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THE FORMATION OF NITRIC OXIDE IN DISTILLATE OIL FLAMES - PREDICTION AND MEASUREMENT

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THE FORMATION OF NITRIC OXIDE IN DISTILLATE OIL FLAMES - PREDICTION AND MEASUREMENT

by

T. D. Brown* and F. D. Friedrich*

ABSTRACT

A simple mathematical model of nitric oxide formation from both atmospheric and fuel nitrogen shows that NO formation reaches a peak as excess air is increased from stoichiometric to about 6%, then declines as excess air is increased further.

This does not agree with measured data from large combustion systems, which show that NO formation increases monotonously with increasing excess air.

Data obtained from a pilot-scale furnace operated at various aerodynamic conditions with three distillate oils confirm the trend of the model's predictions, and indicate that the discrepancies with data from large systems are due to differences in intimacy of fuel-air mixing.

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INTRODUCTION

Nitrogen oxides from the combustion of fuels have long been recognized as an important source of air pollution. However, only in the past few years has much effort been directed to identifying the sources and exploring means for reducing the emissions.

It has been established(1) that, of the total nitric oxide (NO) resulting from the combustion of fuel in Canada, more than half comes from the trasnportation fuels; gasoline and diesel oil. Nearly all the remainder comes from large stationary combustion systems such as heating plants, industrial steam plants, and thermal power stations. Domestic fuels contribute a relatively small proportion.

The formation and control of NO in large stationary combustion systems offers considerable potential for useful results from pilot-scale studies and falls within the field of activity of the Canadian Combustion Research Laboratory (CCRL) where the research described in this paper was conducted.

As part of a research program investigating the formation of oxides of nitrogen in combustion systems a mathematical model of the formation of nitric oxide in a simple temperature-time profile reactor was studied. The object of the study was to determine the effect of simple combustion variables on the yield of nitric oxide in order that an experimental program could be more closely defined. The experimental program itself was intended to define the range of validity of the model within a framework of practical burner geometries.

FORMULATION OF THE KINETIC MODEL

A number of mathematical models of varying complexity(2)(3) have been put forward to predict the quantities of nitrogen oxide formed in combustion systems. As a precursor to the experimental investigation described hereafter a kinetic model of the formation of nitric oxide was studied with the objective of defining potential effects of primary combustion variables i.e. excess air level, that could subsequently be incorporated in the experimental program. The model considered a perfectly mixed plug flow reactor with the temperature-time history profile illustrated in Figure 1 and a mechanism based on the Zeldovich mechanism(4) but incorporating additional terms to assess the importance of the fuel nitrogen. The rate expression (Equation 1) used activation energies and rate constants derived from the study of Bartok(5) for the reactions of atmospheric nitrogen; the values used in the fuel nitrogen oxidation reactions were based on the studies of de Soete(6). To establish the conversion of fuel nitrogen to nitric oxide it was necessary to postulate both a reaction of fuel nitrogen which produced nitric oxide and a reaction which produced molecular nitrogen.

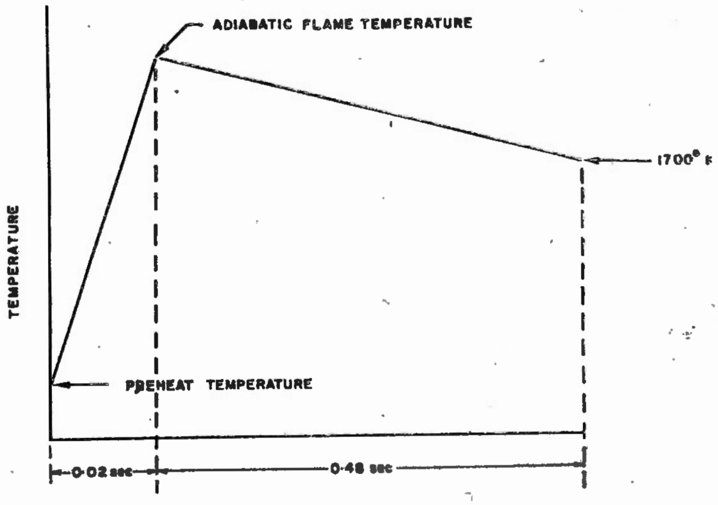

Figure 1. The temperature-time profile assumed in the kinetic model.

The reaction sequences that were studied can be summarized:

Atmospheric Nitrogen	$N_2 \rightarrow N + N$ $O_2 \rightarrow O + O$ $N + O_2 \rightarrow NO + N$ $O + N_2 \rightarrow NO + O$
Fuel Nitrogen	$N_f + O \rightarrow NO$ $N_f + N \rightarrow N_2$

The rate expressions that were used within the framework of the temperature time profile were:

(a) For the rate of nitric oxide formation:

$$\frac{d(NO)}{dt} = 1 \times 10^{8}\, e^{\frac{-10{,}000}{RT}} \left[N_f\right]\left[O_2\right] + 3\cdot 85 \times 10^{5}\, e^{\frac{-136{,}360}{RT}} \left[N_2\right]\left[O_2\right]^{\frac{1}{2}} - 6\cdot 96 \times 10^{2}\, e^{\frac{-92{,}256}{RT}} \left[NO\right]^{2} \left[O_2\right]^{-\frac{1}{2}} \quad \text{------ 1}$$

(b) For the rate of fuel nitrogen depletion:

$$\frac{d(N_f)}{dt} = 1 \times 10^{8}\, e^{\frac{-10{,}000}{RT}} \left[\left[N_f\right]\left[O_2\right] + \left[N_f\right]\right] \quad \text{------ 2}$$

In both rate expressions the term N_f represents the fuel nitrogen expressed as a partial pressure.

APPLICATION OF THE KINETIC MODEL

The fuel considered in the calculation of the adiabatic flame temperature (AFT) was No. 2 heating oil. The rate expressions were integrated between two sets of limits, the first between 0 and 0.02 seconds (at which time the AFT was reached) and the second between 0.02 seconds and 0.5 seconds (by which time the gases had cooled to 1700°K).

The model was used to examine the effects of excess-air level, fuel nitrogen content, and flame temperature on the yield of nitric oxide from the system.

