



Project Summary

The Establishment of Design Criteria for Optimum Burners for Application to Heavy Fuel Fired Package Boilers

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This report describes results of a research program to develop low-NO_x heavy oil burners for application to industrial package boilers. Bench scale studies have been conducted which define the mechanisms of NO_x formation and control during staged combustion. These studies showed that >80% of total NO_x emissions can be due to conversion of fuel-bound nitrogen to NO_x. Conceptual design criteria were established based on these bench scale studies for an optimized two-stage combustion system which minimizes NO_x emissions from conversion of both fuel-bound nitrogen and molecular nitrogen in the combustion air.

Volume I of the report documents Phase 1 of this program, bench scale studies which defined optimum conditions for two-stage combustion. This information led to a conceptual two-stage low-NO_x burner design. Volume II gives results of pilot scale experiments conducted in two test facilities with nominal capacities of 0.9 and 2.9 MW_t, including tests of commercial burners for both firetube and watertube boilers. A wide range of petroleum-, coal-, and shale-derived fuels were investigated. Tests were also conducted with prototype advanced low-NO_x burners which demonstrated that NO_x emissions < 100 ppm (corrected to 0% O₂) could be achieved almost independently of the bound nitrogen content in the fuel. The conceptual design was successfully scaled from 21 kW_t to 0.9 MW_t to 2.9 MW_t with similar NO_x emissions performance.

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 two separate volumes (see Project Report ordering information at back).

Introduction

NO_x emissions from stationary combustors can be reduced by combustion modification techniques which involve staging the heat release process. However, the application of these techniques to residual-fuel-oil-fired combustors has been only partially successful because of a tradeoff in pollutant emissions. The decrease in NO_x emissions is often accompanied by an increase in particulate emissions. The optimization of combustion modification techniques to control NO_x emissions from liquid-fuel-fired combustors has also proved difficult because of the limited knowledge of the controlling phenomena.

The conversion of the nitrogen contained in liquid fuels to NO_x can contribute significantly to the total NO_x emissions when such fuels are burned in stationary combustors. The amount of fuel NO (NO produced from fuel nitrogen) increases with increasing fuel nitrogen content. The other contribution to NO_x emissions, thermal NO (produced from molecular nitrogen), depends primarily on temperature and oxygen availability and is relatively insensitive to fuel properties. Thus, as fuel nitrogen content increases, fuel

NO constitutes an increasing fraction of the total emissions. The formation of thermal NO depends strongly on temperature; therefore, combustion firing density and heat extraction control the amount of thermal NO produced. Fuel NO formation is strongly affected by fuel/air mixing conditions and depends on burner design.

Many studies have dealt with the mechanism of fuel nitrogen oxidation, resulting in the following simplified explanation. Initially the nitrogen in the fuel is released during thermal decomposition. The nitrogen-containing hydrocarbons are pyrolyzed, and the dominant nitrogen compound evolved is probably HCN. The fate of this HCN is then almost totally determined by the local reactant stoichiometry:

- **Fuel-Lean.** The presence of oxygen favors the formation of NO. For homogeneous premixed condition, >75% of the fuel nitrogen could be converted to NO. The heterogeneous nature of liquid fuel combustion usually limits the conversion to <50% (unless the fuel nitrogen content is low), and this depends on atomizer and air delivery system design.
- **Fuel-Rich.** The absence of oxygen favors the formation of N₂. Under fuel-rich conditions, fixed nitrogen species exist in the gas phase mainly as NO, NH₃, or HCN, and their relative concentrations depend on stoichiometry and temperature.

For typical fuels and combustion conditions, equilibrium total fixed nitrogen (TFN) concentrations (the sum of NO, HCN, and NH₃ concentrations) are <1.0 ppm for mixtures containing between 60 and 70% of the theoretical air requirements. Thus, if a combustor could be operated to achieve these near-equilibrium TFN levels, fuel nitrogen conversion would be minimized.

Staged combustion is the modification of the combustion process to minimize fuel NO formation and, provided heat removal occurs in the second stage, thermal NO formation is also restricted. In staged combustion, fuel is mixed with less than the stoichiometric air requirement. These conditions maximize conversion of fuel nitrogen to N₂ prior to the addition of the remaining air to complete combustion. Staged combustion can be achieved through burner design by reducing the rate of fuel/air mixing producing a fuel-rich zone in the core of the flame, or by physically dividing the total airstream, thus giving a well-defined fuel-rich zone. Under most practical con-

ditions the limit of NO_x control for liquid fuels by staged combustion has traditionally been dictated by the onset of smoke emissions.

