

**BURNER TECHNOLOGY  
FOR SINGLE DIGIT NO<sub>x</sub> EMISSIONS  
IN BOILER APPLICATIONS ©**

by

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## ABSTRACT

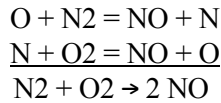
The local air quality districts in the Los Angeles area were the first to implement restrictions to require that NOx emissions on natural gas fired boilers be reduced to single digit levels. Now additional states are being required to develop State Implementation Plans (SIPs) to address bringing into compliance the areas that do not meet the ozone standards set forth in the Clean Air Act Amendments of 1990. One of the most aggressive plans to date has been adopted by the Texas Natural Resource Conservation Commission (TNRCC) to address the Houston-Galveston area (HGA). This SIP plan will call for levels of NOx reduction that exceed what was done in the Los Angeles area in the early 1990's. Ultra low NOx emissions on boilers will be an integral part of meeting the compliance goals set forth in this plan by the 2007 deadline. The use of boiler burner technology that provides the lowest achievable emissions rate (LAER) will be one of the key factors to allow users to meet the proposed reductions.

The reduction of NOx emissions into the sub-9 ppm range requires an understanding of the mechanisms that result in NOx formation. Several techniques exist to address these mechanisms, and to achieve ultra low NOx levels it is necessary to incorporate several of them into the complete system design. Since the lowering of NOx emissions limits in California in the early 1990's, new burner technology has been developed and applied to successfully meet these levels. However, many of the methods used for NOx reduction come with some price, either in terms of impact to system efficiency or increased operational costs. The continued emphasis for combustion companies is on optimization of these systems to increase operational flexibility and to minimize the impact on the overall system. As part of this optimization the development and implementation of new technologies is a key component.

This paper will discuss the specific methods by which NOx is formed during clean (i.e. no fuel bound nitrogen) gas combustion in a boiler and the historical methods that have been applied to address them. The control of NOx emissions on both existing burners and new Low NOx burner designs will be discussed. The third section will cover the development and implementation of a burner designed specifically to meet the requirements of achieving sub-9 ppm NOx levels. The final section addresses some new technologies that are currently being developed to lessen the impact of reducing NOx on the entire boiler system.

## BACKGROUND

In order to discuss NOx reduction techniques, it is first necessary to briefly review the basic theory behind NOx formation. Burning natural gas, and other fuel gases with no bound nitrogen, produces NOx through two main routes. The first is a thermal route where high flame temperatures cause nitrogen molecules from the combustion air to break apart and combine with oxygen to form nitric oxide. The sequence is complicated, but the following two steps represent the essential features.



Combustion is a free-radical process whereby the reactions include intermediate species. In the above sequence, atomic oxygen attacks a nitrogen molecule to yield nitric oxide and a nitrogen radical. In the second step, the nitrogen radical attacks diatomic oxygen to produce another nitric oxide molecule and replenish the oxygen atom. The sequences sum to the overall reaction of one nitrogen and one oxygen molecule producing two nitric oxide molecules.

If we presume that the first step is rate limited (disruption of the N—N triple bond) and that oxygen is in partial equilibrium ( $1/2 \text{O}_2 \leftrightarrow \text{O}$ ) then we generate the following integral kinetic rate equation.

$$[\text{NO}] = \int A e^{-\frac{b}{T}} [\text{N}_2] \sqrt{[\text{O}_2]} dt$$

where:  $A$  and  $b$  are kinetic rate constants,  $T$  is the absolute temperature, the brackets denote concentrations of the enclosed species, and  $t$  is the time.

From the rate equation we deduce that NOx is a primarily a function of temperature, but also affected by oxygen concentration, and the time at those conditions. Figure 1 shows the relationship between adiabatic flame temperature and thermal NOx formation.

