DEVELOPMENT OF A VALIDATED MODEL FOR USE IN MINIMIZING NO_X EMISSIONS AND MAXIMIZING CARBON UTILIZATION WHEN CO-FIRING BIOMASS WITH COAL

Quarterly Report

Reporting Period Start Date: 1/1/2001
Reporting Period End Date: 3/31/2001

Larry G. Felix, SoRI
P. Vann Bush, SoRI

April 30, 2001

DOE Cooperative Agreement No. DE-FC26-00NT40895

Southern Research Institute
2000 Ninth Avenue South
P. O. Box 55305
Birmingham, AL 35255-5305

DISCLAIMER

“This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.”

ABSTRACT

This is the second Quarterly Technical Report for DOE Cooperative Agreement No. DE-FC26-00NT40895. A statement of the project objectives is included in the Introduction of this report. Two biomass co-firing test burns have been conducted. In the first test, up to 20% by weight dry hardwood sawdust and dry switchgrass was co-milled Pratt seam coal. In the second test, also with Pratt seam coal, up to 10% by weight dry hardwood sawdust was injected through the center of the burner. Progress has continued in developing a modeling approach to synthesize the reaction time and temperature distributions that will be produced by computational fluid dynamic models of the pilot-scale combustion furnace and the char burnout and chemical reaction kinetics that will predict NOx emissions and unburned carbon levels in the furnace exhaust. Preliminary results of CFD modeling efforts have been received and Preparations are under way for continued pilot-scale combustion experiments.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The work to be conducted in this project received funding from the Department of Energy under Cooperative Agreement No. DE-FC26-00NT40895. This project has a period of performance that commenced September 20, 2000 and continues through September 19, 2002. A project Work Plan was submitted to DOE on October 18, 2000 as the first deliverable under the cooperative agreement. The Work Plan is not included in this report, but the objectives of the project are restated from the Work Plan in the following paragraphs.

Objectives

The project is designed to balance the development of a systematic and expansive database detailing the effects of co-firing parameters on nitrogen oxides (NOx) formation with the complementary modeling effort that will yield a capability to predict, and therefore optimize, NOx reductions by the selection of those parameters.

The database of biomass co-firing results will be developed through an extensive set of pilot-scale tests at the Southern Company/Southern Research Institute Combustion Research Facility. The testing in this program will monitor NOx, LOI, and other emissions over a broad domain of biomass composition, coal quality, and co-firing injection configurations to quantify the dependence of NOx formation and LOI on these parameters. This database of co-firing cases will characterize an extensive suite of emissions and combustion properties for each of the combinations of fuel and injection configuration tested.

The complementary process modeling will expand the value of the raw test data by identifying the determining factors on NOx emissions and LOI. Niksa Energy Associates will develop and validate a detailed process model for predicting NOx emissions and LOI from biomass co-firing that builds on a foundation of existing and proven fluid dynamics, reaction kinetics, and combustion products models. The modeling will resolve all major independent influences, including biomass composition, coal quality, chemical interactions among biomass-and coal-derived intermediate species, competitive O_2 consumption by biomass- and coal-derived intermediate species and chars, extent of biomass/coal mixing prior to combustion, and mixing intensity during biomass injection.

The overall goal of the project is to produce a validated tool or methodology to accurately and confidently design and optimize biomass co-firing systems for fullscale utility boilers to produce the lowest NO_x emissions and the least unburned carbon. Specific program objectives are:

- Develop an extensive data set under controlled test conditions that quantifies the relationships between NO_x emissions and biomass co-firing parameters.

- Provide a data set of the effects of biomass co-firing over a broad range of fuels and co-firing conditions on flame stability, carbon burnout, slagging and fouling, and particulate and gaseous emissions.

  - Develop and validate a broadly applicable computer model that can be used to optimize NO_x reductions and minimize unburned carbon from biomass co-firing.

Once validated, the model provides a relatively inexpensive means to either (1) identify the most effective co-firing injection configuration for specified compositions of biomass and coal within a particular furnace environment, or (2) to forecast the emissions for a specified pair of fuels fired under an existing configuration. As such an important cost-saving tool, the modeling has the potential to accelerate widespread adoption of biomass co-firing as a NO_x control strategy in the electric utility industry.

EXPERIMENTAL

Model Development

During the second quarter of this work, Niksa Energy Associates (NEA) completed the incorporation of *bio*-FLASHCHAIN® into PC Coal Lab®. At this point, the integration is complete for all aspects of devolatilization and char oxidation behavior. The software can predict the complete distribution of volatile products and the compositions of tar and char from any biomass form (wood, paper, grasses, agricultural residues) at any operating conditions. It also simulates char oxidation with the biomass chars remaining after devolatilization throughout all stages of burnout.

NEA is beginning the software development to implement the equivalent reactor network analysis of the fuel-N conversion chemistry. However, input from the CFD simulations underway at Reaction Engineering will be needed to ultimately determine the equivalent reactor network for NEA's calculations.

CFD Simulations

Reaction Engineering International, Inc. (REI) has completed their first simulation of the single register burner used in the pilot-scale combustor. Burner exit data from the burner simulation was used to define furnace inlet boundary conditions for the first furnace simulation. Copies of two reports submitted to SoRI presenting the results of these simulations are included in Appendix A of this report. These are preliminary reports and some possible discrepancies with observed burner and furnace behavior were noted. In particular, biased flame structure and particle trajectories were observed in the furnace simulation that may not necessarily occur in the furnace. REI has increased the number of mesh points in the lower part of the burner and is repeating the calculation.

Pilot-Scale Combustor Tests

Two combustor tests have been performed. In the first test, hardwood sawdust and switchgrass was co-milled with Pratt seam coal (nominal 1.6% S) and injected as a mixture through the single register burner. Both the sawdust and switchgrass were processed through a small tub grinder before being mixed with coal.

Test 1 Mixtures of 10% and 20% by weight of sawdust and Pratt seam coal were prepared and milled in the CE-Raymond Model 352 deep bowl mill to a fineness of 70% less than 200 mesh. Likewise, mixtures of 15% and 20% by weight of switchgrass and Pratt seam coal were prepared and milled in the CE-Raymond Model 352 deep bowl mill to a fineness of 70% less than 200 mesh. It was intended to prepare a mixture of 10% instead of 15% switchgrass and coal. However, by the time the error was discovered, a large quantity of the 15% mixture had been milled. Testing proceeded with the 15% mixture. No problems were encountered in the mixing or milling of any of these mixtures. However, at the 20% level of addition for both sawdust and switchgrass, mill spring pressures had to be substantially increased to maintain proper mill fineness.

Testing was uneventful and all mixtures combusted well, without slagging or fouling beyond what has been observed with raw Pratt Seam coal, which is very little. Three levels of furnace exit oxygen were tested (2.5%, 3.5%, and 4.5%) along with overfire air levels of 0%, 15%, and 30% (where possible). According to the original plan of testing, operation at 30% overfire air (or deep staging with concomitant low NOx emissions) was not contemplated. However, for this test the condition was included, mainly to obtain additional data for the modeling effort conducted by NEA. At a high value of overfire air, burner exit velocity is reduced, which increases the likelihood of persistent fouling from ash residue falling into in the burner. At lower values of overfire air, burner exit velocities are higher and falling ash residues are more easily ejected from the burner exit. Thus, in the case of 20% switchgrass co-milled with Pratt seam coal, stable operation at 30% overfire air was not achieved and no data for this condition is available.

One peculiarity was encountered in the first test. On the first day of testing, 100% Pratt seam coal was burned to obtain baseline data without biomass addition. The NOx emissions data recorded for this day of testing were much lower than had been recorded previously for this coal at the pilot-scale combustor. The experimental condition was repeated at the beginning of Test 2 and the results obtained were consistent with previous results. Comparisons made in this report refer to baseline data taken during Test 2.

With respect to NOx reduction, the presence of biomass greatly reduced NOx emissions. Detailed results are shown in Appendix B.

Test 2 For the second test, the single register burner was modified so that finely divided hardwood sawdust and switchgrass (prepared by MESA Reduction Engineering) could be injected through the center of the 3.5 inch (outer diameter, 0.125 inch wall thickness) burner. This modification was effected by enlarging the existing blast pilot tube to 1.5 inches outside diameter from the original 1-inch pipe (~1.3 inch outside diameter) and inserting a 1 inch outside diameter tube through the center of the enlarged blast pilot. Biomass is injected through this center tube and natural gas for ignition is directed through the 0.125 inch annular space between the inner and outer tubes. Thus, the blast pilot assembly can function either as a natural gas igniter or as a location for biomass injection. This modification works well, however, many modifications of the system to inject biomass were required for successful operation.

The most successful arrangement for biomass injection was not found until late in the test. This arrangement uses an eductor fed by compressed air to aspirate biomass into an air stream directed through the center tube of the blast pilot assembly. The biomass screw feeder and the plastic tube conveying the biomass-air mixture to the blast pilot assembly is grounded to prevent electrical charge from building up. With this equipment, weight percent additions of biomass up to 20% have been obtained in subsequent testing.

Because of the problems encountered with development of a proper method for biomass injection, only data for 10% sawdust addition at 15% overfire air were acquired. In a subsequent test, Test 3, the goals intended for this test were achieved. Test 3 was recently concluded (in April) and analyses of results of this test are ongoing. Thus, discussion of those results will be presented in the next quarterly report.

