Second Generation Advanced Reburning for High Efficiency NO_x Control

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ABSTRACT

Energy and Environmental Research Corporation is developing a family of high efficiency and low cost NO_x control technologies for coal-fired utility boilers based on Advanced Reburning (AR), a synergistic integration of basic reburning with injection of an N-agent. The period of project performance is five years which include Phase I, 10/1995-09/1997, and Phase II, 10/97-09/2000.

Phase II R&D plan includes (1) development of alternative AR promoters, (2) optimization of prospective AR variants via combustion tests and combined chemistry/mixing modeling, (3) scale up tests at 10 x 106 Btu/hr (Proof-of-Concept) and tests of selected elements in a boiler, and (4) validation of the design methodology and application to a full scale boiler with updated economics and market assessment. Phase II objectives are designed to overcome the remaining technical barriers, broaden the range of applications and develop a data base for a subsequent full scale demonstration.

Initial Phase II activities (January-June 1998) were focused on (1) pilot-scale testing and (2) modeling to simulate unmixedness in a real boiler.

The pilot scale tests were performed with the objective of simulating furnace conditions of ongoing full-scale tests at the 105 MW Greenidge boiler No. 6, owned and operated by NYSEG, and defining the processes controlling AR performance to subsequently improve the performance. The results of the simulation tests demonstrated that high CO concentrations have negative effects on AR performance at the temperature regime of the NH_3/overfire air (OFA) injection location in the Greenidge boiler. The comparison of NH_3/OFA injection temperatures suggests that the Greenidge NH_3/OFA ports are located at the right location. The pilot-scale tests demonstrate up to about 90% NO_x reduction under simulated boiler conditions via synergistic combination of reburning and SNCR.

A combined chemistry-mixing AR model is currently being developed to predict the effect of unmixedness. The Two Stage Lagrangian (TSL) mixing code with detailed chemistry was applied to model NO_x emissions in AR. Modeling results and comparison with experiments are presented.

1.0 INTRODUCTION

Reburning controls NO_x via injection of reburn fuel above the main burners to form a reburning zone in which NO_x is reduced under fuel-rich conditions. Overfire air (OFA) is injected downstream to complete combustion.

Advanced reburning (AR) systems are intended for post-RACT applications in ozone non-attainment areas where NO_x control in excess of 80% is required. AR will provide flexible installations that allow NO_x levels to be lowered when regulations become more stringent. The total cost of NO_x control for AR systems is approximately half of that for SCR.

Several AR variants have been recently reported (Seeker et al., 1992; Zamansky et al., 1996a; 1998a; 1998b; and 1998c). Figure 1-1 presents a general schematic of the AR processes. The N-agent can be injected with or without promoters at one or two locations into the reburning zone, along with OFA or downstream in the burnout (SNCR) zone. Accordingly, there are six AR variants, as shown in Table 1. The promoters are water-soluble sodium salts which can be added to aqueous N-agents.

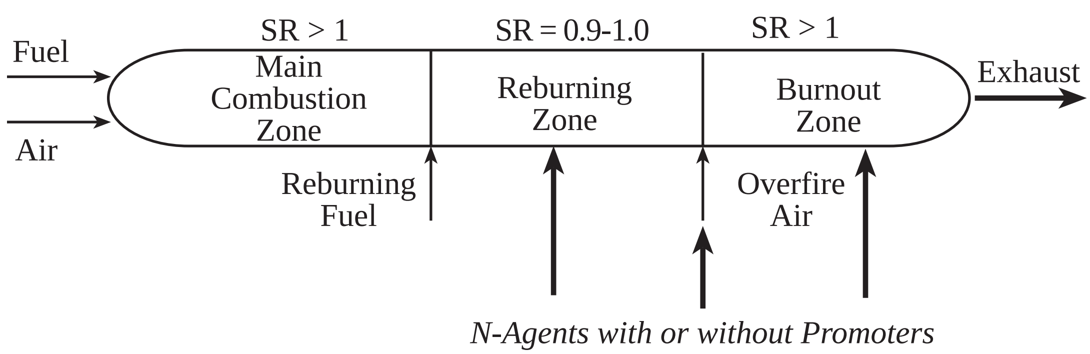

Figure 1-1. Schematic of different AR variants.

Experimental data on different AR systems (AR-Lean, AR-Rich, and MIAR) were reported at recent FETC Contractors Conferences (Zamansky et al., 1996b; 1997). The results of the combustion experiments in 30 and 300 kW combustors firing coal and natural gas as the main and reburning fuels, demonstrated over 90% NO_x control by injections of 10% reburning fuel (stoichiometric ratio SR~0.99), N-agents (ammonia or urea) and small amounts of sodium carbonate in comparison with about 50% NO_x reduction by 10% reburning alone. Kinetic modeling qualitatively described the chemical processes responsible for NO_x reduction.

The objective of the pilot scale experimental study reported here was to simulate furnace conditions of ongoing full-scale boiler tests and define the processes controlling AR performance to subsequently improve the performance. EER's pilot scale facility was configured to simulate the tests in a 105 MW Greenidge boiler No. 6 owned and operated by New York State Electric and Gas (NYSEG). Most attention was given to two AR variants: AR-Lean and Reburning+SNCR.

The objective of the modeling study was to combine detailed chemistry with mixing effects that have a significant influence on reburning performance.

The sections below present a description of the test facility, measurement techniques, experimental conditions, test variables, results of NO_x measurements, and initial results of chemistry/mixing modeling.

Table 1. AR variants (each N-agent can be injected with or without promoters).

AR Techology	Description
Advanced Reburning Lean - AR-Lean	Injection of the N-agent along with overfire air
Advanced Reburning Rich - AR-Rich	Injection of N-agent and promoter into the reburning zone
Multiple Injection AR - MIAR	Injection of N-agents and promoters both into the reburning zone and with overfire air
AR-Lean + SNCR	Injection of N-agents and promoters with overfire air and into the SNCR zone
AR-Rich + SNCR	Injection of N-agents and promoters into the reburning zone and into the SNCR zone
Reburning + SNCR	Basic reburning followed by the promoted SNCR process

2.0 EXPERIMENTAL

2.1 Boiler Simulator Facility

The pilot scale test work was conducted in EER's Boiler Simulator Facility (BSF), which has a full load firing capacity of 300 kW (1 MMBtu/hr). The BSF is designed to provide an accurate subscale simulation of the flue gas temperatures and composition found in a full-scale boiler. A schematic of the BSF is shown in Figure 2-1. The BSF consists of a burner, vertically down-fired radiant furnace, horizontal convective pass, and baghouse. A variable swirl diffusion burner with an axial fuel injector is used to simulate the approximate temperature and gas composition of a commercial burner in a full-scale boiler. Primary air is injected axially, while the secondary air stream is injected radially through the swirl vanes to provide controlled fuel/air mixing. The swirl number can be controlled by adjusting the angle of the swirl vanes. Numerous ports located along the axis of the facility allow access for supplementary equipment such as reburn injectors, additive injectors, overfire air injectors, and sampling probes.

The cylindrical furnace section is constructed of eight modular refractory lined sections with an inside diameter of 56 cm. The convective pass is also refractory lined, and contains air cooled tube bundles to simulate the superheater and reheater sections of a utility boiler. Heat extraction in the radiant furnace and convective pass can be controlled such that the residence time-temperature profile matches that of a typical full-scale boiler. A suction pyrometer is used to measure furnace temperatures.

