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NOx Emission Factors for UnControlled Gas Turbines in Natural Gas Pipeline Compressor Drive Service

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Abstract

The application of emission factors for the determination of NOx emissions from natural gas fueled gas turbines can have significant variability in accuracy, depending on the details of the application. Generally speaking, the factorial approach implies a linear relationship between an independent variable and the desired NOx quantity, or dependant variable. This paper discusses one such factorial approach, known as AP 42, and compares it to natural gas fired turbo-compressor facility stack test results, evaluates the linearity, and consequences of application with a single independent value for purposes such as establishing annual NOx emission inventories. The discussion leads to observing that the true non-linear relationship is more accurately represented by a second order polynomial relationship and that integration with time is needed for determining quantities in the time range of annual NOx inventories. A second order polynomial fit of stack test data of NOx emission rate, as a function of fuel rate, is presented for uncontrolled natural gas fueled gas turbines, showing a curve fit correlation coefficient of 0.97 and comparable deviation from test data to the uncertainty of typical NOx stack reference test method measurements. Compared to an emission factor approach, a polynomial relationship will provide improved NOx inventory accuracy, when applied to variable load gas turbines.

1 Purpose

The purpose of this paper is to communicate to industry a data set of NOx stack test results, compare them to the AP42 emission factor prediction, and describe a practical apparent correlation that could be applied in NOx inventory application, with improved accuracy compared to conventional methods.

2 Background

The development of natural gas pipeline infrastructure in Canada has grown and evolved since the 1950s, with compression systems dominated by reciprocating compressors, followed by the introduction of gas turbine powered turbo-compressors, DLE turbo-compressors, and highly efficient combined cycle facilities. With the life cycle of the associated compression equipment between 25 to 40 years, these developments have occurred gradually over time, with the application of best available technology, at the time of equipment installation either as expansion installations or replacement installations when previous equipment reached the end of its life cycle.

Since the 1990s, much attention has been given to the NOx emissions associated to stationary gas turbine powered industrial facilities. This attention was triggered by the development of knowledge of the environmental problems associated with NOx emissions inherently conflicting with technology developments of simple cycle gas turbines with higher thermal efficiency. In many ways this knowledge and technology conflict was overcome with the development of DLE gas turbine technology.

In gas turbine industrial application, these DLE technologies and other water or steam injection based technologies are forms of NOx controls. The predecessor technologies, without such controls, are generally referred to as UnControlled with respect to their NOx emissions. Care should be taken using such generalizations, since depending on the vintage of gas turbine and its operating Brayton cycle, the difference in emissions between NOx controlled and uncontrolled machines varies significantly. However, it is the focus of this paper to explore the NOx emissions of UnControlled systems. From a gas turbine combustion perspective (Brayton cycle heat input), these UnControlled systems can be described as dominated by diffusion flame combustion processes.

2.1 Spectra Energy (Canada-West) Natural Gas Pipeline Operations

Spectra Energy owns and operates natural gas pipeline infrastructure in British Columbia, Canada under its BC Pipeline and BC Field Services business units, including 22 compressor station facilities with turbo-compressors totaling 38 turbo-compressor units. Of these 38 units, 9 are DLE, which represent 27% of the total turbo-compressor rated power. The general geographic location of these facilities is illustrated in Figure 1.

