1.4

Reference 19

NO_x EMISSION CONTROL TECHNOLOGY UPDATE

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1.0 INTRODUCTION

1.1 BACKGROUND

A Background Information Document (BID) was prepared in support of New Source Performance Standards for industrial sized fossil fuel-fired boilers. The BID discussed the NO_x emission control performance of NO_x emission control technology. However, since the preparation of the BID, NO_x control technologies have continued to be an active area of research. This report follows up on three areas of recent development; 1) low NO_x burners for gas- and oil-fired boilers, 2) low-NO_x burners for pulverized coal-fired boilers, and 3) flue gas recirculation for spreader stoker coal-fired boilers. Data are also presented on the performance of overfire air on coal-fired boilers. For oil- and gas-fired boilers the techniques covered are overfire air and staged combution. This report also investigates the possible application of staged combustion burner designs for process heaters and oil field steam generators to industrial oil- and gas-fired boilers.

1.2 NO_x FORMATION

The principles of NO_x control are best understood when the principles of NO_x formation are understood. While much could be written on NO_x formation, this discussion is intended as an overview of the important principles. The term NO_x represents the combination of NO and NO_2; however, boilers produce predominatly NO due to kinetic limitations in the oxidation of NO to NO_2. NO_x can be formed by two mechanisms. "Thermal NO_x" is the result of the reaction of molecular nitrogen with molecular oxygen, both of which enter with the combustion air. "Fuel NO_x" results from the oxidation of nitrogen that enters with the fuel. The fuel nitrogen is present as part of the molecular structure of the fuel, e.g. pyridine, and is not present as free N_2. Natural gas has no fuel bound nitrogen and, any NO_x formed is, by necessity, thermal NO_x. Distillate oils, residual oils and coals all have fuel bound nitrogen and when these are burned, NO_x is formed by both pathways. Coal combustion produces some thermal NO_x, but produces predominately fuel NO_x since coal is richer in nitrogen than oil fuels.

Thermal NO_x formation is very temperature sensitive since temperature appears as an exponential term in the kinetic expression. Therefore, if the combustion temperature can be controlled, meaning reduced from peak levels, the thermal NO_x can be controlled. In practice this is accomplished by increasing the time during which combustion occurs, and more importantly decreasing the burner zone heat liberation rate (discussed on p. 1-4). Pre-NSPS boilers were designed with tight fireboxes and burners which vigorously mixed the air and fuel. This gave good combustion efficiency and heat transfer, but produced large amounts of thermal NO_x. Post-NSPS boilers that are designed for low NO_x emissions are designed with larger fireboxes and usually some means of introducing the combustion air stagewise in order to reduce the peak flame temperature.

As mentioned, fuel NO_x results from the oxidation of fuel nitrogen. However, not all fuel nitrogen ends up as NO_x; some is reduced to molecular nitrogen. In the case of residual oil and coal, combustion can be broken down into discrete steps. This is illustrated in Figure 5-9.

The figure illustrates the fact that when the coal burns, the first thing to happen volatilization of the lighter components which, with coal, leaves behind a carbon residue termed "char". Recent studies indicate that at conventional combustion temperatures that most of the fuel nitrogen compounds are contained in the volatiles. The volatilized fuel first undergoes thermal cracking to smaller molecules and then reacts with oxygen. The volatile fraction of the coal combusts much more readily than does the char and, therefore control of the volatile combustion is the key to limiting fuel NO_x formation. Low NO_x operation involves introducing the fuel with a substoichiometric amount of combustion air. In this situation combustion initiates and fuel nitrogen is released in a reducing atmosphere which is favorable for reduction to N_2 rather than oxidation to NO_x. The balance of the combustion air enters around or above the substoichiometric flame and the combustion is completed. Here, as with thermal NO_x, controlling excess O_2 is an important part of controlling NO_x formation.

The effect of coal type on NO_x formation is currently a subject of speculation. In terms of fuel nitrogen, bituminous coals are higher than subbituminous. However, the subbituminous coals have significantly more oxygen and, subsequently, a higher oxygen-to-nitrogen ratio. It is speculated that this higher ratio may result in higher conversion of fuel bound nitrogen to NO_x. If this is true it would mean that subbituminous coals may be higher NO_x emitters even though they are lower in fuel nitrogen than bituminous coals. While this hypothesis deserves consideration when setting a standard, it has not yet been conclusively verified.

Control of fuel NO_x formation involves controlling the mixing of the combustion air with the fuel. This can be done in a variety of ways including overfire air, staged combustion, burners-out-of-service and low NO_x burners. When overfire air is used the combustion zone is operated with a stoichiometric amount of air and excess air is added over the combustion zone by overfire air ports. Staged combustion involves introducing air separate from the primary fuel/air mixture. This can be done through separate secondary air ports, through burners operated without fuel and by specially designed burners. Secondary air ports are typically used with tangentially-fired boilers, while these or special burners are used on wall-fired boilers. Operating burners without fuel is a retrofit approach that is not considered for industrial boilers due to the limited number of burners available. Burners which produce staged combustion air termed low NO_x burners.

When considering NO_x formation and its control, it is also important to realize that the boiler and its operation can affect NO_x formation and the performance of control techniques. The primary factors to be considered are:

- burner zone heat liberation rate,
- the number of burners,
- slagging, and
- firing technique.

Burner zone liberation rate is the ratio of heat release rate, Btu/hr, to the heat transfer area in the combustion zone. Small combustion zones which generate high liberation rates and, consequently, high NO_x were typical in pre-NSPS boilers. Modern design enlarge the combustion zone to reduce NO_x formation. The liberation rate for industrial boilers may not be the same as for utility boilers and hence performance data may not be analogous.

The number of burners can affect the ability to control NO_x in that it is more difficult to control the air flow to each burner when there are several. This effect is mitigated by the fact that multi burner arrangement produce more radiant heat transfer which can reduce NO_x. In practice, the net effect is that multi-burner arrangements typically do not perform as well as single burner boilers, all other variables being equal.

Slagging can also be a factor. Slagging is the result of ash softening or melting and depositing on the water wall of the boiler. The result is a reduction in heat transfer in the slagged area and consequently a hot spot in the boiler. If this occurs in the combustion zone the resulting hot spot can cause an increase in thermal NO_x production. Therefore the ash properties of the coal can be a consideration in application of NO_x control techniques such as low NO_x burners or staged combustion since they can affect the slagging tendencies.

The firing technique should be considered when comparing performance data from wall-fired units. Most, if not all, industrial PC boilers and some utility boilers are single wall-fired while some utility boilers are opposed wall-fired. With single wall-firing it is more difficult to control NO_x due to the necessity of adding sufficient combustion air to keep the cold wall in an oxidizing environment to avoid tube wasteage.

2.0 CONCLUSIONS

This report is organized with respect to fuels such that each chapter discusses the new NO_x control techniques applicable to a particular fuel. The fuel classifications are as follows:

- Gas and distillate oil,
- Residual oil,
- Other oil systems,
- Pulverized coal boilers, and
- Stoker coal boilers.

The conclusions are organized in a similar manner. Conclusions relating to emissions are in terms of short term tests and long term averages.

2.1 GAS AND DISTILLATE OIL-FIRED BOILERS

- There are four staged combustion systems applicable to these boilers - staged fuel burners, internal recirculation/staged air burners, staged air burners and overfire air systems.

- Natural gas fired units are capable of achieving NO_x emissions of 0.066 to 0.089 lb $NO_x/10^6$ Btu on an average of short term test basis.

- The limited test data on distillate oil-fired systems indicate that they are capable of achieving NO_x emissions as low as 0.10 on an average of short term test basis.

- Staged combustion systems are commercially available and over 25 have been installed.

- Current vendor guarantees are less than 0.10 lb/10^6 Btu for gas and are 0.11 lb/10^6 Btu for distillate oil.

- The most significant cost when applying staged combustion systems is that of the equipment. The incremental capital cost of a 150,000 Btu/hr staged combustion system over that of a conventional system is $5,000 to $15,000. The incremental capital cost of an overfire air system is from $35,000 to $40,000.

2.2 RESIDUAL OIL-FIRED BOILERS

- NO_x control for residual oil-fired boilers consists of staged combustion through the use of special burners or overfire air systems.

- These techniques are capable of controlling NO_x emissions to 0.24 to 0.30 lb/10^6 Btu on an average of short term test basis (test results include fuel oil nitrogen contents up to 0.45 wt. percent).

- Low NO_x systems are commercially available and currently offered by five vendors.

- Some manufacturers will guarantee NO_x emissions of 0.30 lb/10^6 Btu contingent on such system parameter as the nitrogen content of the fuel, the boiler dimensions, and the burner design.

- Low NO_x systems have been applied to over eight boilers since 1980.

- The incremental cost of a staged combustion burner over the cost of a conventional (150 x 10^6 Btu/hr) is $5,000 to $15,000.

Operating costs data are not available but are much smaller than the capital component.

- The incremental cost of a staged air system is \$35,000 to \$40,000. Operating cost data are not available, but are much smaller than the capital component.

- Additional capital costs for either staging system will be incurred if it is necessary to modify the size of the boiler. These costs can be as high as \$250,000, but are generally expected to be much lower.

Pulverized Coal-Fired Boilers

- Overfire air is not a new technique but is capable of achieving long term average NO_x emissions of 0.60 to 0.63 $lb/10^6$ Btu. The results are from a wall-fired and a tangential-fired boiler. The actual range is likely to be greater since these represent only two data points.

- There are two relatively new NO_x control techniques for pulverized coal-fired boilers, low NO_x burners and in-furnace reburning.

- In-furnace reburning is a promising developmental technology, but will not be available for industrial boilers for several years.

- Low NO_x burners have been only recently applied to industrial boilers.

- The design currently offered are still undergoing development by the various boiler vendors.

- The designs of these burners are based on utility boiler designs which control NO_x by controlling fuel/air mixing.

- Long term performance tests have not yet been performed on low NO_x burners in industrial boiler applications.

- Single burner tests of 50 x 10^6 Btu/hr and less of utility designs have produced NO_x emissions of 0.2 to 0.6 lb/10^6 Btu on an average of short term test basis. These tests were small scale tests conducted during the development of burners for utility applications.

- Utility boilers with the most recent low NO_x burner designs are capable of limiting NO_x emissions to 0.5 lb/10^6 Btu on an average of short term test basis. These data are from both tangential- and single wall-fired units firing predominantly bituminous coal.

- Vendors will currently guarantee 0.7 lb/10^6 Btu for industrial boilers, and possibly a little lower if conditions warrant. Presently, lower guarantees are assessed on a boiler specific basis.

Coal-Fired Stoker Boilers

- Flue gas recirculation, termed stoker gas recirculation, is a commercially available technique for reducing excess air requirements in older boilers.

- NO_x emissions are reduced primarily as a result of lower excess O_2 levels.

- The technique has been installed and tested on a single boiler, but the baseline operation of the boiler was atypical.

- Because of the atypical nature of the boiler tested it is not possible to assess the NO_x control potential of FGR beyond the control potential of LEA.

- FGR was not designed or marketed for NO_x control. The main incentive for purchase is improved particulate control and fuel economy.

3.0 GAS AND DISTILLATE OIL COMBUSTION SYSTEMS

3.1 BACKGROUND

NO_x emissions from natural gas- and distillate oil-fired boilers are formed by essentially the same mechanisms and are controlled by applying the same combustion modification techniques. NO_x emissions from natural gas and distillate oil combustion are composed primarily of thermal NO_x. Staged combustion systems are designed to reduce thermal NO_x emissions by reducing the peak flame temperature and by reducing the concentration of oxygen in the vicinity of initial combustion. There are four staged combustion systems available which apply these techniques for reducing NO_x emissions from natural gas- and distillate oil-fired boilers: staged fuel burners, staged air burners, internal recirculation/staged air burners, and overfire air systems. Staged air burners and overfire air systems are also compatible with residual oil combustion. Staged fuel burners and internal recirculation/staged air burners, although possibly effective for reducing NO_x emissions, are not recommended for residual oil combustion because of problems with elongated flames and flame stability.

3.2 TECHNIQUES

This section discusses the four staged combustion modification techniques currently available for industrial boilers. For each technique the discussion includes a technical description of the technique, emission control performance, capital and operating costs, and commercial availability.

3.2.1 Staged Fuel Burners

Technical Description

Staged fuel burners are designed for the combustion of relatively reactive fuels such as natural gas and distillate oil. The cross-section view of a staged fuel burner is shown in Figure 3-1. This burner achieves staged combustion by introducing the fuel into the flame zone in two stages. The resulting flame is partitioned into almost two separate flames. The partitioned flame is cooler than a standard flame as a result of several factors. The partitioned flame has a greater volume which equates to a lower volumetric heat release rate. The flame also has a greater surface area resulting in more rapid heat radiation to the boiler tubes. Finally the air rich initial flame zone is cooled by the abundance of excess air. As a result of these factors, the flame from a staged fuel burner is cooler than the flame from a standard burner, resulting in a significant decrease in thermal NO_x emissions.

Emission Control Performance

Emission test results are available for a 60,000 lb steam/hr Murray-D boiler retrofitted with a staged fuel burner for the combustion of both natural gas and distillate oil. These NO_x emission tests were conducted using a continuous chemiluminescent NO_x analyzer.[1]

Tests for NO_x emissions from natural gas firing were conducted over a 4 hour period during which the boiler load ranged from 53 percent to 107 percent and averaged 79 percent. All full load, stack oxygen levels were 1.0 percent and at low load stack oxygen levels were as high as 3.5 percent. NO_x emissions during the combustion of natural gas ranged from 0.075 lb NO_x/million Btu heat input at low load to 0.083 lb NO_x/million Btu heat input at high load.[1]

NO_x emission tests for distillate oil combustion were conducted over a 3 hour period during which the boiler load ranged from 20 percent to 104 percent and averaged 63 percent. At full load, stack oxygen levels were 1.1 percent and at low loads stack oxygen levels were increased to 4.3 percent. NO_x emissions during the combustion of distillate oil ranged from 0.070 lb NO_x/million Btu heat input at low load to 0.104 lb NO_x/million Btu heat input at high load.[1]