The Effect of Excess Air Level

Figure 2 shows the yield of nitric oxide as a function of excess air level as predicted by the model for a nitrogen-free fuel. The curve shown is for a system using combustion air preheated to 200° C; other results from the model indicate that preheat temperature has only a modest influence on the total yield of nitric oxide. The dominant feature of the curve is the pronounced peak in nitric oxide yield which occurs at about 6% excess air. Presumably at lower levels of excess air, nitric oxide formation is inhibited by lack of oxygen even though the adiabatic flame temperature increases. At higher levels of excess air, nitric oxide yields are reduced due to the lower levels of flame temperature.

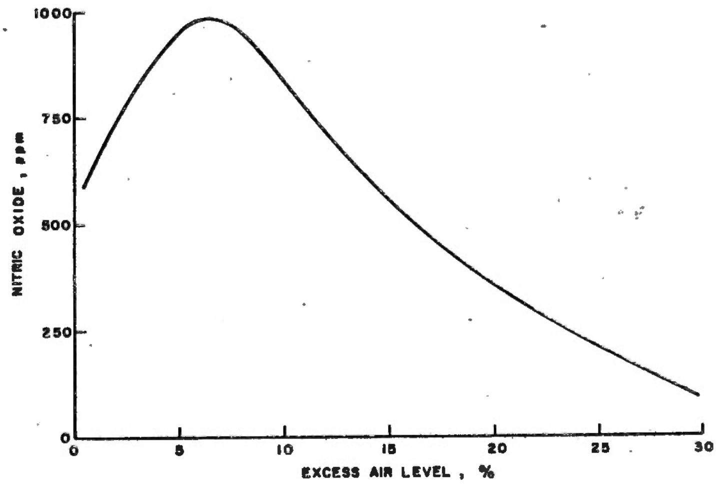

Figure 2. The effect of excess air on NO concentration for a nitrogen-free fuel, as predicted by the kinetic model. Air preheat temperature = 200°C.

The Effect of Fuel Nitrogen

Figure 3 shows the yield of nitric oxide as a function of excess air level as predicted by the model for fuels of differing nitrogen content. The curves are closely similar in shape and retain the dominant feature of a maximum nitric oxide yield at approximately 6% excess air. The increase in nitric oxide yield appears to bear a linear relationship with fuel nitrogen content and increases further with increasing excess air level.

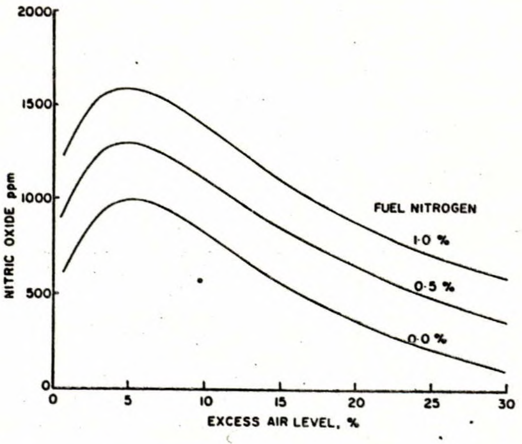

Figure 3. The effect of excess air on NO concentration for fuels of different nitrogen content, as predicted by the kinetic model. Air preheat temperature = 200°C.

The Effect of Peak Temperature

Figure 4 shows the effect of adiabatic flame temperature on nitric oxide formation as predicted by the model. It is clear that virtually no air-source nitric oxide is produced if the flame temperatures are kept below 1900 K. This conclusion leads directly to the practical expedient for control of nitric oxide formation whereby inert combustion products are mixed with combustion air prior to combustion;i.e., external flue gas recirculation. The resultant flame temperatures are low and nitric oxide formation is reduced. Figure 4 also shows that temperature has a negligible effect on the nitric oxide produced from the fuel nitrogen (as would be expected from the magnitude of the activation energy of the nitric-oxide-producing reaction) and that flue gas recirculation will therefore be most effective as a nitric oxide control measure with low-nitrogen fuels.

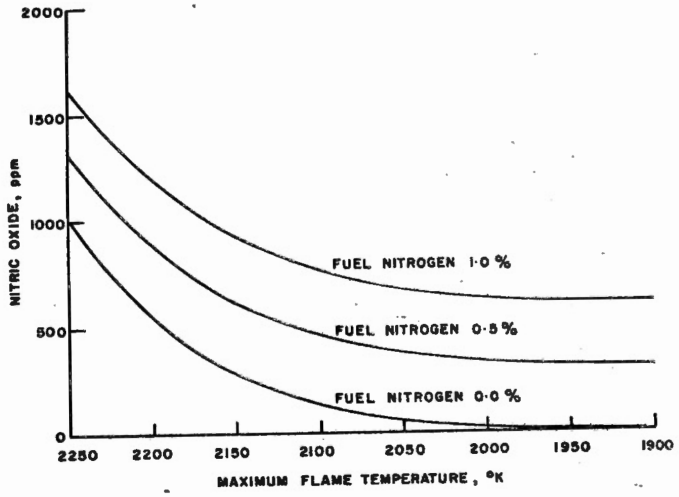

Figure 4. The effect of flame temperature on NO concentration for fuels of different nitrogen content, as predicted by the kinetic model. Air preheat temperature = 200°C. Excess air level = 6%

MEASURED LEVELS OF NITROGEN OXIDES FROM PILOT SCALE EXPERIMENTS

Using a pilot-scale system burning nitrogen-free distillate oil in a refractory combustion chamber, Wasser and Berkau(7) studied the effects of combustion air swirl, firing rate, and excess air on NO formation. By means of a tracer technique which determines residence time, the authors were able to relate NO concentration to combustion intensity. For a given fuel input, increasing excess air from 25% to 45% reduced NO formation substantially, but not as much as the authors had expected from considering the effect on adiabatic flame temperature. They concluded, significantly, that the local air-fuel ratio in the vicinity of burning droplets is critical in the formation of NO, and can be far different from the overall value.

Halstead, Watson and Munro(8) demonstrated in a 130 kWh natural gas fired system that a maximum occurred in the nitric oxide concentration at an excess air level of 5% and that this maximum persisted at mass recirculation ratios up to 20% and water injection ratios up to 10% by weight.