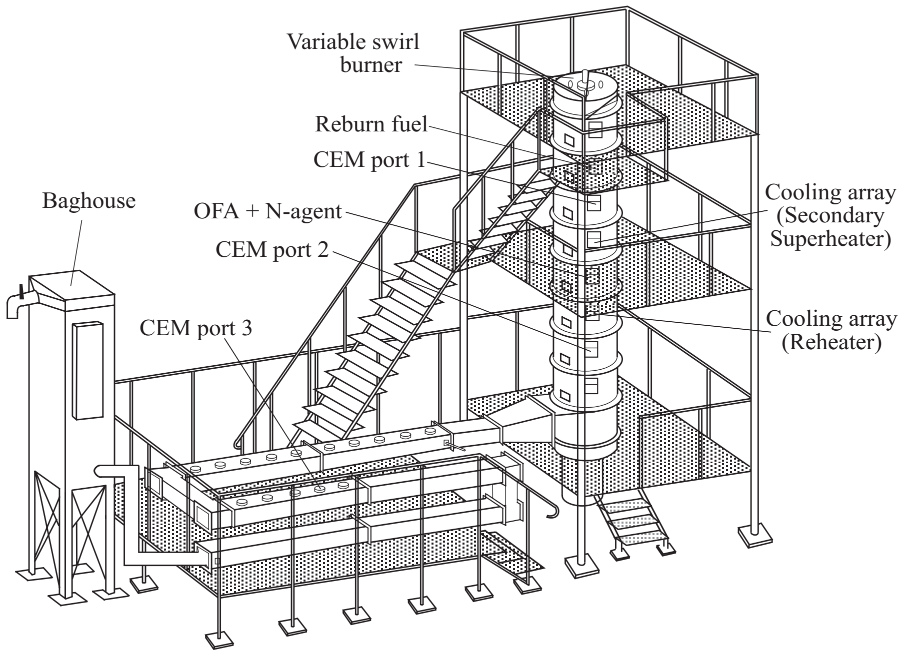

Figure 2-1. Schematic of Boiler Simulator Facility (BSF).

For the Greenidge simulation tests natural gas was used as both the main and reburn fuels. The reburn injector was elbow-shaped, and was installed along the centerline of the furnace, aligned in the direction of gas flow. Overfire air was injected through an elbow-shaped injector to burn out combustibles generated in the reburn zone. Gaseous and aqueous ammonia and urea were used as N-agents. The N-agent was co-injected with OFA in AR-Lean and added downstream in reburn+SNCR.

2.2 Simulation of Greenidge Boiler

The Greenidge boiler is characterized by upper furnace fluctuations in gas concentrations, and contains zones that have simultaneously high levels of CO and O_2 due to incomplete mixing. To evaluate and optimize AR process performance for Greenidge it was necessary to simulate these fluctuations in conditions along with boiler design features. To simulate boiler design and temperature profile, two cooling arrays were installed in the furnace of the BSF (Figure 2-1): one simulating the high temperature secondary superheater, which lowers gas temperature from 1450 to 1340 K, and one simulating the reheater, which lowers gas temperature from 1280 to 1170 K. The reburning fuel was injected upstream of the first cooling array. OFA was injected between the two cooling banks (AR-Lean) or upstream of the first cooling array (reburn+SNCR). The N-agent was injected either between the cooling arrays or downstream the second array. CEM sampling was performed at three locations: just upstream of the first cooling array, just downstream of the second cooling array, and in the convective pass.

To simulate the fluctuations in furnace gas composition that occur at Greenidge, a system was installed at the BSF to pulse the main natural gas. The fuel delivery system consisted of two lines. One carried the nominal main burner gas at a constant flow rate. The other carried 5% of the total main fuel flow rate, and was pulsed from full-open to full-closed. The valve was open and closed for equal time periods. The system was designed to nominally provide square wave pulsations, although the compressibility of the gas affected this to some degree. An electronic timer and solenoid-actuated diaphragm valve were used for the pulsing. It was found that by varying the period of the pulsing it was possible to control the degree of unmixedness, thus providing control over furnace gas O_2 and CO concentrations. It was also found that CO emissions decreased across the three CEM ports due to progressive gas mixing. Actual time-averaged SR_2 values were determined by measuring all air flow rates and exhaust O_2 in the convective pass after burnout of most CO and performing a mass balance.

2.3 Sampling and Analysis Methods

A continuous emissions monitoring system (CEMS) was used for on-line flue gas analysis. The CEMS consisted of a heated sample line, sample conditioning system (to remove moisture and particulate), and gas analyzers. Species analyzed, detection principles, and detection limits were as follows:

- O_2: paramagnetism, 0.1%
- NO_x: chemiluminescence, 1 ppm
- CO: nondispersive infrared, 1 ppm
- CO_2: nondispersive infrared, 0.1%
- N_2O: nondispersive infrared, 1 ppm

Certified zero and span gases were used to calibrate the analyzers. A chart recorder was used to provide a hard copy of analyzer outputs.

3.0 AR-LEAN TEST RESULTS

A series of tests was conducted at the BSF to parametrically evaluate key AR-Lean process variables. The objective of the tests was to define the processes controlling NO_x reduction in light of the gas fluctuations and incomplete mixing at the Greenidge boiler. Test variables included the nitrogen stoichiometric ratio (NSR = N/NO) of the additive, furnace gas CO concentration (varied using the pulsation system), N-agent injection temperature, and initial NO concentration (NO_i).

3.1 Impact of NSR and CO Concentration on Performance

AR-Lean tests were conducted during operation of the pulsing system in which NSR was varied from zero to 2.0. Reburn heat inputs of 10% and 5% were tested, corresponding to reburn zone stoichiometry (SR_2) values of 0.99 and 1.05, respectively. To achieve different CO concentrations, the natural gas pulsing system was operated at four cycle frequencies, ranging from 0 (i.e. no pulsing) to 16 seconds. Although reburn zone CO concentration did not vary directly with pulsing frequency, the pulsing system did provide a means of obtaining high CO levels such as those found at the Greenidge boiler. Specifically, reburn zone CO concentrations were measured to be 2,000 ppm with no pulsing, 13,000 ppm with 4 second pulsing, 15,000 ppm with 8 second pulsing, and 14,000 ppm with 16 second pulsing.

Figure 3-1 shows AR-Lean performance at 10% reburning as a function of NSR at different CO concentrations. With no pulsing, NO reduction increased from 38% at NSR = 0 to 69% at NSR = 1.5. However, during pulsing NO reduction decreased from 52% at NSR = 0 to 30-38% at NSR = 2.0. This suggests that high CO concentrations have negative impacts on AR-Lean performance. The fact that a net decrease in NO reduction was seen with increasing NSR indicates that some of the N-agent was actually being oxidized to form NO. It can also be noted that performance of reburning alone (i.e. at NSR = 0) improved from 38% to 52% during pulsing. This is attributed to the fact that in this test series SR_2 decreased slightly due to the pulsing system. Data below in Section 4 show that pulsations do not significantly affect the performance of basic reburning.

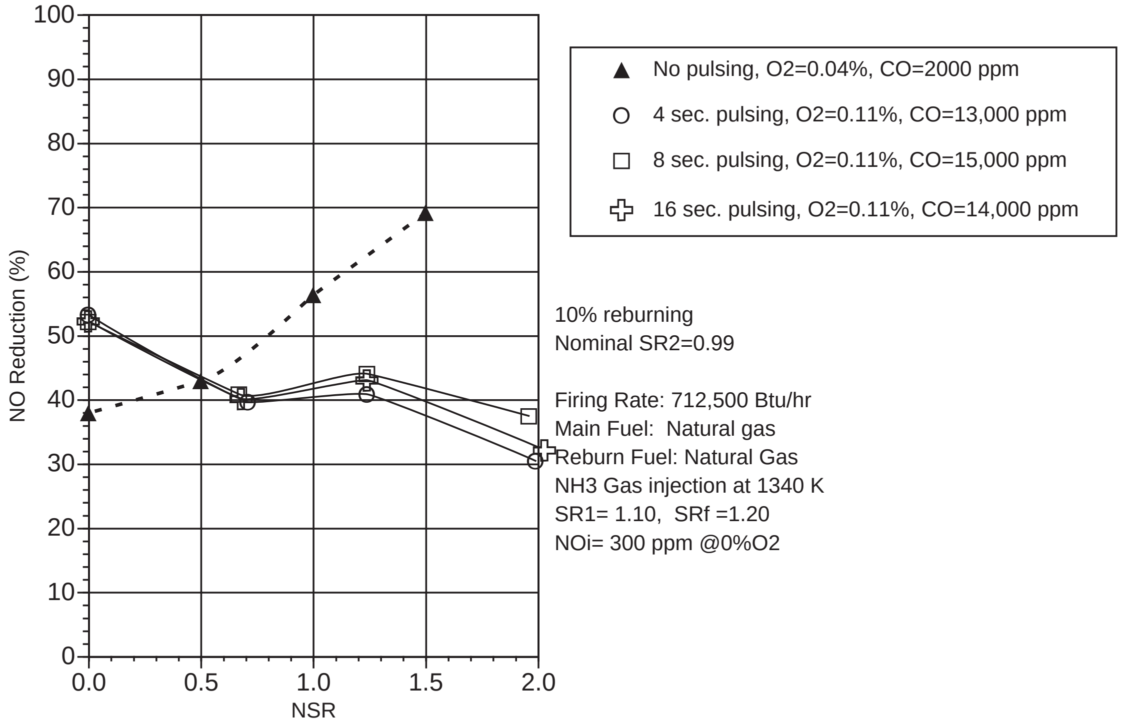

Figure 3-1. AR-Lean performance vs. NSR at different CO concentrations, 10% reburning.

