United States
Environmental Protection
Agency

Research and Development

Air and Energy Engineering
Research Laboratory
Research Triangle Park NC 27711

EPA/600/S7-87/011 May 1987

EPA

Project Summary

Reburning Application to Firetube Package Boilers

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A pilot-scale experimental research program has been conducted to examine the physical and chemical phenomena associated with the NO_x control technology of reburning applied to gas- and liquid-fired firetube package boilers. Reburning (staged fuel combustion) diverts some of the fuel and combustion air from the main burner(s) for injection into the post-flame gases, resulting in three distinct zones in the boiler radiant section: a fuel-lean primary zone, a fuel-rich reburning zone, and a fuel-lean burnout zone. NO_x is reduced both by reduction of NO_x formation and by destruction of primary flame NO_x by secondary fuel radicals.

Several hypotheses were evaluated. Results indicate that the overall NO_x reduction via reburning has a reaction rate order of about 1.5 with respect to primary NO_x. Secondary fuel-bound nitrogen is found to reduce reburning effectiveness. An overall gas-phase reaction time constant of 50 ms is observed for the reburn zone nitrogenous species; the characteristic time constant is greater for liquid fuel reburning due to droplet vaporization requirements. Increased temperature increases N_2 formation in the fuel-rich zone, but decreases N_2 formation in the burnout zone. Secondary fuel injector design does not significantly influence reburning effectiveness in the firetube package boiler class because of large-scale turbulent structures in the reacting flow that dominate secondary fuel jet parameters. Nitrogen-free fuel oil yields slightly greater NO_x reductions than natural gas in reburning application. These results were obtained on a 1.0 MW (3.5×10^6 Btu/hr) research boiler simulator and verified on a commercial Scotch package boiler (2.5×10^6 Btu/hr).

It is shown that, with minimal facility modification, NO_x emissions from a firetube package boiler can be reduced by 50% or more from an initial level of 200 ppm (measured dry, at zero % O_2).

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

Experimental research has been conducted to study the physical and chemical phenomena associated with gaseous and liquid fuel reburning applied to two firetube package boilers. The test results show that reburning is an effective way to control the emission of oxides of nitrogen (NO_x), even at low initial NO_x levels. For initial NO_x levels of >100 ppm, 50-80% NO_x reductions have been obtained. Reburning can be coupled with other NO_x control technologies to yield NO_x emissions of <100 ppm.

Reburning (staged fuel combustion) is an in-furnace NO_x control technology that diverts some of the fuel and combustion air flows from the main burner(s) for injection into the post-flame gases. With this combustion modification, three stoichiometrically distinct zones are established in the boiler radiant section: a fuel-lean primary zone, a fuel-rich reburning zone, and a fuel-lean burnout zone. NO_x reduction via reburning occurs both by the molecular destruction of NO_x formed in the primary combustion zone through reactions with secondary flame radicals and by an overall reduction of NO_x formed due to distributed mixing of fuel and air. Figure 1 is a cartoon depicting this process.

Bench-Scale and Other Tests

Bench-scale tests performed elsewhere identify the important reburning NO_x reduction mechanisms. It has been shown that the methylidyne radical ($CH^{\cdot}$) resulting from pyrolysis of the staged fuel reacts with NO (formed in the primary combustion zone) to form hydrogen cyanide (HCN). In the reburning zone, HCN reacts to form amines which can react with nitric oxide (NO) to form molecular nitrogen. Alternatively, fixed nitrogen species can oxidize in the reburning and burnout zones to form NO_x.

Full-scale field tests in Japan in the late 1970s and early 1980s showed that 50% NO_x reduction is achievable with reburning over a wide range of initial NO_x conditions burning gas, oil, or coal in the reburning zone. These promising results raised fundamental questions leading to further research and development in the U.S. Environmental Protection Agency (EPA), the Department of Energy (DOE), the Electric Power Research Institute (EPRI), and the Gas Research Institute (GRI) have sponsored various parametric reburning studies.

