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

Quarterly Report

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ABSTRACT

This is the seventh 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 additional biomass co-firing test burns were conducted during this quarter. In the first test (Test 12), up to 20% by weight dry hardwood sawdust and switchgrass was comilled with Galatia coal and injected through the single-register burner. Liquid ammonia was intermittently added to the primary air stream to increase fuel-bound nitrogen and simulate cofiring with chicken litter. Galatia coal is a medium-sulfur (~ 1.2% S), high chlorine (~0.5%) Illinois Basin coal. In the second test (Test 13), up to 20% by weight dry hardwood sawdust and switchgrass was comilled with Jim Walters #7 mine coal and injected through the single-register burner. Jim Walters #7 coal is a low-volatility, low-sulfur (~ 0.7% S) Eastern bituminous coal. The results of these tests are presented in this quarterly report. Progress has continued to be made in implementing a modeling approach to combine reaction times and temperature distributions from computational fluid dynamic models of the pilot-scale combustion furnace with char burnout and chemical reaction kinetics to predict NO_X emissions and unburned carbon levels in the furnace exhaust. The Configurable Fireside Simulator has been delivered from REI, Inc. and is being tested with exiting CFD solutions. Preparations are under way for a final pilot-scale combustion experiment using the single-register burner fired with comilled mixtures of Jim Walters #7 low-volatility bituminous coal and switchgrass. Because of the delayed delivery of the Configurable Fireside Simulator, it is planned to ask for a no-cost time extension for the project until the end of this calendar year. Finally, a paper describing this project that included preliminary results from the first four cofiring tests was presented at the 12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection in Amsterdam, The Netherlands, in June, 2002.

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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 (NO_X) formation with the complementary modeling effort that will yield a capability to predict, and therefore optimize, NO_X 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 NO_X, unburned carbon (UBC), and other emissions over a broad domain of biomass composition, coal quality, and co-firing injection configurations to quantify the dependence of NO_X 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 NO_X emissions and UBC. Niksa Energy Associates (NEA) will develop and validate a detailed process model for predicting NO_X 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 fluid dynamics data will be produced from computer models developed by Reaction Engineering International (REI). The modeling process 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 full-scale 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.

RESULTS

Model Development

The three independent aspects of modeling for this project are (1) the mechanisms for fuel devolatilization and char burnout, and (2) the detailed chemical mechanism for combustion and fuel-N conversion in the gas phase, and (3) the equivalent reactor network. Niksa Energy Associates (NEA) has integrated these three aspects into a working version of the NO_X – unburned carbon predictive model and have been testing the model over the range of coal types, biomasses, and fuel injection configurations in Tests 1-6.

Generally speaking, the predicted NO_X emissions agree with the experimental data within experimental uncertainties for all biomass fuel types, excess O_2 levels, and extents of air staging. The predicted unburned carbon (UBC) levels were less accurate, but were generally consistent with the qualitative tendencies in the data. *This level of performance was achieved without any adjustments to the model parameters for any of the biomass cofiring cases*. Instead, calibration factors were specified to match the predicted and observed emissions for the coal-only tests for all excess O_2 levels, and extents of air staging. These same calibration factors were then applied to the operating conditions for the co-fired flames in Test 1. *In this way, the entire Test 1 series was simulated with the detailed chemical reaction mechanisms, based on only two CFD simulations from REI: for the coal-only case and one for the 20% sawdust case at 3.5% furnace exit O_2 with 15% overfire air*.

Comparisons with later tests with Powder River Basin coal must wait until CFD simulations are completed. With the delivery of REI's Configurable Fireside Simulator for the Pilot-Scale Combustion Research Facility, these CFD simulations will completed after initial software tests are completed.

CFD Simulations

Reaction Engineering International, Inc. (REI) delivered the completed Configurable Fireside Simulator on June 6. This program provides a complete CFD simulation of the SRI Pilot-Scale coal Combustion Research Facility with a single-register burner. Unfortunately, because the development of this software required more time and resources that REI had initially estimated, the option of simulating the dual-register burner was eliminated in the final version of this program. Thus, we will not be able to extend the NO_X model to directly simulate low-NO_X burners. The software is presently being tested. The first new calculation to be completed will for Jacobs Ranch Powder River Basin coal. This will be followed with various comilling cases of this fuel with switchgrass and sawdust. After the PRB simulations are completed, the same set of calculations will be completed with Jim Walters #7 low-volatility coal.