MEASURED LEVELS OF NITROGEN OXIDES FROM LARGE COMBUSTION SYSTEMS

A comprehensive study of the NO_x emissions from a series of utility boilers fired with various fuels showed that the effects of excess air level could be summarized as shown in Figure 5. In this instance the results have been normalized with respect to the NO_x emission at 3% oxygen (15% excess air). Results obtained by Winship and Brodeur(9) on a tangentially fired boiler using a Canadian lignite closely follow the same pattern (Figure 6). Several other researchers(10) support the conclusion that in field installations, the nitric oxide emissions decrease monotonously with decreasing excess air level.

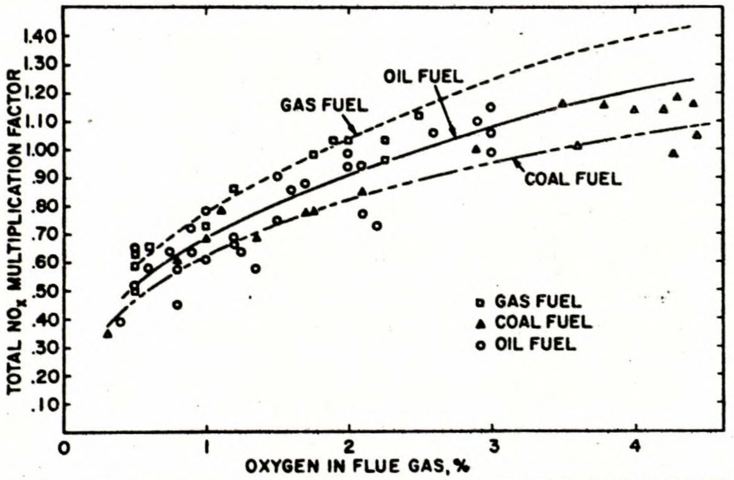

Figure 5. The effect of excess-air level on nitric oxide emissions from various fuels (after Rawdon and Johnson).

The bulk of the technical literature describing field experiments to control nitric oxide emissions can be summarized in the common conclusions:

(1) Nitric oxide increases with increasing excess air.

(2) Nitric oxide increases with fuel source nitrogen.

(3) Nitric oxide can be reduced by flue gas recirculation, by water injection or by two-stage firing.

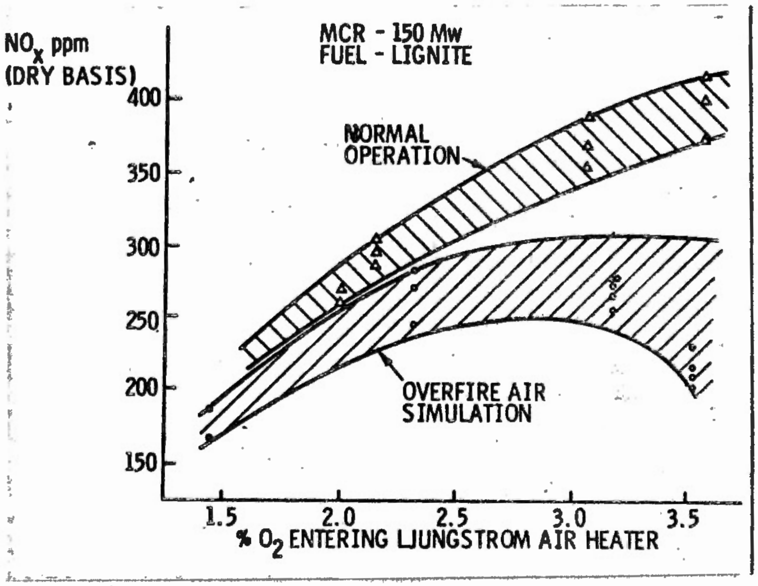

Figure 6. The effect of excess air level on nitric oxide emissions in a tangential-fired lignite-burning boiler. (After Winship and Brodeur.)

The second and third of these conclusions are in agreement with the predictions of the simple model; the first conclusion however does not substantiate the conclusions derived from the model. This conflict between the predictions of the model and field experience is also further complicated by the fact that pilot scale experiments$^{(7)(8)}$ do substantiate the predictions of the model. It is apparent therefore that the model, whilst offering some guide to field experience, does not explain the effect of the simplest combustion variable. The agreement of the model results with pilot scale experiments indicates that the discrepancy between the model and field practice is due to a factor which has been introduced as a consequence of either design changes or scale (or a combination of both).

ANY PROPOSED REVISIONS ON THE

THE LABORATORY RESEARCH PROGRAM

The discrepancy between predictions from theory and measured values can possibly be explained in terms of fuel-air mixing intensity.

Theoretical considerations show that excess air, flame temperature and cooling rate have strong, often opposite, effects, but it appears probable that temperature is the dominant factor, and the others play a part mainly through their influence on temperature. However, reaction rates for NO formation are governed by local conditions, and these may deviate substantially from the average conditions.

In a small burner, where intimate mixing is relatively easy to achieve, flame temperature at a given point may be fairly steady, but intimate mixing is difficult to achieve on a large scale. Most large burners of conventional design do not employ enough energy in terms of windbox pressure to do much more than impose some macro-scale turbulence on the diffusion mechanism. Thus, while average flame temperature, as measured by commercially-available instruments, may appear to be steady, there are likely to be many regions in the flame envelope where temperatures are too low for NO to form or decompose. Concurrently, there may be many regions, varying in size and persistence, where temperatures are well above average, and NO is being formed at rates one or two orders of magnitude higher than would be predicted from average conditions. Since theoretical predictions necessarily assume perfect mixing, they can only be expected to apply to situations where intense mixing exists. This fact may explain the discrepancies between predicted and measured values of NO.

In view of the foregoing argument, there seemed to be merit in testing the model for distillate oil, with respect to the effect of excess air, using a burner having a high mixing intensity. At the same time it was decided to gain information on the effect of fuel-source nitrogen, by firing two fuels falling within the specifications for No. 2 furnace oil, but having different nitrogen contents. This would of necessity be done on a pilot scale, but before the project could proceed it was necessary to obtain a pilot-scale burner having a high mixing intensity.

