SECOND GENERATION ADVANCED REBURNING FOR HIGH EFFICIENCY NO_x CONTROL

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Abstract

This project is designed to develop a family of novel NO_x control technologies, called Second Generation Advanced Reburning (SGAR) which has the potential to achieve 90+% NO_x control in coal-fired boilers at a significantly lower cost than SCR. The twelfth reporting period in Phase II (July 3 – October 15, 2000) included design validation AR-Lean tests (Task #2.6) in the 10×10^6 Btu/hr Tower Furnace. The objective of tests was to determine the efficiency of AR-Lean at higher than optimum OFA/N-Agent injection temperatures in large pilot-scale combustion facility. Tests demonstrated that co-injection of urea with overfire air resulted in NO_x reduction. However, observed NO_x reduction was smaller than that under optimum conditions.

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Executive Summary

This project is designed to develop a family of novel NO_x control technologies, called Second Generation Advanced Reburning (SGAR) which has the potential to achieve 90+% NO_x control in coal-fired boilers at a significantly lower cost than SCR. The twelfth reporting period in Phase II (July 3 – October 15, 2000) included design validation AR-Lean tests (Task #2.6) in the 10×10^6 Btu/hr Tower Furnace. The objective of tests was to determine the efficiency of AR-Lean at higher than optimum OFA/N-Agent injection temperatures in large pilot-scale combustion facility.

The test approach was to parametrically vary key process parameters in order to characterize sensitivity and optimize performance. Test variables included: urea atomization pressure, urea nitrogen stoichiometric ratio, urea solution strength, OFA/Urea port configuration, nitrogen agent type, OFA/Urea injection temperature, and injector position. Each of these conditions was evaluated as reburning heat input was varied from 10% to 20%. For comparison, a series of basic SNCR tests was also performed. Urea, aqueous ammonia and ammonium sulfate were used as N-agents. The best performance was provided by urea. Performance increased as atomizing pressure and nitrogen stoichiometric ratio increased and OFA injection temperature decreased. Performance was also better when urea was injected axially co-current to the furnace gas flow. This configuration provided better urea mixing with flue gas.

Tests demonstrated that moderate NO_x control can be achieved in boilers with existing systems for OFA injection even if temperatures of the OFA injection are too high for the gaseous N-agent to be effective. This can be achieved by injection of N-agent in the form of an aqueous solution with optimized droplet size.

1.0 Introduction

The activities during the twelfth reporting period in Phase II (July 1 – September 30, 2000) included testing of AR-Lean in the 3 MW Tower Furnace described elsewhere [1] and modeling the effect of urea co-injection with overfire air on NO_x reduction.

Tests conducted in 300 kW and 20 kW pilot-scale facilities [2] demonstrated that efficiency of NO_x reduction in Advanced Reburning (AR) could be up to 95% if parameters of AR were optimized. Tests in 3 MW Tower Furnace [3] confirmed that overall NO_x reduction in AR can be up to 96%. This high efficiency of NO_x reduction can be achieved if process parameters including temperature of overfire (OFA) injection are optimized. However, in many boilers that are equipped with OFA injection system the injection occurs at higher than optimum temperatures. Utilization of already existing ports for OFA injection would decrease cost of AR installation. However, efficiency of NO_x reduction in this case is expected to be lower than that at optimum conditions. The objective of current tests is to determine efficiency of co-injection of N-agent with OFA (AR-Lean) in large pilot-scale combustor at temperatures that are higher than optimum.

2.0 Testing of AR-Lean in Tower Furnace

The test approach was to parametrically vary key process parameters in order to characterize sensitivity and optimize performance. Test variables included:

- Urea atomization pressure
- Urea nitrogen stoichiometric ratio (NSR)
- Urea solution strength
- OFA/Urea port configuration
- Nitrogen agent type
- OFA/Urea injection temperature
- Injector position

Each of these conditions was evaluated as reburning heat input was varied from 10% to 20%. For comparison, a series of basic SNCR tests was also performed.

The following sections describe nozzle development studies, test facility configuration and the impacts of each test variable upon performance.

2.1 Atomization Nozzles

Prior to the test work, a series of nozzle development studies was performed. The objective was to develop nozzles capable of providing controllable droplet mean diameters in the range of 200 to 1000 μ. The nozzles were of the twin-fluid type, with pressurized gas used to provide energy to atomize the liquid. A total of 5 nozzle designs were developed, labeled A-1 through A-5. The design had different orifice diameters for the liquid and gas streams. Design A-4 was used for the pilot scale tests.

A total of five nozzles of the A-4 design were built, including four for the test work and one spare. These five nozzles were characterized as a function of atomization gas pressure using a Malvern particle sizer. Figure 1 shows droplet volume mean diameter as a function of atomization gas pressure. As pressure was increased from 10 to 40 psig, mean diameter decreased from approximately 1000 to 100 μ. Results were reasonably similar for the five nozzles. At gas pressures of 5 psig and lower the atomizers began to fail, with the liquid spray sputtering and becoming off-center.

A series of qualitative flow visualization tests was also performed in which the nozzle was oriented horizontally, simulating the configuration used in the pilot scale tests. Atomization pressure was varied from 0 to 60 psig. The liquid spray was observed to extend horizontally outward by a maximum of about 2 feet. Since the Tower Furnace is 4 feet across, it was believed that the liquid spray would not impinge upon the far wall unless it was carried there by the overfire air.

2.2 Test Facility Configuration

The tests were conducted in GE-EER's 10 MMBtu/hr Tower Furnace facility. Natural gas was used as main and reburning fuels. The Tower Furnace has cross sectional dimensions of 4 ft. x 4 ft. It is equipped with adjustable heat extraction panels, allowing the facility’s residence time-temperature profile to be matched to that of a specific full-scale boiler. For the current tests the furnace was configured to nominally simulate the thermal conditions of the target boiler. Figure 2 compares the Tower Furnace temperature to that of the target boiler. The thermal quench rate through the furnace agreed fairly well for the two units.

Urea was injected along with OFA at 2510 ^{o}F. For comparison, tests were also conducted at OFA injection temperature of 2280 ^{o}F to demonstrate the effect of temperature on N-agent performance. The injectors were designed with a central urea atomizer surrounded by an annular OFA port. Two configurations were used for the OFA/Urea injectors, one with four ports and the other with three ports. These configurations were designed to provide different mixing and entrainment characteristics. A brief series of tests was also conducted using axial injectors. This involved inserting two L-shaped injectors into the furnace such that urea was injected axially, co-current to the furnace gas flow. The axial injectors were oriented to provide maximum flow field coverage. Initial NO_x concentration was 240 ppm.