The objective of the beginning of this program was to extend the studies conducted under an earlier EPA contract. The specific goals were to:

- Document conceptual designs for low-emission heavy fuel oil burners suitable for firetube and watertube package boilers.
- Determine the optimum time/temperature/stoichiometry history during staged liquid fuel combustion in order to minimize NO_x and particulate emissions in advanced low-emission burners and combustors.
- Develop optimum atomizers for advanced low-NO_x combustors.
- Extend a prior study of fuel effects to include a wide range of synthetic liquid fuels.

Bench Scale Studies

Volume I of the report documents the bench scale studies conducted in a 21 kW_t down-fired refractory tunnel furnace. The total range of fuels included in the fuel effects studies included 3 distillate petroleum oils, 13 petroleum-derived residual fuel oils, a heavy petroleum crude oil, and 9 coal-and shale-derived liquid fuels. An analysis of each of these fuels is presented in the full report.

Fuel NO_x emission was determined directly in the tunnel furnace by substituting (for combustion air) a nitrogen-free oxidant consisting of argon, oxygen, and carbon dioxide (the furnace is dubbed the "Argon" furnace for this reason). Total and fuel NO_x emissions for all of the fuels tested under excess air conditions are given in the full report. These data were taken at 5% excess O₂, 132°C air preheat, and 0.53 cm³/sec firing rate. An ultrasonic fuel atomizer was used with an air atomization pressure of 103 kPa (gauge). Fuel viscosity was maintained at 12 cSt (0.00012 m²s) by appropriate selection of fuel temperature. Total NO_x refers to emissions produced with air as the oxidant. Fuel NO_x is defined as the emissions measured when burning the fuel in the argon/oxygen/carbon dioxide mixture. Both total and fuel NO_x emissions increase with increasing fuel nitrogen content. The difference between total and fuel NO_x is defined to be thermal NO_x which is approximately constant for all of the heavy residual oils. In general, alternative fuels have higher nitrogen contents than petroleum-derived fuels and therefore produce higher fuel NO_x emissions.

With few exceptions, fuel NO_x emissions from both alternative and petroleum-derived fuels appear to correlate well on the basis of fuel-nitrogen content. The total NO_x emissions from some alternative fuels are higher than from pure petroleum-derived fuels of similar nitrogen content which suggests a greater production of thermal NO_x. Distillation results indicate that both total mass and nitrogen are evolved for these alternative fuels at significantly lower temperatures than for the petroleum-derived residual fuel oils. Thermal NO formation may be increased for these fuels because of higher peak flame temperatures in the early portion of the flame since more fuel is burned prior to vitiation of the combustor air with recirculated combustion products, or because the relatively high vaporization rates produce higher local combustion intensities.

TFN levels were measured at the exit of the fuel-rich first zone as a function of first-stage stoichiometric ratio (SR₁) for the Alaskan diesel oil, three petroleum-derived liquid fuels, three alternate liquid fuels, and methane doped with 0.79% nitrogen (by weight) as ammonia. All fuels investigated showed similar trends. TFN concentration decreased with decreasing SR₁ and minimized at about SR₁ = 0.8. TFN increased significantly as the primary zone stoichiometry was further reduced. TFN for both the ammonia-doped methane and the fuel oil with similar nitrogen content showed similar characteristics under fuel-lean conditions. However, below SR₁ = 0.7 the heavy oil produced significantly less TFN than the gaseous fuel. These results suggest that, although the impact of fuel composition is reduced under staged conditions, there can still be a significant impact on NO_x emissions.

The ultimate level of exhaust NO_x produced during staged combustion results from conversion of TFN existing the first stage and any thermal NO_x production which occurs during burnout. Second-stage thermal NO_x production was not considered to be significant in this study because changes in heat extraction during burnout had almost no effect on final emissions. Minimum exhaust NO_x and TFN concentration at the exit of the first stage were measured as a function of total fuel-nitrogen content for seven liquid fuels and the methane/ammonia mixture. In general, the minimum exhaust NO_x concentration occurred at SR₁ = 0.78 ± 0.02. NO_x emissions and TFN under staged conditions correlate well with total fuel-nitrogen content, but

the slope is significantly less than under excess air conditions. Only the SRC-II heavy distillate exhibited unusually high exhaust NO_x emissions, and this was the direct result of high first-stage TFN yield. NO , NH_3 , and HCN were substantially higher at the optimum stoichiometry for this fuel than for fuels with comparable nitrogen content. The increased TFN may be the result of basic chemical bonding differences between the parent coal from which the SRC-II was derived and petroleum liquids. Since this fuel was not tested at pilot scale, this anomalous behavior could not be confirmed; however it is well outside the limits of normal experimental errors. The results do indicate that high exhaust NO_x levels can be directly associated with high first-stage TFN levels.

