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NO_x Exhaust Emissions for Gas-Fired Turbine Engines

P. C. MALTE* and S. BERNSTEIN
Energy International, Inc., Bellevue, Washington
and
F. BAHLMANN and J. DOELMAN
N.V. Nederlandse Gasunie, Groningen, The Nederlands

ABSTRACT

A database consisting of 18 heavy-duty and aero-derivative gas turbine engine models, fired on natural gas, is evaluated for NO_x exhaust emissions with and without water and steam injection. CO exhaust emissions are also considered. Engine baseload power outputs range from 2.9 to 83.5 MW, compressor pressure ratios are from 7.2 to 30.0, and turbine inlet temperatures are from 1150 to 1515K. The engine models are from the late 1970s to the current period, and all use diffusion flame combustors.

Baseload, uncontrolled NO_x exhaust emissions, corrected to 15% O_2 dry conditions, vary from 67 to 240 ppmv. CO exhaust emissions vary from 7 to 96 ppmv. Except for three low-NO_x aero-derivative engines, the uncontrolled NO_x exhaust emissions scale with engine pressure ratio and fuel-air ratio. A correlation formula is developed, and discussed relative to formulas in the literature. NO_x control by water injection shows a fairly wide band; at a water-to-fuel mass ratio of 0.8, the NO_x reduction varies from 58 to 82 percent. Engines with the highest uncontrolled NO_x show the largest percentage reduction by water injection. On the other hand, NO_x control response with steam injection exhibits less variation across the engine models. The relation of CO to NO_x levels and and the response of CO to water and steam injection are examined, though quantitative correlations are not made.

INTRODUCTION

Gas-fired gas turbine engines used for cogeneration, combined-cycles and peaking electricity generation are rich in experience on NO_x control by water and steam injection. Several hundred operating sites exist worldwide, and with few exceptions, manufacturers offer water and steam injection for their engine models.

For electricity-producing gas turbine engines, NO_x control by water and steam injection is a mature technology, which has been in use for two decades. Nonetheless, new developments have occurred recently which are of significance to the user. These are as follows:

- Guaranteed NO_x exhaust emissions for gas-fired engines are now typically 25 to 42 ppmv (baseload, ISO, 15 percent O_2 dry), depending on the engine model and whether water or steam injection is used.
- Rule 1134 of the South Coast Air Quality Management District, adopted 4 August 1989, sets NO_x limits of 12-to-15 ppmv (ISO, 15 percent O_2 dry) for existing engines larger than 2.9 MW not using SCR (selective catalytic reduction). With SCR, the limit is 9 ppmv (ISO, 15 percent O_2 dry). Rule 1134 mentions steam injection for the compliance of gas-fired aero-derivative engines to the 12-to-15 ppmv limit. Whether these NO_x levels can be accomplished by large steam-to-fuel mass ratios (2.0 and greater is needed) in routine, everyday service without serious engine component degradation and unacceptably high operating/maintenance costs remains to be shown. CO exhaust emissions also increase substantially with this level of steam, and require control.
- Water treatment system design and maintenance for NO_x control have been improved and can be purchased optimized for the site.
- Engine components have been improved to withstand water and steam injection, though long-term effects of continuous operation on high water- and steam-to-fuel mass ratios require study.
- Capital and operating/maintenance costs of NO_x control by water injection are fairly well understood.
- CO exhaust emissions increased by water and steam injection are falling under control by exhaust oxidation catalysts.

* Department of Mechanical Engineering, University of Washington, Seattle, Washington.

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Gas pipeline turbine engines, on the other hand, have not been required to install NO_x control. However, this situation is beginning to change. In the United States, some local air pollution control authorities have required NO_x offsets, e.g., the cleanup of gas-reciprocating engine NO_x exhaust emissions, before permitting construction of uncontrolled gas turbine engines. The United States Environmental Protection Agency (Reilly, 1989), arguing that water injection should have been required, recently withdrew the permit issued by state authorities for a new gas turbine engine site which did not have NO_x control. In southern California, the strict control of gas turbine engine NO_x exhaust emissions by the South Coast Air Quality Management District will affect gas turbine pipeline engines (albeit a small number).

In The Netherlands and the Federal Republic of Germany, gas turbine regulations affect pipeline engines. These regulations are shown in Table 1. In The Netherlands, the exhaust emission regulation for gas pipeline engines is less strict than for cogeneration engines, whereas in the Federal Republic of Germany, no distinction is made between electricity-producing and pipeline gas turbine engines.

The purpose of this paper is to update and evaluate the NO_x exhaust emissions database for typical behavior, including both uncontrolled exhaust emissions and exhaust emissions controlled by water and steam injection. Both heavy-duty and aero-derivative gas-fired engines of late-1970s vintage to current production models, with diffusion flame combustors, are included in the database. Manufacturers' data as well as limited field data are treated. CO exhaust emissions are also considered.

From the user's standpoint, it is important to be able to assess the exhaust emissions of a given engine relative to typical, or expected, behavior. Engines of inherently low exhaust emissions may be able to meet local air pollution regulations without control, with fewer offsets,or with reduced water- or steam-to-fuel mass ratios. Engines which require less water or steam to reach a required NO_x exhaust emission level will benefit from lower capital and operating/maintenance costs, and may avoid the need for CO exhaust treatment.