2.3 Effect of Atomization Pressure

Atomization pressure was varied from 5 to 20 psig. As shown in Fig. 3a, overall NO_x reduction improved with decreasing pressure, particularly at 10% reburning. However, the highest incremental NO_x reduction achieved by urea (Fig. 3b) for any condition was 9%. The incremental reduction here is defined as NO_x reduction by N-agent only.

2.4 Effect of Urea Nitrogen Stoichiometric Ratio

Urea nitrogen stoichiometric ratio (NSR) was varied from 1.0 to 1.5. As shown in Figure 4, performance was slightly better at the higher NSR. However, the incremental NO_x reduction provided by urea remained below 15% in all cases.

2.5 Effect of Urea Solution Strength

The Malvern tests revealed that the atomization nozzles tended to produce larger droplets at higher liquid flow rates. Therefore, as a means of further evaluating impacts of droplet size upon performance, tests were conducted in which the urea solution strength was varied, with a corresponding change in liquid flow rate. Figure 5 shows incremental performance of the urea at solution strengths of 2.5%, 5%, and 10%. Performance was best with the most dilute solution, corresponding to the highest liquid flow rate. This implies that better performance was achieved with larger droplets.

2.6 Effect of OFA Port Configuration

To evaluate mixing and thermal effects, two OFA configurations were tested, including one with four ports and one with three ports. Figure 6 shows overall NO_x reduction for each configuration at 10% and 20% reburning. At 10% reburning, similar results were obtained for the two configurations. At 20% reburning, performance was slightly better with the three-port configuration.

2.7 Effect of Injector Position

The baseline position for the urea injectors was flush with the inner wall of the furnace. A test series was also conducted in which the injectors were recessed back into the OFA port by 5 inches. The objective was to provide time for the velocity of the liquid stream to approach that of the OFA stream, potentially allowing the OFA to better shield the droplets. However, as shown in Figure 7, similar results were obtained for each injector position.

2.8 Effect of N-Agent Type

Urea requires an extra step to decompose relative to ammonia. Thus it was believed that urea would perform better under the subject test conditions that require a delay time. To validate this reasoning, a series of tests was conducted in which aqueous ammonia was used as the N-agent. Figure 8 shows performance of urea and aqueous ammonia as a function of atomization pressure. While at 10% reburning performance was similar for the two additives, at 20% reburning urea performed significantly better than aqueous ammonia.

2.9 Effect of OFA Injection Temperature

To determine the impacts of injection temperature, a series of tests was performed in which the OFA and urea were moved downstream in the furnace by 24”. This corresponded to a furnace gas temperature of about 2280 ^{o}F, as compared to 2510 ^{o}F in previous tests. Figure 9 compares performance at 10% and 20% reburning. In each case overall NO_x reduction was about 10 percentage points higher at the lower temperature.

2.10 SNCR Test Results

Reburning generates CO levels that can impact performance of the N-agent. To characterize these effects, a series of tests was performed involving basic SNCR without reburning. In all cases OFA was injected to maintain the same furnace mixing patterns. Figure 10 shows urea performance as a function of atomization pressure with and without reburning. Significantly higher NO_x reduction was obtained without reburning, indicating that under these conditions CO had a negative impact on performance.

2.11 Axial Injector Tests

Near the end of the test program a series of tests was conducted using axial injectors. This involved inserting two L-shaped injectors into the furnace such that urea was injected axially, co-current to the furnace gas flow. The axial injectors were oriented to provide maximum flow field coverage. The axial injector tests were intended to minimize potential ballistic and wall-impingement effects. For these tests both the OFA and urea injectors were located at 2510 ^{o}F. Reburning heat inputs of 6%, 10%, and 20% were tested with urea injection. One series of tests was also conducted using ammonium sulfate as the N-agent, at 10% reburning. The objective of these tests was to determine whether the ammonium sulfate would have different evaporation characteristics, and thus different NO_x control performance, than urea.

Figure 11 shows NO reduction as a function of atomization pressure for the axial injector tests. Incremental SNCR performance was better at lower reburning heat inputs, pointing to possible CO effects. Urea performance improved with decreasing atomization pressure. At an atomization pressure of zero, overall NO_x reductions were 47% at 10% reburning and 37% at 6% reburning. Incremental urea NO_x reductions at these conditions were 25% at 10% reburning and 26% at 6% reburning. This performance is significantly better than that achieved with the wall injectors. For comparison, under similar conditions at 10% reburning the incremental NO_x control achieved by urea with the wall injection system was 8%.

Both urea and ammonium sulfate were tested with the axial injectors at 10% reburning. Figure 12 shows performance as a function of atomization pressure. At low pressures, performance was similar for the two additives. At higher pressures, urea performed significantly better, possibly indicating that it was less prone to vaporizing prior to complete evaporation of the water droplet.

3.0 Evaluation of Nozzle Performance

As mentioned earlier, nozzle development studies provided an approach to design a nozzle capable of providing controllable droplet mean diameter. Another important parameter that effects nozzle performance is droplet size distribution. The most effective nozzle performance is achieved with narrow droplet size distribution since most N-agent is dispersed as droplets with their sizes being close to the optimum. Larger than optimum droplets evaporate at too low temperatures and contribute to ammonia slip while smaller than optimum droplets evaporate at too high temperatures and contribute to NO_x emissions. One way to evaluate nozzle performance is to install nozzle in a boiler and conduct tests. However, this procedure can be time consuming since it can take several rounds of tests before optimum performance is achieved. Thus, simple approach to evaluate nozzle performance is required.

Method to evaluate nozzle performance was developed by combing CFD and kinetic modeling. The approach was to use CFD modeling to determine droplet evaporation times and temperature-time histories for droplets of different sizes and then use this information in kinetic modeling to determine NO_x reduction corresponding to each droplet size.

A three-dimensional CFD model of Tower Furnace was simulated in FLUENT to characterize times of urea release into the gas phase for droplets of different sizes and temperature-time histories corresponding to droplets of different sizes. Droplets considered were in the range of 30 – 1600 μ. Total 20 droplet sizes from this range were represented in modeling. Concentration of urea in aqueous solution was assumed to be 20% on mass basis. CFD modeling was used to calculate temperature-time history and water evaporation time for each of the selected droplets. It was assumed that urea release into the gas-phase started only after all water evaporated. The urea evaporation time for each droplet size was further assumed 0.6 times the water evaporation time.