TFN concentrations were found in excess of equilibrium levels. It has been suggested that increasing the temperature of the primary zone would prove beneficial. The impact of first-stage heat extraction was investigated in the bench scale tunnel furnace by inserting or removing cooling coils to extract heat along the walls of the furnace, and by inserting or removing choke sections in the furnace which reduce radiative heat loss. The results presented in the full report, obtained with crude shale oil, demonstrate the impact of first-stage heat loss on the fate of fuel nitrogen. The hot conditions refer to the furnace without primary zone cooling and with a choke section installed at the exit of the first stage to minimize radiative heat loss from the first stage. Cooling coils were added to the first stage, and the radiation choke was removed for the cool furnace conditions. Exhaust NO_x and primary zone gas temperature are reported as a function of stoichiometric ratio for these two furnace conditions. Minimum NO_x emissions were reduced for the hot furnace case, and the optimum stoichiometry was shifted toward more fuel-rich conditions.

Axial profiles in the report explain this shift in the minimum emission levels. Heat extraction from the first stage impacts the rate of decay of TFN species. Under cold conditions, both NO and HCN essentially freeze; whereas, without heat extraction, the initial rate of decay for all three species is much faster, leading to low TFN concentrations at the exit of the fuel-rich first stage. Heat extraction also affects the rate of CO oxidation.

The bench scale results demonstrate that a two-stage combustion system can be driven toward equilibrium levels by increasing the temperature in the fuel-

rich first stage. Since the ultimate level of TFN at the exit of the first stage is kinetically limited, the minimum NO_x level is controlled by a tradeoff between temperature in the rich stage and the time required for TFN decay at that temperature. This suggests that an optimum staged combustion system should minimize heat loss from the first stage to maintain gas temperatures as close to adiabatic as possible. Conditions in the second stage should also be optimized. The oxidation of TFN to NO is much lower in diffusion flames than in premixed flames; therefore, mixing should be controlled to provide an attached diffusion flame in the second stage. This suggests that relatively slow mixing should take place between second-stage air and first-stage combustion products. Mixing should also be controlled to minimize peak second-stage flame temperatures, thereby minimizing thermal NO_x formation. Studies undertaken in the tunnel furnace under an earlier EPA study showed that two methods of secondary air injection (radial versus axial injection) providing different mixing rates in the second stage produced similar NO_x emissions, suggesting that NO_x emissions were insensitive to second-stage mixing in that experiment. The scale of the bench scale tunnel furnace is so small that mixing was probably rapid in both cases. However, results obtained at pilot scale showed that mixing can have a significant effect on NO_x emissions. Since mixing is a scale-dependent phenomenon, its significance can be expected to increase as scale increases. Second-stage mixing effects were investigated in this study in the pilot scale experiments.

In practice there are many possible approaches to controlling mixing, including variation in air injection velocity, injection angle, number of injectors, and swirl intensity. The approach taken for a specific application must provide mixing which most closely achieves the mixing goals of the conceptual design while maintaining a flame shape which is commensurate with furnace geometry.

Pilot Scale Studies

The pilot scale studies described in Volume II were aimed at identifying the impact of fuel type and operating conditions on NO_x emissions using conventional package boiler burner equipment, and developing advanced low- NO_x burner concepts based on the optimization of two-stage combustion. Experiments were conducted in two test facilities: a 0.9 MW

test furnace which simulates the thermal environment and geometry of a firetube package boiler furnace (Firetube Simulator), and a 2.9 MW test furnace which simulates the thermal environment of a watertube package boiler (Small Watertube Simulator — SWS).