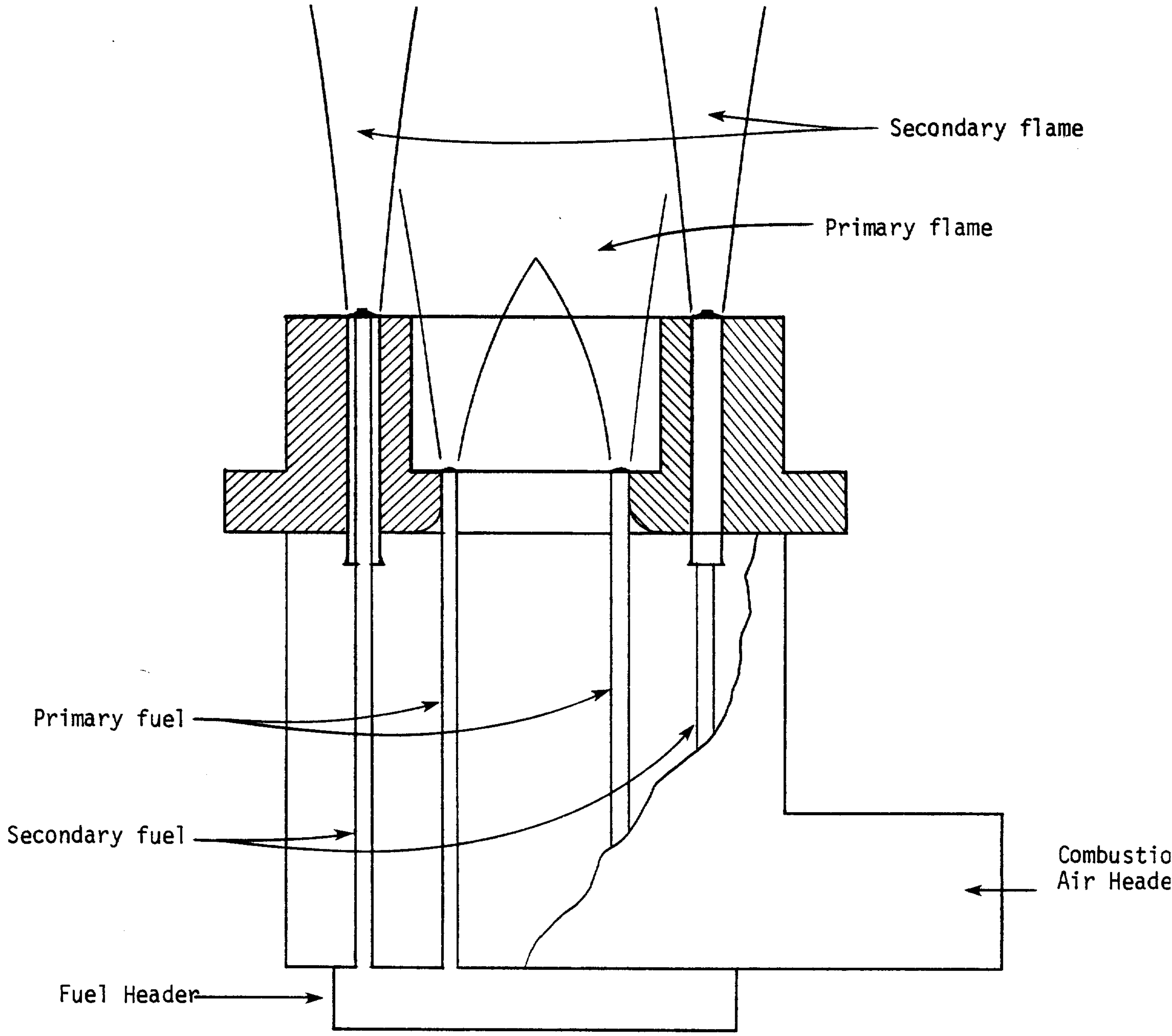

Figure 3-1. Staged Fuel Burner

Cost

The manufacturer of staged fuel burners for natural gas and distillate oil reports that the capital cost of a 150 million Btu/hr (heat input) staged fuel burner is $5,000 more than the capital cost of their same size standard burner. There is no difference between the installation cost nor the maintenance costs of their staged fuel burner and their standard burner. Finally the manufacturer of the staged fuel burner has retrofitted staged fuel burners in 4 boilers without requiring modifications to the boiler size or steam capacity rating.[2]

Commercial Availability

The staged fuel burner is being offered by one manufacturer for application to natural gas- and distillate oil-fired boilers. As shown in Table 3-1, 4 burners have been installed on 4 boilers of different make. One of these burners has been in operation for over 2 years. This manufacturer is currently offering performance guarantees for NO_x emissions of 0.09 lb NO_x/million Btu heat input for natural gas-fired units and 0.11 lb NO_x/million Btu heat input for distillate oil-fired units.[2,3]

3.2.2 Staged Air Burners

Technical Description

Staged air burners can be designed to combust natural gas either singly or in conjunction with a wide range of liquid fuels ranging from light distillate oil to heavy residual oils. To allow flexibility, most staged air burners are designed for multiple fuel capabilities.

The cross-section view of a staged air burner is shown in Figure 3-2. Only a portion of the combustion air is introduced with the fuel at the point of fuel injection. This air is designated as primary combustion air in Figure 3-2. A substantial amount of secondary combustion air is introduced in the burner throat. Finally, the remaining combustion air, designated as tertiary air, is introduced at the burner face and is directed down the boiler walls in such a manner that it does not mix with the flame until the latter portion of the firebox.

TABLE 3-1. STAGED FUEL BURNER INSTALLATIONS

Location	Boiler Manufacturer	Fuel Capabilities	Boiler Size 10^6 Btu/hr
Stockton, CA	Murray (D)	#2/Gas	75
Sunnyvale, CA	Ind. Steam	Gas	63
Sunnyvale, CA	Erie City	Gas	63
Sunnyvale, CA	Keeler	Gas	63

References 2 and 3.

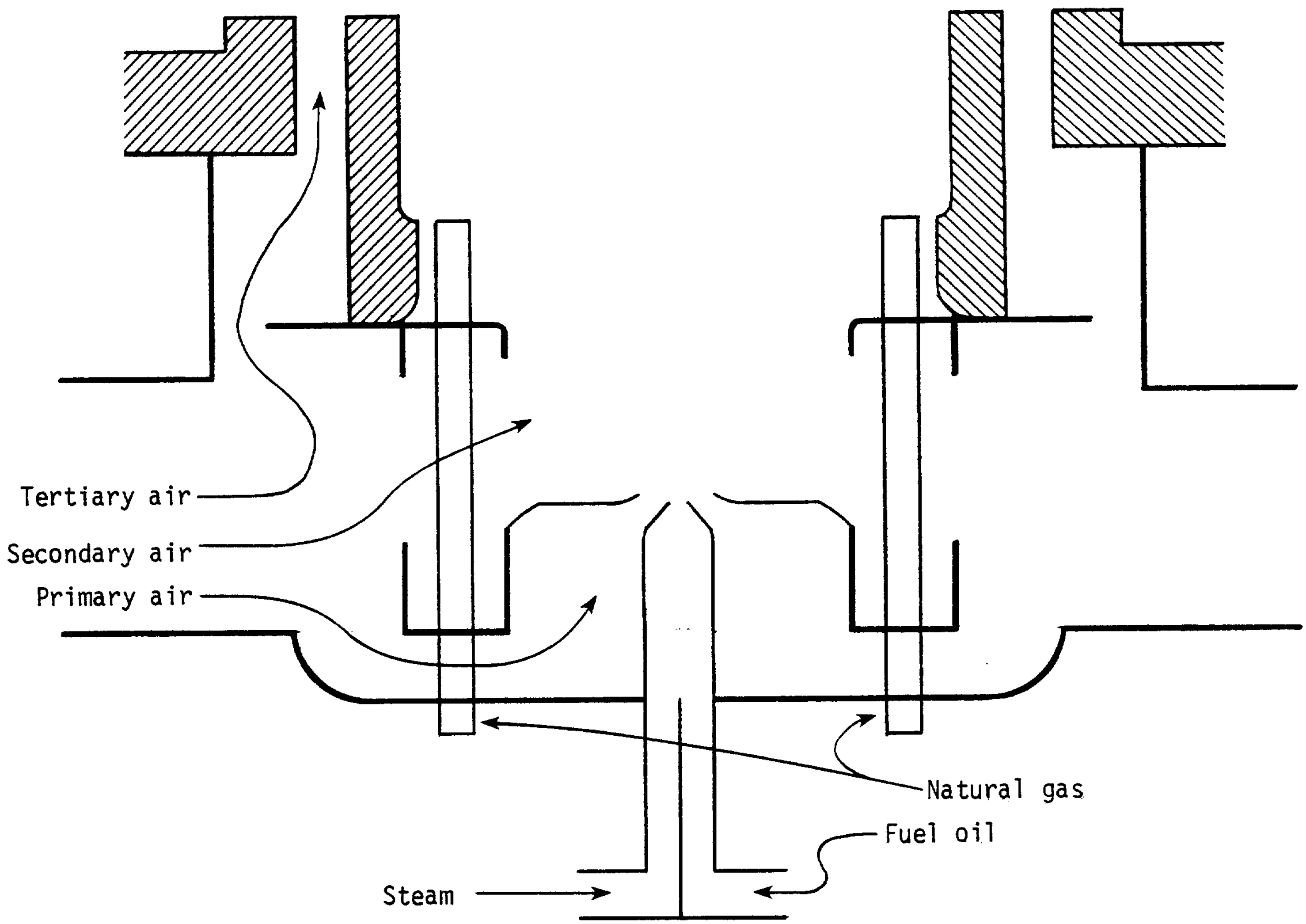

Figure 3-2. Staged Air Dual Fuel Burner

The staged air burner reduces NO_x emission formation by two mechanisms. Staging the combustion air elongates or spreads out the flame. This results in a cooler flame and suppresses thermal NO_x formation. Secondly, with proper combustion air staging, low oxygen levels can be maintained in the specific combustion regions where fuel nitrogen is evolved from the fuel. In the absence of oxygen, the evolved fuel nitrogen will combine to form diatomic nitrogen (N_2).

Emission Control Performance

Test data on NO_x emission control performance are available for four boilers equipped with staged air burners firing natural gas. The burners tested were supplied by two manufacturers. All four tests were conducted for periods of one to two hours using continuous chemiluminescent NO_x analyzers. The results of the NO_x emission test are presented in Table 3-2. These data show NO_x emissions from staged air burners ranged from 0.066 to 0.089 lb NO_x/million Btu heat input.[4,5,6]

No data are available on NO_x emissions from the combustion of distillate oil in staged air burners.

Cost

One manufacturer of staged air burners for industrial boilers reports that the capital cost of a 150 million Btu/hr (heat input) staged air burner is $5,000 more than the capital cost of their same size standard burner. There is no significant difference in either the installation or maintenance costs of their staged air burner and their standard burner.[2]

A second manufacturer of staged air burners reported that the capital cost of their staged air burner was $10,000 to $15,000 higher than that of their standard burner for a 150 million Btu/hr heat input industrial boiler. Data was not available on the installation and operating costs of their staged air burners as compared to their standard burners.[6]

The first three staged air burner installations listed in Table 3-2 are retrofits. All three boilers were capable of accommodating the staged air burners in place of the previously used standard burners without a change in the rated boiler capacity or a modification of boiler dimensions.[2]

Commercial Availability

The staged air burner is being offered by four manufacturers for application to natural gas-fired boilers with multiple fuel-firing capability and ranging in size up to 300 million Btu/hr heat input. However, only two manufacturers have installed staged air burners on boilers in the United States. As shown in Table 3-3, six burners have been installed on six boilers ranging in size from 63 to 156 million Btu/hr heat input. Three boiler manufacturers are represented by these boilers.[2,4,6]

One burner manufacturer is offering NO_x emission performance guarantees of 0.09 and 0.11 lb NO_x/million Btu of heat input for performance on natural gas and distillate fuel oil combustion respectively. The second manufacturer is offering a NO_x emission performance guarantee of 0.10 lb NO_x/million Btu heat input for natural gas combustion without the use of combustion air preheat. The second manufacturer is not offering emission performance guarantees for distillate oil combustion.[3,6] These guarantees apply in general to packaged industrial boilers which seldom employ combustion air preheat. Guarantees for field erected boilers (which generally do include combustion air preheat) and guarantees for some package boilers are determined on a case-by-case basis to account for unusual design features of the boiler.

The remaining burner manufacturers are not offering NO_x emission performance guarantees for their burners.[7,8]

3.2.3 Internal Recirculation/Staged Air Burner

Technical Description

The internal recirculation/staged air burner is designed for the combustion of gaseous fuels only and combines the advantages of a staged air burner with a limited amount of flue gas recirculation. Figure 3-3 shows the cross-section of an internal recirculation/staged air burner. As with other staging burners, only a portion of the combustion air (primary air) is introduced with the fuel. The remaining combustion air, designated as secondary air, is introduced at the burner face and is directed down the

TABLE 3-2. EMISSION CONTROL PERFORMANCE OF GAS-FIRED STAGED AIR BURNERS

Location	Boiler Manufacturer	Fuel Capabilities	Boiler Size (10^6 Btu/hr)	Test Fuel	Boiler Load	NO_x Emissions (lb/million Btu)
Waterford, NY	Combustion Engineering	#6/Gas	125	Gas	Full	0.068
Foster City, CA	Cleaver Brooks	#2/Gas	63	Gas	Full	0.066
Richmond, CA	Cleaver Brooks	#6/Gas	63	Gas	33%	0.088
Walnut Creek, CA	-	Gas	100	Gas	Full	0.089

References 4, 5, and 6.

boiler walls in such a manner that it does not mix with the flame until the latter portion of the boiler fire box. Through the use of venturi action, eddy currents are enduced in the burner throat which serve to recirculate a portion of the initial combustion products back into the initial flame zone.

The internal recirculation/staged air burner reduces NO_x emissions formation from natural gas combustion in part by the same two mechanisms described above for staged air burners. In addition, the internal recirculation/staged air burner reduces thermal NO_x by diluting the oxygen in the combustion zone with recirculating combustion products. These recirculating combustion products are inert and serve to lower the peak flame temperature, a major contributor to thermal NO_x.

Emission Control Performance

Although actively being marketed for use in industrial natural gas-fired boilers, no internal recirculation/staged air burners have been installed on industrial boilers. However, these burners have seen wide spread application on oil field steamers where they are achieving NO_x emission levels for natural gas combustion ranging from 0.04 to 0.05 lb NO_x/million Btu heat input.[8]

Cost

No data available.

Commercial Availability

Internal recirculation/staged air burners are being offered by one manufacturer for use on industrial boilers combusting only gaseous fuels. Through this manufacturer, burners are available in sizes up to 250 million Btu/hr, and are accompanied with a NO_x emission performance guarantee of 0.05 lb NO_x/million Btu heat input.[8]

TABLE 3-3. STAGED AIR BURNER INSTALLATIONS

Location	Boiler Manufacturer	Fuel Capabilities	Boiler Size 10^6 Btu/hr
Waterford, NY	B & W (D)	#6/Gas	156
Waterford, NY	C-E	#6/Gas	125
Foster City, CA	C Brooks	#2/Gas	63
Richmond, CA	C Brooks	#6/Gas	63
San Luis Obispo, CA	C Brooks	#2/Gas	-
Walnut Creek, CA	-	Gas	100

References 2, 4, and 6.

