



Project Summary

A Low NO_x Strategy for Combusting High Nitrogen Content Fuels

Ravi K. Srivastava

A multistaged combustion burner designed for in-furnace NO_x control and high combustion efficiency has been evaluated for high nitrogen content fuel and waste incineration application in a 1.0 MW package boiler simulator. A low NO_x precombustion chamber burner has been reduced in size by a factor of about two (from 600-250 ms first-stage residence time) and coupled with 1) air staging, resulting in a three-stage configuration, and 2) natural gas fuel staging, yielding up to four stoichiometric zones. Natural gas, doped with ammonia to yield a 5.8% fuel nitrogen content, and distillate fuel oil, doped with pyridine to yield a 2% fuel nitrogen content, were used to simulate high nitrogen content fuel/waste mixtures. Minimum NO emission levels of 160 ppm and 110 ppm (corrected to zero percent O₂) were achieved for the natural gas and fuel oil tests, respectively. These results correspond to about 85 percent reduction in NO_x emissions compared to uncontrolled emissions from a conventional burner mounted on a 0.7 MW commercial package boiler. Under the conditions tested, net chemical destruction of NO via reburning does not seem to be evident. This may be due to the existence of rather low primary NO concentrations before the application of reburning. However, a beneficial dilution caused by reburning, as applied here, may provide lower NO emissions (on a ppm or lb/10⁶ Btu basis) along with no loss in heat output.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory,

Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

The family of nitrogen oxide compounds, including nitric oxide (NO) and nitrogen dioxide (NO₂), is generally referred to as "NO_x." These NO_x species are formed during the combustion of coal, oil, and natural gas by the reduction and oxidation of molecular nitrogen (N₂) and nitrogen contained in the fuel. NO₂ is a poisonous gas that the U.S. Environmental Protection Agency (EPA) has designated as a criteria pollutant because of its harmful effects to human health. In addition, NO_x emissions are known to contribute to the formation of photochemical oxidants and are precursors, along with sulfur oxides (SO_x), of acid precipitation. Two more areas of concern are emerging regarding NO_x levels in the atmosphere. First, forest damage as a result of acid precipitation, reported to be extensive in the Federal Republic of Germany, has been linked with increasing NO_x levels. Second, increasing levels of atmospheric nitrous oxide (N₂O) have been measured, levels that are predicted to contribute to both a decline in the abundance of stratospheric ozone and an increase in climatic warming. Studies of N₂O and NO concentration in experimental flames and in flue gases indicate that a correlation may exist between these two gases formed in combustion processes.

The EPA estimates that about 20 million tons (18,000 Gg) of NO_x are emitted annually from stationary and

mobile sources in the U.S. Unlike SO_x emissions, NO_x emissions are increasing. Coal- and oil-fired utility and industrial boilers account for over half of these NO_x emissions.

Only 15 percent of the stationary NO_x sources are regulated by EPA's New Source Performance Standards (NSPS); the remainder must be addressed with retrofit technologies if significant NO_x emission reduction is to be realized. Another NO_x control problem is posed by the potential of incinerating high nitrogen content wastes in industrial boilers. While incineration of these materials would not constitute a significant increase in the overall national N_x emission level, individual plant emissions may be sufficient to cause a local NO_x problem that would prevent governmental permitting of on-site incineration. As thermal destruction is an attractive alternative to landfill storage of wastes, the need continues for developing high efficiency, low NO_x combustion technologies.

Most NO_x in stack combustion gas is NO. Much is known about the mechanisms of NO formation in flames, both from molecular nitrogen (source of thermal NO) and from fuel-bound nitrogen (source of fuel NO). Thermal NO can be reduced by decreasing peak flame temperatures. Fuel NO is very sensitive to reactant stoichiometry and fuel-rich conditions promote N₂ formation over NO formation. Laboratory studies and field test data have established the importance of fuel NO to the total emission of NO_x from residual fuel oil and coal flames. Therefore, minimizing NO_x formation in flames typically involves controlling air and fuel mixing rates to create fuel-rich reducing zones and extracting heat to reduce final oxidation temperatures.

To avoid the need for costly post-combustion NO_x removal, several furnace NO_x control strategies have been developed and applied to boilers. These include reduced air preheat, load reduction, low excess air, flue gas recirculation, overfire air, deep air staging, fuel staging (or reburning), and various low-NO_x burner systems. While NO_x emissions can be reduced by 20-80% using these technologies, from uncontrolled levels exceeding 1,000 ppm for some high nitrogen content coals, the application of these combustion modifications can reduce combustion efficiency and increase sooting and slagging in the boiler. These problems are of concern in the boiler cofiring of fuels and wastes where high waste destruction efficiencies and minimal formation of other

incomplete combustion products are of paramount importance. Furthermore, practical constraints, such as burner and boiler sizes, limit the effectiveness of NO_x control by combustion modification.

EPA is currently involved in the development and field demonstration of two evolving NO_x control technologies: the precombustion chamber burner and reburning (fuel staging). These combustion modification strategies provide alternatives to expensive post-combustion NO_x removal technologies, such as selective catalytic reduction which is being utilized extensively in Japan and West Germany, for achieving low NO_x emissions when firing high nitrogen content fuels or incinerating highly nitrated wastes. The goal of this work was to utilize the precombustion chamber burner and air or air/fuel staging to develop a burner that is practical for both new and retrofit installations and is capable of burning high nitrogen fuel/waste streams with low NO_x emissions and high combustion efficiency. Specifically, a NO_x emission of less than 0.2 lb (as NO₂)/10⁶ Btu (or about 175 ppm NO_x measured dry at zero% O₂) for firing gaseous and liquid fuels doped with up to 5% nitrogen (by weight) was targeted (1 lb/10⁶ Btu = 0.43 kg/GJ).