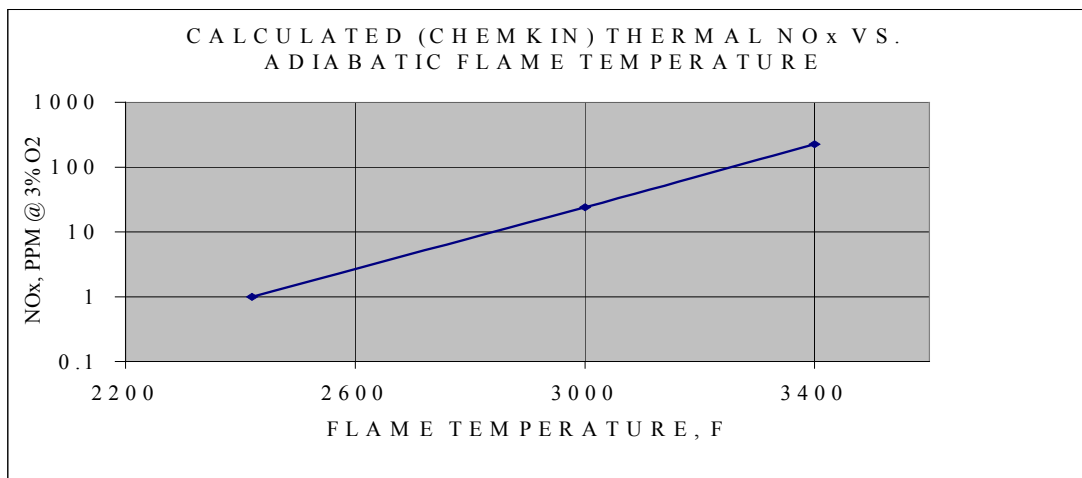
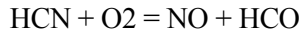
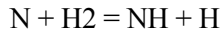
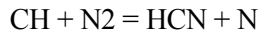


Figure 1

Another method by which NO<sub>x</sub> is formed is called the prompt mechanism. As the fuel pyrolyzes it generates fuel radicals, which combine with available nitrogen to produce carbon radicals. These carbon radicals oxidize promptly at the flame front to generate NO<sub>x</sub> and other species. Under fuel-rich conditions, particularly when stoichiometry is under 0.6, both HCN and NH<sub>3</sub> can be formed through the rapid reaction of CH with N<sub>2</sub> to form HCN and N. As combustion continues the HCN and NH<sub>3</sub> oxidize and result in the generation of NO<sub>x</sub>.



Below a stoichiometry of 0.5, almost all NO<sub>x</sub> formed is attributable to prompt NO<sub>x</sub>. The rate of formation of prompt NO<sub>x</sub> is very rapid, being complete in under 1 ms. Although prompt NO<sub>x</sub> is temperature-sensitive, the temperature sensitivity is not as great as with thermal NO<sub>x</sub>. Unlike thermal NO<sub>x</sub>, simply lowering the peak flame temperatures will not reduce prompt NO<sub>x</sub> into the single digit range. Even if the reaction temperature is lowered to 2,400° F, under fuel-rich conditions, 20 ppm of prompt NO<sub>x</sub> still remains. In order to control the formation of prompt NO<sub>x</sub> it is necessary to take steps in the burner design to minimize the formation of sub-stoichiometric regions within the flame.

### **LOW NO<sub>x</sub> BURNER DESIGN**

In the drive to reduce NO<sub>x</sub> emissions into the 30 ppm range, methods were implemented to lower peak flame temperatures and oxygen availability through the addition of various diluents to the combustion process. Two of the most popular methods have been through the use of recirculated flue gases from the boiler outlet and the use of steam or water injection. Both of these methods have proven very effective in the control of thermal NO<sub>x</sub> formation. Both of these methods can be applied, at least in some limited fashion, to existing conventional burners and in many cases meet a requirement of 30 ppm. The particular burner design, and its ability to maintain stable combustion at these lower flame temperatures, is one of the key factors when adding these to an existing system. Additionally the ability of the rest of the boiler system, such as combustion air fans, to handle the impact resulting from the amount of diluents required must also be addressed.

Initial Low NO<sub>x</sub> burner design initially focused on developing burners which would remain stable with the lower flame temperatures that were required to meet these NO<sub>x</sub> levels. In order to minimize the amount of diluents that were required, burner designs were soon developed that incorporated staged combustion, delaying the mixing of fuel and air. By creating an initial fuel-rich combustion zone, with air added downstream to complete combustion, oxygen availability is limited, peak flame temperature is lowered, and thermal NO<sub>x</sub> formation is reduced. Another staging method is to create a fuel-lean primary combustion zone, with lower flame temperatures and lower thermal NO<sub>x</sub> formation, then inject additional fuel downstream to consume the excess oxygen and complete the combustion process. However, in trying to achieve NO<sub>x</sub> levels in the sub-30 ppm range some burner designs employ an extreme degree of fuel-air staging that can result in unacceptably long flames and reduced flame stability, especially at lower load rates. For these levels of NO<sub>x</sub> emissions a combination of staged low NO<sub>x</sub> burner design and use of flue gas recirculation and/or steam, or water, injection has proven much more successful.

