

# ULTRA LOW NO<sub>x</sub> BURNER WITH WIDENED STABILITY LIMITS

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## ABSTRACT

Burner designs utilizing premix combustion principles are able to achieve single digit NO<sub>x</sub> levels when firing natural gas with increased excess air or higher rates of flue gas recirculation (FGR). The main challenge for applying such burners to industrial boilers is the resultant limited stability range with respect to the deviations in the equivalence ratio and the rate of FGR. Satisfying narrow stability limits becomes especially difficult, when the load modulates fast and over wide ranges. A new burner developed by COEN company specifically addresses these challenges of ultra low NO<sub>x</sub> combustion and operates reliably over a wider range of parameters than other known burners. This QLA burner was developed over two years of work on two research programs funded by The Gas Research Institute, COEN, Southern California Gas, and California Air Resources Board. Most of the development efforts were directed toward making the burner less sensitive to the inaccuracy of the combustion controls, especially at lower loads where correct ratios between the flows is more difficult to achieve. The QLA burner has an optional variable geometry and multiple fuel zones. While the major mechanism of NO<sub>x</sub> reduction is simulated premixed type combustion, the burner also uses some degree of fuel staging. The burner operates with low excess air and practically no CO emissions. It can fire gas or oil and operate with air preheat up to 600°F. The performance of the QLA burner in the field was demonstrated on a 60,000 pph field erected brick set boiler equipped with two gas and oil fired burners fired as one. The boiler operates in automatic with preheated air of 400°F and 10 to 1 turndown. The source test was passed with 7.3 ppm NO<sub>x</sub> and 3 ppm CO (corr. to 3% O<sub>2</sub>, dry). Lower NO<sub>x</sub> - down to 5.5 ppm, was demonstrated with reduced air preheat.

## INTRODUCTION

The Industrial steam generation industry is facing increased challenges in meeting lower and lower NO<sub>x</sub> emission regulations. As industry expands and adds new capacity, steam demands increase requiring the purchase of new boiler equipment. In some areas of the country new installations are required to meet the most strict emissions standards defined as Best Achievable Control Technology (BACT), that by definition is a moving target. The NO<sub>x</sub> requirements of the South Coast Air Quality Management District for new industrial sources were fluctuating recently from 9 to 7 ppm and even down to 5 ppm, corrected to 3% O<sub>2</sub>. Existing boiler owners are also under pressure to comply with this regulations in the immediate future if there is a need to replace any substantial part of the system due to its deterioration with age, or unsatisfactory performance.

Currently, NO<sub>x</sub> emissions on natural gas down to 5,...,7 ppm level can be achieved reliably with low NO<sub>x</sub> burners generating less than 30 ppm NO<sub>x</sub> and such post combustion NO<sub>x</sub> control technique as Selective Catalytic Reduction (SCR). The use of SCR, however, carries very high installation and maintenance costs and involves handling of ammonia that presents danger for the environment and health. Other technologies like CANNON LTO still need to prove their effectiveness for the industry. As the trend to lower emissions continues there is an immediate need to find more a practical solution for these levels of emissions

Substantial efforts in recent years were directed toward developing industrial burners firing natural gas to achieve single digit NO<sub>x</sub> emissions. Numerous devices were designed and tested [ 1 , 2 ]. The dominant ultra low NO<sub>x</sub> approach is to ignite all or a portion of natural gas after it is uniformly mixed with combustion air and large amount of Flue Gas Recirculation (FGR). The premixed, or simulated premixed combustion substantially reduces prompt NO<sub>x</sub> [ 3 ], by eliminating local conditions of fuel rich combustion, while thermal, or Zeldovich [ 4 ] NO<sub>x</sub> - a typical major contributor is controlled by reducing the adiabatic flame temperature with FGR or excess air. These ultra low NO<sub>x</sub> burners, utilizing premixed concepts, have shown the ability to achieve single digit NO<sub>x</sub> emissions, however the advanced requirements to the combustion controls have not been sufficiently addressed.