Engines with methods of NO_x control different from water and steam injection are not studied in this paper, though they are mentioned at this point briefly for completeness. These alternative are listed as follows:

- Dry NO_x Control by Advanced Combustion
  - ◊ Rich-quench-lean combustion
  - ◊ Lean-lean combustion
  - ◊ Lean-catalytic combustion
  - ◊ Lean-premixed and hybrid combustion
- Selective Catalytic Reduction
- Inert Gases

Rich-quench-lean and lean-lean combustors were researched during the 1970s and early 1980s. These were primarily advanced diffusion flame combustors. Results for liquid firing, including nitrogen bearing fuels, are given by Cutrone et al. (1982). Rich-quench-lean combustors have not been developed commercially, though they appear to have potential for gas-firing for reducing NO_x emissions by approximately 50%. A weakness of the rich-quench-lean concept is the need to use an alternative means of primary zone cooling, since conventional internal film cooling leads to stoichiometric zones with high NO_x formation rates. Lean-lean combustion has commercial applicability for advanced combustors. For the lean-lean combustors reported by Cutrone et al. (1982), the primary zone was used as a lean flame stabilization, or pilot, zone. For high engine load, fuel was also injected and burned lean in the second, or main, zone. Test combustors operated at simulated engine conditions showed NO_x exhaust emissions as low as the 60 ppmv (15 percent O_2 dry) range.

Lean-catalytic combustors exist at the research and development stage, though for the long term, these combustors hold promise for significant NO_x control (Miller, 1989). Lean-premixed combustors are being commercially developed for several gas turbine engines. The goal is NO_x emissions of 25 to 30 ppmv (15 percent O_2 dry) without water or steam injection. The Asea Brown Boveri lean-premixed combustor, involving clusters of the premixed burners, is described by Jeffs (1989). The combustors are in operation on six gas-fired engines (11D, 13B, 13D and 13E models) in Europe. NO_x emissions for full load are given as 38 to 60 ppmv (15 percent O_2 dry). The low-NO_x hybrid combustor of Westinghouse and Mitsubishi Heavy Industries is reported by Yabuki et al. (1988) and Farmer (1989). This combustor uses a pilot diffusion flame and a premixed main zone. NO_x emissions for the full load, gas-fired MW701D engine at Tohoku Electric Power Company are given as about 60 ppmv (15 percent O_2). Results for the Siemens-KWU combustors with hybrid premixed burners are given by Becker and Ziegner (1988) and Maghon, Kreutzer and Termehlen (1988). Full-load, gas-fired NO_x emissions under 25 ppmv are reported. The status of advanced combustors under development for heavy duty General Electric engines is discussed by Davis and Washam (1989).

The results on dry NO_x control by lean-premixed and hybrid combustors cited above pertain to the large, heavy-duty engines with power outputs greater than about 35 MW. For small and medium sized gas turbine engines, and for high performance aero-derivative engines, however, NO_x control by water and steam may remain essential. For gas turbine engine sites faced with very strict NO_x exhaust emission regulations, selective catalytic reduction (SCR) is important. Several SCR are in operation and under development, especially in California. However, there are drawbacks to SCR, such as its high cost, narrow temperature operating window and sensitivity to sulfur, which limit applicability. Furthermore, SCR sites typically use water or steam injection to limit NO_x formation in the combustor, before effecting final NO_x cleanup across the SCR catalyst in the heat recovery steam generator.

Inert gases in the fuel, principally CO_2 and N_2, provide another method of NO_x control for gas turbine engines. This has been studied in Europe for engines fired on CO_2-rich landfill gas, and for sites for which premixing the fuel with N_2 is practiced for calorific control of the pipeline gas. Recent landfill gas tests compared the NO_x exhaust emissions of a 5 MW gas turbine engine fired on a low-inert content North Sea gas, on this gas premixed with CO_2 and on a landfill gas (Rajput et al., 1989). The landfill gas (with 42 percent inert gas by volume) gave a 60 percent reduction

Table 1. Gas turbine exhaust emission regulations in Europe (ISO, 15 percent O_2 dry conditions)

The Netherlands

Natural gas sites, effective 1 January 1990.

Maximum NO_x of 200 gm/GJ.

Maximum NO_x of 135 gm/GJ for combined heat power sites.

Correction for engine efficiency and fuel heating value (based on lower heating value):

(200 or 135 gm/GJ) × (EFF/30) × (LHV/31.65 MJ/Nm^3)
1.0 < EFF/30 < 1.1
0.9 < LHV/31.65 < 1.1

Federal Republic of Germany

Natural gas sites, effective between 1 March 1991 and 1 March 1994.

Exhaust flow greater than 60,000 Nm^3/hr (21.6 kg/s).

Maximum NO_x of 300 mg/Nm^3, however, a proposal is being considered to reduce this limit to 150 mg/Nm^3. For engines with less than 60,000 Nm^3/hr flow, the limit is 350 mg/Nm^3. The proposed change for this is 200 mg/Nm^3.

Maximum CO of 100 mg/Nm^3.

Maximum non-methane hydrocarbons of 150 mg/Nm^3, including a maximum formaldehyde emission of 20 mg/Nm^3.

in NO_x exhaust emission compared to the North Sea gas (with 1.7 percent inert gas). CO exhaust emissions increased by a factor of 3.5. Unpublished studies with N_2 injection indicated about a 50 percent reduction in NO_x exhaust emissions when a nitrogen-to-hydrocarbon mass ratio of 2 was used. Further developments on NO_x control by inert gases bear watching.

The following sections of the paper present and discuss the baseline exhaust emissions and the exhaust emissions with water and steam injection.

BASELINE EXHAUST EMISSIONS

The database is comprised of 18 gas-fired turbine engines, including nine heavy-duty engines and nine aero-derivative engines. The data have been compiled from the engine manufacturers; the exhaust emissions are typical levels expected for the given engine. Engine vintage runs from the late 1970s to current production models. In Table 2, the parameters and the NO_x and CO exhaust emissions of the engines are listed. The heat rate of each engine is based on the lower heating value of the fuel. From the given baseload power output and heat rate, we have computed the fuel rate as kJ/s and converted this to fuel flow rate as kg/s assuming a nominal fuel lower heating value (LHV) of 47,500 kJ/kg. This value is the average for natural gases surveyed in the United States (Weaver, 1989). The fuel-air ratio, f, kg fuel/kg air, of each engine has been computed from the fuel flow rate and the exhaust (i.e., total) flow rate. The NO_x and CO exhaust emissions are reported as ppmv (15 percent O_2 dry), that is, as parts per million by volume, corrected to dry exhaust conditions with 15 percent O_2.

