# Evaluation of $NO_x$ Prediction-Correlation Equations for Small Gas Turbines

P.M. Rubins* and N.R. Marchionna†
*Avco Lycoming Division, Stratford, Conn.*

**There is strong pressure on both industry and government regulating agencies to reduce, control, and predict pollutants from gas turbine engines. Several available prediction-correlation methods for $NO_x$ were examined and tested with small gas turbine data. In addition, an alternate approach was used to develop a new $NO_x$ equation. No one equation could be found that was satisfactory for even a small group of engines, much less for all engines. It was possible, however, to find at least one $NO_x$ correlation equation for any specific engine that will predict $NO_x$ within 5-20% over the full range of engine operation. The significance of the study is that a more precise prediction method than a single equation will probably be required in order to adequately predict $NO_x$ over an entire engine cycle from one laboratory test condition. However, for small corrections which are used to transpose engine data to standard-day conditions, most of the equations studied are probably adequate.**

## Nomenclature

| | |
|---|---|
| $A$ | = combustor flow area |
| $f$ | = fuel-air ratio |
| $H$ | = humidity in lb $H_2O$/lb air |
| $K$ | = correlation equation adjustment coefficient |
| $K_f$ | = reaction rate coefficient, defined by Eq. (4) |
| [NO] | = brackets indicate concentration of gaseous component in mols/cc |
| (NO) | = parantheses indicate volumetric fraction of gaseous component |
| $P$ | = pressure in absolute units |
| $R_0$ | = universal gas constant |
| $T_B$ | = burner or combustor average exit temperature |
| $T_s$ | = peak adiabatic flame temperature (°R or K) for stoichiometric mixture, calculated |
| $T_3$ | = combustor inlet air temperature in absolute units, °R |
| $V$ | = velocity |
| $W_a$ | = air mass flow rate |
| $\alpha$ | = function of Zeldovich reaction $N + 0_2 \rightleftharpoons NO + O$ (Eq. 2) |
| $\gamma$ | = defined by Eq. (2) |
| $\phi$ | = equivalent ratio $= f/f_{\mathrm{stoichiometric}}$ |
| $\tau$ | = chemical reaction time for NO |
| *Subscript* | |
| $R$ | = *reference point* |

## Introduction and Background

BOTH government and the gas turbine industry are concerned with the measurement of gas turbine emissions, the setting of achievable low emission levels, and standardization of methods for determining when compliance has been met. This paper is a result of a study to apply existing and new equations for the prediction and correlation of $NO_x$. Data from small Avco Lycoming gas turbine engine combustors were used to evaluate the equations. Our objective was either 1) to find a universal $NO_x$ correlation equation, or 2) to demonstrate the accuracy of such existing prediction methods.

Attempts by several investigators to develop $NO_x$ prediction and correlation equations have been successful, at least in part, for some gas turbine engines. Lipfert[1] plotted $NO_x$ data from many aircraft gas turbine engines versus compressor air discharge temperature ($T_3$) and produced a good correlation. However, small Lycoming engines have different slopes and trends (Fig. 1). The difference between these Lycoming data and the general trend for the group of gas turbine data that were plotted from Lipfert is sufficient to cause large errors in extrapolating and predicting $NO_x$ emissions from Lycoming engines. This is particularly true when Federal EPA compliance error tolerance is small. In addition, single-shaft constant-speed engines operate at nearly constant compressor discharge temperature ($T_3$), and therefore have an entirely different $NO_x$ correlation.

Several investigators have examined more detailed $NO_x$ prediction and correlation approaches. A summary of $NO_x$ prediction-correlation methods is given by Sullivan,[2] and is followed by an equation proposed by Sullivan.[3] Other $NO_x$ prediction equations have been proposed by Marchionna et al.[4] Davis et al.,[5] Vermes,[6] Sarli et al.,[7] Cohen,[8] Kretschmer and Odgers,[9] Touchston and Dibelius,[10,11] and others. Shaw's analysis of the kinetics of NO (or $NO_x$) formation[12]

