DESIGN AND OPERATION OF COAL-FIRED TURBO® FURNACES FOR NO_X CONTROL

by

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RESULTS OF RECENT NO_X TESTS

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ABSTRACT

The results of recent full scale NO_X emission tests conducted on a number of dry bottom Riley Turbo® Furnaces are presented. Included with the data is an evaluation of the major furnace design and operating variables affecting emissions during pulverized coal combustion. A Turbo Furnace flow model is used to provide insight into the combustion process and NO_X formation mechanism. The effectiveness of staged combustion as a method of controlling NO_X emissions is also discussed.

INTRODUCTION

Riley Stoker Corporation has been actively engaged in a NO_X control research program since the mid 1960's. The results of earlier investigations in this program[1,2] have shown the Riley Turbo Furnace to be significantly more effective in controlling NO_X emissions than conventional wall fired furnaces. Recent full scale field testing at a number of pulverized coal fired dry bottom Turbo Furnaces has added considerably to our data base for this design.

The results of this testing which include observations at a variety of operating conditions are presented here. Also discussed is a parameteric evaluation of the data identifying the major variables affecting NO_X emissions in the Turbo design. Five (5) different dry bottom Turbo units ranging in size from 250,000 to 2,000,000 lbs/hr of steam are represented in the data. Coals of differing nitrogen content and coal rank are also included.

Insights into the mechanism of pulverized coal combustion drawn from independent studies and from our own aerodynamic mixing studies in an isothermal Turbo Furnace flow model are used in the parametric evaluation. Both laboratory studies[3,4] and utility boiler test data[5] indicate that the fate of fuel nitrogen is strongly affected by aerodynamic mixing patterns in the flame and by process variables such as excess air. The availability of oxygen is a major factor in the conversion of fuel nitrogen to NO_X. The air/fuel mixing schedule early in the combustion process can significantly affect this conversion.

FURNACE DESIGN FEATURES

The dry bottom Turbo Furnace design, as shown in Figure 1, is characterized by a venturi-shaped bottom with burners on opposite walls tilted downward. This furnace geometry provides an effective aerodynamic system for utilization of the lower furnace cooling surface. Non-swirl burners are used to delay the mixing of combustion air into the fuel jet, thereby producing a low temperature diffusion controlled flame. Directional vanes are incorporated in the burner design to provide control over the schedule of this air/fuel mixing. A description of a pulverized coal directional flame burner is given by the diagram in Figure 2. Fuel and air are introduced to the combustion chamber through slots formed in the downward facing waterwalls. Staged combustion is achieved in this design by the introduction of air above the primary combustion zone through staged combustion ports. Regulating vanes are also included in the staging air duct system to provide control at both high and low load operation.