For the data in Table 2, ISO conditions are assumed to prevail. Power is for engine shaft output, with no duct-loss, except for the cases otherwise indicated in Table 2. The majority of the heavy-duty engines examined are single-shaft machines. In some cases, as noted, it has been necessary to estimate the engine parameters based on results (and extrapolations of data) available for precursor engine models.

Although not listed in Table 2, we have also calculated the nominal combustor inlet temperature for each engine by taking it equal to the discharge temperature of the compressor with an assumed 85 percent isentropic efficiency, drawing inlet air of 288 K. As a check on the computed fuel-air ratio of each engine, the difference between the turbine inlet temperature and the combustor inlet temperature has been plotted (not shown) versus fuel-air ratio. A straight line fit with limited scatter (less than 0.01 in the fuel-air ratio) was found.

The database in Table 2 covers a fairly wide range of conditions. This includes nominal compressor pressure ratio P from 7.2 to 30.0, turbine inlet temperature from 1150 to 1515 K, fuel-air ratio f from 0.014 to 0.019, power output from 2.9 to 83.5 megawatts, and heat rate from 9680 to 14230 kJ/kW-hr, which corresponds to an engine thermal efficiency range from 25 to 37 percent.

Table 2
Exhaust Emissions Data

Heavy-duty or Aero-derivative Engine	Nominal Pressure Ratio P	Turbine Inlet Temperature (K)	Power Output (kW)	Heat Rate (kJ/kW-hr)	Exhaust Mass Flow (kg/s)	Fuel-Air Ratio (47,500 kJ/kg LHV) f	$P^{0.61}f^{0.55}$	NO_x ppmv (15% O_2 dry)	CO ppmv (15% O_2 dry)
HD	7.2	1173	3880	13576	21.1	0.0148	0.33	95	12
HD	9.0	1151	2900	14229	17.3	0.0142	0.37	129	21
AD	9.0	1200*	17748**	10218**	77.4**	0.0140	0.36	105	96
AD	9.5	1308	3787†	12632†	15.4†	0.0185	0.44	115	22
HD	10.2	1269	25300	12996	121	0.0162	0.43	99	10
AD	11.0	1356	28100	11613	108	0.0180	0.47	75	51
HD	11.5*	1415*	38340	11460	140*	0.0187	0.50	147	10
HD	12.0*	1415*	83500	11055	295*	0.0186	0.51	153	10
HD	12.0	1273	6250	11800	28.0	0.0157	0.46	105	7
AD	12.0	1311	4300	11921	20.0	0.0152	0.46	148	10
AD	12.7	1415*	5708	10875	19.8	0.0187	0.53	67	64
HD	13.6	1415*	22600	10651	78.3	0.0183	0.54	135	-
HD	16.0	1269	8000	11250	37.3	0.0143	0.53	135	8
HD	16.0	1350*	10175	10338	38.0*	0.0165	0.57	178	-
AD	18.0	1483	22100	9730	67.5	0.0190	0.66	184	15
AD	19.0	1375*	29080**	8630**	90.1**	0.0166	0.63	185	35
AD	22.0	1514	13980	9680	46.0	0.0175	0.71	140	15
AD	30.0	1514	33760‡	9861‡	122	0.0162	0.83	240	10

* Estimate
** Exhaust gas power of gas generator
† With inlet and exhaust duct losses
‡ Electrical generator output

The NO_x exhaust emissions data from Table 2 are plotted in Fig. 1. All heavy duty engines are denoted by square symbols while the aero-derivative engines are shown as circles. Except for three of the aero-derivative engines, the NO_x data are found to correlate as follows:

$$NO_x \text{ ppmv } (15\% \ O_2 \text{ dry}) = 284 \ P^{0.61} f^{0.55} \pm 30 \qquad (1)$$

The three aero-derivative engines which do not agree with this result have NO_x exhaust emissions significantly below the correlation.

Also indicated by the symbol coding in Fig. 1 are engines with moderate and high baseline CO exhaust emissions. Engines with baseline CO exhaust emissions above 50 ppmv (15 percent O_2 dry) are given solid symbols; engines with baseline CO emissions between 20 and 50 ppmv (15 percent O_2 dry) are given symbols with a cross. The trend is for the high and moderate CO engines to be engines of relatively low NO_x.

Several formulas and procedures exist in the literature for the correlation of NO_x exhaust emissions with engine and combustor parameters and conditions. Some of these require detailed knowledge of the combustor flow and geometry — information which is not readily available. Other formulas are based on the readily available parameters, including combustor pressure (or nominal compressor pressure ratio), P; combustor inlet temperature (or compressor discharge temperature), T_3; fuel-air ratio, f; and total mass flow, m.

Sullivan (1977) reviewed several of these formulas, and also developed the following formula:

$$NO_x \text{ ppmv (wet)} =$$

$$A_{NO_x} P^{0.5} f^{1.4} m^{-0.22} \exp(T_3/250) \qquad (2)$$

where P is as Pascals, m as kg/s and T_3 as K. The alternative formula available from Touchton and Dibelius (1975) has the following form:

$$EI_{NO_x} = B_{NO_x} P^{0.5} \exp(T_3/211 + 21833 \cdot f/T_3) \qquad (3)$$

where EI_{NO_x} is the NO_x emission index (gm NO_x as NO_2 divided by kg fuel) and T_3 is again as K.