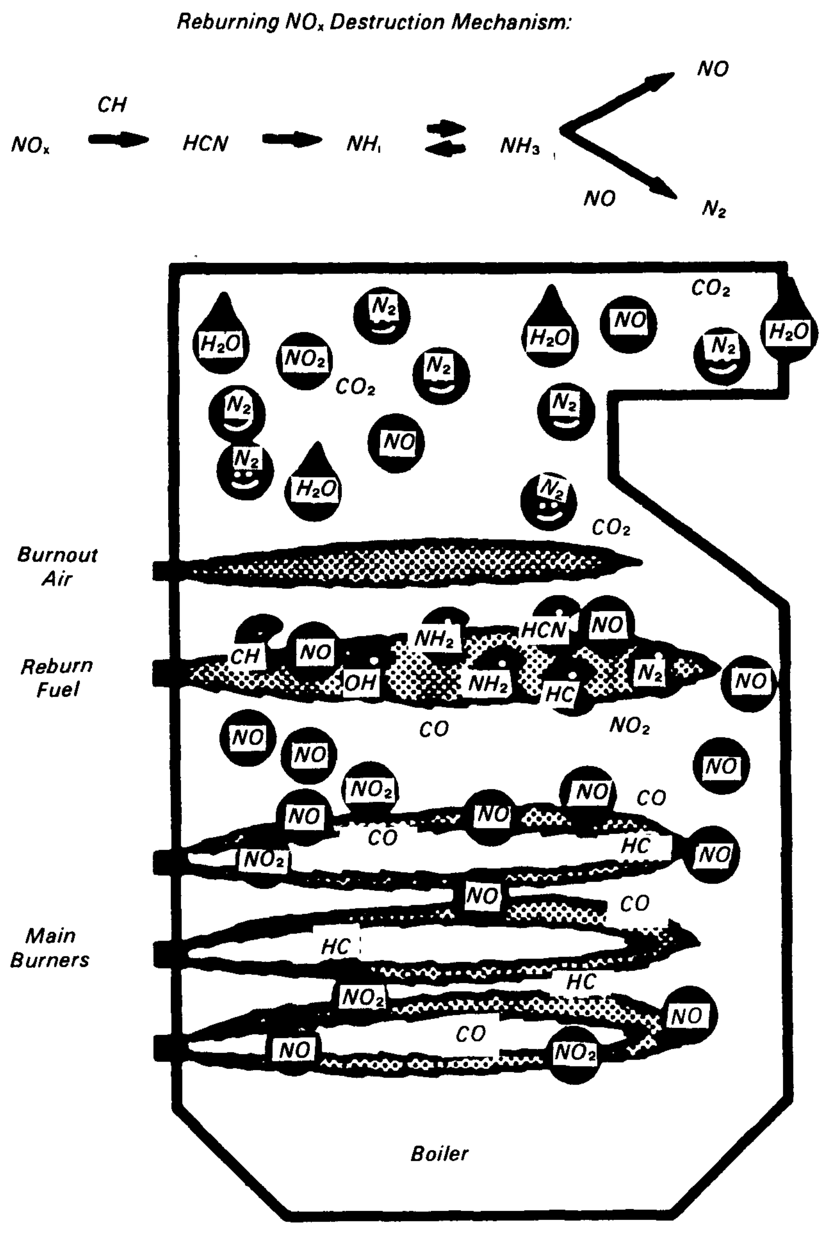

Figure 1. Reburning.

EPA Tests

To bridge the gap between fundamental study of reburning mechanisms and full-scale reburning application, the U.S. EPA conducted in-house reburning tests from May 1983 through May 1985 at its Environmental Research Center in Research Triangle Park, NC. Two pilot-scale firetube package boiler test facilities (a research simulator and a commercial unit) were modified for reburning application, with these key characteristics:

- Nominal firing rate — 0.6 - 0.9 MW (2 - 3 x 10^6 Btu/hr).
- Fuels — natural gas and light and heavy fuel oils.
- Low primary NO_x levels — 50 - 250 ppm (all NO_x concentrations reported dry, at zero % O_2).
- Low reburning zone temperatures — 1300 - 1600 K (1900 - 2400°F).