The control of NO_x emissions from practical boiler/burner systems is usually limited by a tradeoff between decreased NO_x emissions and increased smoke emissions. The report shows NO_x vs. smoke emissions produced in the SWS firing a California No. 6 oil with two different burners. Results were obtained with a commercially available burner which is widely applied on packaged watertube boilers. The combustion air is divided into two coaxial streams with variable swirl and flow through each passage. Air and fuel are mixed in the refractory throat of the burner and the flame is stabilized by recirculation of hot partial products of combustion. The data show that, as the minimum NO_x level decreases through adjustments to the burner and excess O_2 level, smoke emissions increase. The tests indicate that minimum NO_x emissions are similar for similar smoke levels regardless of burner settings. Data are shown with increased furnace insulation to raise gas temperature at the exit of the furnace. This resulted in slightly lower achievable minimum NO_x levels for equivalent smoke emissions, suggesting that the burnout of soot which is formed in the flame is enhanced by the increased furnace temperature.

Data were also obtained with a distributed mixing coal burner (designed under a prior EPA contract) which was modified for oil firing. The burner is similar to the commercial burner except for two major differences: (1) throat diameter is larger to decrease air velocity at the throat, and (2) a portion of the combustion air is added through four ports around the burner throat. This permits the burner to be operated with less than the stoichiometric air requirements at the burner throat. The results is a fuel-rich zone within the core of the flame with progressive air addition farther downstream. Minimum NO_x was again limited by the onset of smoke emissions regardless of burner settings. Comparison of results obtained with the two burners shows that about the same minimum level of NO_x emissions (150 ppm) was achieved at a Bacharach smoke number of 6 in spite of the substantial difference in fuel/air mixing. This suggests that there is a limit to the level of NO_x control

possible with conventional burner systems

The bench scale studies indicated that staged combustion can be further optimized by providing a physically separate first stage. This permits the optimization of conditions in the first stage without affecting the second stage, or vice versa. The bench scale studies suggested that an optimum two-stage combustion system should be designed according to the criteria shown in Table 1. The combustion process is divided into three zones: a fuel injection zone, a fuel-rich holdup zone, and a second stage burnout zone.

The table shows the desired optimum conditions for each zone. Fuel injection should provide rapid mixing of small fuel droplets with the primary air and minimum heat extraction in order to drive the liquid fuel into the gas phase as quickly as possible. The fuel-rich holdup zone should provide a plug flow residence time of >200 ms with minimum heat extraction in order to maximize TFN decay. Conditions in the second-stage burnout zone should provide slow mixing of the second-stage air with the primary combustion products in order to minimize oxidation of TFN to NO_x , and peak flame temperatures should not exceed 1500°C in order to minimize thermal NO_x formation.

Two prototype low- NO_x burners, shown in Figure 1, were constructed with nominal design firing rates of 0.6 and 2.9 MW. The first stage was constructed from high-temperature refractories and insulation to minimize heat loss through the walls of the first stage, permitting near-adiabatic temperatures. Fuel and primary air were injected at the entry of a divergent quarl which forms the initial section of the fuel-rich holdup zone. Calculated plug flow residence time in the fuel-rich zone for a first-stage stoichiometric ratio of 0.7 was about 0.56 sec for the small prototype burner, and 0.43 sec for the intermediate prototype burner. The primary combustion products were directed through a convergent section which serves to minimize radiative heat loss, ensure complete mixing of the primary products, and minimize back-mixing of the secondary air into the primary zone. Secondary air was injected parallel to the burner axis annularly around the primary exit. Two different commercial atomizers were used, an ultrasonic air-assist atomizer and an internal mixing steam-assist atomizer.

Also shown in Figure 1 are the Firetube Simulator and Small Watertube Simulator furnaces. The combustion chamber of

Table 1. Design Criteria for Scaleup of Low- NO_x Concept

A. Fuel Vaporization Zone	
1) Fuel/Air Mixing	Rapid mixing of fuel and air for maximum utilization of residence time.
2) Fuel Injection	Finely atomized droplets to allow rapid vaporization of fuel. 98% of droplets < 50 μm .
3) Heat Extraction	Minimum heat loss to maximize droplet vaporization.
4) Geometry	Not defined.
B. Fuel-Rich Holdup Zone	
1) Residence Time	Mean residence time >200 msec at high temperature.
2) Heat Extraction	Minimize heat extraction to maximize rate of decay of XN species to N_2 . Preferably exit temperature >1400K
3) Geometry	Designed to maximize true residence time/volume ratio.
4) Stoichiometry	Variable from 0.4 to 1.16. Optimum at 0.65-0.85.
C. Second-Stage Burnout	
1) Secondary Fuel/Air Mixing	Slow to minimize peak flame temperature, thus minimizing second stage thermal NO_x formation.
2) Heat Extraction	Optimize to limit peak flame temperature <1811K.

the Firetube Simulator is 3.2 m long with an internal diameter of 0.6 m. The furnace is comprised of calorimetric sections cooled by heat transfer fluid, and the wall temperature is nominally 230°C. The furnace of the Small Watertube Simulator is 5.2 m long with an internal diameter of 1.8 m. The furnace is externally spray-cooled and has a partial refractory lining to control total heat extraction.

