"Staged Combustion for NOx Reduction Using High Pressure Air Injection"

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Abstract: The effects on emissions by applying high-pressure air injection on rotary kilns to achieve effective mixing and staged combustion are presented. A technique of using the energy of high-pressure air jets to achieve cross-sectional mixing in a tertiary combustion zone in rotary kilns resulting in reduced excess air requirement for optimum combustion is described. An additional result of the mixing method is the creation of a sub-stoichiometric secondary combustion zone that reduces the emission of nitrogen oxides.

Introduction: There are numerous regulations providing the incentive to reduce nitrogen oxide emissions. Plants desiring to expand are faced with the Prevention of Significant Deterioration (PSD) criteria and Best Available Control Technology (BACT) requirements, and certain plants are being faced by Federal and State Implementation Plans (FIP and SIP's) requiring the reduction in NOx emissions due to concerns for the Regional Transport of Ozone. Additionally, the Regional Haze rule will bring in requirements for facilities not previously affected requiring Best Available Retrofit Technology (BART). Thus, the cement and lime industries are faced with continuing pressure to reduce the emissions per unit of product and are in dialog with the regulating agencies to find reasonable means to accomplish the objectives of the regulating agencies in a manner that allows continued economical operation of the facility.

The staging of combustion is a generally accepted means of managing NOx emissions. It shows up as a prescriptive technology in the "Alternative Control Techniques Document" (EPA ACT Document) and the "NOx Controls for the Cement Industry" (EPA NOx Report) (references 1 & 2). Additionally, there are new developments that are now available to enhance the staging of combustion. This is the injection of high pressure air into the hot process gas to achieve or enhance both the staging of combustion by managing the availability of oxygen in various zones of the kiln, and by also reducing the amount of excess oxygen to achieve a given level of completeness of combustion as measured by the CO concentration. The reduction of excess oxygen required is achieved by effectively mixing the cross section of the gas in the kiln or duct. This method of mixing also results in limiting the available oxygen in the primary combustion zone as a result of both reducing the excess air required and providing this excess air after the primary combustion zone. This technique can be applied in addition to using multiple fuel firing points on rotary kilns.

Staged Fuel Combustion (SFC): Staged fuel combustion (SFC) as a control technique is well documented in the regulatory references (1-4). Staged Fuel Combustion is the introduction of a portion of the fuel in other than the primary, hottest combustion zone of the kiln. By burning a portion of fuel at reduced temperature, some thermal NOx is avoided and there is possibly some interaction between localized reducing conditions at the secondary firing point and the NOx from the primary combustion zone that results in lower overall NOx emissions. The observed NOx reductions may also be a result of the cooling of the main flame due to the high excess air that results from the fuel substitution. Multiple fuel firing points are used in precalciner kilns, long kilns firing municipal waste, tires or hazardous waste at mid-kiln and in preheater kilns that are introducing tires onto the feed shelf. These means of mid-process firing have received favorable review with respect to NOx reduction in the EPA documents. The EPA NOx Report states that the addition of waste tires on the feed shelf reduces NOx emissions from preheater kilns by 30 to 40%. Similarly, long kilns equipped for mid-kiln firing of waste or tires were reported as achieving significant NOx reductions. From the EPA NOx Report, "In nine tests on dry kilns, the average reduction in NOx emissions was 33% with a range of 11% to 55%. In three tests on the wet kilns, the average reduction in NOx emissions 40%. It should be noted that the three kilns that are known to have CEMS all reported emission reductions of 45% or more." Figure 1 is a graphic tabulation of NOx measurement on long kilns with mid-kiln fuel addition showing NOx reduction. The kilns experiencing NOx reductions by the use of waste derived fuels were primarily motivated by the savings and revenue from substituting waste for the primary fuel and were not driven by the necessity for NOx management.

In cases where waste-derived fuels are not readily available or there is public resistance to the use of tires, lump coal could be used to achieve the same mechanism of control through staged combustion (with some regard for the coal volatility since the hydrocarbons from pyrolysis of the fuel play a role in the NOx reduction). The full potential of Staged Fuel Combustion for NOx reduction has not been fully evaluated since the bulk of data available is incidental to the energy recovery activities.

Staged Air Combustion (SAC): Staged Air Combustion is the multipoint introduction of combustion air. Staged air combustion used in addition to staged fuel firing will allow for the combustion of a portion of the fuel under sub-stoichiometric conditions to both minimize the formation of NOx from the fuel combustion and to provide reducing conditions to destroy NOx formed in the high temperature, primary combustion zone. Staged air combustion is can be achieved in precalciners by splitting the tertiary air so that the calciner fuel is burned under sub-stoichiometric conditions and the additional air to complete combustion is added later in the calciner vessel. However, to achieve significant NOx reduction, the reducing atmosphere needs to be created in the temperature zone of 1000 C to 1200 C as indicated by Conroy.[5] A limitation to the application of staged air combustion at the critical temperatures is the achievement of adequate mixing. By the use of high-pressure jets, energy can be added to the process gas to achieve the necessary mixing.

Development of High Pressure Air Injection: The high-pressure air technique to achieve mixing and staging of the air for combustion was initially developed for long kilns equipped with mid-kiln firing. There is a high incentive to increase the use of mid-kiln fuel because the mid-kiln fuel has not only fuel value also generates revenue from disposal fees. The limitation in the amount of mid-kiln fuel substitution is the loss of flame temperature at the primary burning zone as mid-kiln fuel is increased (the air-through calciner limitation). This loss of flame temperature is the same phenomena that air-through calciners experience, limiting the riser fuel-firing rate. Normally, a cement kiln operates with about 10% excess air to complete combustion. If 15% fuel substitution is done with tires, this results in an increase of excess air at the main flame to 25% (see Example 1. and Example 2.). The addition of mid-kiln fuel results in significant cooling and shortening of the main flame due to the higher excess air (which may be the primary explanation of the NOx reduction observed). Further fuel substitutions, as shown by Example 3, eventually result in flame temperatures insufficient to maintain stable kiln operation. Generally, kilns that have higher secondary air temperatures achieve higher fuel substitution rates for this reason. Wet kilns are typically limited to 15% to 20% substitution and dry kilns to 20% to 25% substitution due to limiting flame temperatures.

