ASME FACT-18, Combustion Modeling, Scaling and Air Toxins, 1994.

LOW NO_X EMISSION FROM AERODYNAMICALLY STAGED OIL-AIR TURBULENT DIFFUSION FLAMES

A.L. Shihadeh, M.A. Toqan, J.M. Beér, P.F. Lewis, J.D. Teare, J.L. Jiménez, and L. Barta

The Combustion Research Facility
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

An experimental investigation on the reduction of nitrogen oxide emission from swirling, turbulent diffusion flames was conducted using a prototype multi-annular burner. The burner utilizes swirl-induced centrifugal body forces to dampen turbulent exchange between the fuel and air streams, allowing an extended residence time for fuel pyrolysis and fuel-N conversion chemistry in a locally fuel-rich environment prior to burnout. This aerodynamic process therefore emulates the conventional staged combustion process, but without the need for physically separate fuel-rich and -lean stages.

Parametric studies of swirl intensity and external air staging were carried out to investigate the feasibility of aerodynamic staging for low NOx combustion with No. 6 heavy fuel oil. NOx emission was reduced from an uncontrolled 300 ppm (3% O2) to 91 ppm in the optimal configuration. A further reduction from 91 ppm to 53 ppm was realized by external staging (primary stage fuel equivalence ratio = 1.13). A detailed flame structure investigation was carried out for a parametrically optimized, staged flame.

INTRODUCTION

Combustion air staging has proven to be a highly effective method for reducing NOx emission in a number of practical systems. Typically, these systems rely on physically separate fuel-rich and fuel-lean combustion zones, between which "overfire" air is injected. Drawbacks to this method include higher operating costs, corrosion of the heat transfer surfaces in the fuel-rich first stage, and difficulty in retrofitting existing systems. As an alternative to relying on physically separate zones for staging, the Radially Stratified Flame Core (RSFC) burner was developed at MIT to implement staging by aerodynamic means, so that all of the combustion air is introduced at the burner.

Analogous to the conventional overfire air systems, the RSFC burner aerodynamically creates two combustion zones, one in which fuel-air mixing is suppressed by radial density stratification, and the other characterized by a high degree of mixedness. In the density stratified zone, relatively cool, highly swirling combustion air surrounds a hot, fuel-rich flame core, which is created by injecting a small portion (~15%) of the combustion air near the central fuel jet. Under certain conditions, the centrifugal body forces associated with the swirl damp turbulent mixing between the fuel-rich core and the surrounding air, effectively containing the fuel within a locally fuel-rich "first stage" for an extended residence time, during which the NO reduction chemistry is active. Further downstream, vortex breakdown occurs, and the peripheral combustion air mixes with the products of the fuel-rich core, creating a fuel-lean burnout stage. A schematic of the internal staging process is shown in Figure 1.

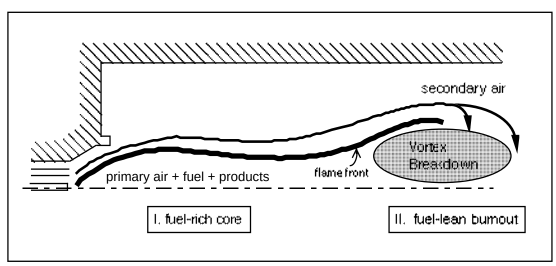

FIGURE 1 INTERNAL STAGING SCHEMATIC.

In previously published studies of natural gas flames (Toqan et al., 1992), the RSFC burner achieved 70 ppm NO_X emission at

3% O_2 (56 ppm CO) without flue gas recirculation, and 15 ppm NO_x (< 10 ppm CO) with 32% of the flue gas recirculated. Using detailed velocity, species concentration, and temperature measurements, those studies demonstrated the role of swirl-induced radial stratification in producing aerodynamically-staged low NO_x flames. In the current work, the applicability of the RSFC burner to No. 6 heavy fuel-oil (0.3 wt % N) flames was investigated. Because the nitrogenous species (fuel-N) in No. 6 fuel-oil are readily converted to NO_x in the presence of O_2, particular attention was given to the residence time available in the fuel-rich core to ensure maximum fuel-N conversion to N_2. The principal source of NOx emission when burning fuels containing chemically bound nitrogen is the conversion of these nitrogen species (Pershing and Wendt, 1977).