Intended for Test 2 (and later achieved in Test 3) were biomass additions of 10% and 20% by weight of dry hardwood sawdust and switchgrass to a pulverized coal flame. Furnace exit oxygen levels of 2.5%, 3.5%, and 4.5% were planned with overfire levels of 0% and 15%. As in Test 1, Pratt seam coal was burned. With separately injected biomass, the biomass is metered from a screwfeeder into an eductor at a predetermined rate. Based on the measured heat content for the added biomass, the firing rate of the pilot-scale furnace is reduced to compensate for the added biomass so that the overall rate of firing remains at the nominal 3.6 million Btu/hour used for all testing.

With respect to NOx reduction, when biomass is injected through the center of the burner, NOx emissions are reduced but not as much as when the same amount of biomass is co-milled with coal. Detailed results are shown in Appendix B and summaries of those results are presented below.

Results Table 1 and Figures 1 through 5 summarize NOx emissions for 100% coal, and for various levels of sawdust and switchgrass addition at overfire air levels of 0% and 15%. The curves shown in these figures are fits to the complete NOx emissions data presented in Appendix B.

Several general comments can be made:

- Percentages of NOx reduction (with co-milling) are greatest at overfire levels of 15%.
- Among the two biomasses tested, co-milled switchgrass (var. Alamo) appears to be superior to co-milled dry hardwood sawdust for achieving NOx reductions with Pratt Seam coal.
- Co-milled biomass appears to generate lower NOx emissions than biomass injected in the center of the coal flame. Results from Test 3 will clarify this observation.

Table 1. NOx Emissions for Various Levels of Overfire Air at 3.5% Furnace Exit O_2, (wet) for Sawdust and for Switchgrass Co-milled with Pratt Seam Coal and for 10% Sawdust Injected through the Center of the Single Register Burner.

Biomass Co-milled with Pratt Seam Coal (Test 1)

Biomass	Weight%	Overfire Air, %	NOx Emissions at 3% O_2, dry ppmv	Reduction of NOx Emissions, %
None	0	0	426	0
		15	334	0
		30	194	0
Sawdust	10	0	386	9.4
		15	276	17.4
		30	180	7.2
	20	0	424	0.5
		15	256	23.4
		30	191	1.5
Switchgrass	15	0	402	5.6
		15	258	22.8
		30	169	12.9
	20	0	360	15.5
		15	250	25.1

Biomass Injected through the Center of the Single Register Burner with Pratt Seam Coal (Test 2)

Biomass	Weight%	Overfire Air, %	NOx Emissions at 3% O_2, dry ppmv	Reduction of NOx Emissions, %
Sawdust	10	15	304	9.0

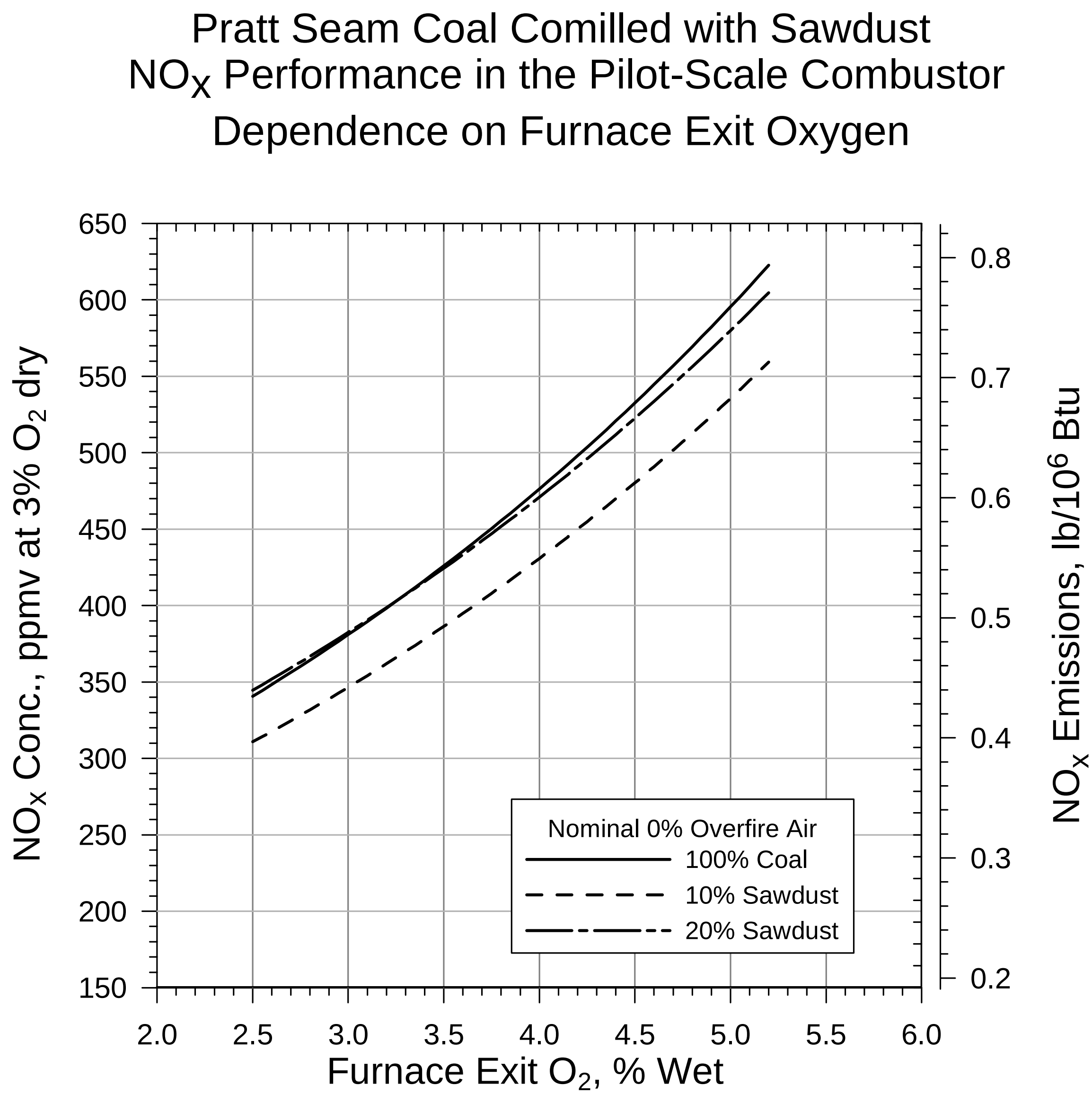


Figure 1. Pratt seam coal co-milled with weight percents of 10% and 20% hardwood sawdust. NOx emissions as a function of furnace exit oxygen at an overfire air level of 0%.

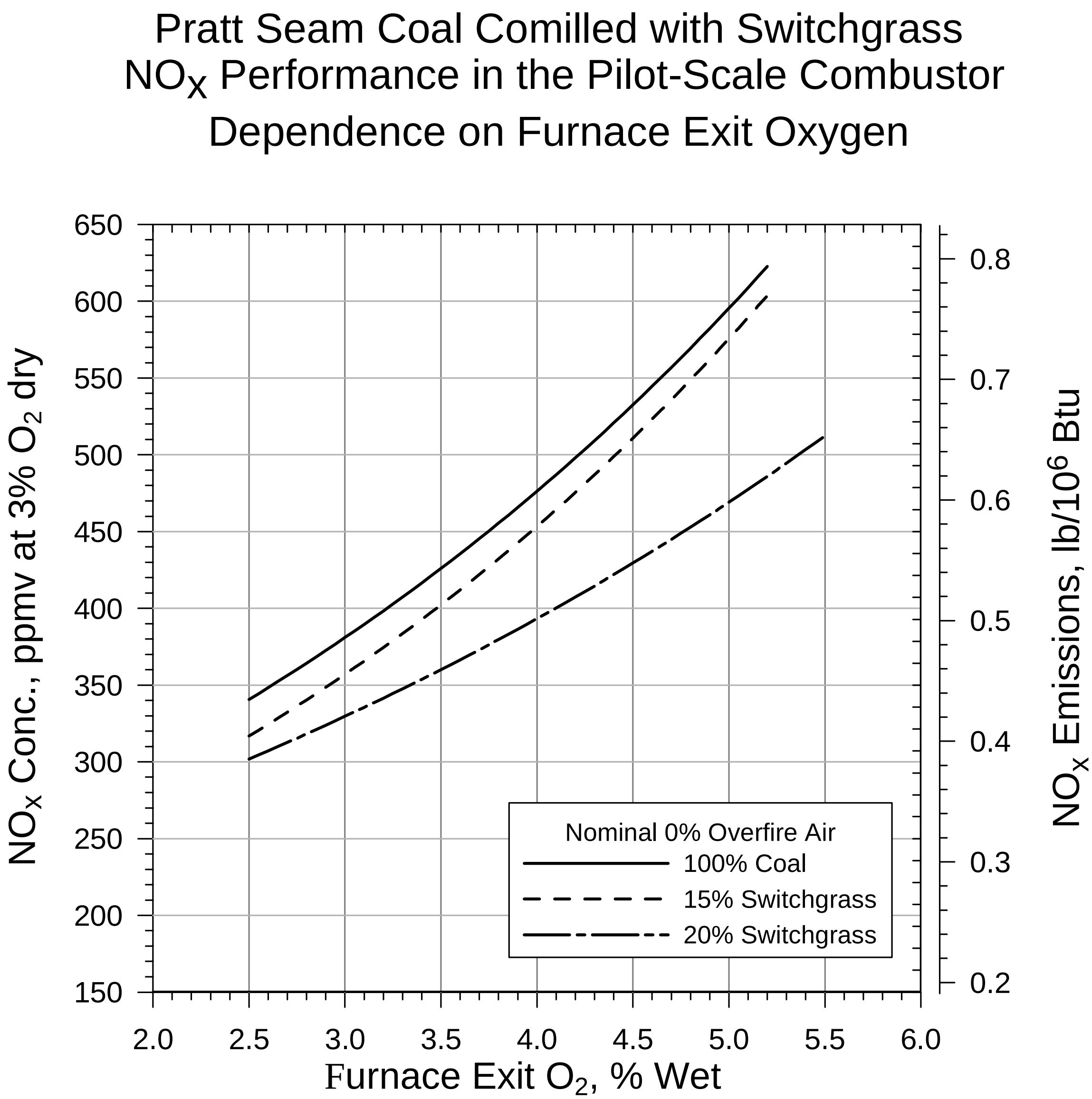


Figure 2. Pratt seam coal co-milled with weight percents of 15% and 20% switchgrass. NOx emissions as a function of furnace exit oxygen at an overfire air level of 0%.