Figure 3-2 shows AR-Lean results at 5% reburning for different pulsing frequencies. In these tests, reburn zone CO concentrations ranged from 200 ppm with no pulsing to 8000 ppm with 8 second pulsing. With no pulsing, NO reduction increased from 17% at NSR = 0 to 71% at NSR = 1.5. During pulsing NO reduction increased with increasing NSR, but by a lesser degree than with no pulsing. Again, performance of reburning alone improved during pulsing due to slightly lower SR_2 in the experimental configuration.

Figure 3-3 shows the incremental performance of the N-agent alone for these same AR-Lean tests, as calculated by the difference between overall NO reduction and reburn-only NO reduction. Again, performance decreases with increasing CO. NO reduction falls off more rapidly at 10% reburning than at 5% reburning. At 10% reburning, negative NO reductions (i.e. NO increases) were observed during all high-CO pulsing conditions.

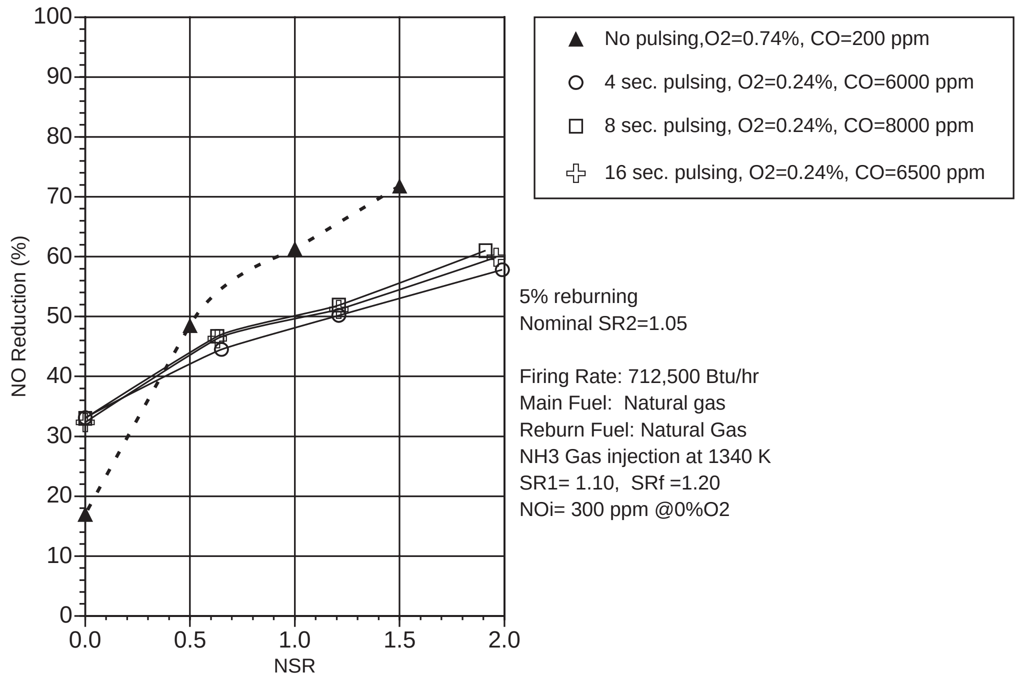

Figure 3-2. AR-Lean performance vs. NSR at different CO concentrations, 5% reburning.

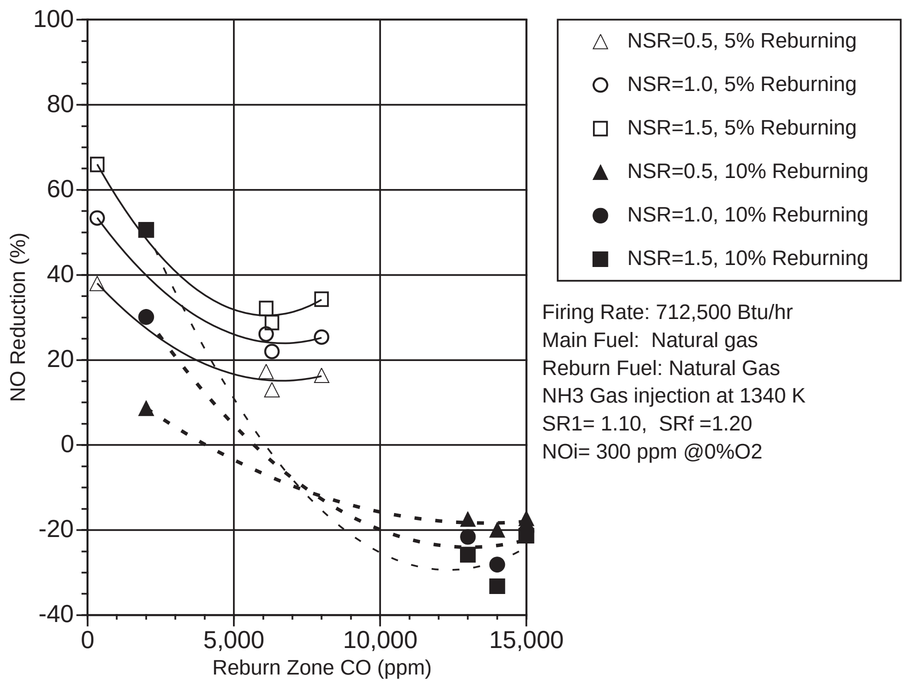

Figure 3-3. AR-Lean, calculated incremental performance of N-agent alone as a function of reburn zone CO concentration.

3.2 Impact of Additive Injection Temperature on Performance

AR-Lean tests were then conducted in which the OFA/NH_3 injection temperature was varied from 1200 K to 1500 K. Figure 3-4 compares AR-Lean performance with and without pulsing at 10% reburning (SR_2 = 0.99). For all cases NO reduction increased with decreasing injection temperature. At NSR values of 1.0 and 1.5, NO reduction was significantly worse during pulsing.

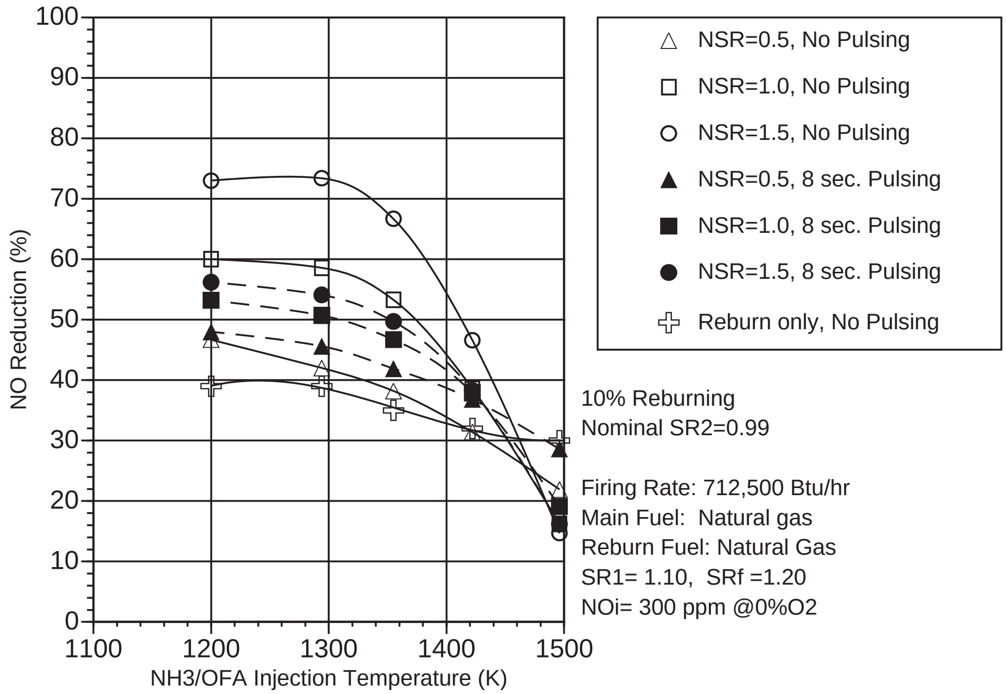

Figure 3-4. AR-Lean performance vs. additive injection temperature with and without main fuel pulsing at 10% reburning.

