rside - GH

l Long Dry

TECHNICAL REPORT ON THE DEMONSTRATION OF THE FEASIBILITY OF NOx EMISSIONS REDUCTION AT RIVERSIDE CEMENT COMPANY, CRESTMORE PLANT

Reference 2
Long Dry Kiln
Primarily NO_x & SO_2 data. Reports in attachment C not written clearly enough to assure more than 1 test.

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Riverside Cement Company

John Croom, Ph.D.
Quantitative Applications

January 13, 1986

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B. E. M. Gartner, Portland Cement Association, Nitrogenous Emissions From Cement Kiln Feeds, June 7, 1983.

C. South Coast Air Quality Management District, California Air Resources Board, KVB, Inc., Historical Source Test Reports, Conducted at Riverside Cement Company, Crestmore Plant.

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E. Commercial Testing & Engineering Company, Coal Ultimate Analyses, November 25, 1985, and August 28, 1985.

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SECTION 1.0

INTRODUCTION

1.1 OVERVIEW

In January 1982, the South Coast Air Quality Management District (SCAQMD) adopted Rule 1112 (see Attachment A), with the goal to reduce emissions of nitrogen oxides (NOx) from gray cement kilns to 3.1 pounds of NOx per ton of clinker produced (pounds per ton). This goal was intended to achieve a 40 percent reduction in NOx emissions from a baseline emission rate calculated from source tests by the California Air Resources Board (CARB) in 1981.

The Rule was drafted to allow the cement manufacturers in the South Coast Air Basin (Basin) to demonstrate through research whether or not a 40 percent reduction is feasible with reasonably available control technology. Rather than becoming effective immediately, Rule 1112 contains a provision that requires the Executive Officer to hold a public hearing in January 1986 to review evidence as to the feasibility of the NOx emission limit established by the Rule. If this emission limit is not supported by the evidence submitted, the Executive Officer must modify Rule 1112 to the extent supported by the evidence.

In response to Rule 1112, Riverside Cement Company (RCC), Riverside, California, undertook an extensive program of research, engineering, plant redesign, and NOx emission monitoring (Crestmore NOx Research Project) for the purpose of determining the feasibility of reducing NOx emission from its gray cement kilns. This redesign and modification resulted in a 26 percent reduction from the pre-1982 emission rate of the Crestmore kilns. In addition, RCC found that the CARB NOx emission baseline of 5.2 pounds per ton used by the SCAQMD in developing the Rule 1112 emission limit was not an accurate estimate of the average NOx emissions from cement kilns in the Basin. This research provides data that establishes that the CARB baseline for cement kilns in the Basin is more accurately 7.6 pounds per ton and that the baseline for the kilns at RCC's Crestmore facility was 7.8 pounds per ton. Also this research on process and combustion modifications made to the Crestmore Number Two kiln provides evidence to support amendment of the rule limiting kiln emissions to 6.4 pounds per ton (monthly average).

RCC accomplished this reduction in NOx emissions through the following tactics and modifications to its Number Two kiln:

1) greater use of secondary air from the clinker cooler for combustion and redesigned heat exchange equipment to reduce fuel consumption and therefore NOx emissions per ton of clinker;

2) use of an indirect coal firing system to reduce oxygen contributed by primary carrier air and primary air temperature and therefore NOx emissions;

3) use of a redesigned burner pipe to improve flame control and therefore reduce NOx emissions;

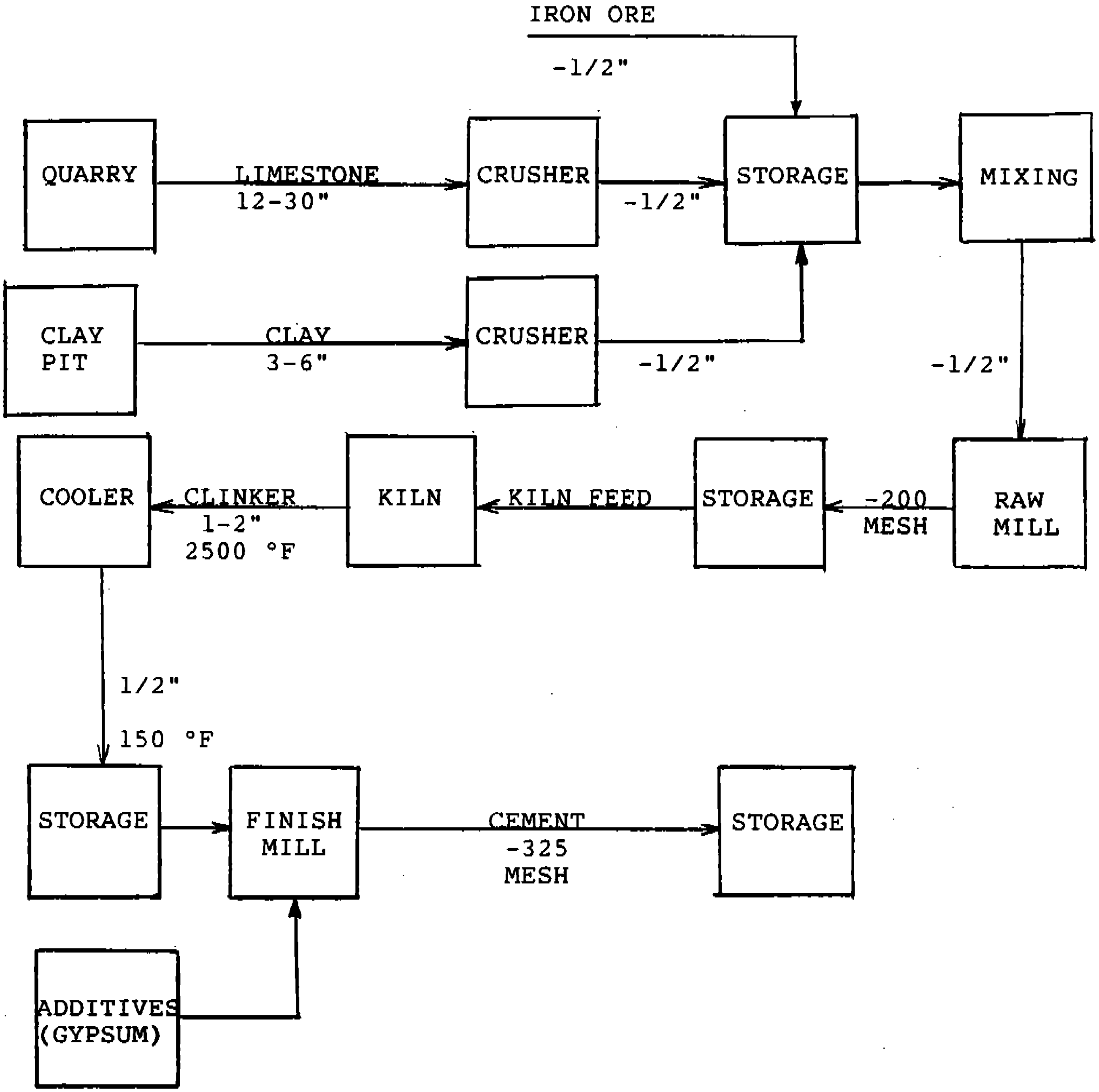
4) the use of improved instrumentation, raw material chemical uniformity, flame control and personnel training to improve kiln stability in order to reduce NOx emission peaks associated with highly variable kiln operation.

To evaluate the effectiveness of its NOx modification program, RCC subjected the data collected at the Crestmore plant to statistical analysis. The statistical hypotheses (H_o = null and H_a = alternative) for testing the results of these modifications on the emissions of NOx, stated in statistical terms, are:

H_o: Post redesign and modification NOx emissions are equal to pre-modification emissions; and

H_a: Post redesign and modification NOx emissions are less than pre-modification emissions (one tailed test).

In the remainder of the introduction, RCC has provided a description of the cement manufacturing process (see Figure 1.1) including information about the complexity of the physical and chemical changes that occur in the production of cement (see Section 1.2). Also provided is a brief explanation of NOx formation, and in particular the formation of NOx in cement kilns (see Section 1.3). Section 1.4 contains a brief history of NOx emissions from the Crestmore plant. Finally, Section 1.5 summarizes the existing research regarding NOx emissions from cement kilns.



CRESTMORE PROCESS FLOW

Figure 1.1

1.2 CEMENT MANUFACTURING PROCESS DESCRIPTION

The physical processes are primarily size reduction and blending. The chemical processes are calcination and sintering of the powdered and blended raw materials. Calcination is the thermal decomposition of calcium carbonate with the evolution of carbon dioxide. Sintering is the partial liquefication of the raw materials with resultant chemical reactions occurring that produce cement clinker. These physical and chemical processes consume approximately 130 KWH and 5 million BTU per ton of cement produced.

The raw materials provide the basic chemical compounds which are combined into complex minerals during the manufacturing process. Limestone supplies calcium carbonate; clay supplies aluminum oxide, silicon dioxide, and some iron oxide; and mill scale or iron ore supplies the remaining quantity of iron oxide. At the Crestmore plant, the raw materials are blended and mixed at a production rate of approximately 300 tons per hour (tph). These raw materials are then ground in a mill at a production rate of about 200 tph and thoroughly mixed in batches of approximately 1000 tons. The raw materials are supplied to the kiln at a rate of approximately 90 tph which results in a clinker production rate of approximately 60 tph.

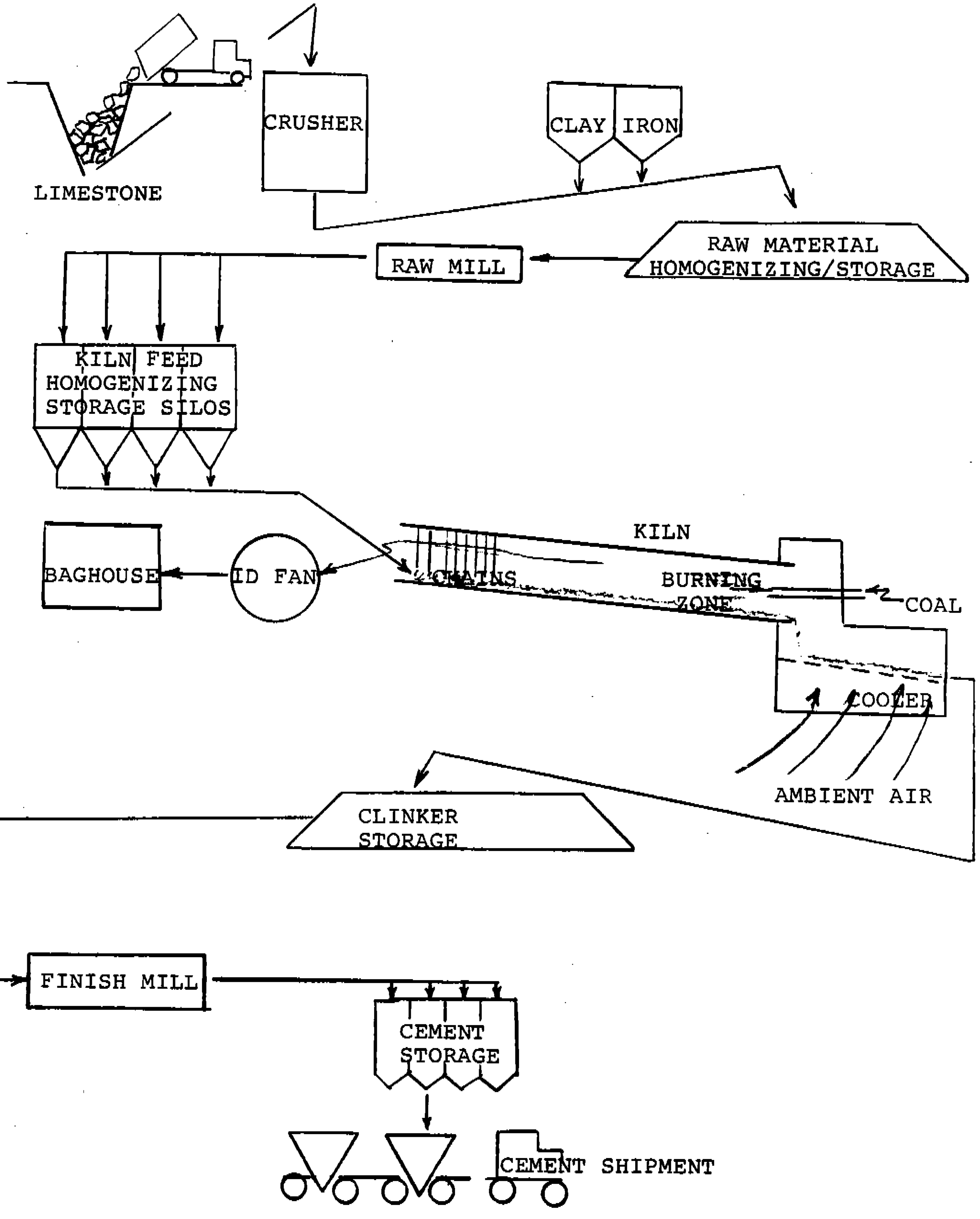
The cement manufacturing process at Crestmore may be described fundamentally by four distinct operations: crushing, raw grinding, pyroprocessing, and clinker grinding (see Figure 1.1). A brief description of each of these four operations is presented below.

1.2.1 Raw Material Crushing

Limestone is the principal raw material used in cement manufacturing, comprising over 80 percent of the total raw materials required. It is removed from natural deposits by drilling and blasting to produce boulders 12 to 30 inches in diameter. Two stage crushing is then used to reduce this material, first to less than 6 inches in diameter in a primary crusher and then to less than one-half inch in diameter in a secondary crusher (see Figure 1.2).

Fifteen percent of the total raw material is clay which supplies the silicon dioxide and aluminum oxide. Clay is mined with a front end loader and transported by truck to the Crestmore plant where a crusher is used to reduce the clay to less than one-half inch in diameter (see Figure 1.2).