The Venturi Low NO<sub>x</sub> burner, such as the TODD Variflame™ or Dynaswirl™, was developed to provide the maximum degree of flexibility in achieving low NO<sub>x</sub> emissions, high burner turndown, and improved flame shaping capability. The basis of the design is to develop a stratified flame structure with specific

sections of the flame operating fuel rich and other sections operating fuel lean. The burner design thus provides for the internal staging of the flame to achieve reductions of NOx emissions while maintaining a stable flame. Controlling combustion stoichiometry to fuel rich conditions inhibits NOx production especially in the burner's flame front. Operating the flame fuel rich also reduces burner NOx emissions dependence on the burner zone heat release (BZHR) characteristics of the furnace. In addition to controlling NOx formation, operating under fuel rich conditions results in the production of combustion intermediates that can result in the destruction of previously formed NOx. In a reducing environment, NO can act as an oxidizer to react with these combustion intermediates resulting in the reduction of NO to N2. Therefore, NO necessarily formed to satisfy the requirements of establishing a strong flame front can be scavenged by this process. To achieve complete fuel burnout at minimum excess O2 the burner design provides for fuel lean zones to directly interact with the center fuel rich sections. This ensures that the "rich" products of combustion from the center flame pass through the oxidizing zone for complete fuel burnout. The burner design allows control of the stoichiometry of the oxidizing zone from being pure air to having varying degrees of excess oxygen. This controls NOx formation by causing the fuel burnout to occur in the form of a premixed flame rather than a diffusion flame.

The basis of the burner design is the low excess air venturi register. The venturi air sleeve for the burner provides for the primary and secondary airflow in the burner. The gas injection is done through multiple gas "pokers" oriented around a curved-bladed swirler and a center-fired gas injection assembly. To increase the flexibility of combustion staging and flame shaping capabilities, the burner is equipped with a tertiary air sleeve assembly installed at the outer periphery of the burner throat. The tertiary air is mixed in the furnace with the bulk furnace gas to achieve complete burnout of the fuel in the post combustion zone where NOx formation is inhibited by lower combustion temperature and reduced O2 concentration.

### **ULTRA LOW NOx BURNER DESIGN**

To achieve NOx levels in the sub-9 ppm range, the relationship between temperature, stoichiometry and NOx formation was used as the basis for the design of the TODD Rapid Mix Burner (RMB™). It was determined that the most direct method of achieving very low NOx emissions from a natural gas flame is to avoid fuel-rich regions with their corresponding potential for prompt NOx and lower the flame temperature to reduce thermal NOx to the desired level. To accomplish this a burner design that avoids fuel-rich regions by rapidly mixing gaseous fuel and air near the burner exit was developed. The rapid mixing results in a nearly uniform fuel/air mixture at the ignition point, which virtually eliminates prompt NOx formation. This rapid and complete combustion is also what results in the virtual elimination of both CO and VOC formation by the burner. Thermal NOx is then minimized by using FGR mixed with combustion air upstream of the burner to control flame temperature. In effect, the burner performs like a pre-mix burner with one important distinction: because the fuel is added inside the burner, just upstream of the refractory throat, the extremely small pre-mixed volume eliminates the possibility of flashback inherent in pre-mix burner designs.

In addition to sub-9 ppm NOx and CO, another benefit of the rapid mix design is an extremely stable flame. Swirler geometry, burner internal geometry and quarl expansion are matched to promote internal recirculation of a large amount of hot combustion gases. This enables the burner to operate at lower flame temperatures and NOx levels than other burners, with a "blow off" point of about 3 ppm NOx. The flame remains stable at 60% FGR, therefore the 25-30% FGR rate typically necessary for sub-9 ppm NOx does not begin to approach the burner's performance limits. The rapid combustion also results in a very short flame length. It is approximately half that of a staged-combustion burner, which eliminates the potential for flame impingement, one of the most common problems experienced with conventional low NOx burner retrofits.

The burner incorporates a gas injection and mixing system that is radically different from all other commercially available low NOx burners. The new gas mixing approach was incorporated into an established

burner geometry that had been optimized to provide an extremely stable flame. The basic Rapid Mix Burner consists of a parallel-flow air register with no moving parts. Combustion air pre-mixed with FGR enters the register, and the entire mixture then passes through a set of axial swirl vanes. These vanes, which are attached to a central gas reservoir, have hollow bases that are perforated for gas injection. Thus, the swirl vanes also serve as the gas injectors, and provide the burner's near perfect fuel/air mixing (Figure 2).

