REPORT ON REVISIONS TO

5TH EDITION AP-42

Section 3.2

Heavy-duty Natural Gas-fired Pipeline Compressor Engines

Prepared for:

Contract No. 68-D2-0160, Work Assignment 50
EPA Work Assignment Officer: Roy Huntley
Office of Air Quality Planning and Standards
Office of Air and Radiation
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711
Prepared by:

Eastern Research Group
Post Office Box 2010
Morrisville, North Carolina 27560

September, 1996

Table of Contents

1.0 INTRODUCTION

This report supplements the Emission Factor (EMF) Documentation for AP-42 Section 3.2, Heavy-Duty Natural Gas-Fired Pipeline Compressor Engines, dated February, 1993. The EMF describes the source and rationale for the material in the most recent updates to the 4th Edition, while this report provides documentation for the updates written in both Supplements A and B to the 5th Edition.

Section 3.2 of AP-42 was reviewed by internal peer reviewers to identify technical inadequacies and areas where state-of-the-art technological advances need to be incorporated. Based on this review, text has been updated or modified to address any technical inadequacies or provide clarification. Additionally, emission factors were checked for accuracy with information in the EMF Document and new emission factors generated if recent test data were available.

If discrepancies were found when checking the factors with the information in the EMF Document, the appropriate reference materials were then checked. In some cases, the factors could not be verified with the information in the EMF Document or from the reference materials, in which case the factors were not changed.

Three sections follow this introduction. Section 2 documents the revisions and the basis for the changes. Section 3 presents the revised AP-42 Section 3.2, and Section 4 contains the EMF documentation dated February, 1993.

2.0 REVISIONS

2.1 General Text Changes

Information in the EMF Document was used to enhance text concerning the process description of turbines, emissions, and controls. A number of references were corrected, and at the request of the EPA, the metric units were removed.

2.2 Carbon Dioxide, CO_2

Based on the equation in the footnote of Table 3.2-1, the CO_2 emission factor was changed from 110 lb/MMBtu to 109 lb/MMBtu. The equation for calculating CO_2 is:

$$CO_2 \text{ (lb/MMBtu)} = (3.67 * C)/E$$

where:

C = carbon content of fuel by weight (0.75)

E = energy content of fuel, 0.0250 MMBtu/lb

This emission factor (and related footnote) were added to the other tables containing emission factors for controlled engines.

2.3 Other Emission Factors

The other emission factors (NO_x, CO, TOC, TNMOC, CH_4, PM-10, etc.) were checked against information in the EMF Document and no changes were required.

3.0 REVISED SECTION 3.2

This section contains the revised Section 3.2 of AP-42, 5th Edition.

4.0 EMISSION FACTOR DOCUMENTATION, FEBRUARY 1993

This section contains the Emission Factor Documentation for Section 3.2 dated February 1993.

EMISSION FACTOR DOCUMENTATION FOR

AP-42 SECTION 3.2,

NATURAL GAS COMPRESSOR ENGINES

Prepared by:

Acurex Environmental Corporation

Research Triangle Park, NC 27709

E.H. Pechan and Associates, Inc.

Rancho Cordova, CA 95742

EPA Contract No. 68-D0-0120

Work Assignment No. II-68

EPA Work Assignment Manager: Michael Hamlin

Prepared for:

Office of Air Quality Planning and Standards

Office of Air and Radiation

U.S. Environmental Protection Agency

Research Triangle Park, NC 27711

April 1993

Disclaimer

This report has been reviewed by the Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

The document "Compilation of Air Pollutant Emission Factors" (AP-42) has been updated and published by the U.S. EPA periodically since 1972. An emission factor relates the quantity (usually in terms of mass) of pollutants emitted from a source to either an input or output specific activity of the source (typically fuel consumption or energy output). Uses of emission factors reported in AP-42 include:

- **Estimates of area-wide emissions**
- **Emission estimates for a specific facility**
- **Evaluation of emissions relative to ambient air quality**

The intent of this emission factor document is to provide background information from all references used to support the revision of emission factors for Section 3.2 - Heavy-Duty Natural Gas Compressor Engines.

AP-42 Section 3.2 was previously updated in 1975. Previously this section contained information on the baseline criteria emission factors for natural gas compressor station reciprocating engines and gas turbines. Emission factors for nitrogen oxides, carbon monoxide, hydrocarbons, sulfur oxides, and particulates were individually calculated for two source categories: reciprocating engines and gas turbines. The purpose of this current revision is to update the data base of the prior AP-42 section and to broaden the source/pollutant coverage. Specifically, the scope of the current update includes:

- **Updating of emission factors for criteria pollutants during baseline, uncontrolled operation using data available since the prior update;**
- **Reclassification of sources to include separate coverage of 2-cycle lean burn engines, 4-cycle lean burn, and 4-cycle rich burn engines and gas turbines**

because of significantly different pollutant forming potential and control potential;

- **Inclusion of several non-criteria emission species for which data are available: volatile and semi-volatile speciation, and global warming gases; and**
- **Inclusion of emission factors and related discussion on engine operation under low nitrogen oxide (NO_x) emission conditions.**

Sulfur oxide (SO_x) and particulate matter (PM) emission factors were not included because of natural gases inherently low sulfur content (even 100 percent conversion of fuel sulfur produces insignificant amounts of SO_x), and characteristically small amounts of particulate matter except under severe sooting conditions. The separation of reciprocating engines into three categories is based on their method of combustion (number of distinct cycles) and air/fuel ratios (lean or rich/stoichiometric). Lean and rich burn engines will have inherently different emission characteristics because of the composition of the premixed gas. Rich burn engines use near-stoichiometric mixtures which produce higher temperatures and promote higher temperature reactions. The low oxygen content will increase the importance of reduction reactions relative to oxidation reactions. Conversely, lean mixtures will produce lower temperatures, which will favor low temperature reactions and the oxygen availability will favor oxidation reactions.

The engine thermodynamic cycle also will inherently affect the emissions of reciprocating engines. With a 4-cycle engine there are four distinct phase/cycles/stroke: the first phase allows the air/fuel mixture to enter the cylinder; secondly, the mixture is compressed and ignited; thirdly, the mixture expands, moving the piston, and producing work; finally, the exhaust gas is forced out of the cylinder to begin a new cycle. The 2-cycle design causes the fresh air/fuel mixture to enter the cylinder at the same time the exhaust is being expelled (stroke 1). The second phase/stroke compresses, ignites, and expands the mixture. With a 4-cycle engine most of the exhaust gas is removed from the cylinder before the new mixture enters. With a 2-cycle engine, some of the exhaust gas remains in the cylinder and mixes with the incoming mixture. The residence times and in-cylinder gas

composition is different for 2 and 4-cycle engines causing them to produce different emission characteristics.

2. SOURCE DESCRIPTION

2.1 CHARACTERIZATION OF THE INDUSTRY

The engines covered in AP-42 Section 3.2 are used in the natural gas industry at pipeline compressor and storage stations. The engines and gas turbines are used to provide mechanical shaft power that drives a compressor. At pipeline compressor stations, the units are used to help move natural gas from station to station. At storage facilities, the units are used to help inject the natural gas into high pressure underground cavities (natural storage tanks), e.g. empty oil fields. Although units can operate at a fairly constant load, pipeline units must be able to operate under varying load conditions as dictated by the pipeline pressures. The industry engine population is characterized in Table 2-1. Turbines occupy the higher end of the power spectrum. Although gas turbines represent only a small percentage of installations, they comprise an equal percentage of total installed power capacity compared to reciprocating engines. The average size of a lean and rich burn reciprocating engine is 2,000 bhp and 800 bhp, respectively. For gas turbines, the average power capacity is 8,000 bhp.

2.2 PROCESS DESCRIPTION

All of the gas turbines used by the natural gas industry for pipeline and storage facilities are simple cycle. A gas turbine is an internal combustion engine that operates with rotary rather than reciprocating motion. Gas turbines are essentially composed of several major components: compressor, combustor, and power turbine. Figure 2-1. shows a cutaway view of a simple cycle engine. Natural gas and compressed air (up to 30 atmospheres pressure) are injected separately into the combustor can, mixed, and reacted.

TABLE 2-1. PROFILE OF NATURAL GAS COMPRESSOR PRIME MOVER POPULATION[2]

Reciprocating Engines Population							Gas Turbine Population	
Manufacturer	2-Cycle PS(lean)	2-Cycle BS(lean)	2-Cycle TC(lean)	4-Cycle NA(rich)	4-Cycle TC(both)	Totals	Manufacturer	Totals
Internal: Ajax	128					128	Allison	89
Cooper	589	654	526	193	31	1,993	Coberra	43
Clark	532	42	778			1,352	General Electric	216
Ingersoll-Rand				598	462	1,060	Hispano	4
Worthington	190	60	166	71	156	643	Norwalk	7
Separate: Caterpillar				66	110	176	Orenda	37
Climax				2		2	Pratt & Whitney	71
Cooper				4	125	129	Rolls Royce	178
White Superior				361	158	519	Ruston	2
Delaval					58	58	Solar	508
Ingersoll-Rand				4		4		
MEP		33		6	0	39		
Nordberg					10	10		
Waukesha				343	69	412		
Total Number of Units	1,439	789	1,470	1,648	1,179	6,525		1,155
Cycle Totals	3,698			2,827		6,525		
Approx. BHP	6,800,000			3,500,000		10,300,000		10,800,00 0

PS = Piston Scavenged.
BS = Blower Scavenged.
TC = Turbocharged.
NA = Naturally Aspirated.
BHP = Brake Horsepower.