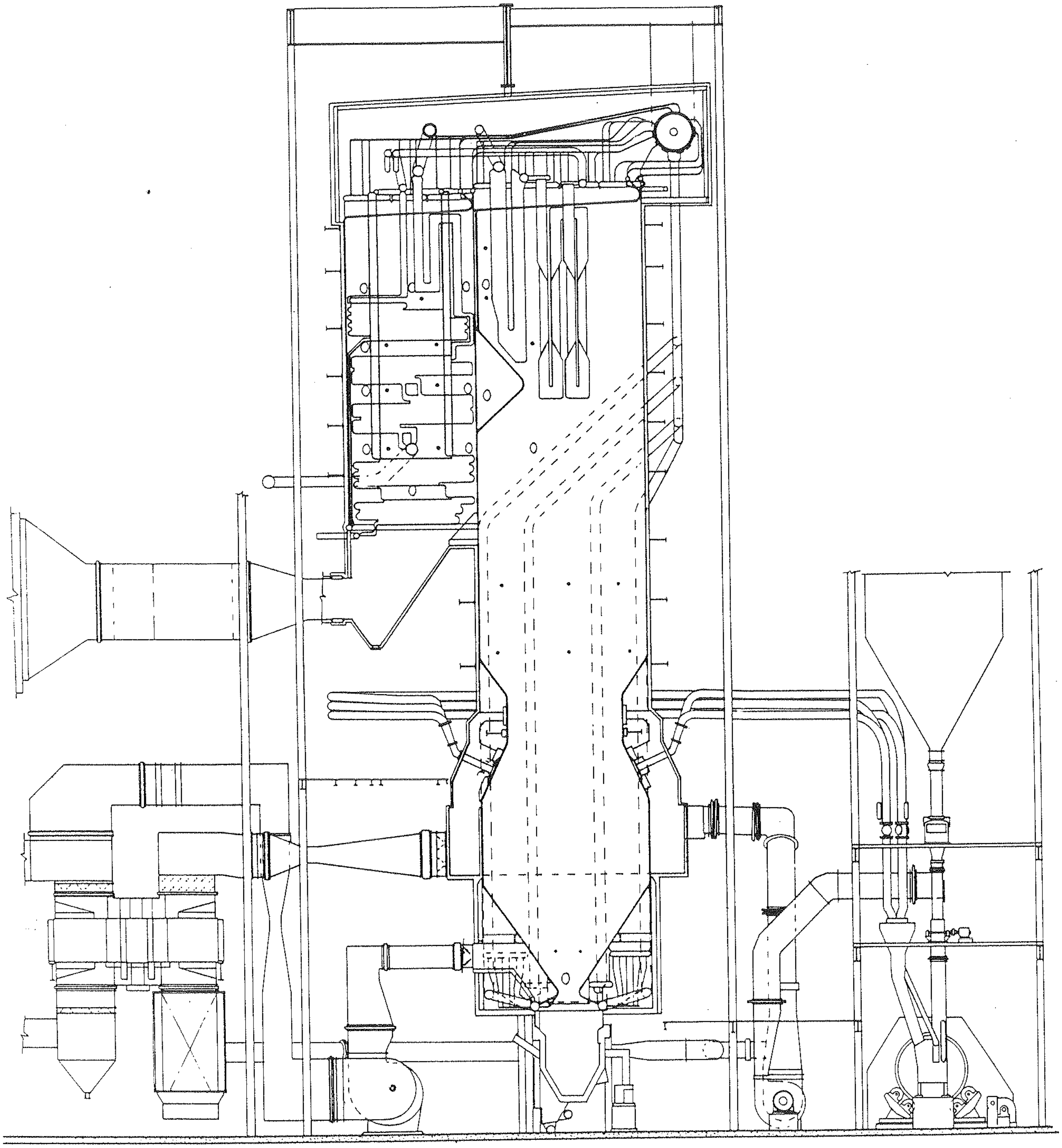

Figure 1 Dry Bottom Riley Turbo Furnace

AERODYNAMIC MIXING

Flow patterns in a combustion configuration such as the Turbo Furnace are complex. In order to gain an understanding of flow and mixing conditions in the Turbo Furnace design, therefore, isothermal flow studies using cold air were conducted in a three dimensional (1/16th scale) model of a utility sized prototype. Mixing patterns in the lower furnace are related to both the structural dimensions of the furnace chamber and burner directional air vane positions. Isothermal velocity field measurements in the lower furnace for a given set of air vane settings are shown in Figure 3. The velocity vectors represent the two-dimensional flow pattern and mixing in a vertical plane at a burner centerline. The lower flow field is characterized by separating streamlines of looping trajectory with mixing occurring at the center of the furnace. This flow pattern is a result of the meeting and intersection of opposite burner streams. Measurements taken in vertical planes between burners reveal upward recirculating streamlines of higher velocity than that shown in Figure 4.

The flow pattern described here is similar to those observed by others in model studies on furnaces of similar configuration.[6] The overall flow field also conforms to the aerodynamic structure of pulverized coal flames observed in full scale Turbo units.

Although the flow is complex, a simplified mixing zone model can be formulated to describe Turbo Furnace mixing patterns. A schematic of a two dimensional furnace zone model is shown in Figure 4. Several recirculation and mixing zones are depicted. A portion of the combustion air flow is shown entering a final mixing zone above the burner. The amount of this air flow separation is controlled by burner directional vane postions.

The schematic shown in Figure 4 may also be used to illustrate the effect of staged combustion on the furnace flame structure. Staging is simulated in the model by the injection of air into the final mixing zone above the burners.

