3.2 Heavy-duty Natural Gas-fired Pipeline Compressor Engines And Turbines

3.2.1 General[1-3]

Natural gas-fired internal combustion engines 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 compressors. At pipeline compressor stations, the engine or turbine is used to help move natural gas from station to station. At storage facilities, they are used to help inject the natural gas into high pressure underground cavities (natural gas storage fields), e. g., empty oil fields. Although they can operate at a fairly constant load, pipeline engines or turbines must be able to operate under varying pipeline requirements. The size of these engines ranges from 800 brake horsepower (bhp) to 5,000 bhp. For gas turbines, the capacity ranges from 1,000 to 15,000 bhp.

3.2.2 Process Description[1-3]

Reciprocating engines are separated into 3 design classes: 2-cycle (stroke) lean burn, 2-stroke ultra lean (clean) burn, 4-stroke lean burn, 4-stroke clean burn, and 4-stroke rich burn. Each of these have design differences that affect both baseline emissions as well as the potential for emissions control. Two-stroke engines complete the power cycle in a single crankshaft revolution as compared to the two crankshaft revolutions required for 4-stroke engines.

In a 2-stroke engine, the air/fuel charge is injected with the piston near the bottom of the power stroke. The intake ports are then covered or closed, and the piston moves to the top of the cylinder, thereby compressing the charge. Following ignition and combustion, the power stroke starts with the downward movement of the piston. Exhaust ports or valves are then uncovered to exhaust the combustion products, and a new air/fuel charge is injected. Two-stroke engines may be turbocharged using an exhaust-powered turbine to pressurize the charge for injection into the cylinder and to increase cylinder scavenging. 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 cycle and the power/exhaust cycle. These engines may be either naturally aspirated, using the suction from the piston to entrain the air charge, or turbocharged, using an exhaust-driven 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 stoichiometric air/fuel ratio 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, 2-stroke designs contribute approximately two-thirds of installed capacity.

Almost 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. Natural gas and compressed air (up to 30 atmospheres pressure) are injected separately into the combustor can, mixed, and reacted.

The hot expanding exhaust gases are then passed into the power turbine to produce usable shaft energy. The heat content of the exhaust 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. The majority of gas turbines used in pipeline installations are simple cycle two-shaft gas turbines. There are three types of combustor can design in use: annular, can-annular, and silo. 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.

3.2.3 Emissions

The primary pollutants from natural gas-fueled reciprocating engines and gas turbines are nitrogen oxide (NO_x), carbon monoxide (CO), and total organic compounds (TOC). 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.

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 regions 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 prompt NO_x forms within the flame and is usually negligible compared to the amount of thermal NO_x formed. 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. The rates of these reactions are highly dependent upon the stoichiometric ratio, combustion temperature, and residence time at the combustion temperature.

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. 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.

3.2.3.2 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) 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. 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 because of 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; or 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.

3.2.3.3 Particulate Matter and PM-10[4] -

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.

3.2.4 Control Technologies

Three generic control techniques have been developed for reciprocating engines and gas turbines: parametric controls (timing and operating at a leaner air/fuel ratio for reciprocating engines and water injection for gas turbines); combustion modification such as advanced engine design for new sources or major modification to existing sources (clean burn reciprocating head designs and dry gas turbine combustor can designs); and postcombustion catalytic NO_x reduction (selective catalytic reduction [SCR] for gas turbines and lean burn reciprocating engines and nonselective catalytic reduction [NSCR] for rich burn engines).

3.2.4.1 Control Techniques for Rich Burn Reciprocating Engines[5] -

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 NSCR, hydrocarbons will be oxidized by O_2 and NO_x, hence the designation "nonselective". This is in contrast to ammonia injection for SCR where ammonia selectively reacts with NO_x. The excess hydrocarbons and NO_x pass over a catalyst, usually a noble metal (platinum, rhodium, or palladium) which reduces the reactants to N_2, CO_2, and H_2O.

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. To achieve optimum NO_x reduction performance, the engine may need to be run in a richer fuel condition than normal.

Prestratified Charge -

Prestratified charge combustion is a retrofit system that is limited to 4-cycle carbureted natural gas engines. In this system, controlled amounts of air are introduced into the intake manifold in a specified sequence and quantity. This stratification provides both a fuel rich ignition and rapid flame cooling resulting in reduced formation of NO_x.