Figure 3-5 shows AR-Lean results obtained at 5% reburning (SR_2 = 1.05). These tests were conducted only with 8 second fuel pulsing to allow direct comparison to the pulsing tests at 10% reburning. NO reduction generally increased with decreasing injection temperature, reaching a maximum at about 1280 K. AR performance during pulsing was significantly better at 5% reburning than at 10% reburning. For example, at an OFA/NH_3 injection temperature of 1280 K, NO reduction was 78% at 5% reburning (Figure 3-5), as compared to 55% at 10% reburning (Figure 3-4).

3.3 Impact of NO_i on Performance

Most of the BSF tests were conducted at an initial NO concentration of 300 ppm to simulate the Greenidge boiler conditions. To determine the functional dependence of AR on NO_i, several tests were also conducted at NO_i = 600 ppm. The tests were performed at 10% reburning with no pulsing of the main natural gas. Figure 3-6 shows the impact of NSR upon AR performance at NO_i concentrations of 300 and 600 ppm. NO reductions were 5 to 10 percentage points better at the higher NO_i concentration. Performance was also significantly better at an injection temperature of 1350 K than at 1420 K.

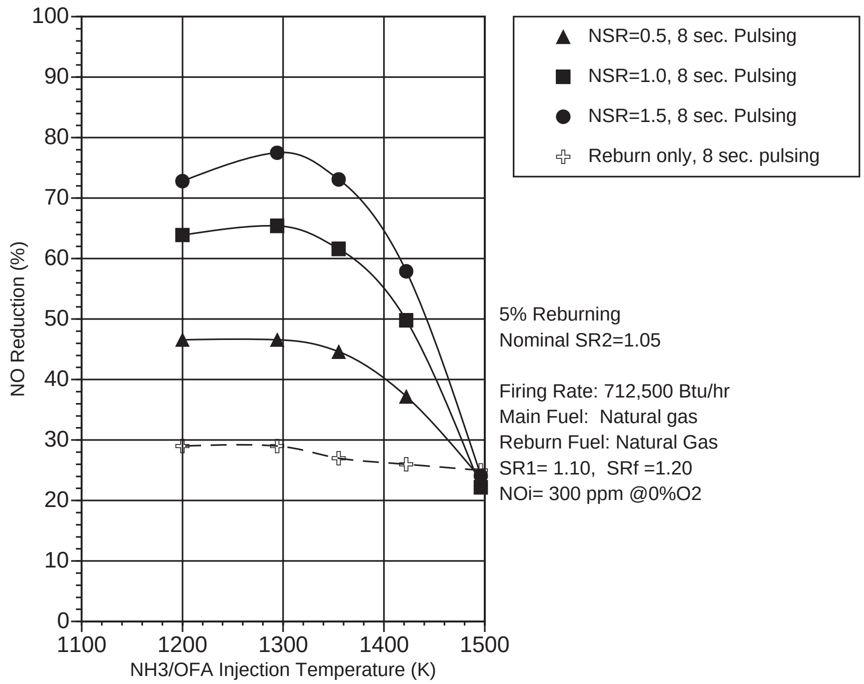

Figure 3-5. AR-Lean performance vs. additive injection temperature with main fuel pulsing at 5% reburning.

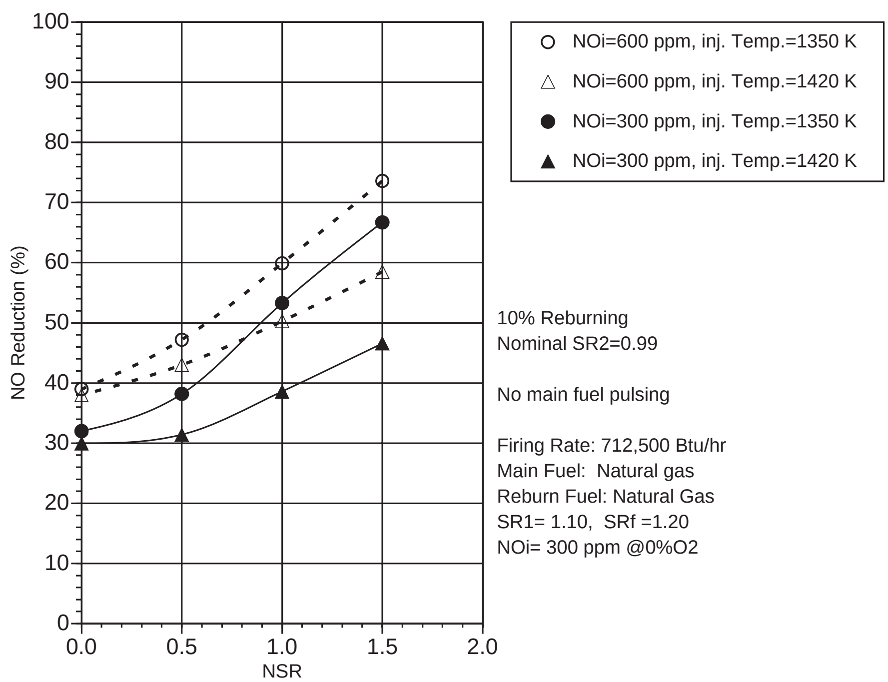

Figure 3-6. AR-Lean performance vs. NSR at initial NO concentrations of 300 and 600 ppm.

3.4 Comparison of Greenidge and BSF Data

Comparison of Greenidge and BSF data was completed, and the results were presented to NYSEG for evaluation and planning future tests. The comparison of injection temperature seems to suggest that the Greenidge NH_3/OFA ports are located at the right location. In general, the pilot-scale data correctly represent and explain AR-Lean test results obtained at Greenidge. The full-scale NO_x reduction performance is less than the BSF counterpart due to the difficulty in controlling the amount of CO concentration at the ammonia injection elevation at Greenidge. In addition, stratification may have contributed to the performance discrepancy between the two systems. Full-scale experiments are scheduled at NYSEG to improve process performance.

4.0 REBURN+SNCR TEST RESULTS

A series of pilot scale tests was performed in which a combination of reburning and SNCR was applied to the BSF under conditions simulating the furnace fluctuations observed at Greenidge. Previous AR-Lean tests suggested that furnace fluctuations and high CO concentrations might be detrimental to process performance. The objective of these tests was to achieve higher NO_x reductions by injecting the N-agent downstream of the overfire air (reburn+SNCR). It was believed that in this configuration, CO concentrations at the point of N-agent injection are lower than in the reburn zone and fluctuations can be dampened out to some degree. To examine the effect of fluctuations on performance of the reburn+SNCR process, it was necessary to find out how the fluctuations affect reburning alone, SNCR alone, and then reburning followed by SNCR. The following paragraphs describe the effect of fluctuations on NO reduction under different test conditions: (1) basic reburning, (2) SNCR alone, (3) combined reburn+SNCR, and (4) variation of fuel pulsing parameters.

4.1 Effect of Pulsing on Basic Reburning

The effect of fluctuations on reburning alone can be seen from data presented in Figure 4-1 that compares NO reduction for basic reburning at different time-averaged SR_2 and pulsing frequencies. The results suggest that there is no visible effect of pulsing on basic reburning. Fuel fluctuations form regions with increased and decreased SR_2, but the time-averaged SR_2 value is the main parameter defining NO emissions. Observed performance, 17-60% NO reduction, is somewhat low for reburning systems, primarily due to short residence time (0.4 sec) and low initial NO concentration (300 ppm).