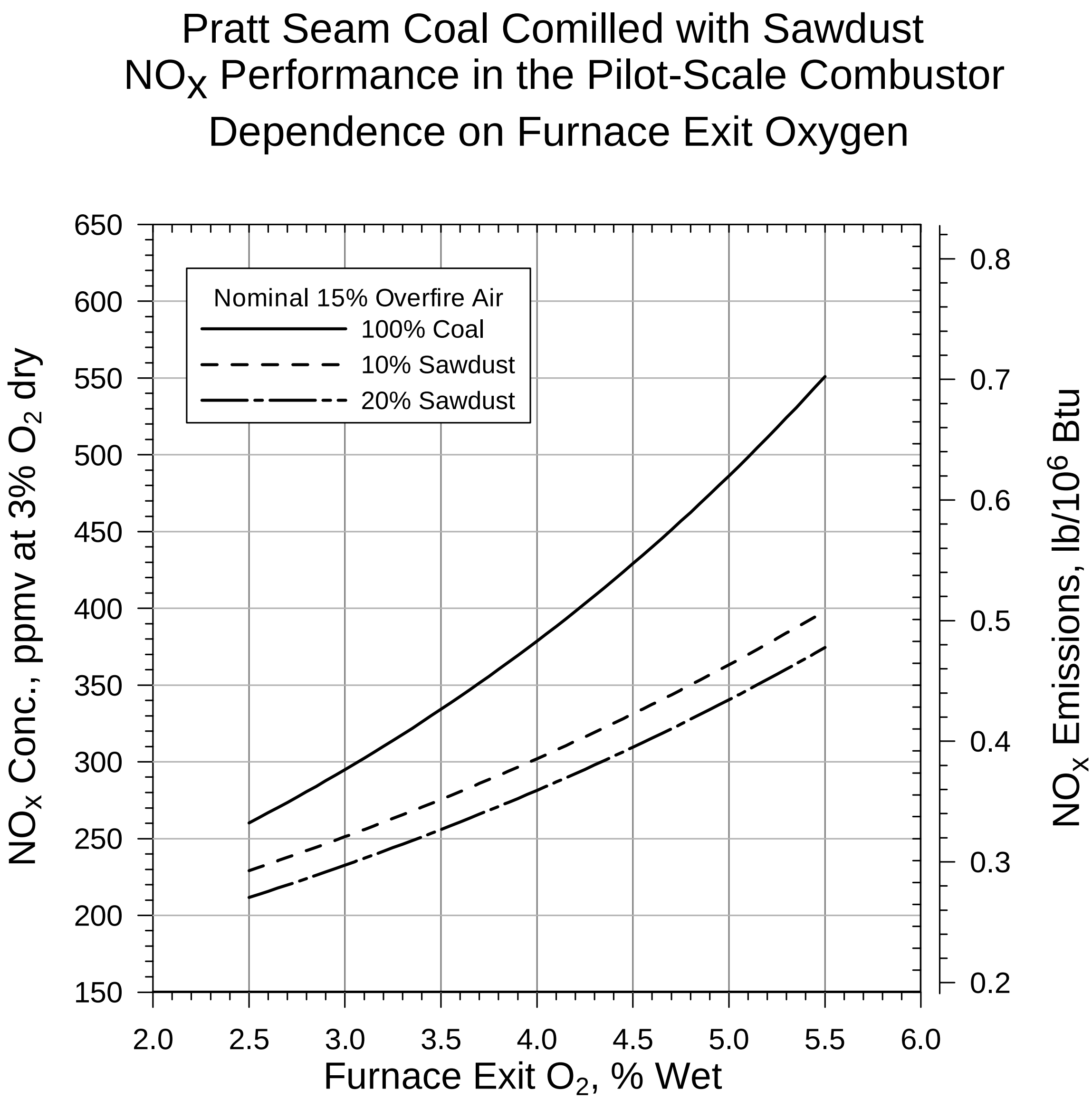


Figure 3. Pratt seam coal co-milled with weight percents of 10% and 20% hardwood sawdust. NOx emissions as a function of furnace exit oxygen at an overfire air level of 15%.

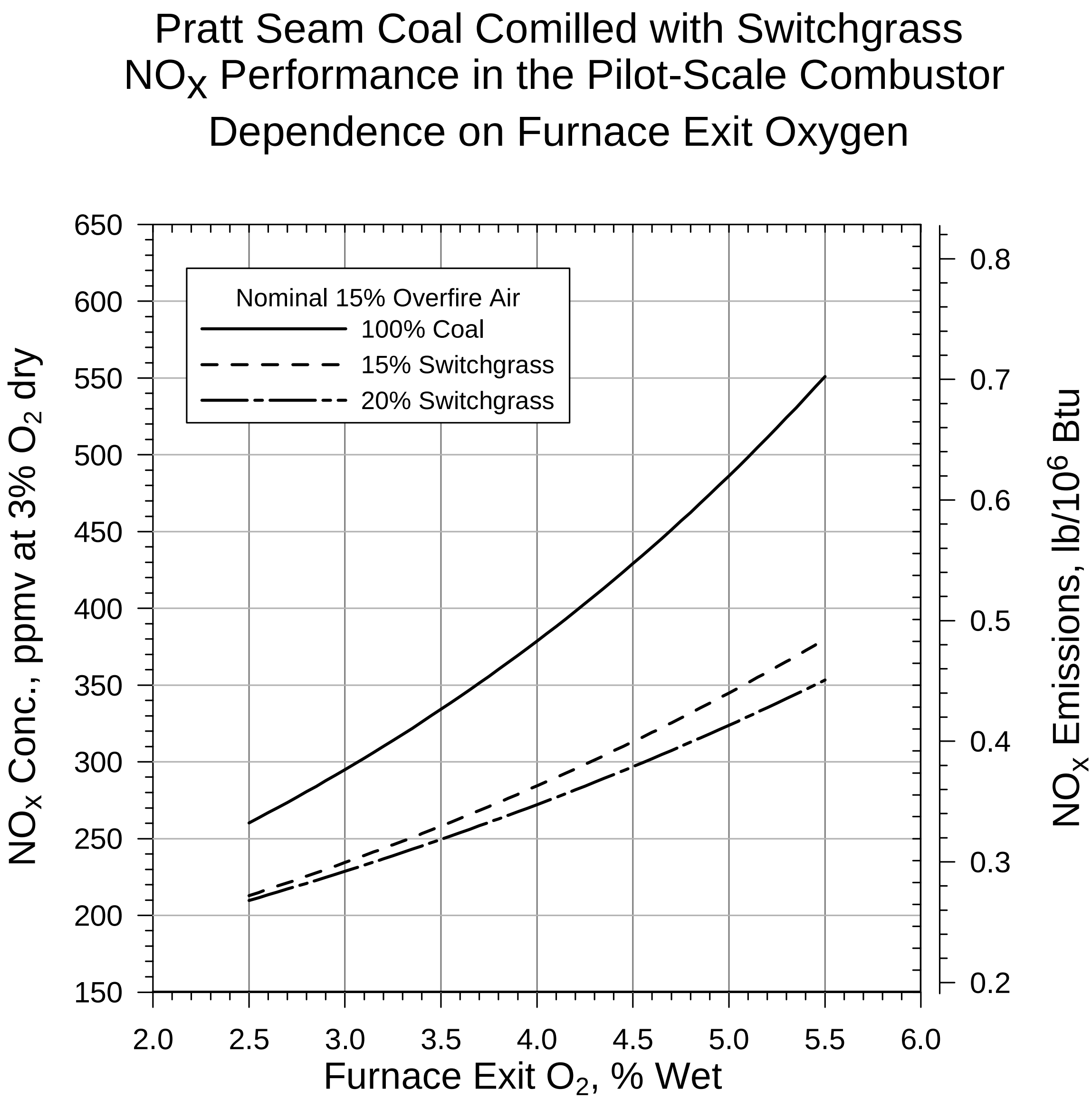


Figure 4. Pratt seam coal co-milled with weight percents of 15% and 20% switchgrass. NOx emissions as a function of furnace exit oxygen at an overfire air level of 15%.