This study was carried out in three phases. Phase 1 dealt with a fundamental exploration of post-flame combustion technology, known as reburning. In this phase the fundamentals of reburning and its suitability to combustion applications were studied in detail. This study lasted from March 1983 to October 1984.

The burner used during Phase 1 was a low NO_x precombustion chamber burner, designed and fabricated under an EPA contract by Energy and Environmental Research Corporation (EERC), Irvine, California. The burner proved to be a useful research tool, though its practicality was limited because of its size and cost. As a follow-on of the reburning work, the burner was reduced in size from 600 ms to 350 ms first-stage residence time. Subsequent proof-of-concept tests involving the reduced size precombustion chamber low NO_x burner and air or air/fuel staging were carried out. The proof-of-concept tests in Phase 2 helped to generate the experimental matrix for Phase 3.

During Phase 3, a vertical downfired combustor was designed, fabricated, and installed. It was of a modular design to allow residence time variations, and was capable of firing gaseous or liquid fuels. It had ports for detailed samplings and variable fuels and air injection locations/

methods. Parametric tests were carried out using this new burner to rigorously test and prove the concepts generated in Phase 2.

This report covers project activities between November 1984 and July 1987.

Experimental Approach and Results

The goal of this study was to minimize NO formation, with an emission target of 175 ppm (dry, at zero percent O₂) or less, and maintain efficient incineration of surrogate fuel/waste mixtures with up to 5 percent fuel nitrogen by using a precombustion chamber burner reduced in size by about half.

The experimental facility, used in Phase 1 and shown schematically in Figure 1a, consists of a precombustion chamber low-NO_x burner and a package boiler simulator. The precombustion chamber burner consists of a primary and air injection module, two 0.91 m long spool modules with 0.51 m internal diameter, and a 0.33 m long convergent module. These burner modules have a thick refractory wall lining to minimize heat loss, maintaining the high temperatures that promote conversion of fuel nitrogen to N₂ under fuel-rich stoichiometries. To achieve rapid mixing in the precombustion chamber, the primary fuel is injected through a divergent nozzle and the primary air, which is not preheated, is passed through fixed swirl vanes. The convergent module minimizes back-mixing of combustion gas and radiation loss to the boiler. A water-cooled transition module, 0.25 m internal diameter, cools the combustion gas before secondary air addition to minimize thermal NO generation. Primary fuel nitrogen is simulated by premixing ammonia into natural gas or pyridine into distillate fuel oil prior to primary fuel injection.

The pilot-scale boiler simulator is rated at 0.9 MW thermal input. The boiler's radiant section is horizontal, 0.6 m in diameter, 3.0 m long, and cooled with Dowtherm G heat transfer fluid. Combustion gas exits the boiler through a vertical stack. The boiler's front face has 8 axial ports for addition of staged air.

The research facility was modified as shown in Figure 1b. The horizontal 2.66 m long precombustion chamber burner was shortened to 1.75 m by removing one of the spool sections. This shorter burner, with a nominal residence time of 350 ms, has all the essential design features of the long horizontal burner, which has a nominal residence time of

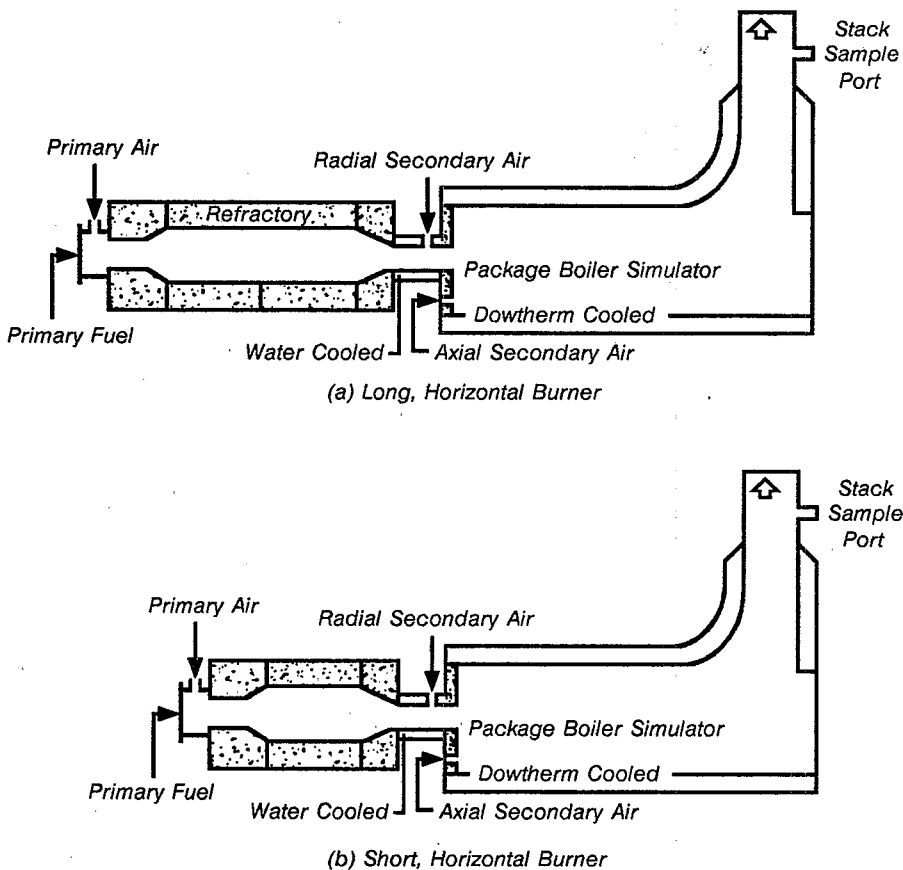


Figure 1. Pilot-scale combustion research facility. The package boiler simulator has been fitted with a precombustion chamber burner and air and fuel staging ports.