3.2.4.2 Control Techniques for Lean Burn Reciprocating Engines -

Lean Combustion -

Lean combustion techniques use increased bulk 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, high energy ignition systems have been developed that promote flame stability at very lean conditions. With high energy 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 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.

Selective Catalytic Reduction -

Selective catalytic reduction (SCR) is applicable to lean burn engines. Ammonia (NH_3) is injected upstream of a noble metal, metal oxide or zeolite catalyst to give an NH_3: NO_x 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. 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 and the inherent variety of engine loading while achieving the necessary exhaust temperature window for efficient SCR operation.

3.2.4.3 Control Technologies for Gas Turbines -

Water Injection -

Water or steam injection is a 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 1. 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.

Selective Catalytic Reduction Systems -

Selective catalytic reduction systems are postcombustion technologies that have recently been applied in limited cases to gas turbines. An SCR system consists of 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. For the SCR system to operate properly, the exhaust gas must be within a particular temperature range (typically between 450 and 850°F). The temperature 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).

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 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 latter 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.

Emission factors for natural gas-fired pipeline compressor engines are presented in Table 3.2-1 for baseline operation and in Tables 3.2-2, 3.2-3, 3.2-4, and 3.2-5 for controlled operation. The factors for controlled operation are taken from a single source test. Table 3.2-6 lists noncriteria emission factors for uncontrolled natural gas prime movers.

3.2.5 Updates Since the Fifth Edition

The Fifth Edition was released in January 1995. Revisions to this section since that date are summarized below. For further detail, consult the memoranda describing each supplement or the background report for this section. These and other documents can be found on the CHIEF electronic bulletin board (919-541-5742), or on the new EFIG home page (http://www.epa.gov/oar/oaqps/efig/).

Supplement A, February 1996

- In the table for uncontrolled natural gas prime movers, the SCC for 4-cycle lean burn was changed from 2-01-002-53 to 2-02-002-54. The SCC for 4-cycle rich burn was changed from 2-02-002-54 to 2-02-02-002-53.

- An SCC (2-02-002-53) was provided for 4-cycle rich burn engines, and the "less than" symbol (<) was restored to the appropriate factors.

Supplement B, October 1996

- The introduction section was revised.

- Text was added concerning process description of turbines.

- Text was revised concerning emissions and controls.

- References in various tables were editorially corrected.

- The inconsistency between a CO_2 factor in the table and an equation in the footnote was corrected.

Table 3.2-1. CRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS[a]

EMISSION FACTOR RATING: A

Pollutant	Gas Turbines (SCC 2-02-002-01)		2-Cycle Lean Burn (SCC 2-02-002-52)		4-Cycle Lean Burn (SCC 2-02-002-54)		4-Cycle Rich Burn (SCC 2-02-002-53)	
	Emission Factor (lb/hp-hr) (power output)	Emission Factor (lb/MMBtu) (fuel input)	Emission Factor (lb/hp-hr) (power output)	Emission Factor (lb/MMBtu) (fuel input)	Emission Factor (lb/hp-hr) (power output)	Emission Factor (lb/MMBtu) (fuel input)	Emission Factor (lb/hp-hr) (power output)	Emission Factor (lb/MMBtu) (fuel input)
NO_x	2.87 E-03	0.34	0.024	2.7	0.026	3.2	0.022	2.3
CO	1.83 E-03	0.17	3.31 E-03	0.38	3.53 E-03	0.42	0.019	1.6
CO_2[b]	0.88	109	0.77	109	0.77	109	0.77	109
TOC	3.97 E-04	0.053	0.013	1.5	0.011	1.3	2.65 E-03	0.27
TNMOC	2.20 E-05	0.002	9.48 E-04	0.11	1.59 E-03	0.18	3.09 E-04	0.03
CH_4	3.75 E-04	0.051	0.012	1.4	9.04 E-03	1.1	2.43 E-03	0.24

[a] References 6-13. Factors are based on large population of engines. Factors for individual engines from specific manufacturers may vary. To convert from lb/hp-hr to kg/kw-hr, multiply by 0.608. To convert from lb/MMBtu to ng/J, multiply by 430. SCC = Source Classification Code. TNMOC = total nonmethane organic compounds.