BURNER AERODYNAMICS

Figure 2 illustrates the important aerodynamic features of a 'typical' low NOx RSFC burner flame. An initial fuel-rich flame core is created by mixing initiated within the burner between the central fuel jet and the primary air. The secondary air, typically constituting 85% of the total burner air, is introduced through a radially displaced annulus. The fuel jet penetrates through an annular internal recirculation zone (IRZ) that extends into the burner quarl. Hot combustion products and some fuel peel off the fuel jet during its passage through the reverse flow zone, and are carried back into the quarl. In the emerging fuel-rich flame, fuel mixes slowly, due to turbulence damping, with the surrounding air. Further downstream of the burner (~ 5 burner diameters), stratification ends, largely due to the decay in tangential velocity, and the remaining secondary air mixes rapidly with the fuel-rich core, completing the combustion.

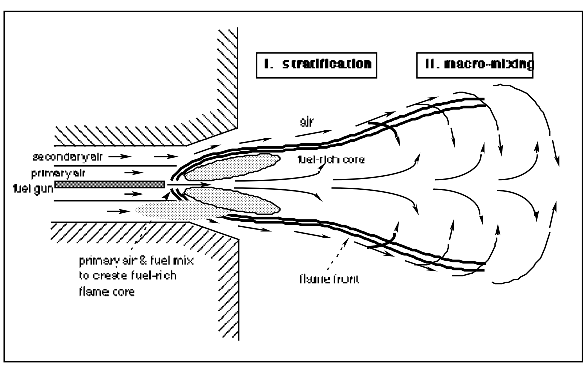

FIGURE 2 TYPICAL LOW NO_X RSFC FLOW FIELD.

Turbulence damping in the density stratified zone results from a combination of the centrifugal force field and the positive radial density gradient (created by the density difference between the hot burning core and the surrounding air). When an individual fluid eddy displaces a parcel of the relatively dense combustion air toward the flame axis, work is expended in the force field, dissipating turbulent energy. The concept is rooted in the work of Rayleigh (1916), which showed that a rotating fluid is stable with regard to radial interchanges if ρWr, the product of density, tangential velocity, and radial position, increases with radial distance from the axis of rotation. Beér et al. (1971) adapted Richardson's dimensionless group for the characterization of turbulence damping under conditions of atmospheric inversion to flames with swirling air flow around a hot central core. More recently, the adaptation of the Richardson number to a radially stratified natural gas flame in a low NO_x gas burner was presented by Toqan et al. (1992).

EXPERIMENTAL

Parametric tests were conducted to study the relationship between exit NOx emission and swirl number, *S*, defined as the non-dimensional ratio of angular momentum to axial momentum and burner radius:

$$S \equiv \frac{G_\phi}{G_x R} \quad \text{(Beér and Chigier, 1963).}$$

In addition, axial profiles of centerline species concentration and temperature were measured for zero and maximum swirl settings to demonstrate the role of swirl in mixing suppression. Parametric studies of external staging (using conventional overfire air) were also conducted to give a relative indication of the efficacy of the RSFC burner internal staging process.

Finally, a detailed flame structure study was conducted in which gas composition and temperature measurements were taken at many locations in an optimized flame. The detailed study was used to elucidate the overlapping mixing and chemistry processes, particularly to address the question of fuel-N conversion. The measurements would indicate the extent to which fuel was confined within a fuel rich core, and whether the temperature in the fuel-rich region was high enough to allow fuel-N conversion to N2 in the available fuel-rich residence time.

The thermal input was maintained at 0.9 MW and the fuel was No. 6 fuel-oil with a 1.5 C/H ratio and a 0.3 wt% N content. The air preheat temperature was 555 K. A twin fluid Y-jet atomizer with air as the atomizing medium was used, except for the detailed flame study, in which steam atomization was employed.

Experimental Burner

A schematic of the RSFC burner is given in Figure 3. The combustion air is introduced through three concentric annular nozzles, of which the positions of the primary and secondary (as well as the fuel gun) can be adjusted to produce a particular flow field. To produce the desired internally staged flame for the experiments, the primary air nozzle was used to introduce approximately 15% of the combustion air while the remaining 85% was introduced through the tertiary nozzle (for the purpose of this discussion, the terms "tertiary air" and "secondary air" are interchangeable).