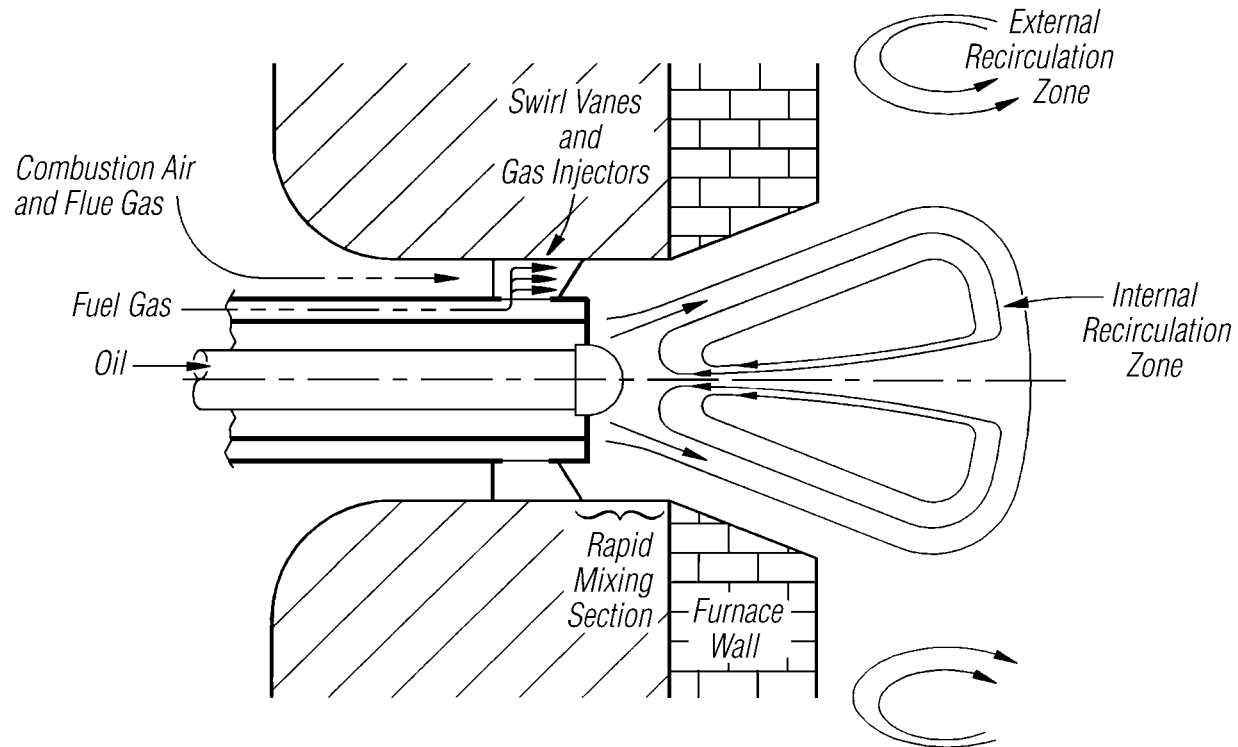


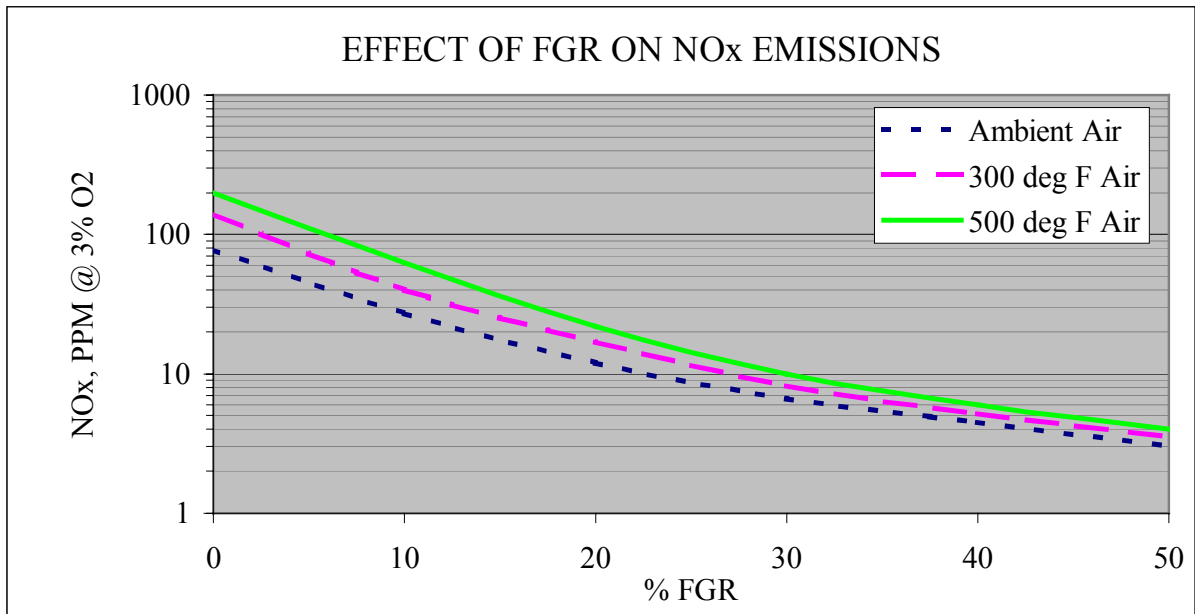
Figure 2

For burner heat inputs greater than about 40 MMBtu/hr, a second parallel-flow air sleeve surrounds the basic burner register, and the burner is called a Dual Rapid Mix Burner (DRMB™). The outer sleeve contains a second set of gas injector vanes attached to an outer gas reservoir. These vanes, however, do not impart any swirl to the airflow. Airflow through the inner and outer burners is designated as "primary" and "secondary" airflow, respectively. Both the primary/swirled and secondary/axial zones operate with the same near-perfect mixing.

Contrary to conventional low NOx burner theory, increasing excess air *reduces* NOx formation in the Rapid Mix Burner. Because the burner employs near perfect mixing, the fuel already has access to all of the oxygen required at the ignition point, and increasing excess air just serves to reduce the peak flame temperatures. Therefore, excess air has the same cooling effect as FGR, which provides major advantages in high excess-air combustion applications, such as dryers, where FGR is impractical or unavailable. In boiler applications, where FGR is available, it is preferred due to its lower impact on the boiler efficiency than high excess air. The rapid mix design is also what allows the burner to operate with pre-heated combustion for increased efficiency, and still retain its single digit emissions performance, by simply increasing the FGR or excess air rates to compensate for the higher air temperature.

The development program for this burner consisted of testing in a 4 MMBtu/hr firetube boiler, a 30 MMBtu/hr watertube boiler, and a 100 MMBtu/hr test facility, and was conducted from mid-1993 to mid-1994. Air preheat was available on both the firetube boiler and large test facility furnace, but not on the watertube boiler. NOx emission while firing into the firetube boiler for ambient air, 300°F preheat and 500°F preheat as a function of FGR rate are shown in Figure 3.