From practicable experience it is well known that industrial burners utilizing premixed combustion are prone to combustion driven pulsation on some operational regimes [ 5 ]. The spectrum of these regimes, defined by the burner load, amount of excess air and FGR, are dependent upon not only the burner design but also upon characteristics and acoustical response of the overall system that is difficult to predict. The main function of the control system is to steer parameters (excess air, FGR and, sometimes, fuel distribution) away from regimes that may develop pulsation or flame blow out. It is interesting to note that the effects of the excess air and FGR on pulsation are not obvious. In some

systems additional air and/or FGR to some extent can help to suppress pulsation. In other systems, the excess air and/or FGR has to be reduced. If the operating range becomes too narrow the control system will not be able to maintain it dynamically during the load shifts, changes in environmental conditions, or other disturbances. This may cause pulsation resulting in a loss of flame, or mechanical damage to the boiler. So, the main difficulty in applying such burners to industrial boilers is narrow stability range with respect to the deviations in the equivalence ratio and the rate of FGR. Satisfying these limits and complying with the emission requirements becomes especially difficult, when the load modulates fast over wide ranges. The quantities of flue gas recirculation required to meet single digit NO<sub>x</sub> and especially 5,...,7 ppm NO<sub>x</sub> also raise questions about flame scanning and safety. These problems have become the primary stumbling block on the way to wider acceptance of ultra low NO<sub>x</sub> technology in industry.

The new QLA burner developed by COEN company specifically addresses these challenges of ultra low NO<sub>x</sub> combustion. The QLA design incorporates numerous features that make operation reliable over a wider range of parameters. The burner was developed within the course of a research program funded by Gas Research Institute, COEN Company, Southern California Gas, and California Air Resources Board. The objectives of the program were

- less than 5 ppm NO<sub>x</sub> emissions (@ 3% O<sub>2</sub>, dry) for ambient combustion air
- less than 9 ppm NO<sub>x</sub> emissions (@ 3% O<sub>2</sub>, dry) for up to 600°F preheated air
- less than 30 ppm CO emissions (@ 3% O<sub>2</sub>, dry)
- low hydrocarbon emissions and VOC

In addition to meeting these performance targets, the resulting burner must have several key features allowing it to be a commercially viable design. These features include a satisfactory turndown over a minimum of 7 to 1 and oil firing capabilities. The burner must not degrade safety or reliability for the industrial user and be suitable for retrofitting existing boilers. Within the outline objectives the main focus was on the reliability and safety of the burner integrated in the system with the specific combustion controls.

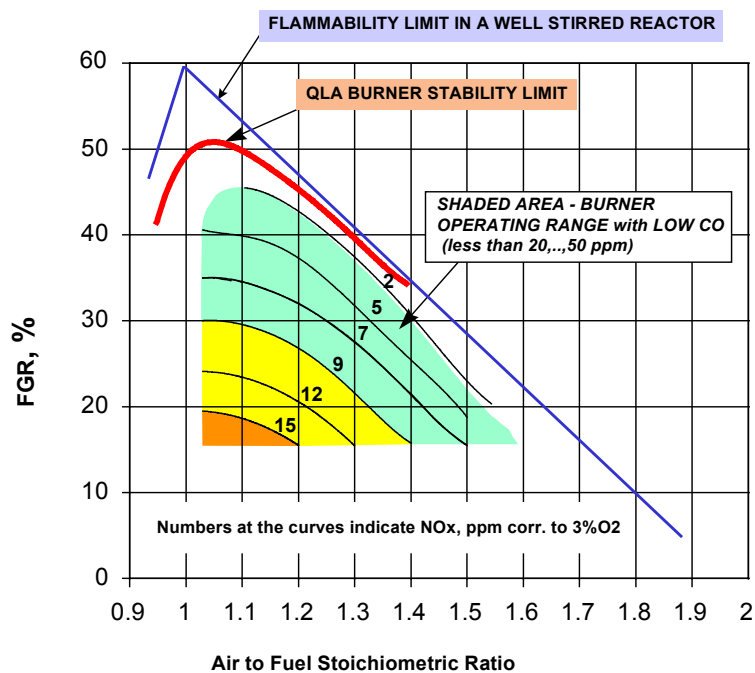
## **BURNER DEVELOPMENT**

By the beginning of the project in 1996 COEN had already accumulated substantial experience with low NO<sub>x</sub> burners utilizing premix, partially premix, and fuel staged combustion concepts for firing gaseous fuels [ 5 ]. It was obvious that major difficulties with ultra low NO<sub>x</sub> burners were not simply reducing NO<sub>x</sub>,

but achieving this reduction without pulsation or flame out over the turn down and with reasonable requirements to the control system accuracy.