Some kilns needed to increase the kiln exit oxygen levels to control CO while burning fuels mid kiln. In examining this limiting factor, extensive computational fluid dynamic computer modeling was done on the atmospheric conditions in the calcining zone of the kiln. In retrospect, it is not surprising that the kiln gas in the calcining zone of a cement kiln is highly stratified. The gasses at the top of the kiln are hotter, 1300 to 1400 C, while the gasses coming off the calcining bed are only 850 C and have a molecular weight 50% higher than the combustion gasses and as a result have more than twice the density. With the significant differences in gas density, there is a tendency for the gasses to remain stratified as they pass through the kiln at over 10 meters per second. Measurements of oxygen levels in the back end of preheater or precalciner kilns confirm this predicted stratification. When one drops a tire or fuel module into the calcining zone of the kiln, it falls into this relatively cool pool of carbon dioxide and hot meal and does not immediately burn but pyrolysises over a period of several minutes. It is not surprising that even though there is enough oxygen in the kiln to complete combustion, there is some sneakage of carbon monoxide due to this stratification of gasses. If one could get enough energy into the kiln to do cross sectional mixing, a reduction in oxygen headroom to get a given CO performance would be possible.

The above considerations led to the development of the injection of high-pressure air into the kiln to provide the energy to do the mixing. Through computational fluid dynamic computer modeling, geometry was developed where the energy in an air jet would couple with the kiln gas, creating a rotational component to the kiln gas and effectively mix the injected air into the kiln gas and mix the kiln gas through the full kiln cross section. Depending on the pressure of air used, this could be accomplished with as little as 2% of the kiln gas. Air velocities of 100 to 200 meters per second are injected with a tangential vector. This velocity compares to the 10 to 15 m/sec kiln gas velocities. There is sufficient energy in the injected air to impart a rotational component to the kiln gas. The stratification is illustrated in Figure 2. The amount of kinetic energy in the injected air is about 0.3 kilowatt hour per metric ton of total gas in the kiln. The amount of air and the pressure are adjusted to specific applications to provide the energy necessary to achieve adequate mixing and the degree of combustion staging desired.

The injected air can function like tertiary air, which will allow higher mid-kiln fuel substitution rates. Note the increase in flame temperature calculated in Example 4 over that in Example 3. However, injecting ambient air at mid-kiln does displace hot air at the null point of the cooler, so generally the air injection is limited to 10% of the total combustion air. A careful distinction needs to be made between tertiary air and mixing air. The quantity of mixing air is intended to be about the same as the quantity of the excess air for combustion. The injected mixing air is principally to introduce energy into the process gas to achieve cross sectional mixing. The quantity is typically limited to provide only the excess air for combustion so as not to substantially move the point of heat release of the fuel. The principal function of tertiary air is to provide combustion air.

The air injection could be placed either uphill or downhill of the mid-kiln fuel introduction point with favorable results predicted with respect to fuel substitution rates. However, due to the growing interest in NOx control, the air injection system was placed uphill of the fuel feeding point in order to limit the oxygen available in the mid-kiln combustion zone where the temperatures are favorable for NOx destruction. Example 4 shows the effect on the kiln atmosphere of the injection of 10% of the combustion above the mid-kiln firing point. Note that the excess air at the main flame is reduced, restoring satisfactory main flame temperature at the higher fuel substitution rate. Additionally, the zone in the kiln between the mid-kiln injection point and the air injection becomes slightly reducing, enabling NOx destruction in the important temperature zone. Figure 3 illustrates the results of using high-pressure air injection on a long wet kiln. It shows the reduction of SO2 and CO while achieving a 50% reduction in NOx emissions while doubling the mid-kiln substitution rate. Figure 4 is a frequency distribution of the NOx data showing a shift in the baseline NOx levels required to make a satisfactory quality clinker.

Application of High Pressure Air Injection on Preheater and Precalciner Kilns: The high-pressure air injection was initially developed to increase the utilization of waste-derived fuels. However, the potential to reduce emissions was not overlooked. Preheater kilns are also in need of a retrofit NOx reduction technique. The staging of fuel combustion by riser firing is reported to have little benefit for NOx reduction. Nielson and Jepsen report that "preheater kilns firing finely ground fuel into the riser duct, the NOx content in the exhaust gas may increase on passing through the riser duct. As the NOx emissions from the kiln may also increase slightly due to an increased excess air rate, the total NOx emissions from the kiln system may increase when starting up riser firing with finely ground fuel."[6] However, the firing of coarse fuel such as tires on the feed shelf of preheater kilns is observed to reduce NOx.[7] When tires are not available, lump coal should perform as effectively.

The use of mixing air to create a rotational component and break up of the stratification at the feed end of a preheater or precalciner kiln may enhance the ability to add secondary fuels on the feed shelf. The rotation of the kiln gas minimizes stratification at the feed hood, potentially eliminating buildup problems and allowing increased coarse fuel use. Also, depending on the amount of fuel that continues to burn in the bed downhill of the air injection point, sub-stoichiometric conditions may also be achieved resulting in a reducing atmosphere in the critical temperature range for NOx destruction. Feed shelf firing of tires or lump coal, and high-pressure air injection is a means of retrofitting staged air combustion on preheater kilns. This type of retrofit may be particularly attractive for preheater kilns with satellite coolers that must reduce NOx emissions. For these kilns, conversion with tertiary air ducts is particularly costly due to the requirement to change out the cooler. The addition of lump coal or tires and high-pressure air injection would have a better cost efficiency per ton of NOx reduced than the addition of tertiary air duct and a precalciner vessel.