Kinetic modeling was conducted to compare efficiencies of urea atomizers in AR-lean. The ODF modeling was used to calculate the level of NO_x reduction provided by each droplet size (totally 20 sizes). The amount of urea released by droplets of the same size was determined using droplet distribution of an atomizer. Three atomizers were considered: nozzle #13, and two-needle atomizers (referred here as #5 and #45). Droplet distributions of these atomizers are shown in Fig. 13.

The predicted NO_x reduction and NH_3 slip for each atomizer are presented in the table form in Fig. 13. The results indicate that NO_x reduction is about 10% for nozzle #13, and 16% and 24% for nozzles #45 and #5, respectively. The ammonia slip for nozzles #13 and #5 was found to be the same (about 30 ppm), while for #45 it was much higher (70 ppm). Atomizer #5 provided the best performance with highest NO_x reduction and lowest ammonia slip among tested atomizers.

Modeling predicts that even higher NO_x reduction can be achieved if mean droplet diameter is about 750 μ. Modeling was conducted for atomizer #5 droplet distribution assuming that mean droplet diameter increases from 630 μ to 830 μ (Fig. 14a.). Figure 14b shows predicted effects of mean droplet diameter on NO_x reduction and ammonia slip. Maximum predicted NO_x reduction for atomizer #5 type distribution is about 60% and is achieved at 730 μm mean droplet size. Note that this increase in NO_x reduction is not accompanied by increase in ammonia slip. Further increase in mean droplet diameter results in decrease in NO_x reduction and increase in ammonia slip.

Overall, the current CFD/kinetics methodology appears to capture the essential physics and will be used to specify the droplet size distribution and mean droplet diameter for future atomizers.

4.0 Summary

Tests in 10 MMBtu/hr MW Tower Furnace demonstrated that efficiency of NO_x reduction in AR-Lean at OFA/N-agent injection temperature of 2500 ^oF is about 60% and is significantly smaller than 96% achieved in the same combustor at optimized conditions. The incremental NO_x reduction provided by N-agent only at this temperature did not exceed 15%. Thus, the importance of optimization of process conditions for achieving high efficiency of NO_x reduction in AR was demonstrated. Tests also indicated that moderate NO_x control can be achieved in boilers with existing systems for OFA injection even if temperatures of the OFA injection are too high for the gaseous N-agent to be effective. This can be achieved by injection of N-agent in the form of an aqueous solution with optimized droplet size. Since additional port for N-agent is not required in AR-Lean, injection of an aqueous solution of N-agent presents an opportunity to provide moderate NO_x control at low cost in boilers already equipped with OFA ports.

5.0 Future Work

Future activities will include pilot-scale coal firing tests at the BSF designed to evaluate coal as the reburning fuel in AR. Several coals will be selected with compositions which can potentially promote the AR process even without additives. Parametric studies will be conducted to optimize advanced coal reburning.

6.0 References

1. Zamansky, V.M., Lissianski, V.V., and Maly, P.M. (1999) Second Generation Advanced Reburning for High Efficiency NO_x Control. *Quarterly Report No. 9, DOE Contract No. DE-AC22-95PC95251*.
2. Zamansky, V.M., Maly, P.M., Ho, l., Sheldon, M.S., Moyeda, D., Folsom, B.A., Seeker, W.R., Gardiner, W.C., and Lissianski (1997) Second Generation Advanced Reburning for High Efficiency NO_x Control. *Phase I Final Report, DOE Contract No. DE-AC22-95PC95251*.
3. Zamansky, V.M., Lissianski, V.V., and Maly, P.M. (1999) Second Generation Advanced Reburning for High Efficiency NO_x Control. *Quarterly Report No. 9, DOE Contract No. DE-AC22-95PC95251*.

Figures

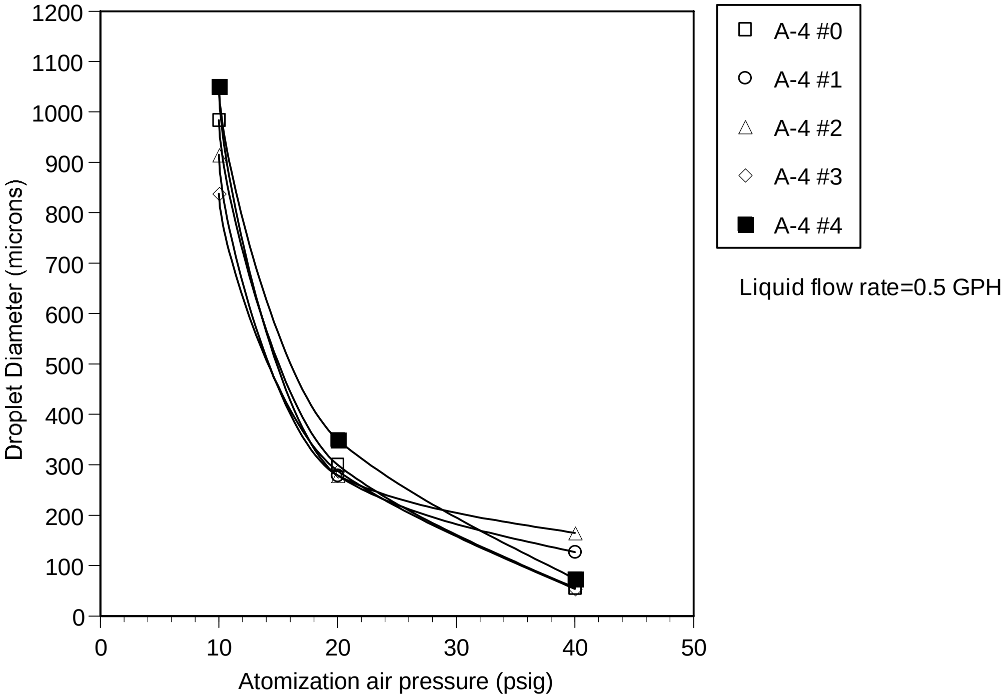


Figure 1. Atomization characteristics of test nozzle.