**First Prototype.** The first prototype of the QLA produced a relatively uniform mixture of fuel air and FGR. The ignition of this mixture was sustained by a strong recirculation area created in the wake of a large axially positioned bluff body. The burner was sized to 50 MBtu/hr and fired to 45 MBtu/hr. Initial tests showed the ability to operate with NO<sub>x</sub> as low as 2 ppm and with FGR as high as 45% without significant CO emissions .

The burner performance at high fire is shown in Figure 1 as “Iso-NO<sub>x</sub>” lines in coordinates of percentages of FGR - Stoichiometric Ratio. Figure 1 also outlines the lower flammability limit of methane mixed with air and FGR in a well stirred reactor. This limit was computed based on flammability of methane in the mixture with air and nitrogen adjusted to the temperature of the mixture when 70°F air is mixed with 350°F flue gas. The shaded area represents the operating range of the burner. At minimum NO<sub>x</sub> the boundary of the range is defined by the CO emissions. This corresponds closely with the condition when the flame pattern visually becomes incomplete, or patchy. There is only a small additional margin beyond this boundary before the flame lifts off completely. A relatively small difference between the theoretical limit of operation and the burner performance envelope was indication of good uniformity of the mixture produced by the burner and adequacy of its source of ignition. The low excess air limit is also defined by CO emissions and sometimes by the stability of the flame. The minimum FGR at about 15% was defined by flashback at mid load range.



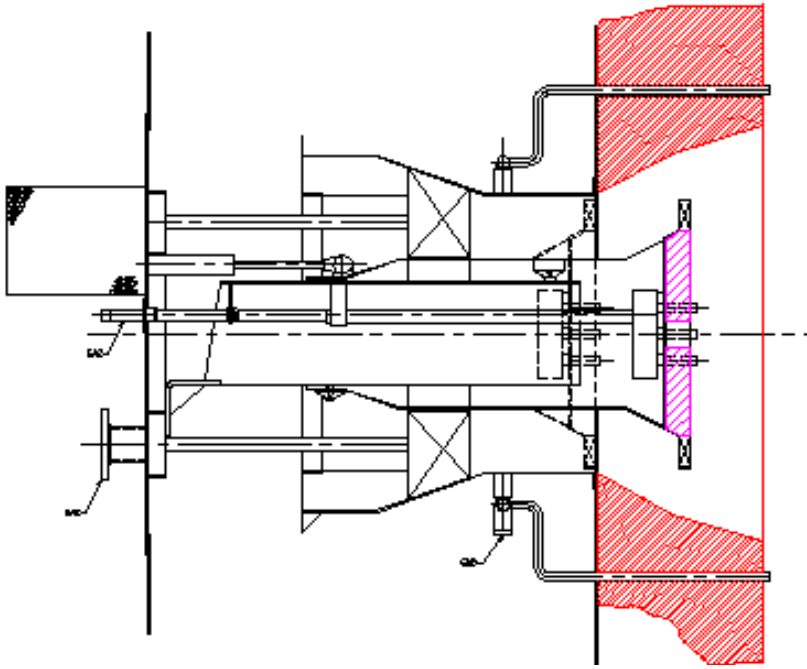
**Figure 1. First Prototype Performance with Ambient Air**

The first prototype also revealed difficulties in controlling combustion induced pulsation when operating below 30% of the burner design capacity. Even at 40,..50% load, firing without pulsation required very high accuracy combustion controls. Small reductions in the excess air or FGR with NO<sub>x</sub> at the range of 7,..,9 ppm, as well as attempts to operate below 30% capacity, resulted in pulsation, or loss of flame. So further developments of the burner itself were targeted on extending the range of combustion stability with respect to the amount of FGR and excess air over the turndown.