The final raw material is iron ore, which comprises 1 to 3 percent of the total raw material requirement. Iron is delivered to the Crestmore plant by truck and is pre-sized to less than one-half inch in diameter (see Figure 1.2).



CEMENT PLANT SCHEMATIC

Figure 1.2

1.2.2 Raw Material Grinding

At Crestmore, the three raw materials (limestone, clay, and iron ore) are proportioned according to chemical requirements and mixed prior to grinding. Proportioning occurs when the three raw materials are discharged onto a belt conveyor at predetermined, fixed rates. For example, if the total proportioning rate for the raw materials was 400 tph, limestone would be placed on a belt conveyor at a rate of about 330 tph, clay would then be placed on this same belt conveyor at a rate of about 60 tph, and iron ore would be placed on the belt conveyor at a rate of 10 tph. The mixing occurs when the raw materials on the belt conveyor are deposited into several hundred horizontal layers on a storage pile containing as much as 30,000 tons of raw materials. A bucket wheel reclaimer then cuts vertically through these layers when supplying the raw milling system, further mixing the raw materials (see Figure 1.2).

In the raw mill, steel balls, 1 to 3 inches in diameter, reduce the minus one-half inch raw material to minus 200 mesh (300 particles to the inch). Following the raw mill, high pressure air is used to blend the raw material, in the storage silos (see Figure 1.2).

1.2.3 Pyroprocessing

In the kiln the metal oxides contained in the raw materials are transformed by pyrolysis into mineral compounds with cementitous properties. The raw materials are introduced at the upper end of a 15-foot diameter and 530-foot long rotary kiln (see Figure 1.2) heated by counter current hot gases generated by coal combustion at the lower end. NOx is formed at the lower end in this combustion zone.

The raw material enters the kiln as a dry powder at a temperature of about 100°F. It passes through a system of chains (see Figure 1.2) which results in a rapid heat exchange between the hot (1600°F) combustion gases and the cooler raw material (see Section 3.1.1). As the raw material slowly moves through the kiln, it gradually heats to a calcination temperature of approximately 1650°F. As the calcined material is moved to the lower, or firing, end of the kiln, it heats further to its sintering temperature (2400 to 3000°F). Chemical reactions between the calcium oxide, silicon dioxide, aluminum oxide, and iron oxide occur at the sintering temperature to produce the four primary cement compounds:

1) tricalcium silicate,
2) dicalcium silicate,
3) tricalcium aluminate, and
4) tetracalcium aluminoferrite.

The resulting product, called clinker, exits the kiln at approximately 2500°F and is cooled by forcing ambient air through the bed of clinker. About one-third of this heated air is used as combustion air. A crusher at the discharge point of the clinker cooler reduces the clinker to a size of less than one-half inch in diameter.

1.2.4 Clinker Grinding

The final step in the cement process is finish grinding. The clinker, with minor additives (primarily gypsum to control the rate of hydration), is fed into a finish mill where steel balls, 1 to 3 inches in diameter grind these materials to minus 325 mesh (600 particles to the inch).

1.3 FORMATION OF NOx

1.3.1 General Discussion

Nitric oxide (NO) and nitrogen dioxide (NO_2), collectively referred to as NOx, are formed during fuel combustion. High temperatures (2800°F and above) (Fleming et al. 1980) are required to disassociate nitrogen and oxygen molecules into radicals; only after disassociation, can NOx formation occur, as shown in Equations 1.1 through 1.4 (Enkegaard 1979):

$O_2 \longrightarrow 2O$ Equation 1.1

$N_2 \longrightarrow 2N$ Equation 1.2

$O + N_2 \longrightarrow NO + N$ Equation 1.3

$N + O_2 \longrightarrow NO + O$ Equation 1.4

A limiting factor in NOx formation is the amount of oxygen in the combustion zone. Nitrogen composes 79 percent of the air introduced into the kiln and oxygen composes only 21 percent. The fuel combustion reaction itself consumes oxygen but does not require nitrogen; therefore, the oxygen in the air is depleted before nitrogen. In addition, the fuel combustion reaction requires a lower heat of initiation than the nitrogen-oxygen reaction that forms NOx. Therefore, combustion is completed (i.e., has consumed its requisite amount of oxygen) before the nitrogen-oxygen reaction forming NOx. Thus, the availability of oxygen in the combustion zone limits the nitrogen-oxygen reaction.

1.3.2 NOx Formation In The Cement Manufacturing Process

Nitrogen is the most abundant element in the air (79 percent) and also occurs in the fuel and raw material used in cement production. However, only a small percentage of the nitrogen contained in these sources, particularly in air, is ever converted to NOx. At Crestmore's Number Two kiln, exit gases rarely contain more than 0.2 percent NOx and currently average approximately 0.06 percent. Therefore, only a small percentage of total nitrogen introduced into the kiln is converted to NOx.

The formation of NOx in a cement kiln may occur through at least three separate mechanisms. First, NOx is formed by the direct oxidation of atmospheric nitrogen at elevated temperatures (thermal NOx) (Fleming et al. 1980 and Miller 1977). Second, NOx is formed through oxidation of nitrogen and nitrogen compounds in the raw materials (feed NOx) (see Attachment B). Third, NOx is formed by oxidation of nitrogen contained in the fuel that is being burned (fuel NOx) (Fleming et al. 1980 and Miller 1977).

Because the raw materials used at the Crestmore plant have a low nitrogen content, they contribute insignificantly to the total NOx formed. Therefore, the primary mechanisms contributing to the formation of NOx at the Crestmore plant appear to be fuel NOx and thermal NOx (Fleming et al. 1980). The reaction that generates thermal NOx requires very high (2800°F or more) temperatures. A cement kiln generally operates with a material temperature of 2500 to 3000°F. The temperature in the flame is higher. The residence time (i.e., length of time that the combustion products remain in this area of elevated temperature) also affects the extent to which the NOx reactions can proceed to completion. The residence time in a cement kiln, because of the length of the kiln tends to allow the nitrogen and oxygen reactions (see Equations 1.1 through 1.4) to proceed to completion.

Stoichiometrically, the oxygen required for the combustion of fuel is easily estimated; thus the volume of air required during pyrolysis can be estimated. In the cement industry "one hundred percent combustion air" refers to the exact amount of oxygen required to burn all of the fuel introduced into the kiln. Providing less than one hundred percent combustion air results in the inefficient use of fuel. Additionally, insufficient oxygen may result in an explosive mixture of combustible particles and infiltration air in the dust collection apparatus. Providing greater than one hundred percent combustion air results in excess oxygen which may react with nitrogen to form NOx. Therefore, operational procedure for cement kilns is to provide slightly greater than 100 percent combustion air (e.g., 110 percent) to avoid unburned fuel and to avoid excess air which unnecessarily absorbs heat and may result in NOx formation. Better control of these procedures provides a tactic for NOx control.

1.4 NOx EMISSIONS AT CRESTMORE

Since 1910, the Crestmore plant has used natural gas, oil, and coal in the manufacture of cement. NOx emissions have been measured at Crestmore during the burning of natural gas and coal. There have been five source tests for which data were adequate to estimate a baseline emission rate prior to this NOx research program. Data for each test are presented in Table 1.1; copies of test reports and their summary analyses are presented in Attachment C.

1.4.1 Gas Firing At Crestmore

The single estimate of NOx emissions from the Crestmore kilns fired with natural gas is 21 pounds per ton (Table 1.1) which is substantially higher than coal fired kilns but is typical for cement kilns fired with natural gas (see Attachment D) (Hilovsky 1977). Estimates from other kilns range from 0.8 to 34.4 pounds per ton (see Attachment D). Natural gas burns with a short, very hot flame compared to the flame formed during coal firing (Fleming et al. 1980) and produces more hydrogen radicals than a coal flame (Miller 1977). It is believed that this is the reason gas fired kilns emit greater quantities of NOx than coal fired kilns (Fleming et al. 1980; Miller 1977; and Hilovsky 1977).

1.4.2 Direct Coal Firing At Crestmore

Four source tests measuring NOx were performed from 1976 to 1981 on the kilns at the Crestmore plant while burning with a direct fired system. These tests provided seven observations ranging from 2.25 to 14.32 pounds per ton (Table 1.1).

Employing all seven observations (equally weighted) from the four separate tests conducted at the Crestmore plant results in an estimated mean of 7.8 pounds per ton as a baseline emission rate for the Crestmore kilns prior to 1982.

TABLE 1.1

NOx EMISSION TESTING ON CRESTMORE KILNS

DATE	ELAPSED TIME	FUEL	NOx (lb/ton)
1974	180 min	Gas	21
1976	Unknown	Coal	2.25
Feb 1977	1 day	Coal	5.34
Feb 1977	1 day	Coal	5.30
Jul 1981	50 min	Coal	8.78
Jul 1981	45 min	Coal	14.32
Jul 1981	180 min	Coal	4.52
Oct 1981	30 min	Coal	13.99

1.5 NOx RESEARCH

1.5.1 KVB Research: Laboratory And Pilot Kiln Tests

The Environmental Protection Agency (EPA) granted a multi-year contract to KVB, Inc. of Irvine, California, (KVB) to test "emission control by advanced combustion modification technology for industrial combustion equipment."

KVB conducted laboratory scale testing and identified several variables that appeared to affect the generation of NOx. KVB then proposed a series of pilot kiln tests to further test the variables that appeared to influence NOx generation (Carter et al. 1982).

During the first months of 1982, RCC offered KVB the use of a pilot kiln located at the Crestmore plant for further development and testing of NOx emissions control techniques. RCC completely renovated the pilot kiln, provided training for KVB personnel, and provided personnel to assist KVB in its efforts to develop NOx control techniques. The approaches to NOx reduction that were taken in the KVB pilot kiln study (Carter et al. 1982) were:

1) reduce fuel injection velocity;
2) distribute cold combustion air to the near burner flame zone; and
3) reduce the oxygen content of the fuel carrier gas.

The data collected during the pilot kiln test program (Carter et al. 1982) led KVB to reach the following conclusions:

1) combustion modifications may be effective in reducing NOx emissions from rotary kilns;
2) NOx emissions are very sensitive to excess oxygen levels; and
3) reduction of the oxygen content of the fuel carrier air was the most effective combustion modification on the pilot kiln.

As was noted in the KVB report, this series of tests was performed on a pilot kiln and it could not be determined if the conclusions reached in these experiments would be directly applicable to a full-scale rotary cement kiln.

1.5.2 Portland Cement Association

The Portland Cement Association (PCA) has conducted experiments to determine the amount of feed NOx that may be formed during the operation of a kiln (see Attachment B). The PCA report concluded that bound nitrogen content of various kiln feeds could contribute from 0.2 pounds of NOx per ton of clinker to as high as 10 pounds per ton for kiln feed with a substantial kerogen content.

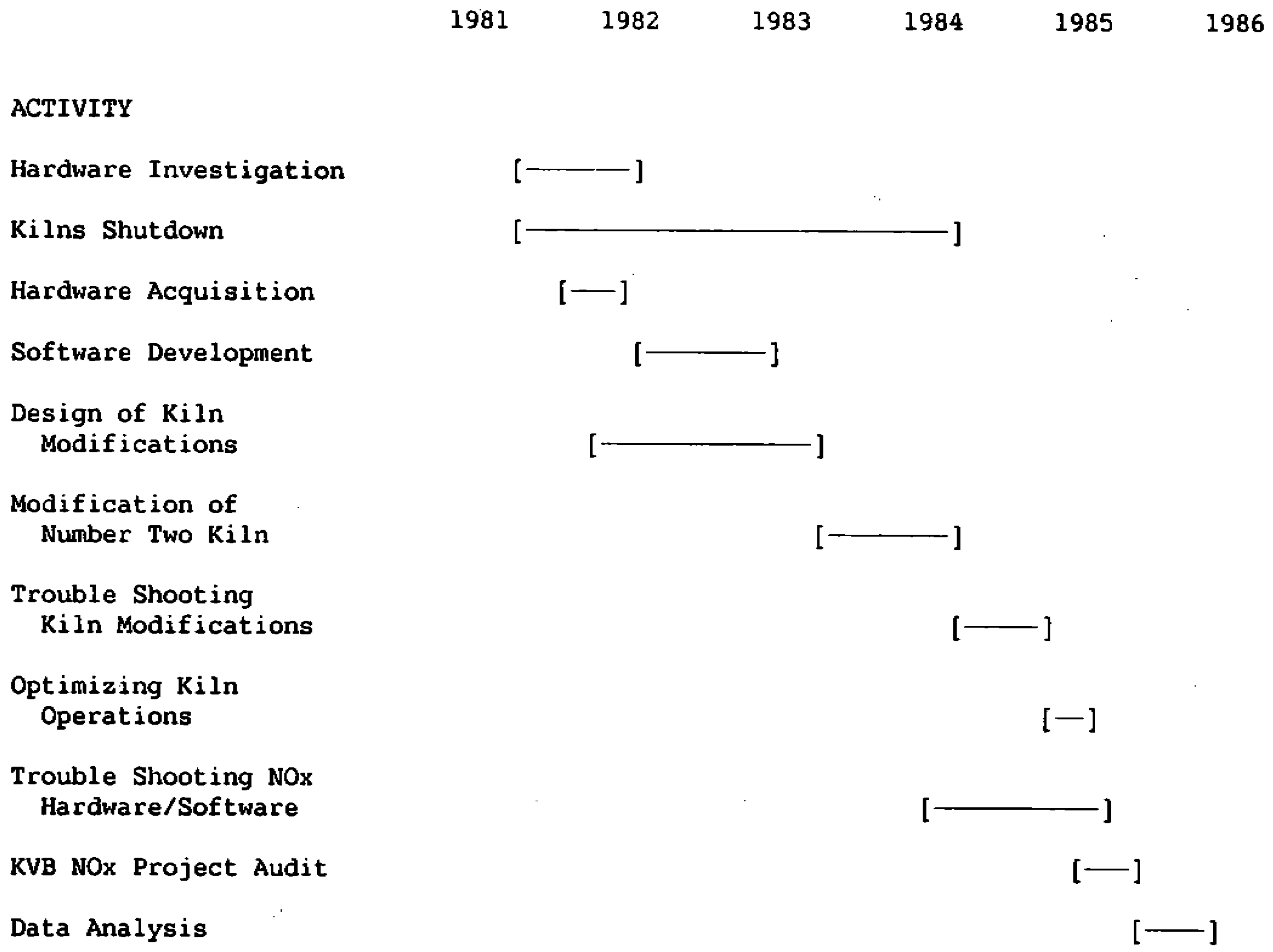
1.5.3 Crestmore NOx Research Project

RCC participated in the following research activities:

1) a review of the available literature on NOx formation and control;
2) visits to cement plants in the United States, Canada, and Japan engaged in NOx monitoring and/or NOx control research;
3) a PCA investigation of the potential contribution of raw material nitrogen to total NOx emissions; and
4) KVB's pilot kiln studies on potential NOx control techniques.