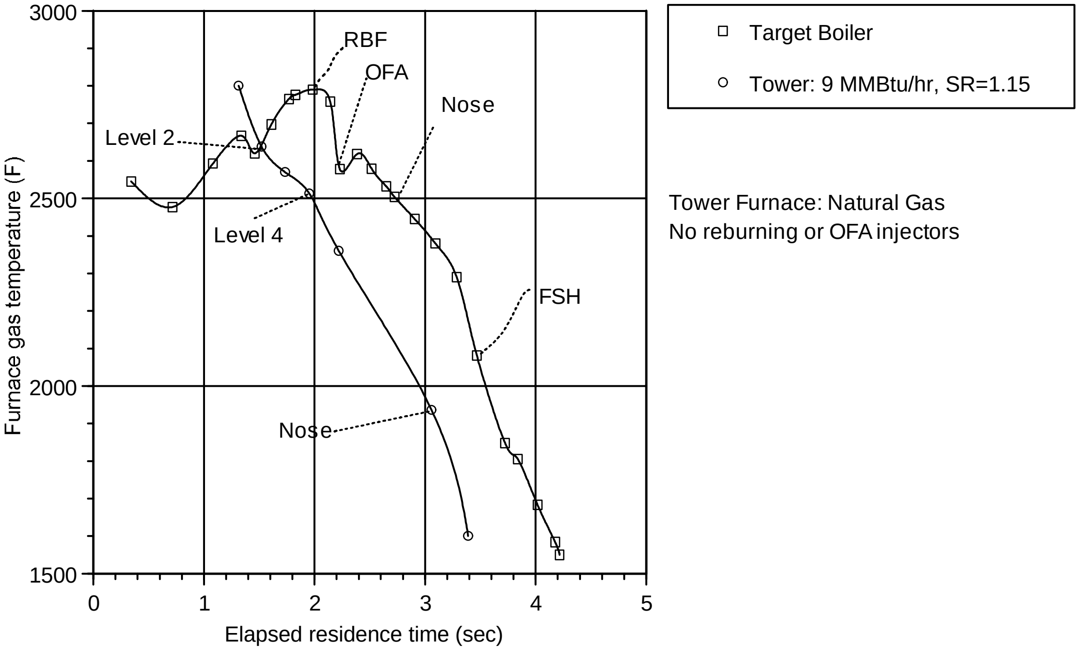


Figure 2. Temperature profiles for the target boiler and Tower Furnace.

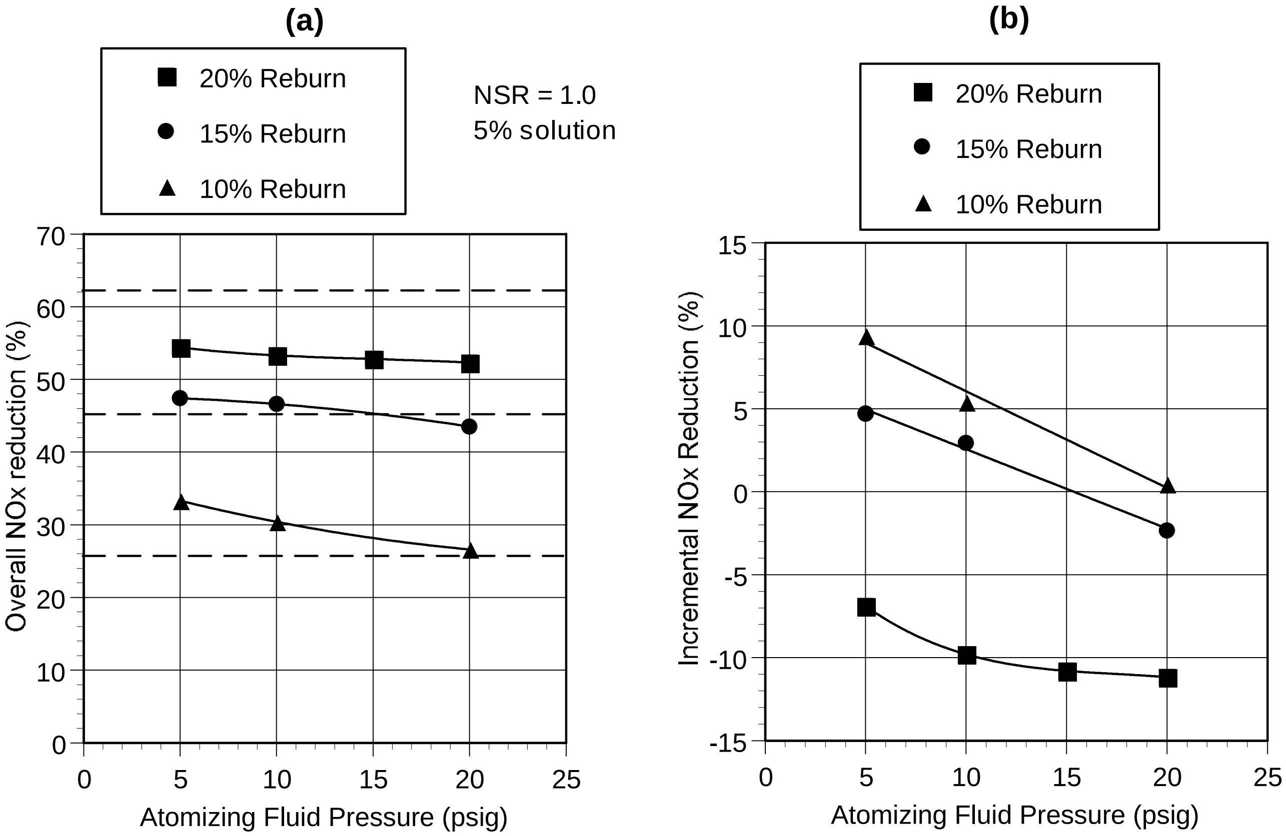


Figure 3. Impact of atomization pressure on overall (a) and incremental (b) NO_x reduction by urea solution co-injected with OFA. Dash lines represent NO_x reduction without urea.

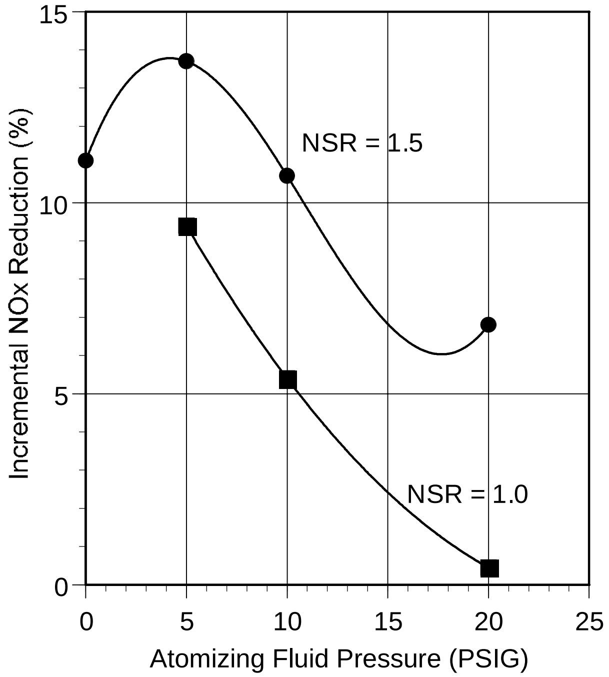


Figure 4. Incremental NO_x reduction for co-injection of 5% urea solution with OFA at 10% reburning.