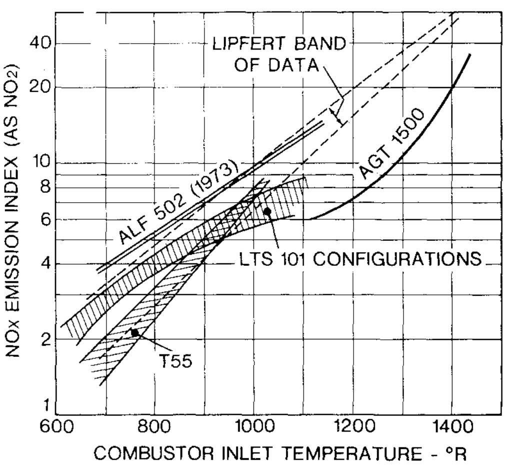


**Fig. 1 $NO_x$ emission index of Avco Lycoming small gas turbines vs Lipfert group of data, humidity = 0.**

Presented as Paper 76-612 at the AIAA/SAE 12th Propulsion Conference, Palo Alto, Calif., July 26-29, 1976; submitted Sept. 27, 1976; revision received March 13, 1978. 

Index categories: Airbreathing Propulsion; Combustion and Combustor Designs; Environmental Effects.

*Supervisor, Combustion Research and Support. Associate Fellow AIAA.

†Senior Development Engineer.

has been widely used by many investigators. These investigators proposed equations which evaluated several of the known combustor $NO_x$ producing factors, and compared or adjusted these factors to experimental data. A tabulation of the factors in these equations is shown in Table 1. Others have developed more complex modeling methods for $NO_x$ prediction. One of these, of moderate complexity, was developed by Hung,[13,14] and shown to be applicable to the limited group of engines which he used to test the method.

Table 1 shows that pressure, air and gas temperature, residence time, and air mass flow parametric effects differ as evaluated by individual investigations. One may conclude that selecting correlating parameters is not a simple matter. The reason that precise prediction of $NO_x$ is complex can be appreciated by examining the processes in the combustor regions (Fig.2). The primary zone is conceded to be the hottest region of the combustor and the principal place where NO is formed.

In the present investigation, we examine some of the more promising $NO_x$ prediction-correlation equations, develop an alternate equation, and evaluate these equations for use with Avco Lycoming small gas turbines. Five equations were selected as typical of those available. Three different types of Lycoming combustors were used in the analysis. With one engine, three fuels were evaluated.

### Development of an Alternate $NO_x$ Equation

In the process of $NO_x$ equation evaluation, the authors investigated a somewhat different $NO_x$ prediction approach based on physical chemistry with simplifying assumptions. The assumptions for this model are reduced to:

1) The controlling NO formation reaction is the Zeldovich reaction:

$$O + N_2 \rightleftharpoons NO + N \tag{1}$$

Marteney[15] made the additional simplifying assumptions that the NO and N concentrations are zero intially, and arrived at the equation

$$[NO]_\tau = 2\gamma\tau - (\gamma/\alpha)(1 - e^{-\alpha\tau}) \tag{2}$$

where $\gamma$ is a function of the Zeldovich reaction [Eq. (1)] and $\alpha$ for the Zeldovich reaction ($N + O_2 \rightleftharpoons NO + O$). He shows that Eq. (1) is dominant for conditions typically found in gas turbine combustors, and that for longer combustor residence times where $\alpha\tau > 3$, Eq. (2) reduces to:

$$[NO]_\tau \cong 2\gamma\tau \tag{3}$$

where $\gamma = K_f[N_2][O]$ and $K_f$ is the rate coefficient (Ref. 15):

$$K_f = (7.0 \times 10^{13})\exp(-38{,}000/T_s) \tag{4}$$

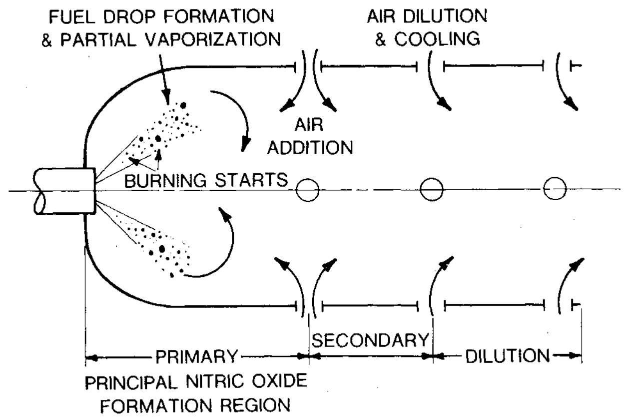


**Fig. 2 Combustor schematic showing nitric oxide formation zone.**

2) The oxygen radical concentration rises rapidly and reaches a partial equilibrium state, while the NO rises slowly. The O-radical can thus be considered to be at temporary equilibrium, and its concentration can be determined from equilibrium tables for conditions present in the combustor primary zone.