THE EFFECT OF BURNER/FURNACE VARIABLES ON NO_X

Because of the quantity of data and number of variables involved, multiple regression analysis was performed on the data sample to determine the influence of various operating and design parameters on the level of total NO_X emissions. The analysis indicates that the overall stoichiometric ratio, SR, is the single most important independent variable affecting the results. The burning area heat release, BAHR, is determined as the second principal factor. The BAHR, as defined in our earlier work[1,2] is the gross heat input to the furnace, divided by the surface area available for cooling the primary flame to below the point where thermal NO_X fixation reactions are quenched. This approach essentially utilizes the heat release rate as a measure of furnace flame temperature.

Regression results correlating NO_X emissions with SR and BAHR at similar directional air vane settings are shown in Figure 5. NO_X emissions are expressed in ppm by dry volume and adjusted to a common sample dilution of 3% oxygen. The correlaton includes test data from four of the units tested at various load conditions. These tests cover an excess air range represented by $1.15 \leq SR \leq 1.54$. It should be noted that all of the results included here represent unstaged combustion.

As shown in Figure 5, a linear correlation function provides the best overall fit to the test data. The equation predicts a decrease in NO_X as both excess air and the rate of heat release decrease. This relatively simple model which includes only two independent variables seems to explain a good deal of the data.

FUEL NITROGEN EFFECTS

Several coal types are also represented in the data. These coal types include both high and low sulfur bituminous coals and a western sub-bituminous coal.

Adding fuel nitrogen as an independent variable to the regression analysis does not significantly improve the correlation fit and does not explain the remaining scatter in the data.