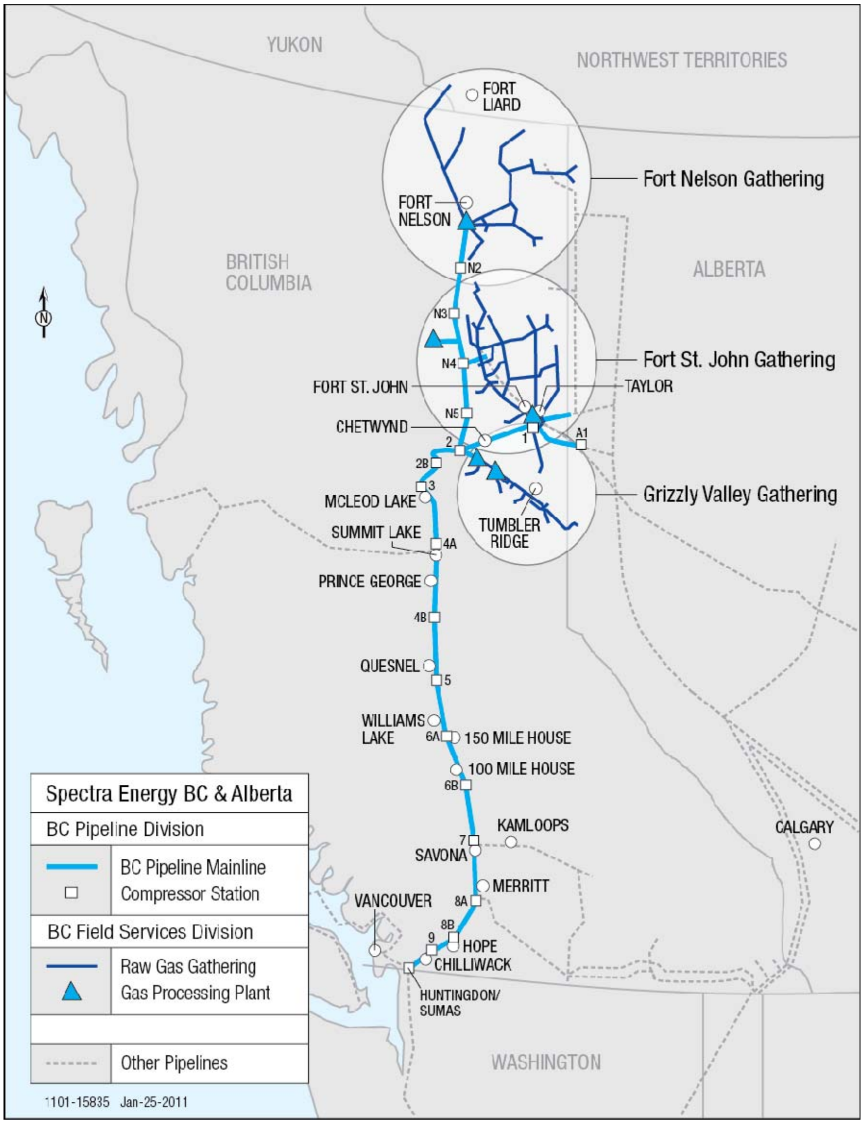

Figure 1: Spectra Energy BC Pipeline and BC Field Services Divisions

2.2 AP 42 Emission Factors

The US Environmental Protection Agency originally published methods for estimating air emissions in 1968, in the form of AP 42. In 1985, AP 42 was separated into two volumes, with Volume I covering Stationary Sources. Published in 1995, the current AP 42 5th Edition of Volume I includes a Third Chapter for Stationary Internal Combustion Sources and Chapter 3.1 specifically for Stationary Gas Turbines [1].

AP 42 Chapter 3.1 outlines a NOx emission factor for uncontrolled natural gas fired stationary gas turbines of 5.2 x 10^{-3} kg NOx as NO_2 per Standard m^3 of natural gas fuel input (3.2 E-01 lb/MMBtu), based on an average fuel gas heating value of 37.97 MJ/m^3 (1020 Btu/scf). This factorial approach implies a linear relationship between the NOx emission and the gas turbine fuel consumption as illustrated in Figure 2.

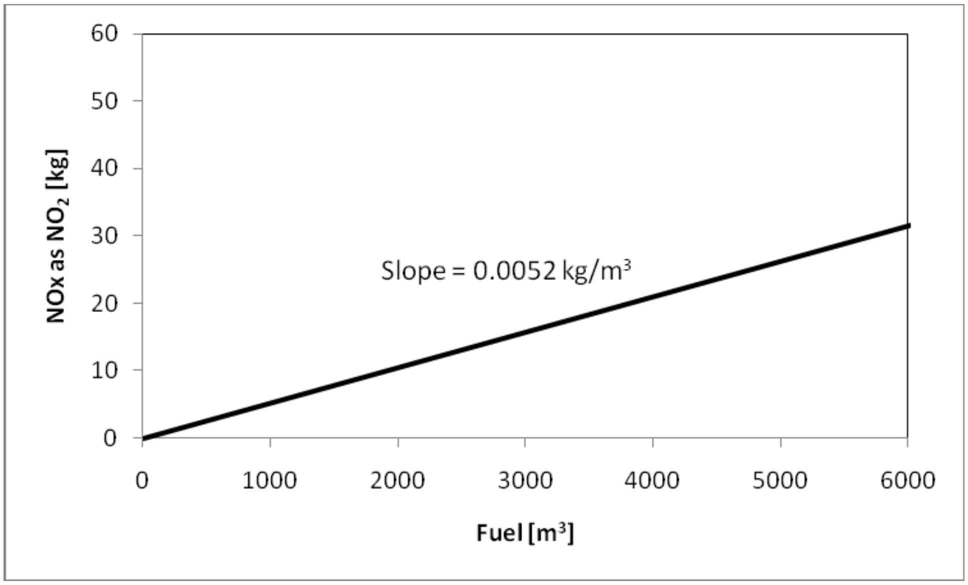

Figure 2: AP 42 UnControlled Stationary Natural Gas Fired Gas Turbine Graphically

This relationship provides a simple method of estimating NOx emissions. For any given period of time, the fuel consumed during that time period is multiplied by the emission factor. This provides a value for the NOx emission for the corresponding time period.

