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 3 design classes: 2-cycle (stroke) lean burn, 4-stroke lean 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 engine revolution compared to 2 revolutions for 4-stroke engines. With the 2-stroke engine, the air/fuel 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 the downward movement of the piston. Exhaust ports or valves are then uncovered to remove the combustion products, and a new air/fuel charge is ingested. Two-stroke engines may be turbocharged using an exhaust-powered turbine to pressurize the charge for injection into the cylinder. Nonturbocharged 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 air/fuel 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, 2-stroke designs contribute approximately two-thirds of installed capacity.

3.2.2 Emissions And Controls

The primary pollutant of concern is nitrogen oxides (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 (CO) and total organic compounds (TOC) 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 (SCR) 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 1990s. Stringent gas turbine NO_x limits have been achieved in California in the late 1980s with SCR. This is an ammonia-based postcombustion technology that can achieve in excess of 80 percent NO_x reductions. Water or steam injection is frequently used in combination with SCR to minimize ammonia costs.

For reciprocating engines, both combustion controls and postcombustion catalytic reduction have been developed. Controlled rich burn engines have mostly been equipped with non-SCR (NSCR) that uses unreacted TOCs and CO to reduce NO_x by 80 to 90 percent. Some rich burn engines can be prestratified charge engines that reduce 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 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 Tables 3.2-4, 3.2-5, 3.2-6, and 3.2-7 for controlled operation. The factors for controlled operation are taken from a single source test. Table 3.2-3 lists noncriteria emission factors. Factors are expressed in units of grams per kilowatt-hour (g/kW-hr) and grams per horsepower-hour (g/hp-hr), and nanograms per joule (ng/J) and pounds per million British thermal unit (lb/MMBtu), indicating metric and English units, respectively, for each set of units.

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

EMISSION FACTOR RATING: A (except as noted)

Pollutant	Gas Turbines (SCC 2-02-002-01)		2-Cycle Lean Burn (SCC 2-02-002-52)		4-Cycle Lean Burn (SCC 2-02-002-53)		4-Cycle Rich Burn (SCC 2-02-002-54)	
	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)	g/kW-hr (power output)	ng/J (fuel input)
NO_x	1.70	145	14.79	1,165	16.1	1,376	13.46	989
CO	1.11	71	2.04	165	2.15	181	11.55	687
CO_2[b]	543	47,424	543	47,424	543	47,424	543	47,424
TOC	0.24	22.8	8.14	645	6.57	516	1.66	116
TNMOC	0.013	0.86	0.58	47.3	0.97	77.4	0.19	12.9
CH_4	0.228	21.9	7.56	615	5.50	473	1.48	103

[a] References 1-5. Factors are based on entire population. Factors for individual engines from specific manufacturers may vary. SCC = Source Classification Code. TNMOC = total nonmethane organic compounds.

[b] EMISSION FACTOR RATING: B. Based on 100% conversion of the fuel carbon to CO_2. CO_2 [ng/J] = 3.67*C/E, where C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 55.6 kJ/g. 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 (English Units). CRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS[a]

EMISSION FACTOR RATING: A (except as noted)

Pollutant	Gas Turbines (SCC 2-02-002-01)		2-Cycle Lean Burn (SCC 2-02-002-52)		4-Cycle Lean Burn (SCC 2-02-002-53)		4-Cycle Rich Burn (SCC 2-02-002-54)	
	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	lb/MMBtu (fuel input)	lb/hp-hr (power output)	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]	0.89	110	0.89	110	0.89	110	0.89	110
TOC	3.97 E-04	0.053	0.013	1.5	0.011	1.2	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 1-5. Factors are based on entire population. Factors for individual engines from specific manufacturers may vary. SCC = Source Classification Code. TNMOC = total nonmethane organic compounds.

[b] EMISSION FACTOR RATING: B. Based on 100% conversion of the fuel carbon to CO_2. CO_2 [lb/MMBtu] = 3.67*C/E, where C = carbon content of fuel by weight (0.75), and E = energy content of fuel, 0.0239 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 (Metric And English Units). NONCRITERIA EMISSION FACTORS FOR UNCONTROLLED NATURAL GAS PRIME MOVERS[a]

EMISSION FACTOR RATING: E

Pollutant	2-Cycle Lean Burn	
	ng/J	lb/hp-hr
Formaldehyde[b]	140	2.93 E-03
Benzene[b]	0.17	3.62 E-06
Toluene[b]	0.17	3.62 E-06
Ethylbenzene[b]	0.086	1.81 E-06
Xylenes[b]	0.26	5.43 E-06

[a] Reference 1. Source Classification Code 2-02-002-52. Ratings reflect very limited data and may not apply to specific facilities.