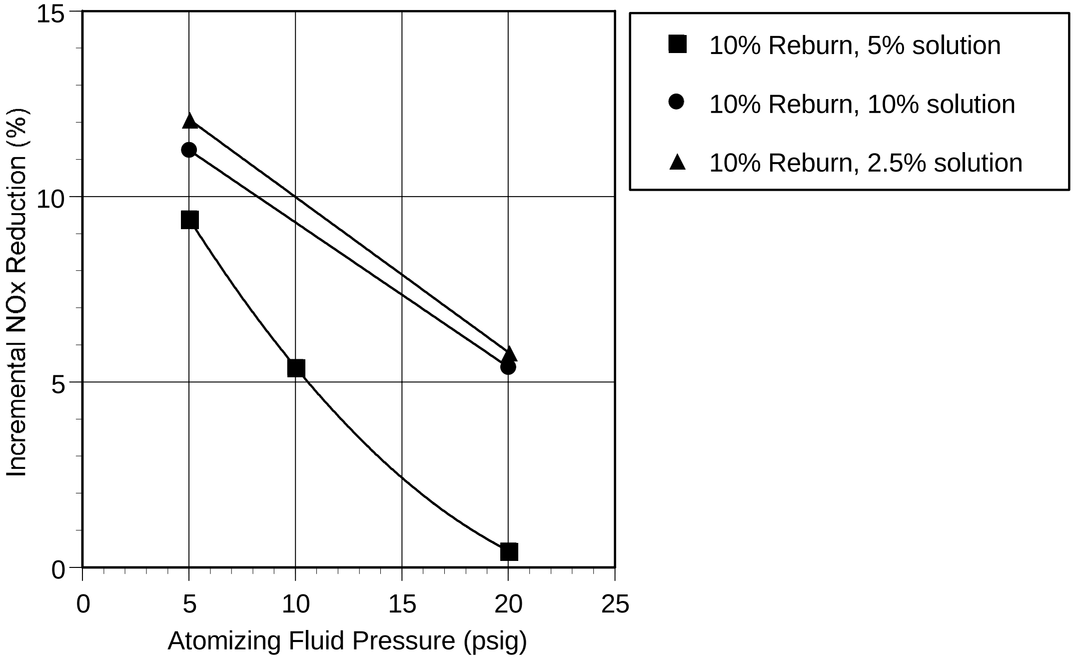


Figure 5. Incremental NO_x reduction for co-injection of different urea solution strengths with OFA.

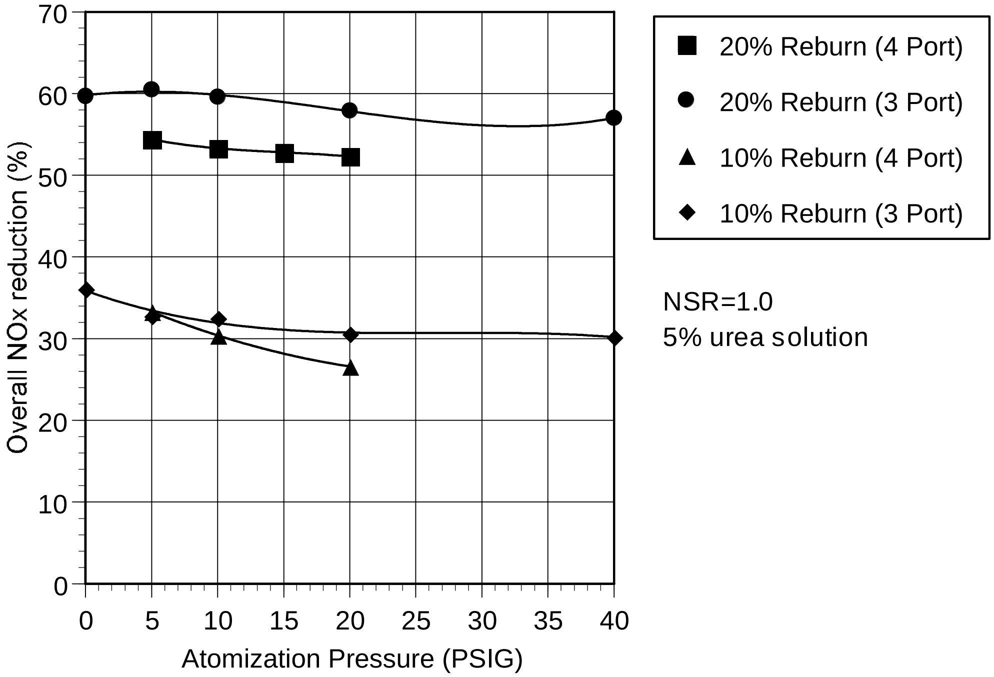


Figure 6. Comparison of overall NO_x reduction by urea solution for 3-port and 4-port configurations of OFA injection.

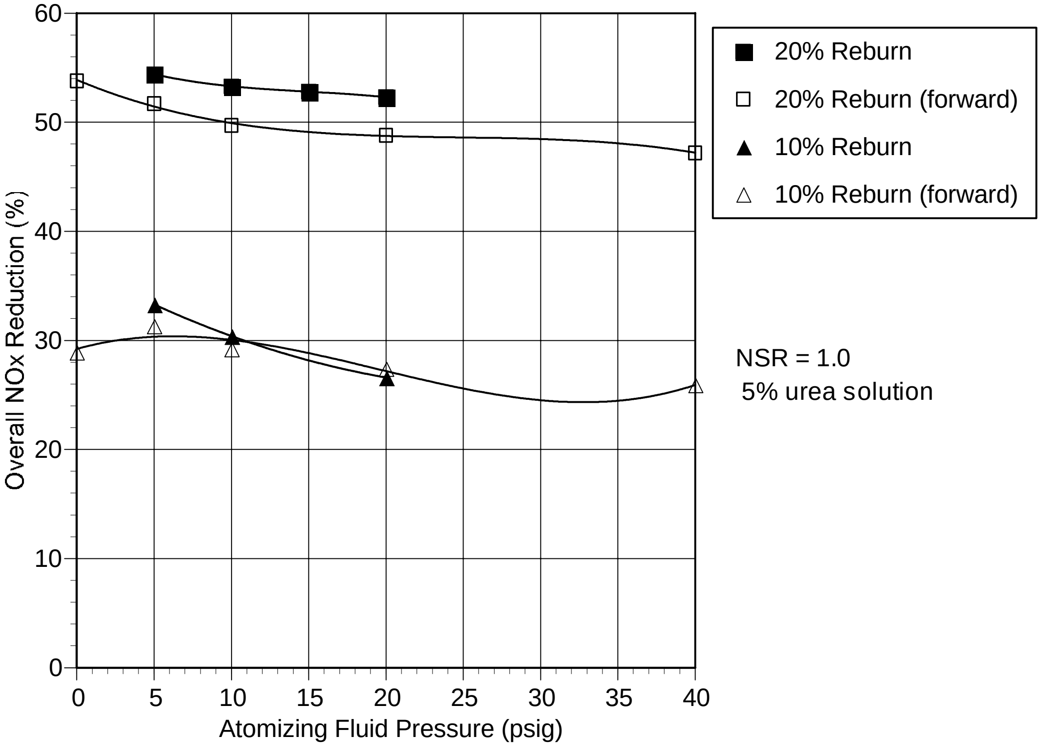


Figure 7. Overall NO_x reduction at different urea injector positions.

