the minimum and the maximum measured performance are presented in Table 3.2.3.

Table 3.2-3. CATALYTIC OXIDATION TEST RESULTS FOR 2SLB ENGINES (CO)[1]

Data Base I.D.	Uncontrolled Emission Factor (lb/hp-hr)	Controlled Emission Factor (lb/hp-hr)	Percent Reduction (%)
29.23/29.27	3.2 E-03	2.3 E-04	93
29.22/29.26	2.8 E-03	2.3 E-04	92
CSU-1.3.1/1.3.2	4.3 E-03	1.8 E-03	58
CSU-1.8.1/1.8.2	2.4 E-03	7.9 E-04	67
		Average	78

[1] Presented tests are for 2SLB engines equipped with a pre-combustion chamber or operating at clean burn conditions. The CSU data is suspect due to poisoning/masking of the catalyst element.

EPA testing at CSU also included testing of a CO oxidation catalyst on a 4SLB engine. Only tests with the minimum and the maximum measured performance are presented in Table 3.2.4. The average CO percent reduction achieved during testing was 95%.

Table 3.2-4. CATALYTIC OXIDATION TEST RESULTS FOR 4SLB ENGINES (CO)

Data Base I.D.	Uncontrolled Emission Factor (lb/hp-hr)	Controlled Emission Factor (lb/hp-hr)	Percent Reduction (%)
CSU-2.5.1/2.5.2	9.43 E-01	6.79 E-02	93
CSU-2.3.1/2.3.2	6.84 E-01	2.61 E-02	96
		Average	95

3.3 Emission Factor Quality Rating System

The quality of the emission factors developed from analysis of the test data was rated utilizing the following general criteria:

A - Excellent: Developed only from A-rated test data taken from many randomly chosen facilities in the industry population. The source category is specific enough so that variability within the source category population may be minimized.

B - Above average: Developed only from A-rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industries. The source category is specific enough so that variability within the source category population may be minimized.

C - Average: Developed only from A- and B-rated test data from a reasonable number of facilities. Although no specific bias is evident, it is not clear if the facilities tested represent a random sample of the industry. In addition, the source category is specific enough so that variability within the source category population may be minimized.

D - Below average: The emission factor was developed only from A- and B-rated test data from a small number of facilities, and there is reason to suspect that these facilities do not represent a random sample of the industry. There also may be evidence of variability within the source category population. Limitations on the use of the emission factor are noted in the emission factor table.

E - Poor: The emission factor was developed from C- and D-rated test data, and there is reason to suspect that the facilities tested do not represent a random sample of the industry. There also may be evidence of variability within the source category population. Limitations on the use of these factors are always noted.

The above criteria for emission factor ratings are defined in an OAQPS document which provided guidance in preparing emission factor documents. The use of these criteria is somewhat subjective and depends to an extent upon the individual reviewer. For this section, as these criteria were applied to the emission factors, the term “number of facilities” was interpreted to mean “number of engines,” where multiple tests on a single engine were counted as one test if the tests are based on the same load. This eliminates cases where multiple tests on one engine dominate the data set. Emission factors for this section were rated in the following manner:

A-Rated — Emission factor average based on results of A or B-rated data from fifteen or more different emissions tests.

B-Rated	Emission factor average based on results of A or B-rated data from ten to fourteen different emissions tests.
C-Rated	Emission factor average based on results of A or B-rated data from three to nine different emissions tests.
D-Rated	Emission factor average based on results of A or B-rated data from two or less emissions tests.
E-Rated	Emission factor average based on engineering judgement or from tests rated at C or below.

3.4 Emission Factors

The emission factors for the sources covered in Section 3.2 of the AP-42 document are presented in Tables 3.4-1 through 3.4-3, with each table representing the uncontrolled emission factors for each category. These tables provide the number of tests used in calculating the various emission factors as well as the relative standard deviation associated with each emission factor. This additional information is intended to provide greater insight to the reader about the background of each emission factor. For further detail on each emission factor, the complete data base used to generate these factor is provided on the EPA CHIEF web site (www.epa.gov/ttn/chief). (See Section 3.2.1 for more details on the data base.)