Based on the results of these investigations, RCC implemented a major redesign and modification program of its kiln and auxiliary equipment including the raw material blending system (see Figure 1.3). The objectives of this program were to reduce fuel consumption, reduce the quantity and temperature of the primary air, improve control of flame configuration and improve the operation of the kiln.

Cement manufacturing at Crestmore was begun with the new system in August 1984 upon completion of these modifications (see Section 3.1). The operation of this redesigned cement manufacturing facility is monitored by an instrumentation system (see Section 3.2) designed to continuously measure 45 variables relating to kiln operations, some of which may be related to NOx formation. The data from this continuous monitoring system is used to evaluate the success of the modifications to reduce NOx.



TIMELINE OF THE CRESTMORE NOx RESEARCH PROJECT

Figure 1.3

SECTION 2.0

RCC's EXPERIMENTAL DESIGN

2.1 FEED AND FUEL NOx EMISSIONS AT CRESTMORE

RCC conducted a review of PCA findings concerning the contribution of kiln feed nitrogen to the generation of NOx. The raw materials used at the Crestmore plant appeared to contribute insignificant amounts of NOx per ton of clinker (see Attachment B). Therefore RCC determined that it would not be of value to attempt to alter the raw materials to lower the emissions of NOx.

Another variable affecting the generation of NOx is the nitrogen content of the fuel. As with all coals, the coal used at the Crestmore plant contains some nitrogen (see Attachment E). Alternative fuels with lower nitrogen contents such as natural gas, result in higher NOx emissions due to the characteristics of the flame generated during combustion (Miller 1977). Therefore, changing the fuel does not appear to have any potential for reducing NOx emissions at the Crestmore plant.

2.2 ASSUMPTIONS REGARDING FACTORS AFFECTING NOx EMISSIONS AND ACTIONS TAKEN BY RCC TO REDUCE NOx EMISSIONS

Based on the pilot kiln studies conducted by KVB and on RCC's investigations, RCC selected four tactics with the potential for reducing NOx emissions. These four tactics are:

1) reduce the quantity of fuel used per ton of clinker;
2) reduce the quantity and temperature of the primary air;
3) better control of the configuration of the flame; and
4) better control of the operation of the kiln.

To reduce the quantity of fuel used per ton of clinker produced, RCC modified the equipment associated with the firing system, kiln auxiliary equipment and made substantial changes to the clinker cooler to permit the use of greater quantities of hot secondary air for combustion. It was anticipated that greater use of secondary air for combustion would result in reduced fuel consumption and that reduced fuel consumption would reduce the quantity of fuel NOx formed per ton of clinker produced. The decision to convert the existing direct fired coal system to a state-of-the-art indirect firing system was made so that the quantity of cool primary air used could be reduced. Then the amount of hot secondary air could be increased, thus reducing fuel usage (see Section 3.1.1 of this report for a detailed discussion of the actions taken by RCC to reduce fuel consumption).

The installation of the indirect firing system also permitted RCC to reduce the temperature of the primary air. According to studies by KVB (Carter et al. 1982), reduced primary air temperature would reduce the amount of NOx formed (see Section 3.1.2 of this report for a detailed discussion of the indirect firing system).

In order to control the configuration of the flame, RCC purchased and installed a redesigned burner pipe. With the redesigned burner pipe, changes to the flame configuration are possible and also the operator may vary the quantity of primary air introduced into the kiln (see Section 3.1.3 of this report for a detailed discussion of the redesigned burner pipe).

To achieve better operational control of the kiln, RCC installed improved instrumentation on the kiln so that the operators could more accurately determine the operational conditions of the kiln. With this additional information, the operator response to kiln operational variables is more precise, which reduces the frequency of temperature excursions in the kiln. In addition to the improved instrumentation, RCC also modified the raw material proportioning and blending systems to achieve a more uniform raw material chemistry. Better raw material chemical uniformity also results in fewer kiln operational problems. Additionally, prior to restarting the redesigned and modified kiln, a systems description manual (see Attachment F) and an operating manual (see Attachment G) were prepared and training was provided to all plant operators to familiarize them with the new equipment and processes (see Section 3.1.4 of this report for a detailed discussion of these modifications).

The modifications that were designed and constructed during the November 1981 through August 1984 shutdown period have resulted in a reduction in fuel consumption of 10 to 20 percent. These modifications also permit a greater degree of control over the kiln operation.

2.3 EXPERIMENTAL HYPOTHESIS

The experimental hypotheses (H_o = null and H_a = alternative) for testing the results of these modifications on the emissions of NOx are:

H_o: Post redesign and modification NOx emissions are equal to pre-modification emissions; and

H_a: Post redesign and modification NOx emissions are less than pre-modification emissions (one tailed test).

SECTION 3.0

MATERIALS AND METHODS

3.1 MODIFICATIONS TO NUMBER TWO KILN AT CRESTMORE

The modifications that were made to the Number Two kiln at the Crestmore cement plant prior to its startup in August 1984 are described below.

In early 1983, following extensive research, RCC began the redesign and construction of the modifications at the Crestmore plant. These modifications made to the kiln and auxiliary equipment were based on the four tactics selected by RCC as being the most likely to reduce the NOx emission rate from the kiln. These four tactics are:

1) reduce the quantity of fuel used to produce a ton of clinker;
2) reduce the quantity and temperature of the primary air;
3) achieve better control of the flame configuration; and
4) achieve better operational control of the kiln.

3.1.1 Modifications To Reduce Fuel Usage

An extensively redesigned kiln chain system was installed to reduce the quantity of fuel used to produce a ton of clinker. This system is composed of approximately 100 tons of stainless steel chains, curtain-hung in a helical pattern. As the kiln rotates, the chains are alternately exposed to the hot (1600°F) gases and the cold (100°F) raw material. When the chains are exposed to the hot gases, they become heated; as the kiln rotates, the chains transmit this heat to the material. This continuous action recovers heat from the hot gases and reduces fuel usage.

If a kiln's cooler throat is undersized, ambient air is drawn from around the firing hood of the kiln for combustion air in preference to heated secondary air from the clinker cooler. Therefore, a modification was made to enlarge the clinker cooler throat. This permits increased usage of hot secondary air from the clinker cooler which reduces fuel usage.

The indirect coal firing system installed on the Number Two kiln also contributes to the improved fuel efficiency of the kiln. Since an indirect firing system uses a reduced quantity of cool primary air as compared to a similarly sized direct firing system, more hot secondary air may be used for combustion, which reduces the fuel consumption of the kiln. An indirect firing system is explained in greater detail in the following section.

3.1.2 Modifications To Reduce The Temperature And Quantity Of The Primary Air

Another major modification which reduced NOx formation was the conversion of the direct fired coal mill system to an indirect fired system. A comparison of these two systems is shown schematically in Figures 3.1 through 3.5. In the direct system all the pulverized coal, hot air, and evaporated moisture pass through the fan to the kiln. In the indirect system, the pulverized coal is separated from the gas stream and collected in a bin while the hot air and evaporated moisture are vented to the atmosphere. The pulverized coal is withdrawn from the bin and sent to the kiln under controlled primary air flow.

For purposes of comparison, Table 3.1 provides the process calculations and Table 3.2 lists the various inputs and outputs from the two systems assuming a mill feed of 400 pounds per minute (12 tph) of wet coal. The advantages of the indirect system as shown by this table are:

1) primary air is reduced from 34 to 15 percent;
2) evaporated moisture is vented to the atmosphere rather than entering the kiln; and
3) heat recovery in the form of secondary air from the cooler is increased by over 15 percent.

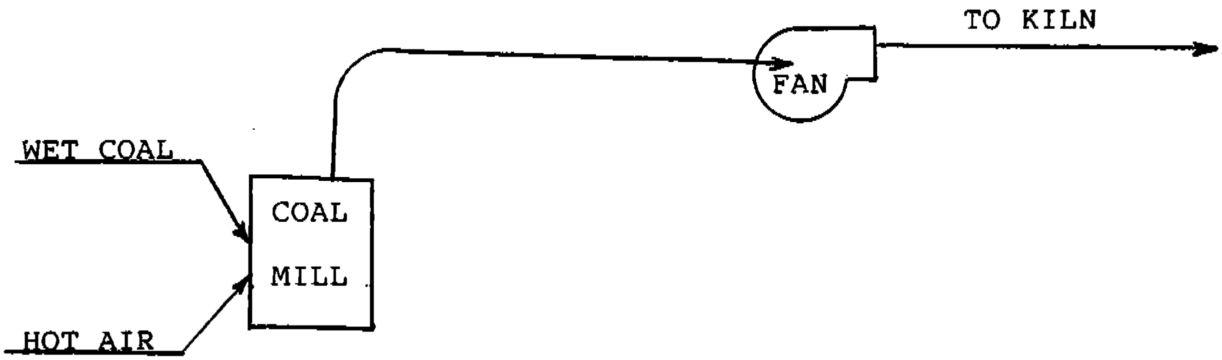
The disadvantages of the indirect system are:

1) the indirect system is mechanically more complicated and therefore, difficult to maintain;
2) the indirect system is more complex and difficult to to operate; and
3) the operational hazards (fire and/or explosion) are considerably greater with an indirect system.

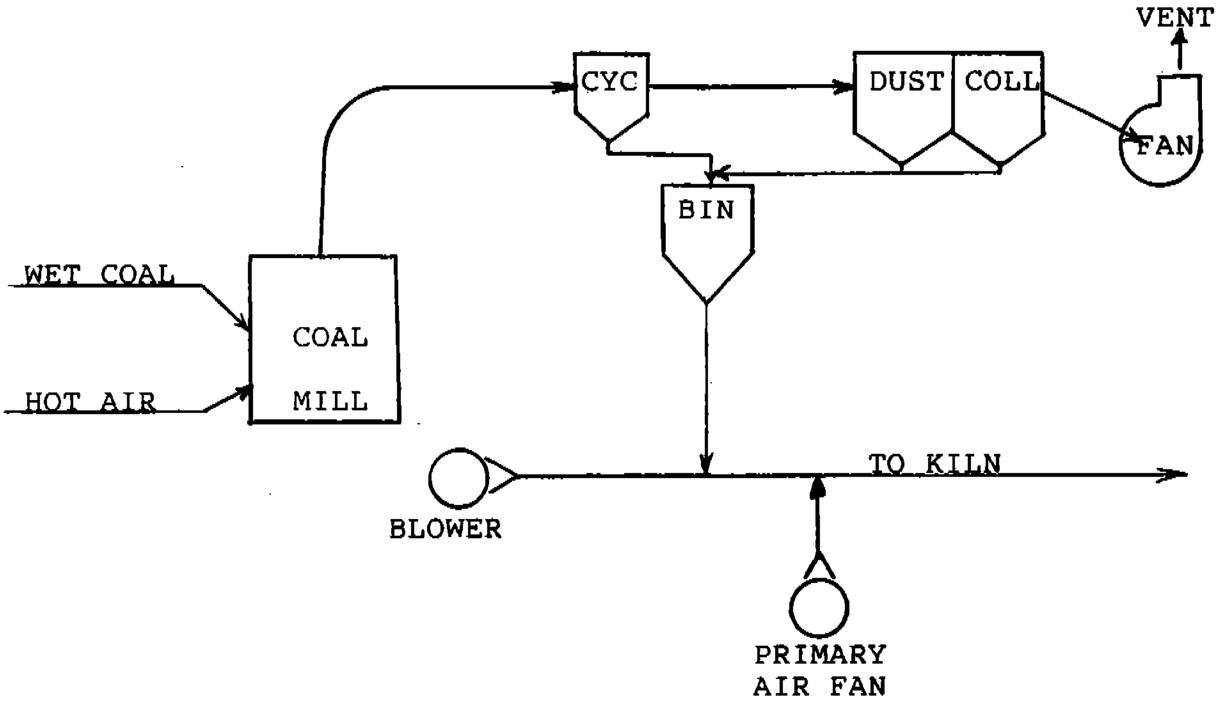
Despite these significant disadvantages, RCC believed that an indirect system would reduce NOx emissions.

The indirect firing system was designed with the capability of varying primary air from 5 to 20 percent of the total combustion air requirements. Also, the indirect firing system uses ambient (cool) primary air and with the redesigned burner, the primary air velocity may be varied. Preliminary results from KVB laboratory scale and pilot kiln testing (Carter et al. 1982) indicated reduced NOx emissions when the primary air was not heated and when the primary air velocity was reduced.