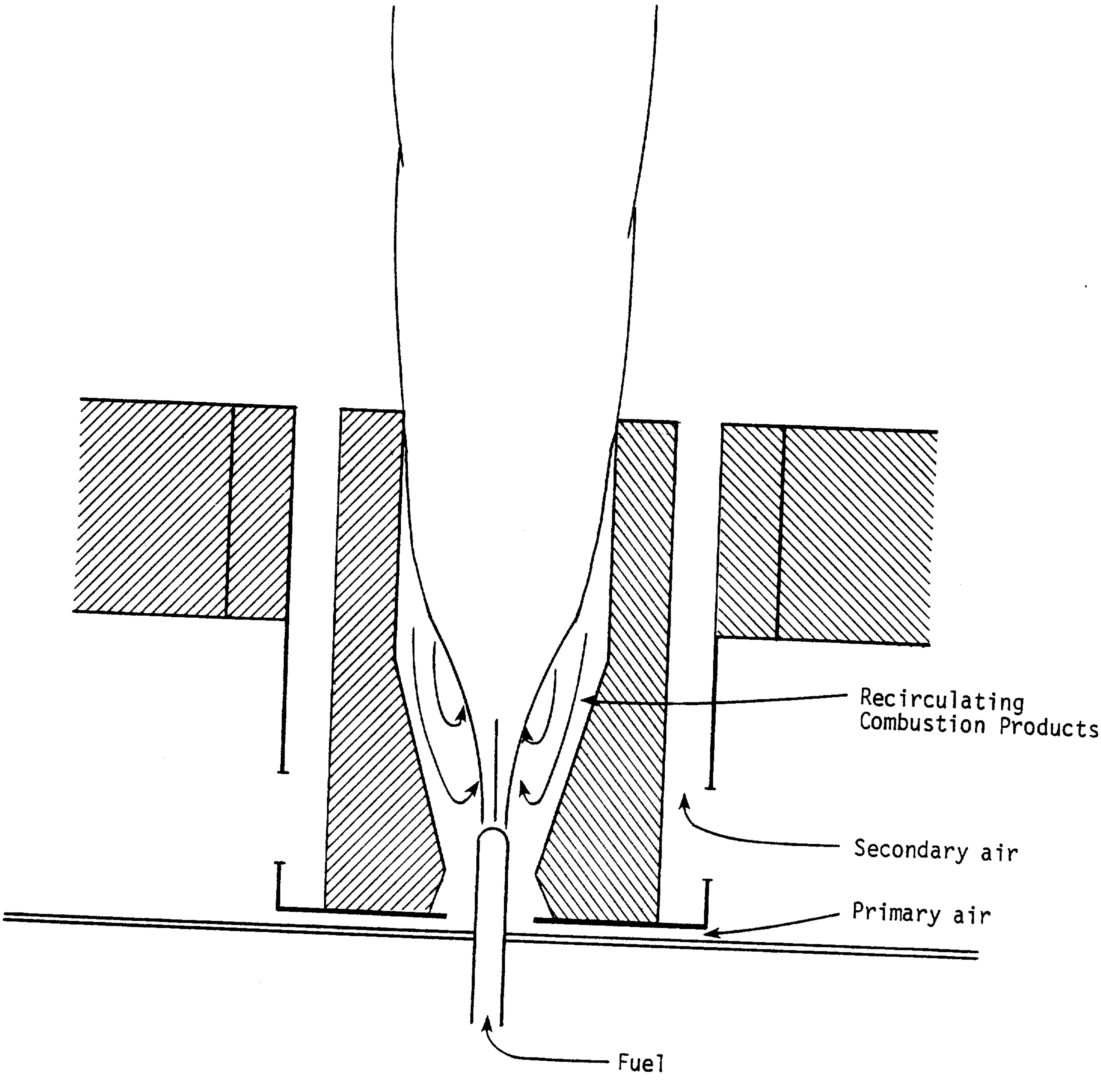

Figure 3-3. Internal Recirculation/Staged Air Burner

3.2.4 Overfire Air Boilers

Technical Description

Overfire air boilers are effective in reducing NO_x emissions from the combustion of both natural gas and fuel oils. In this combustion system, conventional burners are used to introduce the fuel and sub-stoichiometric quantities of combustion air into the boiler. The remaining combustion air is introduced approximately 1/3 of the distance down the firebox through overfire air ports. An overfire air boiler system is shown in Figure 3-4.

The overfire air system reduces NO_x emissions formation by two mechanism. Staging the combustion air partially delays the combustion process, resulting in a cooler flame and suppressed thermal-NO_x formation. The staging of the combustion air also allows the depravation of oxygen in the combustion region when fuel nitrogen is evolved, thereby suppressing fuel-NO_x formation.

The latest overfire air system designs incorporate high pressure injection of the overfire air. The high pressure injection promotes rapid and complete mixing of the remaining unburnt fuel with the secondary air. As a result, the secondary combustion stage is rapid and complete, minimizing flame extension if any occurs.

Emission Control Performance

Emission test results are available for two boilers equipped with overfire air systems. One boiler is a 567 million Btu/hr heat input boiler manufactured by Combustion Engineering and operating at a preheat temperature of 354°F. The average NO_x emissions over a three hour test at full load operation was 0.089 lb NO_x/million Btu heat input.[9]

The second boiler is a 800 million Btu/hr heat input boiler manufactured by Babcock and Wilcox and operating at a preheat temperature of 529°F. The average NO_x emissions over a three hour test at full load operation was 0.086 lb NO_x/million Btu heat input.[10] Although many units have been installed, NO_x emission test data are not currently available on small industrial boilers equipped with overfire air systems.

Cost

The manufacturer which has supplied the majority of the overfire air systems currently in use on package boilers estimates that the capital cost of an overfire air system for a 150 million Btu/hr heat input boiler will be $40,000. This cost includes all air control, ducting, and booster fan costs.[11] A second manufacturer of overfire air systems recently completed bids on equipping a 120 million Btu/hour D-type boiler both with and without an overfire air system. The cost differences between the two bids was $35,000, of which $20,000 was attributable to air controls, ports, and ducting; and $15,000 was attributable to modifications to the dual fuel burner.[12]

There are minimal boiler design modifications required to accommodate the extended flame length associated with overfire air systems. With the use of high pressure air injection, the flame extension in gas-fired boilers is not expected to be significant nor expected to impact the capital cost of the boiler.[13]

There are limited installation costs associated with the overfire air systems but these are not available. However, the installation costs are much smaller than the capital costs.

Commercial Availability

There are two manufacturers of overfire air systems for package natural gas-fired industrial boilers which have manufactured and installed over 13 overfire air systems. Table 3-4 lists eight of these overfire air systems. These systems were installed on boilers ranging in size from 45 to 250 million Btu/hr heat input and firing natural gas, refinery gas, distillate oil, and residual fuel oil.[14] One of these manufacturers offers NO_x emission performance guarantees of 0.12 lb NO_x/million Btu heat input for their overfire air systems when firing natural gas.[12] These guarantees apply in general to packaged industrial boilers which seldom employ combustion air preheat (Guarantees for field erected boilers (which generally do include combustion air preheat) and guarantees for some package boilers are determined on a case-by-case basis to account for unusual design features of the boiler.

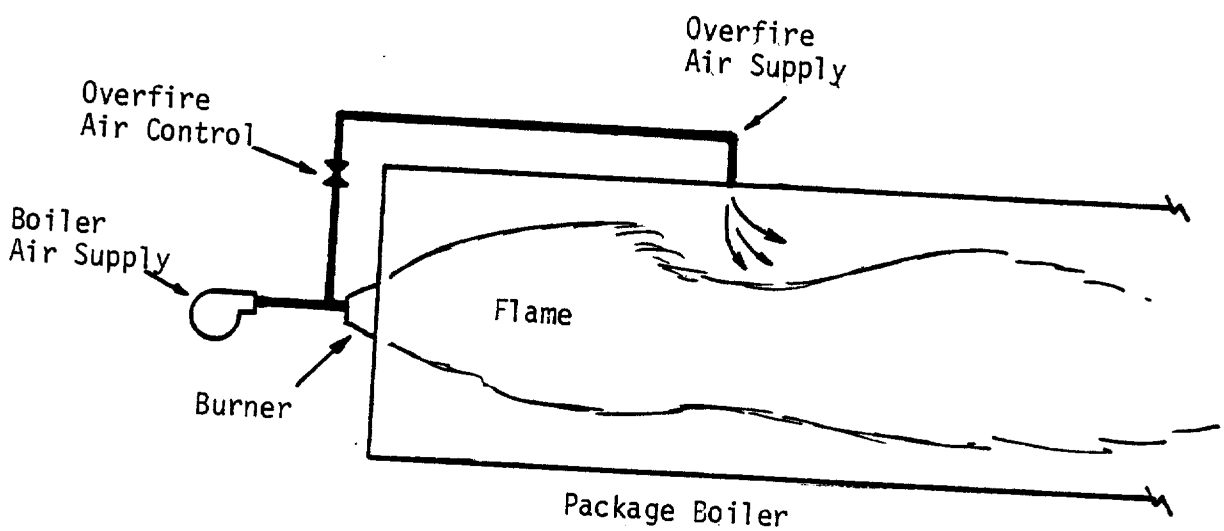

Figure 3-4. Sideview of Overfire Air System

TABLE 3-4. OVERFIRE AIR BOILER INSTALLATIONS

Location	Fuel/S	Heat Input MBtu/Hr
Wilmington, CA	Ref. Gas	178.60 118.67
Convent, LA	Ref. Gas #6 Oil #2 Oil	178.54 160.70 171.82
Parachute Cr., CO	Nat. Gas Plant Mix	124.00 123.00
Wilmington, CA	Ref. Gas	131.30
Freeport, TX	#6 Oil Nat. Gas	44.88 44.68
Freeport, TX	#6 Oil Nat. Gas	49.97 49.91
Bailytown, IN	#2 Oil #6 Oil Nat. Gas	97.26 96.67 99.85
Bakersfield, CA	#6/Gas	200

Reference 14.

There are also two manufacturers offering field erected natural gas-fired boilers equipped with overfire air systems. These systems range in size from 250 million Btu/hr to over 650 million Btu/hr. Each manufacturer has installed several boilers equipped with overfire air systems in the past 3 years, however, information is not available from these manufacturers.[9,10]

3.3 SUMMARY

Table 3-5 summarizes the information presented in this section on staged combustion systems for reducing NO_x emissions from natural gas- and distillate oil-fired boilers. There are four staged combustion systems available for natural gas- and distillate oil-fired boilers; staged fuel burners, internal recirculation/staged air burners, staged air burners, and overfire air systems. The latter two systems are compatible with residual oil combustion also. Tests on seven staged combustion systems firing natural gas exhibited NO_x emissions ranging from 0.066 to 0.089 lb NO_x/million Btu heat input. The single distillate oil fired system exhibited NO_x emissions averaging 0.10 lb NO_x/million Btu heat input.

Seven manufacturers offer staged combustion systems for natural gas and distillate oil combustion. These manufacturers have installed over 25 systems since 1980. Two manufacturers currently offer NO_x emission performance guarantees for natural gas combustion of 0.09 and 0.10 lb NO_x/million Btu heat input. One manufacturer offers a NO_x emission performance guarantee for distillate oil combustion of 0.11 lb NO_x/million Btu heat input. These guarantees apply in general to packaged industrial boilers which seldom employ combustion air preheat. Guarantees for field erected boilers (which generally do include combustion air preheat) and guarantees for some package boilers are determined on a case-by-case basis to account for unusual design features of the boiler.

The incremental capital cost between a staged combustion burner and a conventional burner with a capacity of 150 million Btu/hour is estimated to range from $5,000 to $15,000. The capital cost of an overfire air combustion system excluding the conventional burner cost is estimated to range from $35,000 to $40,000. Other incremental installation and operating costs for staged combustion systems beyond those costs for conventional systems are reported to be negligible when combusting natural gas and distillate oil.

TABLE 3-5. SUMMARY OF INFORMATION ON STAGED COMBUSTION SYSTEMS FOR NATURAL GAS AND DISTILLATE OIL FIRED INDUSTRIAL BOILERS

		NO_x Emission Performance			Incremental Capital Cost[c] ($000 1983)	Commercial Availability	
	Fuel	Number Of Tests	NO_x Emissions ($lb/10^6$ Btu)	Guarantee ($lb/10^6$ Btu)		Number Of Manufacturers	Number Of Installations
Staged Fuel	N. Gas	1	0.083	0.09	5	1	4
	D. Oil	1	0.104	0.11			
Staged Air	N. Gas	4	0.066 - 0.089	0.09 & 0.10	5 - 15	4	6
	D. Oil	None	-	0.11			
Internal Recirc/Staged Air	N. Gas	None	-	0.05	NA	1	0
Overfire Air	N. Gas	2	0.086 - 0.089	None	35 - 40	2[a]	13
						2[b]	Numerous

[a]Package boilers.

[b]Field erected boilers.

[c]Costs are for a 150 million Btu/hr unit.

3.4 REFERENCES

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2. Telecon. Burklin, C. E., Radian Corporation, with Witwer, A., John Zink Company. August 23, 1983. Conversation about staged combustion equipment.

3. Telecon. Burklin, C.E., Radian Corporation, with Martin., R., John Zink Company. October 5, 1983. Conversation about staged combustion equipment.

4. Telecon. Burklin, C. E., Radian Corporation, with Walker, D., John Zink Company. April 2, 1982. Conversation about staged combustion equipment.

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13. Telecon. Burklin, C. E., Radian Corporation, with Siebel, R., Zurn Industries Inc. October 22, 1982. Conversation about stages combustion equipment.

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4.0 RESIDUAL OIL COMBUSTION SYSTEMS

4.1 BACKGROUND

NO_x emissions from residual oil-fired boilers are are composed of both thermal NO_x and fuel NO_x. For the typical residual oil, there are similar quantities of both types of NO_x. However, for the higher nitrogen oils, fuel NO_x will greatly predominate the NO_x emissions.

Staged combustion systems designed for residual oil combustion are all designed to reduce both thermal NO_x in part by reducing the availability of oxygen in the peak temperature flame zone, and reduces fuel NO_x by reducing the availability of oxygen in the flame zone where the fuel nitrogen components evolve from the fuel. Staging combustion air also reduces thermal NO_x by reducing the peak flame temperature. This temperature reduction is achieved by staging the combustion reaction and by providing more flame surface for heat dissipation.

Residual oil-fired boilers achieve combustion air staging by the use of either staged air burners or overfire air systems. Since residual oil-fired boilers are almost always designed to fire auxillary fuels, the manufacturers of both staged air burners and overfire air systems have designed these systems to be effective on natural gas and distillate oil in addition to being effective on residual oil.

4.2 TECHNIQUES

This section discusses the two staged combustion modification techniques currently available for residual oil-fired industrial boilers. For each technique, the discussion includes a technical description of the technique, emission control performance, capital and operating costs, and commercial availability.

TABLE 4-1. EMISSION CONTROL PERFORMANCE OF RESIDUAL OIL-FIRED STAGED AIR BURNERS

Location	Boiler Manufacturer	Fuel Capacity	Boiler Size (10^6 Btu/hr)	Fuel N (Wt.%)	Boiler Load	NO_x Emission (lb/million Btu)
Waterford, NY	Combustion Engineering	#6/gas	125	0.4	Full	0.24
Waterford, NY	Babcock and Wilcox	#6/gas	156	0.4	Full	0.27
Richmond, CA	Cleaver Brooks	#6/gas	63	N/A	Full	0.41

Reference 1 and 2.

4.2.1 Staged Air Burners

Technical Description

A technical description of staged air burners and their operation has been presented in Section 3.2.2.

Emission Control Performance.

Test data on NO_x emission control performance are available for three residual oil-fired boilers equipped with staged air burners. All three tests were conducted for periods of one to two hours using continuous chemiluminescent NO_x analyzers. The results of the NO_x emission tests are presented in Table 4-1. These data show NO_x emissions from residual oil-fired staged air burners ranged from 0.24 to 0.41 lb NO_x/million Btu heat input.[1,2] The two tests with NO_x emissions below 0.30 lb NO_x/million Btu represent the performance of the latest staged air burners designs offered by this manufacturer.

A second manufacturer of staged air burners is offering burners which were first developed on oil field steam generators. On a 0.8 to 1.0 percent nitrogen fuel oil they have oil field steamer tests indicating their staged air burner can achieve NO_x emission levels of 0.20 to 0.21 lb $NO_x/10^6$ Btu heat input.[3]

A third manufacturer is offering staging burners developed for residual oil-fired boilers in Japan. Most of the NO_x performance standard testing conducted by this manufacturer has been conducted on large, multiburner boilers of Japanese design. Based on an extrapolation of their testing results to package boilers, this manufacturer is expecting to achieve NO_x emission levels of 0.12 lb NO_x/million Btu heat input on a 0.2 wt percent nitrogen oil and an emission level of 0.16 lb NO_x/million Btu heat input on a 0.4 wt. percent nitrogen oil.[4]

Cost

The incremental cost for staged air burners above the cost of standard burners was presented in Section 3.2.2. The costs presented were for a

150 million Btu/hr heat input boiler with the capability to combust natural gas or fuel oil. Incremental capital costs were estimated by two manufacturers to range from $5,000 to 15,000. Incremental installation and operating costs were not available, but reported to be much smaller than the incremental capital costs.