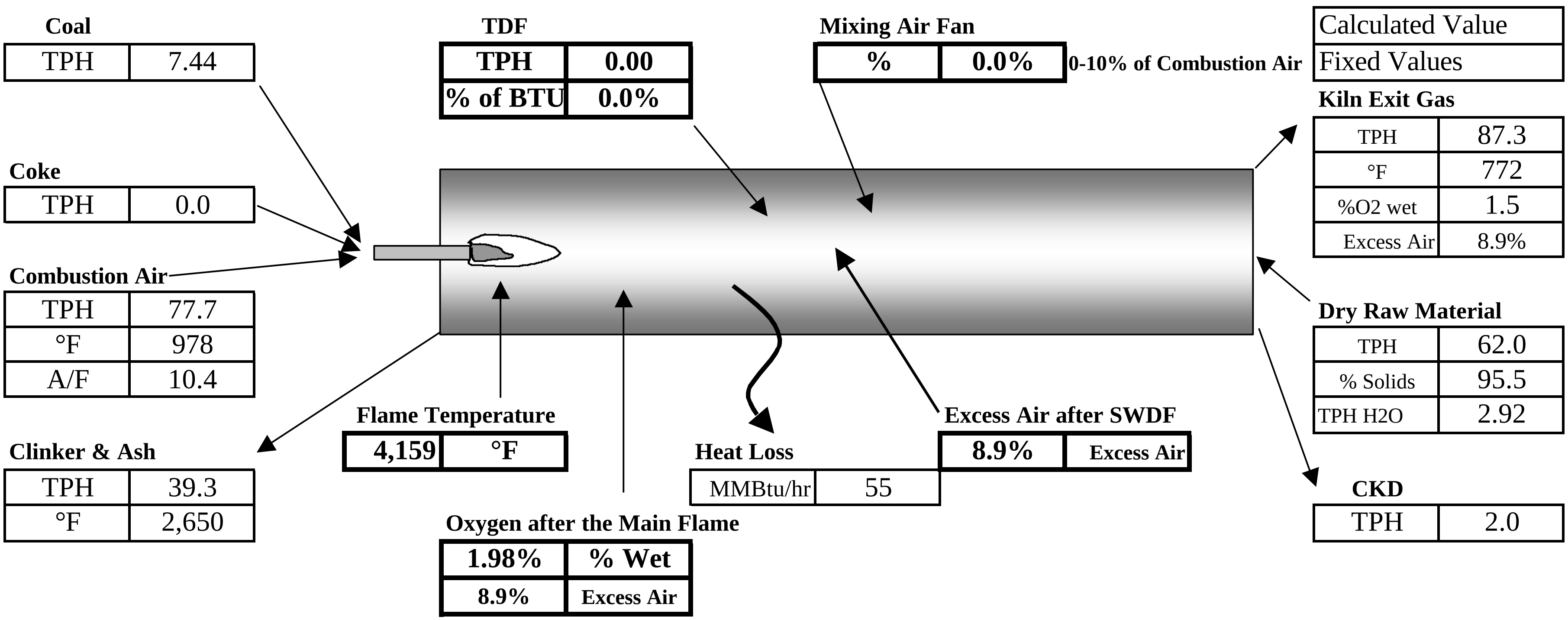
This retrofit is also applicable to the rotary kiln portion of precalciner kilns. For preheater and precalciner kilns, the amount of air injected is kept to the minimum required to introduce sufficient energy to achieve mixing. The theoretical fuel penalty for using ambient air instead of preheated air is a result of the difference in temperature of the air at the null point of the cooler and the ambient air. This hypothetical fuel penalty is small and can be more than cancelled out if the improved mixing allows operation at lower excess air levels for the same degree of completeness of combustion.

Lime Kilns - Staged air combustion for NOx control is also applicable to lime kilns. Since lime kilns can produce a satisfactory product with reducing conditions in the high temperature zone, staged air combustion can be effectively achieved with the mid-kiln introduction of high-pressure air. The calcining zones of lime kilns are also highly stratified, and the lime industry uses trefoils to break up the stratification to improve heat transfer. The idea of introducing energy in the middle of the process to create a rotation of the kiln gasses will actually prevent the formation of stratification and bring the hot gasses at the top of the kiln in direct contact with the limestone bed, adding a mechanism of heat transfer to the kiln. Even for preheater lime kilns, the rotation of the kiln gasses starting several diameters downhill of the kiln gas exit may serve to minimize operating problems in the preheater riser.

Excess Air Management: The use of high-pressure air to achieve cross sectional mixing of the gasses in the kiln is a means of reducing the excess air required for a given carbon monoxide level. To take advantage of reduced excess air requirement, it is important to implement process controls that take into account the trace gas emissions. Controlling at the minimum excess air level shows significant potential for NOx management. From the EPA NOx Report, "The use of state-of-the-art continuous emission monitoring systems and feedback control, excess air can be accurately controlled to maintain a level that promotes optimum combustion and burning conditions in addition to lowering NOx emissions."[2] A study on the effect of excess air on NOx emissions on a precalciner kiln is documented in a report by Hansen.[8] Any NOx management technique must be operated and evaluated using emission measurements and feed back control to be effectively used and accurately evaluated.