DIRECT FIRING SYSTEM

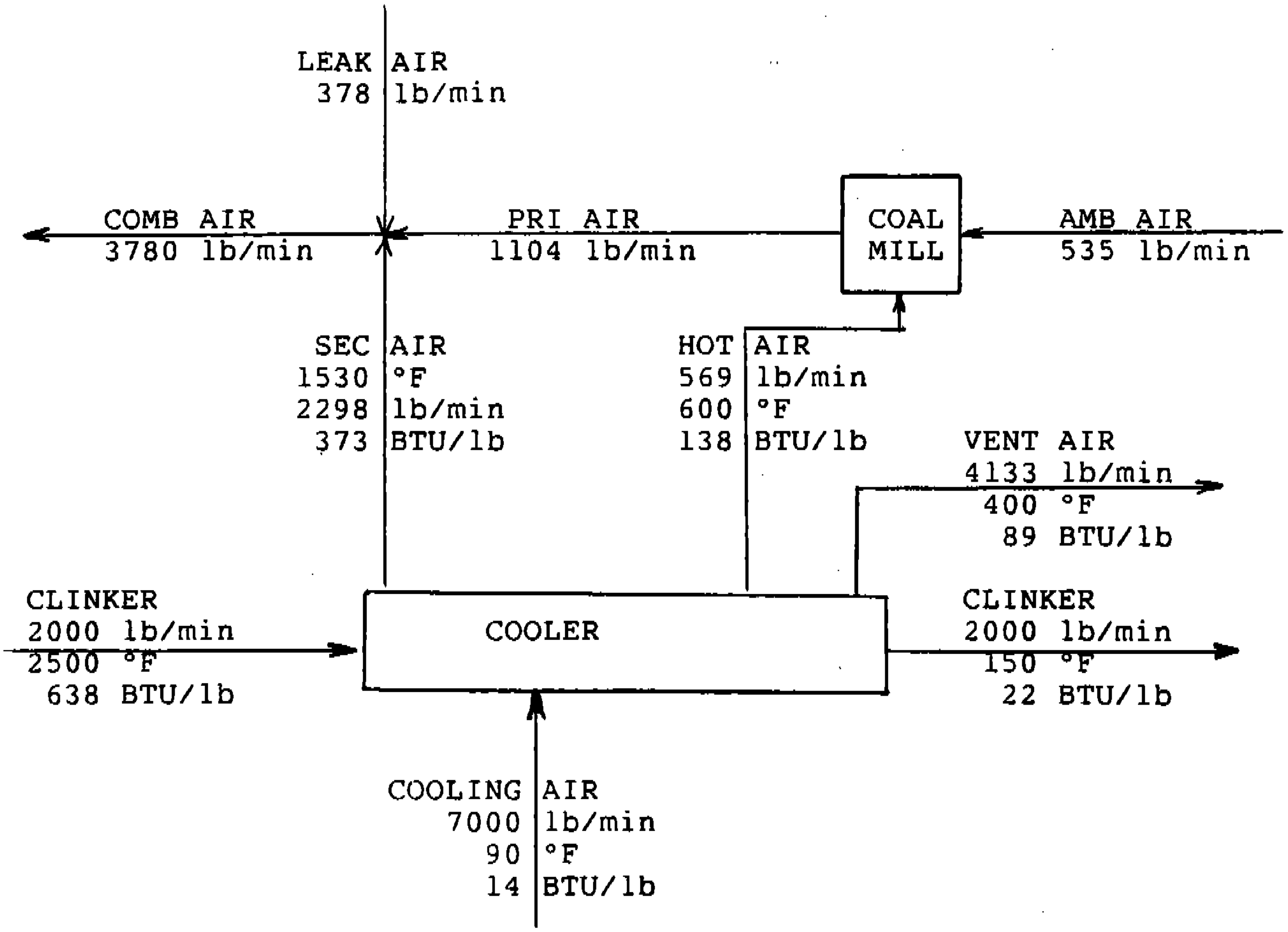


INDIRECT FIRING SYSTEM



COMPARISON OF DIRECT AND INDIRECT FIRING SYSTEMS AT CRESTMORE

Figure 3.1



BTU/min Lost by Clinker = 2000 (638-22) = 1,232,000

Gain by Cooling Air (98%) = 1,207,000

Gain by Vent Air = 4133 (89-14) = 310,000 = 25.7%

Gain by Hot Air = 569 (138-14) = 71,000 = 5.9%

Gain by Sec Air = 2298 (373-14) = 826,000 = 68.4%

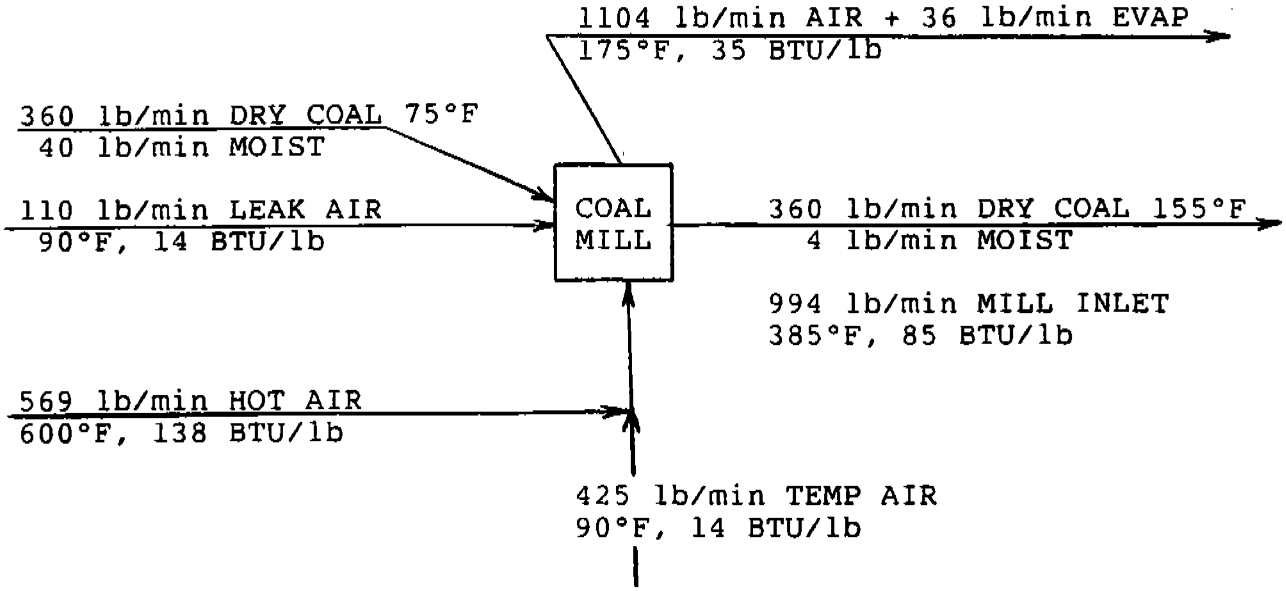
Temp of Sec Air:

826,000/2298 = 360 BTU/lb

360 + 14 = 374 BTU/lb = 1530 °F

COOLER OPERATION WITH DIRECT COAL FIRING SYSTEM

Figure 3.2



HEAT REQUIRED

Dry Coal = 360 (0.30)(155-75) = 8640 BTU/min
Prod Moist = 4 (1.0)(155-75) = 320
Leak Air = 110 (35-14) = 2310
Evap = 36 (1070) = 8520
49790 BTU/min

TEMP REQUIRED

49790/994 = 50 BTU/lb
50 = 35 = 85 BTU/lb = 385°F

(Hot Air) (138-85) = (Temp Air) (85-14)

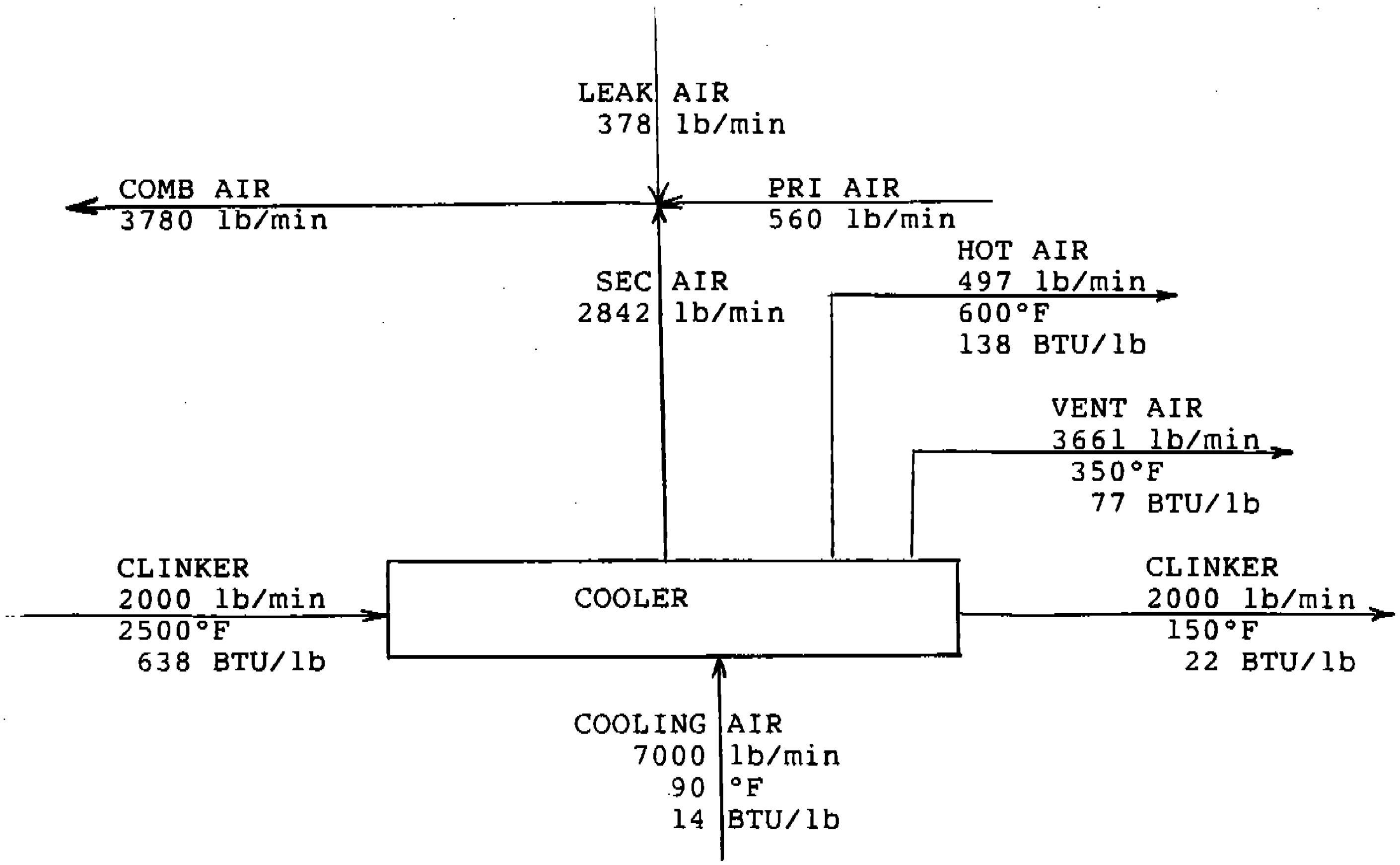
(Hot Air) (53) = (Temp Air) (71)

Hot Air = 569 lb/min

Temp Air = 425 lb/min

COAL MILL DIRECT FIRING SYSTEM

Figure 3.3



BTU/min Lost by Clinker = 2000 (638-22) = 1,232,000

Gain by Cooling Air (98%) = 1,207,000

Gain by Vent Air = 3661 (77-14) = 231,000 = 19.1%

Gain by Hot Air = 497 (138-14) = 62,000 = 5.1%

Gain by Sec Air = 914,000 = 75.7%

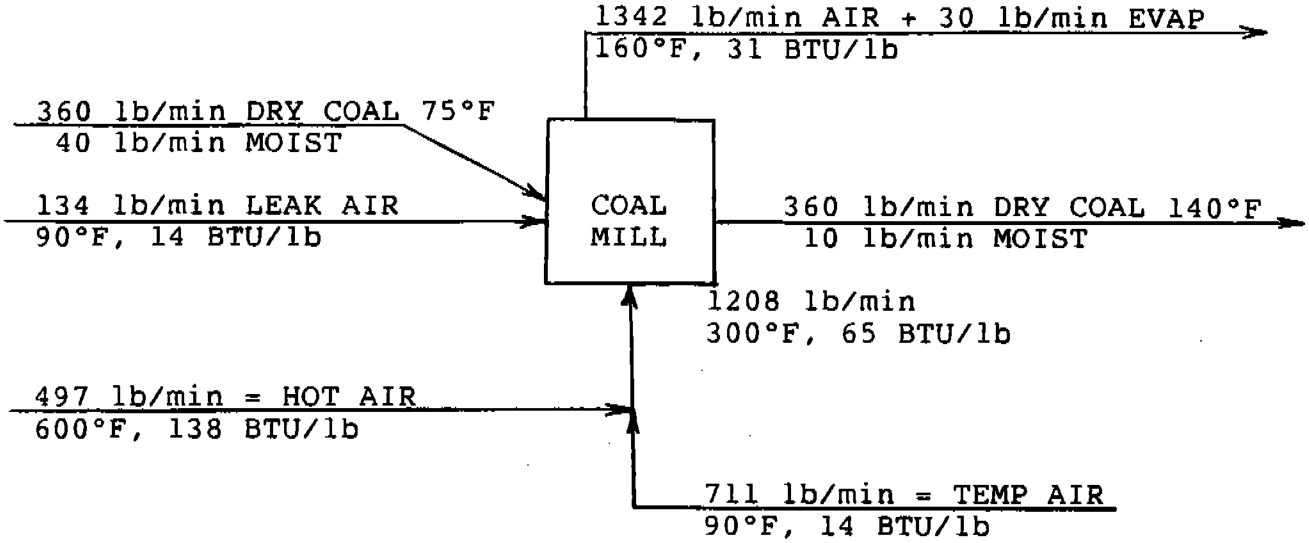
Temp of Sec Air:

914,000/2842 = 322 BTU/lb

322 + 14 = 335 BTU/lb = 1385°F

COOLER OPERATION WITH INDIRECT COAL FIRING SYSTEM

Figure 3.4



HEAT REQUIRED

Dry Coal = 360 (0.30)(140-75) = 7020 BTU/min
Prod Moist = 10 (1.0)(140-75) = 650
Leak Air = 134 (31-14) = 2278
Evap = 30 (1035) = 31050
40998 BTU/min

TEMP REQUIRED

40998/1208 = 34 BTU/lb
34 + 31 = 65 BTU/lb = 300°F

(Hot Air) (138-65) = (Temp Air) (65-14)

(Hot Air) (73) = (Temp Air) (51)

Hot Air = 497 lb/min

Temp Air = 711 lb/min

COAL MILL INDIRECT FIRING SYSTEM

Figure 3.5

TABLE 3.1

PROCESS CALCULATIONS

COOLER THROAT

Original: 70 sq. ft.