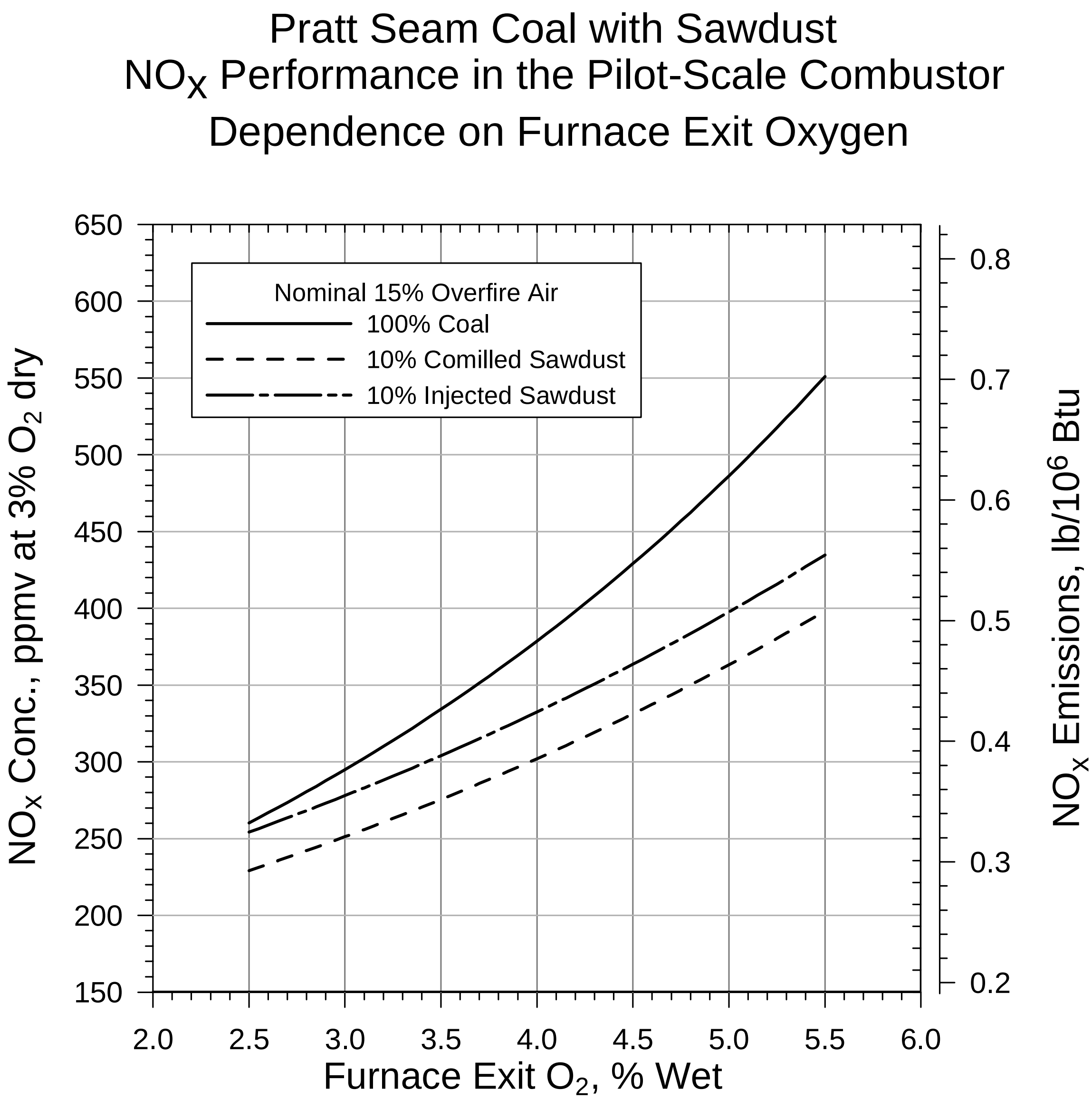


Figure 5. Pratt seam coal co-milled with a weight percent of 10% hardwood sawdust and Pratt seam coal burned with a weight percent of 10% hardwood sawdust injected through the center of the single-register burner. NOx emissions as a function of furnace exit oxygen at an overfire air level of 15%.

As Table 1 and Figures 1-5 show, in terms of the percentage of NOx reduced, the greatest reductions are achieved at a level of 15% overfire air. At 0% overfire air, 20 weight percent co-milled sawdust (Figure 1) appears to show no improvement in NOx reduction. Also, at 0% overfire air, 15 weight percent co-milled switchgrass has a much lesser effect than 20 weight percent co-milled switchgrass. These data sets will be further reviewed and compared with data from Test 3 to determine if such behavior is anomalous.

Comparing co-milled data sets for 15% overfire air, NOx reductions with 10 or 15 weight percent biomass addition are near to those achieved with 20 weight percent addition. At 20 weight percent addition, co-milled switchgrass or sawdust offer reductions in NOx emissions of 25% and 23%, respectively. At 15 weight percent addition, co-milled switchgrass yields a NOx reduction of 23% and at 10 weight percent addition, co-milled sawdust yields a NOx reduction of 17%.

Finally, for the single useful dataset from Test 2, Figure 5 shows that at 10 weight percent addition, NOx reductions are almost 8% greater with co-milled sawdust than with sawdust injected through the center of the burner.

The next quarterly report will contain more data from the first two tests and data from the third test. In particular, unburned carbon present in fly ash samples obtained by isokinetic flue gas sampling will be presented.

Size Reduction of Biomass

In the first Quarterly Report, we reported that SoRI had been contacted by Mesa Reduction Engineering and Processing, Inc., a company that produces a unique collision mill that can be used to reduce biomass to an almost powder-like state. Size of the biomass was added as a test variable during contract negotiations since it is anticipated to affect the burnout and reaction rates during combustion. We have concluded a subcontract with Mesa so that we can generate and test a consistently sized biomass product during pilot-scale tests where biomass is not co-milled. Messa processed the sawdust and switchgrass used in Tests 2 and 3. A portable version of the Mesa collision mill may be available for the preparation of finely divided biomass for co-milling with coal and for direct furnace injection.

DISCUSSION

SRI has provided to REI the information necessary for the production of CFD models of the combustion research facility. To date, two cases have been simulated to include the single register burner configured for testing with coal or co-milled biomass. These simulations are prerequisite to the NOx and carbon burnout modeling. REI reports on the first two simulations are included in Appendix A

NEA has continued to make progress in the development of an innovative approach for the construction of the process model that will yield predictions of NOx emission rates and carbon burnout efficiency. This approach is being developed to help determine the system of reactors in which the CBK, Chemkin III® and bio-Flashchain® modules are used in the PC Coal Lab® calculations of NOx and unburned carbon.

Initial pilot-scale tests have investigated the addition of co-milled sawdust and switchgrass, each mixed at two concentrations with a bituminous coal. After a period of development, a method has been refined that will allow for the injection of up to 20% of finely divided biomass in various locations in the pilot-scale furnace. Biomass processed by Mesa Reduction Engineering and Processing, Inc. is processing all biomass that will be injected into the furnace. Further testing has just been completed where biomass was injected through the center of the single register burner. The results of those tests are under review. Once we are satisfied that the data form a consistent set of results, we will continue tests with the same biomasses for another furnace injection location (side injection into the flame) and start acquiring other coals. Since test results will provide the experimental data to validate the modeling approach, it is advantageous for these initial tests to be simple co-firing cases.

CONCLUSIONS

Important progress has been made in model development and in pilot-scale furnace testing. In particular, software development for the modeling effort and an innovative approach toward defining reaction zones in a combustion system is proceeding. This development is a generally applicable algorithm that, if proven successful, should benefit other process modeling efforts in which carbon consumption or conversion is a major component. Two pilot-scale furnace tests were concluded in the second quarter and further testing is proceeding.

Expenditures have remained less than projected. Scheduling delays are partly responsible for lower billings than planned from NEA. REI expects that the CFD modeling effort will continue to experience more intense activity in the third quarter of CY 2001. Also, because of other work at the SRI/SCS Pilot-Scale Combustor and field test commitments, not as many hours were expended by SRI as were scheduled for planning and preparation. However, during the third quarter of 2001 more intensive project activity is expected.

Plans for the next quarter include continued CFD simulations by REI, Inc., software development to implement the equivalent reactor network analysis of the fuel-N conversion chemistry by NEA, and continued combustor runs with sawdust and switchgrass. In the third combustor run, sawdust and switchgrass were directly injected through the center of the single register burner at target levels of 10% and 20% (mass basis). In the fourth combustor run, it is planned to inject biomass off the axis of the burner, directly into the flame.

APPENDIX A

Reports of CFD simulations completed by REI, Inc.

SoRI
Single Register Burner
GLACIER Simulation

1

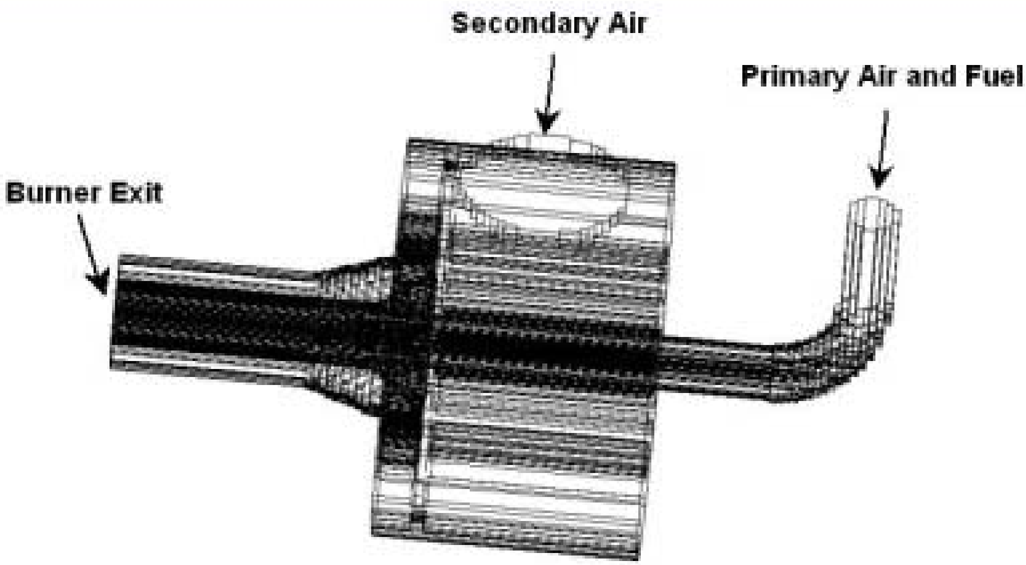
Operating Conditions

- Single register burner: 3.793 MMBTU/HR
- Prim/Sec/Tertiary Air Split
  18% / the balance / 0, 15, or 30 %
- 3.1% O_2 wet
- Coal feed rate: 291.14 LB/HR
- Pratt seam coal