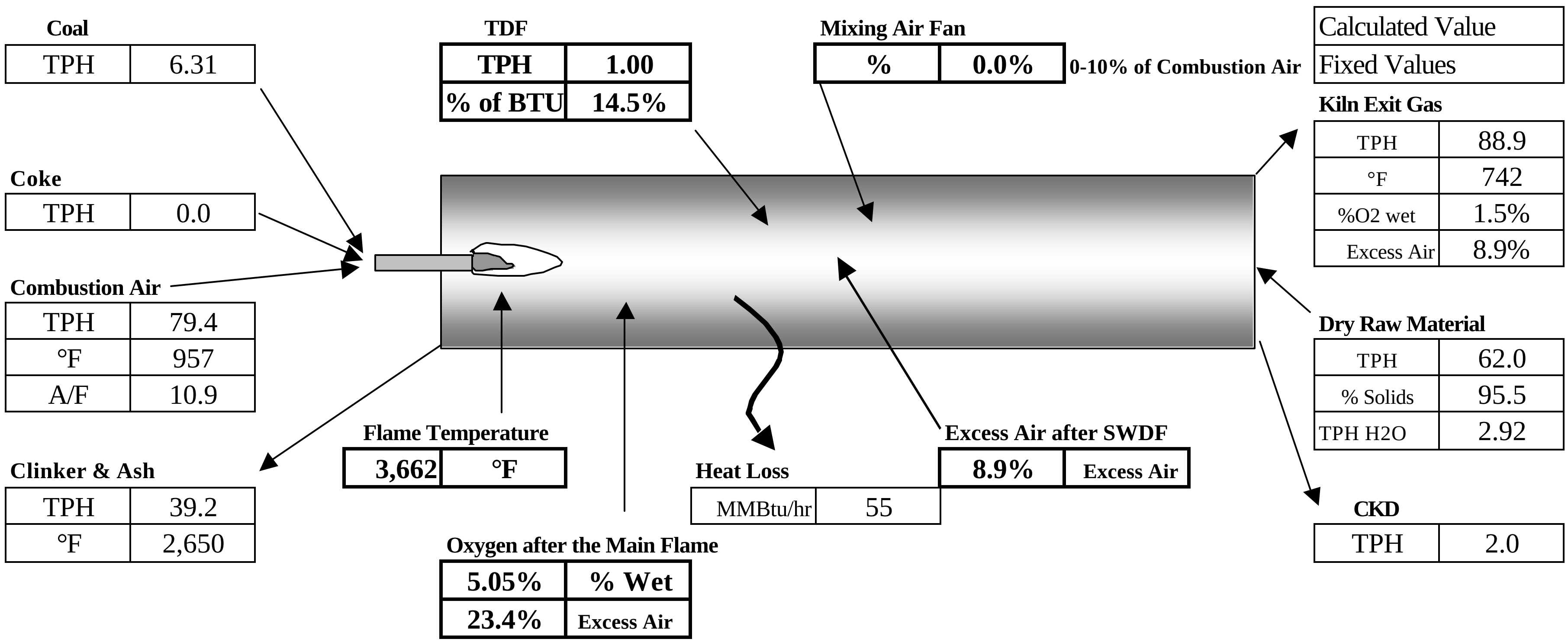
Conclusion: Staged air combustion is an available retrofit NOx control technology for long, preheater and precalciner cement kilns and lime kilns. For cement kilns, this technique is used with staged fuel addition using lump coal or waste-derived fuels such as tires introduced mid-kiln or on the feed shelf. For mineral processing kilns that can tolerate reducing conditions in the hot zone, like lime kilns, the air injection technique can be used alone without the addition of secondary fuel. The air injection technique reduces NOx by limiting the availability of oxygen in a secondary combustion zone and by reducing the overall excess oxygen required to achieve optimum combustion by cross section mixing of the kiln gas. Particularly effective NOx reduction is achieved when the reducing zone can be created in the temperature range of 1000 C to 1200 C. The air injection technique is a practical means of retrofitting a kiln to exploit this mechanism of NOx control, and when waste fuels are available, NOx control can be quite economically implemented.