The test facilities simulate the thermal environment and turbulent diffusion flame aerodynamics of small firetube package boilers. The simple furnace geometry, with a single centerline burner mounted to a horizontal, cylindrical boiler, results in a nearly two-dimensional system, allowing for complete spatial (and temporal) characterization of the combustion gas temperature, velocity, and composition. Natural gas and light and heavy fuel oils were fired in the primary and reburning burners, with ammonia and pyridine dopants used as fuel nitrogen surrogates. A schematic of the research package boiler simulator is shown in Figure 2.

Baseline conditions were established to focus study on low primary NO_x levels for two reasons: (1) to evaluate an apparent discrepancy in results reported by various investigators, and (2) to target most likely candidates for reburning application. First, laboratory and field data reported by Japanese investigators indicate that NO_x reduction by reburning is independent of initial NO_x level; however data from bench-scale tests conducted in the U.S. indicate that NO_x reduction by reburning decreases as initial NO_x levels decrease. Second, application of reburning is likely to be coupled with primary flame NO_x control (e.g., low NO_x burner). Cost effective primary combustion modifications exist to reduce NO_x levels to between

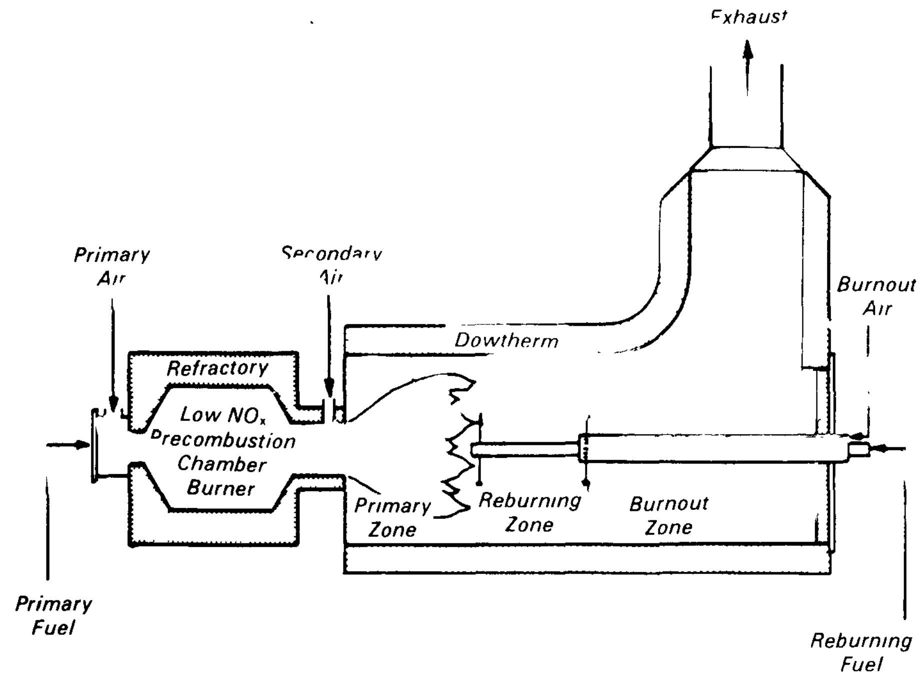

Figure 2. *Package boiler simulator schematic*

200 and 400 ppm; reburning can then be applied to reduce NO_x emission by an additional 50%

Reburning parametric tests included both input/output and detailed sampling of combustion gas temperature, velocity, and speciation. The test matrix included variation of the following parameters to evaluate several hypotheses:

Primary Zone	*Reburning Zone*	*Burnout Zone*
● *Initial NO_x concentration*	● *Stoichiometry*	● *Stoichiometry*
● *Stoichiometry*	● *Fuel nitrogen content*	● *Temperature*
● *Fuel type*	● *Residence time*	● *Mixing rate*
● *Flame shape*	● *Temperature*	
	● *Mixing rate*	
	● *Fuel type*	
	● *Fuel staging location*	

These parameters were varied independently to as great a degree as possible. Primary NO_x concentration was controlled by varying the level of primary fuel dopant; primary zone stoichiometry, by primary combustion air flow rate; and primary flame shape, by primary axial and radial air split. Reburning zone stoichiometry was varied by varying the amount of secondary fuel addition (with primary load held constant) Reburning zone residence time was varied by varying the location of burnout air addition. Variable reburning fuel nozzles were used to adjust secondary fuel mixing rates. The temperature in the boiler was changed by insulating portions of the radiant zone.