TABLE 3.4-1. UNCONTROLLED EMISSION FACTORS FOR 2-STROKE LEAN-BURN ENGINES

Pollutant	Number of Tests	Emission Factor (lb/MMBtu)	Emission Factor (lb/MMscf)	Relative Standard Deviation (%)	Test IDs
NO_x					
90-105% Load	34	3.17 E+00	3.23 E+03	43.4%	29.1x, 29.2x, 29.7- 29.10x, 29.12x, 29.15x-29.18x, 29.20, 29.21x, 31.3x, 31.6x-31.9x, 31.11x, 31.12x, 31.15x, 31.17x-31.19x, 125.3-125.10, 138, 143.
<90% Load	24	1.94 E+00	1.98 E+03	84.7%	107.7-107.9, 107.11, 107.12, 107.15, 107.16, 107.19, 107.20, 29.3x-29.6x, 29.11x, 29.13x, 29.14x, 29.19x, 31.1x, 31.2x, 31.4x, 31.5x, 31.13x, 31.14x, 31.16x.
CO					
90-105% Load	26	3.86 E-01	3.94 E+02	113.4%	29.1x, 29.2x, 29.7x-29.10x, 29.12x, 29.15x-29.18x, 29.20x, 29.21x, 31.3x, 31.6x-31.9x, 31.11x, 31.12x, 31.15x, 31.17x-31.19x, 138, 143.
<90% Load	24	3.53 E-01	3.60 E+02	55.0%	107.7-107.9, 107.11, 107.12, 107.15, 107.16, 107.19, 107.20, 29.3x-29.6x, 29.11x, 29.13x, 29.14x, 29.19x, 31.1x, 31.2x, 31.4x, 31.5x, 31.13x, 31.14x, 31.16x.
TOC	57	1.64 E+00	1.67 E+03	53.3%	29.2x, 29.5x-29.25x, 31.1x-31.19x, 132, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
PM-10 (filterable)	3	3.84 E-02	3.92 E+01	121.4%	31.2x, 31.1x, 31.7x.
1,1,2,2-Tetrachloroethane	3	6.63 E-05	6.76 E-02	13.8%	3.1, 3.2, 3.3
1,1,2-Trichloroethane	3	5.27 E-05	5.37 E-02	13.8%	3.1, 3.2, 3.3
1,1-Dichloroethane	3	3.91 E-05	3.99 E-02	13.9%	3.1, 3.2, 3.3
1,2,3-Trimethylbenzene	2	3.54 E-05	3.61 E-02	2.4%	29.7x, 29.10x.
1,2,4-Trimethylbenzene	4	1.11 E-04	1.13 E-01	70.1%	29.2x, 29.7x, 29.10x, 29.23x.
1,2-Dichloroethane	2	4.22 E-05	4.30 E-02	0.3%	3.1, 3.2, 3.3
1,2-Dichloropropane	3	4.46 E-05	4.55 E-02	13.7%	3.1, 3.2, 3.3
1,3,5-Trimethylbenzene	1	1.80 E-05	1.84 E-02		29.10x.
1,3-Butadiene	16	8.20 E-04	8.36 E-01	25.2%	29.23x, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
1,3-Dichloropropene	3	4.38 E-05	4.47 E-02	13.8%	3.1, 3.2, 3.3

Table 3.4-1. UNCONTROLLED EMISSION FACTORS FOR 2-STROKE LEAN-BURN ENGINES
(Continued)