Example 1

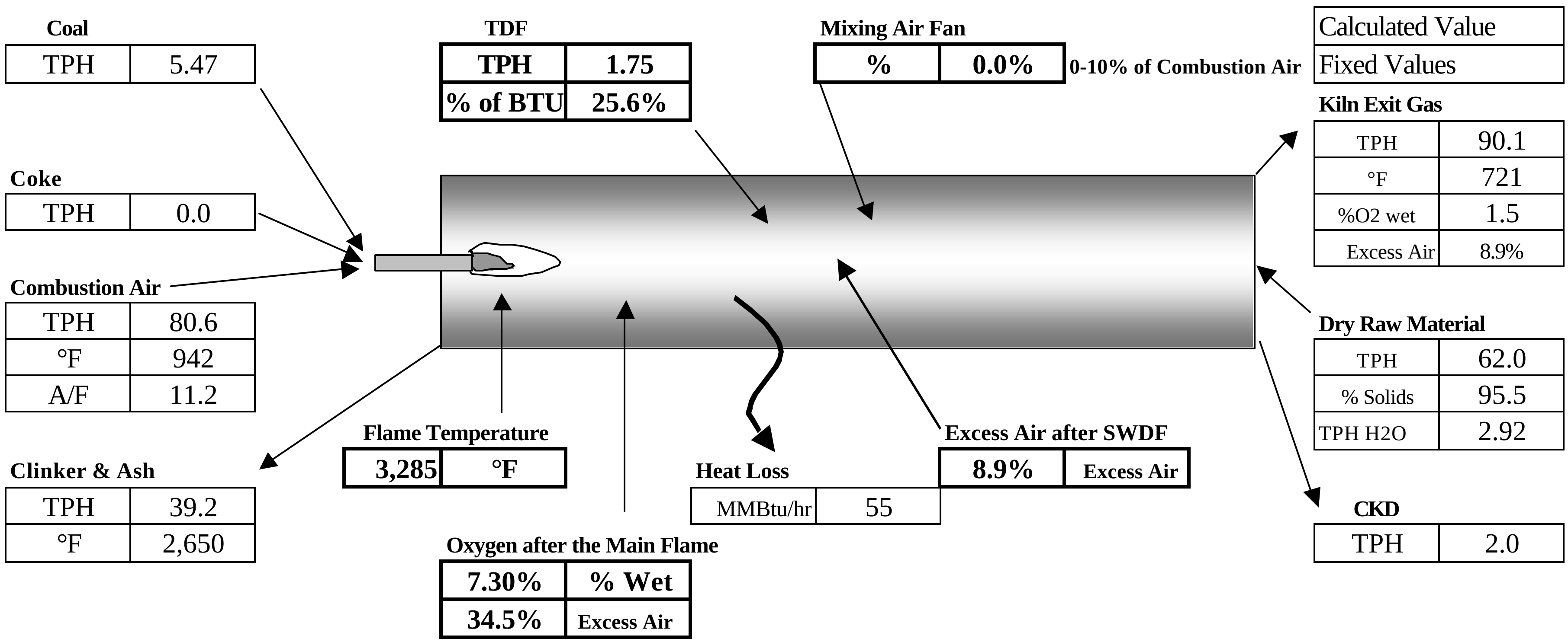


Coal
TPH 7.44
TDF
TPH 0.00
% of BTU 0.0%
Mixing Air Fan
% 0.0%
0-10% of Combustion Air
Calculated Value
Fixed Values
Kiln Exit Gas
TPH 87.3
°F 772
%O2 wet 1.5
Excess Air 8.9%
Coke
TPH 0.0
Combustion Air
TPH 77.7
°F 978
A/F 10.4
Dry Raw Material
TPH 62.0
% Solids 95.5
TPH H2O 2.92
Flame Temperature
4,159 °F
Excess Air after SWDF
8.9% Excess Air
Clinker & Ash
TPH 39.3
°F 2,650
Heat Loss
MMBtu/hr 55
CKD
TPH 2.0
Oxygen after the Main Flame
1.98% % Wet
8.9% Excess Air

Example 2


Coal
TPH 6.31
Coke
TPH 0.0
Combustion Air
TPH 79.4
°F 957
A/F 10.9
Clinker & Ash
TPH 39.2
°F 2,650
TDF
TPH 1.00
% of BTU 14.5%
Flame Temperature
3,662 °F
Oxygen after the Main Flame
5.05% % Wet
23.4% Excess Air
Mixing Air Fan
% 0.0%
0-10% of Combustion Air
Heat Loss
MMBtu/hr 55
Excess Air after SWDF
8.9% Excess Air
Calculated Value
Fixed Values
Kiln Exit Gas
TPH 88.9
°F 742
%O2 wet 1.5%
Excess Air 8.9%
Dry Raw Material
TPH 62.0
% Solids 95.5
TPH H2O 2.92
CKD
TPH 2.0

Example 3


Coal
TPH 5.47
Coke
TPH 0.0
Combustion Air
TPH 80.6
°F 942
A/F 11.2
Clinker & Ash
TPH 39.2
°F 2,650
TDF
TPH 1.75
% of BTU 25.6%
Flame Temperature
3,285 °F
Oxygen after the Main Flame
7.30% % Wet
34.5% Excess Air
Mixing Air Fan
% 0.0%
0-10% of Combustion Air
Heat Loss
MMBtu/hr 55
Excess Air after SWDF
8.9% Excess Air
Calculated Value
Fixed Values
Kiln Exit Gas
TPH 90.1
°F 721
%O2 wet 1.5
Excess Air 8.9%
Dry Raw Material
TPH 62.0
% Solids 95.5
TPH H2O 2.92
CKD
TPH 2.0