The Experimental Combustion System

The experimental program was carried out using the CCRL tunnel furnace, which is a combustion research facility consisting of a cylindrical chamber, 1 metre in diameter and 4.25 metres long with liquid-cooled walls(11). The tunnel furnace has a design firing rate of two million Btu/hr, equivalent to about 12 Igph of No. 2 furnace oil. Unfortunately, in this capacity range the selection of commercial burners is rather limited. In addition to the requirement of high mixing intensity, it was necessary that the burner be capable of operating at low excess air, preferably less than 1% O_2 in the flue gas, to permit study of the region where the model indicated a peak in NO concentration. These were stringent requirements and it was eventually concluded that they could only be met by designing and building a burner for the application.

Largely on an empirical basis, a burner was developed employing conventional pressure-jet atomizing, but splitting the combustion air into primary and secondary streams(12). The air streams were co-axial with the oil nozzle, both were swirled, and the primary air had a fairly high axial velocity. The burner was coupled to a small refractory-lined combustion chamber, shaped to encourage internal flue gas recirculation.

Preliminary combustion trials led to some minor modifications of the burner, and demonstrated some interesting characteristics. With respect to NO emission and low excess air capability, the following burner variables were found to have considerable influence:

1. The quantity of primary air.
2. The amount of primary air swirl, as controlled by the lead angle of the primary swirl head.
3, The amount of secondary air swirl, as controlled by the adjustment of the swirl vanes.
4. The spray angle and spray pattern of the fuel nozzle.

The quantity of primary air was limited by the pressure capacity of the blower to 70 cfm, or about 20% of the combustion air requirement at design firing rate. On the other hand, a primary air flow rate of 15 cfm or less led to overheating of the burner gun. Thus, primary air flow was restricted to the range of 5% to 20% of total air flow.

In general, adjustments which improved the low excess air capability tended to increase NO emission. The best combination of variables from the former viewpoint made possible clean combustion at the design firing rate with as little as 0.5% O_2 in the flue gas.

The small size of the combustion chamber; approximately 15 in. diameter and 12 in. long, resulted in a nominal heat release rate of 1.43 million Btu/cu ft/hr at design firing rate. While this figure is very high compared to conventional combustion systems, it seemed to be valid when the excess-air level exceeded 10%; under those conditions there was little flame outside the combustion chamber. Despite the high heat release rate, the refractory walls did not suffer from overheating. However, under certain conditions carbon formed on the walls, indicating that the chamber was too small for the pattern of fuel spray which developed.

The Experimental Program

Excess air, as the most important variable, was given the most attention. It was thought desirable to vary it in two ways; first, by step-wise adjusting the secondary air, keeping fuel flow fixed, and second, by holding the air flow constant while step-wise adjusting the fuel flow.

The advantage of the first procedure was that it represented the burner trimming methods that are used in practice with on-off burner control systems. The firing rate is fixed and the aerodynamic conditions vary as a consequence of the excess air setting.

The advantage of the latter procedure lay in the fact that a range of excess air could be covered with aerodynamic conditions fixed. The experimental work described in this paper is devoted to the effects of excess air employing the first (constant fuel flow) variation procedure.

It was felt that varying excess air from near stoichiometric to about 20% (4% O_2 in the flue gas) would sufficiently cover the range of interest, both with respect to the model predictions and good industrial practice.

Concerning fuel-source nitrogen, it was felt that the fuels used, albeit different in nitrogen content, should be similar in analysis and distillation range. Thus, differences in NO production would be convincingly tied to fuel-source nitrogen. However, since No. 2 fuel oils having substantially different nitrogen contents are not readily obtained, it was decided that two fuels would be enough. These were designated Fuels A and B.

In order to be certain of carrying out some tests with a fuel having a substantially higher nitrogen content, 5 lb of pyridine (C_5H_5N) were mixed with approximately 80 gal of Fuel B. In this way nitrogen was increased by about 1250 ppm. This mixture is subsequently referred to as Fuel BX.

Experimental Procedures

The equipment used in the research program has already been mentioned, and is described in detail elsewhere(11). For the combustion trials, the combustion chamber was fastened to the front end of the CCRL tunnel furnace, and the burner was mounted on the combustion chamber. Primary and secondary air were supplied by the same high-pressure blower, each flow being separately controlled. Water manometers provided relative indications of the flow rates. The flow rate of primary air was furthermore measured by a rotameter. Fuel oil was supplied to the burner gun by a small gear pump. Oil flow rate was measured by a rotameter, and varied by adjusting a pressure relief valve on the pump discharge.

The flue gas was continuously monitored for O_2, CO_2, CO and NO_x. Gas samples were drawn from the centreline of the tunnel furnace, ten feet from the combustion chamber exit. At this point the combustion process was complete, and the resulting products could be assumed to be well mixed. The sample for the NO_x analyzer was drawn through a water-cooled stainless steel probe to avoid further reaction by catalysis.

To carry out a test, the procedure was generally as follows: the burner was equipped as desired with respect to fuel, nozzle and swirl head, the combustion air blower and the fuel pump were turned on, and the burner was ignited. Fuel, primary air and secondary air were then adjusted to the desired flow rates, and the system was allowed to stabilize for 30 to 45 minutes. A constant concentration of NO in the flue gas was taken as an indication that the combustion chamber had reached thermal equilibrium.

For the tests in which excess air was variable, the secondary air was adjusted step-wise from a level which provided 4% O_2 down to a level which resulted in smoke and CO. Adjustments were made to obtain percentage oxygen levels in the flue gas of 0.4, 0.8, 1.2, 1.8, 2.4, 3.2 and 4.0. Since the changes were small, thermal equilibrium of the combustion chamber was quickly re-established, and 15 minutes of operation at each oxygen level was ample to stabilize the concentration of NO. Periodically the analyzer was switched to the NO_x mode to check for the presence of NO_2. This was done with either three or four levels of primary air and the results are shown in Figures 7, 8 and 9. The near-vertical dotted line on each graph represents the CO threshold. At oxygen concentrations to the left of the threshold, CO in the flue gas exceeded 25 ppm by volume.