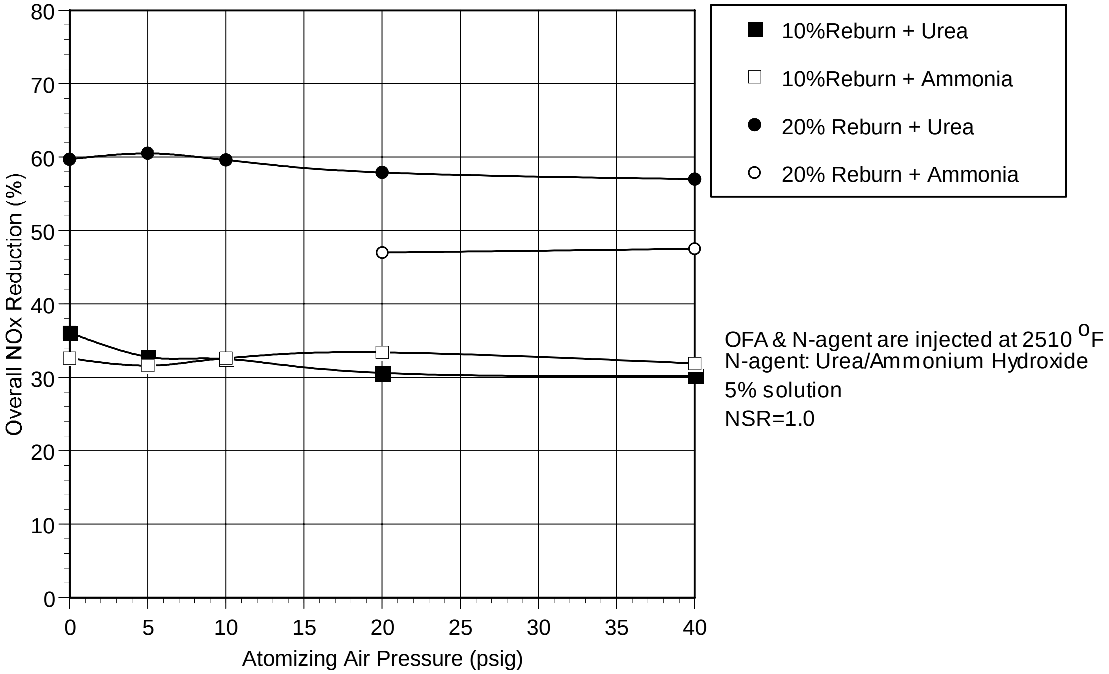


Figure 8. Comparison of performance for urea and aqueous ammonia as a function of N-agent atomizing air pressure.

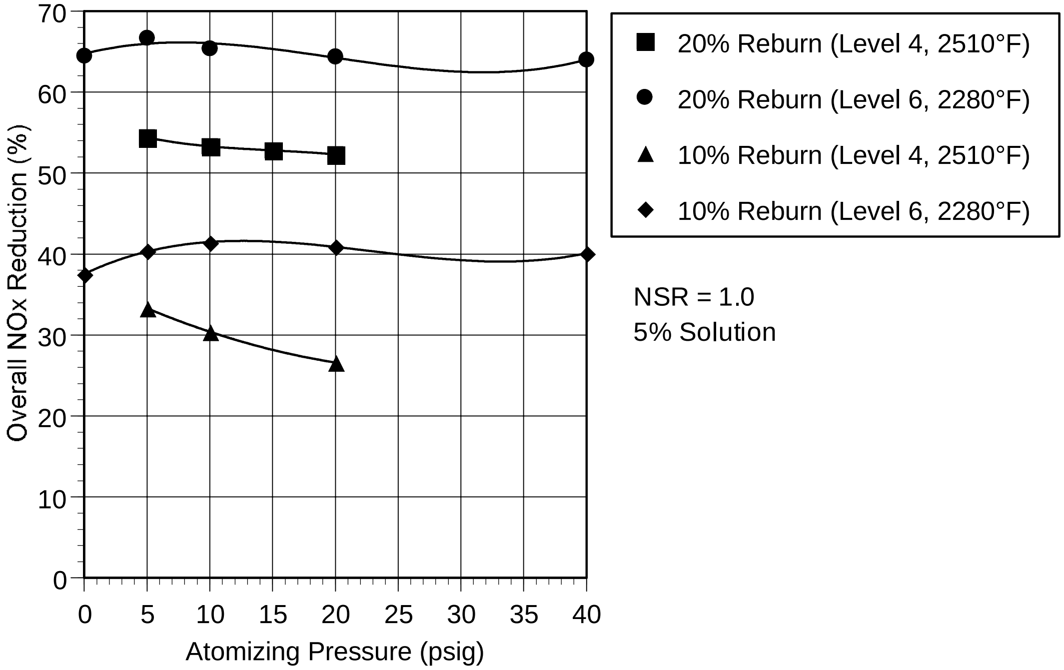


Figure 9. Comparison of overall NO_x reduction at different OFA/urea injection temperatures.