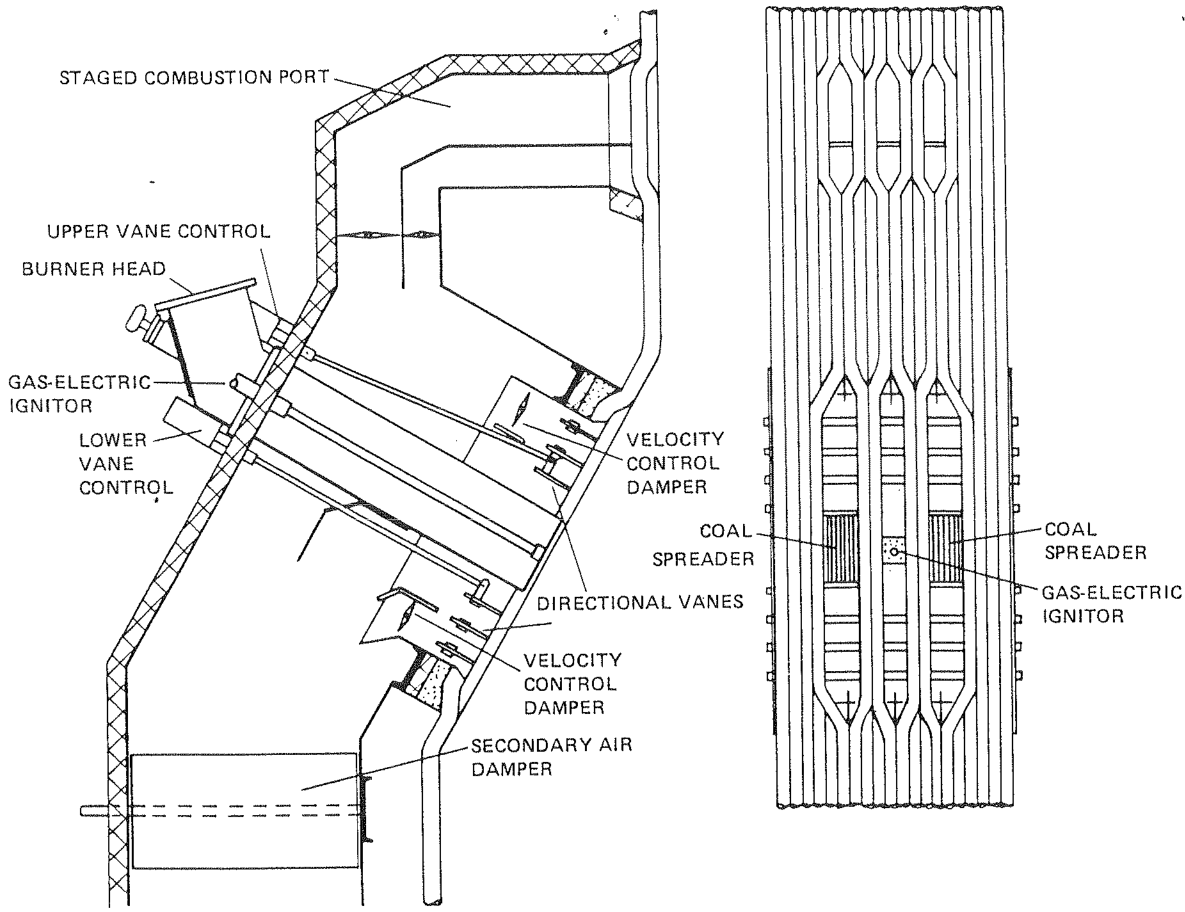

Figure 2 Riley Directional Flame Burner with Staged Combustion Ports for Coal Firing

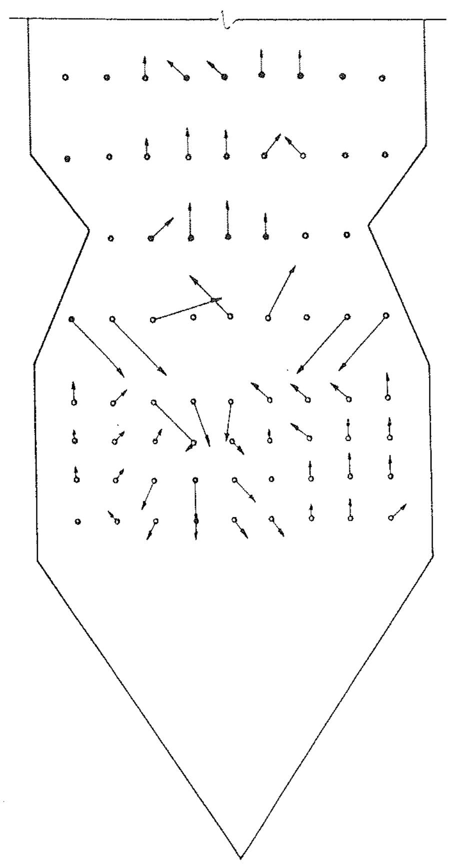

Figure 3 Lower Dry Bottom Turbo Furnace Velocity Field

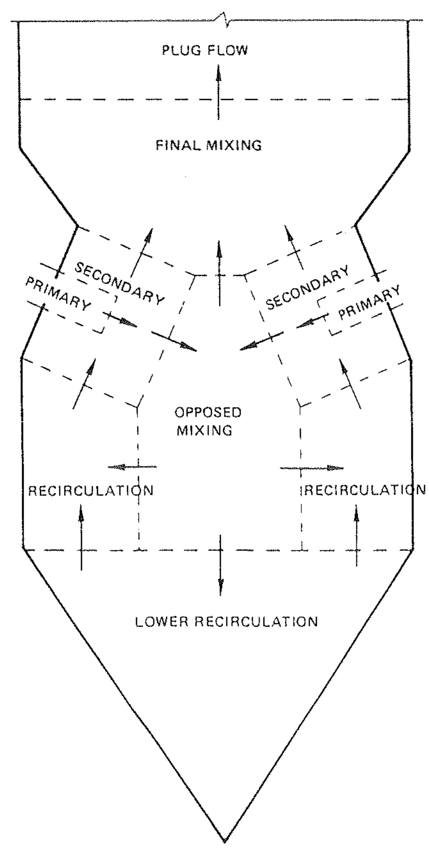

Figure 4 A Simple Turbo Furnace Mixing Zone Model

NO_X emission data plotted versus fuel nitrogen content is shown in Figure 6. A least squares fit through the entire data sample implies a weak and even slightly inverse relationship between these two variables. NO_X emissions for the low nitrogen sub-bituminous coal are in the same range as those for bituminous coals of higher nitrogen content. The results seem to confirm recent observations made by others[5,7] that NO_X emissions cannot be correlated with fuel nitrogen alone and that the conversion efficiency of fuel nitrogen to NO_X is inversely proportional to the weight percent of nitrogen in the coal.