	Flow rate [SCFM]	Temperature [F]
Primary air	131.90	149.95
Secondary air	460.31	600.08
Tertiary air	104.18	600.00

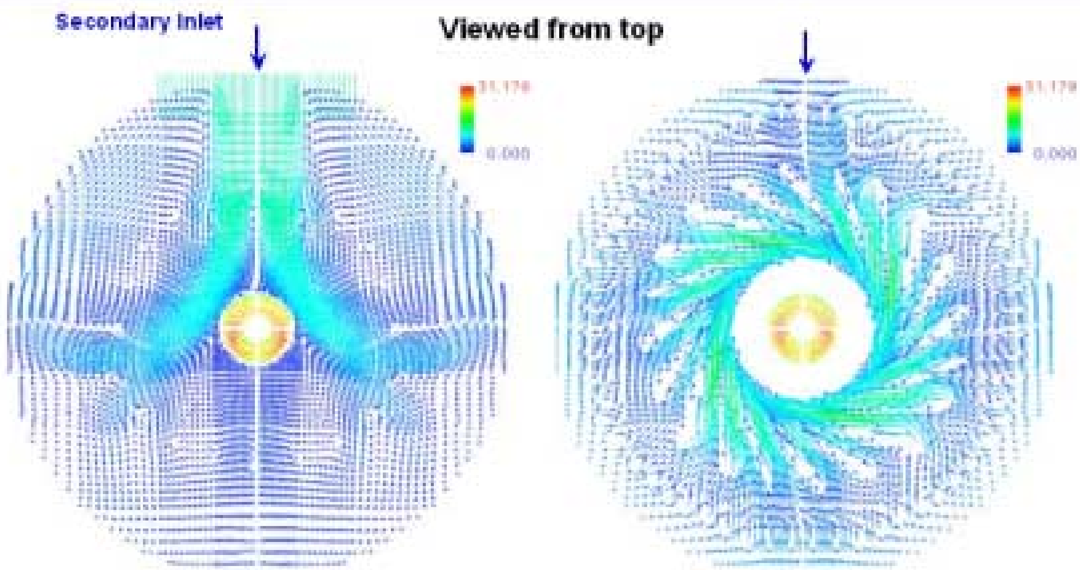
2

Schematic of Single Register Burner



3

Primary and Secondary Air Stream

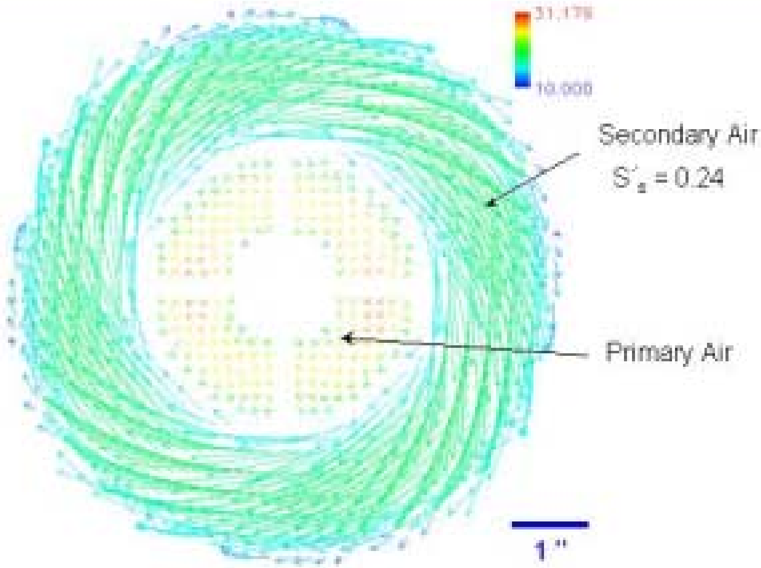


18.8" from the bottom of the primary inlet 27.3" from the bottom of the primary inlet

Gas stream direction shown with color representing magnitude

4

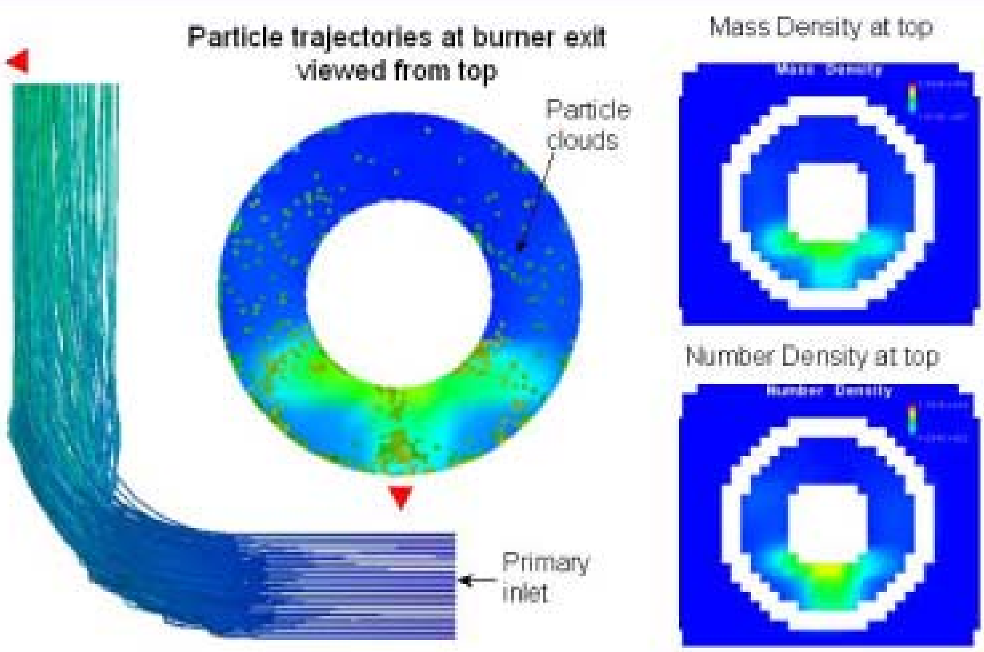
Air Stream at Burner Exit



Viewed from top
44.9" from the bottom of the primary inlet

5

Coal Particle Stream



6

Summary

• *GLACIER* Simulation for single register burner has been performed
  - Pratt seam coal
  - Exit data will be used for the furnace inlet boundary conditions

• Asymmetric particle distribution at burner exit was observed (Slide #6)

• Swirl number for secondary was about 0.24 at the burner exit that was reduced from 0.60 at the exit of swirl generator.

• Furnace and convective section setup is complete and a simulation will be performed.

7

SoRI

FURNACE BASELINE
GLACIER Simulation

March 21, 2001

1

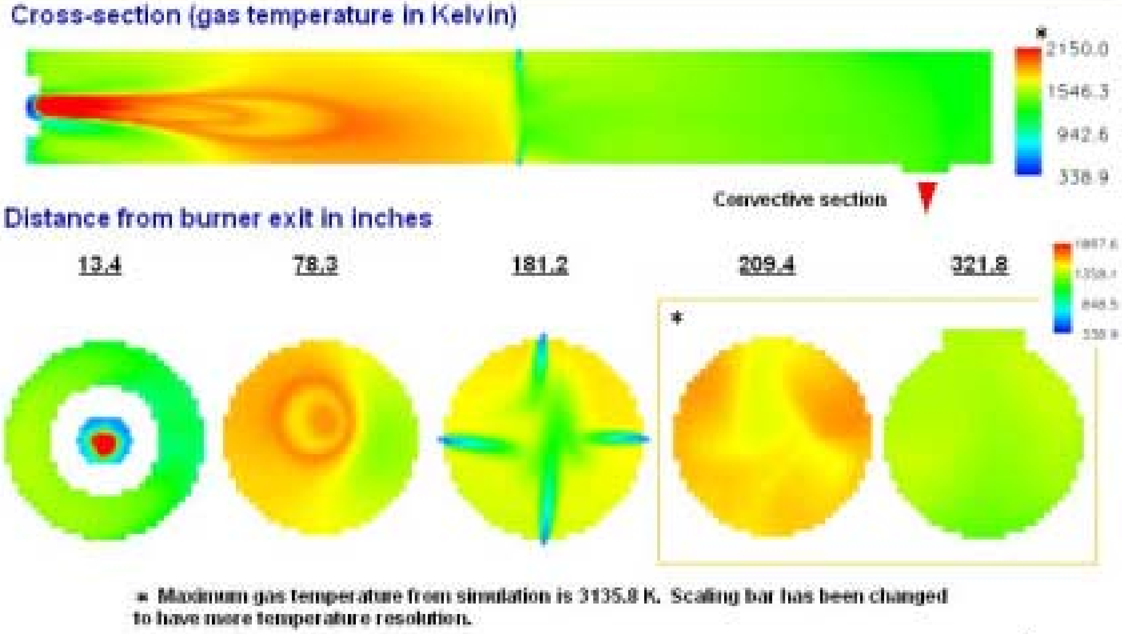
Burner Operating Conditions

- Single register burner: 3.793 MMBTU/HR
- Prim/Sec/Tertiary Air Split
  18% / the balance / 0, 15, or 30 %
- 3.1% O_2 wet
- Coal feed rate: 291.14 LB/HR
- Pratt seam coal