3) Pressure affects the kinetics as calculated by Marteney (Ref. 15), where

$$(NO)_{equil} \propto P^{-0.21} \tag{5}$$

4) The peak NO formation rate occurs at stoichiometric fuel-air ratio ($\phi = 1$).[16] The NO rate drop-off either side of stoichiometric is rapid. We can assume that all of the NO is formed in the stoichiometric mixture burning regions, as proposed by Kretschmer and Odgers.[9]

5) Combustor residence time, effective in producing NO, is based on the assumption that the NO formed in the primary zone at peak gas temperature is suddenly quenched, or its rate drastically reduced, at the first large airjet mixing station of the combustor. The gas residence time at NO-producing temperature is thus.

$$\tau \propto 1/V \propto P/T\, W_a \tag{6}$$

where $T$ is the combustion gas temperature.

The combustor overall fuel-air ratio is introduced as a dilution factor only. From the assumption that all of the NO is formed at $\phi = 1$, the reacting gases are cooled and diluted to the reduced overall combustor exit fuel-air ratio as they progress through the combustor, so that:

$$(NO)_{exhaust} \propto f(\text{combustor average}) \tag{7}$$

In the process of developing the final equation, the fuel-air dilution effect cancels the fuel-air ratio effect determined from the NO residence time.

**Table 1 Comparison of equation factors affecting $NO_x$ production**

| Reference | Pressure | Temperature | Time | Fuel-Air | Mass | Other |
|---|---|---|---|---|---|---|
| Shaw | $P^{0.5}$ | $\exp(1/T_B)$ | $\tau$ | | | $(NO)_{eq.}$ |
| Marchionna et al. | $P^{1.5}$ | $T_3^{-.5}\exp T_3$ | | $f$ | $W_a^{-1}$ | |
| Davis et al. | $P^{0.29}$ | $\exp T_3$ | | $f^{1.48}$ | $W_a^{-0.1}$ | |
| Vermes | $P^{1.5}$ | $\exp\Delta T_3$ | $\tau^a$ | $f - f_0$ | $W_a^{-1}$ | |
| Sarli et al. | $P^{0.5}$ | $\exp T_3$ | | $f$ | | |
| Cohen | $P$ | $T_3^{6.25}$ | | $(1+f)^{-1}$ | $W_a^{-1}$ | |
| Lipfert (approx.) | $P^{0.5}$ | $\exp T_3$ | | $f$ | | |
| Kretschmer, Odgers | | $T_3, \Delta T_{\phi=1}$ | | | | |
| Touchston, Dibelius | $P^{0.5}$ | $\exp(\Delta T_3 + 1/\Delta T_3)$ | $\tau$ | $f, \exp(\Delta f)$ | | |
| Sullivan | $P^{0.5}$ | $\exp\Delta T_3$ | | $f^{1.4}$ | $W_a^{-0.22}$ | |
| Present work | $P^{0.79}$ | $\exp(-1/T_S), T_S^{-1}$ | $\tau$ | $f/f_{stoich.}$ | | $(O)_{eq.}$ |

[a] $\tau \sim P/W_a$, $f_0$ = fuel/air at ($NO_x = 0$).

6) Air humidity effect has been empirically evaluated and was obtained from Ref. 4:

$$(NO)_1/(NO)_2 = \exp[19(H_2 - H_1)] \quad (8)$$

7) The dominant nitrogen gas produced from kinetic rate equations is NO. Some $NO_2$ formation can be predicted, but is usually a small amount. We assume that the total $NO_x$ product ($NO + NO_2$) is proportional to the NO formed, so that:

$$(NO_x)_1/(NO_x)_2 = (NO)_1/(NO)_2 \quad (9)$$

By combining these effects and converting mols/cc to volume fraction via the gas law, where

$$[N_2] = P(N_2)/R_0 T_s$$

$$[O] = P(O)/R_0 T_s$$

where $P$ ($N_2$) and $P$ (O) are partial pressure of $N_2$ and O-radical respectively, we obtain

$$(NO_x)/(NO_x)_R = \{\exp[3.8\times 10^4 (1/T_{sR} - 1/T_s)]\}$$
$$\times [(P/P_R)^{1.79}((O)/(O)_R)$$
$$\times (W_{aR}/W_a)(T_{sR}/T_s)]\exp[19(H_R - H)] \quad (10)$$

The peak gas stoichiometric temperature, $T_s$, is also calculated from Refs. 17 or 18 and is used to select values of O.