4.2 Effect of Pulsing on SNCR

BSF tests were conducted with SNCR alone, to determine how gas fluctuations and high CO concentrations affect N-agent performance in the absence of reburning. Tests were conducted at NSR values ranging from 0.5 to 1.5 at different ammonia injection temperatures. Figure 4-2 shows SNCR performance with and without pulsing. NO reduction increased with increasing NSR and was, at the optimum point, about 10 percentage points better with no pulsing. At NSR = 1.5, a maximum of 88% NO reduction was obtained at 1280 K without pulsing and 78% with pulsing.

4.3 Initial Characterization of Combined Reburning-SNCR Performance

The initial tests were designed to provide combined reburn and SNCR performance data for injection temperatures and residence times simulating those available at Greenidge. Aqueous NH_3 and gaseous NH_3 were tested along with urea as N-agents. Figure 4-3 compares performance of different N-agents in the reburn+SNCR process without pulsing. It appears that gaseous NH_3 has a lower optimum injection temperature than urea or aqueous NH_3. Figure 4-4 compares performance of the different N-agents as a function of NSR at two different injection temperatures (also without pulsing). At the lower temperature (1270-1300 K), best performance was obtained with gaseous NH_3. At the higher temperature (1340 K), best performance was obtained with urea.

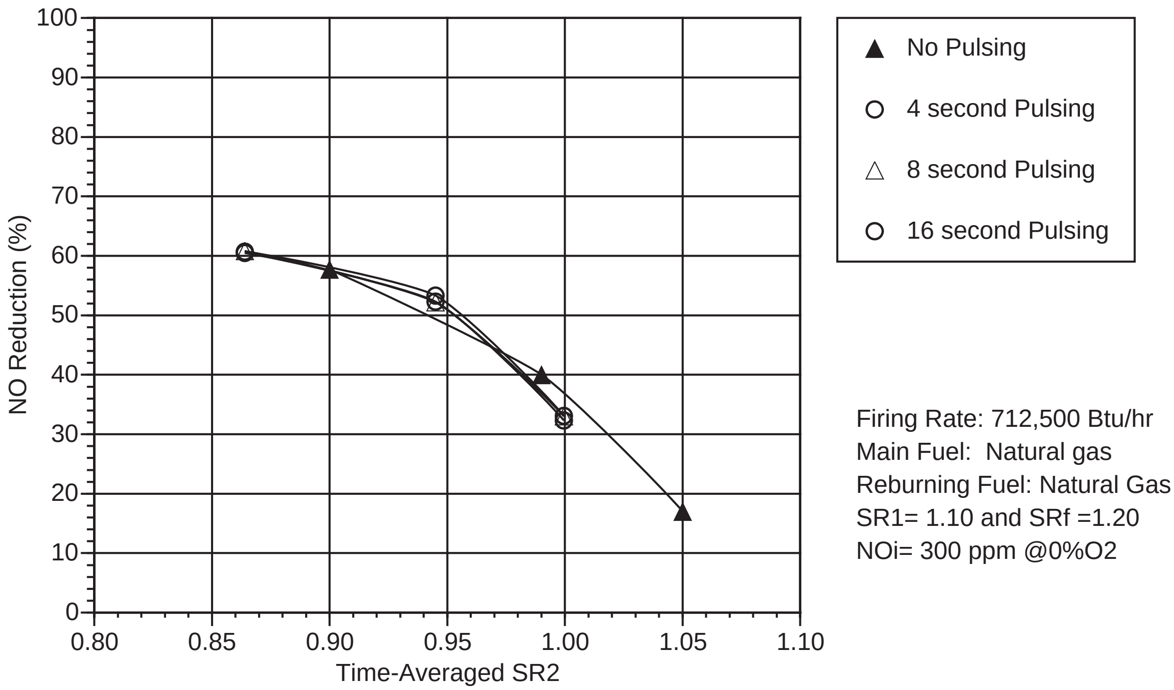

Figure 4-1. Performance of basic reburning at different pulsing frequencies.

Figure 4-5 compares results obtained with the three N-agents during pulsing of the main fuel. High NO reductions, in the range of 73-87%, were obtained in these tests. Results appear to be best with gaseous NH_3, although this is largely a function of the injection temperature selected (see Figure 4-3). The impacts of pulsing frequency upon performance were minimal, again suggesting that injecting the N-agent downstream of the OFA might minimize the detrimental impacts of furnace fluctuations.

4.4 Effects of Fuel Pulsing Parameters on Performance

Tests were performed to characterize the concentration of CO in the reburning and SNCR zones and to examine the effects of reburn fuel flow rate and pulsing amplitude. CEM sampling was performed at three locations: in the reburn zone, in the N-agent injection zone (downstream of the OFA) and in the convective pass. The frequency and amplitude of the pulsing were each varied at 10% and 20% reburning. Measurements of CO concentrations as a function of pulsing frequency demonstrated that CO levels were high in the reburn zone (8,000-40,000 ppm depending on reburn heat input), but were lower than 50 ppm in the N-agent injection zone and convective pass.

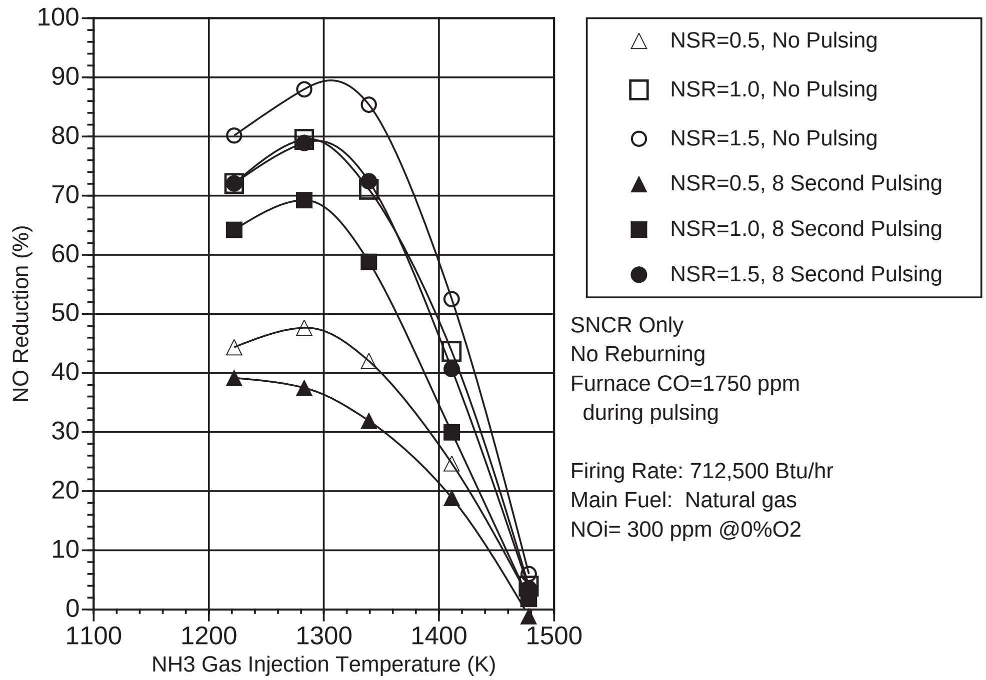

Figure 4-2. SNCR performance as a function of N-agent injection temperature with and without pulsing.