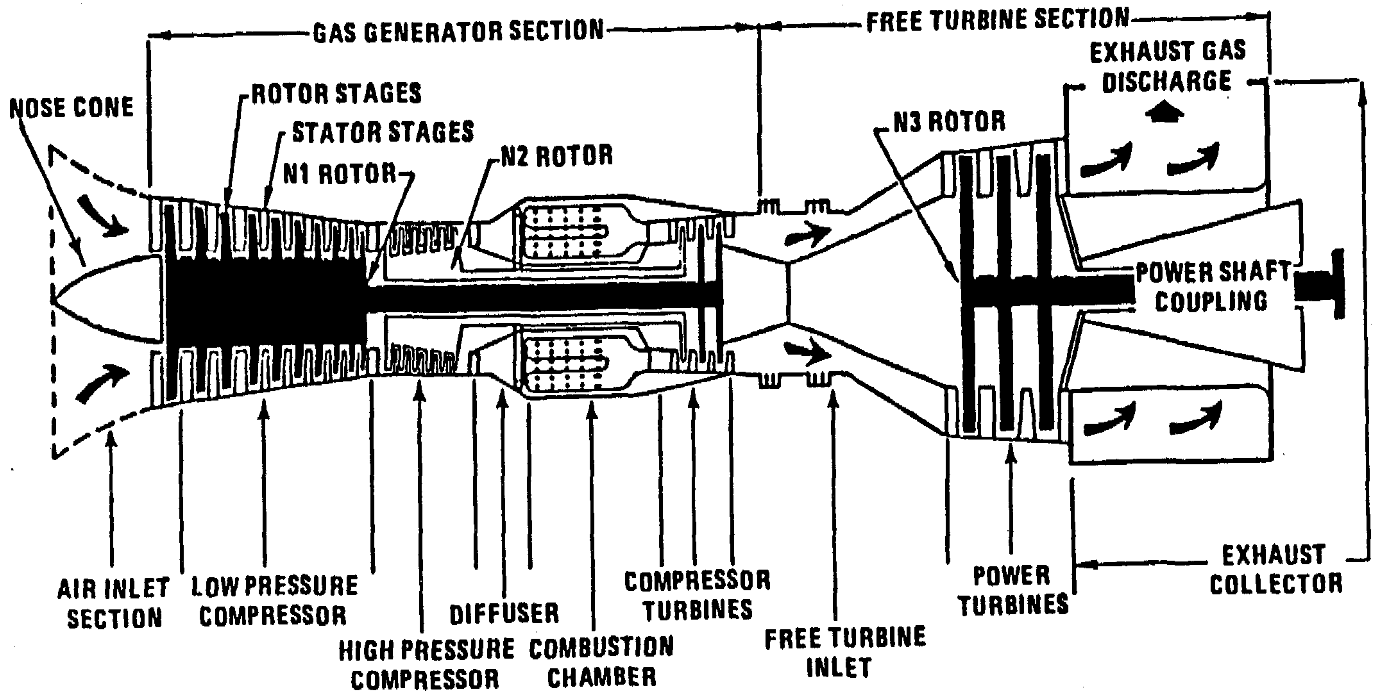

Figure 2-1. Cut-away view of a typical simple cycle gas turbine.[1]

The hot expanding exhaust gases are then passed into the power turbine to produce usable shaft energy. The heat content of the gases exiting the turbine are not commonly utilized with pipeline applications, although other applications use heat recovery steam generators for cogeneration or combined cycle application.

Gas turbines may have one, two, or three shafts to transmit power from the inlet air compression turbine, the power turbine, and the exhaust turbine. There are three types of combustor can design in use: annular, can-annular, and silo. The majority of gas turbines used in pipeline installations are simple cycle two-shaft gas turbines. The type of combustor can design depends on the make/model of the gas turbine. Several stationary engine designs are aircraft derivative using an annular or can-annular design.

The cycle efficiency of the simple cycle gas turbine is typically in the 30 to 35 percent range for existing models in the field, although the efficiency is increasing as turbine inlet temperatures are increasing with materials advances. These efficiencies are lower than reciprocating engines, yielding a higher fuel operating cost. However, the simple cycle offers the lowest installed capital cost. Turbines also have lower emissions than comparable capacities for reciprocating engines which can expedite permitting.

Reciprocating engines are classified by the number of strokes per cycle (two or four stroke), the relative stoichiometry (rich burn, lean burn) and the method of introducing air and fuel into the cylinder (naturally aspirated, turbocharger, supercharger). With the four-stroke cycle, depicted in Figure 2-2., the sequence of events are as follows:

1. **Intake stroke -- suction of the air or air and fuel mixture into the cylinder by the downward motion of the piston.**
2. **Compression stroke -- compression of the air or air and fuel mixture, thereby raising its temperature.**
3. **Ignition and power (expansion) stroke -- combustion and consequent downward movement of the piston with energy transfer to the crankshaft.**
4. **Exhaust stroke -- expulsion of the exhaust gases from the cylinder by the upward movement of the piston.**

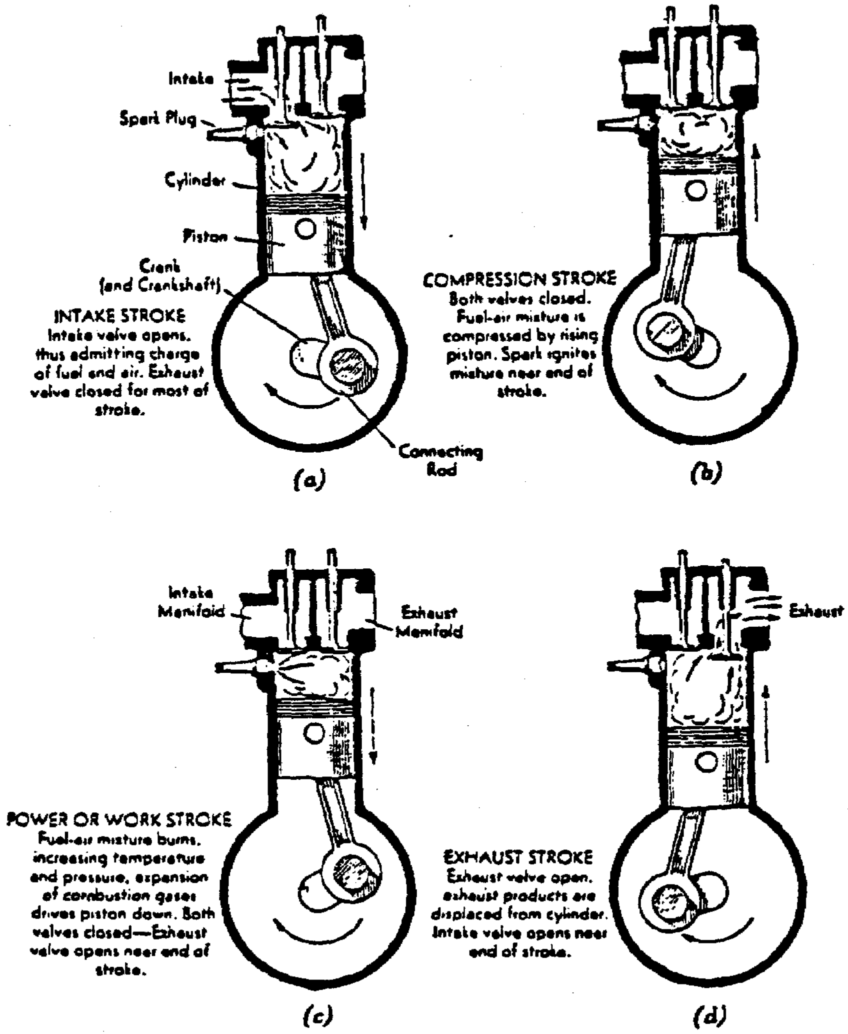

Figure 2-2. The four-stroke, spark ignition (SI) cycle. Four strokes of 180° of crankshaft rotation each, or 720° of crankshaft rotation per cycle.[3]

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

The naturally aspirated engine uses the vacuum created behind the moving piston to pull in the fresh air charge. Alternatively, engines may use turbochargers (powered by an exhaust stream turbine) or superchargers (powered from the engine shaft) to pressurize the air charge. Turbocharging offers higher power output for a specific engine displacement.

With the two-stroke design, depicted in Figure 2-3., the power cycle is completed in one revolution of the crankshaft as compared to two revolutions for the four-stroke cycle. As the piston moves to the top of the cylinder, air, or an air and fuel mixture, is compressed for ignition. Following ignition and combustion the piston delivers power as it moves down. Eventually it uncovers the exhaust ports (or exhaust valves open). As the piston begins the next cycle, exhaust gas continues to be purged from the cylinder, partially by the upward motion of the piston and partially by the scavenging action of the incoming fresh air. Finally, all ports are covered (and/or valves closed) and the fresh charge of air or fuel is compressed.

Air charging in two-stroke designs is often accomplished by means of low-pressure blower scavenging, which also aids in purging the exhaust gases. Naturally aspirated and turbocharged systems are also common. The main advantage of two-stroke engines is their horsepower-to-weight ratios as compared to four-stroke prime movers operating at the same speed.

2.3 EMISSIONS

The primary pollutants from natural gas-fueled reciprocating engines and gas turbines are NO_x, carbon monoxide (CO), hydrocarbons (HC) and other organic compounds. Nitrogen oxide formation is strongly dependent on the high temperatures developed in the cylinder or combustor can. The other pollutants, CO and HC species, are primarily the result of incomplete combustion. Trace amounts of metals and non-combustible inorganic material may be carried over from the lubricating oil, from engine

wear, or from trace constituents in the gas. Sulfur oxides are very low since sulfur compounds are removed in the gas treatment plant prior to entry into the pipeline.

Figure 2-3. Cylinder events for a two-stroke blower scavenged IC engine.[3]

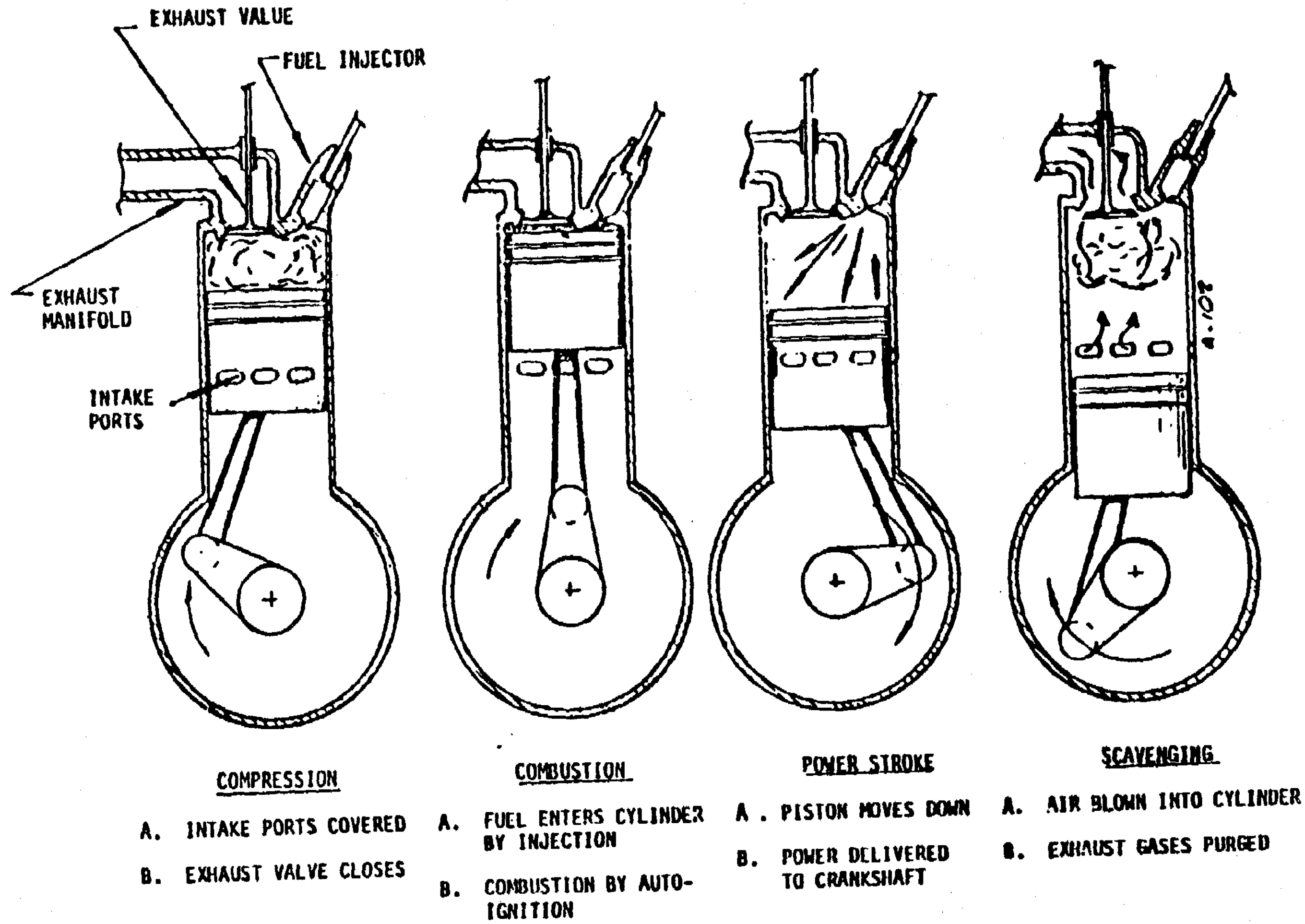

Figure 2-3. Cylinder events for a two-stroke blower scavenged IC engine.[3]