***Pulsation Phenomena:*** With the fuel air mixture greatly diluted by FGR, or high excess air the kinetics of fuel oxidation are slow and, if the flow velocity is high, the flame fronts are not well defined. With high velocity flow the reactions in each mole of gas are stretched over a large volume, and pulsation caused by flame front oscillation does not develop. This “flame stretching” is clearly visible as the dissolving of the distinct blue color at the base of the flame that is typical for natural gas combustion. With reduced flow velocity (low loads) the flame front becomes more determined, thus creating conditions for pulsation. Addition of more FGR or air makes the kinetics even slower so that pulsation disappears. Typical NO<sub>x</sub> at this point is 5,..,6 ppm. With more FGR, or air the margin between the operating point and the flammability limit of the blend becomes too narrow. This phenomenon makes controlling premixed combustion with flame fronts in suspension more difficult and at certain low load levels impossible.

***Consecutive Modifications of the Burner Design.*** With the understanding of the pulsation phenomena the burner design substantially changed. The burner was redesigned with several important features added, including modulation of the bluff body position with load. With a modulating bluff body and other changes to the burner, the discharge velocity and the turbulence in the mixture of fuel, air, and FGR were increased and the flame front stretched especially at low loads. The burner was also equipped with the gas nozzles external to the throat. These nozzles inject a minor portion of fuel into the periphery of the flame. Modification of the burner included adding oil firing capabilities. Figure 2 shows schematic of the burner (patent pending) three fuel zones. Figure 3 shows an assembled burner (gas only version) on the shop floor.

A variable geometry feature made a substantial improvement in the burner turn down and expanded the stability limits at low firing rates. Addition of the external spuds and flexibility with controlling the burner with two fuel control valves resulted in further widening of the operational limits. Figure 4 shows operating ranges of the initial prototype below 50% load. Figure 5 illustrate the effect the new features on the operating ranges at different firing rates.



**Figure 2. QLA Burner Schematic (patents pending)**



**Figure 3. QLA Burner in the Shop**

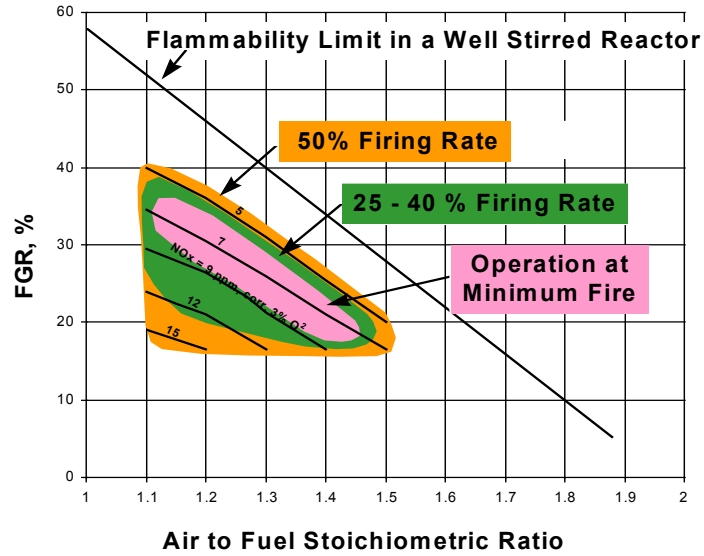


Fig. 4 Operating Ranges of the First Prototype.