Formulas such as equations (2) and (3) explain fairly well the NO_x exhaust emissions behavior of single engines, or closely related engine models, operated over a range of running conditions. Over a significant range of engine types, however, the NO_x reference levels, or the coefficients A_{NO_x} and B_{NO_x}, vary substantially. This may be seen from Sullivan's (1977) paper. For the data of Table 2, the variation of A_{NO_x} is about five-fold, and that of B_{NO_x} is about four-fold.

In order to fit the NO_x exhaust emissions data of this study, involving different engines operated only a baseload, a formula with a fairly weak dependence on compressor pressure ratio was found to be necessary. As given by equation (1), we arrived at P raised to the 0.61 power. This is different from equations (2) and (3), for which the dependence on the compressor pressure ratio shows directly through the $\sqrt{P}$ term, and indirectly through the T_3 terms. For equation (2), Sullivan (1977), the overall effect of these terms is P raised to about the 1.3 power for the range of compressor pressure ratios considered in this study. Our dependence on fuel-air ratio, however, is about the same as given by Sullivan (1977). The representation of NO_x exhaust emission as ppmv (15 percent O_2 dry), as done here, rather than as ppmv (wet), as by Sullivan (1977), leads automatically to a reduction in dependence on fuel-air ratio by multiplying by f raised to about the –0.95 power. This has led to the dependence shown in equation (1): f raised to 0.55 power. Finally no significant dependence on total engine flow is discernable in our database.

Equation (1) correlates the NO_x exhaust emissions of this study well over a broad range of conditions. However, for engines of like conditions, the equation does not have sufficient sensitivity, and NO_x exhaust emissions can differ by as much as 60 ppmv (15 percent O_2 dry) for such cases. This is seen by the scatter in Fig. 1. Also, the three low-NO_x aero-derivative engines are not covered by the equation. On the other hand, the low NO_x exhaust emissions of these three engines clearly stand out by comparison to the balance of the data set and equation (1).

WATER AND STEAM INJECTION

Results from the manufacturers on the control of NO_x exhaust emissions by water injection are plotted in Fig. 2 for seven of the heavy-duty engines and six of the aero-derivative engines of Table 2. The heavy-duty engines are denoted by the number symbols 1 though 8 (engine 7 has only steam injection), and the aero-derivative engines are denoted by the letter symbols A through F. These engines are also listed in Table 3, together with their uncontrolled NO_x and CO exhaust emissions, and the exhaust emissions for a 0.8 water-to-fuel mass ratio. For a few of the engines listed in Table 3, the water-to-fuel mass ratio is different from 0.8, as noted.

By Fig. 2 it is seen that NO_x control by water injection exhibits a fairly wide band for the engines of this study. For the three aero-derivative engines D, E and F, which have high compressor ratios and turbine inlet temperatures, there is strong sensitivity to small ratios of water injection. However, water-to-fuel mass ratios above about 0.6 bring a diminished effect for these three engines. For all of the engines, there is a variation of 58 to 82 percent in the reduction of NO_x by a water-to-fuel mass ratio of 0.8. In order to analyze this behavior, the reduction in NO_x by the 0.8 water-to-fuel mass ratio is plotted in Fig. 3 versus the uncontrolled NO_x exhaust emission. A fairly strong

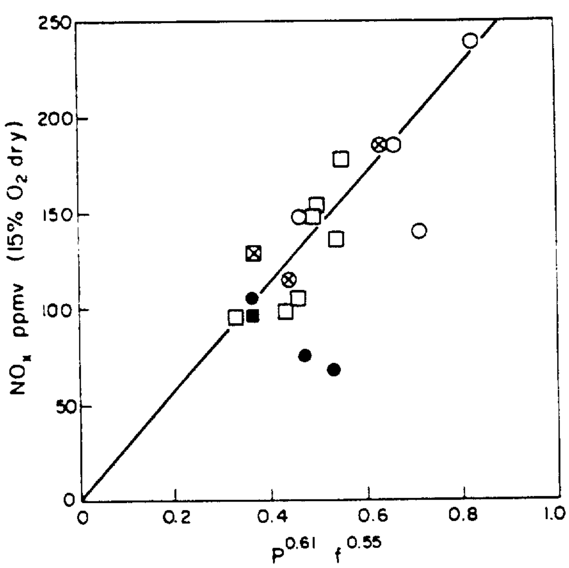

Fig. 1. Baseload, uncontrolled NO_x exhaust emissions for gas-fired turbine engines. Heavy-duty engines denoted by square symbols, aero-derivative engines by circle symbols. Open symbols have CO exhaust emissions below 20 ppmv (15 percent O_2 dry), crossed symbols have CO between 20 and 50 ppmv and solid filled symbols have CO above 50 ppmv.

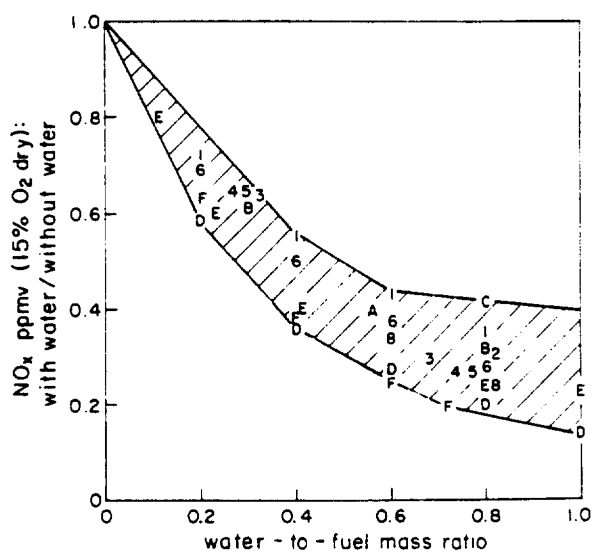

Fig. 2. NO_x response to water injection for baseload, gas-fired turbine engines. Heavy-duty engines are denoted by number symbols, aero-derivative engines by letter symbols.