2.3.1 Nitrogen Oxides

Nitrogen oxide formation occurs by two fundamentally different mechanisms. The principle mechanism with gas fired engines and turbines is thermal NO_x, which arises from the thermal dissociation and subsequent reaction of nitrogen (N_2) and oxygen (O_2) molecules in the combustion air. Most thermal NO_x is formed in high temperature flame fronts in the cylinder or combustor can where combustion air has mixed sufficiently with the fuel to produce the peak temperature fuel/air interface. A component of thermal NO_x, called prompt NO_x, is formed from early reactions of nitrogen intermediaries and hydrocarbon radicals from the fuel. The second mechanism, fuel NO_x, stems from the evolution and reaction of fuel-bound N_2 compounds with oxygen. Natural gas has negligible chemically bound fuel N_2 (although some molecular nitrogen) and essentially all NO_x formed is thermal NO_x. The formation of prompt NO_x can form a significant part of total NO_x only under highly controlled situations where thermal NO_x is suppressed. It is more prevalent with rich-burn engines.

At high temperatures, both N_2 and O_2 molecules in the combustion air dissociate into their respective atomic states, N and O. The subsequent reaction of these atoms to create thermal NO_x is described by the Zeldovich mechanisms:

$$N_2 + O \quad NO + N$$

$$N + O_2 \quad NO + O$$

The rates of these reactions are highly dependent upon the stoichiometric ratio, combustion temperature, and residence time at the combustion temperature. The temperature dependence of the overall global reaction is exponential and hence by far the most important in most cases. Also, the Zeldovich mechanism is an idealized, partial description of the formative kinetics. In reality, some hydrocarbon radicals remain sufficiently active when the slower Zeldovich reactions initiate, so that the complete reaction set is more complex and does involve some hydrocarbon interactions.

The maximum thermal NO_x production occurs at a slightly lean fuel/air mixture ratio because of the excess availability of oxygen for reaction. The control of stoichiometry is critical in achieving reductions in thermal NO_x. Premixing with lean-burn reciprocating

engines is effective in suppressing NO_x relative to rich-burn engines. The thermal NO_x generation decreases rapidly as the temperature drops below the adiabatic temperature (for a given stoichiometry). Thus, maximum reduction of thermal NO_x generation can be achieved by control of both the combustion temperature and the stoichiometry. Gas turbines operate with high overall levels of excess air because turbines use combustion air dilution as the means to maintain the turbine inlet temperature below design limits. Most of the dilution takes place in the can downstream of the primary flame, so that high excess air levels are not indicative of the NO_x forming potential. The combustion in conventional designs is by diffusion flames that are characterized by regions of near-stoichiometric fuel/air mixtures where temperatures are very high and the majority of NO_x is formed. Since the localized NO_x forming regions are at much higher temperatures than the adiabatic flame temperature for the overall mixture, the rate of NO_x formation is dependent on the fuel/air mixing process. The mixing determines the prevalence of the high temperature regions as well as the peak temperature attained. Also, operation at full loads will give higher temperatures in the peak NO_x forming regions.

2.3.2 Carbon Monoxide and Total Organic Compounds (Hydrocarbons)

Carbon monoxide and hydrocarbon emissions both result from the products of incomplete combustion. Carbon monoxide results when there is insufficient residence time at high temperature to complete the final step in hydrocarbon oxidation. In reciprocating engines, CO emissions may indicate early quenching of combustion gases on cylinder walls or valve surfaces. The oxidation of CO to carbon dioxide (CO_2) at gas turbine temperatures is a slow reaction compared to most hydrocarbon oxidation reactions. In gas turbines, failure to achieve CO burnout may result from quenching in the can by the dilution air. In gas turbines, CO emissions are usually higher when the unit is run at low loads.

The pollutants commonly classified as hydrocarbons can encompass a wide spectrum of volatile and semi-volatile organic compounds. They are discharged into the atmosphere when some of the gas remains unburned or is only partially burned during the combustion process. With natural gas, some organics are carryover, unreacted, trace

constituents of the gas, while others may be pyrolysis products of the heavier hydrocarbon constituents. Partially burned hydrocarbons can occur for a number of reasons:

- **Poor air/fuel homogeneity due to incomplete mixing prior to, or during combustion;**
- **Incorrect air/fuel ratios in the cylinder during combustion due to maladjustment of the engine fuel system; and**
- **Low cylinder temperature due to excessive cooling through the walls or early cooling of the gases by expansion of the combustion volume caused by piston motion before combustion is completed.**

Carbon monoxide is a primary (directly emitted) pollutant, unlike ozone and other secondary pollutants which are formed in the atmosphere by photochemical reactions (reactions that require light). Carbon monoxide combines with the hemoglobin in blood, preventing it from carrying needed oxygen, and adversely affects the ability to perform exercise. Total organic compounds are of interest both as precursors to ambient ozone and because some species are designated as air toxics.

2.3.3 Particulate Matter and PM-10

Particulate emissions with gas fired turbines and reciprocating engines are non-detectable with conventional protocols unless the engines are operated in a sooting condition. Otherwise, particulate could arise from carryover of non-combustible trace constituents in the gas or from lube oil that passes to the cylinder.

2.3.4 Carbon Dioxide and Nitrous Oxide[4]

Concern about the increasing release of greenhouse gases such as CO_2 and nitrous oxide (N_2O) has grown out of research that documents the buildup of gases in the atmosphere and estimates the implications of continued accumulations. Carbon dioxide and N_2O are largely transparent to incoming solar radiation, but can absorb infrared radiation re-emitted by the Earth. Because of this energy trapping property, such a gas is referred to as a greenhouse gas.

2.4 CONTROL TECHNOLOGIES

Three generic control techniques have been developed for reciprocating engines and gas turbines:

- **Retrofit combustion modification to existing engines to reduce NO_x formation; this includes timing and fuel/air optimization for reciprocating engines and water injection for gas turbines;**
- **Advanced engine design for new sources or major modification to existing sources; this includes clean burn reciprocating head designs and dry gas turbine combustor can designs; and**
- **Post combustion catalytic NO_x reduction; selective catalytic reduction for gas turbines and lean-burn reciprocating engines and nonselective catalytic reduction (NSCR) for rich-burn engines.**

Control techniques for the rich-burn, lean-burn, and gas turbine designs are summarized in the following paragraphs[5].

2.4.1 Control Techniques for Rich-Burn Reciprocating Engines

2.4.1.1 Nonselective Catalytic Reduction. This technique uses the residual hydrocarbons and CO in the rich-burn engine exhaust as a reducing agent for NO_x. In the presence of oxygen, the hydrocarbons will be oxidized rather than react with NO_x, hence the designation nonselective. This is in contrast to ammonia injection for selective catalytic reduction where ammonia selectively reacts with NO_x. The excess hydrocarbons and NO_x passover a catalyst, usually a noble metal (platinum, rhodium, or palladium) which reduces the reactants to N_2, CO_2, and H_2O. The noble metal catalysts require a temperature window of between 800 and 1,200 °F. To achieve best NO_x reduction performance of 80 to 90 percent, the engine may need to be run in a more rich fuel condition than normal.

The NSCR technique is effectively limited to engines with normal exhaust oxygen levels of 4 percent or less. This includes 4-cycle naturally aspirated engines and some 4-cycle turbocharged engines. Engines operating with NSCR require tight air/fuel control to maintain high reduction effectiveness without high hydrocarbon emissions. Catalyst poisoning and structural failures are also operational and cost concerns. Nonselective

catalytic reduction was developed through a series of demonstrations in California in the late 1970s, and the use has since spread to other regions.

2.4.1.2. Prestratified Charge. Prestratified charge combustion (PSC) is a retrofit system that has been applied to 4-cycle carbureted natural gas engines over 100 hp. In this system, controlled amounts of air are introduced into the intake manifold in a specified sequence and quantity. This stratification provides a flame cooling effect, resulting in reduced formation of NO_x.

Prestratifid charge combustion is limited to 4-cycle, carbureted engines. This represents about 20 to 30 percent of installed engines. The technique has been applied to engines in California where reductions up to 90 percent have been achieved with no reduction in fuel economy, but with increases in CO.

2.4.2 Control Techniques for Lean-Burn Reciprocating Engines

2.4.2.1 Lean Combustion. Lean combustion techniques use increased air/fuel ratios to lower peak flame temperature and reduce NO_x formation. Typically, air/fuel ratios are increased from normal levels of 20 to 35 up to controlled levels of 45 to 50. The upper limit is constrained by the onset of misfiring at the lean limit. This condition also increases CO and HC emissions.

To maintain acceptable engine performance at lean conditions, manufacturers have developed torch ignition systems that promote flame stability at very lean conditions. With torch ignition, a rich mixture is ignited in a small ignition cell located in the cylinder head. The ignition cell flame passes to the cylinder where it provides a uniform ignition source. The technique can be retrofit, with extensive modification, to existing turbocharged 2 and 4-cycle engines. With new engine designs, NO_x reductions of 80 to 90 percent have been achieved compared to spark ignition designs. In most cases, the NO_x reductions have been accompanied by increases in power output and increased fuel economy.