600 ms. Two of the eight axial air ports on the boiler front face were modified to provide ports for staging fuel into the boiler at an angle of 45°. This design allows for reburning application from the boiler front face, with aerodynamic separation of the fuel-lean and fuel-rich zones in the boiler. The end plate of the boiler has been modified to allow the insertion of a water-cooled boom for deep staging of air into the boiler.

The experimental facility is designed for independent control and measurement of each fuel, fuel dopant, and air stream. Stack gas speciation is measured by a continuous emissions monitoring system. NO and NO_x are measured by chemiluminescence. Reported in this paper are NO measurements only, measured on a dry basis and corrected to zero percent O₂, (spot-check measurements of NO_x indicated that NO emissions accounted

for over 95 percent of the exhaust NO_x emissions).

At a primary burner firing rate of 0.6 MW and a nominal first-stage stoichiometry of 0.7, shortening the precombustion chamber burner by removing one of the two modules decreased the bulk combustion gas first-stage residence time from 600 to 350 ms. In baseline tests (without reburning), first-stage stoichiometry was varied, with exhaust excess air held constant at about 15%. Ammonia was doped into the natural gas fuel steam, resulting in a fuel nitrogen content of 0.66% by weight. Figure 2 shows data for both the short and long burners. The minimum NO emission was observed at a first-stage stoichiometry of about 0.7, consistent with earlier data at a similar scale. The sharp minimum in the curve indicates the sensitivity of NO emission to first-stage stoichiometry. The minimum

NO emission increased from 50-75 to 200-250 ppm in going to the shortened burner. These ranges represent average NO emissions achievable given the small fluctuations in fuel and air flows.

The amount of NH₃ dopant was varied at the optimum first-stage stoichiometry (0.7) for both the short and long burners. Figure 3 shows that NO levels in the short burner are more sensitive to fuel nitrogen content than those in the long burner. With no NH₃ addition, NO emission from the short burner was 90 ppm; from the long burner, the NO emission was 40 ppm. These levels indicated the thermal NO component of the NO emission, coming from the molecular nitrogen (N₂) in the air. During operation with the short burner, a longer flame was observed in the boiler than during operation with the long burner, because combustion of the hydrocarbon was less advanced at the secondary air addition location for the short burner. Consequently, the peak temperatures in the boiler burnout zone were slightly higher than for the long burner. With the addition of NH₃ dopant, the long burner NO emissions increased to 100 ppm, or a net 60 ppm contribution from the surrogate fuel nitrogen. The short burner NO emissions for high NH₃ dopant levels in the fuel stream approached 250 ppm, or a 160 ppm net increase due to fuel nitrogen. The reduced first-stage residence time resulted in less fuel nitrogen being reduced to N₂ in the fuel-rich precombustion chamber. As fuel nitrogen content increased above 2%, the resulting increase in NO emissions became small.

Thus, an effect of halving the burner size is to increase minimum NO emissions for high nitrogen fuels from 100-250 ppm. Another effect is to move some of the flame back into the boiler, although still much of the heat release remains in the preburner. With a shorter flame length in the boiler with the preburner than with a conventional burner, reburning, which requires boiler volume, is an ideal technology for achieving additional in-furnace NO reduction.

Subsequently, preliminary tests were performed to evaluate the concept of natural gas reburning of combustion gases from a half-sized precombustion chamber burner. A primary NO level of 260 ppm was maintained by operating the burner at an off-optimum stoichiometry of 0.65 to reduce the amount of fixed nitrogen dopant (NH₃) required to achieve this emission. This NO level represents the maximum