Table 3

Water and Steam Injection Data

Heavy-duty or Aero-derivative	Without Injection		With 0.8 Water-to-Fuel Ratio				With 1.2 Steam-to-Fuel Ratio			
	NO_x ppmv (15% O_2 dry)	CO ppmv (15% O_2 dry)	Power % Increase	Heat Rate % Increase	NO_x ppmv (15% O_2 dry)	CO ppmv (15% O_2 dry)	Power % Increase	Heat Rate % Decrease	NO_x ppmv (15% O_2 dry)	CO ppmv (15% O_2 dry)
HD	95	12	-	-	33	20	-	-	-	-
HD	129	21	-	-	40	-	-	-	-	-
AD	105	96	2.4*	5.1*	42*	450*	-	-	-	-
AD	115	22	7.6	-	37	24	-	-	-	-
HD	134**	10	4.7†	2.5†	35†	10†	6.4‡	3.4‡	35‡	10‡
HD	144	10	4.8†	2.8†	38†	10†	6.7‡	3.1‡	38‡	10‡
HD	153	10	4.5	3.1	40	10	6.1	2.8	40	10
HD	105	7	-	-	29	240	-	-	27	200
AD	67	64	8.0	3.0	28	216	-	-	-	-
HD	135	-	-	-	-	-	-	-	31	-
HD	135	8	-	-	34	-	-	-	-	-
AD	184	15	5.7	3.4	37	65	-	-	30	60
AD	185	35	5.0††	4.2††	42††	200††	6.5‡‡	2.8‡‡	42‡‡	200‡‡
AD	240	10	-	-	50†	-	-	-	42‡‡	10‡‡

* Water-to-fuel ratio of 0.56
** Different uncontrolled NO_x than given in Table 2
† Extrapolation of data from water-to-fuel ratio of about 0.7 to 0.8
‡ Extrapolation of data from steam-to-fuel ratio of about 1.0 to 1.2
†† Water-to-fuel ratio of 1.0
‡‡ Steam-to-fuel ratio of 1.5

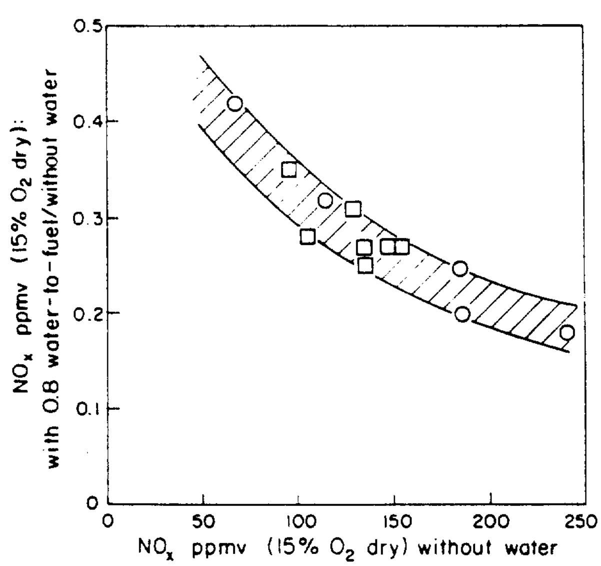

Fig. 3. NOx reduction by water injection of 0.8 water-to-fuel mass ratio versus uncontrolled NO_x exhaust emissions. Heavy-duty engines are denoted by square symbols, aero-derivative engines by circle symbols.

correlation is evident; engines with large uncontrolled NO_x exhaust emissions experience a more substantial percentage reduction in NO_x by water injection. For example, the engine with 67 ppmv (15 percent O_2 dry) uncontrolled NO_x exhaust emission is reduced to 28 ppmv (15 percent O_2 dry) with a 0.8 water-to-fuel-mass ratio, whereas the engines with about 185 ppmv (15 percent O_2 dry) uncontrolled NO_x are reduced to 42±5 ppmv (15 percent O_2 dry).

This behavior is consistent with NO_x theory for gas turbine engines. As uncontrolled NO_x exhaust emissions decrease, the percentage of the NO_x due to the "prompt" mechanism increases relative to the NO_x due to the "thermal" mechanism. Whereas the reduction of thermal NO_x is very sensitive to water injection, prompt NO_x reduction is only weakly sensitive to water injection. This tendency has been computationally modeled by Toof (1985).

Results from the manufacturers for steam injection are available for five of the heavy-duty and three of the aero-derivative engines. The NO_x control by steam injection is plotted in Fig. 4. Results are also listed in Table 3. The band for NO_x control with steam injection is substantially narrower than that for the water injection, and no trend with respect to the uncontrolled NO_x exhaust emission level, as in Fig. 3 for water injection, is evident in the data. In this regard, however, it should be noted that the data set for steam injection is smaller than that for water injection.

The data in Table 3 are consistent with the rule-of-thumb that approximately 50 percent more steam than water is required to effect equivalent NO_x reductions. Also, it should be noted that for most engines the recommended maximum steam-to-fuel mass ratio is 1.2 to 1.5. The data at 2.0 steam-to-fuel ratio for the two aero-derivative engines are experimental.

The response of CO exhaust emissions to water and steam injection is also listed in Table 3. A wide range of behavior is noted and, because of this, no plot of CO exhaust emission trends can be presented. It appears from these data that a necessary condition for preventing the increase of CO with water injection is that the uncontrolled engine exhibit a CO exhaust emission less than about 20 ppmv (15 percent O_2 dry). However, this is not a sufficient condition. Although several of the heavy-duty engines with low uncontrolled CO exhaust emissions [10 ppmv (15 percent O_2 dry)] show no increase in CO by water and steam injection for baseload operation, one of the engines of this category shows counter behavior [i.e., CO of 240 ppmv (15 percent O_2 dry) with water injection]. For engines with high uncontrolled CO exhaust emissions, and for several of the aero-derivative engines, CO exhaust emissions increase significantly with water and steam injection. Generally, the aero-derivative engines show enhanced CO exhaust emissions upon water injection.