## Other Equations Used in the Evaluations

The additional equations selected for further examination were regarded as typical, based on theory or on reasonable empiricism. The reader should refer to the individual papers for a detailed discussion of equation development. Our purpose was to evaluate the precision of the selected group as applied to Lycoming's small gas turbine combustors.

### Sarli, Eiler, and Marshall Equation[7]

This equation was also developed using the Zeldovich NO formation reaction [Eq. (1)] as suggested by Marteney. Residence time was not regarded as an important factor, and the resultant equation, including water vapor effect, is

$$(NO_x)/(NO_x)_R = (P/P_R)^{0.5}\exp[0.00313(T - T_R)]$$
$$\times \exp[19(H_R - H)][(1 + 1/f_R)/(1 + 1/f)] = A \quad (11)$$

Variations on the Sarli equation included adding a combustor residence time factor, $\tau$, where

$$\tau/\tau_R = \sqrt{T_{BR}/T_B} \quad (12)$$

and

$$(NO)_x/(NO_x)_R = A\sqrt{T_{BR}/T_B} \quad (13)$$

The time-variation factor suggested by Touchton and Dibelius [Eq. (17)] was also tried, where

$$(NO_x)/(NO_x)_R = A(P/P_R)(f_R/f)(W_{aR}/W_a) \quad (14)$$

### Sullivan Equation[3]

Sullivan's equation is based on experimental evaluation of the exponents of pressure, fuel-air ratio, and mass flow:

$$NO_x/NO_{xR} = (P/P_R)^{0.5}(f/f_R)^{1.4}(W_{aR}/W_a)^{0.22}$$
$$\times \exp([T - T_R]/396)\exp[19(H_R - H)] \quad (15)$$

where $T$ is inlet air temperature in °R. From Ref. 3, we note that this equation predicts $NO_x$ well for some large constant speed industrial gas turbine engines, and not so well for others, such as the variable speed JT-9D.

### Touchston and Dibelius[10,11]

The model assumptions proposed by Shaw[12] were used to develop an equation based on chemical kinetics (plug flow) and a constant residence time, using the Zeldovich reactions for NO formation. Curve-fitting constants were used to write the final equation in terms of $P, f, T,$ and $H$:

$$NO_x/NO_{xR} = (f/f_R)(P/P_R)^{0.5}\exp([T_3 - T_{3R}]/380)$$
$$\times \exp[39{,}300(f/T_3 - f_R/T_{3R})]\exp[19(H_R - H)] \quad (16)$$

A modification of this equation is obtained by including combustor residence time as a function of combustor mass flow:

$$(NO_x)/(NO_x)_R = (W_{aR}/W_a)(P/P_R)^{1.5}\exp([T - T_R]/380)$$
$$\times \exp[39{,}000(f/T - [f/T]_R)]\exp[19(H_R - H)] \quad (17)$$

The factor 39,000 is considered a "configuration" factor, and was so used in Ref. 11. By modifying this factor $D$, configuration effects can be included.

### Marchionna et al.[4]

This equation was based on experimental data taken at constant combustor inlet Mach number, constant exhaust gas temperature, and variable inlet temperature, using a 40 in. diameter Pratt and Whitney research combustor. A limited amount of experimental data was taken to verify the assumed variation of $NO_x$ with pressure to the 0.5 power and inlet Mach number to the $-1$ power.

$$(NO_x)/(NO_x)_R = \exp[1.14([T_3 - T_{3R}]/520)]$$
$$\times W_{aR}/W_a)(P/P_R)^{1.5}(T_{3R}/T_3)0.5$$
$$\times (f/f_R)([1 + f_R]/[1 + f])\exp[19(H_R - H)] \quad (18)$$

where $T_3$ is in °R.