2.4.2.2 Selective Catalytic Reduction. Selective catalytic reduction (SCR) is applicable to lean-burn engines and is similar in concept to the gas turbine application discussed in Section 2.4.3. Ammonia (NH_3) is injected upstream of a noble metal or metal oxide catalyst to give an NH_3 molar ratio of about 1.1. The mixture of NH_3 and NO_x is

selectively reduced over the catalyst within a temperature range of 600 to 900 °F depending on the catalyst. The major system components are the catalyst and associated housing, the ammonia storage and delivery system, and the control system. Operating experience with lean-burn reciprocating engines has been very limited, and the performance has been less acceptable than NSCR with rich-burn engines, or SCR with gas turbines. The primary difficulty with lean-burn engines has been maintaining air/fuel control, very limited automatic controls, and engine performance while achieving the necessary exhaust temperature window for efficient SCR operation.

2.4.2.3 Exhaust Gas Recirculation. Recirculation of exhaust gas into the engine cylinder reduces the production of NO_x emissions by reducing the maximum combustion temperatures. Small reductions in peak cylinder temperature will result in significant reduction in NO_x. Maximum NO_x emissions reductions have been reported in the range of 35 to 65 percent, with an average of about 50 percent. The percentage reduction attainable is higher with engines with high baseline emissions. The extent of EGR for a specific engine is limited by the possible onset of efficiency loss, CO emissions, or engine misfire. Control of the EGR flow rate to correspond to engine load is a major operational challenge which has not been completely resolved.

2.4.3 Control Technologies for Gas Turbines

2.4.3.1 Water Injection. Water or steam injection is a mature technology that has been demonstrated as very effective in suppressing NO_x emissions from gas turbines. The effect of steam and water injection is to increase the thermal mass by dilution and thereby reduce the adiabatic flame temperature and the peak flame temperatures in the NO_x forming regions. With water injection, there is the additional benefit of absorbing the latent heat of vaporization from the flame zone. Water or steam is typically injected at a water-to-fuel weight ratio of less than one. Depending on the initial NO_x levels, such rates of injection may reduce NO_x by 60 percent or higher. Wet injection is usually accompanied by an efficiency penalty but an increase in power output. Efficiency penalties of 2 to 3 percent are typical. The power increase results because fuel flow is increased to maintain turbine inlet temperature at manufacturers specifications. Power increases with water or

steam injection of 5 to 6 percent are typical. Both CO and HC emissions are increased by large rates of water injection.

The use of wet injection may be constrained in some applications, such as pipeline pumping by the unavailability of pure water for injection. The choice between water or steam is usually driven by the availability of steam. Most operators prefer steam because of fewer operational problems, better heat rate, and increased power augmentation compared to water. The use of water with low mineral content is a significant cost item with water injection. The reliability of the water treatment system and injection pumps also can be a major issue in continuous operation under low NO_x conditions.

2.4.3.2 Selective Catalytic Reduction Systems. Selective catalytic reduction systems are post combustion technologies and have only been applied to gas turbines within the past 10 years. Selective catalytic reduction was first demonstrated in Japan in 1981 and in the United States in 1987 on large power generating gas turbines with waste heat recovery systems, i.e., cogeneration and combined-cycle gas turbines. Since its introduction, SCR (with the aid of water/steam injection) has been the NO_x control technology specified for the most stringent permitting NO_x limits. Because of the high and variable exhaust temperatures (caused by rapid load swings) associated with simple cycle gas turbines, no prime mover turbines currently use this control technology.

An SCR system consists of two major components: an ammonia storage, feed, and injection system, and a catalyst and catalyst housing. Selective catalytic reduction systems selectively reduce NO_x emissions by injecting NH_3 into the exhaust gas stream upstream of the catalyst. Nitrogen oxides, NH_3, and O_2 react on the surface of the catalyst to form N_2 and H_2O. The following equation set outlines the global chemical reactions hypothesized to take place.

$$NH_3 + NO + 1/4\ O_2 \Longrightarrow N_2 + 3/2\ H_2O \quad \&$$

$$NH_3 + 1/2\ NO_2 + 1/4\ O_2 \Longrightarrow 3/2\ N_2 + 3/2\ H_2O$$

For the SCR system to operate properly, the exhaust gas must be within a particular temperature range (typically between 450 and 850 °F). The range is dictated by the catalyst (typically made from noble metals, base metal oxides such as vanadium and

titanium, and zeolite based material). Exhaust gas temperatures greater than the upper limit (850 °F) will pass the NO_x and ammonia unreacted through the catalyst. Ammonia emissions, called NH_3 slip, are a key consideration when specifying a SCR system. Ammonia, either in the form of liquid anhydrous ammonia, or aqueous ammonia hydroxide is stored on site and injected into the exhaust stream upstream of the catalyst. Although an SCR system can operate alone, it is typically used in conjunction with water/steam injection systems to reduce NO_x emissions to their lowest levels (less than 10 ppm at 15 percent oxygen).

The catalyst and catalyst housing used in SCR systems tend to be very large and dense (in terms of surface area-to-volume ratio) because of the high exhaust flow rates and long residence times required for NO_x, O_2, NH_3, and catalyst to react. Most catalysts are configured in a parallel-plate, "honeycomb" design to maximize the surface area-to-volume ratio of the catalyst.

2.4.3.3 Combustion Modifications. Several different methods or approaches of reducing NO_x emissions from gas turbines are currently being researched and developed by the manufacturers of gas turbines. Since thermal NO_x is a function of both temperature (exponentially) and time (linearally), the basis of these controls are to either lower the combustor temperature using lean mixtures air and fuel and/or staging the combustion or decrease the residence time of the combustor. Some manufacturers use a combination of these methods to reduce NO_x emissions. These methods or approaches are as follows:

- **Lean combustion;**
- **Reduced combustor residence time;**
- **Two-stage lean/lean combustion; and**
- **Two-stage rich/lean combustion.**

Most gas turbine combustors were originally designed to operate with a stoichiometric mixture (theoretical amount of air required to react with the fuel). Lean combustion involves increasing the air/fuel ratio of the mixture so that the peak and average temperature within the combustor will be less than that of the stoichiometric mixture. A lean mixture of air and fuel can be premixed before ignition, a stoichiometric

mixture can be ignited and additional air can be introduced at a later stage (staging) creating an overall lean mixture in the turbine, or a combination of both can occur. Introducing excess air at a later stage not only creates a leaner mixture but can also reduce the residence time of the combustor (given enough excess air is added at the later stage to create a mixture so lean that it will no longer combust). Also, the residence time of a combustor can be decreased by increasing the turbulence within the combustor.

Two-stage lean/lean combustors are essentially fuel-staged combustors in which each stage burns lean. The two-stage lean/lean combustor allows the turbine to operate with an extremely lean mixture and a stable flame that should not "blow off" or extinguish. A small stoichiometric pilot flame ignites the premixed gas and provides flame stability. The high NO_x emissions associated with the higher temperature pilot flame is minor compared to the low NO_x emissions generated by the extremely lean mixture.

Two-stage rich/lean combustors are essentially air-staged combustors in which the primary stage/zone is operated fuel rich and the secondary stage/zone is operated fuel lean. The rich mixture will produce lower temperatures (compared to stoichiometric) and higher concentrations of CO and H_2 because of incomplete combustion. The rich mixture decreases the amount of oxygen available for NO_x generation and the increased CO and H_2 concentrations will help reduce some of the NO_x formed. Before entering the secondary zone, the exhaust of the primary zone is quenched (to extinguish the flame) by large amounts of air and a lean mixture is now created. The combustion of the lean mixture is then completed in the secondary zone.

REFERENCES FOR CHAPTER 2

1. **"Standards Support and Environmental Impact Statement; Volume 1: Proposed Standards of Performance for Stationary Gas Turbines," EPA-450/2-77-017a, September 1977.**

2. **"Engines, Turbines, and Compressors Directory," American Gas Association, Catalog #XF0488.**

3. **Standards Support and Environmental Impact Statement, Volume 1: Stationary Internal Combustion Engines, EPA-450/2-78-125a, U.S Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, July 1979.**

4. **"Limiting Net Greenhouse Gas Emissions in the United States, Volume II: Energy Responses," Report for the Office of Environmental Analysis, Office of Policy, Planning and Analysis, Department of Energy (DOE), DOE/PE-0101 Vol II, September 1991.**

5. **Castaldini, C., "Evaluation of Water Injection Impacts for Gas Turbine NO_x Control at Compressor Stations," prepared by Acurex Corp. for the Gas Research Institute, GRI-90/0138, July 1990.**

3. EMISSION DATA REVIEW AND ANALYSIS PROCEDURES

This chapter reviews the procedures used to obtain and evaluate documents or other sources of information for use in updating and augmenting the emission factors. A general discussion of the review findings is presented in Table 3-1 together with an assignment of quality level associated with emissions data. This quality rating is a measure of procedures for sampling methodology and data reduction. The inclusion and/or exclusion of information found in the documents was decided based on data review and analysis following the revised AP-42 criteria guidelines.[1] Following the AP-42 criteria, the emissions data were rated based on the following guidelines:

Definition of Data Rankings:

- **A - When tests are performed by a sound methodology and are reported in enough detail for adequate validation. These tests are not necessarily EPA reference method tests, although such reference methods are preferred and certainly to be used as a guide.**
- **B - When tests are performed by a generally sound methodology, but they lack enough detail for adequate validation.**
- **C - When tests are based on an untested or new methodology or are lacking a significant amount of background data.**
- **D - When tests are based on a generally unacceptable method, but the method may provide an order-of-magnitude value for the source, or no background data is provided at all.**

3.1 LITERATURE SEARCH AND EVALUATION

Several different approaches were followed to obtain literature/data to update and expand the Section 3.1 emission factors. The applicable references and sources (reviewed in Table 3-1) were obtained through literary searches and personal communications with a wide variety of sources such as: a "Dialogue" computer abstract search, an in-house data search, an EPA library search, an Electric Power Research Institute (EPRI) library search, periodicals, and contacts with trade organizations, manufacturers, local, state, and federal air quality agencies, and vendors of control technologies. After reviewing the information provided by the sources, all useful data were entered into summary tables for future updating of AP-42 emission factors.

The data were judged to be of generally high quality because the bulk of the criteria emissions data came from emission source test reports (compiled in several documents and sources, i.e., reports and electronic databases). The quality of noncriteria pollutant (air toxics and VOC speciation) data varied among the many sources so each document was reviewed and rated. Data from all sources were entered into evaluation checklists and summary tables to facilitate calculation of average emission factors and identification of data gaps. Discussions of data and emission factor qualities are discussed in Chapters 4 and 5.

A literature search and compilation of emissions test data for pollutants from controlled and uncontrolled prime movers has been routinely done by the Gas Research Institute (GRI) as part of their charter to address pipeline compressor station environmental issues. From this previous search, more than 100 individual data documents and/or sources were found, including a compilation of source tests for criteria and some noncriteria emissions data. This data base is being augmented with an ongoing comprehensive VOC speciation testing program by GRI for three of the four types of prime movers; data from this program are not yet available. Another source of VOC speciation and air toxics data was found from compliance test reports submitted to regulatory agencies, source testing for California AB2588 (air toxics hot spots), and field tests. Along with pollutant data, equipment profile data (population of all makes and models, average

power rating, duty cycles, emission control technologies) were obtained to better estimate actual emissions from all prime movers (i.e., emissions data were weighed according to actual population and duty-cycles).