ADDITIONAL CONSIDERATIONS

Water and steam injection are also well-established methods for enhancing the power output of gas turbine engines. For power enhancement, the injection may be made into the secondary or dilution zone of the combustor, rather than into the high temperature primary zone, as necessary for NO_x control.

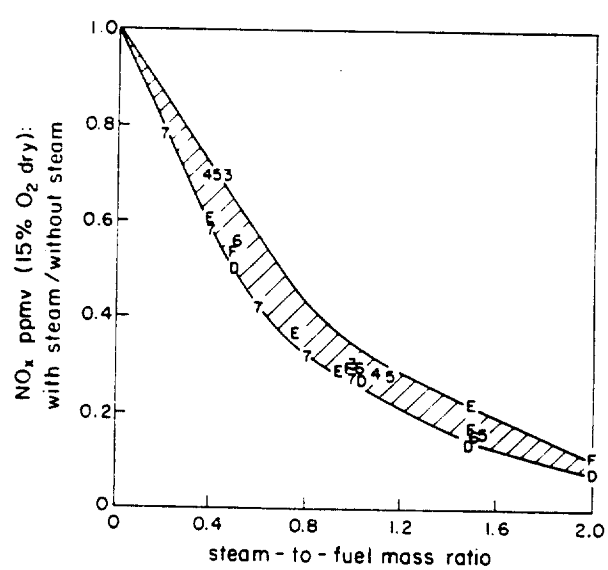

Fig. 4. NO_x response to steam injection for baseload, gas-fired turbine engines. Heavy-duty engines are denoted by number symbols, aero-derivative engines by letter symbols.

In Table 3, the changes in power and heat rate caused by levels of water and steam injection used for NO_x control are listed. For the 0.8 water-to-fuel mass ratio, the average increase in the power of the engines listed is 5.3 percent. The average heat rate increase is 3.6 percent. For 1.2 steam-to-fuel-mass ratio, the four engines for which data are available have an average increase in power of 6.1 percent. The average heat rate decrease for these engines is 2.9 percent.

If the turbine inlet temperature is maintained constant upon injection, it is possible to calculate the power and heat rate changes. For example, a 16.5 MW, gas-fired, heavy-duty engine with a low turbine inlet temperature is treated. Upon water injection at a 0.8 mass ratio, the power output rises 6.6 percent and the heat rate increases 2.0 percent. On the other hand, if steam at the 0.8 mass ratio is used, the power output rises 6.2 percent and the heat rate decreases 2.8 percent. The heat rate decrease with the steam is based on a "free" source of steam, and effects on any cogeneration or combined cycle plants are not considered. Approximately one-half of the power enhancement us attributed to the increased mass flow of the engine; the other half arises because the power turbine specific work is increased.

For NO_x control, water injection has been used more widely than steam injection for a number of reasons:

- A source of steam may not be conveniently available;
- General opinion is that water injection is more cost-effective than steam injection for engines smaller than 15 to 20 MW; and
- Frequent start-ups and shut-downs are more convenient with water injection.

However, steam injection has technical and economic advantages over water injection and, from our viewpoint, appears to have gained favor among operators. For aero-derivative engines with highly-loaded combustors, as well as for some heavy-duty engines, steam injection is now commercially available for 25 ppmv NO_x. Furthermore, as mentioned above, Rule 1134 of the South Coast Air Quality Management District mentions steam as a method for large reductions of NO_x. The general rule for water injection, on the other hand, is 42 ppmv NO_x, except for lower levels [e.g., 25 ppmv (15 percent O_2 dry)] for some heavy-duty engines which have lowly loaded combustors and can accept high water-to-fuel mass ratios.

With steam injection, the advantages are:

- enhance engine efficiency;
- generally less dynamic pressure activity of the combustion process;
- less impact of CO emissions is possible if the steam is premixed with the gaseous fuel;
- cost-effectiveness for large engines; and
- NO_x emissions in the range of those which appear to be feasible with developmental, lean-premixed combustors.

SITE EXPERIENCE

The data presented above have been drawn from the engine manufacturers. For comparison, site NO_x data for five cases are plotted in Figs. 5 and 6. The cases are for late model, gas-fired, steam-injected engines. The conditions are listed in Table 4. All NO_x data have been corrected to ISO, 15 percent O_2 dry conditions.

In the upper plot of Fig. 5, heavy-duty engine results are plotted. Cases A and B, for the same engine, show the advantage of the reduced heating value fuel for NO_x control. NO_x exhaust emissions decreased about 8 percent upon switching from 44,235 kJ/kg (Case A) to 37,500 kJ/kg (Case B) fuel. Case C is for three units of a different model of heavy-duty engine. It has relatively low-NO_x exhaust emissions. Plotted in the lower half of Fig. 5 are the NO_x exhaust emissions of aero-derivative engines (two units of the same engine model) as a function of fuel input rate. In these tests, only enough steam was injected to approach 110 ppmv NO_x (15 percent O_2 dry).

In Fig. 6, these site NO_x data for steam injection are plotted in the same format as used in Fig. 4 for the manufacturers' data. Cases A and B (the solid and crossed square symbols) lie within the manufacturers' band from Fig. 4. However, the site data for Case C (the open square symbols) and for the aero-derivative units 1 and 2 (circles) lie somewhat below the manufacturers' band.