Pilot-Scale Combustor Testing

Furnace Testing Thirteen furnace tests have been completed through the end of March, 2002. Tests 1 through 11 have been reviewed in previous quarterly progress reports. Test 12 (conducted in April, 2002) and Test 11 (conducted in May, 2002) are reviewed below. Table 1 summarizes the tests that have been completed through the end of March, 2002. Figure 1 shows the various locations used for biomass injection.

As indicated above, in this Quarterly Progress Report we present and comment on the results obtained in Tests 12 and 13. In Test 12, 5%, 10% and 20% by weight dry hardwood sawdust was comilled with Galatia coal and injected through the single-register burner. Galatia coal is a medium-sulfur Illinois Basin high-volatility bituminous coal (~ 1.2% S). In the second test, Test 13, two coals were burned. First, the same Galatia coal burned in Test 12 was burned by itself, so that in-furnace char sampling could be performed with a specially designed probe that was not available for use in Test 12. Then, 5%, 10%, and 20% by weight dry hardwood sawdust was comilled with Jim Walters #7 mine coal and injected through the single-register burner. Jim Walters #7 mine coal is a low-volatility, low –sulfur, Alabama bituminous coal (~ 0.7% S, ~20% volatiles). Also, for each fuel, liquid ammonia was injected into the primary air line to increase fuel nitrogen and simulate cofiring with chicken litter. Health considerations and odor precluded open drying and mixing of this biomass with coal in the heavily populated urban surroundings of SRI. For these two tests, all coal and biomass were injected through location 1, as shown in Figure 1.

As previously mentioned, all biomass (sawdust and switchgrass) was processed by MESA Reduction Engineering and Processing, Inc. in a collision mill of their design.

Test 12 For this test, from April 7-13, 2002, biomass was comilled with Galatia coal and injected into the furnace at injection location 1 as shown in Figure 1. The coal used in this test was taken from a second shipment of Galatia coal and was thus not identical to the Galatia coal used in Tests 6 and 7. However, the coal came from the same mine and the same seam as the coal used in Tests 6 and 7. Typical proximate and ultimate analyses for this coal, the coal used in Test 13, and the sawdust used in Test 12 are presented in Tables 2 and 3. Table 4 presents the results of proximate and ultimate analyses of pulverized (comilled) mixtures of coal and sawdust.

Testing was uneventful, and all base coal and comilled mixtures combusted well, without appreciable slagging or fouling. However, even though Galatia coal has moderate ash content (~8%), a considerable amount of fly ash and furnace bottom ash was generated from the combustion of this coal (as well as with combustion of the mixtures of coal and biomass). Three levels of furnace exit oxygen were tested (2.5%, 3.5%, and 4.5%) with overfire air levels of 0% (high NO_X) and 15% (low NO_X). Three levels of biomass addition were tested: 5%, 10% and 20% weight content for the dry hardwood sawdust.

Table 1. Tests Completed Through June, 2002

Test 1: Pratt Seam Coal – Comilled Biomass, single register burner (Location 1), 15%, 20% Switchgrass, 10%, 20% Sawdust. 0%, 15%, 30% overfire air. 1/28-2/3/01

Test 2: Pratt Seam Coal – Biomass through center of burner (Location 2), single register burner, 10% Sawdust. 0%, 15% overfire air. Problems with biomass injection scheme and flame stability. 2/25-3/2/01

Test 3: Pratt Seam Coal – Biomass through center of burner (Location 2), single register burner, 10%, 20% Switchgrass, 10%, 20% Sawdust. 0%, 15% overfire air. Continued problems with flame stability. 4/8-14/01

Test 4: Pratt Seam Coal – no biomass, single register burner (Location 1), extensive characterization of coal-only firing at 0% and 15% overfire air. Corrected flame stability problem. 5/14-17/01

Test 5: Pratt Seam Coal – Biomass injection toward quarl (Location 3), single register burner, 10%, 20% Switchgrass, 10%, 20% Sawdust. 0%, 15% overfire air. 6/10-15/01

Test 6: Galatia Coal – Comilled Biomass, single register burner (Location 1), 10%, 20% Sawdust. 0%, 15%, overfire air. 7/8-7/13/01 (switchgrass not delivered in time for test)

Test 7: Galatia Coal – Comilled Biomass, single register burner (Location 1), 10%, 20% Switchgrass. 0%, 15%, overfire air. Pratt Seam Coal comilled with 20% sawdust. 8/5-10/01

Test 8: Jacobs Ranch Coal – Comilled Biomass, single register burner (Location 1), 10%, 20% Switchgrass, 10%, 20% Sawdust. 0%, 15% overfire air. 9/16-21/01