EPA Findings

Several findings from the research boiler simulator reburning experiments were significant. Figure 3 shows the effects of initial NO_x concentration, reburn zone stoichiometry, and fuel nitrogen content. The overall reburning reaction rate order with respect to primary NO_x is about 1.5, as NO_x reductions decrease with decreasing levels of primary NO_x. There is an optimum reburn zone stoichiometry for NO_x reduction, dependent on initial NO_x level and reburning fuel nitrogen content. The optimum stoichiometry for primary NO_x destruction is about 0.9; however, dilution effects from staged combustion typically result in an optimum reburn zone stoichiometry for overall NO_x reduction in the range of 0.7 - 0.9. Secondary fuel nitrogen content is shown to have a large impact on reburning effectiveness, significantly reducing NO_x reductions for primary NO_x levels less than 250 ppm. However, at high initial NO_x levels (i.e., greater than 500 ppm), reburning fuel nitrogen can actually enhance NO_x reduction.

Figure 4 shows reburning effectiveness as a function of reburn zone residence time for reburning with natural gas, distillate fuel oil, and a distillate/residual fuel oil mixture. A minimum reburn zone gas-phase reaction rate time was found to be 50 msec, which translates to a reburn zone length of 0.61 m (2 ft) and reburn zone bulk residence time of 200 msec in the firetube package boilers tested. Fuel oil reburning required longer residence times to allow for droplet vaporization.

Other important findings included the lack of significant overall effects of temperature and mixing rates in these tests. Over the limited range tested, temperature was not found to have a major influence on overall reburning effectiveness. While increased temperature increased N_2 formation in the reburning zone, N_2 formation in the burnout zone was significant under low temperature reburning conditions. Reburning fuel nozzle design did not significantly influence reburning effectiveness in these tests because of large-scale turbulent eddy structures in the reacting flow that dominated reburning fuel mixing. Thus, secondary fuel jet parameters did not control reburning zone mixing rates in these tests. Detailed probing in the furnace of temperature, velocity, and speciation provided a deeper understanding of the reburning process. The time-resolved nitrogen species profiles shown in Figure 5 demonstrate the kinetic and mixing limitations of reburning.

Conclusions

These results, characterizing the dependence of reburning effectiveness on major parameters, were found to be consistent for natural gas and fuel oil firing in the commercial boiler. Light fuel oil was found to yield slightly greater NO_x reductions that natural gas in reburning application. With minimal facility modification, Figure 6 shows that NO_x emissions can be reduced by 50 - 60% from an initial level of 200 ppm with either natural gas or fuel oil reburning. Reburning is a way to control NO_x emissions with a minimum fuel-rich zone length. However, for reburning to be effective, secondary fuel must be staged downstream of the primary combustion zone, which requires sufficient boiler length.

NO_x formed during combustion by the reduction and oxidation of molecular nitrogen and nitrogen contained in the fuel contribute to the degradation of air quality as well as to acid deposition and forest damage. Reburning is one of many NO_x control technologies presently available. While NO_x control strategies exist that can meet current New Source Performance Standards (NSPS) for NO_x emissions, few technologies exist that can control NO_x emissions to < 100 ppm. Natural gas reburning can be coupled with other NO_x control technologies to achieve this low emission level. Of course, in selecting a NO_x control strategy for a particular application, cost analysis must be considered along with technical feasibility. Reburning, while more expensive and/or difficult to implement than some other in-furnace NO_x control technologies (such as air staging or low NO_x burners), is still much less expensive than pre-combustion fuel cleaning and post-combustion catalytic reduction.