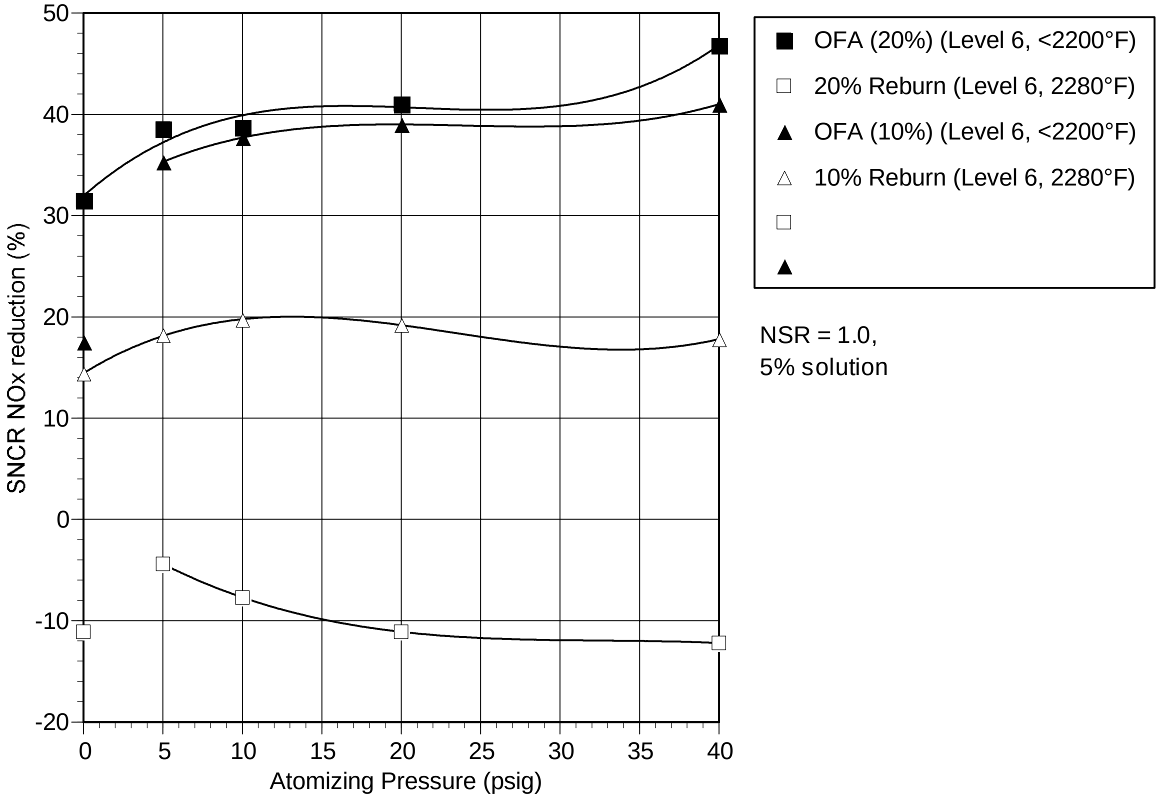


Figure 10. Basic SNCR performance as a function of atomization pressure with and without reburning.

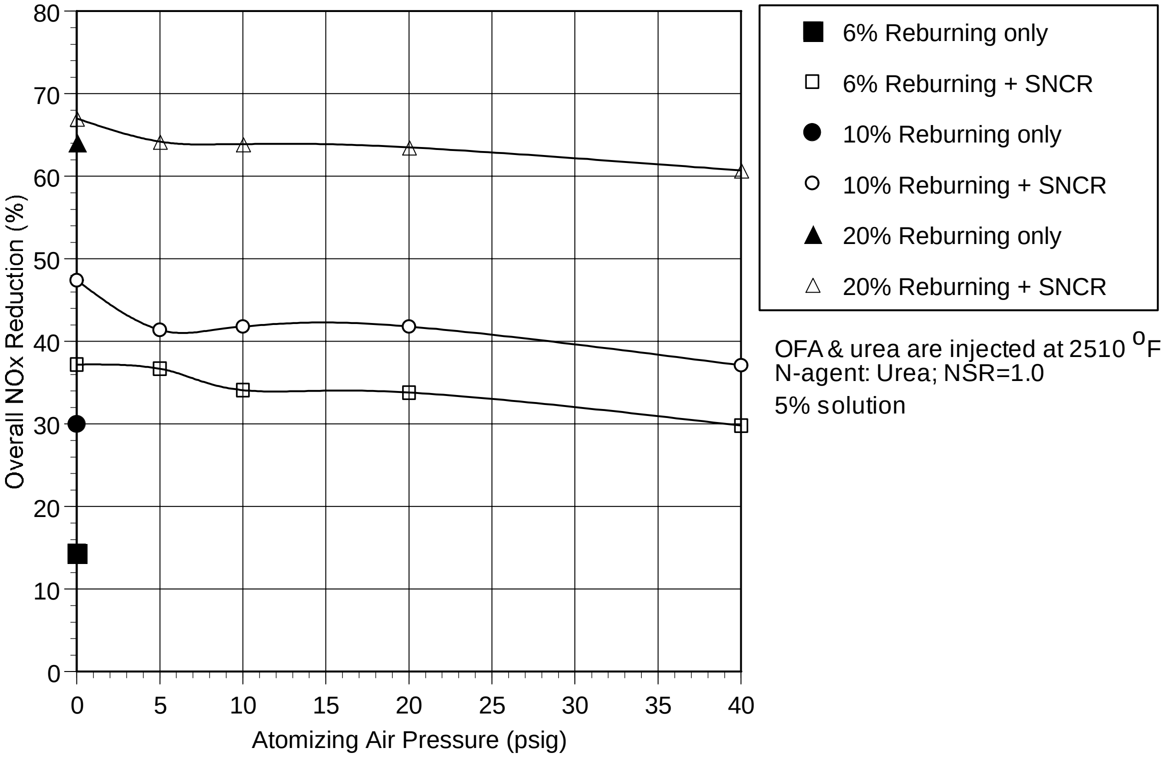


Figure 11. Axial injector tests: impact of atomization pressure on overall NO_x reduction at different reburning heat inputs.