The report shows the influence of first-stage stoichiometric ratio (SR_1) on exhaust emissions from the bench scale studies carried out in the tunnel furnace and from the prototype tests with residual oils containing about 0.6% nitrogen. The dependence of NO_x emissions on SR_1 was similar in all three experiments. Smoke and CO emissions from the small prototype burner were low for $\text{SR}_1 > 0.7$, but increased sharply as SR_1 was decreased further. CO emissions were <100 ppm, and smoke number was generally <5 at the point where the minimum NO_x level occurred. CO and smoke emissions performance for the intermediate prototype was similar. The minimum NO_x level ranged from about 89 ppm in the tunnel furnace to 84 ppm in the small prototype burner and 74 ppm in the intermediate prototype burner. The optimum SR_1 , appears to shift downward as scale increases, going from 0.8 for the tunnel furnace to 0.7 in the small prototype

burner and to 0.56 in the intermediate prototype burner. This shift in the optimum SR_1 and minimum NO_x level is most likely due to reduced first-stage heat loss associated with the increase in scale which leads to higher temperatures in the first stage. Equilibrium calculations (free energy minimization) confirmed that the optimum SR_1 should move more fuel-rich with increased temperature; however, the TFN concentrations which were measured in the tunnel furnace and small prototype burner are greatly (about 2 orders of magnitude) in excess of equilibrium values. Hence, even with first-stage exit temperatures of 1600°C at $\text{SR}_1 = 0.7$ and a first-stage residence time of 500 ms, kinetic limitations are significant. Decreasing SR_1 reduced first-stage NO; but, below about $\text{SR}_1 = 0.8$, significant amounts of NH_3 and HCN were formed. Thus, as in the bench scale studies, there exists a minimum in the exhaust NO_x because of competition between decreased first-stage NO and increased oxidizable nitrogen species. Other than shifting the optimum SR_1 , concept scale-up did little to alter this competition or the TFN species distribution.

The residence time in the fuel-rich zone to achieve the desired TFN concentration is an important practical design parameter since it largely determines the size of the precombustor. Figure 2 sum-