A second potentially significant cost difference between staged air burners and standard burners is associated with size modifications to the boiler itself. The boiler may require enlargement to accommodate an elongated flame caused by the staging of residual oil. When elongation occurs, package boiler manufacturers meet the demand for larger boilers by supplying a larger capacity boiler from their production line. Therefore, the impact of staged combustion can be to effectively derate the capacity of standard package boilers.

None of the residual oil boilers that have been equipped with staging systems, have experienced enough flame extension to require boiler derating.[5] However, the manufacturers of these systems concede that they initially installed the staging systems on boilers with liberal amounts of combustion zone space.

The flame extension associated with staged combustion systems on residual fuel-fired boilers is variable and very dependent on the fuel nitrogen content, the burner design and the emission reduction goals. A typical residual oil containing 0.3 weight percent nitrogen is reported by one manufacturer to meet a 0.3 lb/million Btu standard with very little flame extension.[5] However, two other manufacturers have estimated, respectively, that for a 0.47 weight percent nitrogen oil to meet a 0.27 lb/million Btu NO_x emission limits, or for a 0.9 weight percent nitrogen oil to meet a 0.20 lb/million Btu NO_x emission limit on a typical boiler will require maximum derating. As shown in Table 4-2, the maximum amount of derating required with staged combustion is estimated to range from 15 to 20 percent. The NO_x emission limits referred to in these estimates are short term test results.[5,3] Boiler derate is also more likely to be required on very large package boilers of approximately 200 - 250 million Btu/hr in size. Package residual oil-fired boilers in this size range are

TABLE 4-2. ESTIMATED MAXIMUM BOILER DERATING AT FULL STAGING ON RESIDUAL FUELS

Manufacturer	Maximum Derating at Full Staging
John Zink Co.	20%
Process Combustion Company	20%
Mitsubitchi Heavy Ind.	15%
Zurn Industries	15-20%
Babcock and Wilcox	15%

References 3, 5, 6, 7, 8.

very "tightly" designed with no excess fire box volume to accommodate flame extension.[7]

The estimates of maximum boiler derating in Table 3-4 are based on four manufacturers experience with seven boiler types. Greater amounts of staging and consequently greater amounts of derating are possible, however, boiler manufacturers generally agree that these levels of staging are impractical and ineffective for additional NO_x emission control.[3,5,6,7,8]

If flame extension occurs, then the most significant cost associated with staged combustion systems may be the cost of derating a larger boiler than that otherwise required to provide the steam demand in order to accommodate the large flame volume. The capital cost of boiler derating are shown in Figure 4-1 for various derating levels from none up to 30 percent for a 150 million Btu/hr heat input boiler. Manufacturer generally agree that boiler derating ranges from none to 20 percent depending on the fuel type, the inherent tightness of the boiler design and the degree of staging required. From Figure 4-1 the installed capital cost of a 15 percent derating on a 150 million Btu/hr heat input boiler is approximately $250,000 (mid-1982).[9]

Commercial Availability

The staged air burner is being offered by three manufacturers for application to residual oil-fired boilers ranging in sizes up to 300 million Btu/hr heat input. However, only one manufacturer has installed staged air burners on boilers in the United States. Table 4-1 lists the three staged air burners which have been installed by this manufacturer. The three burners were all retrofits ranging in size from 63 to 156 million Btu/hr heat input, and were installed on three boiler types.[2,3,4]

Only the burner manufacturer which has supplied the three burners discussed above provides NO_x emission performance guarantees for their burners. For a fuel oil nitrogen content of 0.4 weight percent nitrogen, this manufacturer will guarantee NO_x emission levels of 0.30 lb/million Btu heat input.[10]

The remaining staged air burner manufacturers are not currently offering NO_x emission performance guarantees for this staged air burners combustion residual oil.

4.2.2 Overfire Air Systems

Technical Description

A technical description of overfire air systems and their operation has been presented in Section 3.2.4 as they are applied to natural gas-and distillate oil-fired boilers. Overfire air systems applied to residual oil-fired boilers are essentially the same as those described above.

Emission Control Performance

Emission tests have been conducted on only one residual oil-fired industrial boiler with an overfire air system. Four tests, each for a period of 15 to 30 minutes were conducted on a 200 million Btu/hr heat input boiler using a continuous chemiluminescent NO_x analyzer. When combusting a residual fuel oil augmented by carbon monoxide, NO_x emissions averaged 0.3 lb NO_x/million But heat input.[11]

A second manufacturer of overfire air systems reports their system achieves NO_x emission levels of 0.3 lb NO_x/million Btu heat input on typical residual fuel oils having a fuel nitrogen level as high as 0.4 wt. percent. Specific test results are not currently available from this second manufacturer of overfire air control systems.[12]

Cost

The incremental capital cost for overfire air systems above the cost for standard burners was presented in Section 3.2.4. The capital costs presented for a 120 and 150 million Btu/hr boiler were $35,000 and $40,000 respectively. These costs were supplied by two separate manufacturers.[12,13]

In addition to the capital cost differences between the two combustion systems, there may also be capital cost differences associated with size modifications to the boiler itself. As discussed in Section 4.2.1 under the heading of Cost, the boiler may require enlargement to accommodate an elongated flame caused by the staging of residual oil. As explained in Section 4.2.1, the incremental installed capital of a 150 million Btu/hr heat input boiler may be increased by up to $250,000 (mid-1982) in some cases due to the staging of residual oil.

The incremental installation and operating costs were not available for overfire air systems, but are reported to be much smaller than the incremental capital costs.

Commercial Availability

Overfire air systems for residual oil-fired boilers are commercially available through two manufacturers for boiler sizes ranging up through approximately 240 million Btu/hr heat input. Five overfire air systems installations were identified for one manufacturer and are listed in Table 4-3. These five systems range in size from 45 to 200 million Btu/hr heat input. The manufacturer of these five systems does not currently offer NO_x emission performance guarantees on the systems.[14]

A second manufacturer has offered overfire air systems for two years and has installed an unspecified number of systems. This second manufacturer provides NO_x emission performance guarantees which vary with the fuel nitrogen content of the residual oil. When firing a residual oil having a fuel nitrogen content of 0.3 wt. percent, the manufacturer will guarantee a NO_x emission level of 0.3 lb NO_x/million Btu heat input.[12]

4.3 SUMMARY

Table 4-4 summarizes the information presented in this section on staged combustion systems for reducing NO_x emissions from residual oil-fired boilers. There are two staged combustion systems available for residual oil-fired boilers; staged air burners and overfire air systems. Both systems are compatible with multi-fuel combustion. Tests on the three most recent residual oil-fired staged combustion systems exhibited NO_x emissions

TABLE 4-3. RESIDUAL OIL FIRED OVERFIRE AIR INSTALLATIONS

Location	Fuels	Heat Input (10^6 Btu/hr)
Convent, LA	Refinery Gas	179
	#6 oil	161
	#2 oil	172
Freeport, TX	Natural gas	45
	#6 oil	45
Freeport, TX	Natural gas	50
	#6 oil	50
Bailytown, ID	#2 oil	97
	#6 oil	97
	Natural gas	100
Bakersfield, Ca	#6 oil	194
	Natural gas	200

Reference 14.

TABLE 4-4. SUMMARY OF INFORMATION ON STAGED COMBUSTION SYSTEMS FOR RESIDUAL OIL-FIRED INDUSTRIAL BOILERS

	NO_x Emission Performance			Incremental Capital Cost[c] ($000 1983)	Commercial Availability	
	Number Of Tests	NO_x Emissions ($lb/10^6$ Btu)	Guarantee ($lb/10^6$ Btu)		Number Of Manufacturers	Number Of Installations
Staged Air Burners	3	0.24 - 0.27	0.3[a]	5 - 15 250[c]	3	3
Overfire Air	1	0.3	0.3[b]	35 - 40	2	5

[a]Applies to a 0.4 wt. % oil.

[b]Applies to a 0.3 wt. % oil.

[c]Maximum cost if boiler size must be expanded.

[d]Costs are for a 150 million Btu/hr boiler.

ranging from 0.24 to 0.27 lb NO_x/million Btu heat input. NO_x emissions from the first industrial installation were 0.41 lb NO_x/million Btu heat input.

Five manufacturers offer staged combustion systems for residual oil-fired boilers. These manufacturers have installed over eight systems since 1980. Of these five manufacturers, two manufacturers currently offer NO_x emission performance guarantees of 0.30 lb NO_x/million Btu heat input. These guarantees are contingent upon the fuel oil nitrogen contents being below 0.3 weight percent in one case, or below 0.4 weight percent in the other. Both manufacturers report that higher fuel nitrogen contents would lead to higher NO_x emission performance guarantees, determined on a case by case basis.

The incremental capital cost between a staged combustion burner and a conventional burner with a capacity of 150 million Btu/hr is estimated to range from $5,000 to $15,000. The capital cost of an overfire air combustion system excluding the conventional burner cost is estimated to range from $35,000 to $40,000.

A second potentially significant cost difference between staged air systems and conventional combustion systems is associated with size modifications to the boiler itself. The cost of this size modification may be as high as $250,000 for a 150 million Btu/hour heat input boiler, but will generally be much lower.

Incremental installation and operating costs were not available but are reported to be much smaller than the incremental capital costs.

4.4 REFERENCES

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5.0 COAL-FIRED BOILERS

5.1 BACKGROUND

NO_x controls for coal-fired boilers have evolved as a result of utility boiler NSPS and state agencies imposing NO_x emission limitations on utility and industrial boilers. The earliest form of NO_x control was low excess air firing. Later, fuel staging was achieved by taking selected burners out of service and using them to introduce combustion air. Subsequently, staging was achieved without derating by adding overfire air ports above the combustion zone. The test data in Table 5-1 indicate that OFA alone can limit NO_x emissions to about 0.60 to 0.63 lb/10^6 Btu. Performance of an OFA system is dependent on several variables including load, boiler and burner design, the sophistication of the OFA control system and the amount of optimization that is performed.

Subsequent development efforts have been aimed at designing "low NO_x burners" (LNB) which effect air staging at the burner. While specific designs vary, the basic principle is the same. About 20 percent of the combustion air enters as primary air with the coal while the bulk of the air is introduced as secondary air in the annular space surrounding the primary air/coal stream. In this manner, substoichiometric combustion of the volatile material occurs and air/fuel mixing is controlled to give a cooler peak flame temperature, both of which result in lower NO_x emissions. Some designs further stage the combustion by including tertiary air ports or overfire air with the LNB.

Low NO_x burners were initially developed for utility boiler applications in response to the utility boiler NSPS. Development and application of LNB's for industrial boilers has lagged utility applications since only some states require LNB's. Low NO_x burners for industrial boilers are usually modified utility boiler designs. However, utility boiler designs are typically tested initially on the prototype scale, about 50 x 10^6 Btu/hr, which is similar to an industrial size burner. Therefore, utility designs have already been tested at the industrial scale.

5.2 UTILITY EXPERIENCE

All of the techniques mentioned above have been demonstrated on utility boilers. The current state-of-the-art is enlarged combustion zones with low NO_x burners, perhaps combined with overfire air. First generation LNB's have, on some boilers, been reported to produce NO_x levels of less than 0.4 $lb/10^6$ Btu or 40 to 50 percent reduction in uncontrolled emissions. Second generation burners are currently being tested on full scale systems and are vendors expect these to produce a 60 percent reduction in uncontrolled emissions.[9,10,11] Continuous monitoring of three utility boilers produced NO_x emission data which ranged from 0.38 to 0.49 $lb/10^6$ Btu.[16,17,18] Specific test data are presented and discussed in a subsequent section on low NO_x burner performance.

Low NO_x burners have been widely installed on utility boilers with all of the major vendors having sold boilers guaranteed to meet the current NSPS of 0.5 $lb/10^6$ Btu for subbituminous and 0.6 $lb/10^6$ Btu for bituminous. For example, since the 1971 NSPS, Babcock and Wilcox reports to have equipped 20,000 MW of capacity with their dual register burner.

5.3 TECHNIQUES

The techniques for NO_x control are naturally divided into those for pulverized coal (PC) and those for stokers. This report updates technologies which have seen significant development in recent years. For PC boilers this includes LNB's and in-furnace reburning; for stokers it includes flue gas recirculation. In the sections which follow, each technique is discussed separately.

5.3.1 In-Furnace Reburning for Pulverized Coal Burners

In-furnace reburning (also called MACT for Mitsubishi Advanced Combustion Technology) is a relatively new development which involves injecting fuel above the combustion zone. This creates a reducing atmosphere above the flame and, at these temperatures NO_x formed during

TABLE 5-1. NO_x EMISSIONS FROM TWO INDUSTRIAL PULVERIZED COAL-FIRED BOILERS USING OVERFIRE AIR

Boiler	Coal Type	Firing Type	Capacity 10^6 Btu/hr	Period Days	NO_x Emissions, lb/10^6 Btu
A	-	Wall	680	53	0.63
B	Bituminous	Tangential	300	180	0.60

References 22 and 23.

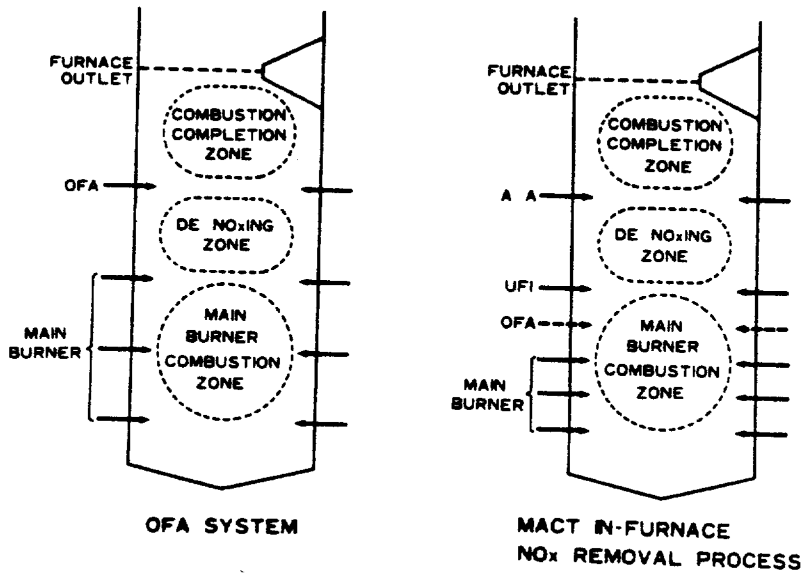


Figure 5-1. Comparison of MACT in-furnace NOx removal process with conventional OFA method.

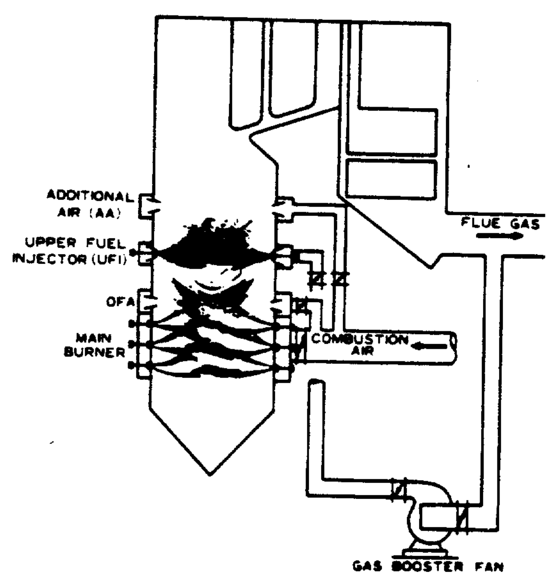


Figure 5-2. Schematic diagram of MACT for steam generator

combustion is reduced to N_2. This is shown schematically in Figures 5-1 and 5-2.