Each nozzle is equipped with moveable block-type swirlers capable of infinitely variable swirl control. For the results reported below, the degree of swirl used in any experiment is indicated by "swirl setting" which is a linear scale of swirler adjustment angle, with 0 representing no swirl and 10 representing maximum swirl. For moveable block swirlers, the theoretical swirl number of the flow issuing from any nozzle is strictly a function of the burner geometry, and can be calculated for any particular swirl setting, as shown in Beér and Chigier (1972). For the burner geometry of the experiments reported here, a swirl setting of 10 corresponds to a swirl number of 0.3 and 0.6 for the primary and tertiary nozzles, respectively.

Experimental Furnace

The MIT Combustion Research Facility (CRF) was used to conduct the experiments. The CRF is an approximately 10 m long tunnel furnace that consists of several interchangeable water-cooled sections, each with either a bare metal or refractory brick lined surface, and a square (1.2 x 1.2 m) or cylindrical (ϕ 0.5 m) cross-section. The thermal capacity of the CRF is 3 MW, though typically it is operated at 1 MW. By varying the sequence of bare-metal and refractory brick sections, the heat extraction along the flame axis can be varied to simulate the temperature history of large scale practical flames. An overfire air injection port is located 3.4 m downstream of the burner.

An access door in each of the furnace sections allows measurement of gas temperature and composition with intrusive traversing probes, including a suction pyrometer for temperature, a water cooled suction probe for major species, and a steam jacketed suction probe for hot cell fourier transform infrared (FTIR) spectrometry for various trace species. The sampling methods and furnace have been described in detail elsewhere (Beér et al., 1985).

EXPERIMENTAL RESULTS

Tertiary Air Swirl

Figure 4 illustrates the effect of tertiary air swirl on NOx emission, demonstrating a reduction from 300 ppm at zero swirl, to 120 ppm at the maximum setting, which corresponds to a swirl number of 0.6. The non-zero slope at the maximum setting suggests that further reductions in NOx might be achieved if the burner were modified by increasing the maximum swirl angle. These results are consistent with previous studies of natural gas RSFC flames which demonstrated the presence of radial stratification as a result of swirl (Toqan et al., 1992). As a simple test that the same process was at work in the oil flames, centerline measurements of gas composition and temperature were taken along the flame axis for maximum and zero tertiary swirl cases. The results, shown in Figures 5 through 9 indicate that in the high swirl case, fuel-air mixing is suppressed, while in the zero swirl case, mixing was rapid. Figure 5 shows that a significant amount of oxygen reaches the flame axis in the no-swirl case, whereas practically none is found at the axis when swirl is applied. Similarly, the CO and CO_2 profiles shown in Figures 6 and 7 indicate that with swirl, fuel consumption proceeds more slowly, partly accounting for the lower temperatures shown in Figure 9.

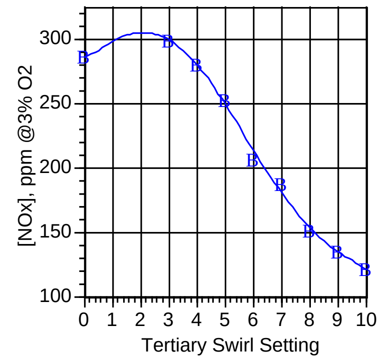

FIGURE 4 NOx EMISSION VERSUS TERTIARY AIR SWIRL SETTING

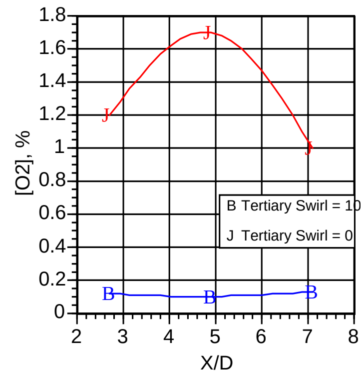

FIGURE 5 OXYGEN CONCENTRATION AT FLAME CENTERLINE FOR ZERO AND MAXIMUM TERTIARY SWIRL; AXIAL DISTANCE IS INDICATED AS BURNER DIAMETERS FROM BURNER FACE.