New: 110 sq. ft. (57% increase)

COAL MILL EXHAUST

Direct System (Original):

20,000 acfm @ 175°F, -15 inches WC

Indirect System (New):

24,000 acfm @ 160°F, -25 inches WC

KILN DATA

Clinker - 60 tph

Coal - 4.5 x 10^6 x 60/60/12500 = 360 lb/min (dry)

Total Comb Air = 10.5 x 360 = 3780 lb/min (incl humidity)

Hood Leak @ 10% = 0.10 x 3780 = 378 lb/min

Coal Feed to Mill @ 10% moist = 360/.90 = 400 lb/min

DIRECT SYSTEM

Mill Exhaust = 20,000 x 530/635 x 379.50/407.6 = 15542 scfm

Evaporated Coal Feed Moisture @ 30%
0.90 x 40 = 36 lb/min x 359/18.016 x 530/492 = 773 scfm

Primary Air = 15542 - 773 = 14769 scfm

Humidity = 0.0056 x 14709 = 83 scfm
= 83 x 18.016/359 x 492/530 = 4 scfm

Dry Air = 14769 - 83 = 14686 scfm
= 14686 x 28.965/359 x 492/530 = 4 lb/min

Total Primary Air = 4 + 1100 = 1104 lb/min
= 29 %

(continued)

TABLE 3.1
continued

Secondary Air = 3780 - 378 - 1104 = 2298 lb/min

Humidity = (.0035/1.0035)(2298) = 8 lb/min = 172 scfm

Dry Air = 2298 - 8 = 2290 lb/min = 30575 scfm

Total Secondary Air = 172 + 30575 = 30747 scfm
30747 x 1990/530 x 407.6/394.5 = 119280 acfm

Cooler Throat Velocity = 119280/70 = 1704 fpm

INDIRECT SYSTEM

Mill Exhaust = 24,000 x 530/620
x 369.5/407.6 = 18598 scfm

Evaporated Coal Feed Moisture @ 75%
0.75 x 40 = 30 lb/min = 644 scfm

Mill Exit Air - 18598 - 644 = 17954 scfm

Humidity = 0.0056 x 17954 = 101 scfm
= 5 lb/min

Dry Air = 17954 - 101 = 17853 scfm
= 1337 lb/min

Total Mill Exit Air = 1342 lb/min

Primary Air

Conveying Air = 2000 acfm
Primary Air Fan = 6000 acfm
Total Primary Air = 8000 acfm
@ 90°F 8000 acfm x 0.70 = 560 lb/min

Secondary Air = 3780 - 378 - 560 = 2842 lb/min

Humidity = 10 lb/min = 213 scfm

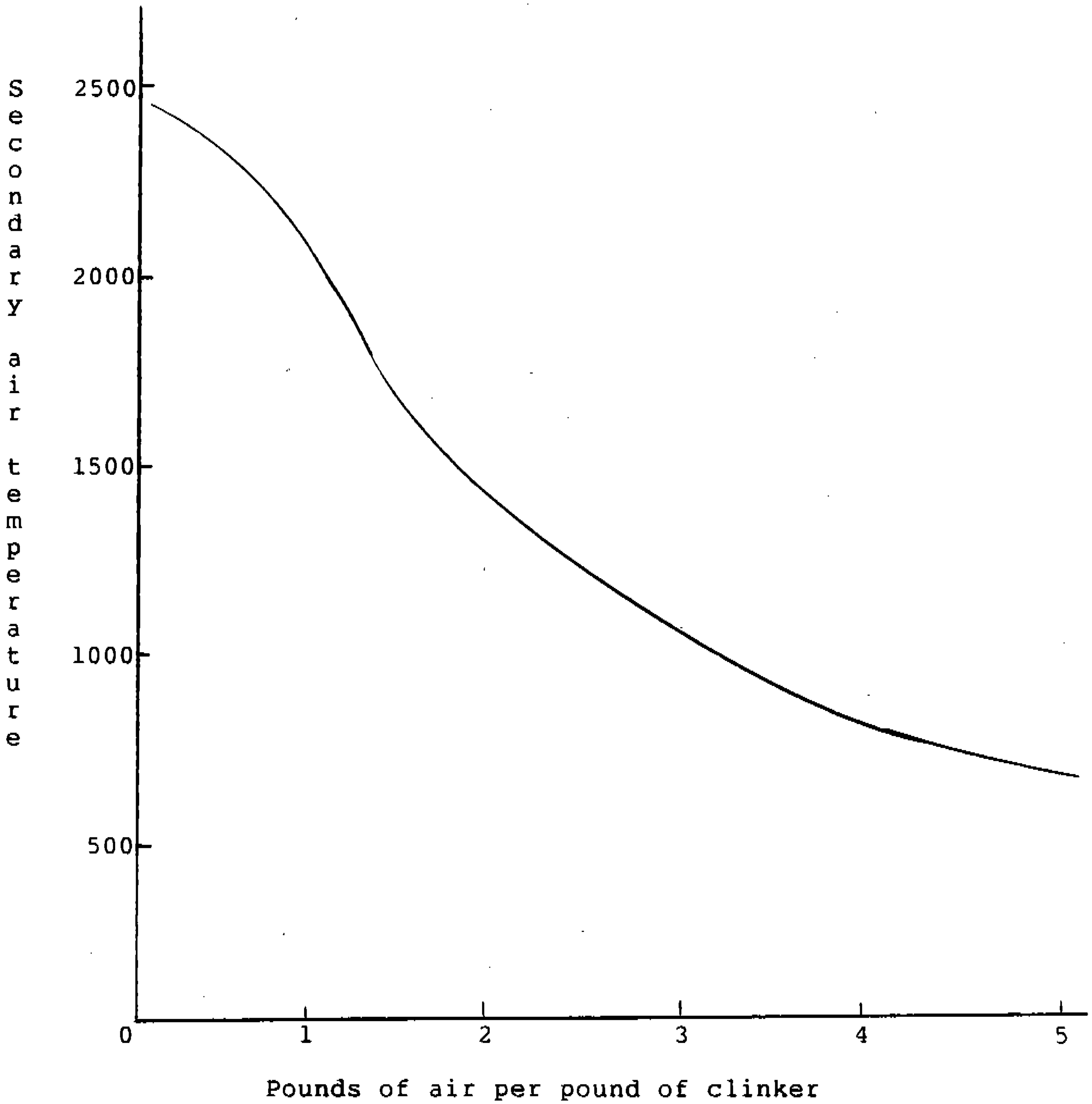
Dry Air = 2832 lb/min = 37945 scfm

Total Secondary Air = 172 + 30575 = 38158 scfm
38158 x 1845/530 x 407.6/394.5 = 137244 acfm

Cooler Throat Velocity = 137,244/110 = 1248 fpm

TABLE 3.2
FIRING SYSTEM COMPARISON
(in pounds per minute, except as noted)

	DIRECT SYSTEM	INDIRECT SYSTEM
DRY COAL	360	360
MOISTURE	+40	+40
WET COAL	400	400
HOT AIR	1300	1300
PRIMARY AIR	0	560
TOTAL INPUT	1700	2260
TO KILN		
DRY COAL	360	360
MOISTURE	+ 4	+10
WET COAL	364	370
PRIMARY AIR	1300	560
EVAPORATED MOISTURE	36	0
TOTAL TO KILN	1700	930
VENT		
HOT AIR	0	1300
EVAPORATED MOISTURE	0	+30
TOTAL VENT	0	1330
TOTAL OUTPUT	1700	2260
COMBUSTION AIR @10.5 lb/lb COAL	3780	3780
HOOD LEAK AT 10%	380	380
PRIMARY AIR (See Table 3.1)	1300	560
SECONDARY AIR (by diff)	2100	2840
TOTAL	3780	3780
PRIMARY AIR (percent)	34	15
SECONDARY AIR (lb/min)	2100	2840
lb/lb CLINKER (2000 lb CLINKER/min)	1.05	1.42
TEMPERATURE (°F Fig 3.6)	1600	1400
HEAT CONTENT (BTU/lb)	393	341
BTU/min	825300	968440
PERCENT INCREASE	0	17



SECONDARY AIR TEMPERATURE
vs
POUNDS OF AIR PER POUND OF CLINKER

Figure 3.6

3.1.3 Installation Of The Redesigned Burner Pipe To Permit Control Of The Configuration Of The Flame

It has long been recognized that design factors of the burner pipe have a decided influence on flame control and kiln operation; these potentially affect NOx emissions. The two main factors are:

1) the primary air velocity at the burner tip; and

2) the ability to produce turbulent air flow.

Since most kilns operate with direct fired coal mill systems, the amount of primary air is fixed within rather narrow limits. In order to change tip velocity in a direct fired system, a burner pipe with a different diameter is required.

Table 3.3 compares burner pipe data from two kilns. The tip velocity of 9,763 fpm at Crestmore represents the engineering practices of the early 1960's regarding tip velocity which generally ranged from 8,000 to 10,000 fpm. The velocity of 16,823 fpm for the other kiln represents a change in engineering practices to a range of 15,000 to 20,000 fpm.

TABLE 3.3

PRIMARY AIR VELOCITY

	HARLEYVILLE	CRESTMORE (pre-1982)
BURNER PIPE DIA (inches)	14	19
BURNER PIP CSA (sq ft)	1.069	1.969
PRIMARY AIR (lb/min dry air)	1066	1101
HUMIDITY	4	4
EVAP	33	37
TOTAL	1103	1142
TEMPERATURE (° F)	175	175
ALTITUDE CORRECTION	1.0	.97
PRIMARY AIR (acfm)	17984	19224
TIP VELOCITY (fpm)	16823	9763

Both kilns had conventional coal burner pipes. These conventional pipes were of a constant diameter with no internal devices or restrictions. The duct which conveyed coal to the burner pipe was also of constant diameter (although somewhat greater than the burner pipe) and generally was horizontal and straight for some 30 to 50 feet ahead of the burner pipe. The entire conventional system was conducive to a laminar flow of gases and pulverized coal as the mixture entered the kiln. Flame control of these systems typically was somewhat difficult, with the degree of difficulty increasing as the kiln diameter increased. Increasing tip velocity appeared to regain some control over flame shaping and kiln stability. The increase from 10,000 fpm to 20,000 fpm was a result of the trend toward larger diameter kilns over this period.

In addition to increasing tip velocity, various means of disturbing the laminar flow were investigated. One of the methods tried more frequently with some success was to install turning vanes within the burner pipe. The vanes produced a swirling effect on the coal/air mixture as it entered the kiln. Often these vanes could be externally adjusted.

Since RCC had already chosen an indirect fired coal mill system, the next decision to be reached pertained to the choice of a burner pipe. Since primary air could be varied from 5 to 20 percent, this meant that primary air volume could range from 3,000 to 12,000 acfm. Selecting a conventional burner pipe would have meant that the tip velocity could vary over a very wide range (5,000 to 20,000 fpm for a 10 1/2 inch diameter burner pipe). Another alternative appeared to be required.

RCC made the decision to install a Pillard burner which appeared to incorporate RCC design principles. Figure 3.7 shows schematically the operating principles of this burner. The burner is a series of four concentric pipes. Starting from the innermost pipe, their purposes are:

1) pipe #1 is a carrier pipe for a natural gas or oil gun. Its purpose is to allow warming up the kiln before starting the coal fire. A gas or oil pilot to supplement the coal can also be used;

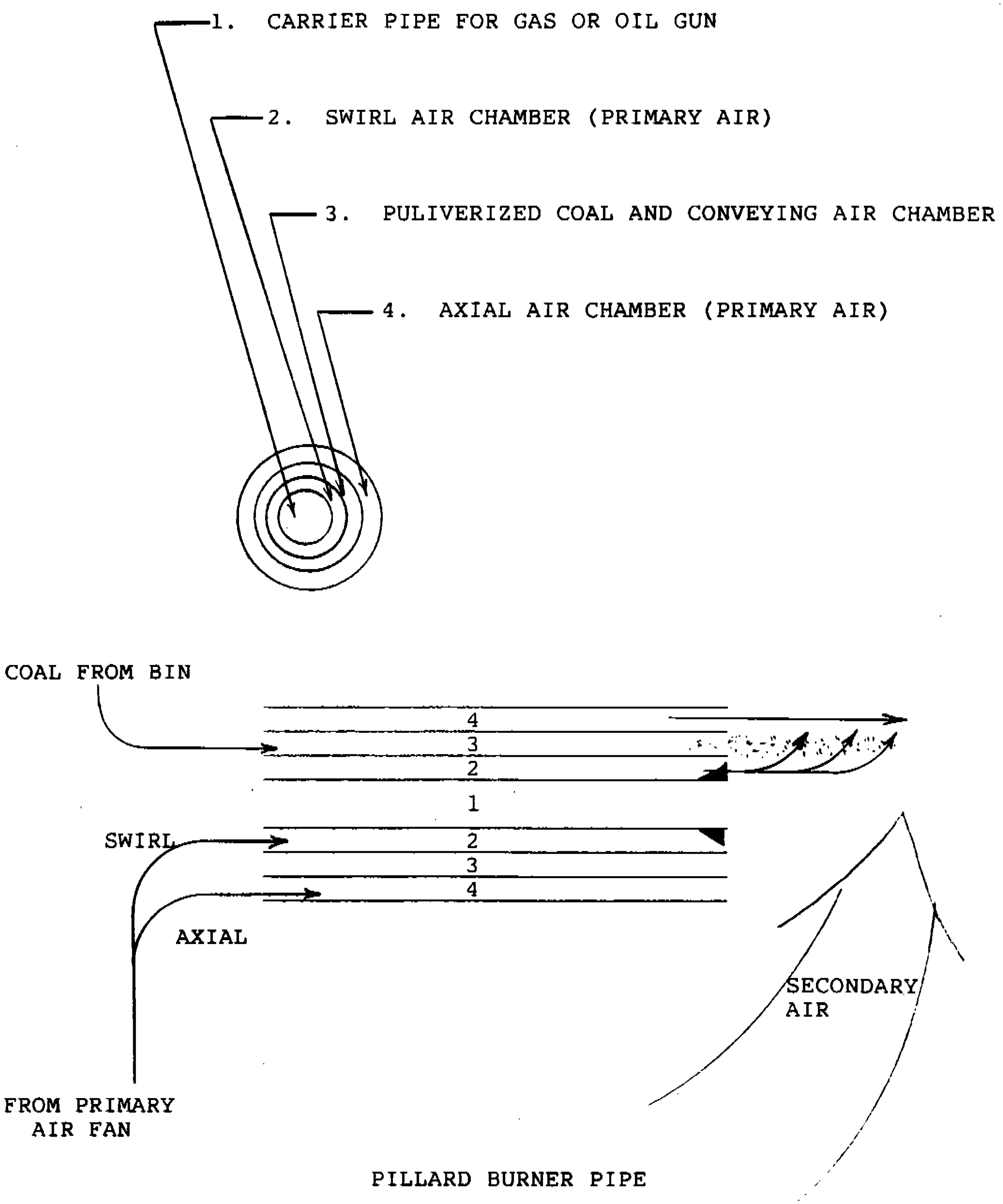
2) pipe #2 is a chamber for what is referred to as swirl air. At the tip of this chamber are fixed turning

vanes or deflectors which cause the swirl air to disturb the laminar flow of the pulverized coal and axial air (see 3 & 4);