Figure 3



NOx emissions without FGR were a function of air preheat level and ranged from approximately 80 ppm with ambient air to 200 ppm with 500°F preheat. The FGR rate required to produce a given NOx emission level varied with air preheat level, but, independent of the preheat level, NOx emissions could be reduced to approximately 3 ppm. In the watertube boiler the NOx emissions without FGR were higher for the larger burner, but when enough FGR was added to reduce NOx below 20 ppm both burners exhibited very similar performance. Similar characteristics were also observed with air preheat in the 100 MMBtu/hr test furnace. Again, the larger burner produced higher NOx emissions without FGR, but once FGR is added the NOx emissions from all three are almost identical for a given FGR rate.

This technology has also been applied extensively since 1994 in single and dual-burner applications on both field erected and packaged boilers. In over forty boiler applications the technology has delivered proven reliable sub-9 ppm NOx and superior operation. In 1997 an extensive demonstration project was undertaken at a utility site in conjunction with the Electric Power Research Institute (EPRI). A 150,000 lb/hr 'D' type packaged boiler with two existing register burners was retrofitted with two DRMB's. Each burner was rated for 88 MMBtu/hr, and the unit was operated with a combustion air pre-heat temperature of 500°F. To minimize the amount of FGR required, staging between the two burners was employed to reduce NOx. Even with the high air pre-heat, the burners were able to reduce the NOx to single digit levels with only 25% FGR and CO was maintained at less than 5 ppm.