	Flow rate [SCFM]	Temperature [F]
Primary air	131.90	149.95
Secondary air	460.31	600.08
Tertiary air	104.18	600.00

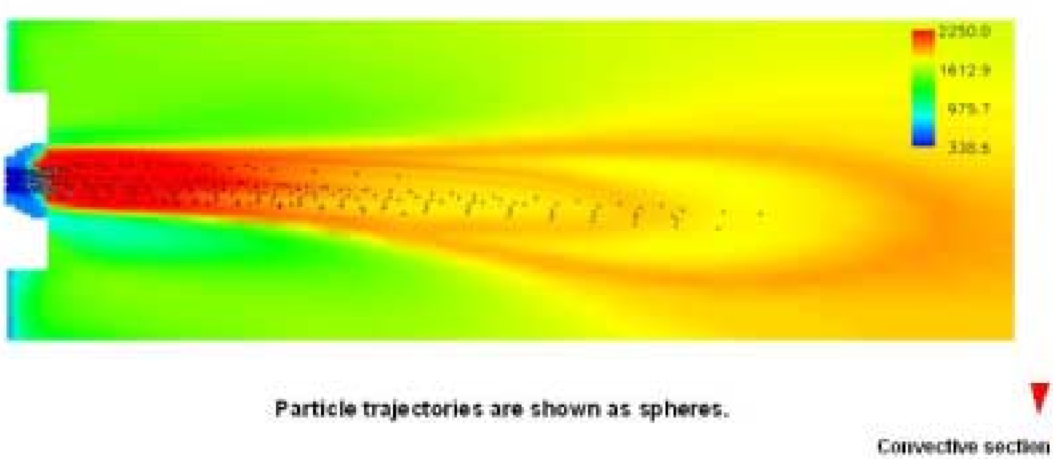
2

Furnace Sections



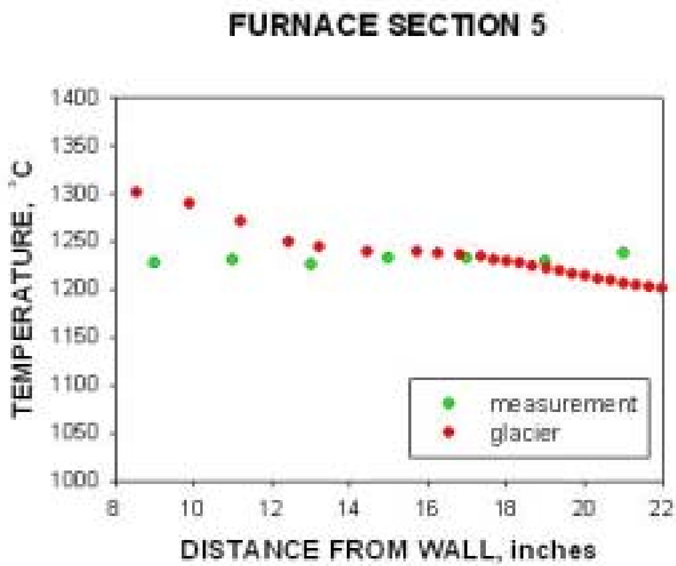
3

Particle Trajectory



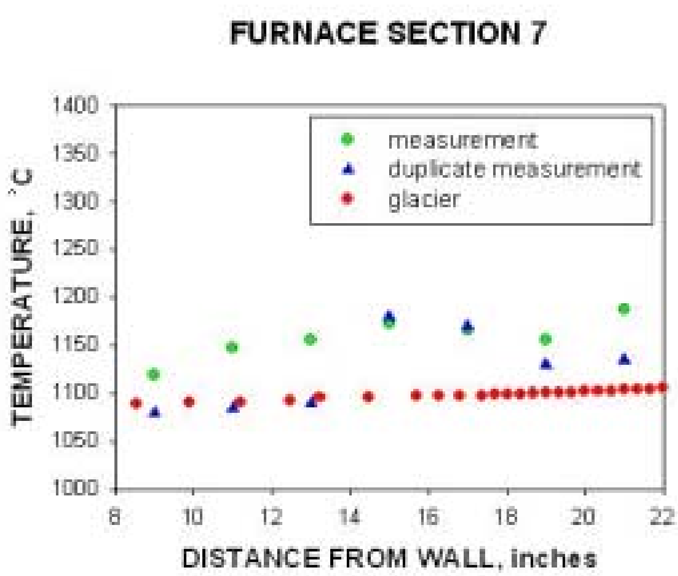
4

Temperature Profile



5

Temperature Profile



6

SUMMARY

• Baseline study on Pratt seam coal was performed.

• Biased flame structure and particle trajectories were observed.

• Temperatures from the simulation were compared well with the measurements at furnace section 5 and 7.

7

APPENDIX B

Results of Pilot-Scale Combustor Tests 1 and 2

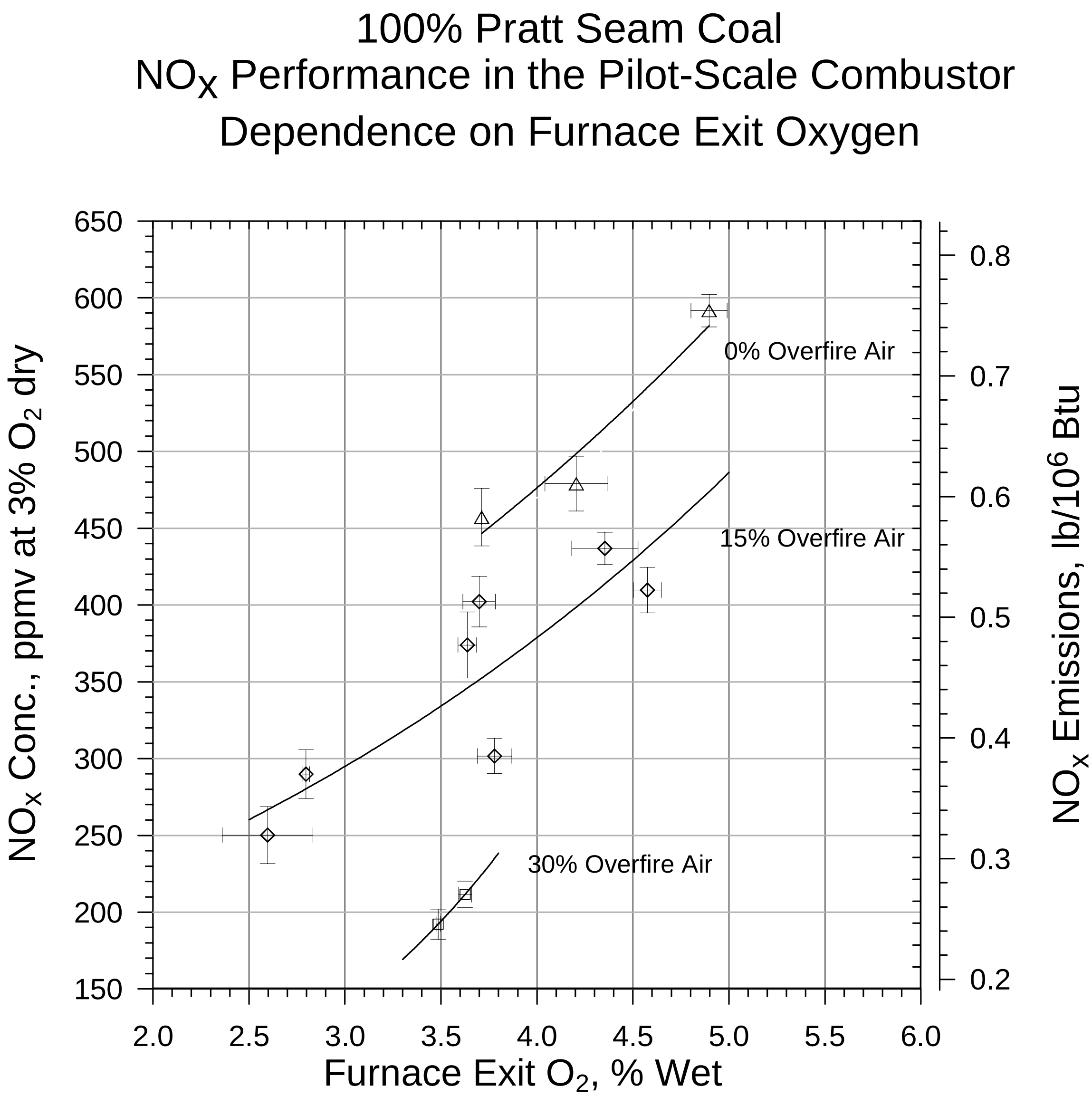


Figure 1. 100% Pratt seam coal. NOx emissions as a function of furnace exit oxygen at overfire air levels of 0%, 15%, and 30%.