Pollutant	Number of Tests	Emission Factor (lb/MMBtu)	Emission Factor (lb/MMscf)	Relative Standard Deviation (%)	Test IDs
2,2,4-Trimethylpentane	10	8.46 E-04	8.62 E-01	94.6%	29.2x, 31.19x, 31.16x, 31.12x, 31.11x, 31.8x, 29.7x, 29.10x, 29.23x, 31.3x.
2-Methylnaphthalene	4	2.14 E-05	2.19 E-02	105.6 %	29.5x, 29.7x, 29.9x, 29.23x.
Acenaphthene	4	1.33 E-06	1.36 E-03	108.8%	29.5x, 29.7x, 29.9x, 29.23x.
Acenaphthylene	4	3.17 E-06	3.23 E-03	110.9%	29.5x, 29.7x, 29.9x, 29.23x.
Acetaldehyde					
FTIR	58	7.76 E-03	7.92 E+00	74.6%	29.1x-29.21x, 29.22x-29.25x, 31.1x-31.9x, 31.11x-31.19x, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
CARB 430	4	5.22 E-03	5.33 E+00	34.6%	3.1-3.3, 7.13.
Acrolein					
FTIR	48	7.78 E-03	7.94E+00	59.1%	29.1x-29.21x, 29.22x-29.25x, 31.1x-31.8x, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
CARB 430	4	2.20 E-03	2.24 E+00		3.1-3.3, 7.13.
Anthracene	4	7.18 E-07	7.32 E-04	124.4%	29.5x, 29.7x, 29.9x, 29.23x.
Benz(a)anthracene	3	3.36 E-07	3.43 E-04	98.6%	29.5x, 29.9x, 29.23x.
Benzene	31	1.94 E-03	1.98 E+00	185.9%	3.1-3.3, 29.2x, 31.19x, 31.16x, 31.12x, 31.11x, 7.14, 31.8x, 29.7x, 29.10x, 29.23x, 11.1, 31.3x, 7.13, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
Benzo(a)pyrene	1	5.68 E-09	5.79 E-06		29.23x
Benzo(b)fluoranthene	1	8.51 E-09	8.68 E-06		29.23x
Benzo(e)pyrene	1	2.34 E-08	2.39 E-05		29.23x
Benzo(g,h,i)perylene	1	2.48 E-08	2.53 E-05		29.23x
Benzo(k)fluoranthene	1	4.26 E-09	4.35 E-06		29.23x
Biphenyl	3	3.95 E-06	4.03 E-03	53.1%	29.5x, 29.7x, 29.9x.

Table 3.4-1. UNCONTROLLED EMISSION FACTORS FOR 2-STROKE LEAN-BURN ENGINES
(Continued)

Pollutant	Number of Tests	Emission Factor (lb/MMBtu)	Emission Factor (lb/MMscf)	Relative Standard Deviation (%)	Test IDs
Butane	3	4.75 E-03	4.84 E+00	59.5%	29.2x, 29.7x, 29.10x.
Butyr/Isobutyraldehyde	6	4.37 E-04	4.46 E-01	119.8%	29.2x, 29.3x, 29.6x, 29.11x, 29.10x, 29.22x.
Carbon Tetrachloride	3	6.07 E-05	6.19 E-02	13.9%	3.1-3.3
Chlorobenzene	3	4.44 E-05	4.53 E-02	13.8%	3.1-3.3
Chloroform	3	4.71 E-05	4.80 E-02	13.8%	3.1-3.3
Chrysene	3	6.72 E-07	6.84 E-04	98.4%	29.5x, 29.9x, 29.23x.
Cyclohexane	3	3.08 E-04	3.14 E-01	56.4%	29.2x, 29.7x, 29.10x.
Cyclopentane	4	9.47 E-05	9.66 E-02	40.2%	29.2x, 29.7x, 29.10x, 29.23x.
Ethane	23	7.09 E-02	7.23 E+01	39.7%	29.1x-29.23x.
Ethylbenzene	27	1.08 E-04	1.10 E-01	72.9%	29.2x, 29.7x, 29.10x, 3.1-3.3, 11.1, 31.3x, 31.8x, 31.11x, 31.12x, 31.16x, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
Ethylene Dibromide	3	7.34 E-05	7.48 E-02	13.9%	3.1-3.3.
Fluoranthene	4	3.61 E-07	3.68 E-04	72.7%	29.5x, 29.7x, 29.9x, 29.23x
Fluorene	3	1.69 E-06	1.72 E-03	154.5%	29.5x, 29.7x, 29.23x.
Formaldehyde					
FTIR	58	5.52 E-02	5.63 E+01	46.3%	29.1x-29.25x, 31.1x-31.9x, 31.11x-31.19x, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
CARB 430	8	4.06 E-02	4.14 E+01	73.7%	3.1-3.3, 7.13, 7.14, 11.1, 14.4x, 14.5x.
Indeno(1,2,3-c,d)pyrene	1	9.93 E-09	1.01 E-05		29.23x.
Isobutane	3	3.75 E-03	3.82 E+00	54.0%	29.2x, 29.7x, 29.10x.
Methane	36	1.48 E+00	1.51 E+03	38.8%	29.1x-29.21x, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
Methanol	43	2.48 E-03	2.53 E+00	47.9%	29.1x-29.25x, 31.1x-31.9x, 31.11x-31.19x.