## NEW NO<sub>x</sub> REDUCTION TECHNOLOGY

Water or steam injection, while effective at NO<sub>x</sub> control, do result in impacts to system efficiency. Steam injection requires the consumption of steam that would normally be supplied to the process and thus reduces the total steam availability of the boiler. Water absorbs heat as part of the vaporization process and carries that heat out of the stack, reducing total boiler efficiency. Flue gas recirculation does not suffer from these problems and results in almost no impact to boiler efficiency. However, any recycling of flue gas increases the total mass flow through the boiler, which results in increased convective section pressure drops and can increase superheat and reheat temperatures. This results in increased duty and costs for operation of the combustion air fans, as well as possible costs associated with steam superheat and reheat attemperation. Conventional methods of implementing FGR also require large rotating equipment to transport the flue gases and results in additional accompanying power usage. The amount of flue gas required to reach ultra low NO<sub>x</sub> levels, and accompanying lower flame temperatures resulting from this, also cause these burners to operate closer to the limits of flammability than conventional burners. This requires that control systems be designed to allow much tighter control of air-fuel ratios, and can also result in limited burner turndown, slower ramp rates, and less tolerance to air-fuel upset conditions.

For all the reasons stated above, improved methods of reducing NO<sub>x</sub> are being developed that reduce the amount of diluents required and lessen the impact on the total system. Once such technology that has proven effective at doing this is TODD's COOLfuel™ gas conditioning. Gas conditioning is a patent-pending method of conditioning the gas fuel to a burner in order to reduce NO<sub>x</sub> and other emissions. This technology uses the motive force of the fuel, and steam if added, to aspirate flue gases from the boiler exhaust and mix them into the fuel supply to the burner. The mixture of fuel and flue gas results in a diluted fuel, which generates lower NO<sub>x</sub> emissions similar to the firing of low BTU gases. This technology has proven that mixing the flue gases with the fuel, instead of with the combustion air, is 30-50% more effective at reducing NO<sub>x</sub>. Gas conditioning technology reduces thermal NO<sub>x</sub> by reducing the flame temperature and lowering the local oxygen concentration. Since it also increases the fuel mass flow, it improves fuel-air mixing, reduces the residence time under NO<sub>x</sub> forming conditions, and homogenizes the flame, which serves to further lower the peak flame temperature. Because gas conditioning technology reduces the carbon radical concentrations in the combustion zone, it also reduces prompt NO<sub>x</sub> formation in addition to thermal NO<sub>x</sub>. This has resulted in the ability to achieve higher NO<sub>x</sub> reductions than with conventional flue gas recirculation system using the same mass flow of flue gases.

Since this method also uses the motive force of the fuel gas to aspirate flue gases, it allows emissions reductions without the requirement of additional fan horsepower to move the flue gases. This results in lower operating costs, and eliminates the maintenance issues involved with hot flue gases contacting rotating fan parts. When added to the system, steam serves a dual role of providing additional NO<sub>x</sub> reduction through its added mass flow, and also providing a motive force for inducing more flue gases. This results in larger increases in NO<sub>x</sub> reduction while using only small amounts of steam. When combined with other NO<sub>x</sub> reduction techniques such as; mixing of flue gases with the combustion air (FGR), fuel staging, and burner biasing, gas conditioning can be utilized as part of the total NO<sub>x</sub> reduction system. The benefit of this approach are its ability to achieve the required NO<sub>x</sub> emissions levels with less impact to system operational costs and efficiency, as well as improved burner operational characteristics.

## **CONCLUSION**

The application of several techniques to both lower flame temperature and control the formation of prompt NOx has allowed us to reduce NOx emissions from natural gas combustion by more than 90%. The experience gained through the application of this technology over the past eight years give us a very clear understanding of the true impact of ultra low NOx combustion. These impacts are not only in terms of increased expenses to operate the system, but also in terms of the operational limitations that can be imposed. The continuing drive is to develop new technologies that will lessen these impacts, both in terms of the cost and operational flexibility. One such new technology has been developed and is currently being implemented specifically for these reasons. In addition extensive research and development efforts continue to uncover new techniques which both lower NOx and result in lower impact on the system. As new regulations come into effect for states to comply with the ozone standards set forth in the U.S. Clean Air Act Amendments of 1990 the control of NOx emissions will take a larger roll in the operation of existing equipment and the installation of new systems. The ability to provide the lowest possible emissions at the lowest cost and operational impact to the system will be the benchmark by which all new combustion equipment will be judged.