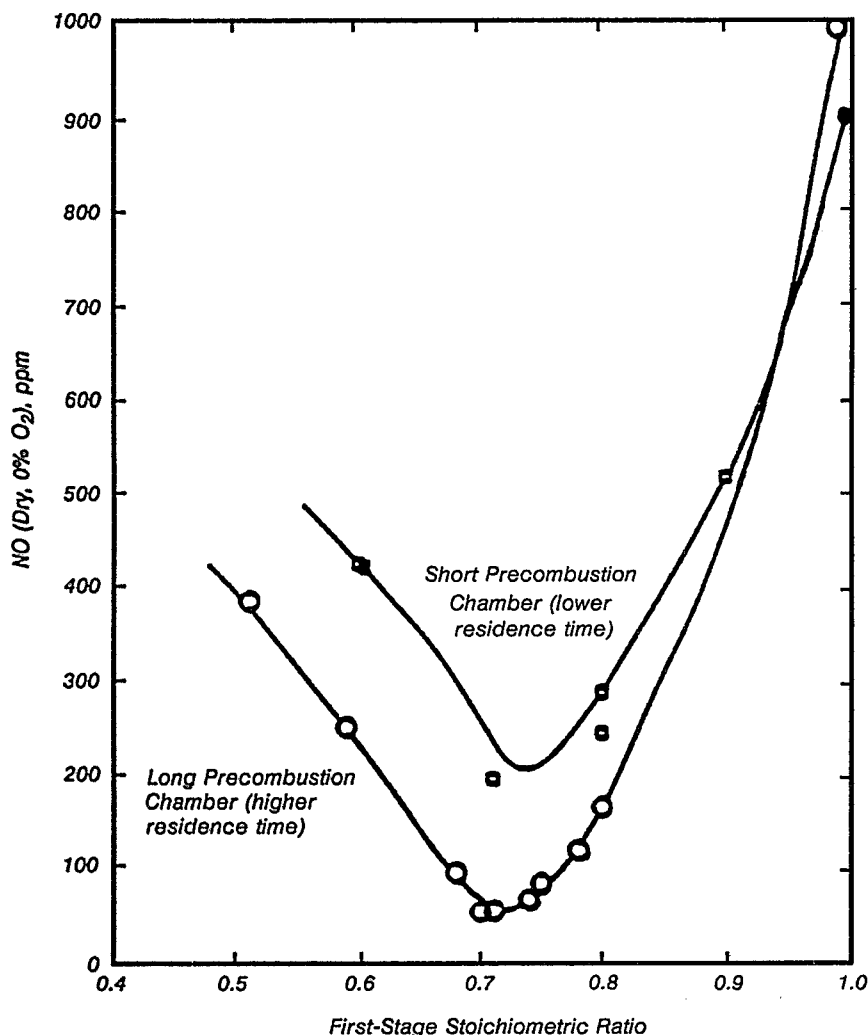


Figure 2. Influence of first-stage residence time on NO emission for short and long preburners.

emission of the half-sized burner when burning fuels with up to a 4% fuel nitrogen. Primary flame zone stoichiometry leaving the preburner was fixed at 1.1. The locations of staged fuel and air addition were varied.

Figure 4 shows the effect of reburn fuel injection location on NO emissions. Reburning fuel was added at the 107, 30, and 10 cm axial locations in the boiler. Burnout air was added at 168 cm. Figure 4 it was observed that slightly lower NO emissions were achieved injecting the reburn fuel downstream of the primary flame. However, even injecting reburn fuel at the outlet of the precombustion chamber resulted in significantly reduced NO emissions. The data suggest that reburn fuel can be injected at the boiler front face and still achieve NO emissions of less than 150 ppm.

Figure 5 shows the effect of burnout air injection location on exhaust NO levels. With reburning fuel injected at 30 cm, air was injected through axial ports on the boiler front face. The results show only slightly higher NO emissions than with deep-staged (168 cm) burnout air. Thus, injecting burnout air from the boiler front face results in NO emissions that approach the 175 ppm level.

Based on the results of the preliminary tests, a new burner system was designed and installed so that reburning fuel and air could both be injected from the boiler front wall. The new burner, shown in Figure 6, was made vertical to increase preburner temperatures by reducing radiative heat loss to the boiler and by taking advantage of thermal buoyancy effects. This vertical burner, with a nominal residence time of 250 ms, has all

the essential features of the horizontal precombustion chamber burner.

A North American (NA) Scotch-type package boiler was used to provide conventional burner results for comparison with the multistaged burner results. This boiler is a three-pass unit, with a continuous service rating of 0.3 kg of steam per second (2,400 lb/h). Its size and thermal characteristics are nearly identical to those of the package boiler simulator.

The parameters affecting the NO_x emissions from the facility with unstaged controls were fuel nitrogen content, combustion gas residence time in the prechamber, first-stage stoichiometry, and exhaust stoichiometry. The residence time of combustion gas in the burner depended on precombustion chamber length, load, and stoichiometry. The nominal load was 0.6 MW and 15% excess air, respectively. Nominal fuel nitrogen content for the fuel oil/pyridine mixture was 2% by weight; for the natural gas/ammonia fuel the nominal fuel nitrogen content was 5.8%. Preburner stoichiometry was optimized for all tests on this facility.

Burner Stoichiometry Variation

First-stage stoichiometry was varied by changing the primary air flow. Secondary radial air was adjusted to maintain 15% excess air. The results are plotted in Figure 7. The curves indicate a strong sensitivity of stack NO to changes in burner stoichiometry. For the gas tests, a minimum NO emission of 315 ppm occurred at a burner stoichiometry of about 0.78; for the oil tests, a minimum of 190 ppm occurred at 0.65. Thus, additional combustion modifications were necessary to meet the program goal of less than 175 ppm.

The shift in optimum burner stoichiometry suggests a variation in the thermal environment in the precombustion chamber. Figure 8, shows burner temperatures measured by suction pyrometry. Radiation and conduction errors are estimated to be less than 30°C. The burner temperatures were found to be higher for the oil tests; thus, the shift in optimum stoichiometry.

In tests on the North American boiler, a NO emission of 1,000 ppm resulted when firing the 5.8% nitrogen gas fuel at 15% excess air. A NO emission of 765 ppm resulted when firing the 2% nitrogen oil mixture at 15% excess air. Thus, the low NO_x burner reduced NO emissions by