Table 3.4-1. UNCONTROLLED EMISSION FACTORS FOR 2-STROKE LEAN-BURN ENGINES (Continued)

Pollutant	Number of Tests	Emission Factor (lb/MMBtu)	Emission Factor (lb/MMscf)	Relative Standard Deviation (%)	Test IDs
Methylcyclohexane	4	3.38 E-04	3.45 E-01	47.6%	29.2x, 29.7x, 29.10x, 29.23x.
Methylene Chloride	3	1.47 E-04	1.50 E-01	70.1%	3.1-3.3.
n-Hexane	9	4.45 E-04	4.54 E-01	62%	29.2x, 29.23x, 31.16x, 31.12x, 31.11x, 31.18x, 29.7x, 29.10x, 31.3x.
n-Nonane	3	3.08 E-05	3.14 E-02	95%	29.7x, 29.10x, 29.23x.
n-Octane	4	7.44 E-05	7.59 E-02	104.6%	29.2x, 29.7x, 29.10x, 29.23x.
n-Pentane	4	1.53 E-03	1.56 E+00	48.8%	29.2x, 29.7x, 29.10x, 29.23x.
Naphthalene	7	9.63 E-05	9.83 E-02	96.8%	29.5x, 7.14, 31.8x, 29.7x, 29.9x, 7.13, 29.23x.
NMHC	44	2.96 E-01	3.02 E+02	99.6%	29.2x, 29.5x-29.10x, 29.12x-29.21x, 107.8, 107.9, 107.11, 107.12, 107.15, 107.16, 107.19, 107.20, 107.23, 107.24, 114.1, 114.2, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
PAH	2	1.34 E-04	1.37 E-01	66.3%	31.8x, 7.13.
Perylene	1	4.97 E-09	5.07 E-06		29.23x.
Phenanthrene	4	3.53 E-06	3.60 E-03	116.7%	29.5x, 29.7x, 29.9x, 29.23x.
Phenol	3	4.21 E-05	4.30 E-02	64.0%	29.5x, 29.7x, 29.9x.
Propane	4	2.87 E-02	2.93 E+01	42.2%	29.2x, 29.7x, 29.10x, 29.23x.
Pyrene	4	5.84 E-07	5.96 E-04	92.9%	29.5x, 29.7x, 29.9x, 29.23x.
Styrene	21	5.48 E-05	5.59 E-02	21%	3.1-3.3, 29.2x, 29.7x, 29.10x, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
Toluene	31	9.63 E-04	9.82 E-01	86.5%	3.1-3.3, 29.2x, 29.7x, 29.10x, 29.23x, 31.3x, 31.11x, 31.12x, 31.8x, 31.16x, 31.19x, 11.1, 7.14, 7.13, CSU tests: 1.1.1, 1.3.1-1.6.1, 1.8.1-1.16.1, 1.2/7.1.
Vinyl Chloride	3	2.47 E-05	2.52 E-02	13.9%	3.1-3.3.
Xylene	15	2.68 E-04	2.73 E-01	153.7%	3.1-3.3, 29.2x, 29.7x, 29.10x, 29.23x, 31.3x, 31.11x, 31.12x, 31.8x, 31.16x, 11.1, 7.14, 7.13.