Reburning has been tested on oil and was reported as giving a 50 percent NO_x reduction. It has recently been tested on coal in Japan and has produced NO_x emissions as low as 0.2 lb/10^6 Btu. Reburning is still at the developmental stage in the U.S. There are no domestic commercial applications nor are long term test data available. Given its current state of development, reburning is not currently applicable to industrial boilers.

5.3.2 Low NO_x Burners for Pulverized Coal Boilers

Low NO_x burners are a NO_x control technique designed pulverized coal-fired boiler applications. They were initially developed for utility applications and have, more recently, been applied to industrial boilers. The technical aspects, performance, costs and availability of LNB's are discussed separately in the sections which follow.

Technical Description

Low NO_x burners control NO_x formation by controlling the fuel/air mixing. This is accomplished by introducing the coal with a minimum amount of combustion air. Secondary combustion air is introduced annualarly around the primary air/coal mixture. While the burners offered by the various manufacturers have certain design differences, the basic design for all wall-fired boilers is the same. One utility boiler design is shown in Figure 5-3. In this design, the distributed mixing burner, the coal and primary air enter through the burner nozzle. Secondary air is introduced through two separate registers around the burner nozzle. Turning vanes swirl the air around the coal stream to improve stability and control mixing. The distributed mixing burner design can stage air even further by introducing the final portion through tertiary air ports located on the boiler wall. Conceptually, the effect of air staging is shown in Figure 5-4.

This design is more complex than others where only a single secondary air register is used. An example of this design is shown in Figure 5-5.

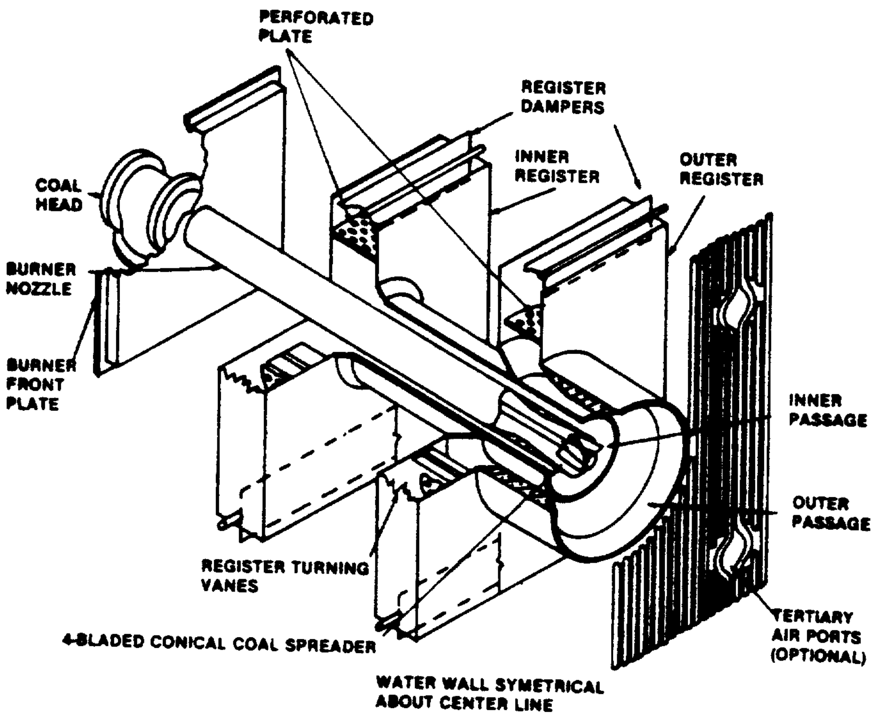
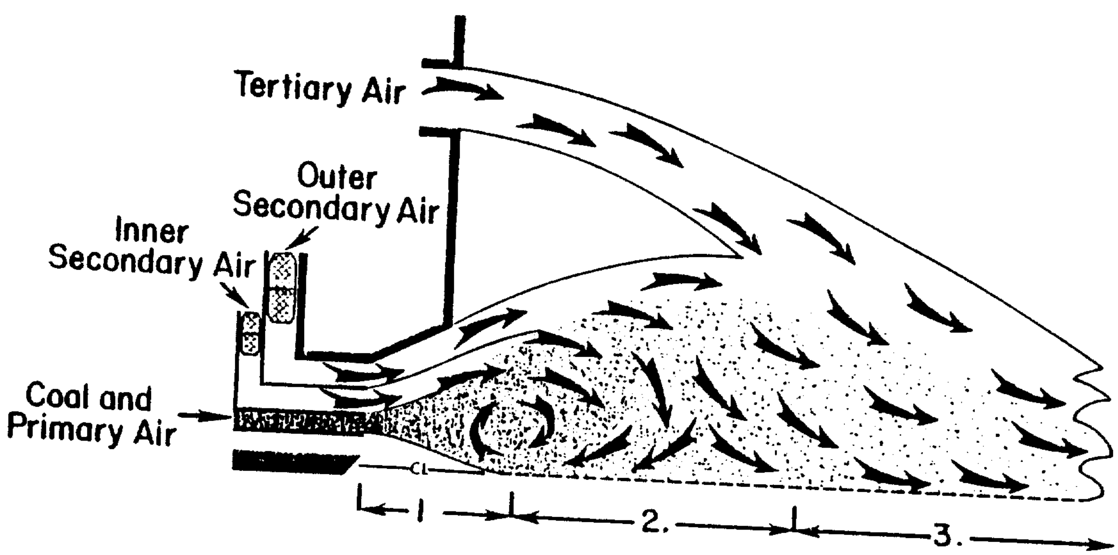


Figure 5-3. Distributed Mixing Burner Utility Boiler Design



1. Very fuel rich zone (average stoichiometry 40%)
2. Progressive air addition zone (overall stoichiometry 70%)
3. Final air addition zone (overall stoichiometry 120%)

Figure 5-4. Conceptual Diagram of Distributed Mixing Burner

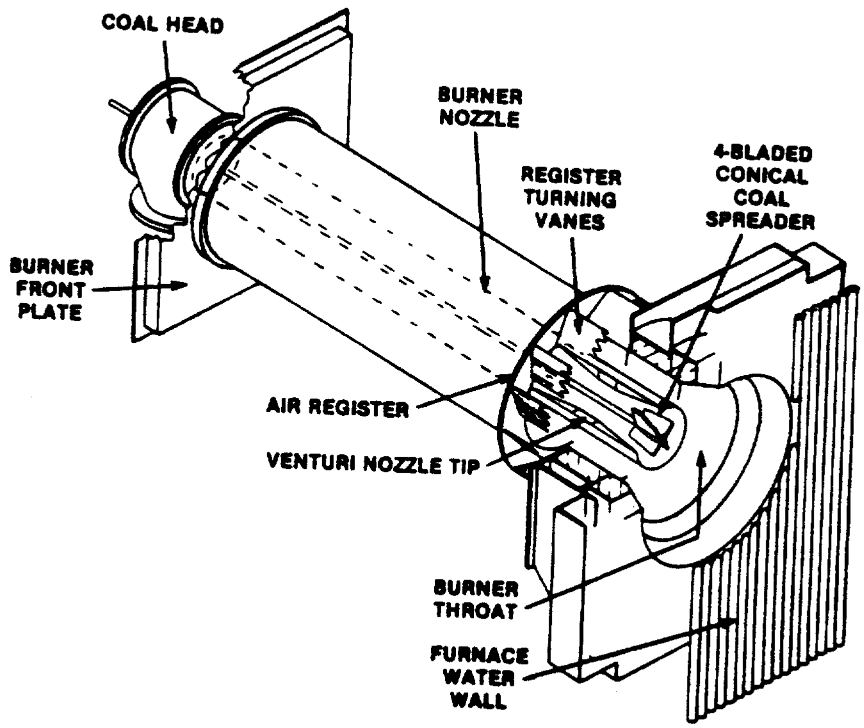


Figure 5-5. Riley Stoker's controlled combustion venturi (CCV) burner utility boiler design

The basic principles are the same in that the burner controls fuel/air mixing.

In the coal/primary air mixture, combustion takes place under substoichiometric conditions which create a reducing, rather than oxidizing, atmosphere. This reduces the oxidation of the volatile portion of the fuel bound nitrogen, much of which is converted to molecular nitrogen rather than NO_x. The second effect of controlling the air/fuel mixing is to essentially extend the combustion zone and hence reduce the peak flame temperature. This results in a reduction in the production of thermal NO_x.

While the burner designs illustrated here are utility designs, the industrial low NO_x burners are essentially scaled down versions of utility designs. In fact, utility designs are typically tested at the 50×10^6 Btu/hr level which means they have been tested on industrial boiler scale equipment, e.g. a test furnace.

There are two primary considerations with respect to application of these designs to industrial boilers. One is that, due to the secondary air registers, LNB's are larger in diameter. This can be addressed in the design stage on a new boiler, but can cause problems on some retrofits. Retrofitting a LNB can require some additional bending of the watertubes to accomodate the larger burner. It may also necessitate removal or modification of some of the buckstays.

A second consideration is that LNB's may have longer flame lengths. With utility designs, some vendors indicate that flame lengths are increased while others indicate that the advanced designs have the same flame size as pre-NSPS burners. It is not clear whether or not flame length will be substantially longer with industrial LNB's. Longer flame lengths would require boilers to be built with larger combustion zones.

Low NO_x burners for tangentially-fired boilers are different in design than those for wall-fired boilers. With tangential firing, an array of coal and air nozzles is used, as shown in Figure 5-6. The simplist form of NO_x control involves using an upper array of nozzles to introduce overfire air. More rigorous NO_x control can be achieved by introducing the secondary air at a larger angle to the combustion zone as shown in Figure 5-7. This has

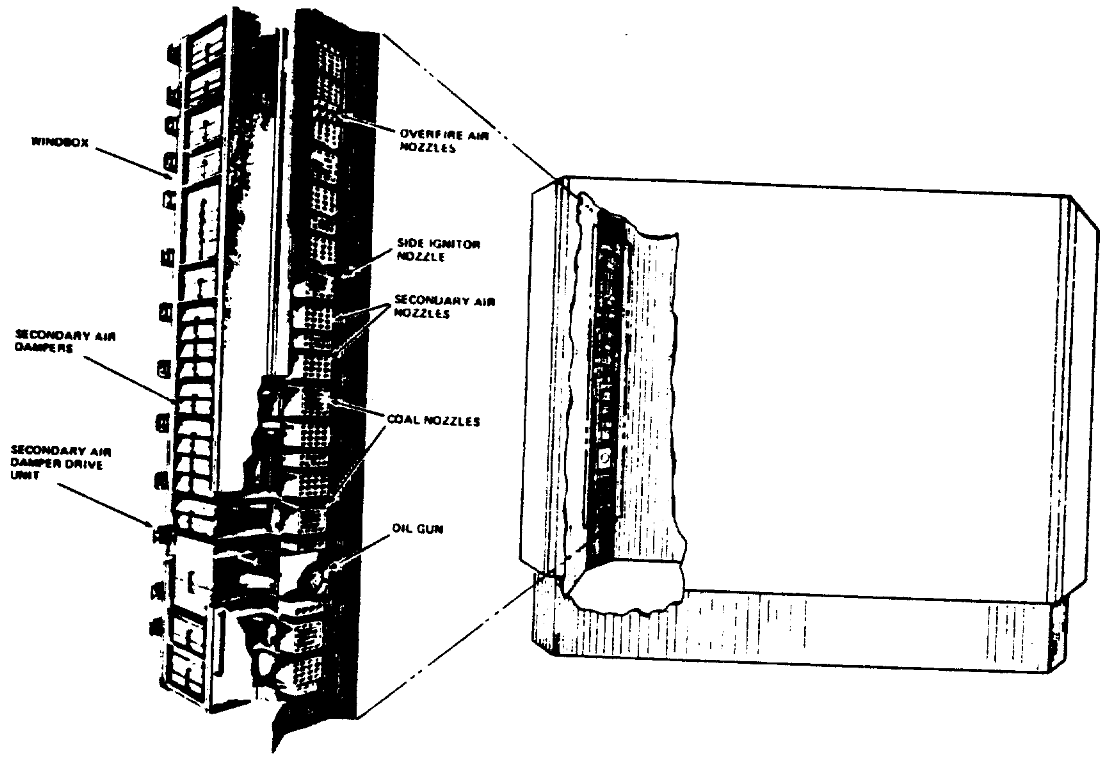


Figure 5-6. Tangential firing system incorporating overfire air for NOx control-coal firing.

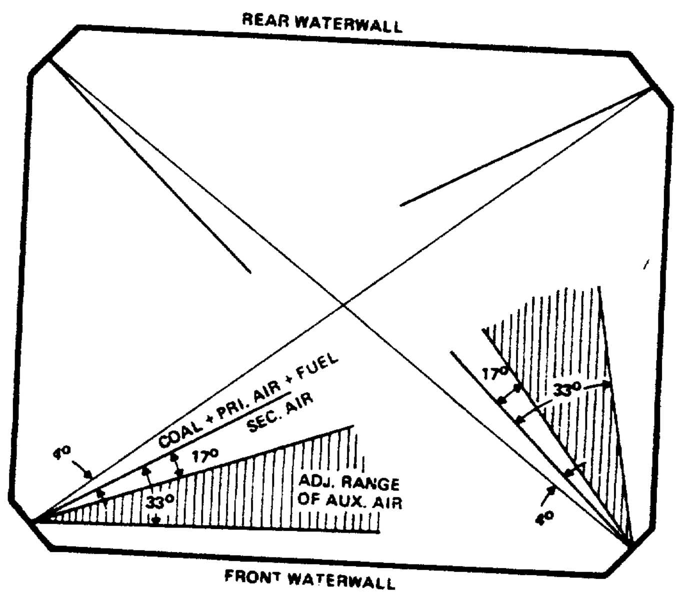


Figure 5-7. Injection angles for fuel and air--Utah Power & Light Company.

the effect of generating a fuel-rich fireball in the center of the boiler. Initial combustion occurs in the center of the fireball and subsequently with the auxillary air and overfire air. The net effect is the same as achieved with low NO_x burners.

Tangential firing has always produced lower NO_x emissions than a similar wall fired unit. This is shown graphically in Figure 5-8 where uncontrolled NO_x emissions are plotted against burner zone liberation rate. Therefore it is reasonable to expect that a tangentially-fired boiler with offset secondary air will outperform a wall-fired unit with low NO_x burners. This statement assumes that boiler-independent variables, e.g. coal type, are similar.

Emission Control Performance

Applications of LNB's to coal-fired industrial boilers are only recent development and, as such, performance data are very limited. There are some utility data that, if used with judgement, can be used to predict the performance of low NO_x burners on industrial boilers. The data are of three types:

(1) tests of prototype utility and industrial burners, usually 50×10^6 Btu/hr single burner tests,

(2) test on utility boilers with low NO_x burners, some small enough to be industrial boiler analogs, and

(3) results from compliance tests or parametric test programs on utility and industrial boilers.

Data of each type are discussed below.

Prototype data are those developed when burner designs are tested on small scale equipment. Most, if not all, of the burners designed for utility boilers have been tested at approximately the 50×10^6 Btu/hr scale in single burner test facilities. Since industrial burners are typically 50 to 100 million Btu/hr in heat output, these prototype utility burners are analogous to full scale industrial burners. There are several considerations that are important when evaluating data from test burners. The first is that these are single burner tests which typically give results that are better than can be achieved in multi-burner installations. A rule-of-thumb would be to add 0.05 to 0.10 lb/10^6 Btu to single burner test results in order to approximate multi-burner performance.[7] A second consideration in interpreting the results of these and all tests is that the burner zone liberation rate, Btu/hr-ft^2, can affect NO_x emissions. Higher liberation rates give higher emissions, and differences between test and actual conditions can affect the burner performance.