## Configuration Adjustment Factor

From our analysis thus far, it becomes obvious that none of the equations examined will predict a priori the $NO_x$ concentration for the full range of engine combustor operation. By calculating the ratio $NO_x/NO_{xR}$, in which $NO_{xR}$ is an

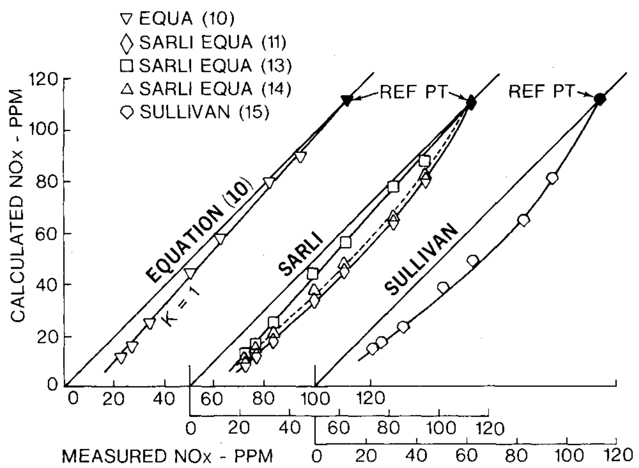


**Fig. 3 LTP 101 correlation of measured vs calculated $NO_x$ (JP-5 fuel, humidity = 0).**

experimentally determined point, we can determine the $NO_x$ at other conditions, providing that the extrapolation is within an established error limit. An extrapolation using a $NO_R$ point is shown in Fig. 3. If $NO_R$ is selected at the high-power end of operation, extrapolation to the low-power end produces some error. However, we can see that if the extrapolation is short, a small correction factor can be added to the equation that will produce very close correlation of $NO_x$ values. The difference between measured results and calculated results can be attributed to a "configuration" factor. This is handled by the Touchston-Dibelius equation with a variable $D$ factor. The method chosen by the present authors was to select *two* $NO_{xR}$ values at opposite ends of the power spectrum, and to examine the data for deviation from linear interpolations.

The $NO_x$ values can then be calculated from the equation

$$(NO_x)_{\text{corr.}} = [(NO_x)_R/K]\,[K-1+(NO_x)/(NO_x)_R] \quad (19)$$

where $K$ is a slope term determined from two measured and two calculated values of $NO_x$.

## Experimental Data

The NO (or $NO_x$) correlation-prediction equations were applied to data from three Avco Lycoming engines with combustors of different design, and for different engine cycle operating conditions. These engines are all two-shaft, free-power turbine designs. The combustor configurations were from these engines.

1) The LTP 101 is a small gas turbine in the 600 shp range, using an annular combustor with several large turbulence-generating wall jets, producing a unique aerodynamic pattern.

2) The ALF 502 is a high-bypass-ratio turbofan engine, with the combustor operating at inlet pressures up to 12 atm. The combustor is also annular, but more conventional in design.

3) The AGT 1500 engine is a 14.5:1 pressure ratio recuperative engine with combustor inlet temperature over 1000°F. The combustor is can-type.

Data were obtained for both engine and combustor laboratory tests. $NO_x$ data were taken with sampling systems using a chemiluminescence detector for NO and $NO_x$, following the procedures recommended by the EPA in CFR 40, Part 87.

## Discussion of Results

The equations were evaluated by comparing measured $NO_x$ with calculated $NO_x$ from one of the correlation equations. In some cases, a reference value was selected at a high $NO_x$ value. In others, a reference at high $NO_x$ and a second reference at a low $NO_x$ value were selected and the coefficient $K$ was used in making this adjustment. "Good" correlation was defined by 1) a 5-10% deviation from the 1:1 correlation line with a single point reference, or 2) 5-10% of nonlinearity when two reference points were used.