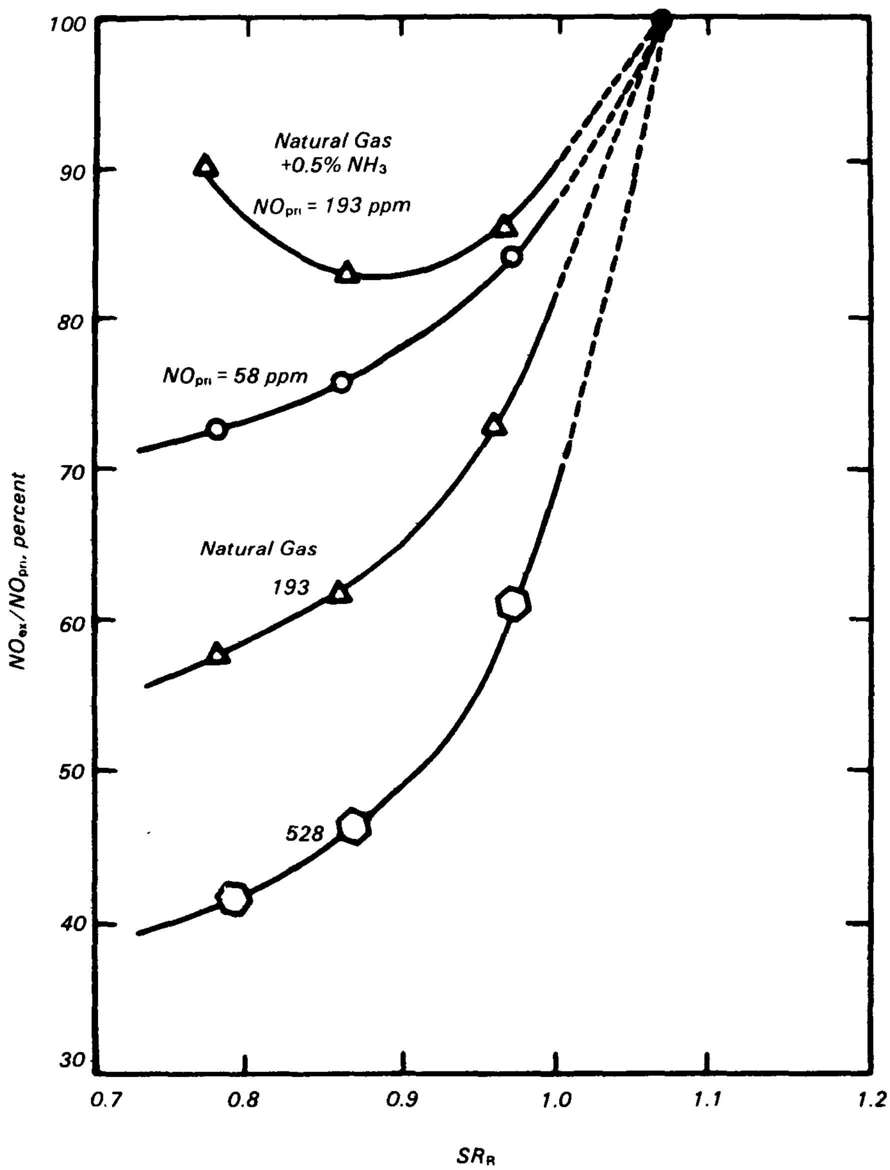

Figure 3. *Natural gas reburning effectiveness.*