Babcock and Wilcox (B&W) has tested both a dual register burner and a controlled mix burner at the 30 x 10^6 Btu/hr level. The test results are shown in Figure 5-9 where the burners are compared to B&W's circular burner, a pre-NSPS burner. At 30 x 10^6 Btu/hr the NO_x emissions range from 350 to 425 ppm or approximately 0.5 to 0.6 lb/10^6 Btu. These tests were conducted using a 50 x 10^6 Btu/hr boiler, but with the burner firing only 30 x 10^6 Btu/hr. Therefore, the burner zone liberation rate, Btu/hr/ft^2, are probably lower than is typical for a boiler operated at full load. It is quite likely that, if this boiler and burner were operated at the full load of 50 x 10^6 Btu/hr, the result would be higher NO_x emissions.

Foster Wheeler has published test results of a 50 x 10^6 Btu/hr prototype of their controlled flow/split flame burner and compared these results to two utility applications in Figure 5-10. As the figure shows the small test burner achieved 0.2 to 0.25 lb/10^6 Btu while the utility boilers emissions ranged from 0.25 to 0.43 lb/10^6 Btu. This illustrates the point that single burner tests will typically outperform multi-burner tests. One reason for this is that it is more difficult to control air flow to each burner in a multiburner arrangement.[7] Considering this, industrial boiler performance may fall in between that of utility boilers and single burner tests, all other things being equal.

Riley Stoker has tested their controlled combustion venturi (CCV) burner and distributed mixing burner (DMB) on prototype scale equipment. Both of these are low NO_x burners. The results with 50 x 10^6 Btu/hr test burners is summarized in Figure 5-11 which plots NO_x as a function of burner zone liberation rate. As the rate increases from 80 to 280 Btu/hr-ft^2 the NO_x produced by the CCV burner increases from 315 ppm (0.45 lb/10^6 Btu) to

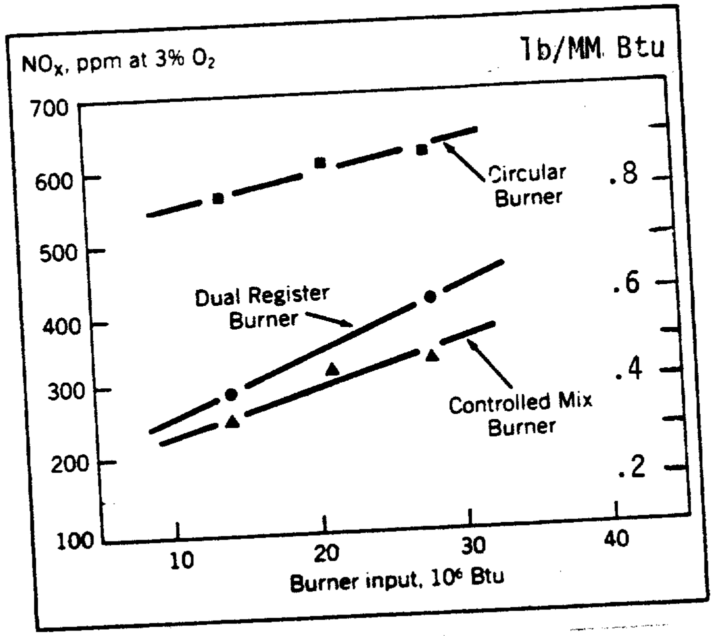


Figure 5-8. Results of Babcock & Wilcox's prototype scale low NOx burners. B&W FM Boiler

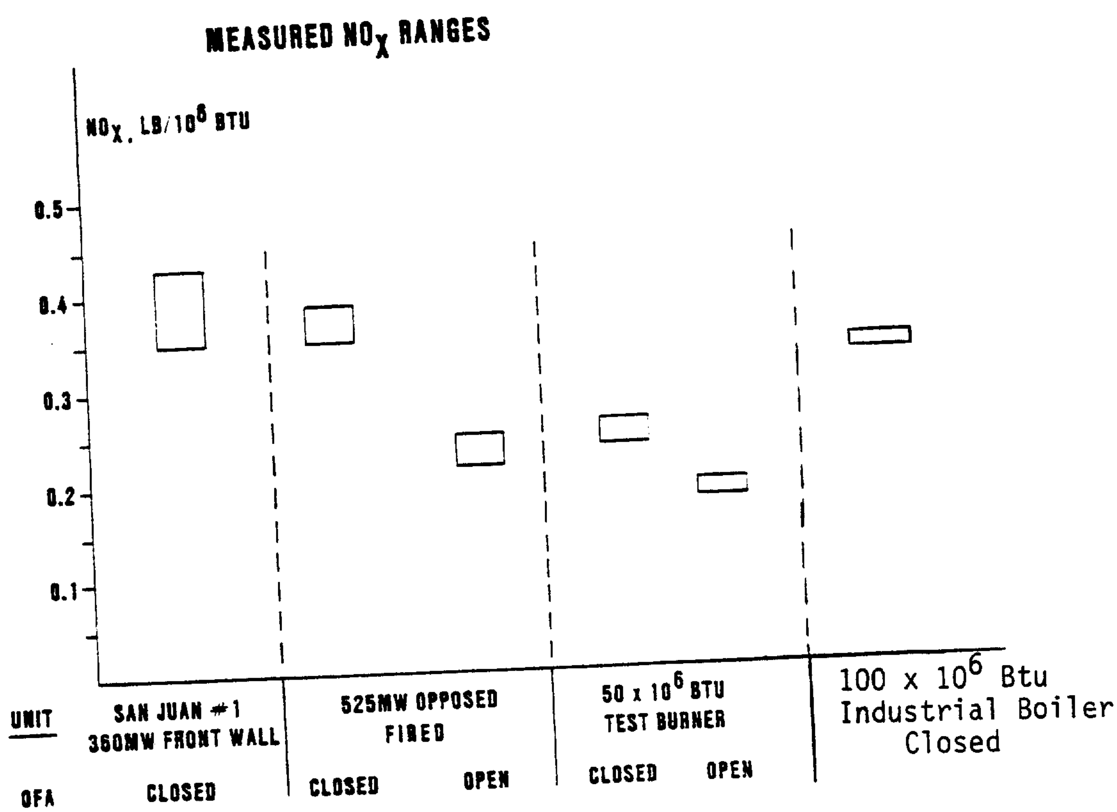


Figure 5-9. Tests of Foster Wheelers prototype burner compared to full scale performance.

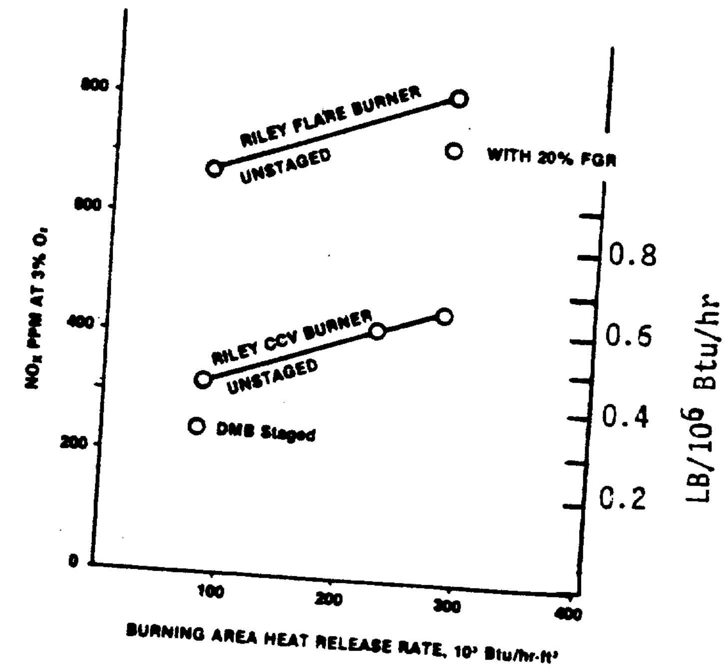


Figure 5-10. Tests by Riley Stoker on NO_x emissions with small scale equipment. Wall Fired Boiler

450 ppm (0.64 lb/10^6 Btu). The DMB appears to produce about 23 percent less NO_x than the CCV burner.

The second form of data that can be used to predict industrial boiler LNB performance are data gathered on utility boilers with similar burners. The EPA has sponsored testing of several utility boilers which have employed LNB's and these tests are summarized in Table 5-2. These data are all from utility boilers. The data from utilities A, B, and C are presented in the form of 30 day rolling averages, while utility D data is the result of parametric testing and utility E is the result of a compliance test.

The 30 day rolling average data is the most desirable since this number will account for load swings and other operating variables than can affect NO_x emissions. Utility A is particularly interesting since the boiler is a 215 x 10^6 Btu/hr unit which is small enough to be considered an industrial boiler analog. This unit achieved average NO_x emissions of 0.49 lb/10^6 Btu for a 30 day period with retrofit LNB's firing bituminous coal. These emissions may be higher than typical since this boiler has a relatively high burner zone liberation rate and the burner is still being optimized. More test data will be available in 1984.

The units at utilities B and C are much larger than industrial boilers, but the burner designs are similar to those being developed for industrial boilers. Utility B is a tangentially fired unit (bituminous coal) that has been retrofit with offset secondary air firing. The data taken from utility B consists of four 30 day tests in which 30 day rolling average NO_x emissions were calculated. Data for the individual 30 day tests are presented in Table 5-3. The table shows that the load varied substantially during each 30 day period indicating that the data represent typical operations for a cycling unit. The NO_x emissions were consistent from test to test, averaging 0.41 lb/10^6 Btu.

Utility C is a wall-fired unit (bituminous coal) that was designed with low NO_x burners, thus avoiding any retrofit problems. The NO_x emissions from these two large units are very similar, about 0.4 lb/10^6 Btu, however, several important factors are different, including coal type, firing type, burner design and initial design of the combustion zone.

TABLE 5-2. SUMMARY OF TEST DATA ON UTILITY BOILERS WITH LOW NO_x BURNERS

Utility Boiler	A	B	C	D	E
Size					
MW Output	20	400	265	60	360
10^6 Btu/Hr Input	215	4,174	2,760	651	3,420 (est)
Coal Type	Bitum	Bitum	Bitum	Bitum	Subbitum
Date Operational	1965	1981	1979	Pre NSPS	-
Stack O_2, %	4	4.2	5.5	4.5	9.7
Firing Arrangement	Front Wall	T-Fired	Front Wall	T-Fired	Front Wall
New or Retrofit	Retrofit	Retrofit	New	Retrofit	Retrofit
Days of Continuous Data					
Existing	30	120	69	0*	1**
Planned	55	30	0	0	0
NO_x Emissions, lb/10^6 Btu (avg. for total existing tests)	0.49	0.41	0.38	0.57	0.41
Range of Daily Averages	0.43 - 0.67	0.19 - 0.56	0.30 - 0.48	-	-

*Parametric tests, not long term performance tests.
**More are available and have been requested.

TABLE 5-3. RESULTS OF FOUR 30-DAY TESTS AT UTILITY B - TANGENTIAL FIRED BOILER WITH OFFSET SECONDARY AIR

	Test Number 1	2	3	4	Average of the Four
NO_x Emissions lb/10^6 Btu, 3% O_2	0.42	0.37	0.41	0.42	0.41
Stack O_2 %	5.8	3.8	3.3	3.9	4.2
CO, ppm	58	30	25	26	35
Load Variation, MW					
Minimum	438	538	544	480	500
Maximum	736	749	634	664	696

Reference 16.

Utility D was the subject of parametric testing to see the effect of several variables on NO_x emissions and is arguably small enough to be considered on industrial boiler analog. It achieved 0.57 lb/10^6 Btu when its tangential firing system was retrofit offset secondary air.

Utility E is, once again, a large wall-fired boiler which was retrofit with LNB's. This data point, 0.41 lb/10^6 Btu, is the result of a 24 hour compliance test required by the state.

While there are two many variables for the data to be conclusive, the natural observation is that NO_x emissions are lower for larger boilers than they are for smaller boilers. This observation is an apparent contradiction of the previous observation that small single burner tests give lower NO_x emission values than are experienced with full scale equipment. It can be speculated that there are some aspects of these smaller boilers that make them higher NO_x emitters. For example, the smaller units are both older units and, as a result, may have higher zone liberation rates, as is typical with older boilers.

The last set of data on low NO_x burner performance are results that were reported by Foster Wheeler. The results, presented in Figures 5-12 and 5-13, were obtained during parametric testing of a 4-burner, 125,000 lb/hr (approximately 100 x 10^6 Btu/hr) industrial boiler. The test results in Figure 5-10 compare the performance of the pre-NSPS intervane burner with Foster Wheelers two low NO_x burner designs. In Figure 5-12, the industrial boiler performance is also compared to the performance of Foster Wheelers second generation low NO_x burner, termed controlled flow/split flame, applied to a utility boiler - both are retrofit situations. The results indicate that the industrial boiler was able to achieve approximately 0.33 lb/10^6 Btu at full load. Emissions for the utility boiler were higher, 0.49 lb/10^6 Btu.[15] Since these are single point tests rather than long term averages.

One final aspect of LNB performance regards vendor guarantees. The four principal vendors of large industrial boilers were contacted and asked what NO_x level they would guarantee with low NO_x burners. All indicated that they would guarantee to meet 0.7 lb/10^6 Btu, which is the current

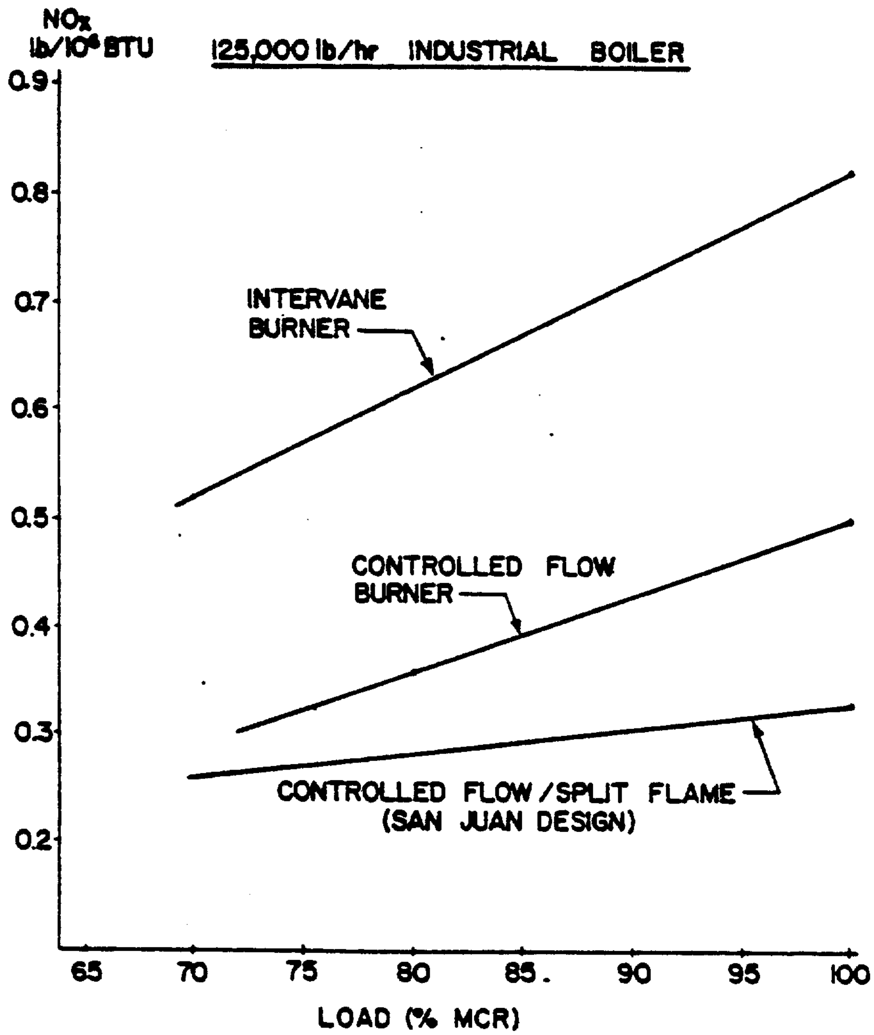


Figure 5-11. Performance of Foster Wheelers low NOx burners compared to a pre-NSPS burner applied to an industrial boiler.