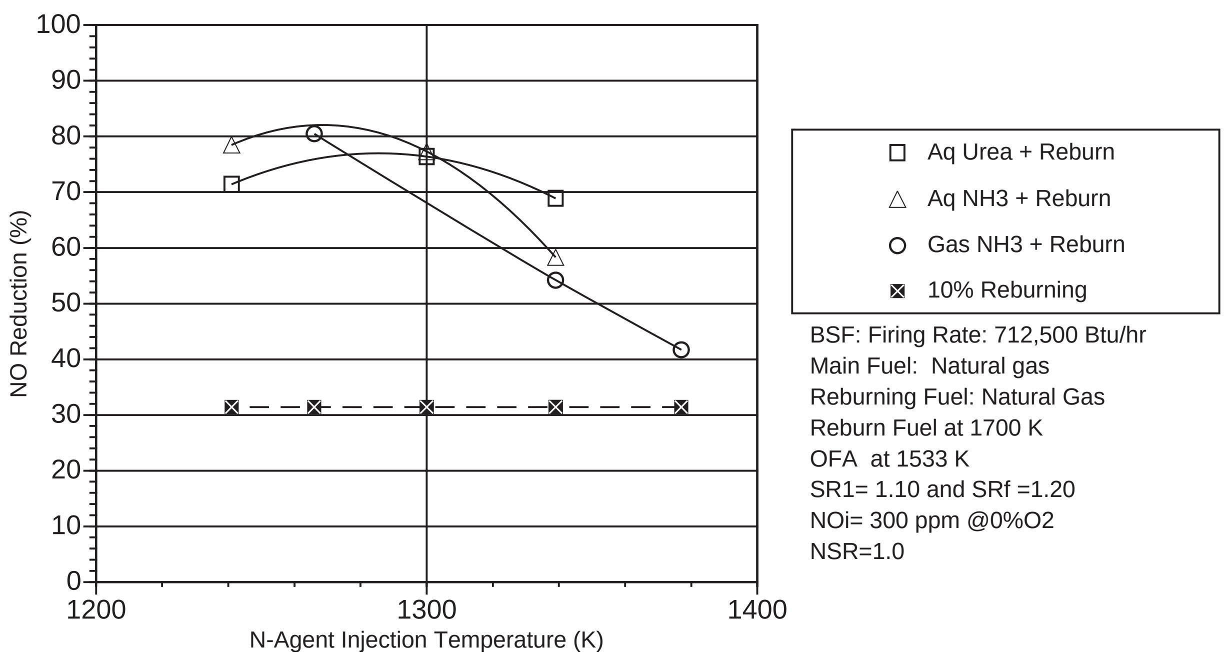

Figure 4-3. Performance of different N-agents as a function of injection temperature without pulsing.

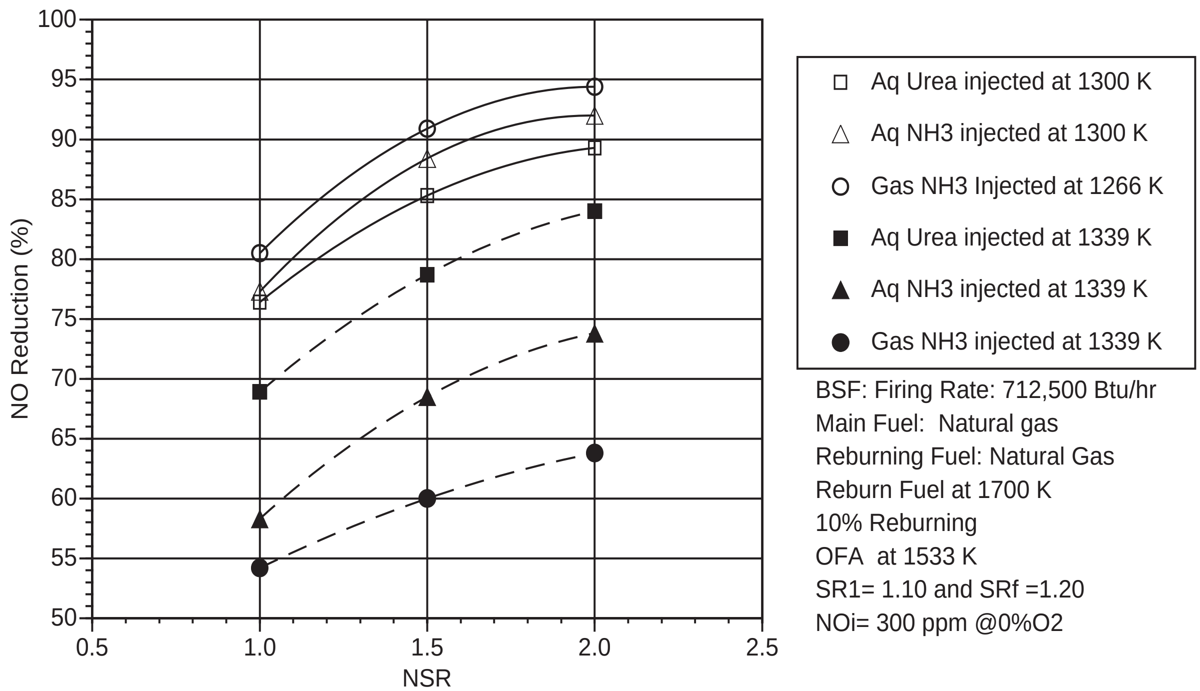

Figure 4-4. Performance of different N-agents as a function of NSR without pulsing.

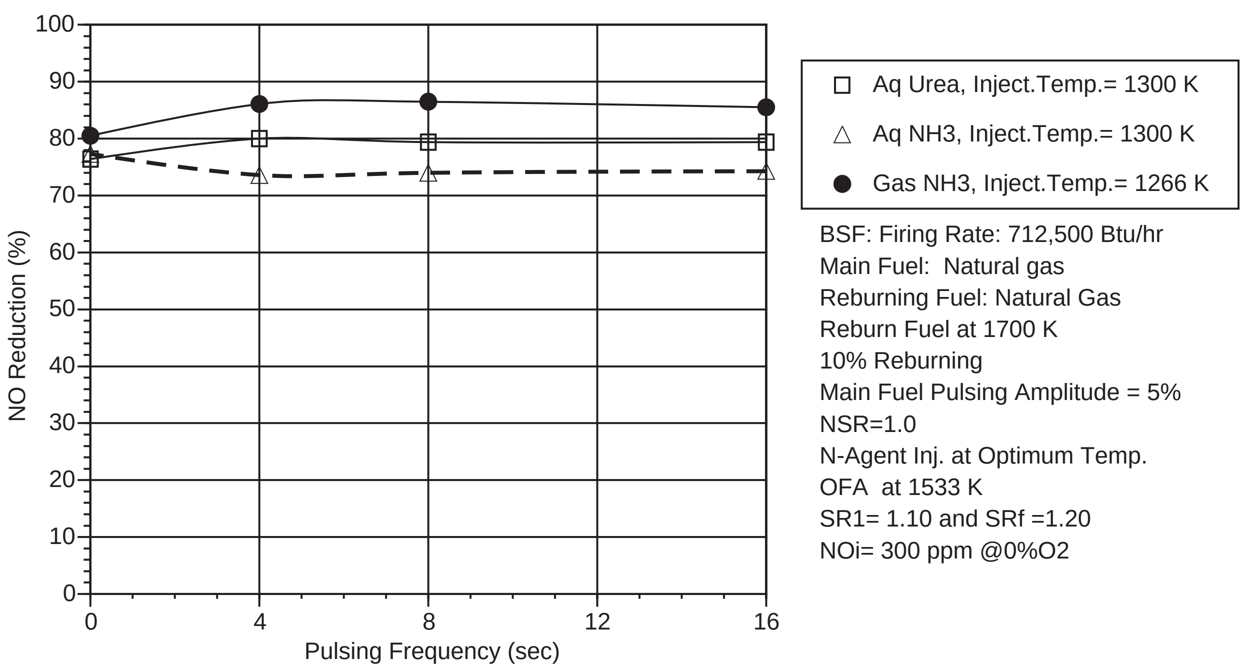

Figure 4-5. Performance of different N-agents during main fuel pulsing.

Figure 4-6 shows reburn+SNCR results as a function of pulsing frequency at 10% and 20% reburning. Varying pulsing frequency did not significantly impact NO reduction. It can be also observed that results are similar at 10% and 20% reburning. It is noted that the urea injection location was the same for 10% and 20% reburning, but injection temperature varied slightly due to impacts of reburn heat input on temperature profile. Figure 4-7 compares results obtained at different pulsing amplitudes. Performance was worse at 10% pulsing than at 5% pulsing.