2.3 Spectra Energy (Canada-West) NOx Management Plan

Spectra Energy (Canada-West) has been required to determine the discharge rate of NOx from compressor drive units by an air permit issued from the BC Ministry of Water, Land and Air Protection and later the Ministry of Environment. In 1992, in collaboration with the BC Ministry's requirements, Spectra Energy (Canada-West) developed its NOx Management Plan to facilitate air permit compliance.

As part of the NOx Management Plan, a site stack test program was initiated, with the first phase of stack tests completed in 1996. These stack test results were used to modify the estimated emission factors of each model of gas turbine in pipeline compression service.

Initially, NOx testing was conducted at full or close to full load and during cooler ambient temperatures, when pipeline demand is high, to achieve the highest NOx result. Subsequent validating stack test programs were initiated in 2003, 2007, and 2010. From stack testing it was learned that NOx is heavily influenced by the load at which the unit is running. During the first round of tests it has been noted that maintaining a constant load, even within a 1 hour sample period, is difficult. Therefore, since 2007, NOx testing has extended to, as much as possible, wider load ranges in order to characterize a correlation between NOx emission and load related parameters. At the same time, Spectra has also targeted summer and winter testing to investigate the impact of ambient temperature. The details will be discussed in Section 3 and 4.

Included in the current NOx Management Plan are plans for further stack testing over the period of 2011-2015.

3 Spectra Energy (Canada-West) Pipeline NOx Stack Testing

Site stack testing has been an integral component of Spectra Energy's (Canada-West) NOx Management plan since 1992.

3.1 Reference Test Stack Test Data Set

Of all the stack tests completed under the NOx Management Plan, those meeting the following criteria are presented in this paper:

- Test data includes log of load related (turbine speed(s), and gas generator exhaust gas temperature) operating data
- One hour stack sample(s) (typically 3 per test) taken with turbine at constant load
- Fuel measurements validated

For example, several stack tests were removed from the data set for reasons including: no load related data recorded and not recoverable from systems such as SCADA, thus fuel measurement validation was not possible; some tests showed extreme load change over 1 hour sample period and since update time for a CEMS lags real time measurements could not be used; on occasion recorded fuel data appeared higher than maximum for machine and thus these tests were not included in the data set.

Even with the intent to conduct testing with the gas turbine operating at rated power, prior to the 2004 stack testing program it was recognized that load related data was often not recorded, making it difficult to evaluate test results. The maximum power of a gas turbine at any given site, at any given point, in time, varies significantly and so correspondingly does its NOx emissions. Further, it is often interpreted that stack testing requires the machine be operated at > 80% load to constitute a full load test. Initiated during the 2004 test program, more focus was given to recording the turbine loading during stack tests and optionally, if the operation could facilitate at the time, each of the three 1 hour stack samples would attempt to cover discretely varying load conditions (i.e.: three samples at constant but different load). This testing regime provided more insight into the relationship between NOx and load, but in some regards provided more opportunity for mis-interpretation and invalid tests.

As part of the 2007 stack test program, attempts to explore the influence of ambient temperature on NOx emissions were included by scheduling "summer" and "winter" tests. This has provided somewhat limited ranges of ambient temperatures between stack tests. More focus will be given on future tests targeting specific ambient temperatures (i.e.: a warm "winter" day can be at a similar ambient temperature to a cold "summer" day).

Table 1 presents the previously described Spectra Energy (Canada-West) Pipeline stack test data set. Of the 24 NOx Management Plan stack tests on record, this data set represents 10 tests fulfilling the criteria above.

The stack testing and exhaust gas analysis were conducted through third party environmental consultancy with the general work scope to provide reference test methods via portable CEMS.