An extensive evaluation of criteria pollutant data for natural gas prime movers revealed that more than 90 percent of the engines/turbines models in current service have been tested for NO_x, CO, and HC. Sulfur oxide and PM emissions were of little concern since all sources fired pipeline quality natural gas with more than 85 percent methane. All the data have been collected and compiled in references 8,9,11. These documents are essentially updated revisions of the original database used for the previous AP-42 emission factors. Therefore, all of the data used to calculate the previous emission factors will also be included. The current emissions database also includes controlled criteria data

Table 3-1 shows a list of the documents reviewed for speciated VOC and air toxics data. The table also explains why a document was used or not used to calculate emission factors Because of the different types of engines/turbines and the number of controls available for each type, determining speciated VOC and air toxic emission factors for each configuration was extremely difficult In cases where emission factors were calculated, they were based on a very scarce database of information (typically one data point) A data search was conducted using the EPA supplied databases of XATEF, SPECIATE, and CHIEF. The data found from that search were of little direct use because of inadequate information supplied concerning engine specifics.

A search for data on N_2O, a global warming gas, showed that all existing data were taken in the early 1980s. All N_2O data taken before 1988 are considered highly unreliable because of artifacts in the sample handling and analysis method that led to very high spurious reported N_2O values. The artifact was caused by generation of N_2O in grab samples in the presence of sulfur and moisture. Therefore, all the N_2O data were discarded and an emission factor for N_2O was not developed. The GRI tests (mentioned previously) include the measurement of N_2O with a new EPA recommended testing procedure, but data will not be available for this update.

All of the emissions data used to update the emission factors were reviewed for engine/turbine design specifications. All the data were separated into the four types of engines. If the document did not clearly specify engine/turbine design details, the data were not used.

TABLE 3-1 SUMMARY REVIEW AND EVALUATION OF REFERENCES

Ref. No.	General Information Concerning Document	Use in AP-42 (Data or Info.)	If Data, what Quality?
2	Source test report for controlled engine (air/fuel controls), baseline and controlled data 2-Cycle Lean Burn Engine	Criteria & spec. of VOC	B
3	Source test report for controlled engine (NSCR), baseline and controlled, 4-Cycle Rich Burn Engine	Criteria & spec. of VOC	A
4	Source test report for controlled engine (SCR), baseline and controlled, 4-Cycle Lean Burn Engine	Criteria & spec. of VOC	A
5	4 different source tests for compliance. Only the results were obtained, test methods are still with SBAPCD	Criteria and air toxics	C
6	Summary of NO_x controls for Natural Gas Prime Movers	Info only	
7	Summary of Water Injection for Natural Gas Prime Movers	Info only	
8	Summary of SCR for Natural Gas Prime Movers	Yes, NO_x only	D
9	Compilation of emissions data for all types of prime movers	Criteria	A
10	Additional supplement for ref. 9	Criteria	A
11	Prime Mover Profile Information (population, power, eng. description, etc.)	Population	B
12	Computer database that incorporates all of ref. 9 & 10 information	Criteria	A

REFERENCES FOR CHAPTER 3

1. **Technical Procedures for Developing AP-42 Emission Factors and Preparing AP-42 Sections (Draft), Emission Inventory Branch, Technical Support Division, Office of Air and Radiation, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC, March 6, 1992.**

2. **Castaldini, C., "Environmental Assessment of NO_x Control on a Spark-Ignited Large Bore Reciprocating Internal Combustion Engine," U.S. Environmental Protection Agency, Research Triangle Park, NC, April 1984.**

3. **Castaldini, C., and L.R. Waterland, "Environmental Assessment of a Reciprocating Engine Retrofitted with Nonselective Catalytic Reduction," EPA-600/7-84-073B, U.S. Environmental Protection Agency, Research Triangle Park, NC, June 1984**

4. **Castaldini, C., and L.R. Waterland, "Environmental Assessment of a Reciprocating Engine Retrofitted with Selective Catalytic Reduction," EPA Contract No. 68-02-3188, U.S. Environmental Protection Agency, Research Triangle Park, NC, December 1984**

5. **Compliance Test Reports from Santa Barbara Air Pollution Control District (SBAPCD) including: "Pooled Source Emission Test Report: Gas-Fired IC Engines in Santa Barbara County," ENSR Consulting and Engineering, July 1990; "Air Pollution Source Testing for California AB2588 of Engines at the Chevron USA, Inc. Carpinteria Facility," Engineering-Science, August 1990; "Air Pollution Source Testing for California AB2588 on an Oil Platform Operated by Chevron USA, Inc., Platform Hope, California," Engineering-Science, August 1990, "Air Toxics Hot Spots Testing at Southern California Gas Company Goleta Station - IC Engine #3," Pape & Steiner Environmental Services, June 1990; "CEMS Certification and Compliance Testing at Chevron USA, Inc.'s Gaviota Gas Plant," Pape & Steiner Environmental Services, June 1989; "Emission Testing at the Bonneville Pacific Cogeneration Plant," Steiner Environmental, Inc., March 1992.**

6. **Castaldini, C., "NO_x Reduction Technologies for Natural Gas Industry Prime Movers," prepared by Acurex Corp. for the Gas Research Institute, GRI-90/0215, August 1990.**

7. **Castaldini, C., "Evaluation of Water Injection Impacts for Gas Turbine NO_x Control at Compressor Stations," prepared by Acurex Corp., for the Gas Research Institute, GRI-90/0124, September 1989.**

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

9. Urban, C., "Compilation of Emissions Data for Stationary Reciprocating Gas Engines and Gas Turbines in Use by American Gas Association Member Companies," prepared by SouthWest Research Institute for the Pipeline Research Committee of the American Gas Association, Project PR-15-86, May 1980.

10. Fanick, R.E., H.E. Dietzmann, and C.M. Urban, "Emissions Data for Stationary Reciprocating Engines and Gas Turbines in Use by the Gas Pipeline Transmission Industry - Phase I & II," prepared by SouthWest Research Institute for the Pipeline Research Committee of the American Gas Association, Project PR-15-613, April 1988.

11. "Engines, Turbines, and Compressors Directory," American Gas Association, Catalog #XF0488.

12. Martin, N.L., and R.H. Thring, "Computer Database of Emissions Data for Stationary Reciprocating Natural Gas Engines and Gas Turbines in use by the Gas Pipeline Transmission Industry Users Manual (Electronic Database Included)," prepared by SouthWest Research Institute for the Gas Research Institute, GRI-89/0041.

4. EMISSION FACTOR DEVELOPMENT

The new and prior AP-42 data identified in the data search discussed in Chapter 3 were compiled and evaluated. The data were entered into an evaluation worksheet to rate various quality and completeness factors according to the AP-42 guidelines.[1] The data were screened for inclusion and rejection. The emission factors were reviewed and ranked using a different quality criteria than was used for determining data quality.

Definition of Emission Factor Rankings:

- **A - Developed only from A-rated source test data taken from many randomly chosen facilities in the industry population. The source category is specific enough to minimize variability within the source population.**
- **B - 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. As with the A rating, the source is specific enough to minimize variability within the source population.**
- **C - 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. As with the A rating, the source category is specific enough to minimize variability within the source population.**
- **D - The emission factor was developed only from A- and B-rated test data from a small number of facilities, and there may be 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 population.**

E - The emission factor was developed from C- and or D- rated test data, and there may be 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.

Emissions factors and emissions data were presented in terms of both a specific energy input basis and a specific power output basis. For example, in English units, the emissions were reported as both lb of pollutant per MMBtu (million Btu) heat input as well as grams of pollutant per horsepower hour output. Appendix A presents the conversions between the different emission factors used. All data were ranked and entered into the appropriate tables, and then were separated into appropriate categories of engines and weighted by a population profile to produce an emission factor.

4.1 CRITERIA POLLUTANTS

4.1.1 Review of Previous Data

The prior AP-42 update for Section 3.2 presented only baseline emission factors and did not present any controlled criteria data. A review of the test data and data reduction procedures for the prior AP-42 update showed the emission factors were based on the average emissions of 40 different engines and 16 turbines. The development of the prior emission factors did not take into account the population profile of prime movers. The emission factors in the prior update were rated as "A" quality in 1976. After reviewing the quantity and quality of the emissions test data as part of the present update, the original data were determined to be of "A" quality because the testing was generally well documented and reflected proper protocols and data reduction procedures. Although the quality and quantity of data used to determine the emission factors of the criteria pollutants was very good, the emission factor development did not account for significant design variations within the engine category and did not weight the data by the population profile. The emission factor quality judged to be "B" in view of current criteria.

4.1.2 Review of New Data

Since the last update, the primary data source for engine and turbine test data has been updated twice, and supplemented once.[2,3] This expanded data base has been entered

into a computer database for easier access.[4] The composite expanded emissions data base includes coverage of over 90 percent of in-use engines/turbines. The data base compiles emissions (NO_x, CO, TOC, and total non-methane organic compounds (TNMOC) (reported as ppm, lb/hr, lb/MMBtu, and g/hp-hr) and engine operating parameters (power output, rpm, fuel analysis, temperatures, humidity, etc.) Reference 3 (an appendix) presents the data reduction methodology and computer algorithms used to reduce the emissions data. The data reduction procedure detailed the assumptions made and tabulated the actual data required to compute the emission factor. The original data were used to spot check the computerized data base to ensure data consistency. Other emissions data (baseline data of controlled engines, compliance test reports, and manufacturers data) were also used and compared to the computerized data file. The results of the spot checks showed good agreement, and the data quality was judged to be "A." The population profile database was spot checked with a recent GRI study.[5,6] The population data were used to weight the emissions data to produce emissions factors. The overall emission factor rating for criteria pollutants was judged to be an "A" because of the quality and quantity of emissions data and the inclusion of the four engine/turbine types and population.

4.1.3 Compilation of Baseline Criteria Emission Factors

The primary raw emissions data are not presented here in their totality because of the immense size of the data base. References 2 and 3 contain over 300 sheets of raw data, Reference 6 contains 50 pages of raw data, and Reference 4 contains 1500 individual tests. Table 4-1 summarizes the raw and reduced data used to develop the emissions factors. A search of specific make/model of engines/turbines was used to determine the emission factors for specific units. These emission factors were then averaged with appropriate population weighing factor, i.e. percentage of total installed capacity, to produce the final emission factors for prime movers (see Table 4-1).