3) pipe #3 creates a chamber for introducing the pulverized coal and conveying air into the kiln in more or less laminar flow (conveying air represents 3 to 4 percent of the combustion air requirements); and

4) pipe #4 is a chamber for what is referred to as axial air, which enters the kiln also in more or less laminar flow.

As can be seen from the cross section of the Pillard burner, the swirl air spins outward from the center of the pipe at high velocity and blasts through the concentric rings of pulverized coal and axial air. The purpose of this action is to promote more rapid ignition of the pulverized coal. The total primary and conveying air represents about 15 percent of the combustion air requirement. Coal ignition cannot occur until the pulverized coal contacts sufficient oxygen in the secondary air from the cooler. The outside ring of laminar axial air delays contact between the pulverized coal and secondary air and thus promotes a long "lazy" coal flame. Increasing the amount of swirl air at the expense of axial air accelerates contact between the pulverized coal and secondary air and thus promotes a short, "snappy" coal flame.



PILLARD BURNER PIPE

Figure 3.7

It has been observed by experienced kiln operators that if the flame is too long (and cold) the clinkering reaction is lost (and NOx levels may be at their lowest). If the flame is too short (and hot), damage to coating and brick can occur (and NOx levels may be at their highest). Proper flame configuration is achieved by selecting the proper balance of swirl and axial air.

3.1.4 Modifications To Achieve Better Operational Control Of The Kiln

Operational control of the kiln is more readily achieved when kiln hood draft is under control and some means of flame shaping is possible. Experience with many operating kilns revealed that hood draft and flame control are more easily accomplished on some kilns than on others. This is more easily understood if one visualizes a rotary kiln as a fire within a tube with fans at each end attempting to pull the flame in opposing directions. Only under a steady state of operation is flame control possible. Loss of flame control generally leads to loss of the clinkering reaction and a raw, or cold, kiln which must be overheated to re-establish clinkering. During these periods of overheating, NOx formation may be at its highest.

Observations of operating kilns have revealed two important items relating to operational control of the kiln:

1) high velocity of air through the cooler throat makes it more difficult to control the kiln; and

2) a low ratio of the cross sectional areas (CSA) between the cooler throat and the kiln shell also make it more difficult to control the kiln.

Table 3.4 compares two kilns of the same diameter (15 ft). The velocity of air through the original Crestmore cooler throat was 1925 fpm compared to 1230 fpm for the other kiln. The cooler throat-to-kiln CSA ratios were 0.49 versus 0.70. Control of hood draft and the flame was considerably more difficult with the unmodified Crestmore kiln, because of its higher secondary air velocity and lower CSA.

In addition to this "tug-of-war" between the two fans, another factor should be considered. When velocity increases, the pressure drop increases by a factor equal to the square of the velocity. Thus, a 50 percent increase in velocity is accompanied by a 125 percent increase in pressure drop (1.5 x 1.5 = 2.25). The net effect is that the kiln fan preferentially selects ambient air infiltrating around the kiln hood for combustion at the expense of hot combustion air from the cooler. This chills the flame as well as upsetting hood draft control.

Since the Crestmore system originally had a high secondary air velocity and a low cross-sectional area (CSA) ratio, a decision was made to enlarge the cooler throat from 70 to 110 square feet. The enlarged cooler throat reduced the velocity of the hot secondary air to 1230 fpm and increased the CSA ratio to 0.77, both of which improved control of the Crestmore kiln.

The clinker cooler fans, cooler dust collector, kiln induced draft fan, and kiln exit gas baghouse were also renovated in order to permit better control of the air flows through the kiln system. These changes also resulted in improved operational control of the kiln.

The instrumentation on the kiln was renovated so that the kiln operators would be better informed on the operational variables of the kiln. This permits the operators to make more precise decisions regarding required process changes to achieve more stable operation of the kiln.

Many kiln temperature excursions can be traced to changes in the chemical composition of the kiln feed. Therefore, the raw material proportioning system was completely redesigned to improve the chemical uniformity of the feed to the kiln, which has eliminated most of the feed induced temperature excursions in the operation of the kiln.

TABLE 3.4

COMPARISON OF SECONDARY AIR FLOW CHARACTERISTICS

	HARLEYVILLE	CRESTMORE ORIGINAL	CRESTMORE MODIFIED
Kiln Size	15 x 220	15 x 530	15 x 530
Kiln i.d. (ft Inside Brick)	13.5	13.5	13.5
Kiln CSA (sq ft)	143	143	143
Cooler Throat CSA (sq ft)	100	70	110
Ratio CSA	0.70	0.49	0.77
Clinker (tph)	78	55	60
Kiln (BTU/ton)	3.3×10^6	5.0×10^6	4.5×10^6
Coal (BTU/lb)	12500	12500	12500
Coal (lb/min)	330	367	360
Combustion Air (10.5 lb/lb)	3465	3850	3780
Hood Leak (lb/min)	345	385	380
Primary Air (lb/min)	1070	1105	560
Sec Air Thru Throat (lb/min)	2050	2360	2840
Pri Air Thru Throat (lb/min)	270	550	0
Air Thru Cooler Throat (lb/min)	2320	2910	2840
lb of Air/lb Clinker	0.93	1.59	1.42
Degrees F	1650	1325	1375
Altitude Correction	1.0	.97	.97
Secondary Air (acfm)	123,000	135,000	135,000
Cooler Throat Velocity (fpm)	1230	1925	1230

3.1.5 Summary Of Section 3.1

RCC redesigned the Number Two kiln and associated equipment at a cost of 6.5 million dollars to reduce the emissions of NOx. The four tactics that were selected to reduce NOx were:

1) reduce the quantity of fuel used to produce a ton of clinker (see Section 3.1.1);
2) reduce the quantity and temperature of the primary air (see Section 3.1.2);
3) achieve better control of the flame configuration (see Section 3.1.3); and
4) achieve better operational control of the kiln (see Section 3.1.4).

A complete list of over 45 separate items is included as Attachment H. Those modifications which were judged to have the greatest impact on NOx were:

1) enlarging the clinker cooler throat;
2) converting the direct firing system to indirect;
3) improvement of the raw material proportioning and blending system; and
4) installing a redesigned burner pipe.

Following the construction of the redesigned kiln and auxilliary systems, the kiln was restarted in August 1984. Experienced kiln operators noted that they were able to achieve better operational control of the kiln. Approximately 10 to 20 percent less fuel was required to produce a ton of clinker when compared to pre-1982 kiln fuel usage. The indirect firing system also resulted in a reduction of the quantity and temperature of the primary air when compared to the pre-1982 direct firing system. The redesigned burner allows the kiln operators to control the configuration of the flame to a much greater extent than was possible with the pre-1982 burner pipe.

The aforementioned design changes resulted in a reduction in the NOx emissions of 26 percent with indirect coal firing, as compared to the pre-1982 NOx emission rate when direct coal firing. This is the NOx emission rate reduction achievable using all reasonably available control technology.

3.2 NOx PROJECT MONITORING SYSTEM

In addition to the redesign and modification of the kiln and associated systems, a continuous NOx monitoring system was installed as part of the Crestmore NOx Research Project. Since this project involved new applications of existing technology dealing with the formation and control of NOx in a cement kiln, the instrumentation, data logging and reduction software, the quality assurance activities, and the calibration and maintenance of the instrumentation were, to some extent, developed as the project evolved.

Beginning in August 1980, investigations began to determine the equipment most suitable for collecting the field instruments signals, converting these analog signals to digital signals, transmitting them to a data storage device, and analyzing these data in an attempt to determine the kiln operational variables affecting the generation of NOx.

3.2.1 Instrumentation

The instrumentation includes 45 field sensors which continuously monitored operational variables. These analog field signals are transmitted to a Kaye Instrument Digilink which averages these signals over a six-minute time period, converts the analog signals to digital signals, and then transmits these digital signals to an IBM-PC. This computer stores these raw field signals on a diskette, performs various calculations relating to the operational conditions of the kiln, stores these calculated values on a diskette, and then transmits selected data to three printers, once every six minutes (for a complete listing of the hardware associated with this project, see Attachment I). Instrumentation such as the Lear-Siegler (LSI) SM-810 NOx/SOx gas analyzer, the LSI CM-50 oxygen analyzer, the Kaye Digilink, the IBM-PC, and the printers, were added to the existing equipment to enhance the data acquisition and analyses exclusively for the Crestmore NOx Research Program.

The acquisition of this hardware began with an investigation in the last half of 1981 into the types of field instrumentation and data logging and analyses hardware available. An LSI SM-810 NOx/SOx continuous gas analyzer and a CM-50 continuous oxygen analyzer were purchased in January 1982.

From December 1981 through May 1982, devices capable of converting analog field instrument signals to digital signals that could be received by data processing equipment were investigated. By July 1982, a Kaye Instruments Digilink had been purchased, installed, and programmed to receive 45 analog field signals and convert these signals to digital signals for transmission to a computer.

From January 1982 through May 1982, an IBM-PC, three printers, and various interfaces were purchased and installed so that the data received from the Digilink analog/digital converter could be analyzed and stored.

On August 14, 1985, a dynamic calibration was performed on the LSI SM-810 NOx/SOx gas analyzer and the LSI CM-50 oxygen analyzer. At that time all instruments providing signals used to calculate pounds of NOx per ton of clinker were properly calibrated and operating reliably. Since then approximately 9,000 sets of data have been collected.

3.2.2 NOx Research Program Software

In April 1982, software development for the NOx research project began and by July 1982 the preliminary development of the software required to calculate pounds of NOx per ton of clinker had been collected. The preliminary development of the software necessary to calculate mass and heat balances on the kiln on a continuous basis was completed by February 1983. By May 1983 the preliminary development of the data logging and recording sections of the software was finished. Numerous trial runs were made on the developed software to debug the programs that had been developed and the data logging system was functional when the Number Two kiln resumed production in August 1984.

In September 1985 the final revision was made to the software, and the data collected subsequent to August 14, 1985, was recalculated using the equations in their final form (see Attachment J for a complete listing of the software revisions).

3.2.3 NOx Project Quality Assurance

After the Number Two kiln had operated for several months following the August 1984 restart, a NOx Research Project Manager was assigned to insure that the data collected were valid. An intensive investigation of the instrumentation, calibration procedures and staff procedures was started February 1, 1985. A Quality Assurance Manual was begun to provide a standardized instrumentation preventive maintenance program, a list of equipment calibration procedures, and an outline of staff reporting functions, responsibilities, and procedures associated with the NOx Research Project. The manual was essentially completed in June 1985 and was audited by KVB (see Section 3.2.4) as part of an intensive audit of the NOx project.

The recommendations made by KVB relating to the Quality Assurance Manual were implemented and a revised Quality Assurance Manual was issued in September 1, 1985 (see Attachment K, the Quality Assurance Manual; Attachment L, KVB's Audit Report; and Attachment M, RCC's response to the KVB Audit Report).

In addition to calibrating the field instrumentation, all electronic equipment used during the calibration of field instruments is sent to an independent laboratory, on a periodic basis, for calibration and certification to insure accuracy (see Attachment N for copies of electronic instrument certifications, standard gases certifications, certifications of weights used in calibrations and the exit gas cooling water spray turbine meter certification).

3.2.4 Audit Of The NOx Research Project By KVB

In June 1985 when the instrumentation, data logging and reduction hardware and software, calibration procedures and operating procedures were essentially in final form, RCC contracted with KVB to perform an audit of the NOx Research Project. The purpose was to insure that proper procedures were being followed and that all data collected were as accurate as possible.

The first task assigned to KVB was to conduct a series of three velocity traverses of the Number Two kiln exit gas duct to determine the quantity of exit gases flowing out of the kiln. This task was to verify the calculated value for exit gas volume used by the NOx Research Project software to determine the pounds of NOx emitted by the kiln. KVB concluded that the volume of exit gases as calculated by the NOx Research Project software was accurate and was the preferred method for the determination of exit gas volume for the Number Two kiln at the Crestmore plant. KVB also performed a kiln exit gas chemical analysis to verify the accuracy of the NOx Research Project NOx, SOx, and oxygen continuous gas analyzers. KVB found that the exit gas chemical analysis compared very closely with the analysis provided by the continuous analyzers (see Attachment O for the report by KVB detailing the above described activities, findings, and recommendations).