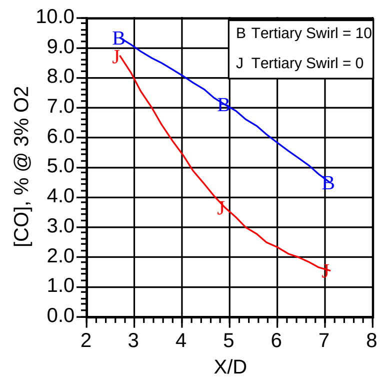

FIGURE 6 CENTERLINE CO CONCENTRATION.

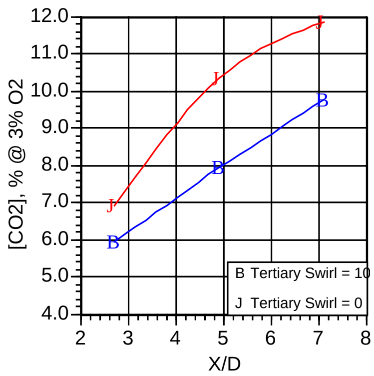

FIGURE 7 CENTERLINE CO2 CONCENTRATION.

These differences account for the striking contrast in NO evolution shown in Figure 8. In the no-swirl case, NO concentration increases drastically along the axis, as should be expected given the presence of oxygen, whereas in the maximum swirl case, NO continues to decrease along the axis, since both conditions for NO reduction are met: high temperature, and a fuel rich environment. It is interesting to note that at X/D = 2.7, the NO concentration is considerably greater for the high swirl case, possibly due to the fact that the mixture is so rich there that the needed H and OH radicals are present in insufficient concentrations to decompose the NO precursors, such as cyanogen and ammonia species, to N2.

Primary Air Swirl

Compared to tertiary swirl setting, primary air swirl had the opposite, but quantitatively less significant, effect on NOx emission. As shown in Figure 10, increasing swirl setting from 4 to 10 increased NOx emission from 92 to 120 ppm. The increase in emission is likely due to an increase in the strength of the internal recirculation zone in the near-burner field. As the recirculation zone strengthens, a greater portion of the fuel is diverted around the IRZ (instead of passing through it) to the outer periphery of the flame core, where it readily mixes with the surrounding air, thereby reducing stratification. This increase in mixing rate, however, had the desirable effect of stabilizing the flame; when primary air swirl setting was reduced to below 5, ignition became unstable.

External Air Staging

Conventional external staging provided a relative indication of how well the internal staging produced by the RSFC burner reduced NOx emission. As shown in Figure 11, external staging reduced NOx emission from 91 ppm to 53 ppm in the best case. Burnout was complete by the furnace exit, and CO emissions were below 50 ppm in all cases. Staging beyond phi = 1.2 did not further reduce emission, likely due to the fact that as fuel equivalence ratio increases, the concentration of oxygen-containing radicals required to decompose the NOx precursors to N2 decreases. The fuel-equivalence ratio at which NOx decomposition is arrested is temperature dependent, with higher temperatures yielding a higher optimal fuel-equivalence ratio and lower NOx concentration (Shihadeh, 1994).

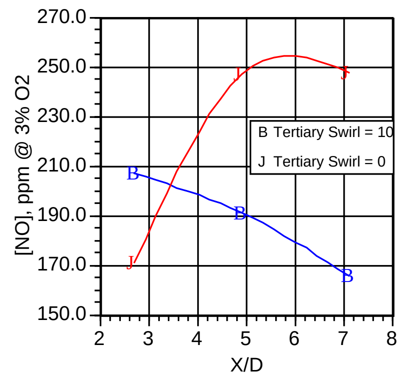

FIGURE 8 CENTERLINE NO CONCENTRATION.

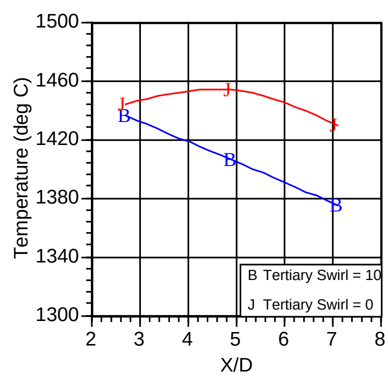

FIGURE 9 CENTERLINE GAS TEMPERATURE.