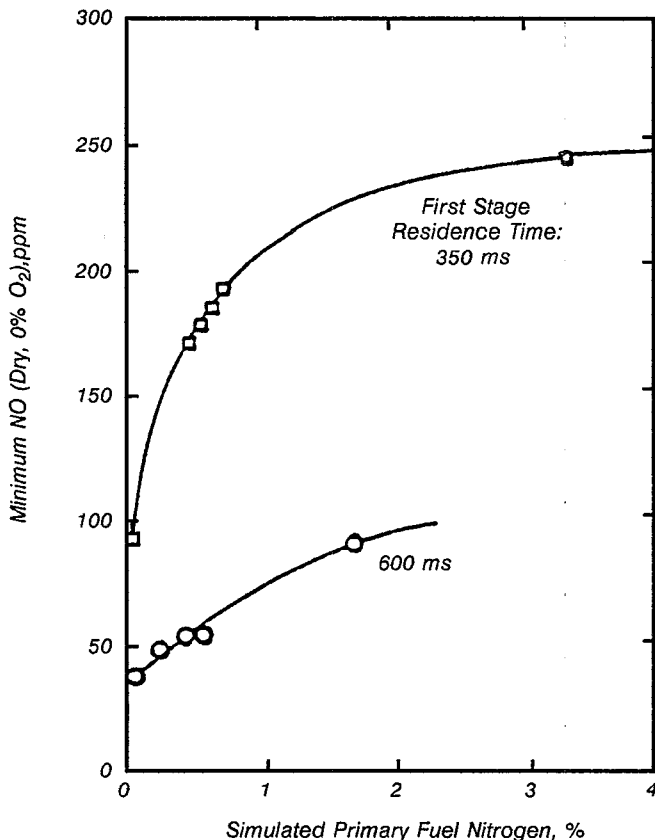


Figure 3. Influence of fuel nitrogen content on minimum NO emission for short and long preburners.

68% for the gas fuel and by 75% for the oil mixture.

Fuel Nitrogen Variation

The effect of fuel nitrogen variation is shown in Figure 9. Exhaust NO level increased with increasing fuel nitrogen content in the fuel/waste stream, as expected, with a much greater sensitivity observed in the conventional North American burner tests. These results demonstrate the precombustion chamber burner's ability to reduce fuel nitrogen to molecular nitrogen, even with its reduced size (250 ms). The full size (600-800 ms) precombustion chamber burner produces NO emissions even less sensitive to fuel nitrogen content.

Reburning Tests

In these tests, the total boiler load was held constant while fuel was diverted from the primary injector to two secondary injectors. In this case, the

staged fuel (undoped natural gas) was injected into the boiler downstream of the secondary radial air addition. Thus, a four-stage combustion process was established, consisting of a fuel-rich burner zone and three boiler zones characteristic of reburning (i.e., fuel-lean, fuel-rich, fuel-lean). The stoichiometry in the third stage (SR_3 , the fuel-rich reburning zone in the boiler) is critical in this NO_x control process. As already described, all of the staged air and fuel flows were injected from the front face of the boiler at various angles, resulting in the three boiler stoichiometric zones.

Fuel oil/pyridine and natural gas/ammonia results are given in Figure 10. Two second-stage stoichiometries (SR_2) were established: 1.1 and 1.0. The NO emissions under no staging conditions for the 5.8% nitrogen gaseous fuel firing and 2.0% nitrogen liquid fuel firing were 315 and 190 ppm, respectively. With 35% fuel staging and 5.8% nitrogen gaseous fuel firing, the NO emissions decreased to 195 ppm at a SR_2 of 1.1 (and a SR_3 of

0.72) and to 160 ppm at a SR_2 of 1.0 (and a SR_3 of 0.65). Again, with 35% fuel staging and 2.0% nitrogen liquid fuel firing, the NO emissions decreased to 120 ppm at a SR_2 of 1.1 (and a SR_3 of 0.76) and to 110 ppm at a SR_2 of 1.0 (and a SR_3 of 0.69). Due to less distinct stoichiometric zones than typically established in reburning application, the decrease in NO levels by fuel staging was not quite as great as that obtained when the staged fuel was injected farther downstream of the fuel-lean primary combustion zone; however, the configuration used in these tests requires no boiler penetrations. In addition, complete destruction of the primary fuel/waste stream appears to be ensured by providing all of the required primary combustion air prior to entry into the boiler.

Discussion and Conclusions

The combination of shortened precombustion chamber burner and reburning met the program goal of attaining an NO emission of about 175 ppm from firing gaseous and liquid fuels doped with up to 5% nitrogen. For reburning (as applied here), the net decrease in NO emissions seems to be predominantly due to a dilution of primary combustion gases by secondary combustion gases. This can be seen in Table 1 where NO concentrations obtained after adding appropriate dilution to base NO concentrations are very close to those obtained during corresponding reburning applications. Thus, net chemical destruction of NO during reburning under these experimental conditions does not seem to be evident. This may be because of the existence of rather low primary NO concentrations before applying reburning. However, a beneficial dilution caused by reburning, as applied here, may provide lower NO emissions (on a ppm or lb/10⁶ Btu basis) along with no loss in heat output. This beneficial dilution aspect of reburning application can be seen by comparing Figures 9 and 10. Substituting 35% of a 5.8% nitrogen gaseous fuel with a nitrogen-free one would yield a primary nitrogen content of 3.77%, and from Figure 9, firing this fuel would result in about 290 ppm NO. However, for reburning, NO emission can be as low as 160 ppm.