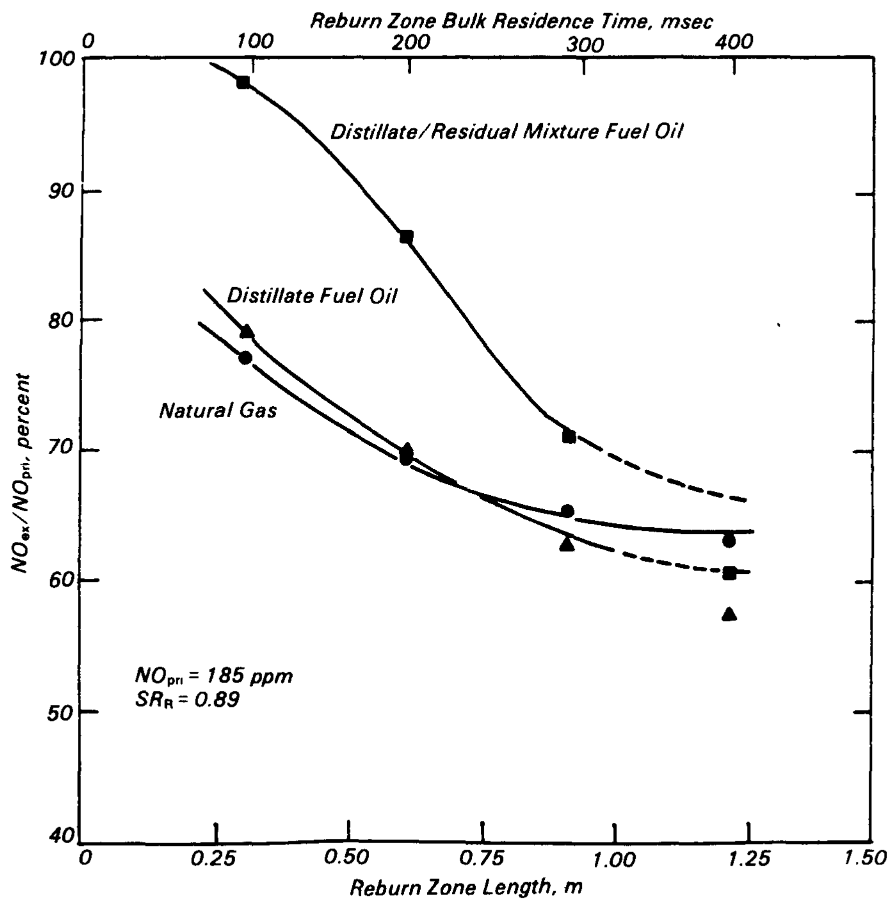

Figure 4. Reburning zone residence time effect.