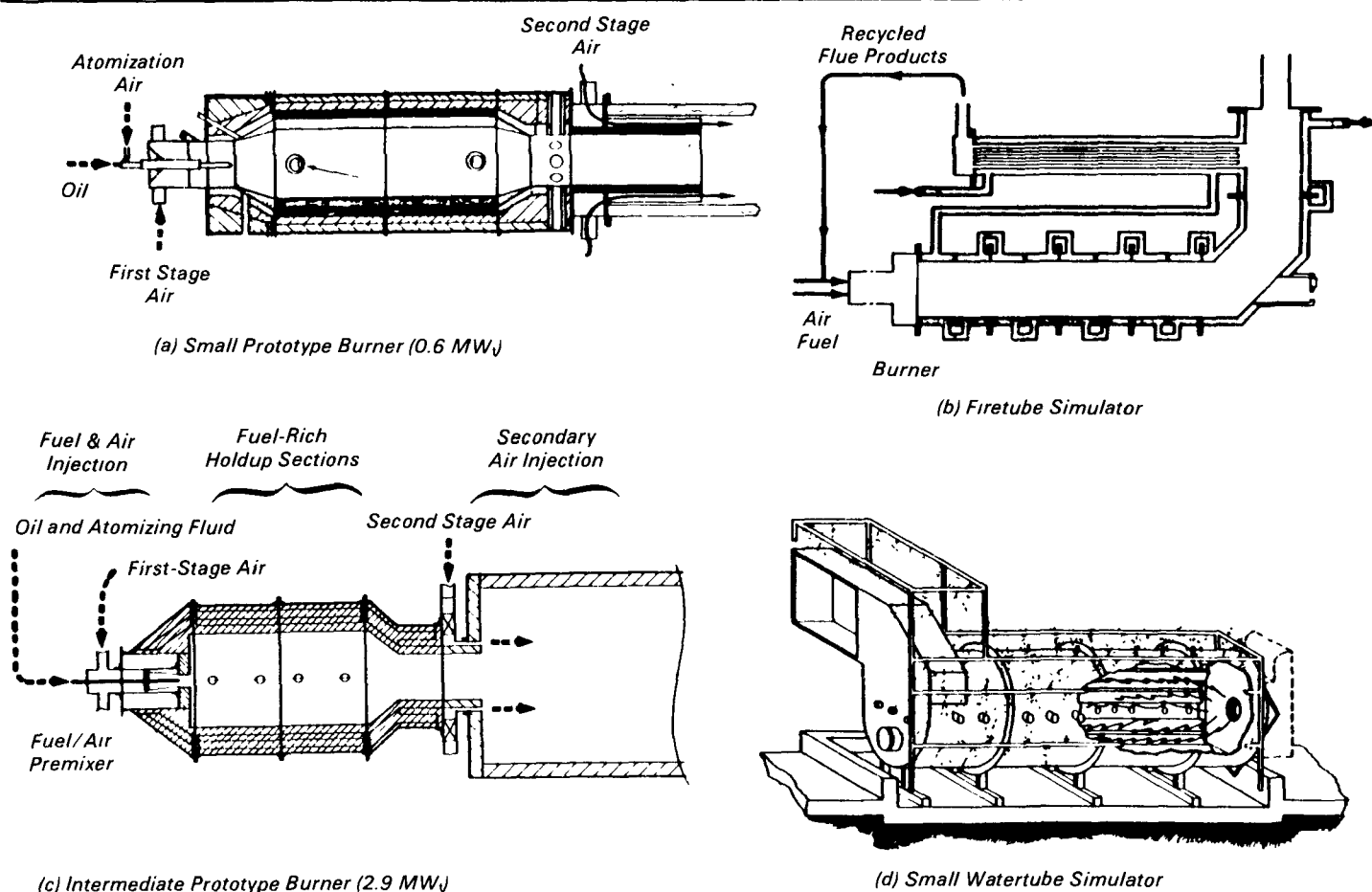


Figure 1. Prototype burners and experimental test furnaces.

marizes minimum exhaust NO_x and TFN data for the tunnel furnace and for the two prototype burners firing in both the Firetube Simulator and the Small Watertube Simulator. In both the bench- and pilot-scale studies, increasing the first-stage residence time significantly decreased exhaust NO_x and TFN concentration. The TFN concentration in the prototype burners was lower than in the tunnel furnace because of the increased rich-zone temperature associated with the increase in scale.

Mean first-stage residence time was varied in both the small prototype burner/firetube simulator tests (by altering the firing rate) and the small prototype burner/watertube simulator tests (by changing the length of the first-stage chamber). A strong correlation between the two sets of experiments suggests that the controlling processes are dominated by kinetics (time and temperature) and not by aerodynamics, and that the principal influence of firing rate is on

residence time. Clearly, increasing firing rate also increased first-stage temperature, but this effect is small because even at 0.6 MW the prototype heat losses were low. Gas temperatures at the exit of the first stage were about 1600°C at $\text{SR}_1 = 0.7$, compared with an adiabatic flame temperature of about 1750°C .

Since the time/temperature history of the fuel-rich zone was found to be the primary scaling parameter, one-dimensional kinetic calculations were conducted to quantify this influence. The model assumed a 2 ms well-stirred reactor ignition zone followed by a variable-length plug-flow reactor, and the fuel was methane containing 1% nitrogen as HCN. Preliminary runs showed that the initial speciation at the inlet to the first stage had little effect on the ultimate TFN level. The model showed that TFN decay is rapid at high temperature, but that decay slows dramatically $<1425^\circ\text{C}$. Thus, increasing first-stage residence time is only beneficial if the heat extraction rate is

low enough to keep the local gas temperature $>1425^\circ\text{C}$. Further, the rate of NO decay decreases significantly when the NH_3 concentration falls to zero, indicating that TFN speciation is important in first-stage processing. These calculations support the concept that reactions in the form: $\text{NO} + \text{NH}_3 \rightarrow \text{N}_2$ are controlling the fuel-rich TFN reduction, and that it is essential to have both high temperatures ($>1425^\circ\text{C}$) and a proper TFN species distribution in order to achieve very low exhaust NO_x levels. The calculations also indicate the need for a long residence time in the primary zone, but that the required time to achieve a given level of TFN decreases with increasing first-stage temperatures.