[b] Based on 99.5% conversion of the fuel carbon to CO_2. CO_2 [lb/MMBtu] = (3.67)(%CON)(C/E), where %CON = percent conversion of fuel carbon to CO_2, C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 0.0250 MMBtu/lb.

Table 3.2-2. EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: COMBUSTION MODIFICATIONS ON 2-CYCLE LEAN BURN ENGINE[a] (SCC 2-02-002-52)

EMISSION FACTOR RATING: E (except as noted)

Pollutant	Baseline		Increased Air/Fuel Ratio With Intercooling	
	Emission Factor (lb/hp-hr)	Emission Factor (lb/MMBtu)	Emission Factor (lb/hp-hr)	Emission Factor (lb/MMBtu)
NO_x	0.022	2.9	0.011	1.5
CO	2.07 E-03	0.28	3.31 E-03	0.46
CO_2[b]	0.77	109	0.77	109
TOC	0.017	2.2	0.019	2.6
TNMOC	0.011	1.6	0.013	1.8
CH_4	5.07 E-03	0.68	5.51 E-03	0.75
PM-10				
Total (front+back halves)	3.53 E-04	0.046	3.97 E-04	0.055
Solids (front half)	2.16 E-04	0.029	2.87 E-04	0.038
Condensables (back half)	1.26 E-04	0.017	1.28 E-04	0.017

[a] Reference 10-14,17-19. Factors reflect a single data set and as such baseline emissions for this engine were slightly different from the uncontrolled emission factor for 2-cycle lean burn engines. To convert from lb/hp-hr to kg/kw-hr, multiply by 0.608. To convert from lb/MMBtu to ng/J, multiply by 430. TNMOC = total nonmethane organic compounds. PM-10 = particulate matter ≤ 10 micrometers (µm) aerodynamic diameter. (All particulate is assumed to be ≤ 1 µm aerodynamic diameter). SCC = Source Classification Code.

[b] EMISSION FACTOR RATING: A. Based on 99.5% conversion of the fuel carbon to CO_2. CO_2[lb/MMBtu] = (3.67)(%CON)(C/E), where %CON = percent conversion of fuel carbon to CO_2, C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 0.0250 MMBtu/lb. CO_2 emissions are not affected by controls.

Table 3.2-3. EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: NONSELECTIVE CATALYTIC REDUCTION ON 4-CYCLE RICH BURN ENGINE[a] (SCC 2-02-002-53)

EMISSION FACTOR RATING: E (except as noted)

Pollutant	Inlet		Outlet	
	Emission Factor (lb/hp-hr)	Emission Factor (lb/MMBtu)	Emission Factor (lb/hp-hr)	Emission Factor (lb/MMBtu)
NO_x	0.017	1.8	5.51 E-03	0.58
CO	0.026	2.8	0.022	2.4
CO_2[b]	0.77	109	0.77	109
TOC	7.28 E-04	0.079	4.41 E-04	0.047
NH_3	1.10 E-04	0.012	1.81 E-03	0.19
C7 - C16	4.19 E-05	0.0042	9.04 E-06	0.0009
C16+	3.75 E-05	0.004	1.32 E-06	0.0001
PM solids (front half)	6.61 E-06	0.0007	6.61 E-06	0.0007
Benzene[c]	ND	7.1 E-04	ND	1.1 E-04
Toluene[c]	ND	2.3 E-04	ND	<2.3 E-05
Xylenes[c]	ND	<5.9 E-05	ND	<4.0 E-05
Propylene	ND	<1.6 E-04	ND	<1.6 E-04
Naphthalene[c]	ND	<4.9 E-05	ND	<4.9 E-05
Formaldehyde[c]	ND	<1.6 E-03	ND	<7.2 E-06
Acetaldehyde[c]	ND	<6.1 E-05	ND	<4.8 E-06
Acrolein[c]	ND	<3.7 E-05	ND	<9.6 E-06

Table 3.2-3 (cont.).