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

Table 3.2-4 (Metric And English Units). EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: COMBUSTION MODIFICATIONS ON 2-STROKE LEAN BURN ENGINE[a]

EMISSION FACTOR RATING: E

Pollutant	Baseline				Increased Air/Fuel Ratio With Intercooling			
	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu
NO_x	13	0.022	1300	2.9	6.8	0.011	650	1.5
CO	1.3	2.07 E-03	120	0.28	2.1	3.31 E-03	200	0.46
TOC	10	0.017	960	2.2	11	0.019	1100	2.6
TNMOC	7.0	0.011	670	1.6	8.1	0.013	780	1.8
CH_4	3.1	5.07 E-03	290	0.68	3.4	5.51 E-03	320	0.75
PM-10								
Total (front+back halves)	0.21	3.53 E-04	20	0.046	0.25	3.97 E-04	24	0.055
Solids (front half)	0.13	2.16 E-04	13	0.029	0.17	2.87 E-04	16	0.038
Condensables (back half)	0.076	1.26 E-04	7.3	0.017	0.078	1.28 E-04	7.3	0.017

[a] Reference 6. Ratings reflect a single data set. Source Classification Code 2-02-002-52. CO_2 emissions are not affected by control. TNMOC = total nonmethane organic compounds. PM-10 = particulate matter ≤ 10 micrometers (μm) aerodynamic diameter (all particulate is assumed to be ≤ 1 μm aerodynamic diameter).

Table 3.2-5 (Metric And English Units). EMISSION FACTORS FOR CONTROLLED NATURAL GAS PRIME MOVERS: NSCR ON 4-CYCLE RICH BURN ENGINE[a]

EMISSION FACTOR RATING: E

	Inlet				Outlet			
Pollutant	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu
NO_x	10	0.017	770	1.8	3.4	5.51 E-03	250	0.58
CO	16	0.026	1208	2.8	14	0.022	1000	2.4
TOC	0.44	7.28 E-04	33.97	0.079	0.27	4.41 E-04	20	0.047
NH_3	0.07	1.10 E-04	5.16	0.012	1.10	1.81 E-03	82	0.19
C7 - C16	0.026	4.19 E-05	1.81	0.0042	0.0055	9.04 E-06	0.39	0.0009
C16+	0.029	3.75 E-05	1.72	0.004	0.0008	1.32 E-06	0.043	0.0001
PM solids (front half)	0.004	6.61 E-06	0.301	0.0007	0.004	6.61 E-06	0.30	0.0007
Benzene[b]	ND	ND	0.31	7.1 E-04	ND	ND	0.047	1.1 E-04
Toluene[b]	ND	ND	0.099	2.3 E-04	ND	ND	0.0099	<2.3 E-05
Xylenes[b]	ND	ND	0.025	<5.9 E-05	ND	ND	0.017	<4.0 E-05
Propylene	ND	ND	0.069	<1.6 E-04	ND	ND	0.069	<1.6 E-04
Naphthalene[b]	ND	ND	0.021	<4.9 E-05	ND	ND	0.021	<4.9 E-05
Formaldehyde[b]	ND	ND	0.69	<1.6 E-03	ND	ND	0.003	<7.2 E-06
Acetaldehyde[b]	ND	ND	0.026	<6.1 E-05	ND	ND	0.0021	<4.8 E-06
Acrolein[b]	ND	ND	0.016	<3.7 E-05	ND	ND	0.0041	<9.6 E-06

[a] References 4,7. Ratings reflect very limited data and may not apply to specific facilities. ND = no data.
[b] Hazardous air pollutant listed in the *Clean Air Act*.

Table 3.2-6 (Metric And English Units). CONTROLLED EMISSION FACTORS FOR NATURAL GAS PRIME MOVERS: SCR ON 4-CYCLE LEAN BURN ENGINE[a]

EMISSION FACTOR RATING: E

Pollutant	Inlet				Outlet			
	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu
NO_x	26	0.042	2,800	6.4	4.8	7.94 E-03	510	1.2
CO	1.6	2.65 E-03	160	0.38	1.5	2.43 E-03	160	0.37
NH_3	ND	ND	ND	ND	0.36	5.95 E-04	39	0.091
C7 - C16	0.009	1.54 E-05	0.99	0.0023	0.0042	6.83 E-06	0.56	0.0013
C16+	0.017	2.87 E-05	1.9	0.0044	0.0032	5.29 E-06	0.34	0.0008

[a] Reference 8. Ratings reflect very limited data and may not apply to specific facilities. CO_2 emissions are not affected by control. ND = no data.

Table 3.2-7 (Metric And English Units). CONTROLLED EMISSION FACTORS FOR NATURAL GAS PRIME MOVERS: CLEAN BURN AND PRECOMBUSTION CHAMBER ON 2-CYCLE LEAN BURN ENGINE[a]

EMISSION FACTOR RATING: C

Pollutant	Clean Burn				Precombustion Chamber			
	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu	g/kW-hr	lb/hp-hr	ng/J	lb/MMBtu
NO_x	3.1	5.07 E-03	360	0.83	3.9	6.39 E-03	370	0.85
CO	1.5	2.43 E-03	130	0.30	3.3	5.29 E-03	290	0.67
TOC	3.4	5.51 E-03	330	0.77	8.6	0.014	760	1.8
TNMOC	0.16	2.65 E-04	65	0.15	1.2	1.94 E-03	110	0.25
CH_4	3.3	5.29 E-03	260	0.62	7.4	0.012	650	1.5

[a] Reference 9. Source Classification Code 2-02-002-52. CO_2 emissions are not affected by control. TNMOC = total nonmethane organic compounds.

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