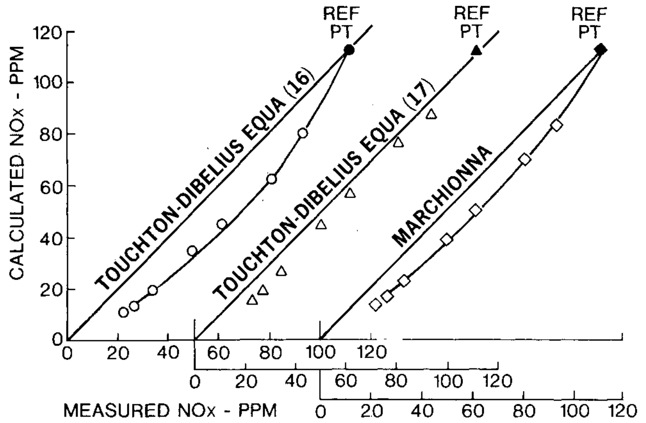


**Fig. 4 LTP 101 correlation of measured vs calculated $NO_x$ (JP-5 fuel, humidity = 0).**

### LTP 101 Results

The plotted correlations for this engine are shown in Figs. 3 and 4 for the five equations evaluated. Of these, Eq. (10) produces precision within 5% after the correction factor was applied. The Sarli et al equation (13), with a residence time modification, also produced a straight-line correlation. With application of the $K$ factor, 5% accuracy could be reached.

Several of the equations, including the Sullivan equation (15), produce correlations that deviate by a nonlinear function. A correction factor addition in this situation is not simple. The Touchston-Dibelius correlation, Eq. (16), produces poor correlation, but after introducing the time function, correlation was improved. Still further improvements were realized by changing the $D$ configuration factor

The results are summarized in Table 2. We conclude that Eqs. (10), (14), and (17) all produce correlations for the LTS 101 with potential accuracy over the full engine operating range of 5%.

### ALF 502 Results

The correlations for this engine are summarized in Table 3. As shown, relatively poor correlations are produced by *all* of the equations. The most promising is the Marchionna equation, which can be fitted to the data by using the linear correction, Eq. (19), with an accuracy potential of 5%. Application of the Marchionna equation to the ALF 502 is shown in Figs. 5 and 6, both with and without the linear correction applied

### AGT 1500 Results

This engine was tested with JP-4, JP-5, and DF-2 fuel. The $NO_x$ data are similar for all three fuels. This is not surprising, considering the high combustor inlet air temperature from the recuperator.

**Table 2 LTP 101 $NO_x$ correlation equation evaluation**

| Equation | Time factor, $\tau$ | Full operating range prediction accuracy: No correction factor | With correction factor |
|---|---|---|---|
| Present work (10) | Function of mass flow | 40% | 5% |
| Sarli et al. (11) | None | 50% | |
| Sarli et al. (13) | Function of mass flow | 40% | |
| Sarli et al. (14) | Function of $\sqrt{1/T_4}$ | 40% | 5% |
| Sullivan (15) | None | 35% | |
| Touchston-Dibelius (16) | Function of mass flow | 45% | |
| Touchston-Dibelius (17) | Do | 30% ($D$ constant) | 5% |
| Touchston-Dibelius (17) | Do | 30% ($D$ variable) | |
| Marchionna et al. (18) | Function of $M^{-1}$ | 40% | |

**Table 3 ALF 502 NO$_x$ correlation equation evaluation**

| Equation | Full operating range prediction accuracy: No corr. factor | Full operating range prediction accuracy: With corr. factor |
|---|---|---|
| Present work (10) | ±20% | |
| Sarli et al. (11) | 50% | |
| Sarli et al. (13) | 30% | |
| Sarli et al. (14) | ±20% | |
| Sullivan (15) | 30% | |
| Touchston-Dibelius (16) | 45% | |
| Touchston-Dibelius (17) | +15% −20% | |
| Touchston-Dibelius (17) | +7% −20% $D$=30,000 and 40,000 | |
| Marchionna et al. (18) | −25% | 5% |

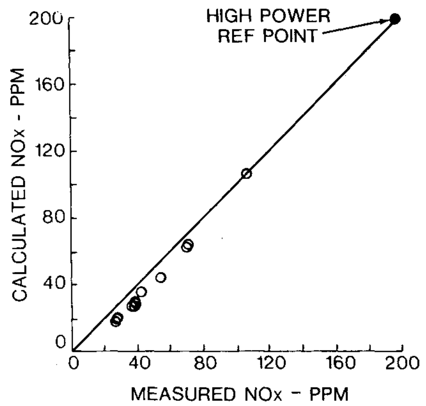


**Fig. 5 ALF 502 engine NO$_x$, Marchionna equation without slope correction factor (JP-5 fuel, humidity = 0).**

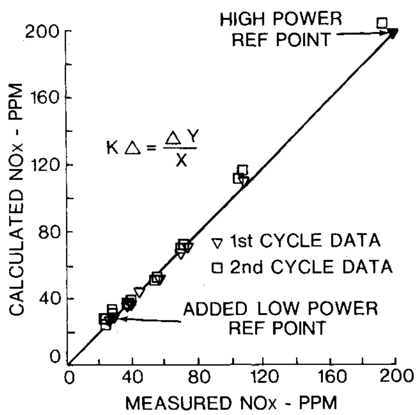


**Fig. 6 ALF 502 engine NO$_x$, Marchionna equation with slope correction factor ($K$) applied (JP-5 fuel, humidity = 0).**