The second task assigned to KVB was a detailed audit of:

1) all field instrumentation, including its operation and calibration;

2) methods of data logging and reduction, including a review of the equations and programming used;

3) the data collected and an analysis of this data for accuracy and precision;

4) the engineering constants used in the software for variability; and

5) the Quality Assurance Manual for completeness.

KVB personnel observed the operation and calibration of most of the instrumentation used to calculate the pounds of NOx per ton of clinker. Several recommendations were made by KVB and adopted by RCC relating to calibration procedures.

KVB examined the hardware and software used by the NOx Research Project for data logging and reduction. Their primary recommendation was to modify the equations used to calculate the pounds of NOx per ton of clinker so that each element of the equation was logically and independently developed to aid in the clarity of the programming. KVB's recommendation was implemented immediately (see Attachment J for a complete listing of all changes made to the NOx Research Project software).

As part of Task 2, KVB analyzed the data collected for precision and accuracy. This analysis provided the NOx Research Project staff with a listing of the engineering constants and field signals that have the greatest effect on the calculated pounds of NOx per ton of clinker value. KVB also performed an analysis of the variability of the engineering constants used to calculate pounds of NOx per ton of clinker.

Finally, KVB reviewed the Quality Assurance Manual for completeness (see Attachment K). Several changes were recommended which were included in a revised Quality Assurance Manual.

The third, and final, task assigned to KVB was a weekly audit of the project to insure that the operations and procedures agreed upon after the issuance of the KVB audit report had been implemented and were being followed. These audits were conducted on September 19, October 8 and October 16, 1985 (see Attachment P for the reports by KVB of its findings during these weekly audits).

3.3 DATA COLLECTION AND REDUCTION

3.3.1 Data Collection

In August 1984, after extensive plant redesign and modifications and installation of monitoring equipment, RCC began the collection of NOx emissions data from the Crestmore Number Two kiln. To insure that the NOx emission rate reflects emissions during normal operating conditions when firing only with coal, RCC excluded data collected when:

1) the kiln was beginning to produce clinker or stopping production;
2) MMBTU/ton (millions of British thermal units per ton of clinker) was less than 3.5 or the coal feed rate was less than 2.0 tons per hour;
3) when instruments were being calibrated; and
4) the water spray was at least 20 gallons but less than 70 gallons per minute (values outside of this range indicate malfunction of either the water spray or the water spray meter).

These exclusion criteria were applied only to data recorded since August 13, 1985. Data collected during temperature excursions were not excluded as they are part of normal operations. All 6-minute averages of pounds of NOx per ton of clinker values from August 1984 through October 1985 are presented in Attachment Q.

3.3.2 Equation Used To Calculate Pounds Of NOx Per Ton Of Clinker

The equation used in the Crestmore NOx Research Project software to calculate pounds of NOx per ton of clinker is:

$$\frac{\text{lb NOx}}{\text{Ton Clinker}} = \frac{(\text{ppm}_v\text{NO})\ (46)\ (1.56 \times 10^{-7})\ (\text{SWCFM})}{\text{Tons/hour of clinker}}$$

where

ppm_vNOx = the measured volumetric concentration of NO (on a wet basis) in parts per million in the kiln exit gases

tons per hour clinker = the measured production rate of the kiln.

SWCFM = The standard wet cubic feet per minute of kiln exit gases.

3.3.3 Statistical Methods

All methods and equations employed in the statistical evaluation of the NOx emissions data collected by RCC are contained in Snedecor and Cochran, 1980. The equations used are for determining central tendency, dispersion and sample size. Accurate estimation of mean or average pounds of NOx per ton of clinker emission (central tendency) requires that individual observations be weighted by tons of production as they are summed, i.e.,

$$\text{Weighted mean} = \overline{X} = \frac{\sum_{i=1}^{n} (Y_i)(P_i)}{\sum_{i=1}^{n} P_i} \qquad \text{Equation 3.1}$$

where

Y_i = NOx observation in pounds per ton

P_i = tons of production associated with Y_i emissions

n = number of observations composing the weighted mean $\overline{X}$.

It is necessary to estimate NOx emission as $\overline{X}$ rather than the arithmetic mean (X_a) (the average of observations where production is not considered)

$$\text{Arithmetic mean} = X_a = \frac{\sum_{i=1}^{n} Y_i}{n} \qquad \text{Equation 3.2}$$

because the arithmetic mean is not an accurate estimate of average emissions unless the production rate is constant. The following example illustrates this requirement:

> If three observations have pounds per ton emissions rates of 2, 5, and 8 and production rates of 5, 10, and 15 tons of clinker, then the arithmetic mean is:
>
> $X_a = (2 + 5 + 8)/3 = 5.0$ lb NOx/ton.

The weighted average takes into account the varying production and accurately estimates the mean of the NOx emissions:

$\overline{X} = [(5x2) + (10x5) + (15x8)]/30 = 180/30 = 6.0$ lb NOx/ton

If production rates had been equal, $\overline{X}$ and X_a would have been identical and both would be accurate estimates of average NOx emissions per ton of clinker.

Since the daily weighted average has no estimate of dispersion (variance), the variance associated with the daily arithmetic mean must be used as an estimate of dispersion of $\overline{X}$. Variance is calculated as:

$$\text{Variance} = S^2 = \frac{\left\{\sum_{i=1}^{n} (Y_i)^2\right\} - \left\{\frac{(\sum_{i=1}^{n} Y_i)^2}{n}\right\}}{n-1} \qquad \text{Equation 3.3}$$

Where S^2 = variance of the arithmetic mean

Y_i = NOx observation in pounds per ton

n = number of observations composing the arithmetic mean.

The standard deviation is the square root of the variance,

$$\text{Standard Deviation} = S = \sqrt{S^2} \qquad \text{Equation 3.4}$$

and is also an estimate of the precision of X_a or $\overline{X}$. Another estimate of precision of the mean is the standard error of the mean (SEM) and is calculated as:

$$\text{Standard Error of the Mean} = \text{SEM} = \sqrt{\frac{S^2}{n}} \qquad \text{Equation 3.5}$$

The standard error of the mean (SEM) is always less than the standard deviation (S) by the factor $\sqrt{n}$, where n is the number of observations composing $\overline{X}$. This is because a mean (the average of n observations) is inherently more accurate as an estimate of the true population mean than any single observation (Snedecor and Cochran, 1980).

The sampling time period was 24 hours, so that each "observation" is the daily, weighted mean NOx emission rate in pounds per ton, or actually the average of a maximum of 240 six-minute NOx emission rates. A 24-hour period was chosen for two reasons:

1) the variance of a 24-hour observation was shown to be stable; and

2) 24 hours comprises the three labor shifts and therefore will include all variation related to operator discretion; and

While there are 240 six-minute periods in each 24 hours, no observation will ever be composed of the maximum number of observations because:

1) data collected during twice-daily calibration of monitoring instruments are excluded;

2) occasional monitoring instrument malfunctions and subsequent repairs reduce the number of observations; and

3) the inability to retrieve data from a faulty or damaged computer diskette.

The sample size N required to insure that the precision of the estimated mean is no more than plus or minus 10 percent of the population mean is calculated by:

$$N = \frac{(t^2_{.95})\ (S^2)}{[(.01)\ (\bar{X})]^2} \qquad \text{Equation 3.6}$$

where

N = the estimated number of observations such that accuracy of the mean is within the confidence specified in the t-value

$t_{(.95)}$ = a table value of probablistically indexed, standardized precision

S^2 = variance

$\bar{X}$ = mean.

3.3.4 Method For Determining The Emission Limit

An objective of the Crestmore research was to establish an emission limit which represents the emissions of NOx from cement kilns after the application of reasonably available control technology. An average or mean value cannot be a limit as it will generally be exceeded one-half of the time. On occasion it may be exceeded by as much as three times its standard error. The limit must be at some value higher than the mean and based upon the variability of the observations composing the mean.

Emission Limit = Mean + ($t_{.95}$ for N) (SEM) Equation 3.7

where

Mean = from Equation 3.1

$t_{.95}$ = t table value for probability 0.05 for sample size N

SEM* = $\sqrt{\frac{S^2}{N}}$

*where

S^2 is from Equation 3.3
N is from Equation 3.6

---

modification. The primary air after the modification was reduced to 15 percent of the total volume of combustion air. Hence, the second objective was achieved.

Assessment of the objectives to achieve better kiln operational and flame control must be qualitative since quantitative estimates of pre-redesign and modification conditions do not exist. However, in interviews, experienced kiln operators have stated that kiln temperature excursions are fewer and that flame control has improved since the modifications.

4.2 POST MODIFICATION NOx EMISSIONS

Observations of all variables (see Section 3.3.2) pertaining to NOx emissions have been recorded since August 1984. From these observations, 6-minute averages were calculated. All of these values are shown in Attachment Q. From these 6-minute averages, daily, weighted mean emission rates were calculated. These daily means are also shown in Attachment Q.

As the result of continued monitoring system refinement, calibration, and the development of the QC/QA program, the observations since August 1984 have been segregated into three time periods representing increases in the accuracy of the observations. These periods are August 1984 through May 31, 1985, June 1, 1985 through August 13, 1985 and August 14, 1985 through October 22, 1985. October 22, 1985 was the last date for which observations could be made, analyzed and incorproated into this report.

From the daily means for each time period, summary statistics were calculated. The means for the three periods are 6.1, 6.0 and 5.8 pounds per ton, respectively, as shown in

Table 4.1. The 95 percent confidence interval about the mean of 5.8 (n=55) is 5.2 to 6.3, i.e., five percent of the population of means about the value 5.8 will fall outside of the range 5.2 to 6.3; all values within this range are considered not significantly different (probability = 0.05) from the value 5.8 pounds per ton. Average emission rates for the two earlier time periods are not signficantly different (probability = 0.05) from the highly accurate emission rate of 5.8 pounds per ton.

TABLE 4.1

POST REDESIGN AND MODIFICATION NOx EMISSION RATES FROM CRESTMORE NUMBER TWO KILN

TIME PERIOD*	DAILY MEAN	ST.DEV.	N
Aug 1984 - May 31, 1985	6.1	2.52	165
Jun 1 - Aug 13, 1985	6.0	2.21	64
Aug 14 - Oct 22, 1985	5.8	1.96	55

* Individual daily data sheets can be found in Attachment Q.

Daily Mean = Weighted mean pounds per ton, i.e., daily average based on the mean NOx emission for a given day proportionally weighted by the number of observations for that day.

St. Dev. = standard deviation of the weighted daily means.

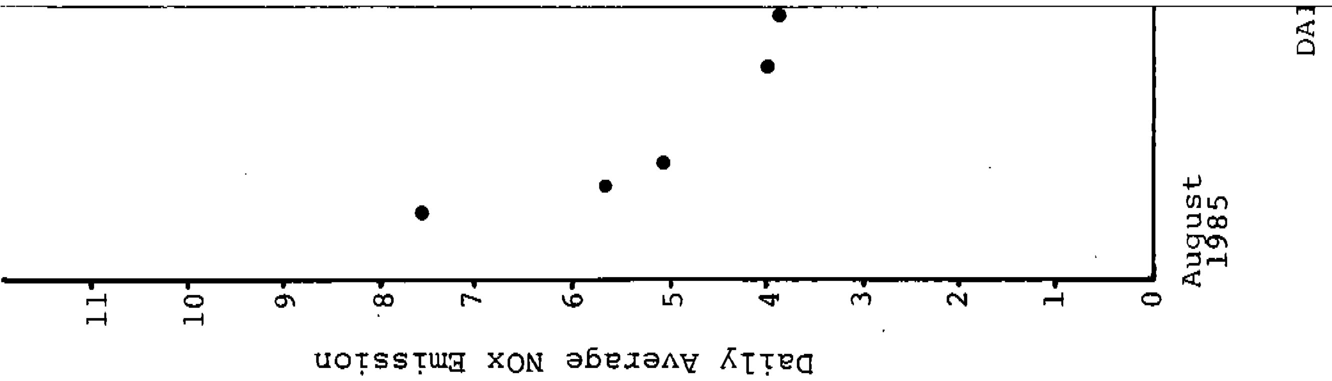
N = number of days during the time period for which there are NOx emission observations.

31 days) averaging will result in an estimated emission rate that is within 10 percent of the true emission rate:

$$N = \frac{(t_{.95})(S^2)}{[(0.1)(x)]^2}$$

$$N = \frac{(1.64^2)(1.96^2)}{[(0.1)(5.8)]^2}$$

$$N = 30.7 \text{ days.}$$



SECTION 5.0

DISCUSSION

The goal of redesign and construction was to reduce NOx emissions from the Crestmore Number Two kiln. Four major objectives in reaching the goal were achieved in the redesign and modification of the Number Two kiln. It was assumed that achieving these objectives would reduce NOx emissions; these assumptions proved correct. NOx emissions were reduced by 26 percent.