EFFECT OF BURNER DIRECTIONAL VANE POSITION

As discussed earlier, the air fuel mixing history can be controlled to a degree by the use of directional vanes at the burner. The effectiveness of this method in controlling overall Turbo Furnace NO_X emissions is most clearly seen by examining the results for a single unit firing western sub-bituminous coal. Regression results for this data set are shown in Figure 7. The effect of aerodynamic changes in the flame structure are included along with excess air and heat release rate. The lower lines represent the optimum directional air vane position which produces the minimum NO_X flame conditions while the upper lines represent the non-optimum case. Directional vane positions which direct a portion of the secondary air to the final mixing zone above the burners, as well as to the lower mixing and recirculation zones, are shown to produce lower NO_X emissions. These zones have been identified previously in Figure 4.

STAGED COMBUSTION

Staged combustion achieved by the introduction of combustion air above the burners further increases the fuel/air ratio in the early stages of combustion. The locally fuel rich environment provided by this method reduces the conversion of both volatile nitrogen and char nitrogen to NO.[3] Thermal NO_X is also reduced as a result of lower peak flame temperatures.

The effect of this combustion technique on NO_X emissions measured at two different dry bottom Turbo units operating at normal full load conditions is shown in Figure 8. Both of the units represented operate on high volatile bituminous coal. The use of staged combustion ports reduces NO_X emissions to 0.6 pounds $NO_2/10^6$ Btu or less in each case.

FUEL NO_X MODEL

Understanding the mechanism of NO_X formation is important in developing a NO_X control strategy. As suggested throughout this paper the conversion of fuel bound to NO_X plays a significant role in NO_X formation in pulverized coal flames. In order to aid and extend the interpretation of empirical results it is helpful to separate the contribution of thermal and fuel generated NO_X from the overall emission level. The mechanism of fuel NO_X conversion in large pulverized coal flames is a complicated process. It has been shown[3,4] that fuel NO_X can originate from both volatile nitrogen combustion and char nitrogen combustion.

We have found that a relatively simple fuel NO_X model of the form

$$NOx_{fuel} = (a \times SR - b)\, N^{1/c}$$

where N is the fuel nitrogen content on a dry ash free basis and a, b, and c are constants with values greater than unity, provides a reasonable explanation of this conversion mechanism to our full scale data. The fractional exponent for fuel nitrogen results from an assumed inverse relationship between conversion efficiency and nitrogen content.

The importance of oxygen availability in the fuel nitrogen conversion process is reflected by the presence of the stoichiometric ratio SR in the model. Although this converson is controlled by local oxygen concentration in the early stages of the flame, the overall stoichiometry provides at least a first order estimate of these conditions in the Turbo Furnace flame.