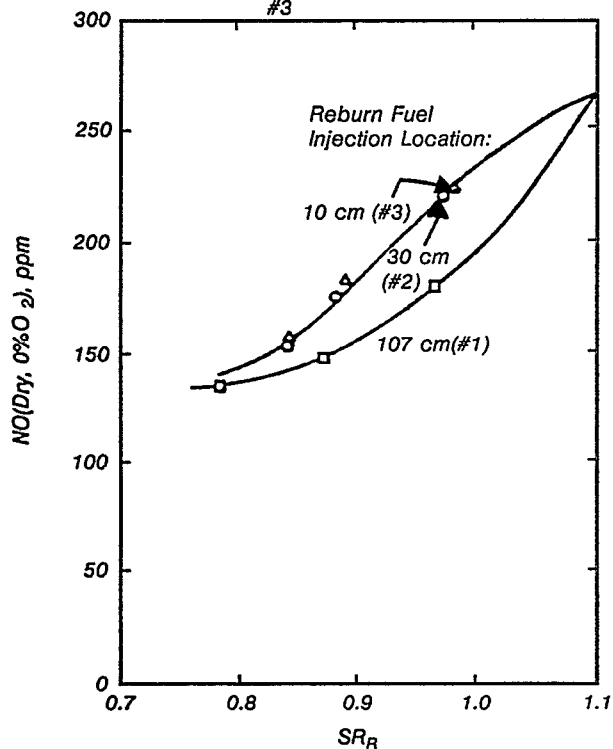
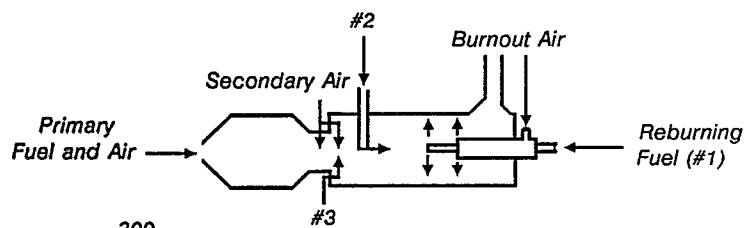


Figure 4. NO emissions as a function of reburn zone stoichiometry for various reburn fuel injection locations.

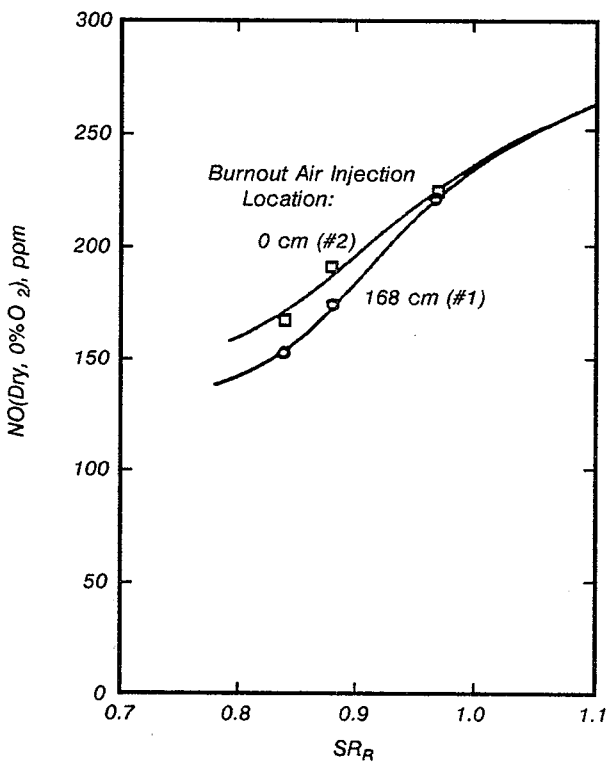
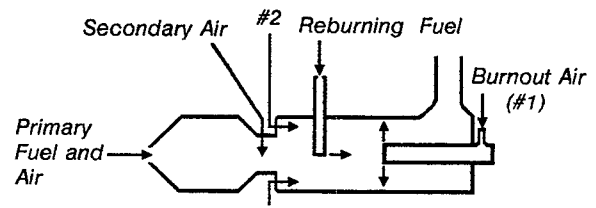


Figure 5. NO emissions as a function of reburn zone stoichiometry for various burnout air injection locations.

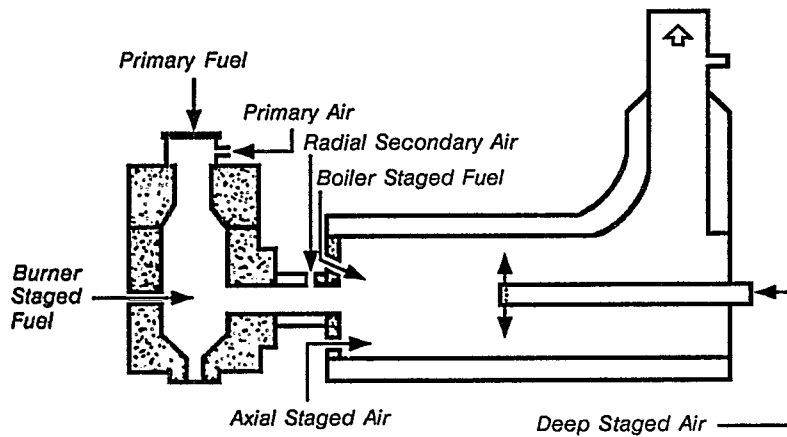


Figure 6. Pilot-scale combustion facility including a vertical precombustion chamber burner.