Test 9: Jacobs Ranch Coal – Biomass through center of burner (Location 2), single register burner, 10%, 20% Switchgrass, 10%, 20% Sawdust. 0%, 15% overfire air. 10/21-26/01

Test 10: Galatia Coal – Comilled Biomass, dual register burner (Location 1), 10%, 20% Switchgrass, 10%, 20% Sawdust. 0%, 15%, overfire air. 1/6-11/02

Test 11: Pratt Seam Coal – no biomass, single register burner (Location 1), regular (~70%<200 mesh) and finely ground (~90%<200 mesh) coal at 0% and 15% overfire air. 2/10-13/02

Test 12: Galatia Coal – Comilled Biomass, single register burner (Location 1), 5%, 10%, 20% Sawdust. 0%, 15%, overfire air. Liquid NH_3 injected into primary air line to increase fuel-bound nitrogen. 4/7-13/02

Test 13: Galatia Coal (only) and Jim Walters #7 coal – Comilled Biomass, single register burner (Location 1), 5%, 10%, 20% Sawdust. 0%, 15%, overfire air. Char sampling below overfire air ports. 5/19-24/02

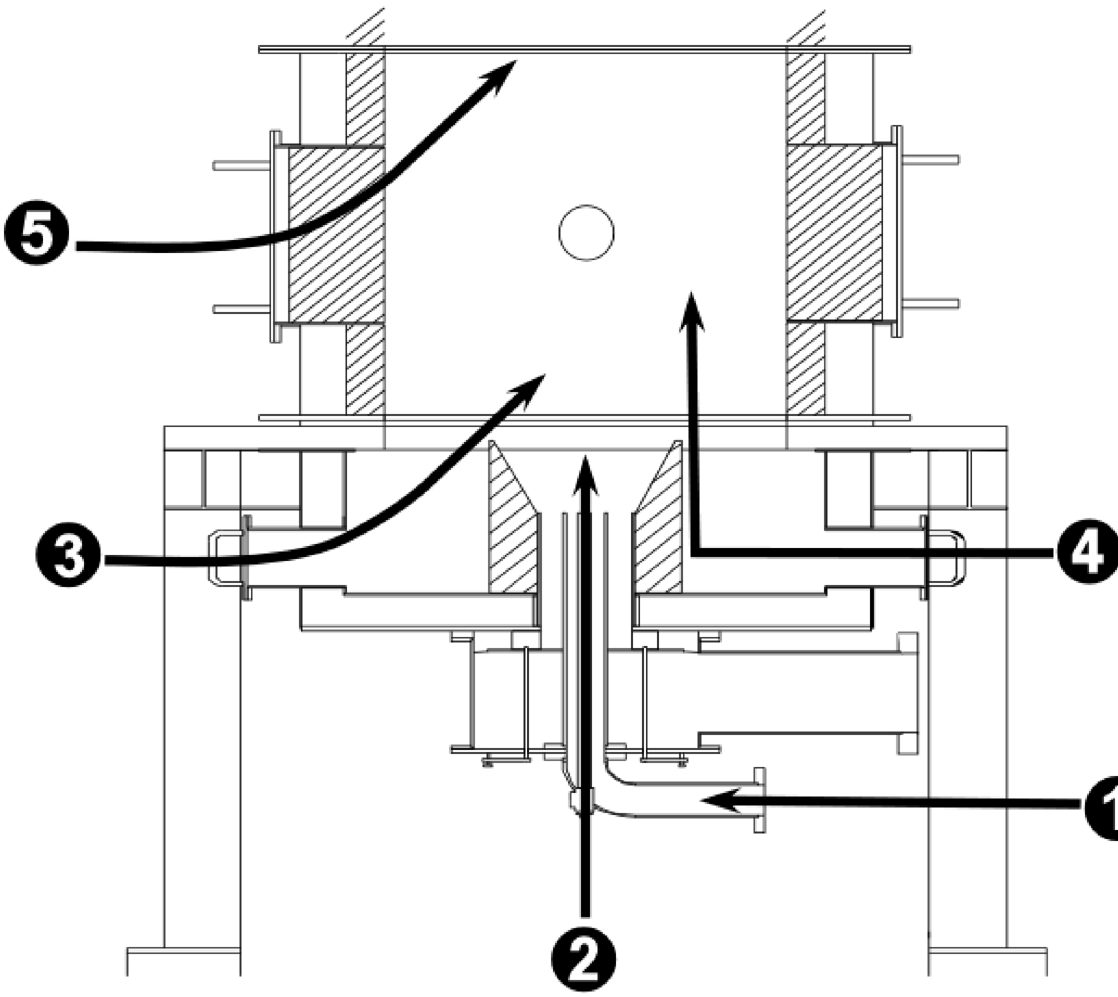

Figure 1. Locations for biomass injection in the SRI/SCS furnace equipped with the single-register burner.