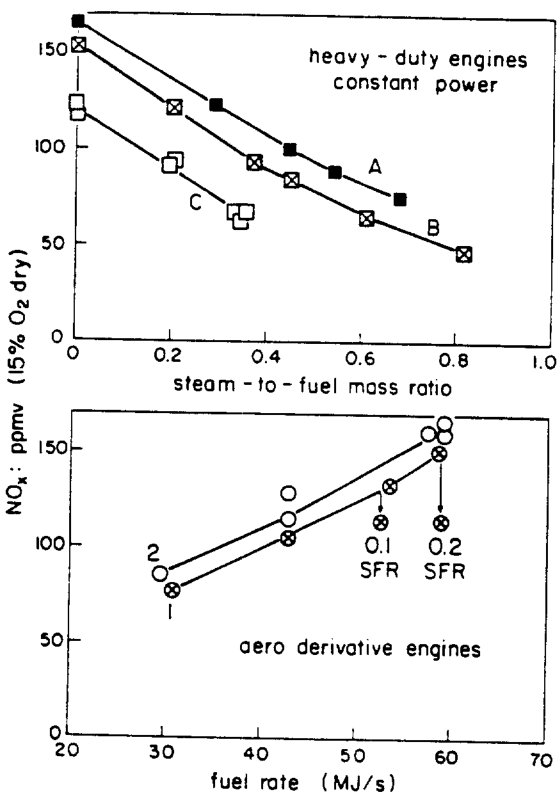

Fig. 5. Site measurements of NO_x exhaust emissions for gas-fired engines. Conditions of each case given in Table 4. SFR means steam-to-fuel ratio.

The discussion of site experience is concluded with three issues not treated above: costs; water treatment; and operator satisfaction.

Capital costs involve the engine hardware and water treatment plant. For water injection, the engine hardware includes the nozzles, boost pump, manifold and plumbing, controller and actuator. For steam injection, the items are nozzles, manifold and plumbing, steam valve and control equipment. The nozzles show great cost variability; nozzle costs must be obtained from the engine manufacturers. A data set for six engines of 3 to 15 MW, involving both water and steam injection, indicates engine hardware capital costs of between \$15,000 and \$80,000 per MW engine power output.

Water treatment system capital costs are also available. From several water-injected sites with engines of 3 to 25 MW, the costs varied from \$5,000 to \$15,000 per MW. Only a few sites which we have examined claimed significantly higher costs.

A well-engineered and well-maintained water treatment plant is essential for satisfactory water and steam injection. Engine manufacturers' water quality requirements are listed in Table 5. Water quality of 0.1 to 1.0 micromho/cm conductivity is recommended. Also, the silica content should be low. Usually a cation-anion deionizer system followed by a cation- or mixed-bed polishing unit is used. However, if the source water contains more than 500 ppmw (parts per million by weight) total dissolved solids, a reverse osmosis membrane system should most likely be used ahead of the deionizer system. Usually the amortized cost of replacement membrane elements is less than the cost of frequently regenerating the deionizer system.

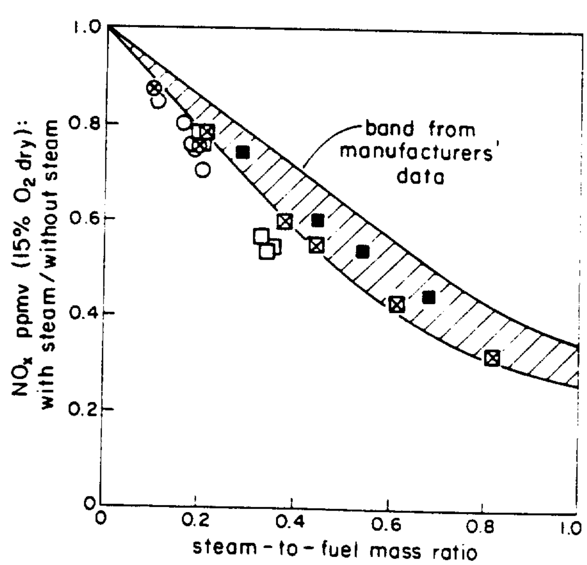

Fig. 6. Summary of site measurements of NO_x response to steam injection. Manufacturers' band is from Fig. 4.

Table 4

Field Data

I. **Heavy-duty Engines for Electric Generation with Steam Injection.**

NO_x data in upper plot of Figure 5.

Case A:

- 1986 installation
- Fuel LHV of 44,235 kJ/kg
- 31.6 MWe power output without steam (5.5% increase for 0.6 SFR)
- 14,105 kJ (LHV)/kWe-hr heat rate without steam (3.0% decrease for 0.6 SFR)

Case B:

- Same engine as case A
- Fuel LHV of 37,500 kJ/kg
- 32.5 MWe power output without steam (3.0% increase for 0.6 SFR)
- 13,700 kJ (LHV)/kWe-hr heat rate without steam (no change for 0.6 SFR)

Case C:

- 1987 installation — three units
- Fuel LHV of 45,190 kJ/kg
- 35.0/37.0/37.5 MWe power output without steam (no change for 0.35 SFR)
- 11,180/10,730/10,830 kJ (LHV)/kWe-hr heat rate without steam (no change for 0.35 SFR)

II. **Aero-derivative Engines for Electric Generation with Steam Injection.**

NO_x data in lower plot of Figure 5.

- Two units
- Fuel LHV of 38,600 kJ/kg
- Power output not measured

Annual (8,000 hr) operating and maintenance costs for the water treatment plant run from $2,000 to $5,000 per MW for engines of 3 to 25 MW. The annual operating and maintenance costs of the engine hardware attributable directly to water or steam injection are difficult to ascertain because they are closely associated with the routine maintenance of an engine. However, nozzle cleaning and more frequent than normal replacement of combustor liners are issues which contribute to higher operating and maintenance costs with injection. Considerable variability exists across the engine models on these cost issues.