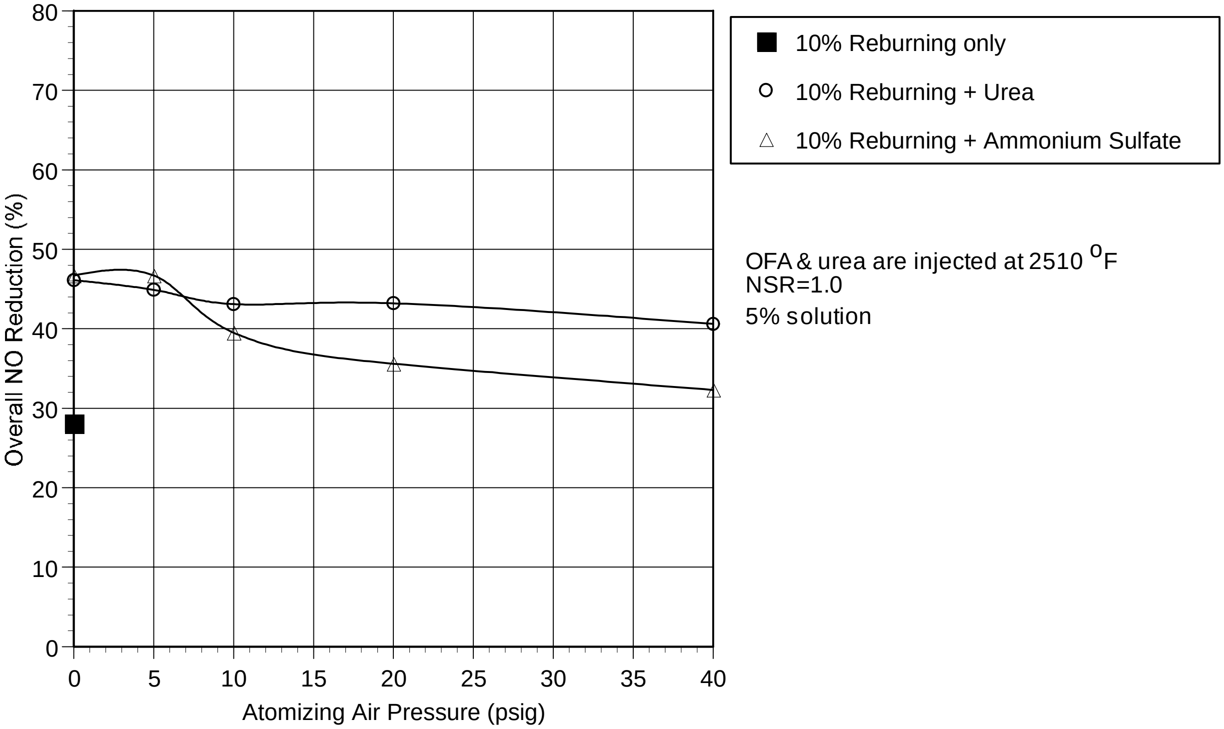
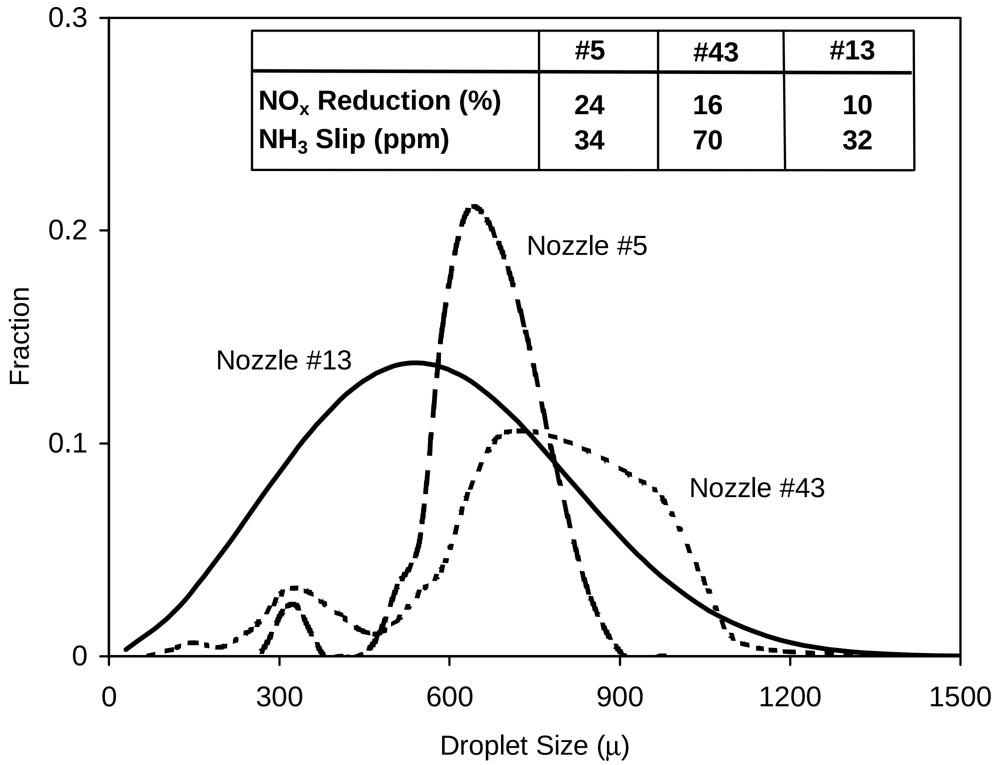


Figure 12. Axial injector tests: comparison of urea and ammonium sulfate impacts on NO_x reduction.



	#5	#43	#13
NO_x Reduction (%)	**24**	**16**	**10**
NH_3 Slip (ppm)	**34**	**70**	**32**

Figure 13. Droplet size distributions and predicted performances of atomizers #13, #5, and #45.

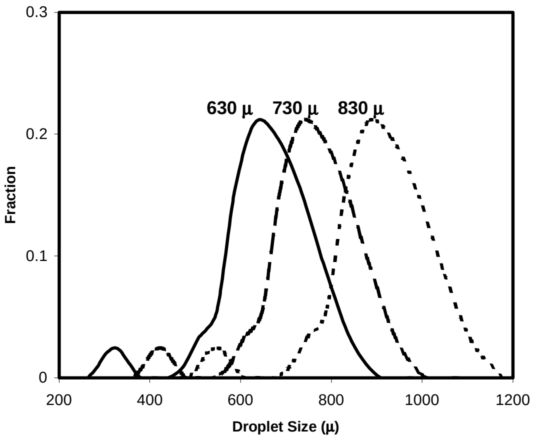


Fig. 14a. Assumed change in droplet distribution for atomizer #5.

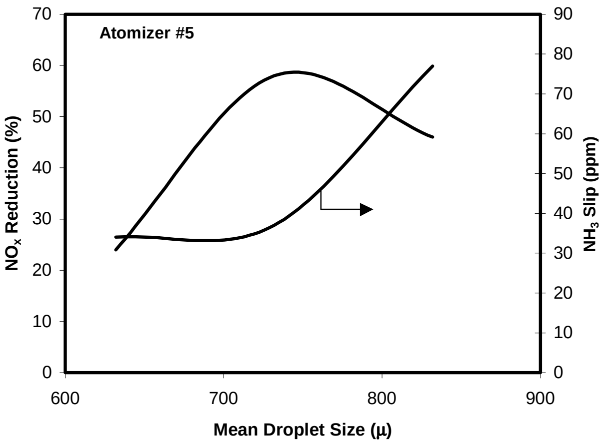


Fig. 14b. Effect of mean droplet diameter on NO_x reduction and NH_3 slip.