Example 4

Calculated Value
Fixed Values

Coal

TPH	5.47

TDF

TPH	1.75
% of BTU	25.6%

Mixing Air Fan

%	10.0%	0-10% of Combustion Air

Coke

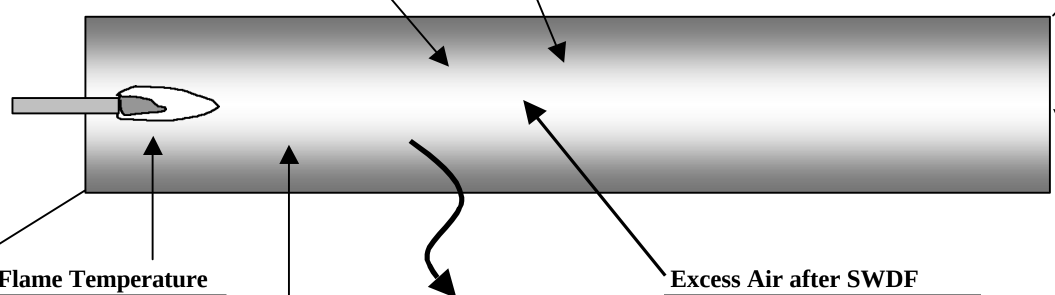
TPH	0.0

Combustion Air

TPH	72.6
°F	1,039
A/F	10.1

Kiln Exit Gas

TPH	90.1
°F	721
%O2 wet	1.5
Excess Air	8.9%



Dry Raw Material

TPH	62.0
% Solids	95.5
TPH H2O	2.92

Flame Temperature

3,597	°F

Excess Air after SWDF

-1.1%	Excess Air

Clinker & Ash

TPH	39.2
°F	2,650

Heat Loss

MMBtu/hr	55

CKD

TPH	2.0

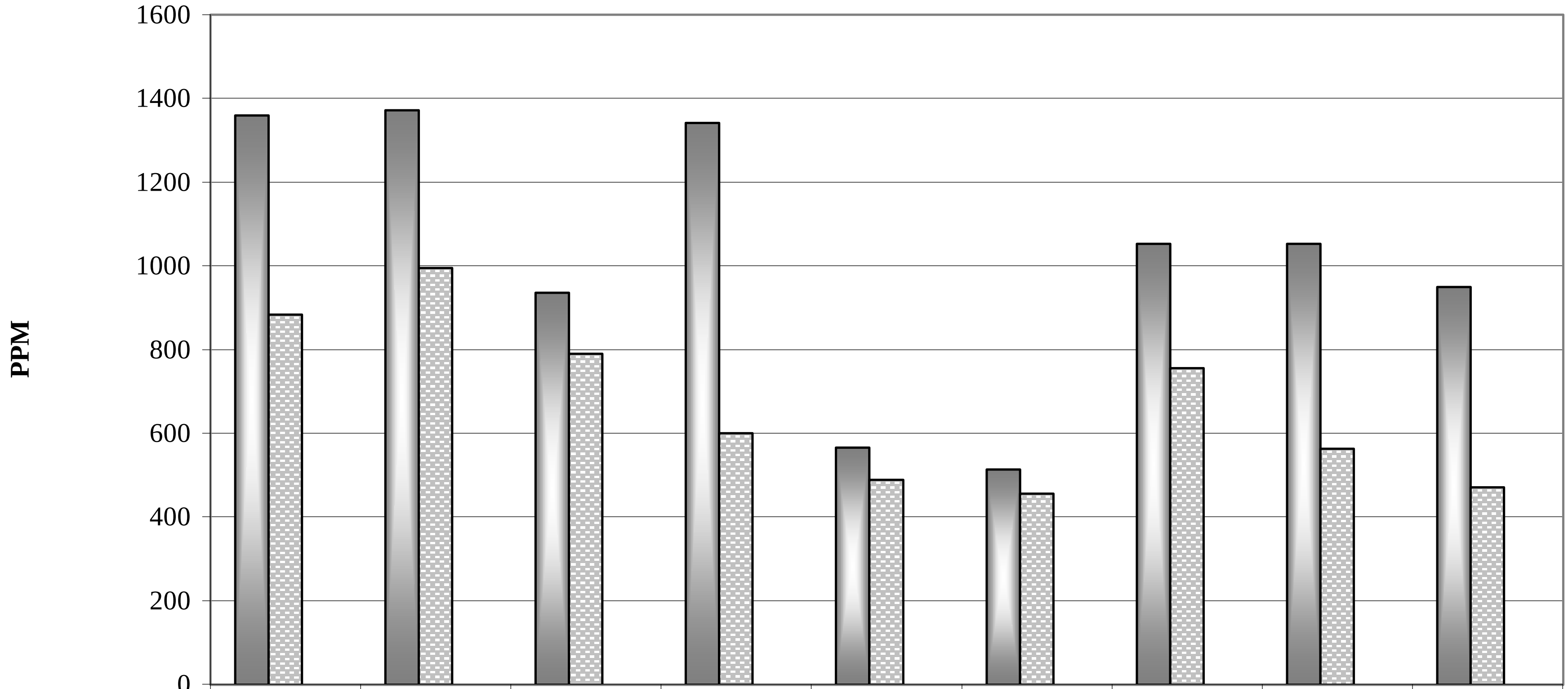
Oxygen after the Main Flame

5.85%	% Wet
24.5%	Excess Air

Heat Loss Due to Ambiant Air At Mid Kiln in MMBTU/hr	-2.2
Heat Loss As A Percentage of Total Heat Input	-1.06%

Figure 1
Nox Reduction on Nine Kilns Using Mid-Kiln Firing

NOx Reduction at Cement Kilns
Feeding Whole Tires Using the Cadence Mid-Kiln Technology



	Plant #1	Plant #2	Plant #3	Plant #4	Plant #5 Kiln #1	Plant #5 Kiln #2	Plant #6 9% Tires	Plant #6 15% Tires	Plant #6 23% tires
Baseline	1359	1372	936	1342	565	513	1053	1053	949
With Mid-Kiln Fuel	883	994	790	600	488	456	755	562	471
Percent Reduction	35.0%	27.6%	15.6%	55.3%	13.6%	11.1%	28.3%	46.6%	50.4%