Figure 3 summarizes NO_x emissions from each of the pilot- and bench-scale experiments as a function of fuel nitrogen content. Figure 3a shows NO_x from the commercial burners tested in the Firetube Simulator and the Small Watertube Simulator, the 3 MW distributed mixing

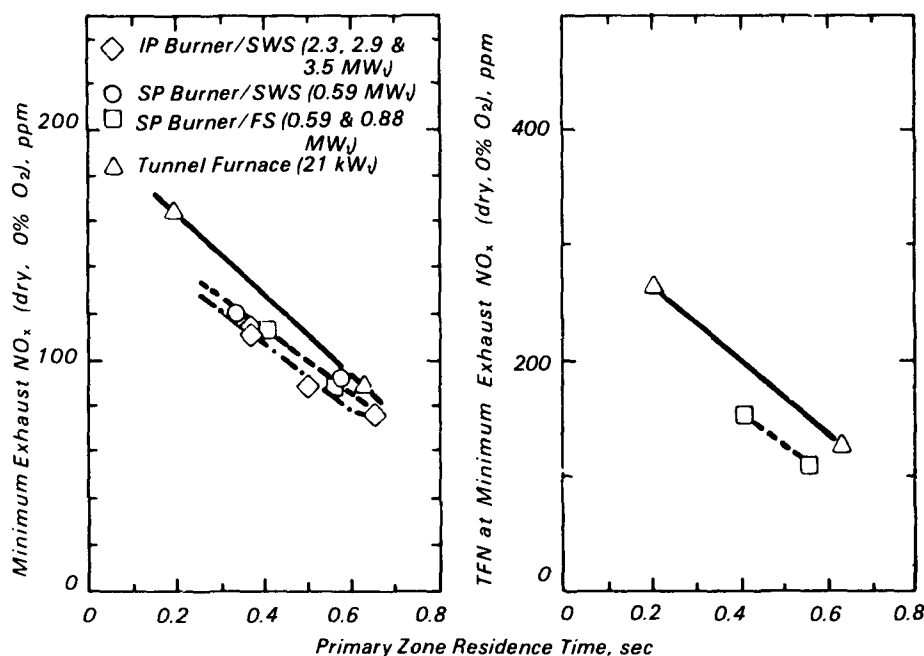


Figure 2. Effect of first-stage residence time on exhaust NO_x emissions and TFN decay for bench-scale, small pilot-scale (SP), and intermediate pilot-scale (IP) staged combustors.

burner, the bench scale tunnel furnace, and the two pilot-scale prototype burners. Data from the tunnel furnace showed that NO_x emissions were > 1000 ppm for fuels with nitrogen content >0.6%. However, the application and optimization of staged combustion dramatically reduced NO_x emissions to 190 ppm at this same level of fuel-bound nitrogen. NO_x emissions from the Firetube Simulator with commercial burner A were also high, reaching 1060 ppm when burning the high nitrogen (2.08 wt % nitrogen) crude Paraho shale oil. In contrast, NO_x from commercial burner B in the same furnace were only 550 ppm when firing the same fuel. This illustrates the strong dependence of NO_x emissions on burner design for conventional burner systems. The application of staged combustion to commercial burner A further decreased NO_x emissions to 490 ppm when burning the shale oil, but at the expense of increased smoke emissions

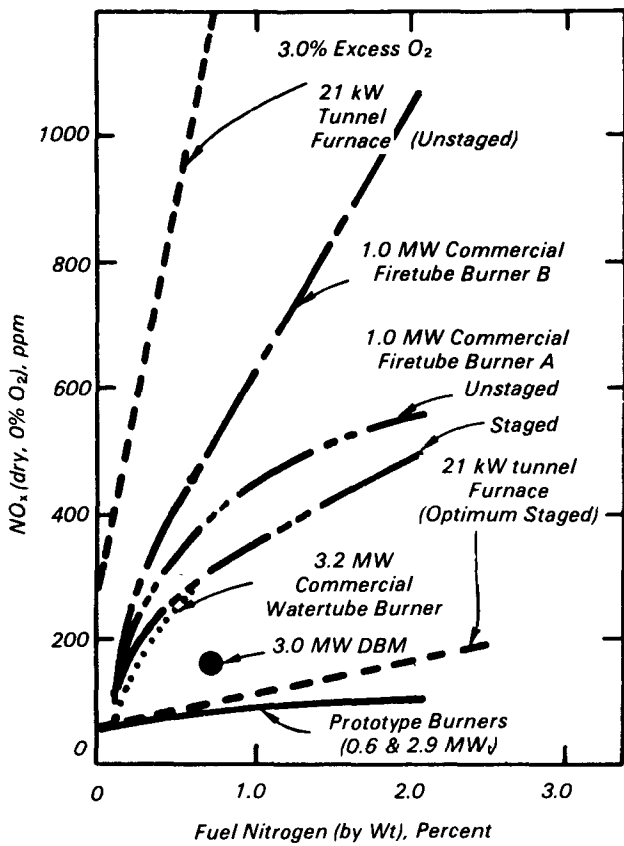
NO_x emissions from a 3 MW commercial watertube burner in the Small Watertube Simulator were much lower than either of the commercial firetube burners for fuels with equivalent bound nitrogen content. NO_x emissions were very strongly dependent on fuel nitrogen content with all of the conventional burner systems which were tested. The NO_x