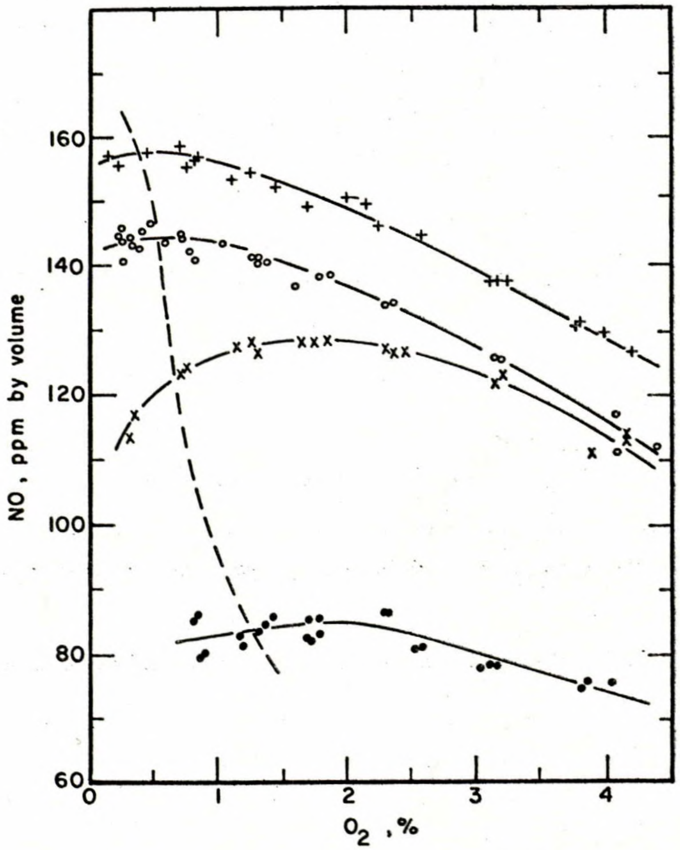

Figure 7. Concentration of NO vs O_2 in the flue gas for Fuel A, fired at 12 Igph through a Monarch 30° HV nozzle. The dash line shows the CO threshold of 25 ppm.

+ 70 cfm (20%) primary air x 35 cfm (10%) primary air
° 53 cfm (15%) primary air • 17 cfm (5%) primary air

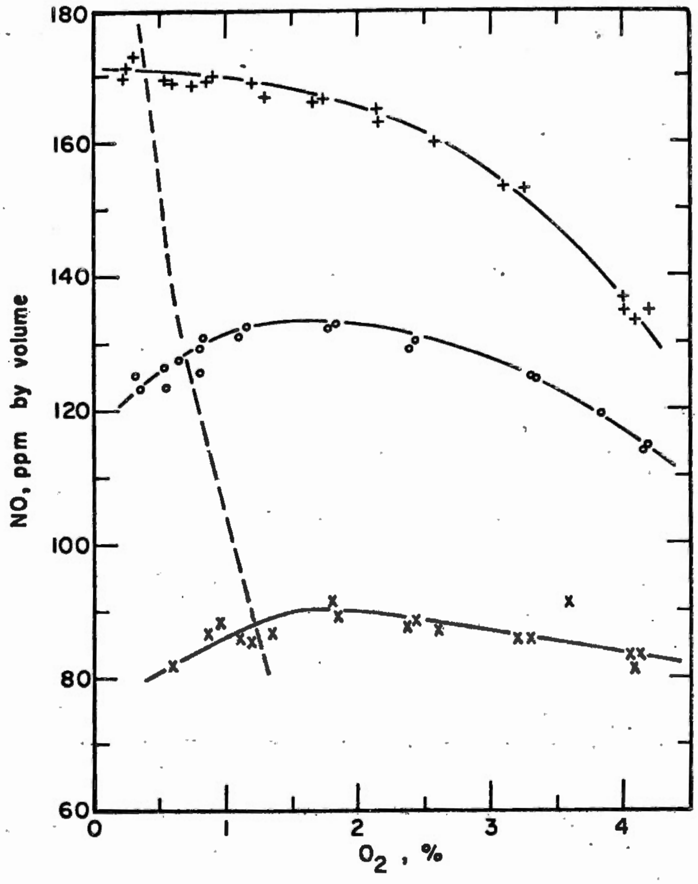

Figure 8. Concentration of NO vs O_2 in the flue gas for Fuel B fired at 12 Igph through a Monarch 30° HV nozzle. The dashed line shows the CO threshold of 25 ppm.