Baseline   With Mid-Kiln Fuel

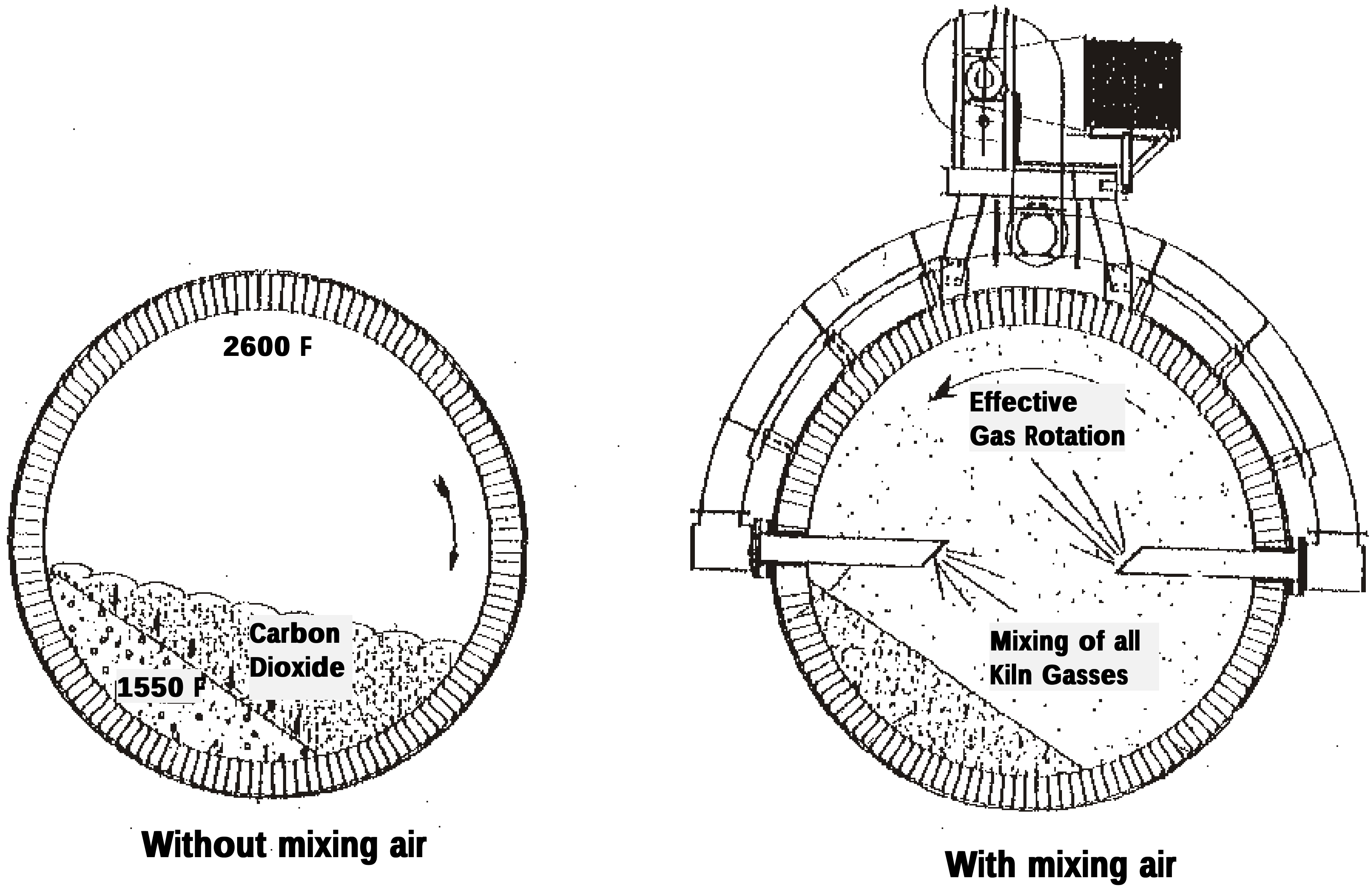


Figure 2
Illustration of the Stratification of Gasses in the Calcining Zone and the Effect of Mixing air

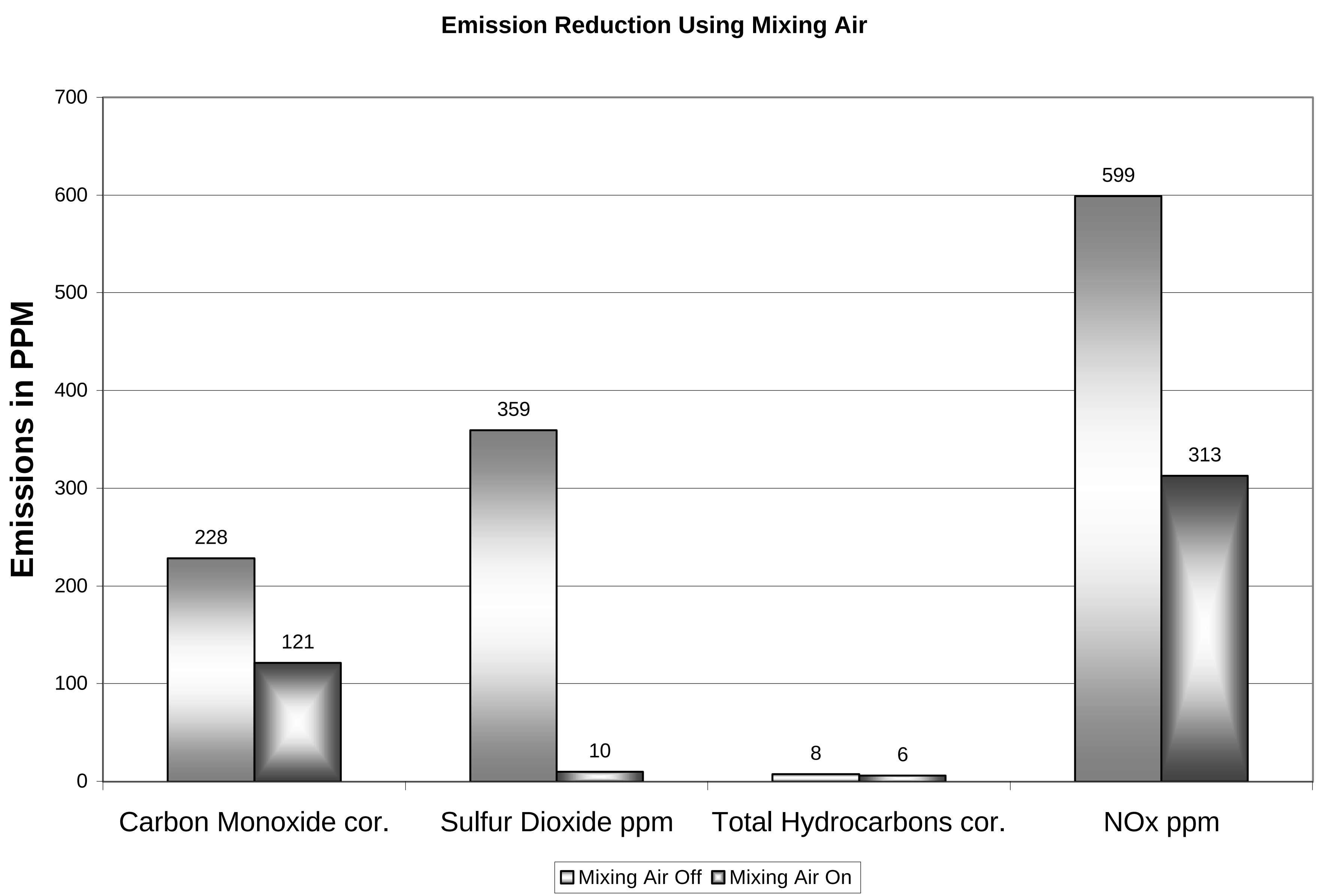


Figure 3

Effect of Mixing Air on Carbon Monoxide, Sulfur Dioxide, and Nitrogen Oxide Average Concentration