Table 3.4-2. UNCONTROLLED EMISSION FACTORS FOR 4-STROKE LEAN BURN ENGINES

Pollutant	Number of Tests	Emission Factor (lb/MMBtu)	Emission Factor (lb/MMscf)	Relative Standard Deviation (%)	Test IDs
NO_x					
90-105% Load	25	4.08 E+00	4.16E+03	106.8%	118, 29.33x, 29.34x, 29.37x, 29.38x, 29.40x, 29.41x, 125.11-125.15, CSU tests: 2.1.1, 2.4.1-2.6.1, 2.8.1-2.16.1.
<90% Load	13	8.47 E-01	8.64 E+02	206.9%	29.35x, 29.36x, 29.39x, 144.1-144.6, 147, CSU tests: 2.2.1, 2.3.1, 2.7.1.
CO					
90-105% Load	20	3.17 E-01	3.23 E+02	44.8%	118, 29.33x, 29.34x, 29.37x, 29.38x, 29.40x, 29.41x, CSU tests: 2.1.1, 2.4.1-2.6.1, 2.8.1-2.16.1.
<90% Load	13	5.57 E-01	5.68 E+02	35.0%	29.35x, 29.36x, 29.39x, 144.1-144.6, 147, CSU tests: 2.2.1, 2.3.1, 2.7.1.
TOC	37	1.47 E+00	1.50 E+03	27.2%	29.33x-29.41x, CSU tests: 2.1.1-2.16.1.
PM-10 (filterable)	2	7.71 E-05	7.86 E-02	60.3%	29.34x, 29.38x.
Inorganic Condensable PM	2	5.50 E-03	5.62 E+00	28.9%	29.34x, 29.38x.
Organic Condensable PM	2	4.41 E-03	4.50 E+00	71.2%	29.34x, 29.38x.
1,1,2,2-Tetrachloroethane	9	<4.00 E-05	<4.08 E-02	13.1%	3.7-3.15.
1,1,2-Trichloroethane	9	<3.18 E-05	<3.24 E-02	13.1%	3.7-3.15.
1,1-Dichloroethane	9	<2.36 E-05	<2.40 E-02	13.1%	3.7-3.15.
1,2,3-Trimethylbenzene	1	2.30 E-05	2.35 E-02		29.42x.
1,2,4-Trimethylbenzene	3	1.43 E-05	1.46 E-02	21.2%	29.39x, 29.42x, 29.45x.
1,2-Dichloroethane	9	<2.36 E-05	<2.40 E-02	13.1%	3.7-3.15.
1,2-Dichloropropane	9	<2.69 E-05	<2.74 E-02	13.1%	3.7-3.15.
1,3,5-Trimethylbenzene	2	3.38 E-05	3.44 E-02	6.1%	29.39x, 29.42x.
1,3-Butadiene	1	2.67 E-04	2.72 E-01		25.2
1,3-Dichloropropene	9	<2.64 E-05	<2.70 E-02	13.2%	3.7-3.15.
2-Methylnaphthalene	3	3.32 E-05	3.39 E-02	170.5%	29.42x, 29.44x, 29.45x.

Table 3.4-2. UNCONTROLLED EMISSION FACTORS FOR 4-STROKE LEAN BURN ENGINES
(Continued)