Table 2. Typical Proximate and Ultimate analyses of Fuel Samples from Tests 12and 13.

Sample I.D. Fuel	J947-93-CC-1 Galatia Coal		J947-127-CC-1 JW #7 Coal		J-947-64-SDC-1 Sawdust	
Proximate Analysis	As Rec.	Dry Basis	As Rec.	As Rec.	As Rec.	Dry Basis
Moisture, %	5.21	---	1.96	---	7.45	---
Ash, %	8.16	8.61	12.93	13.19	6.93	7.49
Volatile, %	31.84	33.59	20.45	20.86	63.12	68.20
Fixed Carbon, %	54.79	57.80	64.66	65.95	22.50	24.31
Sum	100.00	100.00	100.00	100.00	100.00	100.00
Heat Content, Btu/lb	12806	13510	13000	13260	7264	7849
Sulfur, %	1.15	1.21	0.73	0.74	0.08	0.09
MAF Btu/lb	---	14783	---	15275	---	8484
Ultimate Analysis	As Rec.	Dry Basis	As Rec.	As Rec.	As Rec.	Dry Basis
Moisture, %	5.21	---	1.96	---	7.45	---
Carbon, %	72.91	76.92	75.43	76.94	42.69	46.13
Hydrogen, %	4.44	4.68	3.85	3.93	5.39	5.82
Nitrogen, %	1.66	1.75	1.45	1.48	1.19	1.29
Sulfur, %	1.15	1.21	0.73	0.74	0.08	0.09
Ash, %	8.16	8.61	12.93	13.19	6.93	7.49
Oxygen (diff.), %	6.47	6.83	3.65	3.72	36.27	39.18
Sum	100.00	100.00	100.00	100.00	100.00	100.00
Chlorine, %	0.21	0.21	0.02	0.02	0.24	0.26
Hardgrove Grindability	53		---	88	---	

Table 3. Proximate and Ultimate analyses of coal feeder discharge samples of Galatia (Illinois Basin) coal and Jim Walters #7 Mine (low volatility Eastern bituminous) coal from Tests 12 and 13.

Sample I.D. Fuel	J947-93-CFD-1 Galatia Coal		J-947-128-CFD-1 Jim Walters #7	
Proximate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	4.53	---	0.75	---
Ash, %	7.46	7.81	14.61	14.72
Volatile, %	35.44	37.12	20.00	20.15
Fixed Carbon, %	52.57	55.07	64.64	65.13
Sum	100.00	100.00	100.00	100.00
Heat Content, Btu/lb	12786	13393	13215	13315
Sulfur, %	1.24	1.30	0.72	0.73
MAF Btu/lb	---	14528	---	15613
Ultimate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	4.53	---	0.75	---
Carbon, %	72.88	76.34	75.72	76.29
Hydrogen, %	4.50	4.71	3.91	3.94
Nitrogen, %	1.70	1.78	1.48	1.49
Sulfur, %	1.24	1.30	0.72	0.73
Ash, %	7.46	7.81	14.61	14.72
Oxygen (diff.), %	7.69	8.06	36.27	2.83
Sum	100.00	100.00	100.00	100.00
Chlorine, %	0.48	0.50	0.01	0.01
Ash Fusion	Reducing	Oxidizing	Oxidizing	Oxidizing
Initial Deformation, °F	2090	2550	2590	2695
Softening, °F	2180	2600	2590	2725
Hemispherical, °F	2275	2645	2665	2765
Fluid, °F	2350	2690	2730	2790

Table 4. Proximate and Ultimate analyses of coal feeder discharge samples of Galatia coal and dry hardwood sawdust from Test 12.