10% Sawdust - 90% Pratt Seam Coal
NO_X Performance in the Pilot-Scale Combustor
Dependence on Furnace Exit Oxygen

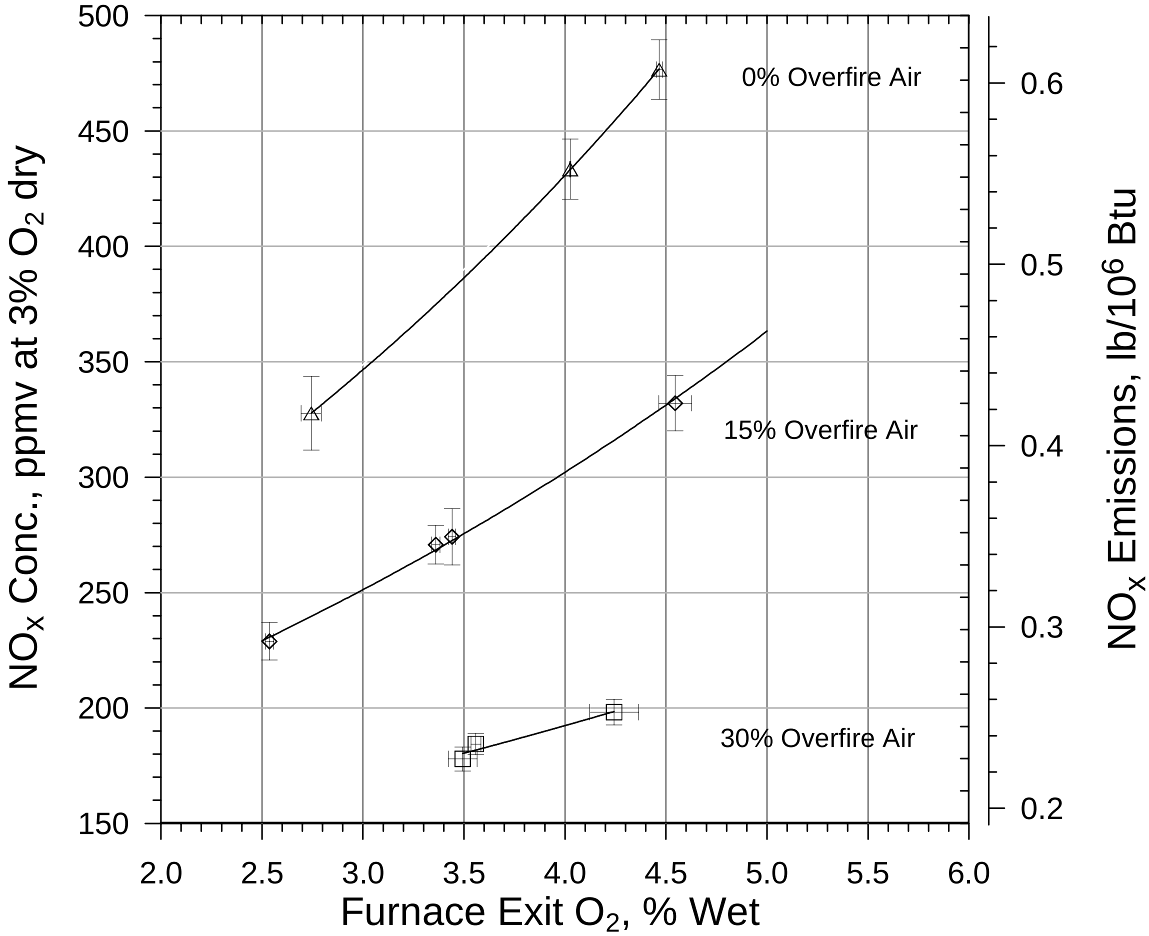


Figure 2. 10% sawdust co-milled with 90% Pratt seam coal. NOx emissions as a function of furnace exit oxygen at overfire air levels of 0%, 15%, and 30%.

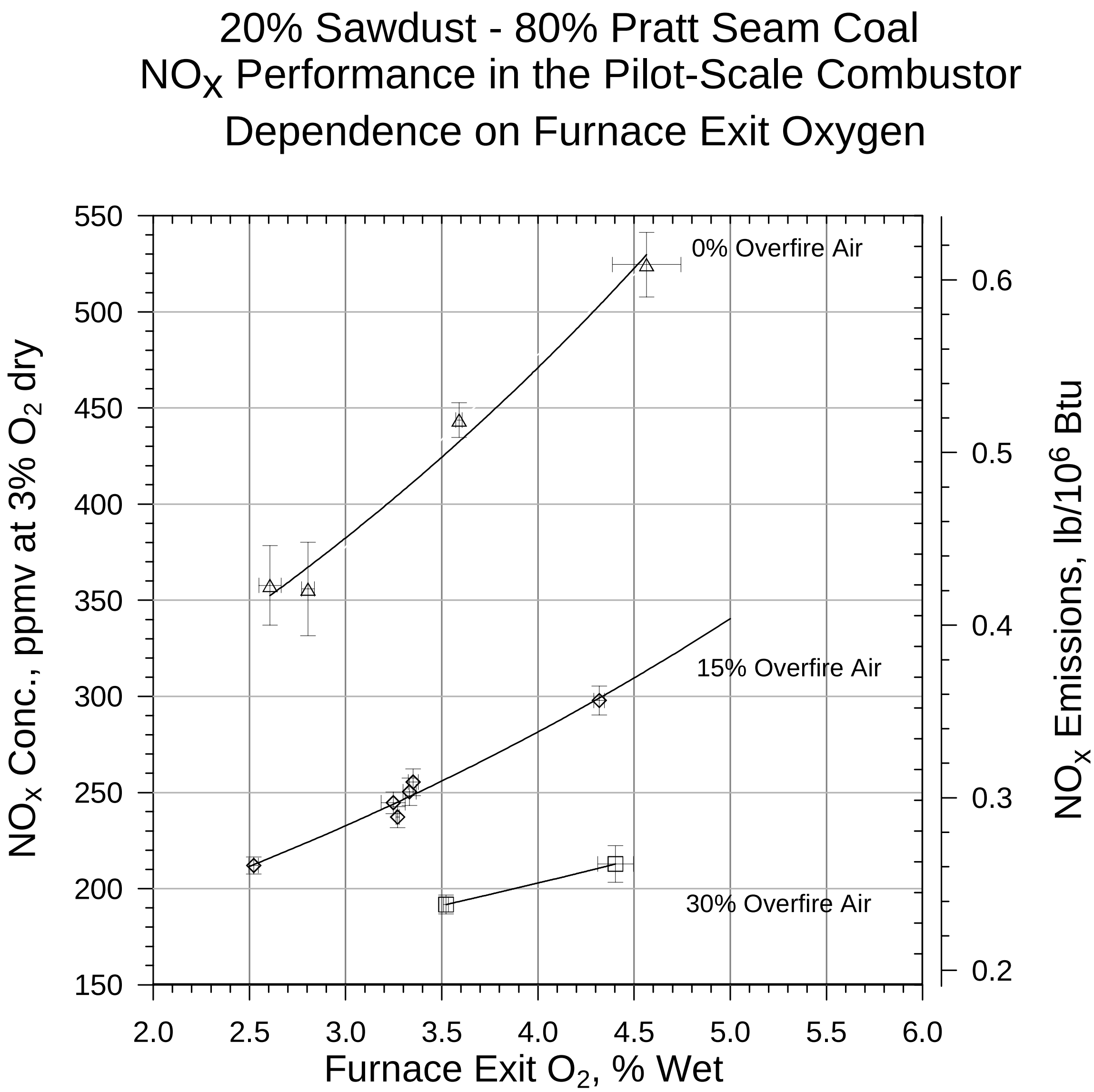


Figure 3. 20% sawdust co-milled with 80% Pratt seam coal. NOx emissions as a function of furnace exit oxygen at overfire air levels of 0%, 15%, and 30%.