emissions from the optimized tunnel furnace and the prototype pilot scale burners were influenced by fuel nitrogen to a much lesser extent and were only a fraction of the emission level from the commercial burners.

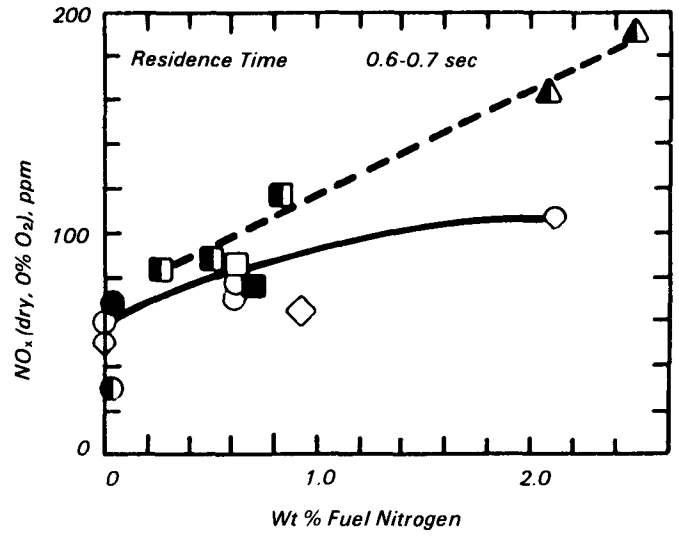
Figure 3b shows the fuel nitrogen dependence more clearly for the tunnel furnace and for the pilot-scale prototype burners. Data are shown for various fuels including a distillate oil (with and without pyridine), residual oils, a coal-derived liquid, and a propane/NH₃ mixture. The data indicate that NO_x is only weakly dependent on nitrogen content with the small and intermediate prototype burners. Comparison of results obtained with the NH₃-doped gas, pyridine-doped distillate oil, and actual residual oils shows that differences in NO_x due to fuel volatility are small in absolute terms, especially for systems with short residence time in the first stage where the characteristic time for the vaporization of fuel approaches the time available for TFN decay. Scale-up of the concept resulted in dependence of NO_x emissions on fuel nitrogen level. This is probably due to the increased temperature in the fuel-rich zone because of the increase in scale.

In conclusion, these results indicate that it should be possible to apply the low-NO_x burner concept developed in this

program to systems of different scale in order to achieve NO_x emissions <100 ppm even when firing high-nitrogen fuels. Successful scaling criteria for advanced low-NO_x burners were developed and verified over a range in scale of 750 to 1.



(a)



Legend:

Intermediate Prototype 2.3 MW _t	Small Prototype 0.59 MW _t	Argon Furnace 21 kW _t	
●	○	◐	Propane + NH ₃
■	□	◑	Distillate (+ Pyridine)
	◇	◒	Residual Oil
		◓	Coal Liquids
		◔	Shale Liquids

(b)

Figure 3. Effect of fuel nitrogen content on NO_x emissions from: (a) all bench- and pilot-scale burners tested, and (b) low-NO_x prototype burners.

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The complete report consists of two volumes, entitled "The Establishment of Design Criteria for Optimum Burners for Application to Heavy Fuel Fired Package Boilers:"

"Volume I. Laboratory Scale Tests," (Order No. PB 87-145 637/AS; Cost: \$18.95, subject to change).

"Volume II. Pilot Scale Tests," (Order No. PB 87-145 645/AS; Cost \$18.95, subject to change).

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