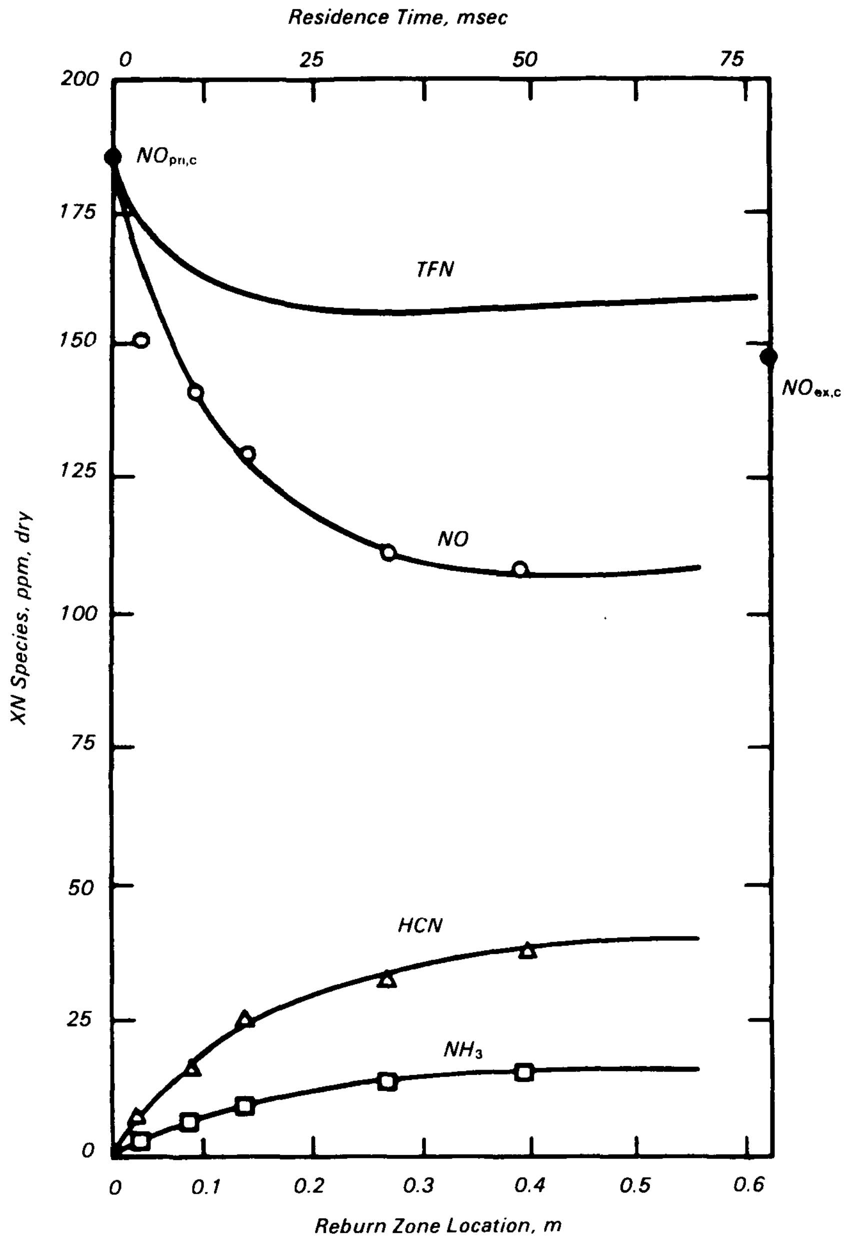

Figure 5. *Reburning zone nitrogen species profiles (SR_R = 0 86).*

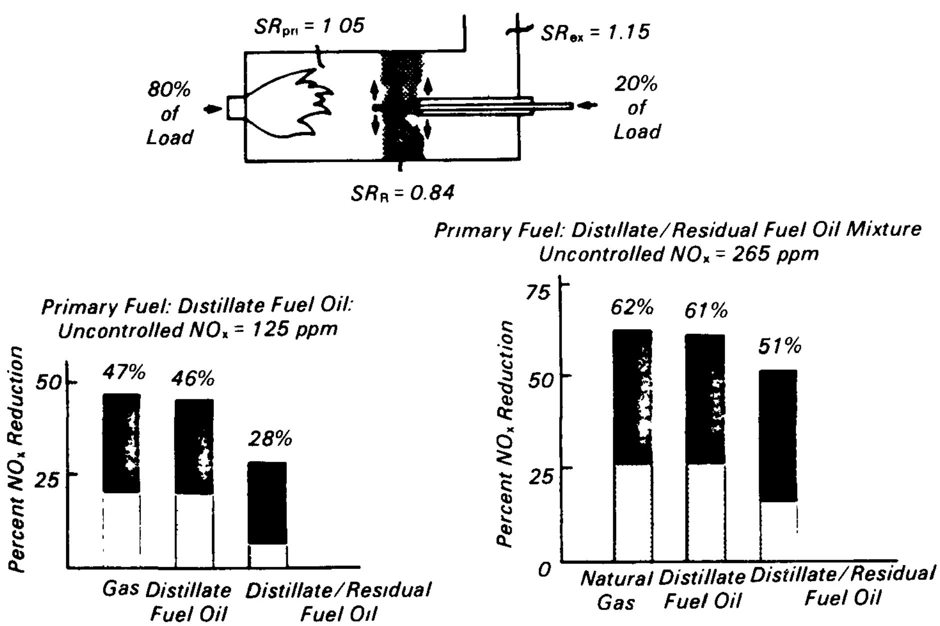

Figure 6. *North American boiler reburning application test results*

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***Robert E. Hall** is the EPA Project Officer (see below).*
The complete report, entitled "Reburning Application to Firetube Package Boilers," (Order No. PB 87-177 515/AS; Cost: $36.95, subject to change) will be available only from:

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