Pollutant	Number of Tests	Emission Factor (lb/MMBtu)	Emission Factor (lb/MMscf)	Relative Standard Deviation (%)	Test IDs
2,2,4-Trimethylpentane	3	2.50 E-04	2.55 E-01	48.9%	29.39x, 29.42x, 29.45x.
Acenapthene	3	1.25 E-06	1.27 E-03	170.3%	29.42x, 29.44x, 29.45x.
Acenaphthylene	3	5.53 E-06	5.64 E-03	170.4%	29.42x, 29.44x, 29.45.
Acetaldehyde					
FTIR	31	8.36 E-03	8.53 E+00	72.9%	29.33x-29.38x, 29.41x, 29.44x-29.51x, CSU tests: 2.1.1-2.16.1.
CARB 430	1	8.56 E-04	8.73 E-01		25.2.
Acrolein					
FTIR	32	5.14 E-03	5.24 E+00	58.7%	29.33x-29.38x, 29.41x, 29.44x-29.52x, CSU tests: 2.1.1-2.16.1.
CARB 430	3	9.10 E-04	9.28 E-01	81.4%	3.7, 3.1, 25.2.
Benzene	16	4.40 E-04	4.49 E-01	80.3%	29.33x, 29.37x, 29.39x, 3.7-3.15, 4, 25.2, 29.42x, 29.45x.
Benzo(b)fluoranthene	2	1.66 E-07	1.70 E-04	138.3%	29.44x, 29.45x.
Benzo(e)pyrene	2	4.15 E-07	4.23 E-04	138.5%	29.44x, 29.45x.
Benzo(g,h,i)perylene	2	4.14 E-07	4.23 E-04	138.8%	29.44x, 29.45x.
Biphenyl	2	2.12 E-04	2.16 E-01	22.7%	29.33x, 29.37x.
Butane	2	5.41 E-04	5.52 E-01	17.9%	29.33x, 29.37x.
Butyr/Isobutyraldehyde	3	1.01 E-04	1.03 E-01	94.2%	29.39x, 29.44x, 29.45x.
Carbon Tetrachloride	9	<3.67 E-05	<3.74 E-02	13.1%	3.7-3.15.
Chlorobenzene	10	<3.04 E-05	<3.11 E-02	39.5%	3.7-3.15.
Chloroethane	1	1.87 E-06	1.91 E-03		4
Chloroform	9	<2.85 E-05	<2.90 E-02	13.1%	3.7-3.15.
Chrysene	3	6.93 E-07	7.06 E-04	169.8%	29.42x, 29.44x, 29.45x.

Table 3.4-2. UNCONTROLLED EMISSION FACTORS FOR 4-STROKE LEAN-BURN ENGINES (Continued)

Pollutant	Number of Tests	Emission Factor (lb/MMBtu)	Emission Factor (lb/MMscf)	Relative Standard Deviation (%)	Test IDs
Cyclopentane	3	2.27 E-04	2.31 E-01	47.7%	29.39x, 29.44x, 29.45x.
Ethane	6	1.05 E-01	1.08 E+02	102.6%	29.34x, 29.33x, 29.37x, 29.38, 29.44x, 29.45x.
Ethylbenzene	14	3.97 E-05	4.05 E-02	52.7 %	29.39x, 3.7-3.15, 4, 25.2, 29.42x, 29.45x
Ethylene Dibromide	9	<4.43 E-05	<4.52 E-02	13.2%	3.7-3.15.
Fluoranthene	3	1.11 E-06	1.13 E-03	170.1%	29.42x, 29.44x, 29.45x.
Fluorene	5	5.67 E-06	5.78 E-03	102.9%	29.33x, 29.37x, 29.42x, 29.44x, 29.45x..
Formaldehyde					
FTIR	32	5.28 E-02	5.39 E+01	31.7%	29.33x-29.38x, 29.41x-29.52x, CSU tests: 2.1.1-2.16.1.
CARB 430	5	1.38 E-02	1.41 E+01	63.7%	3.12, 21, 3.7, 3.11, 25.2.
Methane	20	1.31 E+00	1.34 E+03	26.7%	29.33x, 29.34x, 29.37x, 29.38x, CSU tests: 2.1.1-2.16.1.
Methanol	15	2.50 E-03	2.55 E+00	47.5%	29.34x-29.38x, 29.41x, 29.44x-29.52x.
Methylcyclohexane	3	1.23 E-03	1.25 E+00	60.0%	29.39x, 29.42x, 29.45x.
Methylene Chloride	9	2.00 E-05	2.04 E-02	23.6%	3.7-3.15.
n-Hexane	5	1.11 E-03	1.13 E-00	111.0%	29.33x, 29.37x, 29.39x, 29.42x, 29.45x.
n-Nonane	3	1.10 E-04	1.13 E-01	52.7%	29.39x, 29.42x, 29.45x.
n-Octane	3	3.51 E-04	3.58 E-01	59.5%	29.39x, 29.42x, 29.45x.
n-Pentane	5	2.60 E-03	2.65 E+00	109.5%	29.33x, 29.37x, 29.39x, 29.42x, 29.45x.
Naphthalene	6	7.44 E-05	7.59 E-02	213.2%	29.37x, 29.33x, 29.44x, 29.45x, 25.2, 4.
NMHC	18	1.06 E-01	1.08 E-02	16.1%	116.1, 116.2, CSU tests: 2.1.1-2.16.1.
PAH	1	2.69 E-05	2.74 E-02		25.2.
Phenanthrene	2	1.04 E-05	1.06 E-02	138.3%	29.44x, 29.45x.
Phenol	2	2.40 E-05	2.45 E-02	80.9%	29.33x, 29.37x.