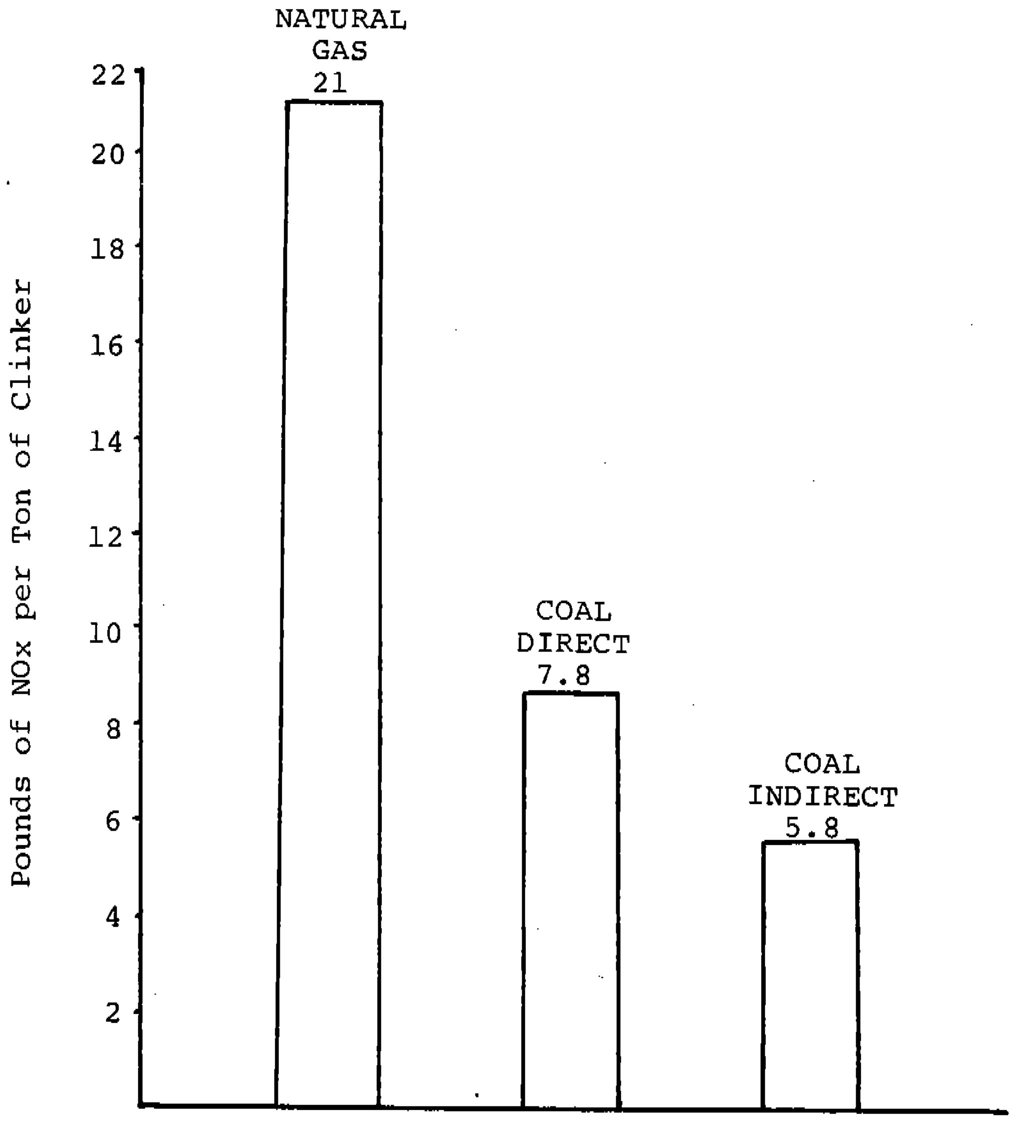
RCC did not use the CARB's 1981 baseline to measure the NOx emission reduction achieved at the Crestmore facility. As discussed below, the CARB baseline is imprecise and is probably inaccurate. Instead, RCC used all available pre-1982 data for coal firing at the Crestmore facility to develop a pre-modification NOx emissions baseline.

5.1 CARB 1981 NOx BASELINE

In 1981, the California Air Resources Board (CARB) conducted tests at California Portland Cement while direct coal firing and two direct coal fired kilns at Crestmore. CARB found an average NOx emission rate of 5.7 pounds of NOx per ton of clinker for the California Portland kiln, and individual test results of 4.7, 8.78, and 14.8 pounds per ton for the two Crestmore kilns. CARB concluded, however, that the Crestmore

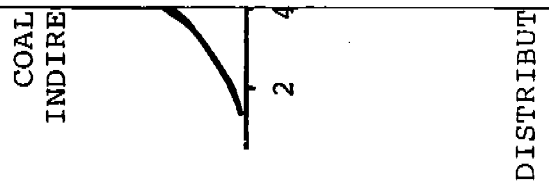
Number Two kiln had experienced an upset, and the NOx emission rate of 14.8 pounds per ton was disregarded; the 8.78 value observed at the Crestmore plant received no additional mention in the CARB study. The NOx emission rates from the California Portland kiln (5.7 pounds per ton) and Crestmore's Number One kiln (4.7 pounds per ton) were averaged to produce the baseline relied upon by CARB and SCAQMD of 5.2 pounds of NOx per ton of clinker for cement kilns in the Basin.

Data exclusion and CARB testing methodology was unjustifiable for estimation of a baseline emission rate for NOx. The NOx emission rates of 4.7, 8.78, and 14.8 pounds of NOx per ton of clinker are well within the expected range of variation for large cement kilns. The Portland Cement Association (see Attachment D) found variation of NOx emissions rates between kilns of 150 to 400 percent. General Portland (Chadbourne 1980) found variation between 8-hour tests at a coal fired dry kiln to be 260 percent; within a single 8-hour test, NOx concentration in exit gas was found to vary by greater than 600 percent. On the basis of these observed variations, 4.7, 8.78, and 14.8 pounds of NOx per ton of clinker are easily within the same population of emission rates, and must be considered with the 5.7 pounds per ton value (from California Portland's kiln) in estimating a baseline emission rate for NOx. The resulting baseline, if all of the CARB data is used, is 7.6 pounds per ton. Using all available pre-1982 NOx emissions data on the Crestmore kilns while firing



COMPARISON OF NOx EMISSIONS WITH
VARIOUS FUELING SYSTEMS

Figure 5.1



convention for statistical inference, in fact, the expected distribution of repeated 55-day NOx emission averages about the mean of 5.8 pounds per ton would include values of 7.8 or larger less than 1 in 10000 times (probability less than 0.0001). Therefore, the null hypothesis in Section 2.3 is rejected and the alternative hypothesis is accepted; the post-redesign and modification NOx emission rate from the Crestmore Number Two kiln is significantly less than the pre-1982 emission rate.

5.3 SELECTED TIME PERIOD FOR NOx EMISSIONS REPORTING

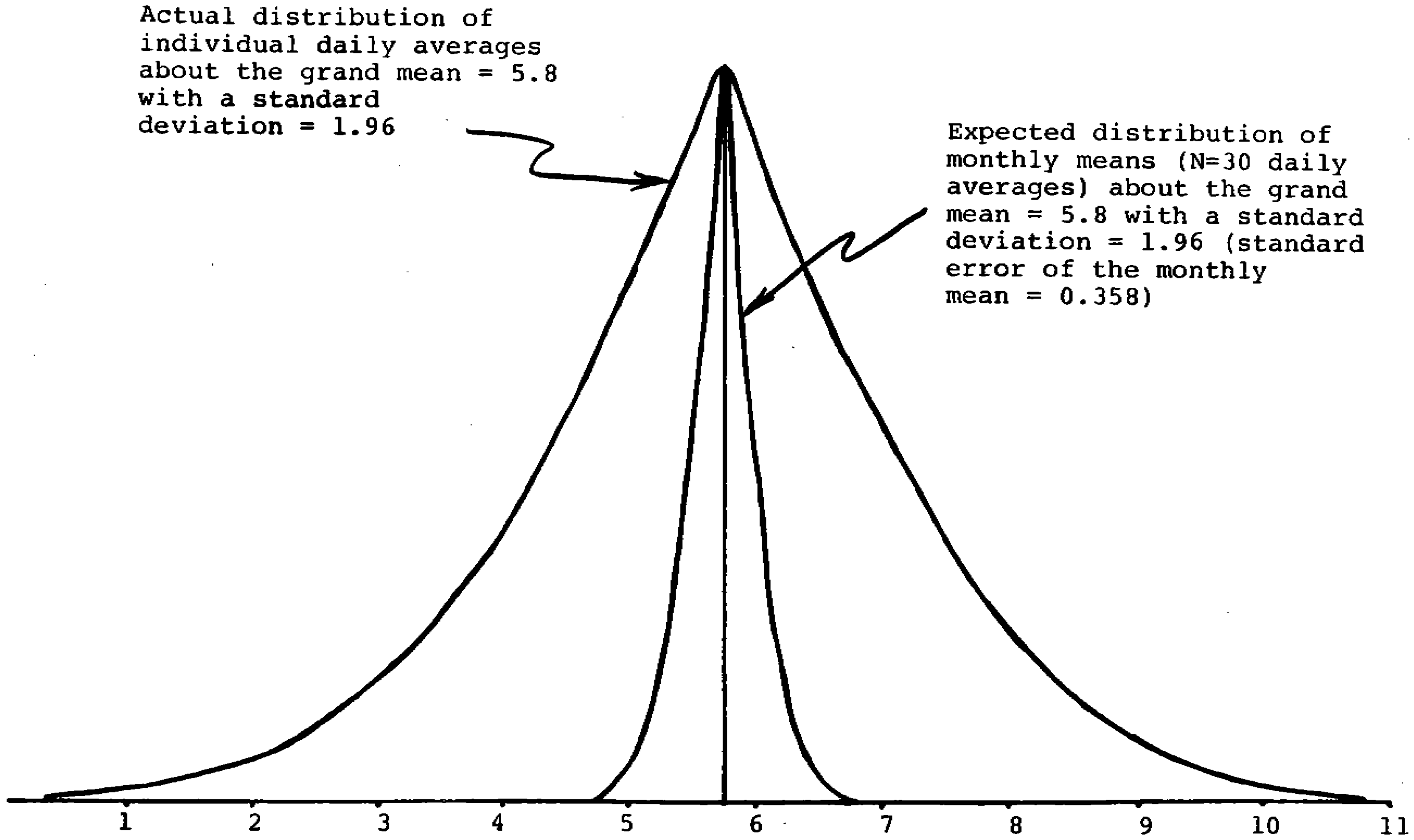
A monthly (30 or 31 days) time period is the proper time period for calculation of the limit. Figure 5.3 presents the distribution of daily averages and the expected distribution of monthly means (n = 30 daily averages) about the long-term mean of 5.8 pounds per ton. The distribution of individual daily average rates is much broader than the distribution of the mean of a fixed number of days, e.g., n = 10 or n = 30 (see the discussion of standard deviation versus the standard error of the mean in Section 3.3.3). Because of the highly variable nature of cement kiln operation, the limit in Rule 1112 must be a long-term mean.

Reporting a monthly (30 or 31 day) average will result in an estimated mean whose accuracy is within 0.6 pounds (10 percent of 5.8) per ton of clinker; the estimated emission rate can be expected to exceed 6.4 pounds per ton (the upper 95% confidence limit) one out of every 20 months. Therefore, Rule 1112 must include the possibility of discretionary kiln shut down to avoid anticipated limit violation.

Monthly average emissions must be based on 100 percent of time rather than actual operational time because:

1) this emission rate will accurately state the real average emission rate over time for the Crestmore Number Two kiln; and

2) this method of calculation allows for the operational strategy of shutting the kiln down if continued operation would result in exceeding the monthly NOx emission limit.



DISTRIBUTION OF OBSERVATIONS AND MEANS (N=30)
ABOUT THE MEAN NOx EMISSION RATE OF 5.8 POUNDS PER TON

Figure 5.3

SECTION 6.0

CONCLUSIONS AND RECOMMENDATIONS

- Redesign and modification of Crestmore's Number Two gray kiln achieved:

  1) a reduction in fuel consumption;
  2) a reduction in primary air use;
  3) more stable kiln operation; and
  4) better flame control.

- NOx emission rates from the Crestmore kilns for gas, direct coal and indirect coal (post modifications) firing have been 21 pounds, 7.8 pounds and 5.8 pounds per ton, respectively.

- The post-modification NOx emission rate of 5.8 pounds per ton is a statistically significant (probability = 0.05) reduction from pre-modification emissions.

- The modifications to the Crestmore Number Two kiln resulted in a reduction in NOx emissions of 26 percent from the pre-modification direct coal fired emission rate. These modifications represent reasonably available control technology for gray cement kilns.

- Based on the post-modification mean NOx emission rate of 5.8 pounds per ton and its statistical variance (3.84), an emissions compliance limit of 6.4 pounds per ton for a monthly average is proposed.

- Calculation of the monthly average NOx emission must include kiln down time to provide the option of shutting down the kiln to avoid an emissions limit exceedance.

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A

Crestmore SOX data reduction

Long-dry kiln → Daily Averages from continuous monitor

J-date	SOx lb/T				
198 5224	0.09	5258	0.15	0.09	0.15
5225	0.15	5259	0.13	0.15	0.13
5226	0.19	5260	0.24	0.19	0.24
5227	0.14	5261	0.23	0.14	0.23
5228	0.1	5262	0.31	0.1	0.31
5229		5263	0.08		0.08
5230		5264	0.09		0.09
5231		5265	0.15		0.15
5232	0.09	5266	0.06	0.09	0.06
5233		5267			
5234	0.11	5268		0.11	
5235	0.63	5269		0.63	
5236	0.84	5270		0.84	
5237	0.96	5271		0.96	
5238	0.4	5272		0.4	
5239	0.17	5273	0.08	0.17	0.08
5240	0.14	5274	0.1	0.14	0.1
5241		5275	0.11		0.11
5242	0.25	5276	0.17	0.25	0.17
5243	0.27	5277	0.09	0.27	0.09
5244	0.13	5278	0.07	0.13	0.07
5245	0.33	5279	0.09	0.33	0.09
5246	0.13	5280	0.23	0.13	0.23
5247	0.14	5281	0.07	0.14	0.07
5248	0.19	5282	0.12	0.19	0.12
5249	0.26	5283	0.1	0.26	0.1
5250	0.07	5284	0.07	0.07	0.07
5251	0.18	5285	0.06	0.18	0.06
5252	0.38	5286	0.05	0.38	0.05
5253		5287	0.11		0.11
5254		5288	0.08		0.08
5255		5289	0.14		0.14
5256		5290	0.07		0.07
5257		5291	0.07		0.07
		5292	0.06		0.06
		5293	0.06		0.06
		5294			
		5295	0.08		0.08

Average 0.179 lb/T
lb/T of clinker

Project at Riverside CA. All methodology QC/QA ed by independent auditor.