4.1.4 Compilation of Controlled Criteria and Noncriteria Emission Factors

Several sources were identified with emissions data for almost all types of controlled engines.[3,7-10] The only major control not included is PSC for small 4-cycle rich-burn engines. The control techniques include increasing the air/fuel ratio (combustion modification), NSCR, SCR, CleanBurn by Cooper-Bessemer, and Pre-Combustion Chamber (PCC) design by Dresser-Rand. For each control technique (except for CleanBurn and PCC), there was only one data source (mostly "A," some "B" quality) used so there are no summary tables used to calculate an average. Tables 4-2 through 4-5b contain the test data taken from the primary references converted in some cases to emission factor units. Since only one data source of "A or B" data quality was used in most cases, the corresponding emission factor quality for all controlled emission factors is "E."

4.2 BASELINE SPECIATED VOCs AND AIR TOXICS DATA

4.2.1 Review of New Data

The new speciated VOC and air toxics baseline emissions data resulted from testing as part of California's air toxics reporting initiative, AB2588.[10] The emission factors were not averaged together but were evaluated and presented separately, because the data represented a diversity of engine/turbine and control configurations. Therefore, the resultant emission factors are mostly based on a single data point. Reference 5 presents formaldehyde, benzene, toluene, ethylbenzene, and xylene emission data for 2-cycle lean engines. Only the test results were available and only partial information was documented on test protocols. Therefore the data quality was rated "C."

4.2.2 Compilation of Emission Factors

Table 4-6 presents a summary of the raw data used to calculate the non-criteria emission factors. The amount of data obtained did not warrant a population weighing Because of the low data quality and quantity, the quality of the emission factors were judged to be an "E." Additional higher quality data should be available when GRI releases the results of its test program.

4.3 CARBON DIOXIDE AND NITROUS OXIDE - GLOBAL WARMING GASES

4.3.1 Review of New Data

All N_2O emissions data were taken with pre-1988 protocols which have proven to be erroneous. Therefore, no useable data were available and no emission factor for N_2O could be developed For CO_2 emissions, all carbon in the fuel was assumed to be converted into CO_2 which was emitted via the exhaust gas Carbon conversion to CO and unburned hydrocarbons is insignificant on a total mass basis. The emission factor for CO_2 was developed from the carbon content of the fuel assuming 100 percent conversion of carbon into CO_2. The average carbon content of natural gas is taken to be 70 percent by weight, which corresponds to approximately 85 to 95 percent methane.

4.3.2 Calculation of Emission Factor

For each pound of natural gas fired, there is 0.70 pounds of carbon (0.0583 lb-moleC) that will convert to 2.57 pounds of CO_2 in the exhaust (0.0625 lb-moleC * 44 lbCO_2/lb-moleCO_2 * 100 percent (lb-moleCO_2 / 1lb-moleC). The energy content of natural gas is approximately 23,900 Btu/lb, the emission factor for CO_2 (on a heat input basis) is 110 lbCO_2/MMBtu. The emission factor in terms of the fuel carbon content, is 160C lb/MMBtu, where C represents the fractional carbon content of the fuel.

TABLE 4-1. CRITERIA EMISSIONS DATA FOR UNCONTROLLED NATURAL GAS PRIME MOVERS[2-4,6]

Prime Mover Type	NOx	TOC	TNMOC	CO	NOx	TOC	TNMOC	CO	NM/TOC Ratio	Ratio of Total Population
	lb/MMBtu				g/hp-hr					
Gas Turbines										
Total	0.338	0.053	0.002	0.166	1.270	0.177	0.010	0.830	0.013	1.000
2-cyc Lean										
AJAX	1.132	4.318	0.000	0.338	4.728	19.128	0.000	1.462	0.000	0.040
CLARK	2.636	1.703	0.147	0.613	9.960	6.286	0.610	2.329	0.085	0.360
CB	3.009	1.164	0.067	0.174	12.821	4.706	0.260	0.760	0.057	0.470
Fairbanks-Morse	0.556	1.220	0.000	0.473	4.413	5.126	0.000	3.112	0.000	0.010
Worthington	2.466	1.618	0.174	0.528	9.880	6.487	0.697	1.937	0.063	0.120
Total	2.710	1.539	0.105	0.384	11.031	6.070	0.426	1.158	0.065	1.000
4-cyc Lean										
CB	2.610	1.517	0.070	0.554	8.784	5.153	0.238	1.848	0.042	0.200
IR	3.647	0.631	0.060	0.412	13.332	2.388	0.321	1.683	0.135	0.480
Waukesha	0.350	1.364	0.188	0.653	1.265	4.938	0.683	2.358	0.135	0.090
White-Superior	4.002	2.311	0.521	0.213	16.256	9.698	2.187	0.879	0.241	0.230
Total	3.225	1.261	0.180	0.416	12.009	4.852	0.723	1.592	0.141	1.000

TABLE 4-2. EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: COMBUSTION MODIFICATIONS ON 2-CYCLE LEAN BURN[7]

Pollutant	Baseline		Increased air/fuel ratio with intercooling			
	[grams/hr/hp]	[lb/MMBtu] (fuel input)	[grams/hp/hr]		[lb/MMBtu] (fuel input)	
NO_x	9.87	2.93	5.06	A	1.52	A
CO	.94	.28	1.53	A	.46	A
TOC	7.51	2.23	8.51	A	2.56	A
TNMOC	5.22	1.55	6.01	A	1.81	A
CH_4	2.29	.68	2.5	A	.75	A
P.M(total - front+back)	.155	.0461	.183	A	.055	A
(solids - front half)	.098	.0291	.125	A	.038	A
(condensibles - back half)	.057	.0170	.058	A	.017	A

TABLE 4-3. EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: SCR ON 4-CYCLE LEAN BURN[9]

Pollutant	Inlet		Outlet	
	[grams/hr/hp]	[lb/MMBtu] (fuel input)	[grams/hp/hr]	[lb/MMBtu] (fuel input)
NO_x	19.2	6.42	3.57	1.19
CO	1.19	.38	1.1	.367
NH_3			.27	.091
C7 -> C16	.007	.0023	.0031	.0013
C16+	.013	.0044	.0024	.0008

TABLE 4-4. EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: NSCR ON 4-CYCLE RICH BURN ENGINE[6,8]

Pollutant	Inlet		Outlet	
	[grams/hr-hp]	[lb/MMBtu] (fuel input)	[grams/hp-hr]	[lb/MMBtu] (fuel input)
NO_x	7.79	1.79	2.53	.58
CO	12.2	2.81	10.4	2.40
TOC	.33	.079	.2	.047
NH_3	.05	.012	.82	.191
C7 -> C16	.019	.0042	.0041	.0009
C16+	.017	.004	.0006	.0001
P.M(solids - front half)	.003	.0007	.003	.0007
Benzene		7.1E-4		1.1E-4
Toluene		2.3E-4		<2.3E-5
Xylenes		<5.9E-5		<4E-5
Propylene		<1.6E-4		<1.6E-4
Naphthalene		<4.9E-5		<4.9E-5
Formaldehyde		<1.6E-3		<7.2E-6
Acetaldehyde		<6.1E-5		<4.8E-6
Acrolein		<3.7E-5		<9.6E-6

TABLE 4-5a. EMISSION FACTORS FOR COMBUSTION CONTROLLED PRIME MOVERS: CLEAN BURN TECHNOLOGY[a]

NO_x	TOC	TMNOC	CO	NO_x	TOC	TNMOC	CO
lb/MMBtu				grams/hp-hr			
				1.980			
				2.100			
				2.250			
0.757	0.984		0.405	2.458	3.194		1.314
0.670	1.019		0.318	2.198	3.344		1.044
1.534	0.834		0.261	4.994	2.713		0.850
0.792	0.979		0.382	2.580	3.190		1.246
0.757	1.005		0.419	2.453	3.256		1.356
0.675	1.013		0.440	2.190	3.294		1.428
0.674	1.027		0.428	2.185	3.329		1.388
0.669	1.029		0.430	2.166	3.330		1.391
				1.850	2.550		1.440
				1.970	2.380		1.280
				1.920	2.330		1.410
				3.780	2.390		1.260
				0.960	3.620		1.620
0.873	0.174	0.033	0.033	2.992	0.604	0.116	0.111
0.874	0.180	0.038	0.020	2.832	0.592	.0125	0.069
0.901	0.190	0.385	0.190	2.794	0.594	0.122	0.127
				2.100			
				2.200			
				2.340			
				0.970			
				1.260			
0.834	0.767	0.152	0.302	2.313	2.544	0.121	1.083

[a]Emission factors for Copper-Bessemer "Cleanburn" all data are "A" quality, emission factors are "C" quality because of the limited data from Reference 3.

TABLE 4-5b. EMISSION FACTORS FOR COMBUSTION CONTROLLED PRIME MOVERS: PCC TECHNOLOGY[a]

NO_x	TOC	TNMOC	CO	NO_x	TOC	TNMOC	CO
lb/MMBtu				grams/hp-hr			
0.799	1.969		0.792	3.044	7.501		3.018
0.736	1.978		0.796	2.802	7.528		3.030
0.720	1.945		0.824	2.743	7.409		3.140
0.372	2.600		1.162	1.480	10.329		4.517
0.377	2.666		1.087	1.508	10.658		4.348
0.259	2.036	0.265	0.778	0.880	6.910	0.900	2.640
1.310	1.461	0.139	0.369	4.510	5.030	0.480	1.270
1.340	1.190	0.120	0.390	4.560	4.030	0.410	1.340
0.570	1.260	0.120	0.540	2.000	4.400	0.420	1.190
1.060	1.750		0.380	3.680	6.100		1.130
0.630	1.660		0.400	2.290	6.080		1.450
0.748	2.021	0.409	0.967	2.480	6.680	1.350	3.200
0.722	3.473	0.646	0.918	2.610	12.560	2.340	3.320
0.694	2.160	0.413	0.983	2.300	7.180	1.370	3.270
2.901	0.497	0.131	0.225	10.050	1.720	0.450	0.780
1.095	1.146	0.118	0.825	3.600	3.770	0.390	2.720
0.390	1.079	0.178	0.567	1.380	3.810	0.630	2.000
1.158	0.644	0.074	0.299	4.100	2.280	0.260	1.050
0.502	0.901	0.146	0.502	1.770	3.180	0.520	1.770
0.626	2.656	0.461	0.633	0.430	10.530	1.930	2.480
0.850	1.756	0.250	0.672	2.911	6.384	0.881	2.428

[a]Emission factors for Dresser-Rand "PCC" units all data are "A" quality, emission factors are "C" quality because of the limited data from Reference 3.

TABLE 4-6. NONCRITERIA EMISSION FACTORS FOR UNCONTROLLED PRIME MOVERS [lb/MMBtu][5]

Pollutant	2-Cycle Lean		
	Data	Ref	Data Quality[a]
Formaldehyde (lb/MMBtu)	.65 .0014	9 9	C C
Benzene (lb/MMBtu)	.0006 .0001	9 9	C C
Toluene (lb/MMBtu)	.0007 .0001	9 9	C C
Ethylbenzene (lb/MMBtu)	.0002	9	C
Xylenes (lb/MMBtu)	.0006	9	C

[a]Data quality results are based on single or limited tests. Emission Factors resulting from these data are rated "E."