Table 1: UnControlled Gas Turbine Stack Test Data Set

Coberra 3045 (Spey) - Nov 28/08 — Site A - Elevation 820 m

Fuel [Standard m^3/h]	NOx [ppmv] [dry @15% O_2]	NOx [kg/h]	EGT [°C]	Ambient Temperature [°C]
2197	77.5	9.7	490.8	3
2380	85.5	11.5	513.3	0
2397	85.5	11.9	515.3	-1

Coberra 3045 (Spey) - Mar 1/03 — Site B - Elevation 850 m

Fuel [Standard m^3/h]	NOx [ppmv] [dry @15% O_2]	NOx [kg/h]	EGT [°C]	Ambient Temperature [°C]
3525	106.0	21.6	609.9	3
3486	100.2	20.2	609.4	1
3048	65.3	11.5	567.9	3

GT51 (LM1500) - Nov 24/07 — Site A - Elevation 650 m

Fuel [Standard m^3/h]	NOx [ppmv] [dry @15% O_2]	NOx [kg/h]	EGT [°C]	Ambient Temperature [°C]
3814	114.2	24.8	541.5	2.6
3641	102.6	21.2	410	1.1
2696	83.8	13.0	378.9	3.2

GT51 (LM1500) - Aug 22/02 — Site A - Elevation 650 m

Fuel [Standard m^3/h]	NOx [ppmv] [dry @15% O_2]	NOx [kg/h]	EGT [°C]	Ambient Temperature [°C]
3216	74.8	13.9	541.9	19
3164	73.2	13.4	541.3	19

PGT25 (LM2500GE) - Nov 29/08 — Site A - Elevation 540 m

Fuel [Standard m^3/h]	NOx [ppmv] [dry @15% O_2]	NOx [kg/h]	EGT [°C]	Ambient Temperature [°C]
2973	86.4	14.8	560.6	3
2650	85.3	13.0	534.1	0
2596	82.5	12.2	531.8	-1

PGT25 (LM2500GE) - Nov 6/01 — Site B - Elevation 820 m

Fuel [Standard m^3/h]	NOx [ppmv] [dry @15% O_2]	NOx [kg/h]	EGT [°C]	Ambient Temperature [°C]
4402	120.8	30.7	668.6	1
4166	114.7	27.6	652.1	1
4810	128.6	35.8	704.6	2
5062	131.8	38.7	723.7	3

PGT25 (LM2500GE) - Aug 21/02 — Site B - Elevation 820 m

Fuel [Standard m^3/h]	NOx [ppmv] [dry @15% O_2]	NOx [kg/h]	EGT [°C]	Ambient Temperature [°C]
4902	152.7	43.8	775.9	21
4856	145.6	41.3	760.5	24
4880	149.4	42.6	766.8	25

DR60G (LM1600) - Nov 24/07 — Site A - Elevation 650 m

Fuel [Standard m^3/h]	NOx [ppmv] [dry @15% O_2]	NOx [kg/h]	EGT [°C]	Ambient Temperature [°C]
3697	137.8	29.5	722.2	3.3

DR60G (LM1600) - Feb 28/03 — Site A - Elevation 650 m

Fuel [Standard m^3/h]	NOx [ppmv] [dry @15% O_2]	NOx [kg/h]	EGT [°C]	Ambient Temperature [°C]
3532	119.4	24.5	740.4	2
3548	128.9	26.5	740.3	2
3534	125.9	25.8	740.4	0

Taurus 60 (T7000) - Mar 10/10 — Site A - Elevation 695 m

Fuel [Standard m^3/h]	NOx [ppmv] [dry @15% O_2]	NOx [kg/h]	EGT [°C]	Ambient Temperature [°C]
1043	65.4	4.0	588.3	2
1101	67.1	4.3	617.4	3
1036	65.3	4.0	615.4	5

3.2 Comparison to AP 42

Figure 3 graphically illustrates the stack test data set of Table 1 and compares it to the uncontrolled natural gas fired stationary gas turbine factor of AP 42. An MS-Excel second order curve fit with a zero intercept is applied to the data set (labeled “Poly. (all)”), resulting in a best fit curve of:

$$\textbf{NOx [kg/h]} = 0.000001467 \times (\text{Fuel [Standard } m^3/h])^2 + 0.0009896 \times (\text{Fuel [Standard } m^3/h]) \qquad (1)$$

With a curve fit R-Squared value of 0.944 (square root = 0.97) good correlation is apparent.

The dashed lines of Figure 3, labeled “Poly. +20%” and “Poly. -20%”, represent an error band of ±20% of the best fit curve and will be discussed further in the Measurement Uncertainty section.