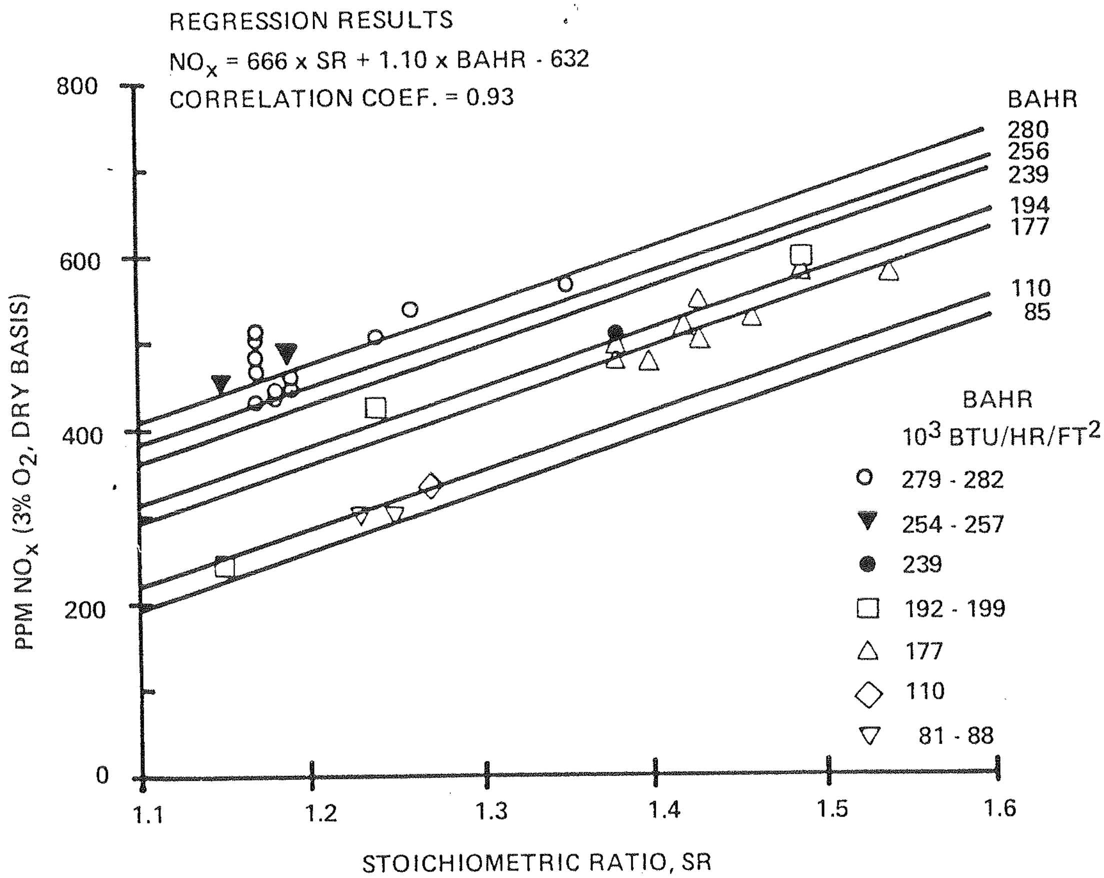

Figure 5 Correlation of NO_x Emissions with Stoichiometric Ratio and Burning Area Heat Release