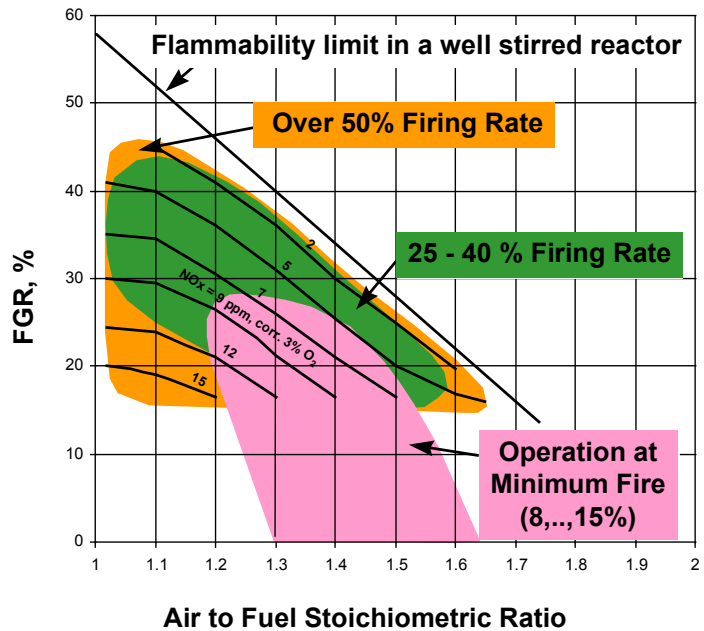


Figure 5. QLA Burner Operating Ranges  
(Variable Geometry. Two Fuel Control Valves)

**Operation with Preheated Air.** Operation of the burner with preheated air was similar to the operation with ambient air, when the difference between the increase in adiabatic flame temperature with air preheat was compensated by additional amount of FGR or excess air. During the tests with up to 550°F combustion air, NO<sub>x</sub> emissions were reduced to same levels as with ambient air. It was also observed that some improvements to the flame stability were obtained with air preheat at low loads due to higher velocity of the mixture. Operation with air preheat at ultra low NO<sub>x</sub> levels creates, however, additional difficulties with combustion controls. At low loads the air temperature changes significantly with load and is more affected by the thermal inertia of the system during the load swings, or during the burner light off.

## FIELD DEMONSTRATION OF THE BURNER

**Demonstration Site.** A 60,000 pph balanced draft boiler located at the Central Heating Plant in Sacramento became the first site for the QLA burner. The boiler supplies heating and cooling to a large group of government buildings and operates all year round. It is equipped with two burners firing natural gas or light oil. The boiler is brick set and its radiant section has a very high percentage of the walls not covered by water tubes. The front wall, floor, side and rear walls at the lower half of the furnace are all refractory. The upper portion of the front wall and the side wall have tubes spaced apart by two and a half tube diameters. The furnace is only 10 ft long. The boiler is equipped with a Lungstrom type air heater preheating air up to 425 °F .

With the original burners, the boiler capacity was limited to 50,000 pph due to the problems complying with the permitted NO<sub>x</sub> level of 30 ppm even with the air heater bypassed, massive amounts of FGR and some steam injection. It seemed that the original burner vendors grossly miscalculated the effect of the furnace refractory on the NO<sub>x</sub>.

The scope of the retrofit included the burners, controls, combustion air and induced draft fans and fuel trains. The new system had to comply with 9 ppm NO<sub>x</sub> on natural gas, 30 ppm CO and be able to fire gas or oil producing up to 60,000 pph of steam. The plant was also interested in having wide turndown and flexibility of fast load changes on this main boiler of the facility. As a demo site for the project co funded by the Gas Research Institute, the burner had to be tested with the air heater bypassed to demonstrate a target NO<sub>x</sub> of 5 ppm.

**Controls.** For the first site we chose traditional pneumatic controls with parallel positioning with a trim applied to the combustion air fan VFD. The controls were governed by a new COEN 'Fyr-Monitor' system based on the Allen-Bradley SLC. The system included trim functions compensating for the variable environmental conditions and levels of air preheat. The performance of the actuators was monitored by position feed back modules. The selection of