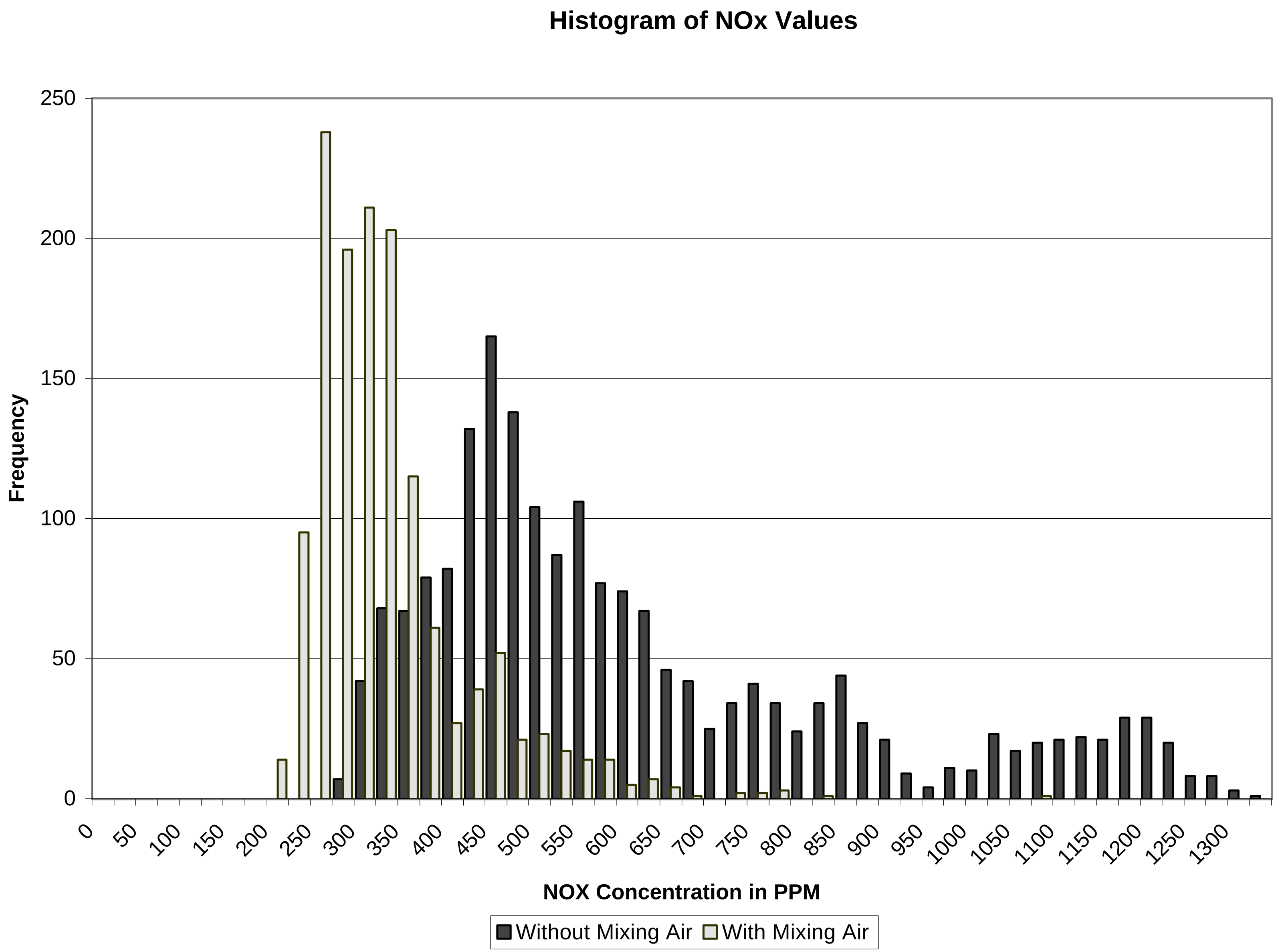


Figure 4

Frequency Distribution of NOx Concentrations With and Without Mixing Air

References:

1. "Alternative Control Techniques Document-Control of NOx emissions from Cement Manufacturing," U.S. EPA, Office of Air Quality and Standards, February 1993.
2. "NOx Control Technologies for the Cement Industry," U.S. EPA, Office of Air Quality Planning and Standards, Ozone Policy and Standards Group, September 19, 2000.
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4. 40 CFR Parts 52 and 98, Federal Implementation Plans to Reduce the Regional Transport of Ozone; Proposed Rule," October 21, 1998.
5. G.H. Conroy, "Low NOx Pyro-Systems Design and Operation," *34th Annual IEEE Cement Industry Technical Conference,* Dallas, Texas, May 10-14, 1992, pp303-330.
6. Nielsen, P. B., and O.L. Jepsen. *An overview of the Formation of SOx and NOx in Various Pyroprossing Systems.* Presented at the IEEE Cement Industry Technical Conference XXXII, Fl. May 22-24, 1990.
7. Shumway, D.C. *Mitsubishi Cement Corporation's Cushenbury Plant* presented at the IEEE West Coast Cement Industry Conference. Victorville, CA Oct 1995.
8. Hansen, E.R., "The Use of Carbon Monoxide and Other Gases for Process Control," IEEE Transactions on Industry Applications, Vol. IA-22, NO. 2, March/April 1986.

Figures:

1. NOx Reduction on Nine Kilns Using Mid-Kiln Firing.
2. Stratification of Kiln Gasses and Mixing Illustrated
3. Emission Results With and Without Mixing
4. NOx Histogram With and Without Mixing

Examples:

1. Baseline Flame Temperature without Mid-kiln Fuel or Mixing
2. Flame Temperature with 15% Mid-kiln Fuel Substitution
3. Flame Temperature with 25% Mid-kiln Fuel Substitution
4. Flame Temperature with 25% Mid-kiln Fuel Substitution and 10% Mixing Air