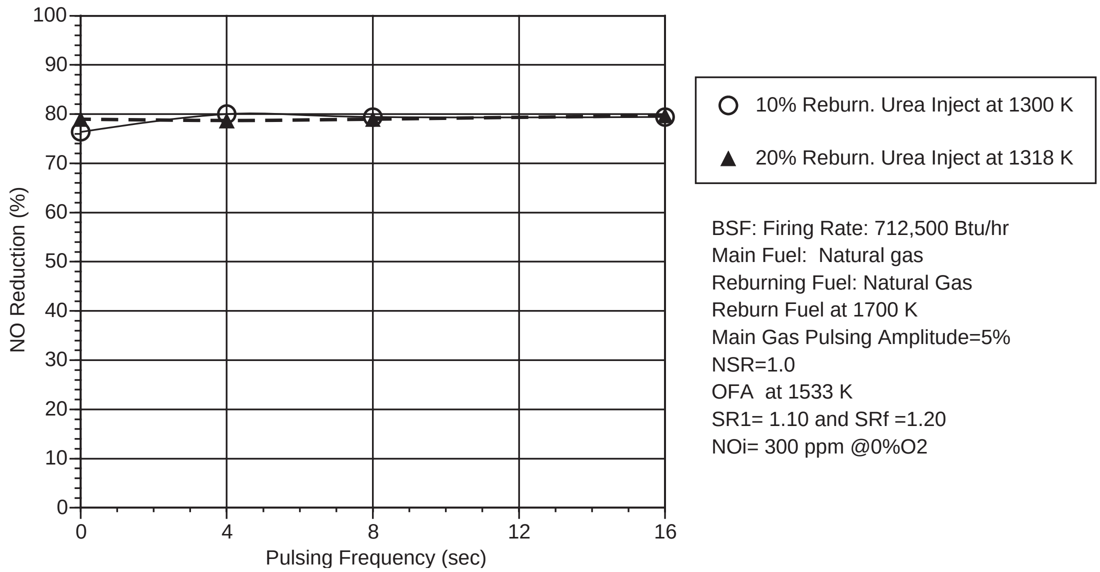

Figure 4-6. Effect of pulsing frequency on performance at 10% and 20% reburning.

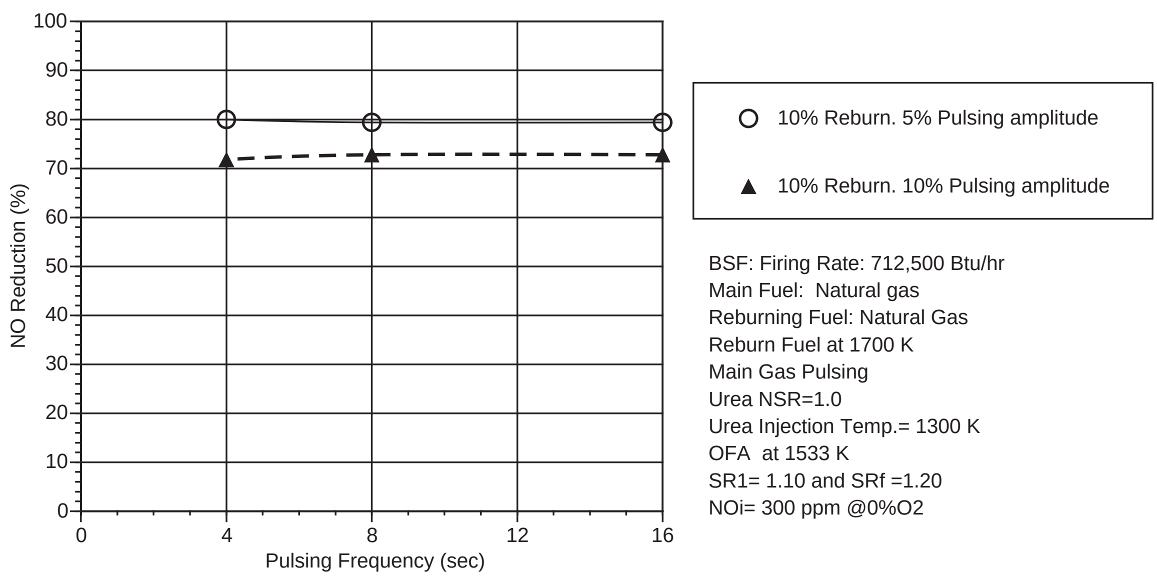

Figure 4-7. Effect of pulsing frequency on performance at 5% and 10% amplitude.

5.0 PILOT-SCALE TESTS: DISCUSSTION AND CONCLUSIONS

Pilot-scale tests were conducted under different process conditions to simulate and predict the performance of AR-Lean and reburn+SNCR in the Greenidge 105 MW tangentially fired boiler. The boiler is characterized by upper furnace fluctuations in CO and O_2 concentrations due to incomplete mixing. A pulsing system was installed in the main fuel delivery line to simulate the fluctuations in furnace gas composition that occur at Greenidge. Pilot-scale test results are discussed separately for two experimental configurations: AR-Lean and reburn+SNCR.

5.1 AR-Lean

The NO_x reduction performance at Greenidge is similar to that of the BSF pulsing tests for basic reburning, but less than the BSF counterpart for AR-Lean. This discrepancy is most likely due to the difficulty in controlling the amount of CO concentration in the ammonia injection elevation at full scale.

The results of the BSF simulation tests demonstrated that high CO concentrations have negative effects on AR-Lean performance at the NH_3/OFA injection location in the Greenidge boiler. For optimum AR-Lean performance, the CO concentration at the point of N-agent/OFA injection should in the range of 1000-5000 ppm with a low (less than 0.5%) concentration of oxygen. Experimental observations at Greenidge demonstrate that the upper furnace zone is affected by stratification and there are regions with much higher and much lower CO and O_2 concentrations. In both cases, the performance of AR-Lean is lower than under optimum conditions. The results show that high CO concentrations in the N-agent/OFA injection zone of AR-Lean may result in negative NO reductions, i.e. NO increases. This effect can be explained by formation of higher concentrations of active species (OH radicals and O atoms) due to the chain branching reaction of CO oxidation. Under these conditions, the NH_2 radicals formed from the N-agent have higher tendency for oxidation to NO than for NO reduction.

The performance of AR-Lean is better at lower flow rate of the reburning fuel. For instance, 78% NO reduction was achieved at 5% reburning and ammonia/OFA injection at 1280 K compared to only 55% NO reduction at 10% reburning (Figures 3-4 and 3-5). This can be attributed to the negative effect of higher CO levels formed in the gas mixture due to increased fuel concentration.

The comparison of OFA/N-agent injection temperatures suggests that the Greenidge NH_3/OFA ports, located at a temperature of about 1300 K, approximately correspond to optimum injection temperature for urea and slightly higher than the optimum injection temperature for gaseous ammonia.

5.2 Reburn+SNCR

Test results demonstrated that fuel pulsing, and consequently pulsations of CO and O_2 concentrations, do not affect the performance of basic reburning, but decrease NO_x reduction of SNCR by about 10% for tested experimental configuration.

Performance in combined reburning -SNCR tests was almost independent on pulsing frequency and the reburn fuel flow rate, but decreased with pulsing amplitude. NO reduction in the range of 73-87% was achieved at a pulsing amplitude of 5% for 10% reburning and NSR=1.0 (Figure 4-5).

Higher N-agent levels (NSR = 1.5 and 2) increased NO reduction to 85-94% (Figure 4-4). Results demonstrate that about 70-80% NO reduction can be achieved under Greenidge conditions using an optimized reburn+SNCR regime. Combination of reburning and SNCR has the following synergistic advantages over using reburning or SNCR alone:

- The combined method can provide higher level of NO reduction at full scale than individual technologies.

- SNCR performance is higher at low fuel pulsations and relatively low concentration of CO in the gas mixture. Injection of OFA upstream of the N-agent injection provides additional mixing in the upper furnace zone, reduces the concentrations of CO, and prepares conditions for a more effective SNCR process. Thus, deterioration of SNCR performance in the presence of CO might be minimized by injecting the N-agent after the OFA.

- Combined reburn-SNCR process requires relatively low input of the reburning fuel. As shown in Figure 4-6, injection of 10% and 20% reburning fuel resulted in almost identical high level of NO reduction, about 80%.

- High NO reduction level can be achieved with relatively low input of the N-agent compared to SNCR alone. For example, if the initial NO concentration is 300 ppm, SNCR alone requires 300 ppm ammonia or urea to provide NSR=1. In the combined process, reburning reduces NO by about 50-60%, and 120-150 ppm of N-agent is necessary for providing NSR=1. Reduced consumption of N-agent reduces ammonia slip and N_2O emissions.

6.0 CHEMISTRY-MIXING MODELING

The objective of combined chemistry-mixing modeling is to create a model for predicting the NO_x control performance via reburning and AR in a real boiler. It was recently demonstrated by utilizing EER's One Dimensional Flame code (Zamansky et al., 1997) that distributed fuel addition significantly affects NO_x emissions in AR.