Operators generally regard water and steam injection as routine aspects of electricity-producing gas turbine engines. For well-engineered and well-maintained systems, we find operator satisfaction with water and steam injection. However, site operators do voice concern about the operating and maintenance costs associated with the water treatment plant, and the reduced lifetimes of combustor components. Also, for engines which use water injection but could use steam injection, there is a tendency to favor a switch to steam injection because of the recent improvements in this method.

For gas pipeline engines, water and steam injection have not been used. Thus, the costs for any future application of NO_x control to such sites must be estimated based on the available experience with electricity-producing engines.

CONCLUSIONS

Water and steam injection are important methods of NO_x control for electricity-producing gas turbine engines. In this paper, the typical NO_x behavior of uncontrolled gas-fired engines has been shown. This behavior may be used to comparitively assess the NO_x exhaust emission of an engine. Control of NO_x by water and steam injection has also been examined, and the trends have been discussed. From discussions with site operators, steam injection for effecting NO_x exhaust emissions control is increasing in interest. However, for sites requiring only modest reductions in NO_x, commercially available combustors with reduced NO_x exhaust emissions, de-rating and fuel modification may be interesting options. Gas turbines with advanced combustion for dry NO_x control are providing the large-engine user with an additional option in the 1990s for obtaining low NO_x exhaust emissions.

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Table 5

Water Quality Requirements
(Manufacturers' Maximum Recommended Levels).

Engine Manufacturer	A	B	C	D	E	F	G
Engine Types	AD	HD	AD	HD	HD	HD	HD
Total Solids (ppmw)	2	5	5	5	2.6		
Conductivity (micromho/cm)	1					2	1
Particle Size (microns)	10			10–20 (16%) 5–10 (18%) 0–5 (Bal.)	10 0–5 (90%)		
pH		6.7–7.5	6.5-7.5	6.5–7.5	5.5–8.5	5–9	
Trace Metals (ppmw)				2.0			
Na+K+V+Pb (ppmw)		0.5	0.1				
Na+K (ppmw)				0.2	1.0		0.1
Pb (ppmw)				0.5	1.0		
V (ppmw)				0.5	0.5		
Ca (ppmw)				1.0	2.0		
Si (ppmw)				0.02	0.1		0.2
Chlorides (ppmw)					1.0		

sites which provided data and information for this study.

REFERENCES

Anon. (1989). "Rule 1134, Emissions of Oxides of Nitrogen from Stationary Gas Turbines," Adopted August 4, 1989, South Coast Air Quality Management District, El Monte, California.

Becker, B., and Ziegner, M. (1988). "The New Siemens/KWU Model V64.3 Gas Turbine," *Motortechnische Zeitschrift, 49*, pp. 233–240.

Cutrone, M.B., Hilt, M.B., Goyal, A., Ekstedt, E.E., and Notardonato, J. (1982). "Evaluation of Advanced Combustors for Dry NO_x Suppression with Nitrogen Bearing Fuels in Utility and Industrial Gas Turbines," *Journal of Engineering for Power, 104*, pp. 429–438.

Davis, L.B., and Washam, R.N. (1989). "Development of a Dry Low NO_x Combustor," Paper No. 89-GT-255, presented at the Gas Turbine and Aeroengine Congress and Exposition, Toronto, Canada, June 4–8, 1989; The American Society of Mechanical Engineers, New York, NY.

Farmer, R. (1989). "150 MW Class 501F Design to Begin Full Load Factory Testing This Summer," *Gas Turbine World, 19*, No. 3, pp. 12–17.

Jeffs, E. (1989). "Asea Brown Boveri Introducing a Dual Fuel Dry Low-NO_x Burner Design," *Gas Turbine World, 19*, No. 3, pp. 20–24.

Maghon, H., Kreutzer, A., and Termuehlen, H. (1988). "The V84 Gas Turbine Designed for Base-load and Peaking Duty," paper presented at the American Power Conference, Chicago, Illinois, April 18–20, 1988.

Miller, H.E. (1989). "The Quiet Combustor for Better Noise and Emissions Control," *Diesel and Gas Turbine Worldwide, 21*, No. 7, pp. 11–14.

Rajput, A.P., Hurd, P.J., and Wood, R.D. (1989). "The Effects of Inerts on Emissions and Performance of an Industrial Engine," Paper No. 89-GT-256, presented at the Gas Turbine and Aeroengine Congress and Exposition, Toronto, Canada, June 4–8, 1989; The American Society of Mechanical Engineers, New York, NY.

Reilly, William K. (1989). PSD Appeal No. 88–11, Before the Administrator, U.S. Environmental Protection Agency, Washington, D.C.

Sullivan, D.A. (1977). "A Simple Gas Turbine Combustor NO_x Correlation Including the Effect of Vitiated Air," *Journal of Engineering for Power, Transactions of the ASME*, pp. 145–152, April 1977.

Toof, J.L. (1985). "A Model for the Prediction of Thermal, Prompt, and Fuel NO_x Emissions from Combustion Turbines," Paper No. 85-GT-29 presented at the 30th International Gas Turbine Conference and Exhibit, Houston, Texas, March 18–21, 1985; The American Society of Mechanical Engineers, New York, NY.

Weaver, C.S. (1989). "Natural Gas Vehicles — A Review of the State of the Art," Report No. SR89-04-01, Sierra Research Inc., Sacramento, California.

Yabuki, M., Fukue, I., and Johnson, K.W. (1988). "Operating Experience of a Dry Low NO_x Combustor and SCR in a Japanese Utility, and Future Developments," Paper No. 88-JPGC/GT-2 presented at the ASME/IEEE Power Generation Conference, Philadelphia, Pennsylvania, September 25–29, 1988; The American Society of Mechanical Engineers, New York, NY.