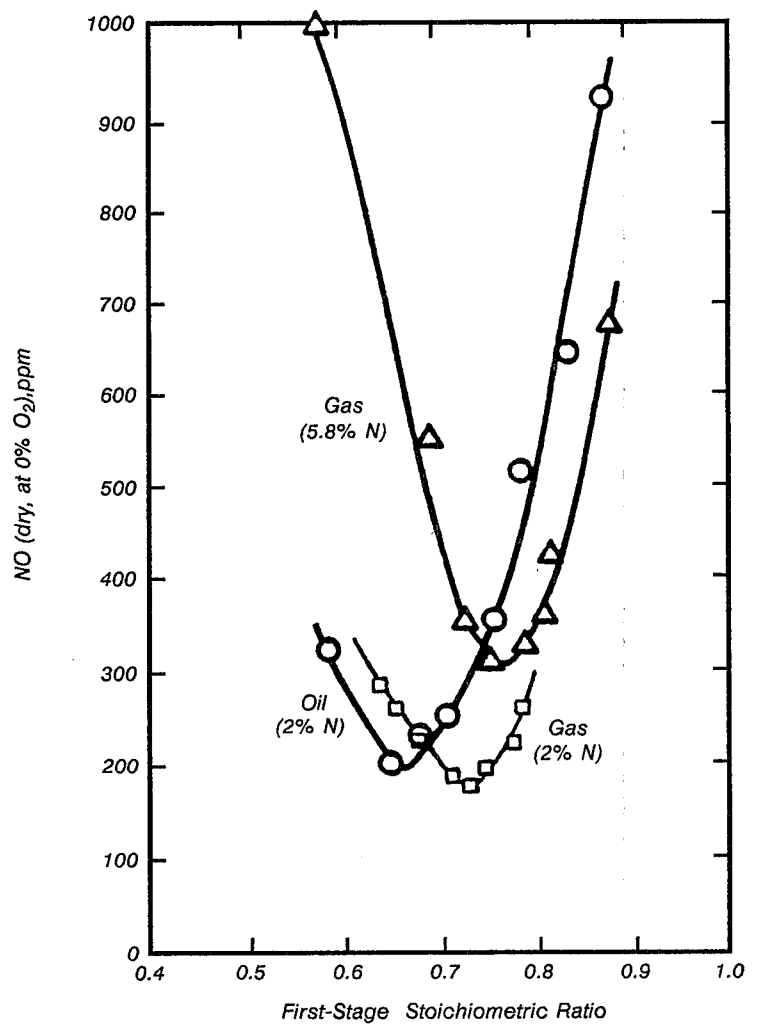


Figure 7. Effect of burner stoichiometry. Shown are results from tests firing 2.0% and 5.8% nitrogen gas fuel and a 2.0% nitrogen distillate fuel oil/pyridine mixture.

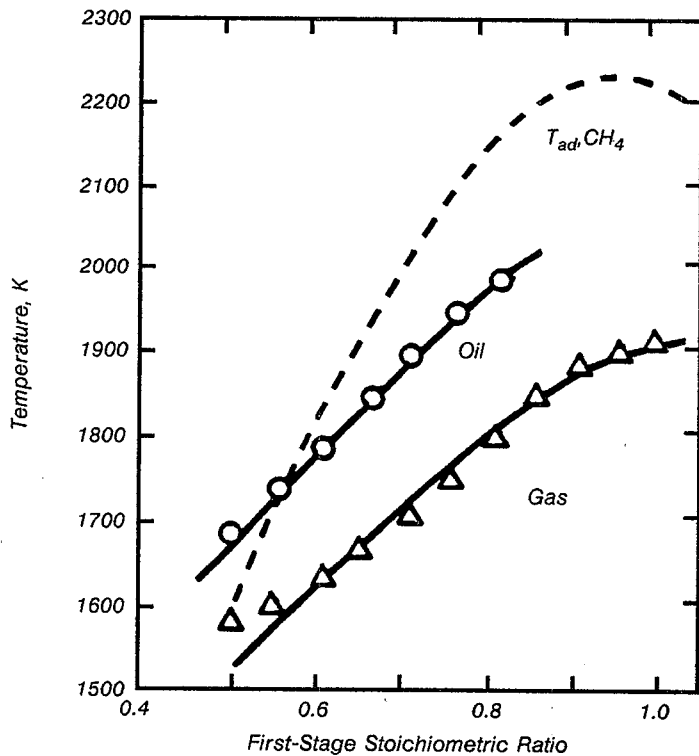


Figure 8. Burner temperatures.. Shown are measurements firing the low NO_x burner on gas and oil fuels. The dashed line represents the adiabatic flame temperature of methane in air at 1 atm.

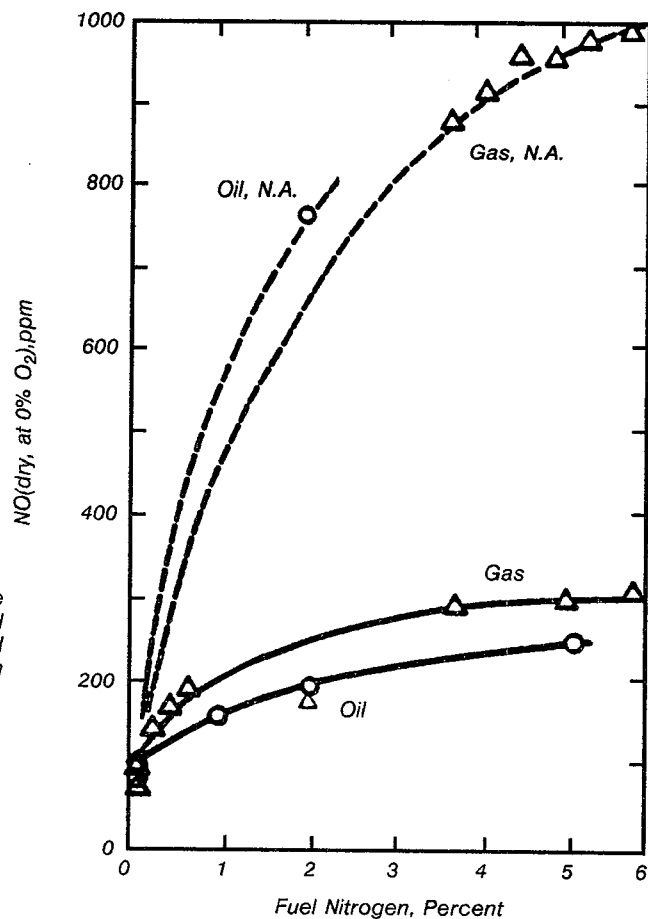


Figure 9. Fuel nitrogen variation results. Shown are results from firing a 5.8% nitrogen gas fuel and a 2% nitrogen oil mixture. The dashed lines represent data from the North American (N.A.) boiler tests.