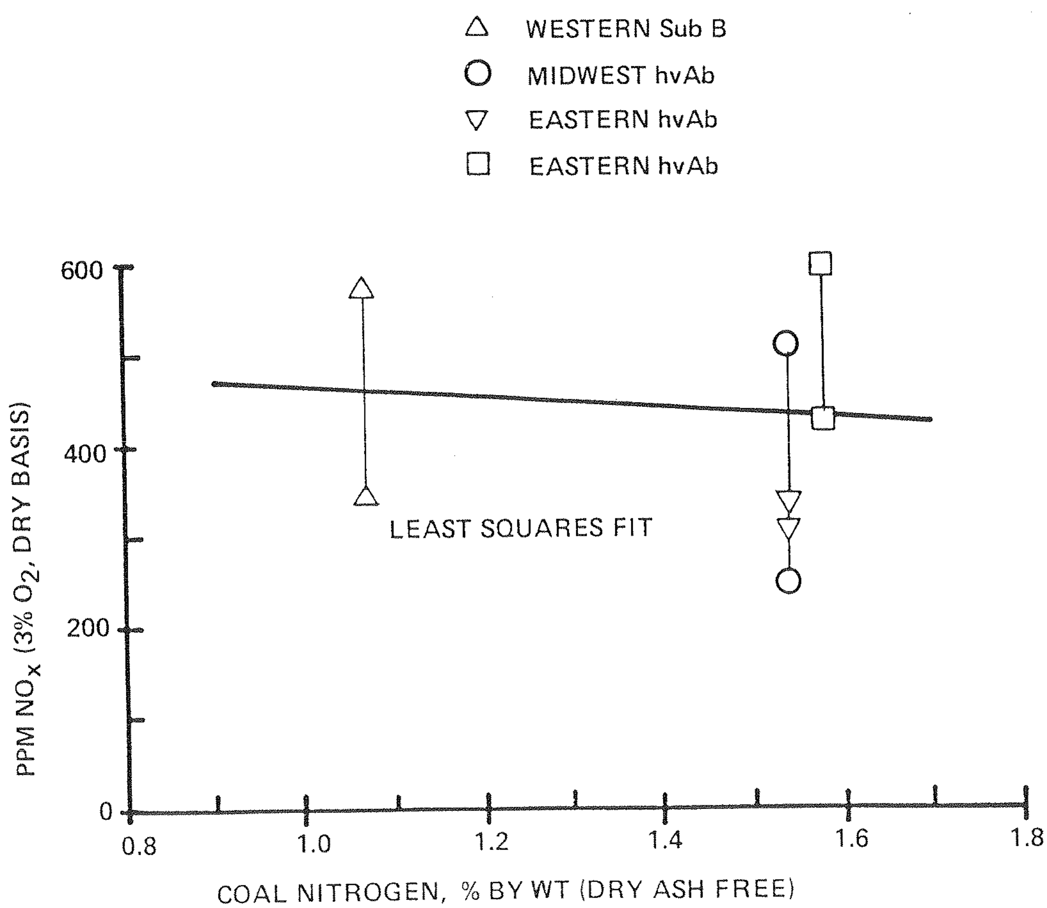

Figure 6 Effect of Coal Nitrogen on NO_x

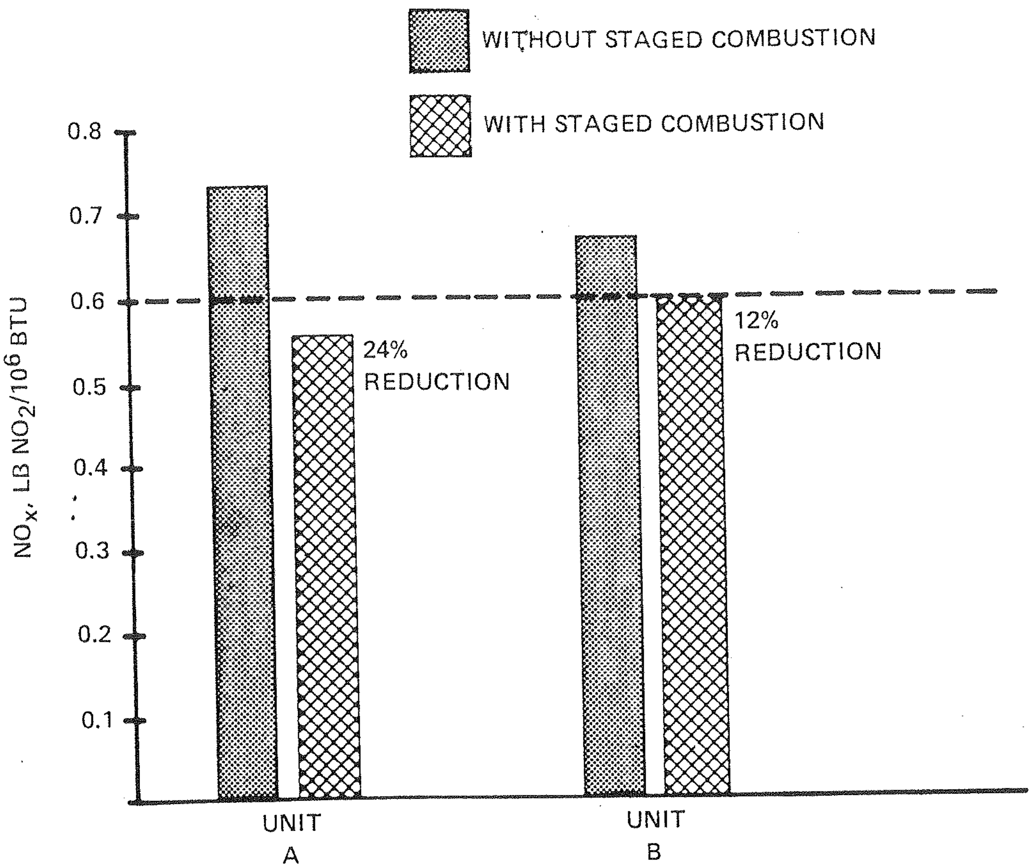

Figure 7 Effect of Directional Air Vane Position for a Single Unit Firing Western Sub-Bituminous Coal