+	70 cfm primary air
°	35 cfm primary air
x	17 cfm primary air

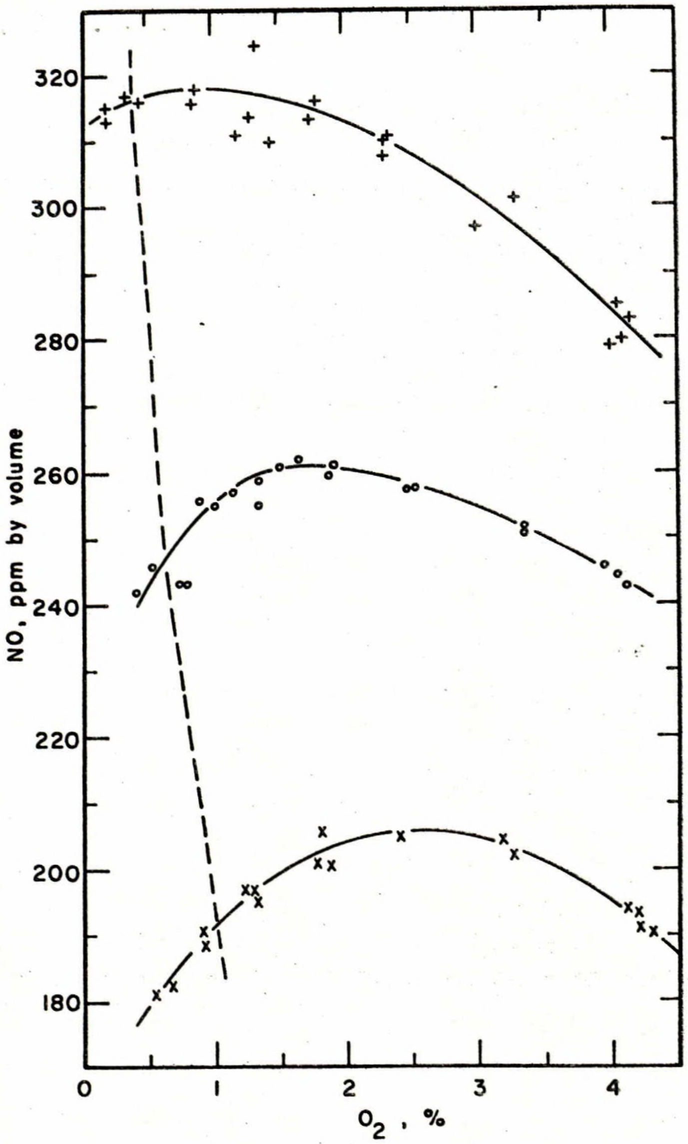

Figure 9. Concentration of NO vs O_2 in the flue gas for Fuel BX fired at 12 Igph through a Monarch 30° HV nozzle. The dashed line shows the CO threshold of 25 ppm.

+	70 cfm primary air
°	35 cfm primary air
x	17 cfm primary air

In addition a series of experiments were carried out using Fuel A in which the primary air swirler was replaced with a simple locating spider to centralize the oil nozzle thus giving an unswirled primary air flow. The results for three levels of primary are shown in Figure 10.

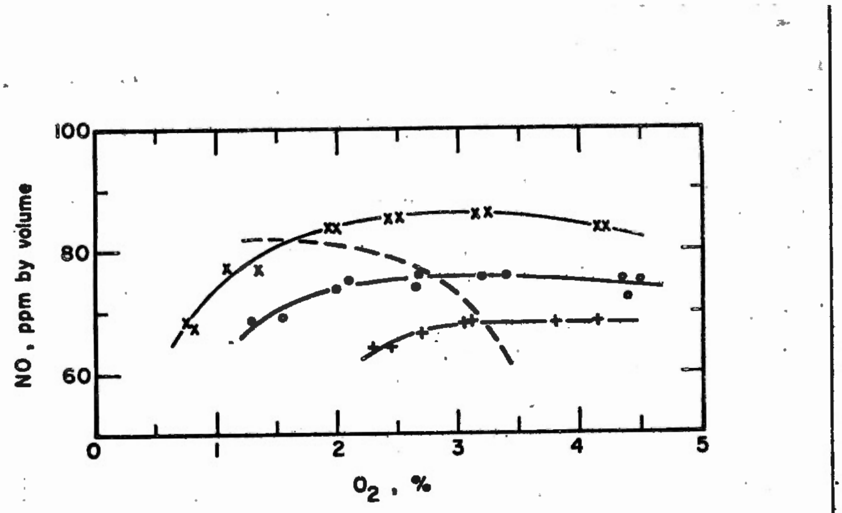

Figure 10. Concentration of NO vs O_2 in the flue gas for Fuel A fired at 12 Igph through a Monarch 30° HV nozzle. Primary air was unswirled. The dashed line shows the CO threshold of 25 ppm.

+ 53 cfm primary air
° 35 cfm primary air
x 17 cfm primary air

Comparison of the Experimental Data With the Kinetic Model

The Effect of Excess Air

The results of all tests in which firing rate was held constant convincingly support the model. All the curves in Figures 7, 8, and 9 show either a peak or plateau at low excess air, and a decline as excess air increases. Beyond this, the agreement between predicted and measured values is qualitative only. Some curves, generally those representing high primary air, do not show a peak, only a region of constant NO concentration at excess air levels below 1% O_2. Other peaks vary in location and definition but generally occur between 0.5 and 2.5% O_2. The slope of the decline also varies from curve to curve. Thus, in detail, the measured curves vary considerably from the pattern predicted in Figures 2 and 3.

Although the NO concentration consistently declines with increasing excess air, the relationship between NO formation and excess air level is somewhat erratic. Figures 11, 12, 13 and 14 eliminate the dilution effect of excess air by rendering the curves in terms of lb NO/lb of fuel versus O_2 in the flue gas. In this form most of the curves still show a peak, although it has been shifted upward and to the right of its former position. However, some curves show only a steady rise in NO production as excess air is increased. Presumably in those cases a peak occurs at an excess air level higher than the range covered in the tests.

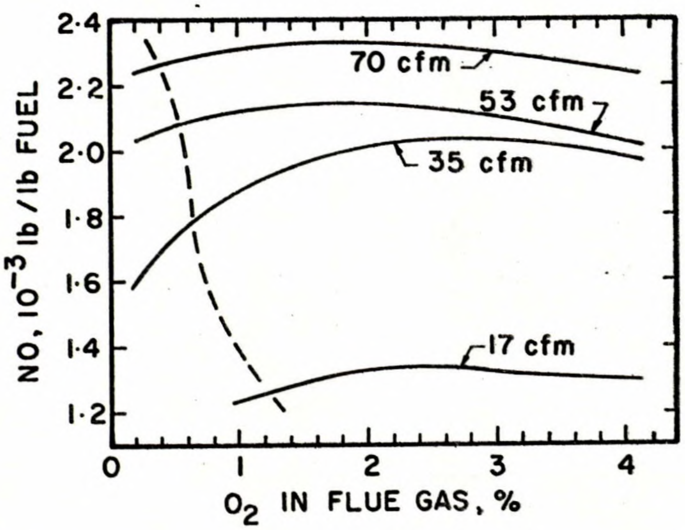

Figure 11. Formation of NO at different levels of primary air, for Fuel A, fired at 12 Igph through a Monarch 30° HV nozzle. The dashed line shows the CO threshold of 25 ppm.

To summarize; in combustion trials at constant firing rate using swirled primary air, NO concentration generally reached a peak at low excess air, and then declined as excess air was increased. NO formation in terms of lb NO per lb of fuel reached a similar peak in some, but not all, cases. The trend in concentration disagrees with most of the published experimental data, but it agrees with the experimental results of Halstead, Watson and Munro(8) and the calculated values of Steffensen, Agnew and Olsen(13). Thus, it appears that the model is valid in principle.