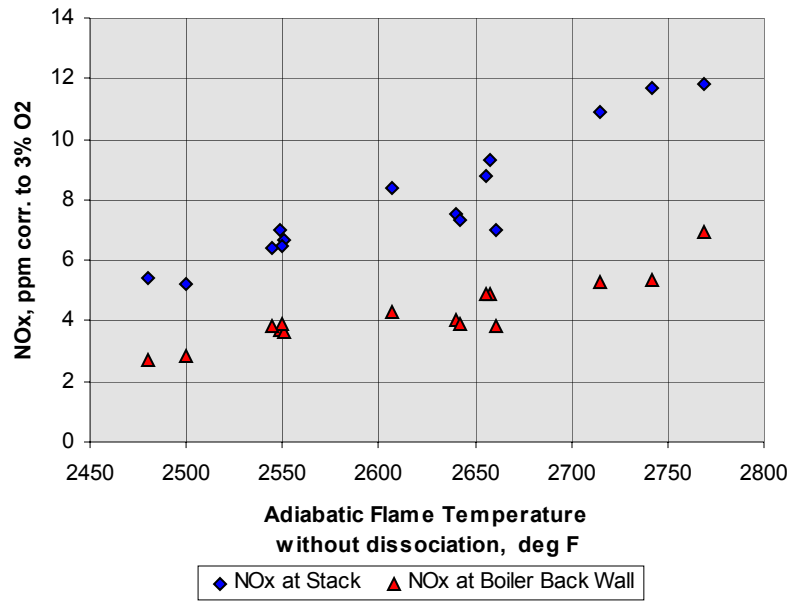
parallel positioning was based on the desire to have fast reacting controls performing over a wide turn down.

**Demonstration Site Results.** The overall performance of the QLA burners with respect to the width of the stability ranges was similar to what is shown by Figure 5. The actual quantities of FGR and excess air necessary for achieving the same NO<sub>x</sub> levels at the stack were higher than in the prototype testing. With different levels of air preheat it is convenient to relate NO<sub>x</sub> emissions to adiabatic flame temperature of the mixture discharging into the furnace, Figure 6. The adiabatic temperature was computed based on the measurements of wind box O<sub>2</sub>, wind box temperature and O<sub>2</sub> at the back wall of the furnace. Plotting the data versus adiabatic flame temperature effectively normalizes the data with different levels of air preheat (some data were taken with the air heater bypassed) and excess air. Adiabatic flame temperature at 2650°F, for example, corresponds to the combustion of mixture of air at 70°F and 15% above the stoichiometric, and 34% FGR at 350°F. At this temperature NO<sub>x</sub> at the stack was 9 ppm. In the prototype testing 27,...,28% FGR would be sufficient for 9 ppm NO<sub>x</sub>, Figure 5. This difference can be attributed to the effect of refractory surrounding the flame on the level of NO<sub>x</sub>.

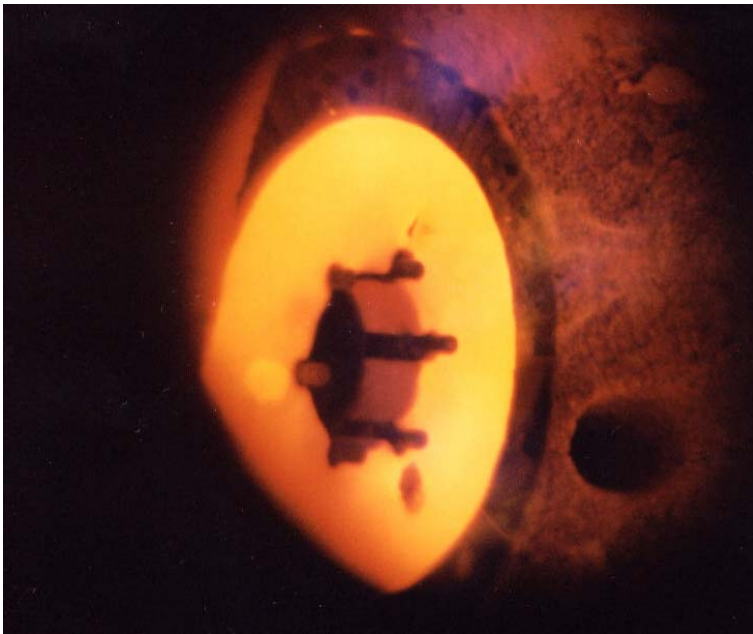
With the increased amount of FGR and excess air the minimum NO<sub>x</sub> emissions at the stack at high fire were measured as low as 5.2 ppm, CO emissions were below 1 ppm. At this level it was difficult to see the flame even in the core area. The signals from the UV scanners at this point were also weakening, so that we did not try to operate with even lower NO<sub>x</sub>. However, at the back wall NO<sub>x</sub> was only 2.5 ppm NO<sub>x</sub>, corr. to 3% O<sub>2</sub>. The flame scanning difficulties combined with the effect of massive amount of furnace refractory on NO<sub>x</sub> made it impossible to formally operate at below 5 ppm NO<sub>x</sub> even with manual controls.