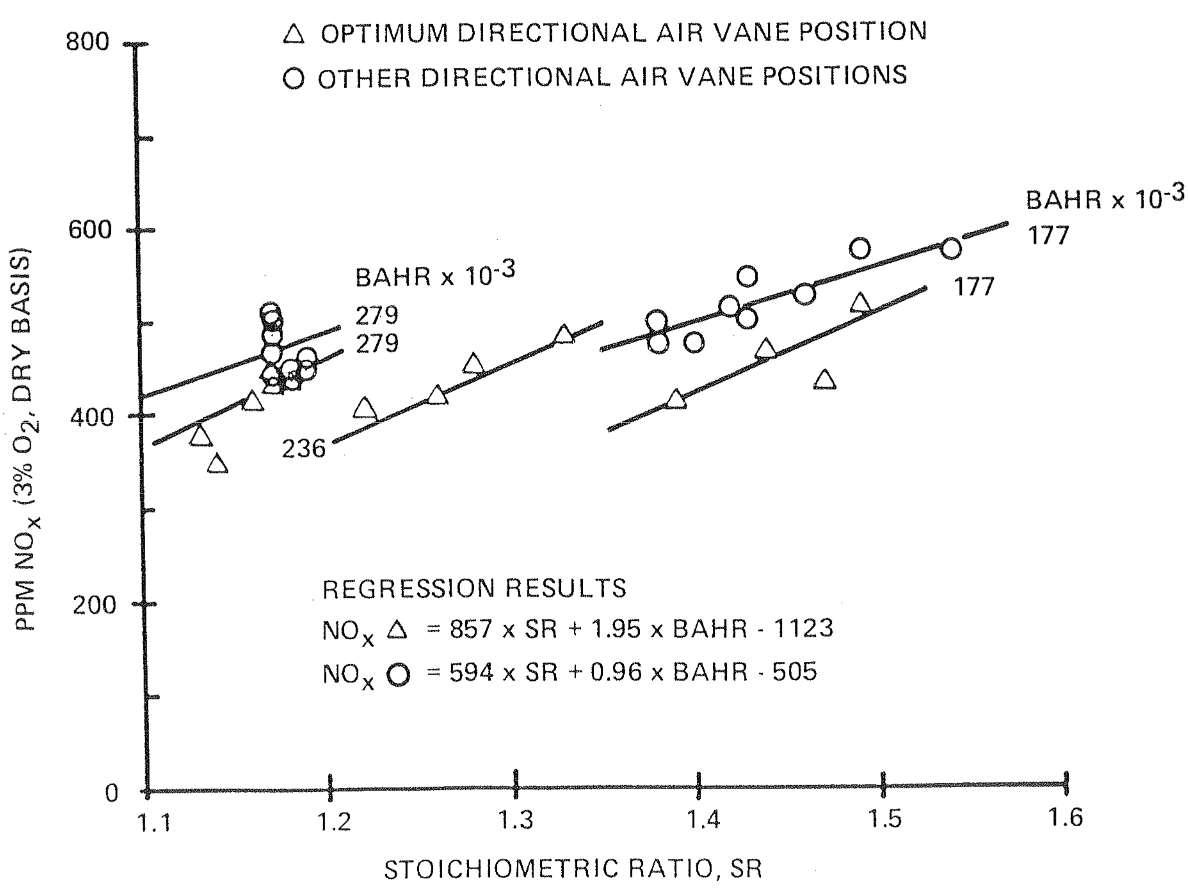

Figure 8 The Effect of Staged Combustion on NO_x Emission from Coal Fired Dry Bottom Turbo Furnaces

SUMMARY

The Riley Turbo Furnace offers a number of unique burner/furnace design features for limiting NO_x emissions from pulverized coal flames. Recent full scale testing has demonstrated the effectiveness of the dry bottom Turbo Furnace in controlling emissions on several U.S. coals. Future, more stringent NO_x regulations will require the use of more advanced combustion techniques such as a staged combustion. Tests have shown that the present dry bottom Turbo design equipped with staged combustion ports is capable of meeting EPA's proposed new standard of 0.6 pounds of NO_2 per million Btu on bituminous coal.

Improved Turbo Furnace NO_x prediction methods are being developed by Riley through an active testing and analysis program. The information obtained from this program is being used in the development of improved combustion techniques for meeting even more stringent NO_x regulations projected for the 1980's.

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