In the current study, the Two Stage Lagrangian (TSL) model (Broadwell, 1988; Broadwell and Lutz, 1998) was applied. The model was initially utilized for predicting performance of the BSF reactor without taking into account the fluctuations in furnace gas composition observed at Greenidge. In the TSL model, the reaction of fuel and oxidizer is modeled as two well-stirred reactors. The first reactor represents the initial meeting of fuel and air forming a flame sheet, and the products are fed to a second reactor in which a fuel reacts with product mixture. The fuel concentration in the second reactor decreases due to dilution with the products. Simplified description of mixing thus eliminates the need to calculate the detailed flow field, allowing to incorporate a detailed chemical mechanism.

The strength of the TSL model is that it allows computation of some important features of mixing with detailed chemistry, so that the effect of various fuels, N-agents, and reburning promoters can be explored. It is important to incorporate the full chemistry in the model since concentrations of NO_x in flue gas are highly sensitive to chemical additives.

In the TSL model, the entrainment rate is an empirical input; for this application, the results of the jet in crossflow were taken from Mungal et al., 1998.

The reaction mechanism used for modeling was based on the GRI-Mech version 2.11 (Bowman et al., 1995) with additional reactions (Bowman, 1996) characterizing the Thermal $DeNO_x$ process and the effect of sodium. The complete mechanism was presented elsewhere (Zamansky et al., 1996a and 1997). The total mechanism included 355 reactions of 65 species.

TSL model inputs for the BSF are shown in Figure 6-1. Comparison of experimental and modeling results is presented in Figure 6-2. The initial NO concentration was 600 ppm. The combustion process in the main combustion zone was modeled as a well-stirred reactor and solved using Chemkin-II (Kee et al., 1992) code with the measured temperature profile. The reburning fuel is injected at 1710 K in the form of 8 transverse jets oriented at 27_ upstream, and originating from a single pipe. Injection of the reburning fuel results in slightly fuel rich mixture, SR_2 = 0.99. Aqueous urea is added as an N-agent with NSR = 1.5. Mixing of the N-agent with the products was assumed instantaneous. OFA was added in the form of 24 transverse jets.

Figure 6-2 shows the experimental data and initial modeling results on prediction of NO reduction by basic and advanced reburning processes. The unknown temperature of the overfire air jets was used (within a range consistent with operating conditions) as a single fitting parameter for all predictions. For basic reburning, the model predicts 51% remaining NO, compared with the experimental results showing the remaining NO to be between 49 to 53%. For the advanced reburning process, the model predicts NO remaining in the range of 30-40% depending on the injection temperatures with a very good agreement with the test data.

It should be pointed out that although the TSL-based model includes a detailed chemical mechanism, the calculation time is minimal. It requires about 20 minutes of computation time using an Intel Pentium-based machine to simulate the BSF with selected operating conditions. Thus, the model can be utilized as a practical design tool for the determination of optimal operating conditions.

7.0 ONGOING AND FUTURE ACTIVITIES

Pilot-scale tests on simulation of Greenidge conditions are currently continued in two directions. First, conditions of N-agent injection are being optimized for minimization of ammonia slip. Second, addition of sodium compounds is tested as a means for increasing NO reduction.

The main experimental activities of the next year will include:

- development of alternative AR promoters based on sodium promotion mechanisms studied in Phase I;

- optimization of prospective AR variants and process synergism with alternative promoters at 1 MMBtu/hr scale.

Further model development will include an update of the chemical mechanism, more extensive comparison with experimental data, and model extension to take into account the fluctuations in furnace gas composition.

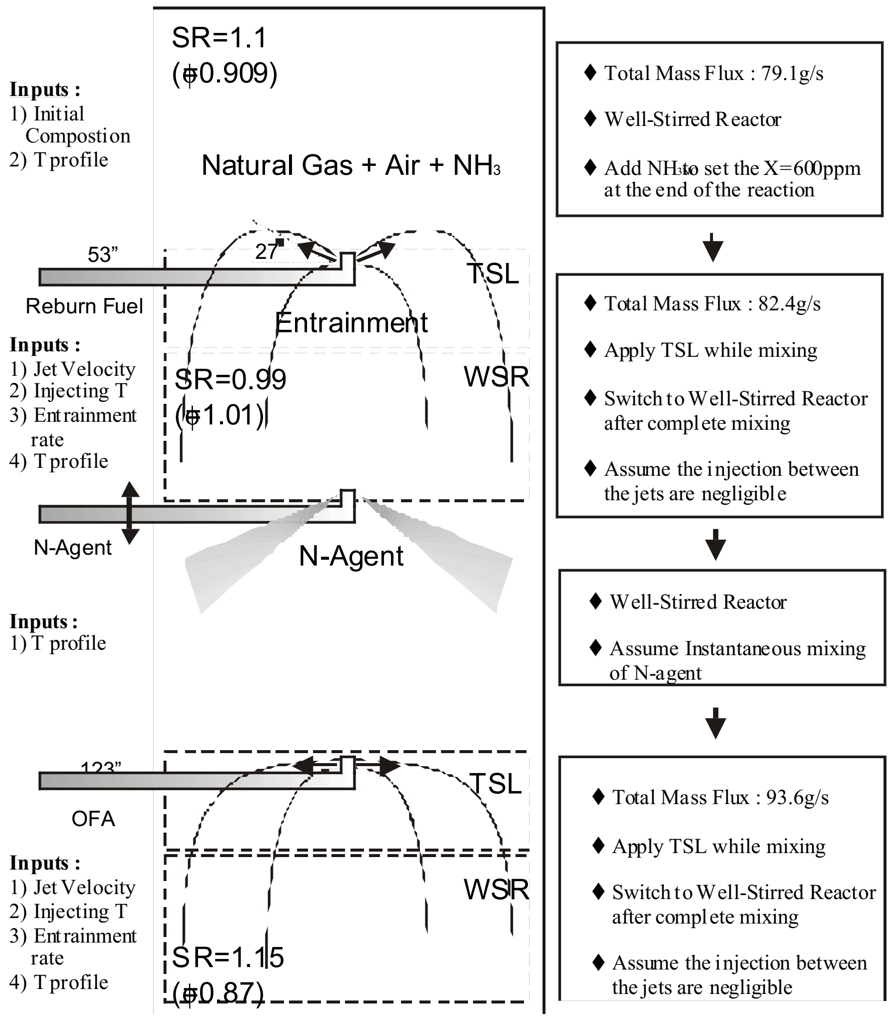

Figure 6-1. The modeling scheme and inputs required at each stage.

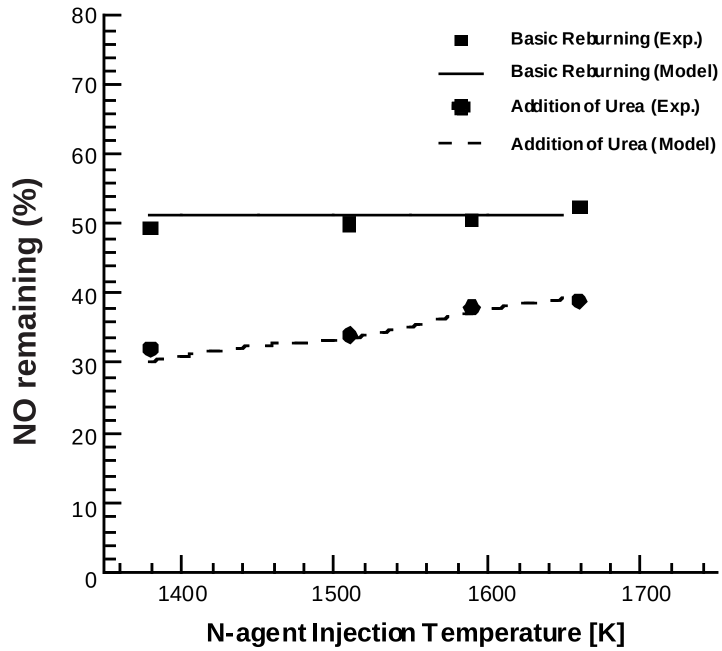

Figure 6-2. Comparison of TSL model predictions with experimental data.

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