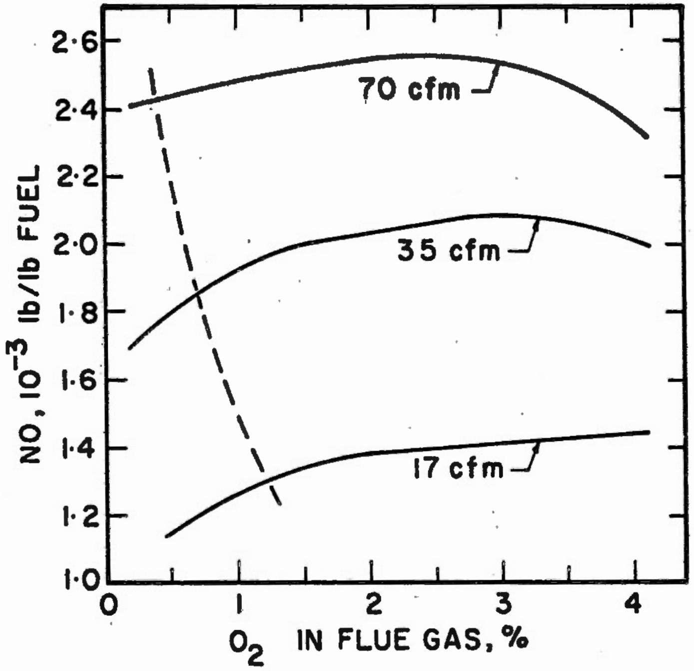

Figure 12. Formation of NO at different levels of primary air, for Fuel B, fired at 12 Igph through a Monarch 30° HV nozzle. The dashed line shows the CO threshold of 25 ppm.

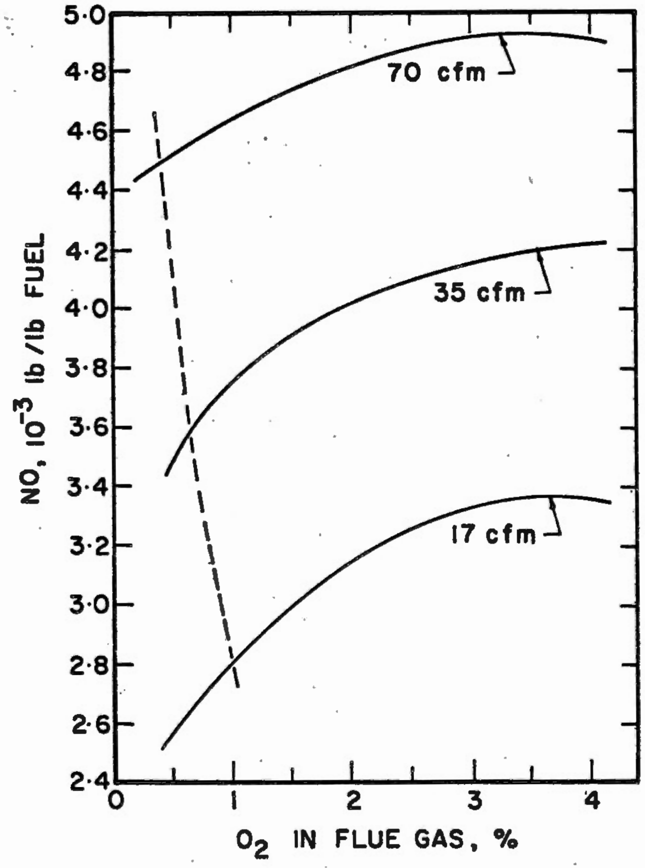

Figure 13. Formation of NO at different levels of primary air, for Fuel BX, fired at 12 Igph through a Monarch 30° HV nozzle. The dashed line shows the CO threshold 25 ppm.

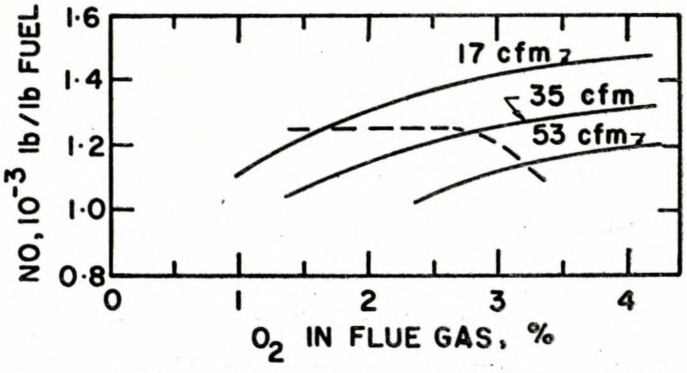

Figure 14. Formation of NO at different levels of primary air, for Fuel A, fired at 12 Igph through a Monarch 30° HV nozzle. Primary air was unswirled. The dashed line shows the CO threshold of 25 ppm.

An exception to the general trend is provided by the results of the tests with unswirled primary air. As shown in Figure 10, these curves rise to a very weak peak or a plateau as excess air is increased. When plotted as lb NO/lb fuel, Figure 14, they show a continuing upward trend as excess air increases. The significance of this will be discussed later.

The Effect of Fuel Nitrogen

The effect of increased fuel nitrogen can be assessed by comparing Figures 12 and 13. The former represents Fuel B, while the latter represents Fuel BX, which contained about 1270 ppm by wt more nitrogen than Fuel B. The curves are similar in shape, but for the same firing conditions Fuel BX resulted in approximately twice the concentration of NO.

To determine the extent to which the added nitrogen was converted to NO, values from the curves of Figure 12 have been subtracted from corresponding values of Figure 13. The differences, divided by 1270 x $\frac{30}{14}$, have been plotted in Figure 15 in terms of percent. The results are remarkable. At high (70 cfm) primary air, conversion ranged from about 75% at 0.5% O_2 to nearly 95% at 4% O_2, and indicated that 100% conversion might occur if O_2 were increased further. Even at low primary air (17 cfm) in combustion conditions that produced smoke and CO, about 50% conversion occured, and the results show a peak in degree of conversion; about 71% at 3.5% O_2.