The third party source test at high fire with preheated air was passed with 7.3 ppm NO<sub>x</sub> and 3 ppm CO. The turn down with NO<sub>x</sub> less than 9 ppm, was set to 4 to 1 in order to be able to modulate the load from low to high fire within a few minutes. The variable geometry feature over 4 to 1 turn down was locked, thus proving that a modulating core for boilers with relatively low turn down can be optional. Higher turn down with less than 9 ppm NO<sub>x</sub> would likely be possible in a single burner boiler. From 10 to 25% load NO<sub>x</sub> was varying from 9 to 18 ppm. Lower NO<sub>x</sub> at low loads could of been demonstrated with the bypassed air heater. The boiler was tested in automatic with load changing from minimum to maximum, or vice versa within 5 minutes. At numerous points over the load range the flow of air and FGR was varied by 8,...,10% or more away from the automatic setting without any stability problems. Figure 7 shows the business end of the burner during operation at 30% load with less than 9 ppm NO<sub>x</sub>.

There were no problem firing light oil up to full boiler load. For oil firing the bluff body in the center of the burner stayed in a fixed position.



**Figure 6. QLA Burner Performance at High Fire. Sacramento, Central Heating Plant**



**Figure 7. QLA Burner Firing Gas**

Figure 6 also shows NO<sub>x</sub> data taken at the stack and at the furnace back wall. As seen from the data more than 50% of total NO<sub>x</sub> was generated in the furnace well after all the combustion reactions were complete (there were practically no CO emissions at the back wall). Somewhat smaller differences were earlier observed in the test furnace, when firing the prototype burner at 45 MBtu/hr. The test furnace was an 8 ft diameter, 40 ft long water cooled tunnel with only minimum amount of refractory at the bottom. At the location 26 ft from the burner the NO<sub>x</sub> was about 2 ppm (~ 25%) higher than at 12-14 ft away from the burner throat. At both locations there were no significant CO emissions. The magnitude of the furnace effect as well as a relatively weak relation between the NO<sub>x</sub> and the adiabatic flame temperature indicate that main NO<sub>x</sub> formation mechanism can not be completely described by mostly thermal, or Zeldovich NO<sub>x</sub>. Calculations of thermal NO<sub>x</sub> show, that in this temperature range NO<sub>x</sub> increases by about three times with every 100 deg F increase in the flame temperature.

## **SUMMARY AND CONCLUSIONS**

Different burner concepts utilizing premix combustion can fire gaseous fuels and achieve single digit NO<sub>x</sub> emissions by utilizing premixed combustion with high levels of flue gas or excess air with minor differences in the relation between the adiabatic flame temperature and NO<sub>x</sub>. The true comparison between these burners, or systems should be with respect to the operational flexibility and safety over the required turndown.

The QLA burner described in this paper successfully demonstrated the necessary flexibility and performance in one of the most difficult environments: multiple burner boiler; high percentage of refractory coverage in the radiant section; preheated air; 10 to 1 overall turn down on gas; fast load swings and the necessity to fire oil. The boiler was set for automatic operation with less than 9 ppm NO<sub>x</sub> over 4 to 1 turn down. The transition from low to high fire was within 5 minutes and there are ways to reduce this time much further.

The threshold of flame stability is at about 2 ppm NO<sub>x</sub>. When operated with or without preheated air NO<sub>x</sub> emissions at the stack were approaching 5 ppm at steady loads. Lower NO<sub>x</sub> could of been achieved in the furnace with less refractory. Automatic operation with NO<sub>x</sub> less than 5 ppm requires additional improvements with the controls and scanners in order maintain adequate safety.

The effect of the furnace on NO<sub>x</sub> is surprisingly strong and the relation between NO<sub>x</sub> and flame temperature does not follow Zeldovich mechanism.

## ACKNOWLEDGMENTS

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