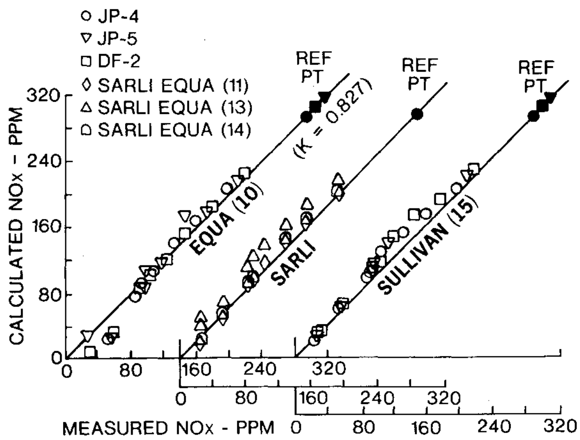


**Fig. 7 AGT 1500 engine NO$_x$ correlations (JP-4, JP-5, DF-2 fuel, humidity = 0).**

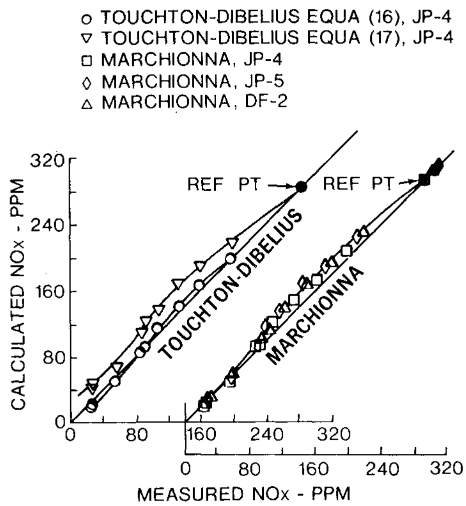


**Fig. 8 NO$_x$ correlation for AGT 1500 (JP-4, JP-5, DF-2 fuel, humidity = 0).**

**Table 4 AGT 1500 NO$_x$ correlation equation evaluation**

| Equation | Full operating range prediction accuracy |
|---|---|
| Present work (10) | +15% or more, nonlinear |
| Sarli et al. (11) | +5%, −20% |
| Sarli et al. (13) | ± 10% |
| Sarli et al. (14) | +50%, nonlinear |
| Sullivan (15) | +20%, nonlinear |
| Touchston-Dibelius (16) | +7%, −15% |
| Touchston-Dibelius (17) | +30% |
| Touchston-Dibelius (17) | ± 10% with $D$ factor |
| Marchionna et al. (18) | +15%, nonlinear |

From Figs. 7 and 8 and the summary in Table 4, we find that the best correlation is obtained from the Sarli et al. equation *without* a combustor residence time correction, which is contradictory with the precision of this equation applied to the LTP 101. Other reasonable correlations are obtained with the Touchston-Dibelius equation *without* the residence time factor. Improvement with the Touchston-Dibelius equation could be obtained by changing the configuration coefficient. Equation 10 (present work) can be adjusted to produce good correlation, only at the high-power end of the plot.

#### Comparison with Other Engines

Equation 10 was used for correlations by the authors of Ref. 10 with General Electric MS 7001C (simple cycle) and a 7001B (regenerative cycle) engine. These are constant-speed industrial-type engines. This correlation indicates that Eq. (10) may have application to large constant-speed engines. Further work is required to establish constant-speed engine use for Eq. 10.

## Summary and Conclusions

Many attempts have been made to arrive at and evaluate equations for predicting and correlating gas turbine NO$_x$ data. The authors have evaluated some of these as applied to Avco Lycoming small gas turbine data. A newly developed additional equation has also been evaluated. The accuracy demanded of these equations is high because of 1) demands of regulating agencies for reduced emissions and a "universal" correlation method and 2) the desire of engine manufacturers to be able to make precise predictions of emissions.