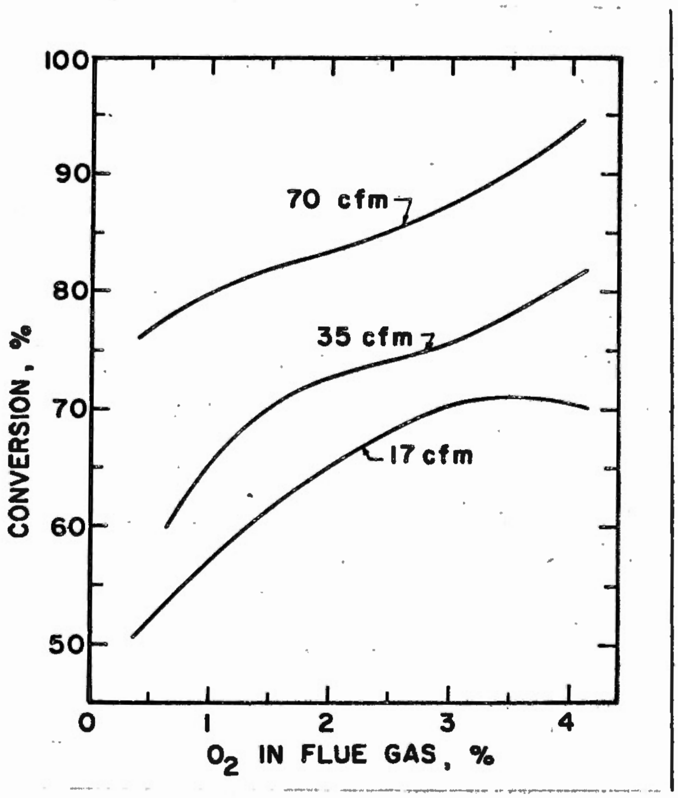

Figure 15. Conversion of fuel nitrogen in Fuel BX at different levels of primary air.

The formulation of the model permits fuel nitrogen to convert either to NO or N_2. The experimental results show higher percentages of conversion than the model predicts, but both show similar trends of increased conversion with increasing excess air.

THE EFFECT OF MIXING ON NITRIC OXIDE FORMATION

The results of the present experiments provide strong circumstantial evidence that mixing intensity plays a major role in the formation of NO. To define "mixing intensity" in precise terms would require delving into the theory of turbulence for parameters which cannot be measured in a flame. However, some qualitative statements can be made.

The model assumed perfect mixing and adiabatic combustion. It predicted NO concentrations much higher than have been measured under any conditions of equivalent excess air and fuel nitrogen. Mixing in a real burner is imperfect to a varying degree, and a proportionate quantity of the reacting species do not reach adiabatic flame temperature. Consequently, for equivalent input conditions, real burners can generally be expected to produce lower concentrations of NO than the model. However, if a combustion system had a residence time above 1700°K greater than the 1/2 sec assumed in the model, actual concentrations of NO might be higher than predicted.

The present experiments were carried out with a burner designed to create intense mixing. Furthermore, the excess air range was kept fairly close to stoichiometric. Under these conditions it appears that for a given level of excess air, any aerodynamic parameter which has increased the NO concentration has also increased the mixing intensity. Certainly it is safe to say that any parameter which has lowered the CO threshold has increased the mixing intensity.

Swirled Primary Air

Primary air injected with a high level of swirl just around the fuel nozzle can be expected to improve mixing. Thus, using the reasoning outlined above, we should expect NO to increase as primary air is increased. This is indeed the case, as shown in Figures 7, 8, 9, 11, 12 and 13. Conversely, we should find that the CO threshold rises, that is, shifts to the right, as primary air is decreased. Again this is confirmed by the experimental results in the same figures.

Unswirled Primary Air

When the primary air is in the form of an axial jet, it would have a different effect on the fuel spray than when it is swirled. Swirled primary air, by virtue of its radial velocity component, tends to pull the fuel spray into the secondary air stream. Unswirled primary air should have the opposite effect; it should deflect the fuel spray axially and delay mixing with the secondary air. Thus, we might expect a reduction in NO concentration with increasing unswirled primary air. This is confirmed by the data in Figure 14. Also, since increasing unswirled primary air reduces mixing, it should raise the CO threshold. Again the data bear this out. It may be observed that the lowest NO concentrations in the entire research program were obtained with unswirled primary air. The same conditions also produced the least satisfactory flames. Poor mixing should not be considered a suitable route to low NO emissions.

The Nitric Oxide Concentration Peak As a Mixing Indicator

These experiments suggest yet another aspect of the effects of mixing on NO concentration. We have already discussed how a poorly-mixed flame can inhibit NO formation by permitting only a small part of the fuel and air to approach the flame temperature theoretically possible. The large flame envelope produced at low excess air by a burner with poor mixing characteristics further reduces flame temperature through increased radiation.

For poorly-mixed flames, then, it follows that as excess air is increased, NO concentration is likely to increase. The increased mass flow, increased oxygen and mixing power, overwhelm the increased dilution effect, resulting in generally higher temperature levels. Since intimate mixing is more difficult to achieve as burner size is increased, this probably explains why results from large combustion systems generally show an increase in NO concentration with increasing excess air.

It is clear that ultimately NO concentration must decrease as excess air continues to increase, and the point at which NO concentration reaches a peak is perhaps a good indication of mixing intensity.

With respect to the last comment, these experimental results show a significant trend. Generally, though not invariably, as primary air is decreased and consequently mixing intensity is decreased, the peak in NO concentration shifts to the right. For unswirled primary air, mixing intensity decreases as primary air increases, and as might be expected, the NO peak shifts to the right as primary air flow increases.

CONCLUSIONS

The experimental results support the most significant prediction of the model, i.e., that NO concentration in the flue gas should reach a peak at a low level of excess air, and then decline monotonously as excess air increases.

The conflict with most of the experimental results in the literature (which indicate that NO concentration in the flue gas increases monotonously with increasing excess air) can be resolved in terms of mixing intensity at the burner. The present results show that as mixing intensity is reduced, the peak in NO concentration shifts to progressively higher levels of excess air. Thus, in large combustion systems where intense mixing is difficult to achieve, the peak may occur at higher levels of excess air than are normally employed.

It is clear that mixing intensity plays an important role in NO formation, but this role is presently not well understood. Theoretical considerations suggest that intense mixing should reduce NO formation at high excess air, and increase it at low excess air, yet there is a possibility that intense mixing, strategically used, can reduce NO formation at low excess air.

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