REFERENCES FOR CHAPTER 4

1. Technical Procedures for Developing AP-42 Emission Factors and Preparing AP-42 Sections (Draft), Emission Inventory Branch, Technical Support Division, Office of Air and Radiation, Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC, March 6, 1992.

2. Urban, C., "Compilation of Emissions Data for Stationary Reciprocating Gas Engines and Gas Turbines in Use by American Gas Association Member Companies," prepared by Southwest Research Institute for Pipeline Research Committee of the American Gas Association, Project PR-15-86, May 1980.

3. Fanick, R.E., H.E. Dietzmann, and C.M. Urban, "Emissions Data for Stationary Reciprocating Engines and Gas Turbines in Use by the Gas Pipeline Transmission Industry -Phase I & II," prepared by Southwest Research Institute for the Pipeline Research Committee of the American Gas Association, Project PR-15-613, April 1988.

4. Martin, N.L., and R.H. Thring, "Computer Database of Emissions Data for Stationary Reciprocating Natural Gas Engines and Gas Turbines in use by the Gas Pipeline Transmission Industry Users Manual (Electronic Database Included)," prepared by Southwest Research Institute for the Gas Research Institute, GRI-89/0041.

5. "Engines, Turbines, and Compressors Directory," American Gas Association, Catalog #XF0488.

6. Castaldini, C., "NO_x Reduction Technologies for Natural Gas Industry Prime Movers," prepared by Acurex Corp., for the Gas Research Institute, GRI-90/0215, August 1990.

7. Castaldini, C., "Environmental Assessment of NO_x Control on a Spark-Ignited Large Bore Reciprocating Internal Combustion Engine," prepared by Acurex Corp., TR-81-79/EE, for U.S. Environmental Protection Agency, Research Triangle Park, NC, April 1984.

8. Castaldini, C., and L.R. Waterland, "Environmental Assessment of a Reciprocating Engine Retrofitted with Nonselective Catalytic Reduction," prepared by Acurex Corp., TR-84-153/EE, EPA-600/7-84-073b, for U.S. Environmental Protection Agency, Research Triangle Park, NC, June 1984.

9. Castaldini, C., and L.R. Waterland, "Environmental Assessment of a Reciprocating Engine Retrofitted with Selective Catalytic Reduction," prepared by Acurex Corp., EPA Contract No. 68-02-3188, for U.S. Environmental Protection Agency, Research Triangle Park, NC, December, 1984.

10. Compliance Test Reports from Santa Barbara Air Pollution Control District (SBAPCD) including: "Pooled Source Emission Test Report: Gas-Fired IC Engines in Santa Barbara County," ENSR Consulting and Engineering, July 1990; "Air Pollution Source Testing for California AB2588 of Engines at the Chevron USA, Inc. Carpinteria Facility," Engineering-Science, August 1990; "Air Pollution Source Testing for California AB2588 on an Oil Platform Operated by Chevron USA, Inc., Platform Hope, California," Engineering-Science, August 1990, "Air Toxics Hot Spots Testing at Southern California Gas Company Goleta Station - IC Engine #3," Pape & Steiner Environmental Services, June 1990; "CEMS Certification and Compliance Testing at Chevron USA, Inc.'s Gaviota Gas Plant," Pape & Steiner Environmental Services, June 1989; "Emission Testing at the Bonneville Pacific Cogeneration Plant," Steiner Environmental, Inc., March 1992.

5. AP-42 SECTION 3.2: NATURAL GAS COMPRESSOR ENGINES

The revision to Section 3.2 of AP-42 is presented in the following pages as it would appear in the document.

3.2 HEAVY DUTY NATURAL GAS FIRED PIPELINE COMPRESSOR ENGINES

3.2.1 General

Engines in the natural gas industry are used primarily to power compressors used for pipeline transportation, field gathering (collecting gas from wells), underground storage, and gas processing plant applications, i.e. prime movers. Pipeline engines are concentrated in the major gas producing states (such as those along the Gulf Coast) and along the major gas pipelines. Gas turbines emit considerably smaller amounts of pollutants than do reciprocating engines; however, reciprocating engines are generally more efficient in their use of fuel.

Reciprocating engines are separated into three design classes: 2-stroke lean burn, 4-stroke lean burn and 4-stroke rich burn. Each of these have design differences which affect both baseline emissions as well as the potential for emissions control. Two-stroke engines complete the power cycle in a single engine revolution compared to two revolutions for 4-stroke engines. With the two-stroke engine, the fuel/air charge is injected with the piston near the bottom of the power stroke. The valves are all covered or closed and the piston moves to the top of the cylinder compressing the charge. Following ignition and combustion, the power stroke starts with he downward movement of the piston. Exhaust ports or valves are then uncovered to remove the combustion products, and a new fuel/air charge is ingested. Two stroke engines may be turbocharged using an exhaust powered turbine to pressurize the charge for injection into the cylinder. Non-turbocharged engines may be either blower scavenged or piston scavenged to improve removal of combustion products.

Four stroke engines use a separate engine revolution for the intake/compression stroke and the power/exhaust stroke. These engines may be either naturally aspirated, using the suction from the piston to entrain the air charge, or turbocharged, using a turbine to pressurize the charge. Turbocharged units produce a higher power output for a given engine displacement, whereas naturally aspirated units have lower initial cost and maintenance. Rich burn engines operate near the fuel-air stoichiometric limit with exhaust excess oxygen levels less than 4 percent. Lean burn engines may operate up to the lean flame extinction limit, with exhaust oxygen levels of 12 percent or greater. Pipeline population statistics show a nearly equal installed capacity of turbines and reciprocating engines. For reciprocating engines, two stroke designs contribute approximately two-thirds of installed capacity.

3.2.2 Emissions and Controls

The primary pollutant of concern is NO_x, which readily forms in the high temperature, pressure, and excess air environment found in natural gas fired compressor engines. Lesser amounts of carbon monoxide and hydrocarbons are emitted, although for each unit of natural gas burned, compressor engines (particularly reciprocating engines) emit significantly more of these pollutants than do external combustion boilers. Sulfur oxides emissions are proportional to the sulfur content of the fuel and will usually be quite low because of the negligible sulfur content of most pipeline gas. This section will also discuss the major variables affecting NO_x emissions and the various control technologies that will reduce uncontrolled NO_x emissions.

The major variables affecting NO_x emissions from compressor engines include the air fuel ratio, engine load (defined as the ratio of the operating horsepower to the rated horsepower), intake

(manifold) air temperature and absolute humidity. In general, NO_x emissions increase with increasing load and intake air temperature and decrease with increasing absolute humidity and air fuel ratio. (The latter already being, in most compressor engines, on the "lean" side of that air fuel ratio at which maximum NO_x formation occurs). Quantitative estimates of the effects of these variables are presented in Reference 10.

Because NO_x is the primary pollutant of significance emitted from pipeline compressor engines, control measures to date have been directed mainly at limiting NO_x emissions. Reference 11 summarizes control techniques and emission reduction efficiencies. For gas turbines, the early control applications used water or steam injection. New applications of dry low NO_x combustor can designs and selective catalytic reduction are appearing. Water injection has achieved reductions of 70 to 80 percent with utility gas turbines. Efficiency penalties of 2 to 3 percent are typical due to the added heat load of the water. Turbine power outputs typically increase, however. Steam injection may also be used, but the resulting NO_x reductions may not be as great as with water injection, and it has the added disadvantage that a supply of steam must be readily available. Water injection has not been applied to pipeline compressor engines because of the lack of water availability.

The efficiency penalty and operational impacts associated with water injection have led manufacturers to develop dry low NO_x combustor can designs based on lean burn and/or staging to suppress NO_x formation. These are entering the market in the early 1990's. Stringent gas turbine NO_x limits have been achieved in California in the late 1980's with selective catalytic reduction. This is an ammonia based post-combustion technology which can achieve in excess of 80 percent NO_x reductions. Water or steam injection is frequently used in combination with selective catalytic reduction (SCR) to minimize ammonia costs.

For reciprocating engines, both combustion controls and post-combustion catalytic reduction have been developed. Controlled rich burn engines have mostly been equipped with non-selective catalytic reduction which uses unreacted hydrocarbons and CO to reduce NO_x by 80 to 90 percent. Some rich-burn engines can be equipped with prestratified charge which reduces the peak flame temperature in the NO_x forming regions. Lean burn engines have mostly met NO_x reduction requirements with lean combustion controls using torch ignition or chamber redesign to enhance flame stability. NO_x reductions of 70 to 80 percent are typical for numerous engines with retrofit or new unit controls. Lean burn engines may also be controlled with selective catalytic reductions (SCR), but the operational problems associated with engine control under low NO_x operation have been a deterrent.

Emission factors for natural gas fired pipeline compressor engines are presented in Tables 3.2-1 and 3.2-2 for baseline operation and in 3.2-4 through 3.2-7 for controlled operation. The factors for controlled operation are taken from a single source test. Table 3.2-3 lists non-criteria (organic) emission factors.

TABLE 3.2-1. (ENGLISH UNITS) CRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS[a]
(Source Classification Codes)

Pollutant [Rating]	Gas Turbines (SCC 20200201)		2-Cycle Lean Burn (SCC 20200202)		4-Cycle Lean Burn SCC		4-Cycle Rich Burn SCC	
	[grams/hp-hr]	[lb/MMBtu] (fuel input)	[grams/hp-hr]	[lb/MMBtu] (fuel input)	[grams/hp-hr]	[lb/MMBtu] (fuel input)	[grams/hp-hr]	[lb/MMBtu] (fuel input)
NO_x [A]	1.3	.34	11	2.7	12	3.2	10	2.3
CO [A]	.83	.17	1.5	.38	1.6	.42	8.6	1.6
CO_2 [B][b]	405	110	405	110	405	110	405	110
TOC [A]	.18	.053	6.1	1.5	4.9	1.2	1.2	.27
TNMOC [A]	.01	.002	.43	.11	.72	.18	.14	.03
CH_4 [A]	.17	.051	5.6	1.4	4.1	1.1	1.1	.24

[a]Reference 1 - 5. Emission factors are based on entire population. Emission factors for individual engines from specific manufacturers may vary.
[b]Based on 100 percent conversion of the fuel carbon to CO_2. CO_2[lb/MMBtu] = 3.67*C/E, where C = carbon content of fuel by weight (0.7), and E = energy content of fuel, 0.0023 MMBtu/lb. The uncontrolled CO_2 emission factors are also applicable to natural gas prime movers controlled by combustion modifications, NSCR, and SCR.