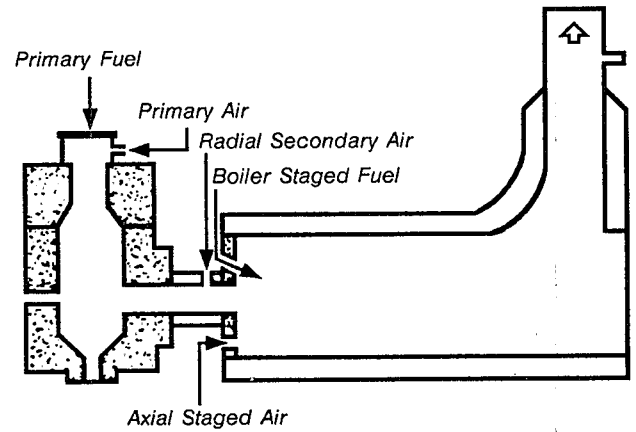
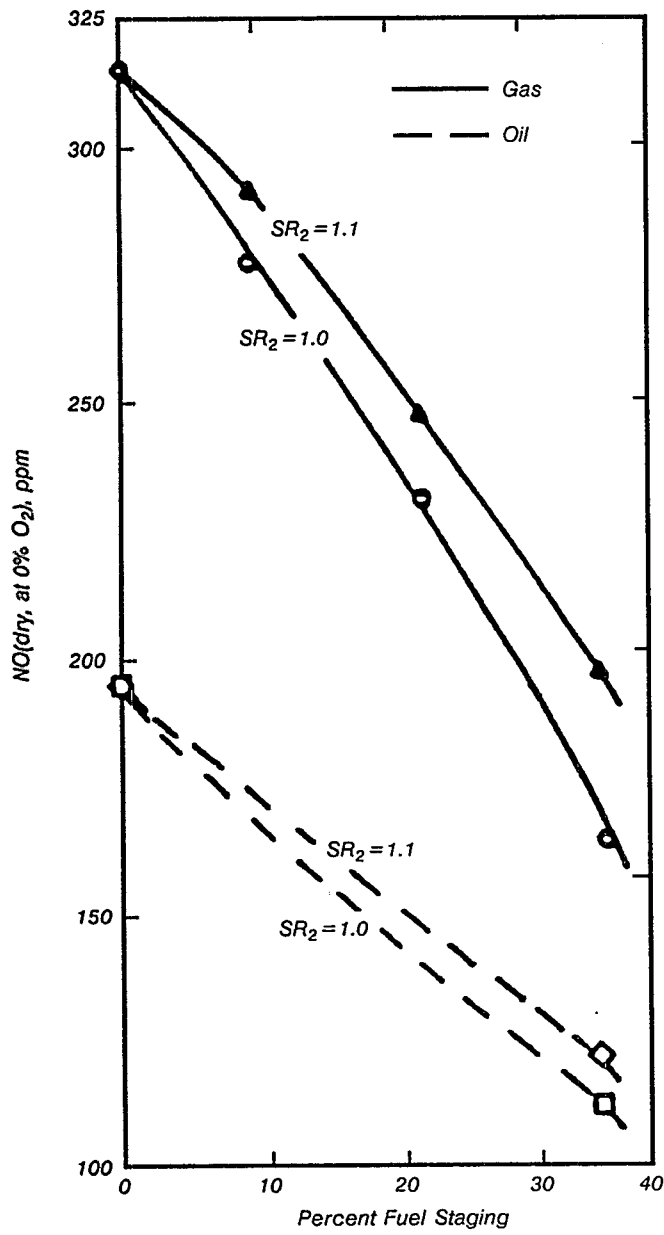


Figure 10. Boiler fuel staging results. Shown are results from firing a 5.8% nitrogen gas fuel and a 2.0% nitrogen oil mixture.

Table 1. Dilution Corrections

Configuration	Two Stage		Dilution Added To Two Stage	Reburn	Air	Staging
Waste Load %	100	65	65	65	100	100
Fuel				(SR ₂ = 1.0)	Axial	Deep
No. 2 Fuel Oil/Pyridine (2% N)	190	135	88*	110	150	130
Natural Gas/Ammonia (2% N)	185	130	--	--	--	--
Natural Gas/Ammonia (5.8% N)	315	260	169*	160	220	160

*Calculations showing addition of dilution:

Natural gas/ammonia (5.8%N): $0.65 \times 260 \text{ ppm} = 169 \text{ ppm}$

No. 2 fuel oil/pyridine (2.0 %N): $0.65 \times 135 \text{ ppm} = 88 \text{ ppm}$

R.K.Srivastava is with Acurex Corporation ,Research Triangle Park,NC 27709

James A. Mulholland is the EPA Project Officer (see below).

The complete report, entitled "A Low NO_x Strategy for Combusting High Nitrogen Content Fuels," (Order No. PB 90-155 664/AS; Cost: \$17.00 subject to change) will be available only from:

National Technical Information Service

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The EPA Project Officer can be contacted at:

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