Table 3.4-2. UNCONTROLLED EMISSION FACTORS FOR 4-STROKE LEAN-BURN ENGINES (Continued)

Pollutant	Number of Tests	Emission Factor (lb/MMBtu)	Emission Factor (lb/MMscf)	Relative Standard Deviation (%)	Test IDs
Propane	5	4.19 E-02	4.28 E+01	104.2%	29.33x, 29.37x, 29.39x, 29.42x, 29.45x.
Pyrene	3	1.36 E-06	1.41 E-03	170.2%	29.42x, 29.44x, 29.45x.
Styrene	26	<2.36 E-05	<2.41 E-02	133.0%	29.33x, 3.7-3.15, CSU tests: 2.1.1-2.16.1.
Tetrachloroethane	1	2.48 E-06	2.53 E-03		4
Toluene	14	4.08 E-04	4.16 E-01	79.9%	3.7-3.15, 29.39x, 29.42x, 29.45x, 25.2, 4.
Vinyl Chloride	9	1.49 E-05	1.52 E-02	13.2%	3.7-3.15.
Xylene	14	1.84 E-04	1.88 E-01	94.5%	29.39x, 3.7-3.15, 29.42x, 29.45x, 25.2, 4.

Table 3.4-3. UNCONTROLLED EMISSION FACTORS FOR 4-STROKE RICH-BURN ENGINES

Pollutant	Number of Tests	Emission Factor (lb/MMBtu)	Emission Factor (lb/MMscf)	Relative Standard Deviation (%)	Test IDs
NO_x					
90-105% Load	21	2.21 E+00	2.26 E+03	23.7%	108.5.1-108.7.1, 151.1, 151.3, 151.5, 151.7, 151.9, 151.11, 151.13, 151.15, 151.17, 151.19, 151.21, 151.23, 151.25, 151.27, 160.1.1-160.4.1.
<90% Load	7	2.27 E+00	2.31 E+03	19.7%	120, 108.1.1-108.4.1, 29.28x, 29.29x.
CO					
90-105% Load	18	3.72 E+00	3.79 E+03	34.3%	151.1, 151.3, 151.5, 151.7, 151.9, 151.11, 151.13, 151.15, 151.17, 151.19, 151.21, 151.23, 151.25, 151.27, 160.1.1-160.4.1.
<90% Load	3	3.51 E+00	3.58 E+03	74.3%	120, 29.28x, 29.29x.
TOC	7	3.58 E-01	3.65 E+02	79.7%	129.1-129.4, 141, 29.28x, 29.29x.
1,1,2,2-Tetrachloroethane	3	2.53 E-05	2.58 E-02	40.9%	3.16, 3.18, 3.20.
1,1,2-Trichloroethane	3	<1.53 E-05	<1.56 E-02	0.4%	3.16, 3.18, 3.20.
1,1-Dichloroethane	3	<1.13 E-05	<1.16 E-02	0.5%	3.16, 3.18, 3.20.
1,2-Dichloroethane	3	<1.13 E-05	<1.16 E-02	0.5%	3.16, 3.18, 3.20.
1,2-Dichloropropane	3	<1.30 E-05	<1.33 E-02	0.0%	3.16, 3.18, 3.20.
1,3-Butadiene	2	6.63 E-04	6.76 E-01	74.2%	25.3, 25.4
1,3-Dichloropropene	3	<1.27 E-05	<1.30 E-02	0.5%	3.16, 3.18, 3.20.
Acetaldehyde	9	2.79 E-03	2.84 E+00	84.5%	7.5-7.8, 7.12, 29.29x, 29.28x, 25.3, 25.4.
Acrolein	9	2.63 E-03	2.69 E+00	125.0%	7.5-7.8, 7.12, 29.29x, 29.28x, 25.3, 25.4.
Benzene	18	1.58 E-03	1.61 E+00	152%	7.1-7.8, 7.10-12, 11.2, 11.3, 3.16, 3.18, 3.20, 25.3, 25.4.
Butyr/isobutyraldehyde	1	4.86 E-05	4.96 E-02		29.28x.
Carbon Tetrachloride	3	<1.77 E-05	<1.81 E-02	0.0%	3.16, 3.18, 3.20.
Chlorobenzene	3	<1.29 E-05	<1.32 E-02	0.4%	3.16, 3.18, 3.20.
Chloroform	3	<1.37 E-05	<1.40 E-02	0.4%	3.16, 3.18, 3.20.