Compared to the linear relationship of AP 42 (see Figure 3), it is apparent that a higher order curve is necessary to cover the operating range of the turbines of this data set to accurately represent their true NOx emissions.

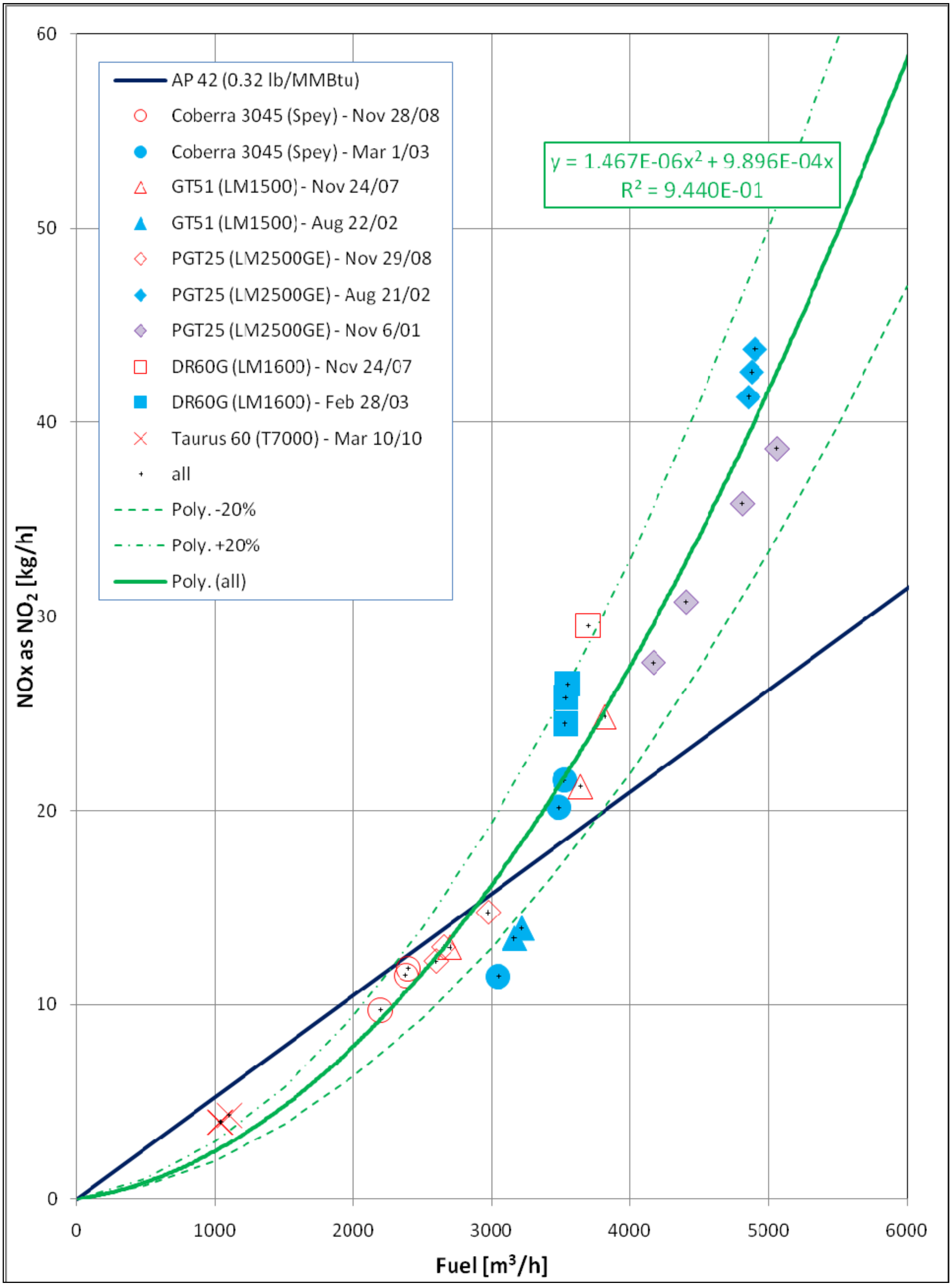

Figure 3: Data Set Compared to AP 42

4 Discussion

4.1 Measurement Uncertainty

As with any measured quantity, the accuracy or measurement uncertainty is important. The NOx concentration measurements and oxygen concentration measurements used to derive NOx mass flow rate values included in this paper are based on methods considered as reference methods. These are the measurement methods used to qualify various types of NOx emission quantification mechanisms (e.g.: relative accuracy testing). However, every physical or derived measurement has uncertainty.