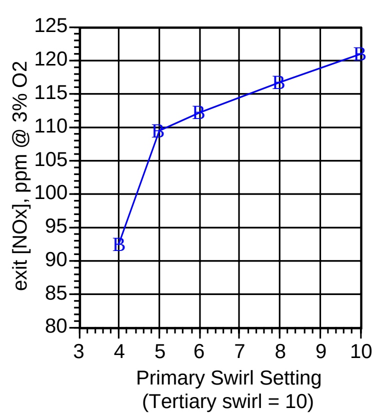

FIGURE 10 NOx VERSUS PRIMARY SWIRL SETTING.

The success of external staging in reducing NOx indicated that the internal staging process of the RSFC burner had room for improvement, particularly by increasing residence time and/or temperature in the stratified zone to allow the fuel-N to N2 conversion reactions to equilibrate. If stratification ends after all or most fuel-N has been converted to N2, then external staging will have only a marginal effect on NOx emission; at present, its function is to maintain fuel-rich conditions after stratification ends so that the fuel-N reduction reactions may continue.

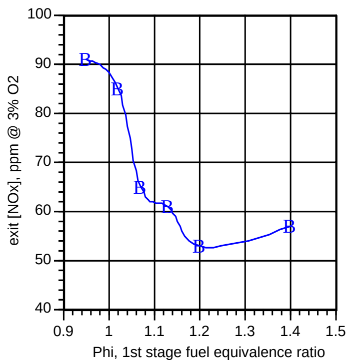

FIGURE 11 NOx EMISSION VERSUS PRIMARY STAGE FUEL EQUIVALENCE RATIO.

Flame Structure Study

Detailed in-flame measurements of gas composition and temperature were taken for an externally staged, parametrically optimized flame. The input parameters used to generate this flame are listed in Table 1.

TABLE 1 BURNER CONDITIONS FOR DETAILED STUDY.

Nozzle	Flow, % of burner air	Swirl No.	Axial Velocity [m/s]
Primary	15	0.3	33
Tertiary	85	0.6	50

A 0° Y-jet atomizer was used with steam as the atomizing medium. The first stage was operated at a fuel equivalence ratio of 1.13, with the over-fire air injection port positioned at 3.4 m (11 burner diameters) from the burner. Thermal input was maintained at 0.9 MW. These conditions resulted in the following exit emissions:

NOx	58 ppm
O2	2 %
CO2	13 %
CO	< 30 ppm

Figures 13 to 18 below show measured concentration and temperature distributions in the near-burner field. They illustrate the ways in which the high-swirl RSFC flame yields low NOx emission. In Figure 12, contours of NO concentration are plotted as a function of axial and radial distance (expressed as burner diameters) from the burner. In the figure, the NO formation and destruction chemistry regimes are apparent in two distinct zones, delineated by the 140 ppm iso-concentration line. In the formation zone, fuel-N is oxidized in an oxygen-rich environment, as evidenced by the O2 contours shown in Figure 13, and the absence of CO in the same region, shown in Figure 14. In a fuel-lean environment fuel-N will be converted to NOx, and thermal NOx will be formed, explaining the observed increase in NO concentration in this zone.

Within the NO reduction zone, there is a particularly intense region of NO destruction near the burner axis, indicated in Figures 13 to 18 by the shaded area. In this region, it can be seen that the O2 concentration is low, while CO (Figure 14) and CH4 (Figure 15) concentrations are relatively high, indicating a fuel-rich local atmosphere. In this context CH4 is important as an indicator of the presence of hydrocarbon fragments, such as CH and CH2. These hydrocarbon fragments play a major role in NOx reduction via the NO “reburn” mechanism (CHi + NO --> HCN + ...) and are likely responsible for the particularly intense NO destruction seen here. It should also be noted that within this region, the rate of destruction increases along the axis, reaching a maximum at a distance between 2.5 and 3.2 burner diameters. This rate increase can be partly explained by the peaking of gas temperature in the same location, as shown in Figure 17, since the fuel-N and NO decomposition reaction rates increase with temperature. The remainder of the NO reduction zone results from the high temperature, oxygen deficient conditions where “reburn” also occurs, though at a slower pace because of the lower concentration of CHi fragments there.