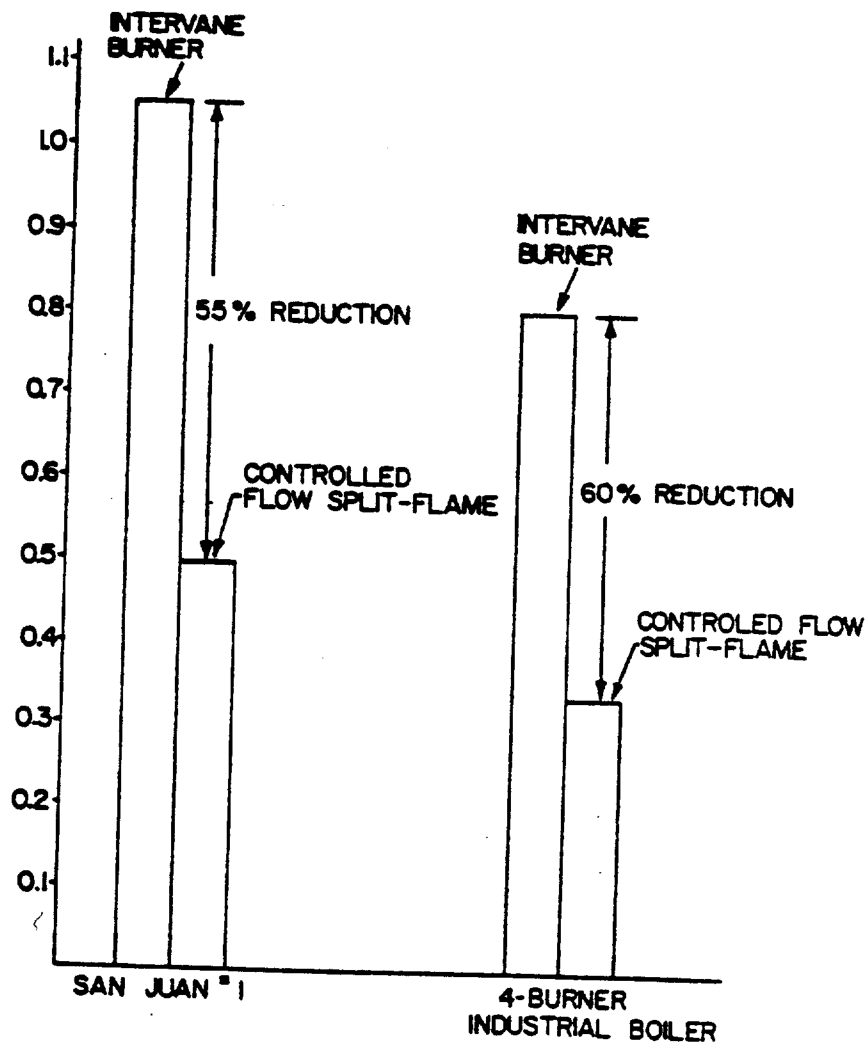


Figure 5-12. Comparison of performance of Foster Wheelers low NOx burner when retrofitted to a utility and an industrial boiler.

regulation under Subpart Da for industrial boilers larger than 250 x 10^6 Btu/hr.[4,5,6,7] Some felt that 0.6 lb/10^6 Btu or lower could be offered if the conditions warranted. Such conditions would be a combination of bid specifications, the competitive environment and site specific factors.

Costs

An effort was made to get cost data on industrial low NO_x burners from the various vendors; however, they indicated that this information was not available. The vendors consider this information confidential since it could affect their competitive position. Furthermore, since there are not many applications, information in terms the cost difference between conventional burners and LNB's may have never been developed. Costs should consider at least two items - the increase capital cost of supplying a low NO_x burner and any impacts on coal combustion efficiency, i.e. operational costs. The capital cost is not the cost of a new burner but rather the difference in costs between a low NO_x burner and a conventional burner. Also, if the combustion zone is increased in size, there will be an associated capital cost.

The most significant cost impacts will result from any loss in coal combustion efficiency. One vendor indicated that initial tests of an industrial design low NO_x burner had shown carbon loss increasing from 1 percent to 2 percent. The vendor also indicated that development efforts were aimed at reducing carbon loss with this burner to 1 percent, which is typical for industrial boilers.

Commercial Applications

Although LNB's for industrial boilers are a more recent development than those for utility boilers, there have been several applications. These have been in response to Subpart Da requirements for boilers greater than 250 x 10^6 Btu/hr heat input or state permit requirements.

While the vendors were reluctant to provide list of their clients who had purchased boilers with low NO_x burners, several did indicate some had been sold.[4,5,6,7] Of these, some have commenced operation. Subsequently, a request was made to the American Boiler Manufacturers Association (ABMA) for a list of industrial boilers with low NO_x burners. A partial listing was received and available data from these units is contained in this report.

5.3.3 Flue Gas Recirculation for Coal Fired Stoker Boilers

Spreader stoker boilers, by their design, naturally achieve staging. Part of the fuel is combusted on the grate while the remainder is burned in suspension above the grate. Combustion air is split and introduced both below the grate, and above the grate through overfire air ports.

Low excess air (LEA) operation is achieved by design and adjustment of the combustion air delivery system. Typical stack O_2 levels are over 6 percent on older units, 5 to 6 percent on new units and 4 to 5 percent when LEA is applied. LEA operation has an economic incentive since it results in more efficient heat recovery. However, LEA controls also require closer boiler operator attention and/or more reliable combustion air controls to insure safe operating conditions.

In the past FGR has not been applied to stokers since inherent staging and LEA were effective in meeting applicable regulations while providing improved fuel efficiency. These NO_x control technologies were discussed in the Background Information Document for Industrial Boiler Source Categories. However, Zurn Industries recently introduced an FGR design for stokers, termed Stoker Gas Recirculation.[2] Since flue gas recirculation represents the only area of recent development in terms of NO_x control for stokers technology this section will specifically focus on FGR controls.

Technical Description

Stoker Gas Recirculation was designed as a technique for reducing excess air requirements and improving boiler control. This particular design also improves the particulate control efficiency of the cyclone dust collector. The system was not designed for nor is it marketed as a NO_x control system. It is intended to be a means in which an existing stoker can reduce excess air requirements, especially at low loads, and reduce fuel costs by decreasing heat loss to excess combustion air.

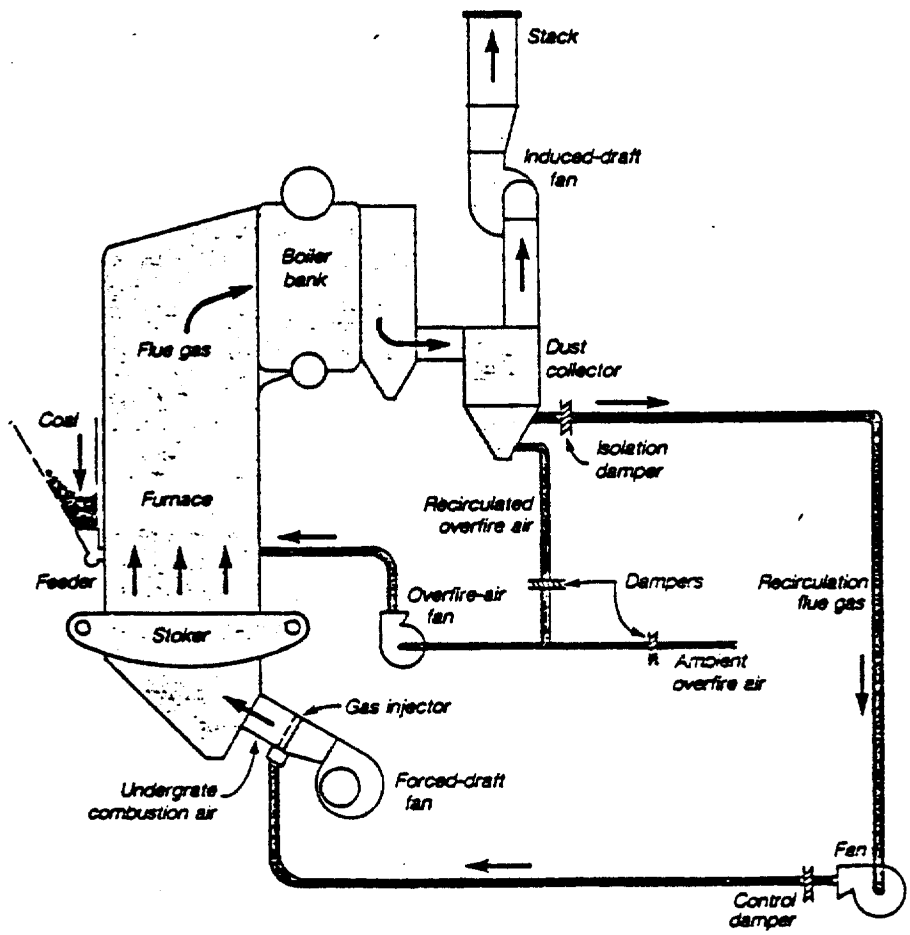


Figure 5-13. Flow diagram of KVB/Zurn stoker gas recirculation system.

The Zurn process was developed by KVB and is shown schematically in Figure 5-14. The process achieves a reduction in particulate emissions by extracting flue gas from the hopper section of the dust collector. This has the dual effect of using the grate as a secondary filter and recycling entrained particles both of which aid particulate collection. With FGR, excess air can be reduced since the flue gas injected under the grate is of higher heat capacity and thus more effective at keeping the fuel bed cool and avoiding clinker formation. With FGR, temperatures above the bed are reduced as much as 250°F. This cooling effect and the lower excess air lead to lower NO_x emissions. A previous study has shown that NO_x emissions from stokers vary directly with excess air levels.[1]

Emission Control Performance

This FGR technique is currently operational on only one boiler, one which is atypical of stokers in general. Therefore the data cannot be applied to all stokers.

This FGR system was applied to an eight year old, 100,000 lb/hr stoker boiler with high excess air problems such that the stack O_2 concentration was 9 percent rather than the 5 percent that is typical of modern stokers. The boiler also has an unusually low grate heat release rate and consequently very low NO_x. After the FGR system was installed the stack O_2 was reduced from 9 percent to 4.5 percent as shown in Figure 5-15 and there was a correspondingly 50 percent decrease in NO_x (from 0.55 lb/10^6 Btu to 0.28 lb/10^6 Btu). The results on NO_x emissions for this boiler are shown in Figure 5-16.

The question remains as to how well FGR will work on modern stokers which run typically at 5 percent stack O_2 and sometimes as low as 4.1 percent stack O_2.[7] New stoker boilers without FGR, while having excess air levels similar to this test boiler with FGR, about 5 percent, will have higher grate heat release rates and, consequently, higher NO_x emissions. These facts infer that new stokers will have NO_x emissions greater than 0.28 lb/10^6 Btu. The effectiveness of FGR on a new stoker has not been resolved since there are no applications to new stokers. In order for the

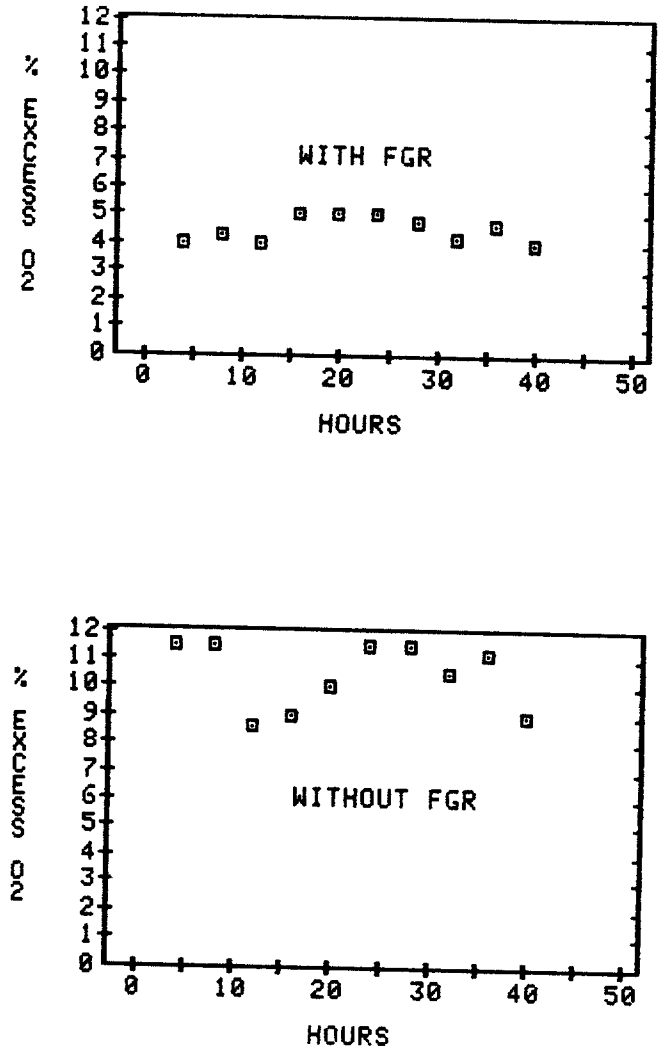


Figure 5-14. Effects of flue gas recirculation on excess O_2, KVB stoker boiler test.