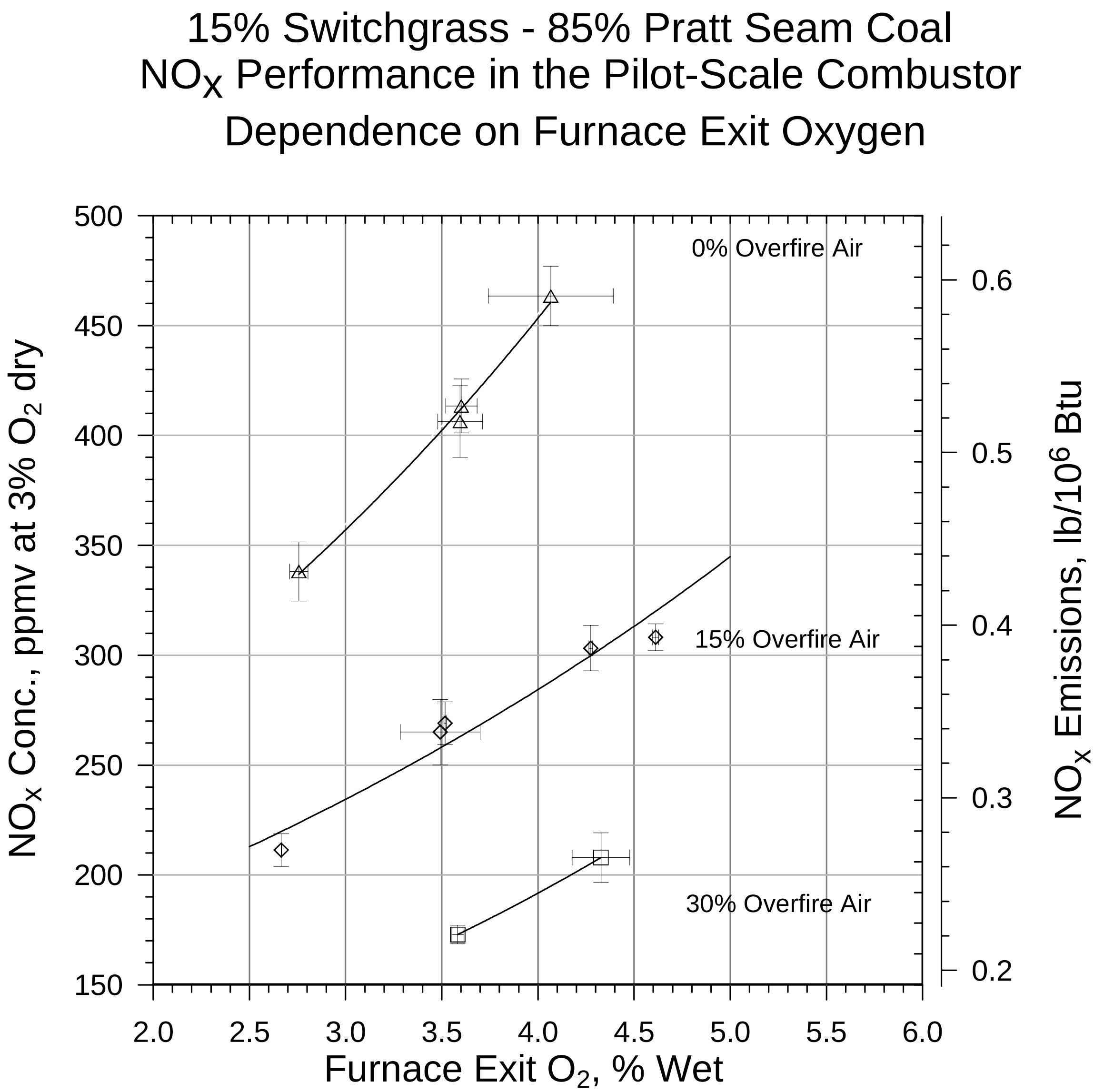


Figure 4. 15% switchgrass co-milled with 85% Pratt seam coal. NOx emissions as a function of furnace exit oxygen at overfire air levels of 0%, 15%, and 30%.

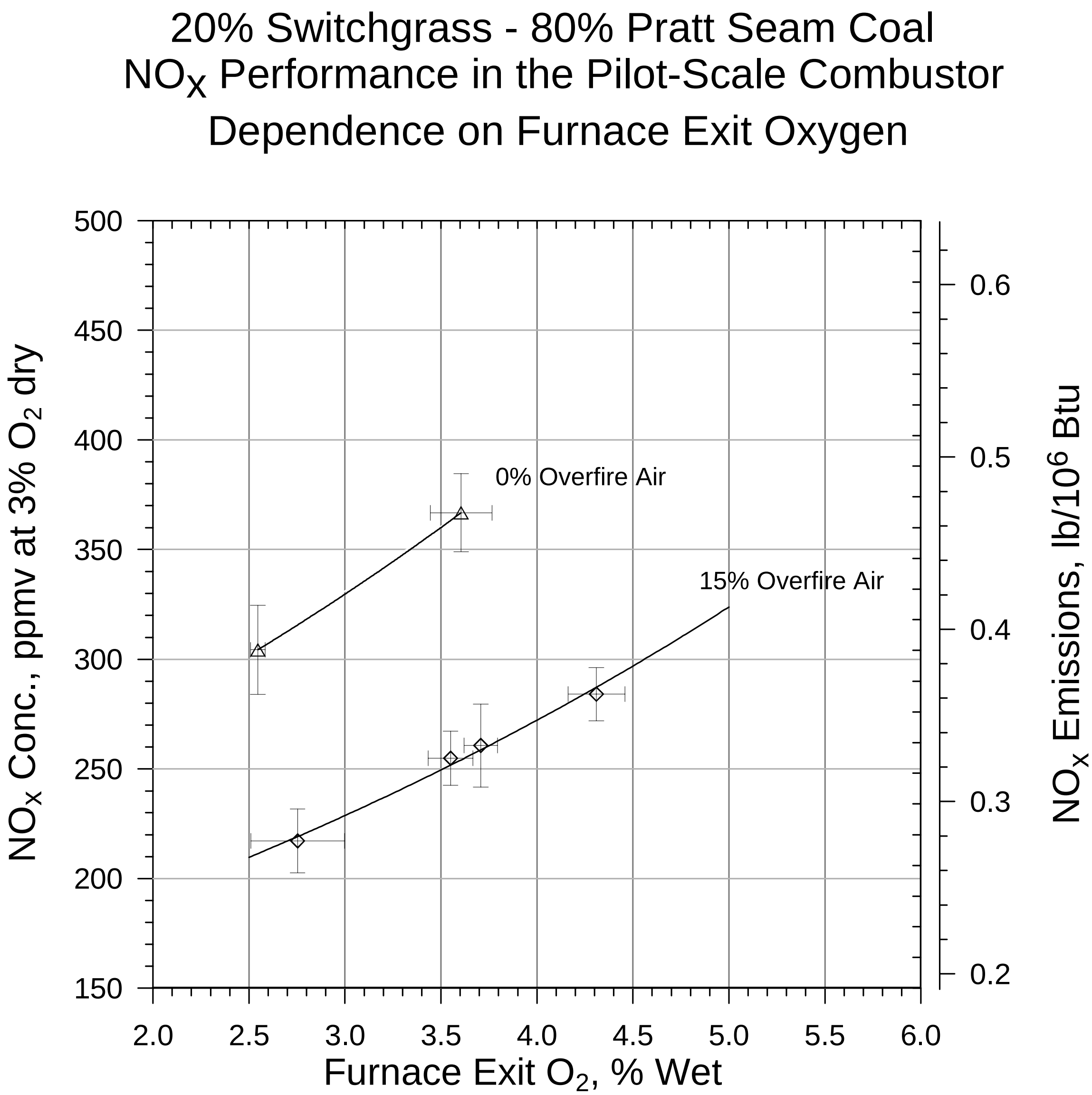


Figure 5. 20% switchgrass co-milled with 80% Pratt seam coal. NOx emissions as a function of furnace exit oxygen at overfire air levels of 0% and 15%.

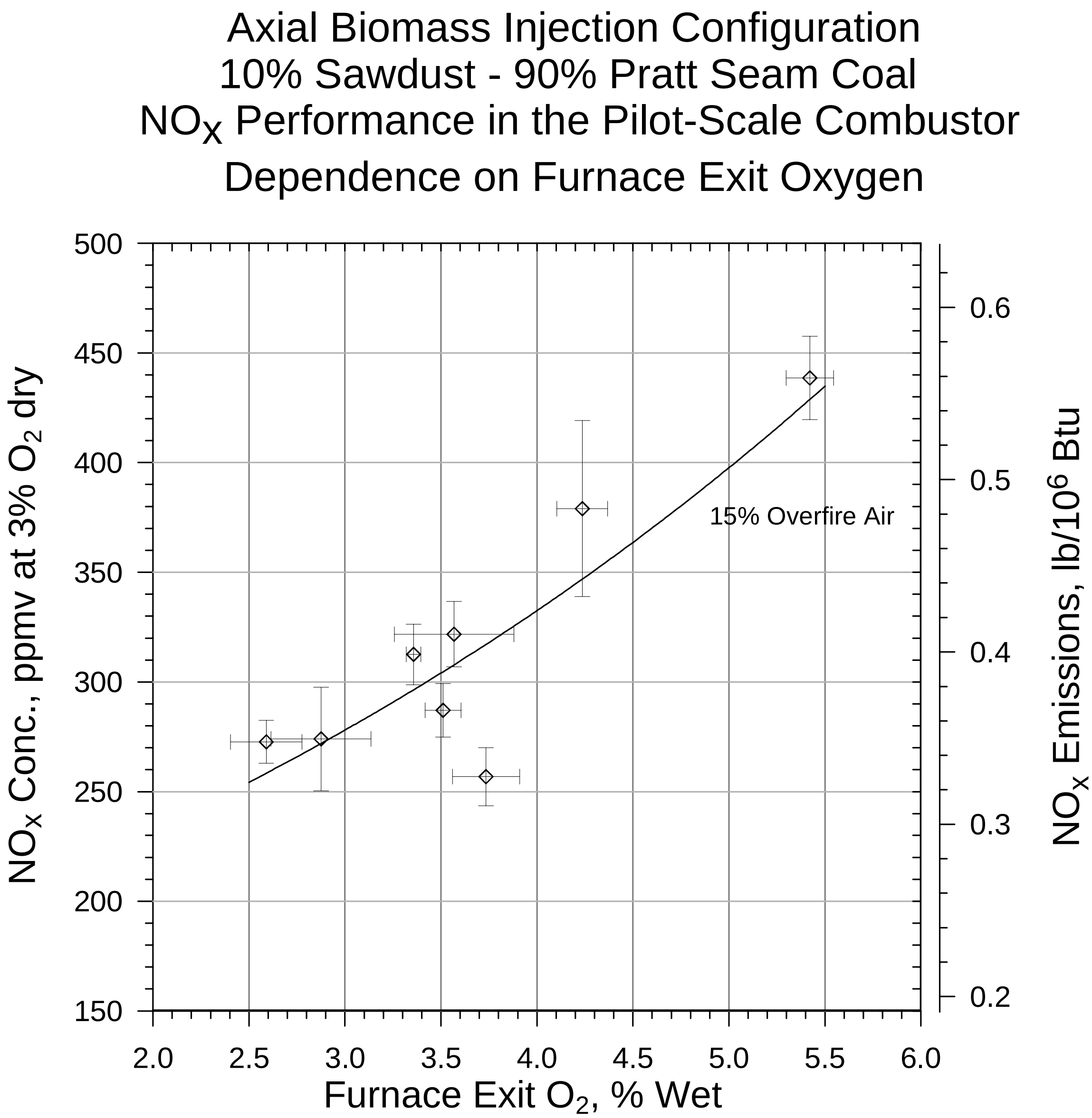


Figure 6. 10% sawdust injected through the center of the single register burner with 90% Pratt seam coal. NOx emissions as a function of furnace exit oxygen at an overfire air level of 15%.