Returning to the question of external staging, it can be seen in the NO contour plot that if the over-fire air (OFA) injection port had been positioned anywhere within the plotted axial domain (instead of at X/D = 11), higher NOx emission would have resulted since the NO reduction reactions had not yet been completed (i.e., taken the mixture to the equilibrium NOx concentration). For example, if the OFA were positioned at X/D = 3.9, it is likely that the exit NOx emission would have been closer to 120 ppm, rather than the achieved 58 ppm.

CONCLUSIONS

The experiments demonstrated that aerodynamic staging can be highly effective in reducing NOx emission from No. 6 fuel-oil flames, from and uncontrolled 300 ppm to 91 ppm. By imposing external staging on the low NOx RSFC flame, a 40% reduction in NOx emission was obtained (from 91 to 53 ppm), indicating that the internal staging realized in the experiments can theoretically be improved. To some extent, improvements could be achieved by delaying vortex breakdown, and by further optimizing the near burner flow field to create conditions for turbulence damping earlier in the flow - by accelerating ignition, for example.

Even with these improvements, however, it may be difficult to match the NOx emission reduction that can be achieved with conventional external staging, mainly due to the fact that with internal staging, the NO reduction chemistry is limited by the wide distribution of local fuel/air ratios (in the stratified zone) from zero to infinity. As a result, some portion of the mixture is too rich for converting NOx to N2, while elsewhere it is too lean. With external staging, a well-stirred flow pattern can be utilized so that the distribution about the mean equivalence ratio is narrower, allowing the majority of the combustion to occur at an optimal fuel/air ratio, but at the expense of higher corrosiveness in the fuel-rich stage.

One promising strategy, then, may be to combine the two methods of staging, in which case a deeply-staged condition could be achieved (in effect) without as high a first-stage overall fuel-equivalence ratio, and therefore without the normally associated degree of corrosiveness. In cases where physical constraints make staging via over-fire air impossible, staging by aerodynamic means alone is an effective low NOx alternative.

REFERENCES

Beér, J.M. and N.A. Chigier, "Swirling Jet Flames from an Annular Burner," *5 me Journeé d'Études sur les Flammes*, Paris, 1963.

Beér, J.M. et al.: "Laminarization of Turbulent Flames in Rotating Environments," *Combustion & Flame*, 16, 39-45, 1971.

Beér, J.M. and N.A. Chigier: *Combustion Aerodynamics*, Robert Krieger Publishing Co., Malabar, Fl., 1972.

Beér, J.M., Farmayan, W.F., Teare, J.D., and Toqan, M.A.: "Laboratory-scale study of the combustion of coal derived liquid fuels," EPRI AP4033 Report, p. 182, 1985.

Pershing, D.W. and J. Wendt: "Pulverized Coal Combustion: The Influence of Flame Temperature and Coal Composition on Thermal and Fuel NOx," *Sixteenth Symposium (International) on Combustion*, The Combustion Institute, p. 389-399, 1977.

Rayleigh, L. 1916. *Proc. Roy. Soc*. A93. 148-154

Shihadeh, A.S., "NOx Control and Environmental Regulation: Techniques and Discriminatory Social Outcomes," S.M. Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Toqan, M. A. et al: "Low NO Emission from Radially Stratified Natural Gas - Air Turbulent Diffusion Flames," *Twenty-Fourth Symposium (International) on Combustion*, The Combustion Institute, p. 1391-1397, 1992.

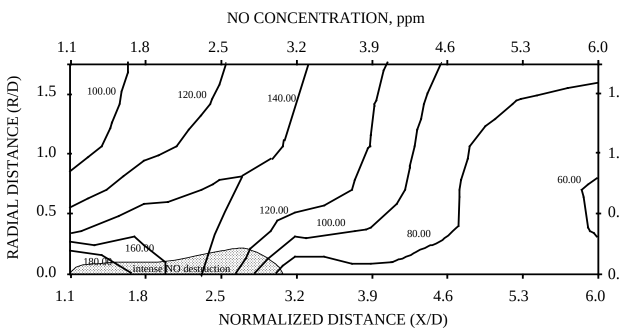

FIGURE 12 MEASURED NO CONCENTRATION.