The analysis of these equations clearly shows that none of the single-equation prediction-correlations are universally applicable to wide operating range predictions for all combustors and engine cycles. Most of the equations are satisfactory when used for small corrections normally required in adjusting emissions data to standard-day conditions. It also shows that, by cut-and-try, one or more equations can be found that can be applied to a specific engine and combustor and produce "good" correlation capability—to within 5-10% of the measured value.

## References

[1]Lipfert, F.W., "Correlations of Gas Turbine Emissions Data," ASME Paper 72-GT-60, 1972.

[2]Sullivan, D.A. and Mas, P.A., "A Critical Review of $NO_x$ Correlations for Gas Turbine Combustors," ASME Paper 75-WA/GT-7, Dec. 1975.

[3]Sullivan, D.A., "A Simple Gas Turbine Combustor $NO_x$ Correlation Including the Effect of Vitiated Air," ASME Paper 76-GT-5, March 1976.

[4]Marchionna, N.R., Diehl, L.A., and Trout, A.M., "Effect of Inlet Air Humidity, Temperature, Pressure and Reference Mach Number on the Formation of Oxides of Nitrogen in a Gas Turbine Combustor," NASA TN D-7396, Oct. 1973.

[5]Davis, L.B., Murad, R.J., and Wilhelm, C.F., "Emission and Control of $NO_x$ in industrial Gas Turbine Combustors: Experimental Results," presented at the 66th Annual AIChE Meeting, Nov. 1973.

[6]Vermes, G., "A $NO_x$ Correlation Method for Gas Turbine Combustors Based on $NO_x$ Formation Assumptions," ASME Paper No. 74-WA/GT-10, Nov. 1974.

[7]Sarli, V.J., Eiler, D.C., and Marshall, R.L., "Effects of Operating Variables on Gaseous Emissions," Air Pollution Control Association Conference Paper, Oct. 1975.

[8]Cohen, J.D., "$NO_x$ Emissions at High Power Settings/Engine Data Correlation," The General Electric Company, TM 74AEG, Nov. 1974, p. 448.

[9]Kretschmer, D. and Odgers, J., "Modelling of Combustors: The Effects of Ambient Conditions Upon Performance," ASME Paper 73-WA/GT-6, Nov. 1973.

[10]Touchston, G.L. and Dibelius, N.R., "A Correlation of Nitrogen Oxides Emissions with Gas Turbine Operating Parameters," ASME Paper 76-GT-14, March 1976.

[11]Touchston, G.L. and Dibelius, N.R., "A Correlation of Nitrogen Oxides Emissions with Gas Turbine Operating Parameters Considering Variable Combustion Residence Time," APCA Northeast Section Conference, Hartford, April 1976 (Proceedings to be published).

[12]Shaw, H., "The Effects of Water, Pressure, and Equivalence Ratio on Nitric Oxide Production in Gas Turbines," ASME Paper 73-WA/GT-1, Nov. 1973.

[13]Hung, W.S.Y., "An Experimentally Verified $NO_x$ Emission Model for Gas Turbine Combustors," ASME Paper 75-GT-71, March 1975.

[14]Hung, W.S.Y., "A Diffusion Limited Model that Accurately Predicts the $NO_x$ Emissions from Gas Turbine Combustors Including the Use of Nitrogen Containing Fuels," ASME Paper 75-Pwr-11, Oct. 1975.

[15]Marteney, P.J., "Analytical Study of the Kinetics of Formation of Nitrogen Oxide in Hydrocarbon-Air Combustion," *Combustion Science and Technology* Vol. 1, June 1970, pp. 461-469.

[16]Heywood, J.B., Fay, J.A., and Linden, L., "Jet Aircraft Pollutant Production and Dispersion," *AIAA Journal,* Vol. 9, May 1971, pp. 841-850.

[17]Powell, H.N., Shaffer, A., and Suciu, S.N., *Properties of Combustion Gases; System: $C_n$ $H_{2n}$ - Air,* General Electric Company, 1955.

[18]Gordon, S. and McBride, B.J., "Computer Program for Calculation of Complex Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman - Jouguet Detonations," NASA SP-273, 1971.