Table 3.4-3. UNCONTROLLED EMISSION FACTORS FOR 4-STROKE RICH-BURN ENGINES
(Continued)

Pollutant	Number of Tests	Emission Factor (lb/MMBtu)	Emission Factor (lb/MMscf)	Relative Standard Deviation (%)	Test IDs
Ethylbenzene	7	<2.48 E-05	<2.53 E-02	48.9%	11.2, 11.3, 3.16, 3.18, 3.20, 25.3, 25.4.
Ethylene Dibromide	3	<2.13 E-05	<2.18 E-02	0.3%	3.16, 3.18, 3.20.
Formaldehyde	18	2.05 E-02	2.09 E+01	87.5%	7.1-7.8, 7.10-7.12, 3.16, 11.2, 11.3, 29.29x, 29.28x, 25.3, 25.4.
Methanol	2	3.06 E-03	3.12 E+00	0.2%	29.29x, 29.28x.
Methylene Chloride	3	4.12 E-05	4.21 E-02	65.7%	3.16, 3.18, 3.20.
Naphthalene	13	<9.71 E-05	<9.90 E-02	131.1%	7.1-7.8, 7.10-7.12, 25.3, 25.4.
NMHC	12	1.00 E-01	1.02 E+02	93.6%	112.11, 112.15-112.18, 112.20, 120, 157.1, 157.2, 133, 102.1, 102.2..
PAH	2	1.41 E-04	1.43 E-01	121.1%	25.3, 25.4.
Styrene	3	<1.19 E-05	<1.22 E-02	0.5%	3.16, 3.18, 3.20.
Toluene	18	5.58 E-04	5.70 E-01	131.1%	7.1-7.8, 7.10-7.12, 11.2, 11.3, 3.16, 3.18, 3.20, 25.3, 25.4.
Vinyl Chloride	3	<7.18 E-06	<7.32 E-03	0.2%	3.16, 3.18, 3.20.
Xylene	18	1.95 E-04	1.99 E-01	102.3%	7.1-7.8, 7.10-7.12, 11.2, 11.3, 3.16, 3.18, 3.20, 25.3, 25.4.

3.5 REFERENCES FOR SECTION 3

1. *Procedures for Preparing Emission Factor Documents*, Third Revised Draft Version, Office of Air Quality Planning and Standards, U.S. EPA, Research Triangle Park, NC 27711, November 1996.

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3. Shareef, G.S., and D.K. Stone, Evaluation of SCR NO_x Controls for Small Natural Gas-Fueled Prime Movers, prepared by Radian Corporation, for the Gas Research Institute, GRI-90/0138, July 1990.

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4.0 Revised AP-42 Section 3.2