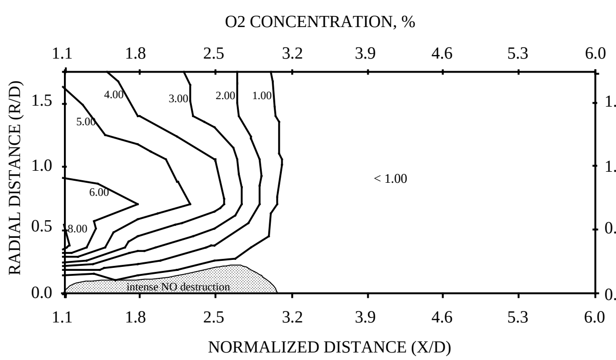

FIGURE 13 MEASURED O2 CONCENTRATION.

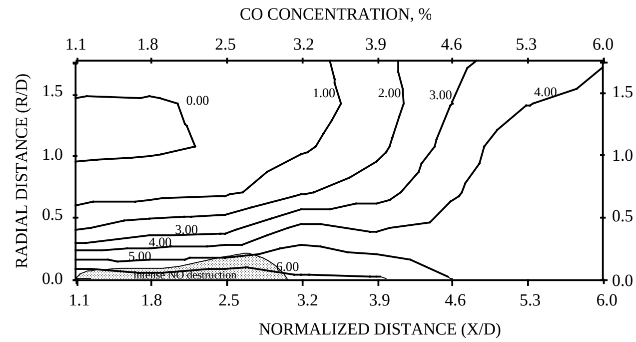

FIGURE 14 MEASURED CO CONCENTRATION.

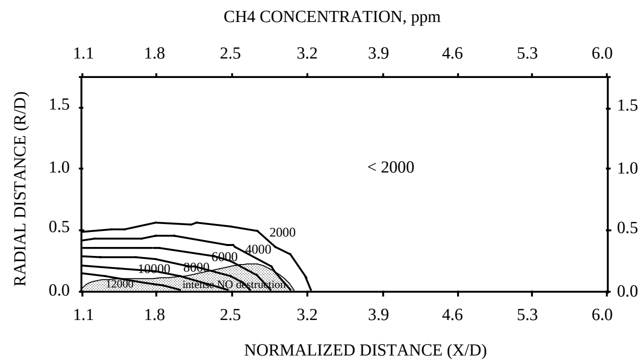

FIGURE 15 MEASURED CH4 CONCENTRATION (FTIR MEASUREMENT).

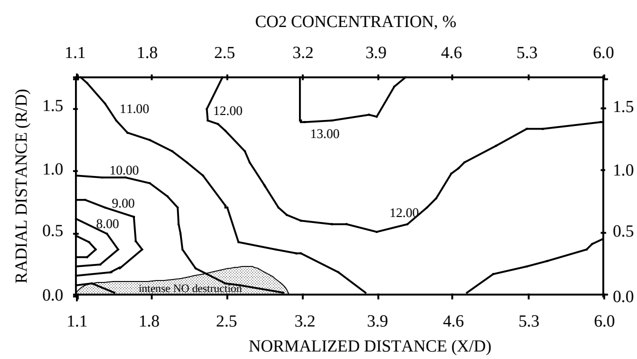

FIGURE 16 MEASURED CO2 CONCENTRATION.

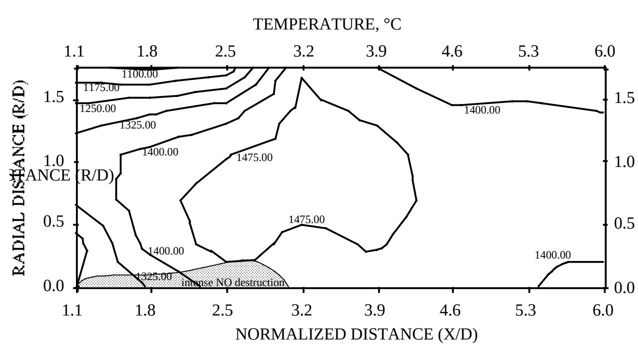

FIGURE 17 MEASURED GAS TEMPERATURE.