TABLE 3.2-2. (METRIC UNITS) CRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS[a]
(Source Classification Codes)

Pollutant [Rating]	Gas Turbines (SCC 20200201)		2-Cycle Lean Burn (SCC 20200202)		4-Cycle Lean Burn SCC		4-Cycle Rich Burn SCC	
	[grams/ kW-hr]	[ng/J] (fuel input)	[grams/ kW-hr]	[ng/J] (fuel input)	[grams/ kW-hr]	[ng/J] (fuel input)	[grams /kW-hr]	[ng/J] (fuel input)
NO_x [A]	1.70	145	14.79	1165	15.49	1286	13.46	980
CO [A]	1.11	71	2.04	165	10.29	1195	11.55	697
CO_2 [D][b]	741	47,424	741	47,424	741	47,424	741	47,424
TOC [A]	.24	22.8	8.14	662	5.50	447	1.66	116
TNMOC [A]	.013	.86	.58	47.3	.76	60.2	.19	12.9
CH_4 [A]	.228	21.9	7.56	615	4.73	387	1.48	103

[a] References 1 - 5. Emission factors are based on entire population. Emission factors for individual engines from specific manufacturers may vary.
[b] Based on 100 percent conversion of the fuel carbon to CO_2. CO_2[lb/MMBtu] = 3.67*C/E, where C = carbon content of fuel by weight (0.7), and E = energy content of fuel, 0.0023 MMBtu/lb. The uncontrolled CO_2 emission factors are also applicable to natural gas prime movers controlled by combustion modifications, NSCR, and SCR.

TABLE 3.2-3. (ENGLISH AND METRIC UNITS) NON-CRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS[a]
(Source Classification Code: 20200202)

EMISSION FACTOR RATING: E[b]

Pollutant	2-Cycle Lean Burn	
	[grams/kW-hr]	[ng/J]
Formaldehyde	1.78	140
Benzene	2.2E-3	0.17
Toluene	2.2E-3	0.17
Ethylbenzene	1.1E-3	0.086
Xylenes	3.3E-3	0.26

[a]Reference 1.
[b]All emission factor qualities are "E" are due to a very limited data set. "E" rated emission factors may not be applicable to specific facilities or populations.

TABLE 3.2-4. (ENGLISH AND METRIC UNITS) EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: COMBUSTION MODIFICATIONS ON TWO-STROKE LEAN BURN ENGINE[a]
(Source Classification Code: 20200202)

EMISSION FACTOR RATING: E[b]

Pollutant	Baseline				Increased A/F Ratio With Intercooling			
	[g/hp-hr]	[g/kW-hr]	[lb/MMBtu]	[ng/J]	[g/hp-hr]	[g/kW-hr]	[lb/MMBtu]	[ng/J]
NO_x	9.9	13	2.9	1300	5.1	6.8	1.5	650
CO	.94	1.3	.28	120	1.5	2.1	.46	200
TOC	7.5	10	2.2	960	8.5	11	2.6	1100
TNMOC	5.2	7.0	1.6	670	6.0	8.1	1.8	780
CH_4	2.3	3.1	.68	290	2.5	3.4	.75	320
PM (total = front+back)	.16	.21	.046	20	.18	.25	.055	24
(solids = front half)	.098	.13	.029	13	.13	.17	.038	16
(condensibles = back half)	.057	.076	.017	7.3	.058	.078	.017	7.3

[a]Reference 6. CO_2 emissions are not affected by control.
[b]All emission factor qualities are "E" due to a very limited data set, for one engine, and may not be accurate for source populations.

TABLE 3.2-5. (ENGLISH AND METRIC UNITS) EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: NSCR ON FOUR-CYCLE RICH BURN ENGINE[a]

EMISSION FACTOR RATING: E[b]

Pollutant	Inlet				Outlet			
	[g/hp-hr]	[g/kW-hr]	[lb/MMBtu]	[ng/J]	[g/hp-hr]	[g/kW-hr]	[lb/MMBtu]	[ng/J]
NO_x	7.8	10	1.8	770	2.5	3.4	.58	250
CO	12	16	2.8	1208	10	14	2.4	1000
TOC	.33	.44	.079	33.97	.2	.27	.047	20
NH_3	.05	.07	.012	5.16	.82	1.10	.19	82
C7 -> C16	.019	.026	.0042	1.81	.0041	.0055	.0009	.39
C16+	.017	.029	.004	1.72	.0006	.0008	.0001	.043
PM (solids = front half)	.003	.004	.0007	.301	.003	.004	.0007	.30
Benzene			7.1EE4	.31			1.1E-4	.047
Toluene			2.3EE4	.099			<2.3E-5	.0099
Xylenes			<5.9E-5	.025			<4E-5	.017
Propylene			<1.6E-4	.069			<1.6E-4	.069
Naphthalene			<4.9E-5	.021			<4.9E-5	.021
Formaldehyde			<1.6E-3	.69			<7.2E-6	.003
Acetaldehyde			<6.1E-5	.026			<4.8E-6	.0021
Acrolein			<3.7E-5	.016			<9.6E-6	.0041

[a]Reference 7 (criteria pollutants) and Reference 4 (air toxics).
[b]All emission factors are rated "E" due to a very limited data set. "E" rated emission factors may not be applicable to specific facilities or populations.

TABLE 3.2-6. (ENGLISH AND METRIC UNITS) EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: SCR ON FOUR-CYCLE LEAN BURN ENGINE[a]

EMISSION FACTOR RATING: E[b]

Pollutant	Inlet				Outlet			
	[g/hp-hr]	[g/kW-hr]	[lb/MMBtu]	[ng/J]	[g/hp-hr]	[g/kW-hr]	[lb/MMBtu]	[ng/J]
NO_x	19	26	6.4	2800	3.6	4.8	1.2	510
CO	1.2	1.6	.38	160	1.1	1.5	.37	160
NH_3					.27	.36	.091	39
C7 -> C16	.007	.009	.0023	.99	.0031	.0042	.0013	.56
C16+	.013	.017	.0044	1.9	.0024	.0032	.0008	.34

[a]Reference 8. CO_2 emissions are not affected by control.
[b]All emission factor qualities are "E" due to a very limited data set. "E" rated emission factors may not be applicable to specific facilities or populations.

TABLE 3.2-7 (ENGLISH AND METRIC UNITS) EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: "PCC" AND "CLEAN BURN" ON TWO-CYCLE LEAN BURN ENGINE[a]
(Source Classification Code: 20200202)

EMISSION FACTOR RATING: C

Pollutant	"CleanBurn"				"PreCombustion Chamber"			
	[g/hp-hr]	[g/kW-hr]	[lb/MMBtu]	[ng/J]	[g/hp-hr]	[g/kW-hr]	[lb/MMBtu]	[ng/J]
NO_x	2.3	3.1	.83	360	2.9	3.9	.85	370
CO	1.1	1.5	.30	130	2.4	3.3	.67	290
TOC	2.5	3.4	.77	330	6.4	8.6	1.8	760
TNMOC	.12	.16	.15	65	.88	1.2	.25	110
CH_4	2.4	3.3	.62	260	5.5	7.4	1.5	650

[a]Reference 9. CO_2 emissions are not affected by control.

References for Section 3.2

1. Engines, Turbines, and Compressors Directory, American Gas Association, Catalog #XF0488.

2. Martin, N.L. and R.H. Thring, Computer Database of Emissions Data for Stationary Reciprocating Natural Gas Engines and Gas Turbines in use by the Gas Pipeline Transmission Industry Users Manual (Electronic Database Included), prepared by SouthWest Research Institute for the Gas Research Institute, GRI-89/0041.

3. Air Pollution Source Testing for California AB2588 on an Oil Platform Operated by Chevron USA, Inc. Platform Hope, California, Chevron USA, Inc., Ventura, CA, August 29, 1990.

4. Air Pollution Source Testing for California AB2588 of Engines at the Chevron USA, Inc. Carpinteria Facility, Chevron USA, Inc., Ventura, CA, August 30, 1990.

5. Pooled Source Emission Test Report: Gas Fired IC Engines in Santa Barbara County, ARCO, Bakersfield, CA, July, 1990.

6. Castaldini, C., Environmental Assessment of NO_x Control on a Spark-Ignited Large Bore Reciprocating Internal Combustion Engine, U.S. Environmental Protection Agency, Research Triangle Park, NC, April 1984.

7. Castaldini, C. and L.R. Waterland, Environmental Assessment of a Reciprocating Engine Retrofitted with Nonselective Catalytic Reduction, EPA-600/7-84-073B, U.S. Environmental Protection Agency, Research Triangle Park, NC, June 1984.

8. Castaldini, C. and L.R. Waterland, Environmental Assessment of a Reciprocating Engine Retrofitted with Selective Catalytic Reduction, EPA Contract No. 68-02-3188, U.S. Environmental Protection Agency, Research Triangle Park, NC, December 1984.

9. Fanick, R.E., H.E. Dietzmann, and C.M. Urban, Emissions Data for Stationary Reciprocating Engines and Gas Turbines in Use by the Gas Pipeline Transmission Industry - Phase I&II, prepared by SouthWest Research Institute for the Pipeline Research Committee of the American Gas Association, April 1988, Project PR-15-613.

10. Standards Support and Environmental Impact Statement, Volume I: Stationary Internal Combustion Engines, EPA-450/2-78-125a, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC, July 1979.

11. Castaldini, C., NO_x Reduction Technologies for Natural Gas Industry Prime Movers, prepared by Acurex Corp., for the Gas Research Institute, GRI-90/0215, August 1990.

APPENDIX A

SAMPLE CALCULATION PROCEDURE FOR CONVERTING EMISSION FACTOR UNITS

Example: NO_x emission for gas fired G.T= 100 ppmvd @ 15% O2
Convert to: lbm/MMBtu and g/hp-hr

Assumptions:
Molecular Weight of NO_x (as NO2) = MWNO_x = 46 lb/lb-mole
Volume of one mole of gas at STP = 385 scf/lb-mole
Average Heat Rate of Gas Turbines considered in this section = 8000 Btu/hp-hr
(from 1988 Diesel & Gas Turbine Catalog)
Fuel Factors: For Gas = 8740 dscf(exhaust gas)/MMBtu(fuel input)
For Oil = 9220 dscf(exhaust gas)/MMBtu(fuel input)
(from EPA-600/2-91-029, p.H-2)

To convert from ppm to lbm/MMBtu:

NO_x(lbm/MMBtu)= NO_x * 1E-6 * (ppmvd@x%O2)* (20.9/(20.9-x)) * MWNO_x * F-factor(Gas) / (vol/mol ratio)
= (100 * 1 E-6 * (20.9/(20.9-15)) * 46 * 8720) / 385
= .369

To convert from lbm/MMBtu to g/hp-hr:

NO_x(g/hp-hr) = NO_x(lbm/MMBtu)*avg.heat rate(Btu/hp-hr)*454e-6(MMBtu/Btu)*(g/lbm)
= .369 * 8000 * 454E-6
= 1.34

Frequently used conversion factors:

Units	Multiply By	To Get
ng/J	.002326	lbm/MMBtu
kilogram	2.2026	lbm
kw	1.341	hp

APPENDIX B

MARKED-UP PREVIOUS AP-42 SECTION