Hung and Campbell's work [2] includes a detailed review of these uncertainties. For this application, or in the magnitude of these NOx levels, this is ±20% [2].

4.2 Comparison to OEM NOx

Many of the machines included in this stack test data set can be described as legacy equipment, designed and manufactured prior to the current knowledge of the environmental problems associated to NOx emissions. Thus, OEM design or expected NOx emissions are not available for these types of machines. Two more recent vintage machine types included in this data set (PGT25 with SAC LM2500GE, and DR60G with SAC LM1600) show a good agreement of brochure type NOx emissions at ISO rated conditions to the NOx emissions predicted by the curve fit of section 3.2.

4.3 Additional Potentially Influencing Parameters

This paper has considered a single parameter relationship between a gas turbine's fuel gas and its NOx emission. There are other parameters that could influence the NOx emissions. These include ambient temperature, ambient humidity, and ambient or barometric pressure. Prevailing ambient temperature is shown in Table 1. Related to the average barometric pressure, the site elevation is similarly shown in Table 1.

Within this data set, a correlation between these parameters is not apparent, or does not appear to be significant within the uncertainty range of the NOx measurements.

4.4 Time Resolution of Fuel Data

The purpose of this paper is not to detail variability of loading or the corresponding variability in fuel consumption. However, general discussion in this regard is considered here.

Hypothetical example using equation 1:

On an annual basis (8760 hours), say the machine operates at a fuel consumption rate between 3000 m^3/h and 5000 m^3/h, giving an average of 4000 m^3/h. At 4000 m^3/h, equation 1 gives 240 Tonne/year NOx. Hypothetically, consider that this same unit actually operated 50% of the time with a fuel rate of 3000 m^3/h and 50% of the time with a fuel rate 5000 m^3/h. With Equation 1, 253 Tonne/year NOx would be calculated (5% higher than assuming the average rate).

Experience with unit type NOx mass flow rate emission factors, with the equipment discussed in this paper, shows variation in the order of ±50%. Investigation into the actual operating range of this equipment, with respect to load and (or) fuel consumption from season to season, or in some cases, daily load swings, shows it to be in the order of ±100% of an average or median point.

Considering the non-linear nature, with respect to fuel of the NOx emissions presented herein, an appreciation is gained for potential errors introduced with the application of a single emission factor applied on an annual basis for emission inventory purposes. Typical natural gas pipeline operations maintain hourly accumulated fuel data. The highest time resolution of fuel data practical should be applied to equation 1, and these results accumulated for applications such as annual NOx inventories, as opposed to accumulating annual fuel and multiplying this value by a single emission factor.

5 Conclusion

NOx emissions of UnControlled gas turbines in natural gas pipeline compression service can be quantified as a function of measured natural gas fuel with a second order polynomial representative of many models of gas turbines.

6 Nomenclature

CEMS	Continuous Emissions Monitoring System.
DLE	Dry Low Emission. Lean premixed combustion system designed to minimize flame temperatures and the formation of thermal NOx.
Emission Factor	Numerical value used as a multiplier with an independent variable to arrive at a dependant variable or value.
EGT	Exhaust Gas Temperature. Turbine gas path temperature at the gas generator outlet and the power turbine inlet. Limiting this typically defines the maximum warm weather power.
NOx Emission Rate	Mass rate of NOx emissions (in units of kg/h) are given as equivalent to NO_2 (i.e.: no segregation of NO and NO_2; all NOx assumed to be NO_2).
OEM	Original Equipment Manufacturer.
Standard	Reference state condition for volumetric quantities of compressible fluids. In particular herein, natural gas fuel flow quantities in units of "Standard m^3/h" are at the Standard state condition of 15 °C temperature and 101.325 kPa pressure.
Turbo-Compressor	Gas Turbine driven centrifugal compressor package commonly used in natural gas pipeline compression service.
UnControlled	Gas Turbine combustion system without NOx formation control mechanisms (e.g.: DLE, water / steam injection, etc.). These uncontrolled systems allow for NOx formation at the prevailing diffusion type combustion process conditions.

References

[1] AP 42, Fifth Edition, Volume I Chapter 3: Stationary Internal Combustion Sources, Section 3.1, Final Section, Table 3.1-1, http://www.epa.gov/ttn/chief/ap42/ch03/index.html

[2] Hung, W., and Campbell, A., 1998, "Uncertainty in Gas Turbine NOx Emission Measurements", ASME Paper 98-GT-075.