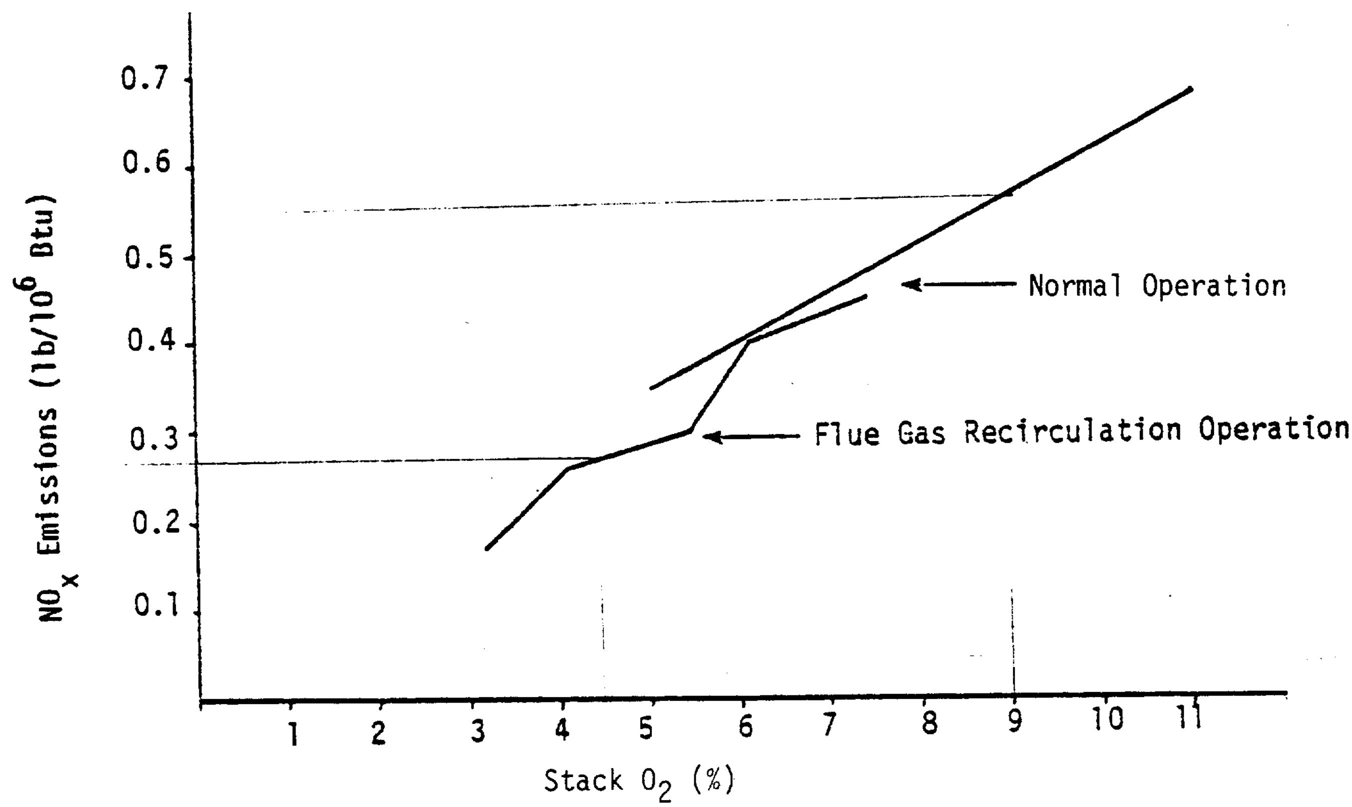


Figure 5-15. Effects of stack O_2 on NOx emissions in KVB tests of an coal-fired stoker.

emission control performance of FGR to be properly assessed, it will have to be applied to and tested on a modern stoker with typical excess air levels.

Cost

The FGR technique has been applied to an eight-year-old, 100,000 lb/hr industrial boiler located in the midwest. The capital cost of this system was $80,000. Operating costs are presumably negative especially if the stoker is designed with FGR in mind. However, no operating cost data are available at this time.

Commercial Applications

One Zurn FGR system has been installed and is operating on a 100,000 lb/hr stoker boiler firing Kentucky coal. The boiler operator, presumably the University of Wisconsin, has ordered three additional systems. According to Zurn, nine systems have been ordered but not installed.

5.4 SUMMARY

NO_x controls for coal-fired industrial boilers such as low excess air, overfire air, staged combustion have not undergone any recent development and are adequately covered by the BID. The same is true for flue gas recirculation (FGR) for pulverized coal-fired boilers (PC). The techniques which received recent development efforts are low NO_x burners and in-furnace reburning for PC boilers, and FGR for stoker boilers. These are summarized below.

5.4.1 In-Furnace Reburning

This technique is under development in Japan and more recently in the U.S. In Japan, it has only recently been tested on a coal-fired boiler, reportedly achieving NO_x emissions of 0.2 $lb/10^6$ Btu. Reburning is not sufficiently developed for near-term application to industrial boilers.

5.4.2 Low NO_x Burners

The major vendors of coal-fired industrial boilers are all developing low NO_x burners for this application and some have been solid either as retrofits or with new boilers. The industrial boiler designs are simply modifications of utility boiler designs and control NO_x formation by controlling air/fuel mixing. There are only limited data, none of it long term or thirty day rolling average, available from industrial boilers. However, performance data are available from some utility boiler test programs and some of these are small enough to be considered industrial boiler analogs. These data, discussed earlier, are summarized in Table 5-4. In general these data range from 0.4 to 0.6 $lb/10^6$ Btu; however, in interpreting these results it is important to remember that NO_x emissions are also affected by the boiler design and perhaps by the type of coal burned.

Data on the extent of application of LNB's to industrial boilers was solicited from the boiler vendors and the ABMA. While applications were acknowledged, specific information was considered confidential and, therefore, not provided.

Cost data are similarly lacking for similar reasons. Vendors consider the costs proprietary and there are not enough publicized applications to allow general costs to be developed.

5.4.3 Flue Gas Recirculation (Stokers)

This is a technique developed by KVB and marketed by Zurn for use in reducing excess air requirements in stokers. NO_x control is an incidental effect of lowering the excess air. The process was not designed or marketed for NO_x control. There is one application to a 100,000 lb/hr stoker; however, because of the atypical nature of the boiler tested it is not possible to assess the NO_x control potential of FGR beyond the control potential of LEA. The technique has the capability of reducing excess air to 4.5 percent stack O_2; however, modern stokers can achieve these, and sometimes lower, levels without FGR. A total of nine systems have been ordered.

TABLE 5-4. SUMMARY OF AVAILABLE TEST DATA FOR PULVERIZED COAL-FIRED BOILERS

Application	Heat Input 10^6 Btu/hr	NO_x Emissions, lb/10^6 Btu	Comment
<u>Prototype or Small Scale</u>			
Babcock & Wilcox	30	0.5 - 0.6	Low heat release rate
Foster Wheeler	50	0.2 - 0.25	
Riley Stoker	50	0.45 - 0.64	Varying heat release rate
Riley Stoker	50	0.35	Advanced design
<u>Full Scale Utility</u>			
A	215	0.49	Continuous monitoring
B	4,174	0.41	Continuous monitoring
C	2,760	0.38	Continuous monitoring
D	651	0.57	Parametric testing, No overfire air
E	3,600 (est)	0.41	Compliance testing, No tertiary air
<u>Industrial Boiler</u>			
Foster Wheeler	125 (est)	0.33	Parametric testing

Based on the limited test data, FGR does not appear to be necessary for new stokers in order to achieve the low stack O_2 levels which correspond to low excess air operation. More conclusive data may be available when the additional units are installed and tested.

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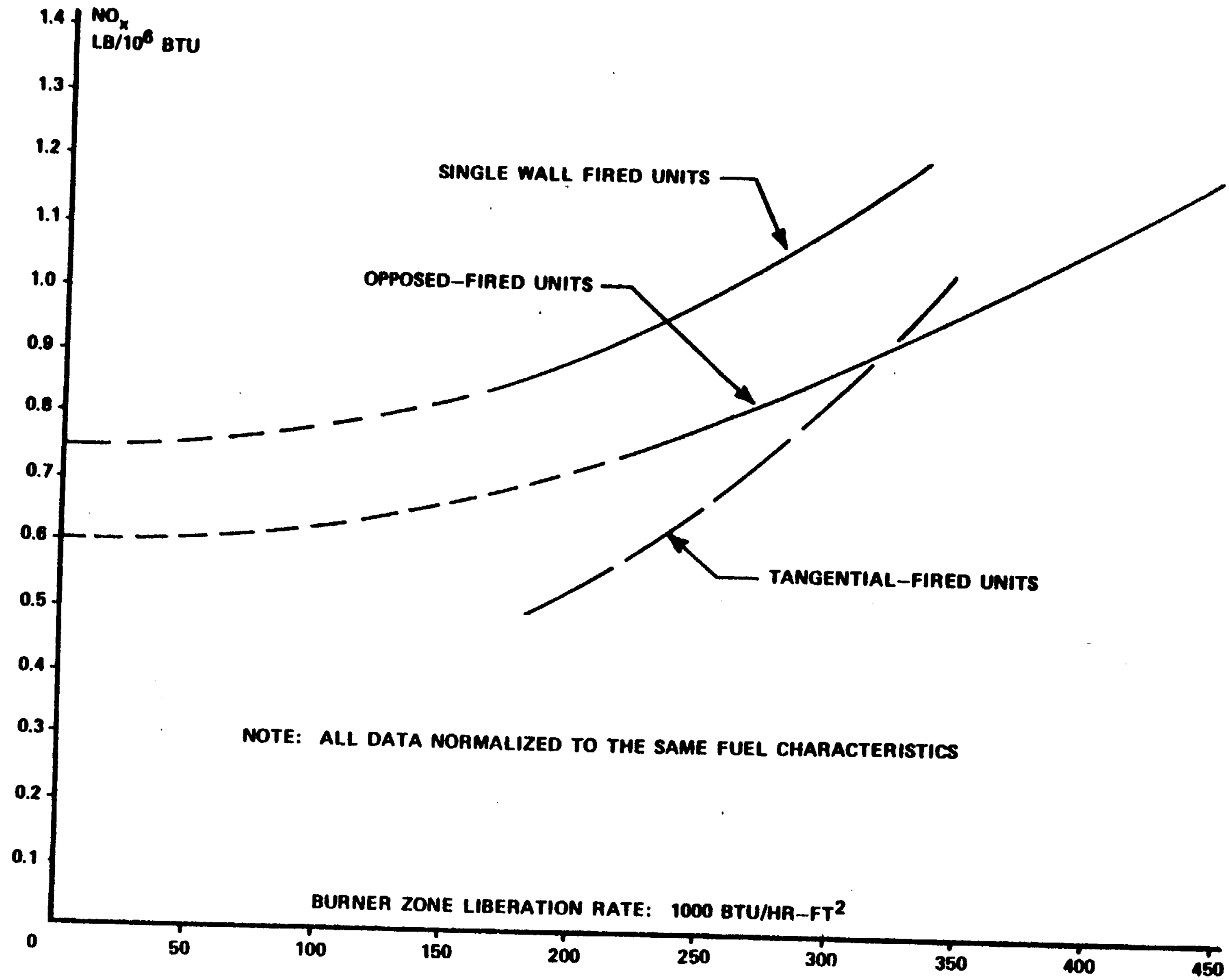

Figure 5-8. Uncontrolled NO_x Emissions as a Function of Burner Zone Liberation Rate and Firing Design

6.0 OTHER APPLICATIONS OF STAGED COMBUSTION CONTROLS

Staged combustion controls have been widely applied on oil field steam generators and process heaters for controlling NO_x emissions. This section reviews the development of staged combustion controls for both steam generators and process heaters, and evaluates the applicability of these staged combustion controls to industrial boilers.

6.1 STAGED COMBUSTION CONTROLS FOR OIL FIELD STEAM GENERATORS

Oil field steam generators (steamers) are package boilers used in the oil fields to provide saturated steam for enhanced oil recovery operations. Steamers are fueled with either oil or gas, with the oil often being unrefined crude oil recovered from the same oil field. The oils burned in oil field steamers often have fuel nitrogen concentrations of approximately 1 weight percent. The high number of oil field steamers burning high nitrogen fuels in the proximity to areas with nitrogen oxide emission problems lead to the early development and application of staged combustion controls for this emissions source.[1]

6.1.1 Emission Control Performance

Five of the largest manufacturers of oil field steamers were contacted about the performance of their staged combustion controls on NO_x emissions. All five manufacturers approached NO_x control with the use of staging burners. None of the manufacturers used overfire air ports to achieve staged combustion. Of the five manufacturers, four are currently offering staged burners for industrial boiler applications. The performance of their staging burners on industrial boilers has been discussed in detail in Sections 3 and 4 of this report.

The remaining manufacturer of staging burners for oil field steamers uses a staged air burner design. This burner is manufactured in sizes up to 65 million Btu/hr based on heat input. In oil field steamer applications, this burner can lower NO_x emissions to less than 0.06 lb NO_x/million Btu heat input when combusting natural gas. Additionally, when firing oils with fuel nitrogen levels ranging from .7 to .9 weight percent, this burner can achieve NO_x emission levels of 0.11 to 0.13 lb NO_x/million Btu heat input.[2] These emission estimates are based on short term test results on two 60 million Btu/hr oil field steamers operating at stack oxygen level of 1.2 to 1.8 percent.

6.1.2 Applicability to Industrial Boilers

Staged combustion burners developed for oil field steamers can be applied to packaged industrial boilers with a limited amount of modification. Oil field steamers are similar enough to industrial boilers in dimensions to allow this transfer of technology. The transferability of staged combustion burners from steamers to industrial boilers is further supported by the fact that four of five large steamer or steamer burner manufacturers are currently supplying staging burners for industrial burner applications.

Although applicable to industrial boilers, staging burners developed for oil field steamers will not necessarily achieve the same low NO_x emission levels when applied to industrial boilers. Oil field steamers have lower heat release rates, larger radiant sections, and a more stable operating load than industrial boilers. These factors mean that steamers have lower inherent NO_x formation characteristics. Additionally, the larger dimensions of oil field steamers for a given steam capacity, can accommodate the enlarged flame from a highly staged burner much more easily.[1]

6.2 STAGED COMBUSTION FOR PROCESS HEATERS

Process heaters are used throughout the chemical and petroleum industries to directly heat process fluids. For several years, process heaters have employed staging burners to lower NO_x emissions from the combustion of natural gas and fuel oils.

6.2.1 Emission Control Performance

Staged combustion controls for process heaters all consist of various types of staged combustion burners. Overfire air ports have not found significant application in the process heater area. Staged combustion burner designs being applied in process heaters include staged fuel burners, staged air burners, internal recirculation burners and combinations of the three. A description of these burner designs and their principles of operation are discussed in Section 3.2.

A study of 10 process heaters equipped with staging burners was conducted for the EPA's Industrial Environmental Research Laboratory. This study concluded that staging burners could achieve NO_x emission levels of 0.06 lb NO_x/million Btu heat input on gas-fired heaters without combustion air preheat. On gas-fired heaters using combustion air preheat, staging burners exhibited NO_x emission levels ranging from 0.06 to 0.10 lb NO_x/million Btu heat input. The burners tested in this study were much less effective on NO_x emissions from oil firing, exhibiting emissions ranging from 0.5 to 0.65 lb NO_x/million Btu heat input.[3]

In preparation for developing a New Source Performance Standard for process heater, an EPA study reviewed the available information base on NO_x emission from process heaters.[4] NO_x emission data from short term test on nine natural gas fired process heaters were included in the EPA study. Three gas-fired heaters equipped with convention burners averaged NO_x emissions of 0.16 lb NO_x/million Btu heat input. Six gas-fired heaters equipped with staged combustion burners averaged NO_x emissions of 0.09 lb NO_x/million Btu heat input.

Short term test data on oil-fired burners in the above EPA study were less conclusive. The data from a single oil-fired process heater equipped with a conventional burner exhibited averaged NO_x emissions of 0.36 lb NO_x/million Btu heat input. Two heaters equipped with staging burners and combusting a mixture of 30 percent oil and 70 percent gas each exhibited average NO_x emissions of 0.12 lb NO_x/million Btu heat input, on similar short term tests.

6.2.2 Applicability to Industrial Boilers

Staging burners developed for process heater applications are not directly applicable to packaged industrial boilers for reason of size and combustion zone environment. Staging burners for process heaters range in size from one to 20 million Btu heat input per hour. A typical process heater may use 20 or more burners in a single combustion zone. Packaged industrial boilers use a single burner which ranges in size up to 250 million Btu heat input/hour.

Because of significant differences in the combustion zone environment between process heaters and industrial boilers, process heaters have inherently lower uncontrolled NO_x emissions than do industrial boilers, and burner designs which are effective for process heaters may not be effective nor practical when scaled up for packaged industrial boilers. Fire box conditions are much less intense in process heaters than in industrial boilers. The heat release rate for a process heater is typically less than 17,000 Btu/ft^2-hr, as compared to a typical heat release rate of 100,000 Btu/ft^2-hr for a packaged industrial boiler. Furthermore, process heaters will often employ 20 or more small burners, resulting in as manly small flames inside the heater fire box.

6.3 REFERENCES

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