[a] References 8,10-13,15-18. Factors reflect very limited data and as such inlet emissions were slightly different from the uncontrolled emission factor for 4-cycle rich burn engines. To convert from lb/hp-hr to kg/kw-hr, multiply by 0.608. To convert from lb/MMBtu to ng/J, multiply by 430. ND = No data. SCC = Source Classification Code.

[b] EMISSION FACTOR RATING: A. Based on 99.5% conversion of the fuel carbon to CO_2. CO_2(lb/MMBtu) = (3.67)(%CON)(C/E), where %CON = percent conversion of fuel carbon to CO_2, C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 0.0250 MMBtu/lb. CO_2 emissions are not affected by controls.

[c] Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.2-4. EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: SELECTIVE CATALYTIC REDUCTION ON 4-CYCLE LEAN BURN ENGINE[a] (SCC 2-02-002-54)

EMISSION FACTOR RATING: E (except as noted)

Pollutant	Inlet		Outlet	
	Emission Factor (lb/hp-hr)	Emission Factor (lb/MMBtu)	Emission Factor (lb/hp-hr)	Emission Factor (lb/MMBtu)
NO_x	0.042	6.4	7.94 E-03	1.2
CO	2.65 E-03	0.38	2.43 E-03	0.37
CO_2[b]	0.77	109	0.77	109
NH_3	ND	ND	5.95 E-04	0.091
C7 - C16	1.54 E-05	0.0023	6.83 E-06	0.0013
C16+	2.87 E-05	0.0044	5.29 E-06	0.0008

[a] References 10-13,16-19. Factors reflect very limited data and as such inlet emissions were slightly different from the uncontrolled emission factor for 4-cycle lean burn engines. To convert from lb/hp-hr to kg/kw-hr multiply by 0.608. To convert from lb/MMBtu to ng/J, multiply by 430. ND = No data. SCC = Source Classification Code.

[b] EMISSION FACTOR RATING: A. Based on 99.5% conversion of the fuel carbon to CO_2. CO_2 [lb/MMBtu] = (3.67)(%CON)(C/E), where %CON = percent conversion of fuel carbon to CO_2, C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 0.0250 MMBtu/lb. CO_2 emissions are not affected by controls.

Table 3.2-5. EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: CLEAN BURN AND PRECOMBUSTION CHAMBER ON 2-CYCLE LEAN BURN ENGINE[a] (SCC 2-02-002-52)

EMISSION FACTOR RATING: C (except as noted)

Pollutant	Clean Burn		Precombustion Chamber	
	Emission Factor (lb/hp-hr)	Emission Factor (lb/MMBtu)	Emission Factor (lb/hp-hr)	Emission Factor (lb/MMBtu)
NO_x	5.07 E-03	0.83	6.39 E-03	0.85
CO	2.43 E-03	0.30	5.29 E-03	0.67
CO_2[b]	0.77	109	0.77	109
TOC	5.51 E-03	0.77	0.014	1.8
TNMOC	2.65 E-04	0.15	1.94 E-03	0.25
CH_4	5.29 E-03	0.62	0.012	1.5

[a] Reference 7,10-13,17-19. CO_2 emissions are not affected by controls. To convert from lb/hp-hr to kg/kw-hr, multiply by 0.608. To convert from lb/MMBtu to ng/J, multiply by 430. TNMOC = total nonmethane organic compounds. SCC = Source Classification Code.

[b] EMISSION FACTOR RATING: A. Based on 99.5% conversion of the fuel carbon to CO_2. CO_2 [lb/MMBtu] = (3.67)(%CON)(C/E), where %CON = percent conversion of fuel carbon to CO_2, C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 0.0250 MMBtu/lb.

Table 3.2-6. NONCRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS 2-CYCLE LEAN BURN ENGINES

EMISSION FACTOR RATING: E

Pollutant	Emission Factors (lb/hp-hr)
Formaldehyde[b]	2.93 E-03
Benzene[b]	3.62 E-06
Toluene[b]	3.62 E-06
Ethylbenzene[b]	1.81 E-06
Xylenes[b]	5.43 E-06

[a] Reference 20. Source Classification Code 2-02-002-52. Ratings reflect very limited data and may not apply to specific facilities. To convert from lb/hp-hr to kg/kw-hr, multiply by 0.608.
[b] Hazardous air pollutant listed in the *Clean Air Act*.

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