Sample I.D. Fuel	J947-98-CFD-3 5% Sawdust		J947-104-CFD-1 10% Sawdust		J947-109-CFD-1 20% Sawdust	
Proximate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	4.53	---	4.85	---	4.63	---
Ash, %	7.15	7.49	6.69	7.03	6.15	6.45
Volatile, %	35.51	37.20	38.11	40.05	41.48	43.49
Fixed Carbon, %	52.81	55.31	50.35	52.92	47.74	50.06
Sum	100.00	100.00	100.00	100.00	100.00	100.00
Heat Content, Btu/lb	12691	13293	12338	12967	12056	12641
Sulfur, %	1.20	1.26	1.11	1.17	1.01	1.06
MAF Btu/lb	---	14369	---	13897	---	13513
Ultimate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	4.53	---	4.85	---	4.63	---
Carbon, %	72.50	75.94	70.79	74.40	69.64	73.02
Hydrogen, %	4.60	4.82	4.62	4.86	4.75	4.98
Nitrogen, %	1.62	1.70	1.53	1.61	1.43	1.50
Sulfur, %	1.20	1.26	1.11	1.17	1.01	1.06
Ash, %	7.15	7.49	6.69	7.03	6.15	6.45
Oxygen (diff.), %	8.40	8.79	10.41	10.93	12.39	12.99
Sum	100.00	100.00	100.00	100.00	100.00	100.00
Chlorine, %	0.49	0.51	0.46	0.48	0.42	0.44
Ash Fusion	Reducing	Oxidizing	Reducing	Oxidizing	Oxidizing	Oxidizing
Initial Deformation, °F	2125	2555	2080	2470	2120	2525
Softening, °F	2205	2610	2170	2540	2195	2575
Hemispherical, °F	2300	2650	2260	2595	2285	2620
Fluid, °F	2375	2695	2340	2650	2360	2665

One objective of this test was to simulate the cofiring of chicken litter with coal. Chicken litter is an interesting fuel because the amount of fuel nitrogen in this biomass can exceed 5%. Various attempts were made to secure several tons of dry chicken litter but none could be obtained locally or by MESA Reduction Engineering and Processing, Inc. (located in New York State). Large quantities of relatively wet chicken litter are available. However, wet chicken litter has a strong odor and in a densely populated urban area such as the area that surrounds SRI, such an odor source is unacceptable. Further, wet chicken litter contains chicken urine and feces, which can be a biohazard to technicians who would spread the wet litter out to dry or mix the dried material with coal. When dry, dust from this material could constitute a breathing hazard for workers and nearby residents.

After determining that chicken litter was not a viable choice for increasing fuel nitrogen, urea was investigated as a source of fuel nitrogen. Urea is 49% nitrogen and can be mixed with dry sawdust and coal to approximate chicken litter. However, urea is so hydroscopic that it is not distributed in granular form or as a powder, except for very small quantities. Because urea aggressively takes up water from the atmosphere, chemists familiar with this compound warned that the interior of our mill and fuel transport system would become coated with moist urea after milling even small quantities of coal-urea-sawdust mixtures. Exposed iron and steel surfaces contaminated with moist urea are highly susceptible to corrosion, and would be difficult to clean. Thus, this approach was also abandoned.

A third approach to increasing fuel nitrogen was to inject gaseous or liquid ammonia into the primary air line, just upstream of the single-register burner. Discussions with a local ammonia supplier revealed that liquid ammonia was the best choice, as the injection of gaseous ammonia would require large heated tanks to maintain the delivery rates necessary for testing. Accordingly, liquid ammonia was injected into the primary air line where it was allowed to flash into gaseous ammonia.

A variety of schemes for injecting liquid ammonia were evaluated. At first, a chemical metering pump was used to convey liquid ammonia through a heated stainless steel transport line, where it would flash to gaseous ammonia, before it reached the primary air line. However, small chemical metering pumps suitable for ammonia service are not off-the-shelf items. Because of the long lead time required to acquire the proper pump, another scheme was employed to inject liquid ammonia.

The configuration that was used for testing consisted of a ~350 lb tank of liquid ammonia mounted on a calibrated scale that reported the weight of the tank to the combustor data acquisition system. Instructions on each tank required horizontal mounting for proper delivery of liquid ammonia and a cradle was fabricated to hold each tank. Pressure within the tank was used to convey liquid ammonia through a liquid flow meter mounted at the tank discharge point that was connected to a coiled stainless steel transport line that discharged into the primary air line. Liquid ammonia was flashed to gaseous ammonia in the coiled section of the stainless steel line that was kept submerged in a warm water bath. Throughout the test, problems were continually encountered with uneven ammonia delivery to the liquid flow meter and some tests had to be curtailed. Conversations with the ammonia supplier finally revealed that the instructions printed on the side of each tank were in error and that the tanks should have been mounted in an upright position. Once the tanks were mounted upright, the delivery problems were corrected. Unfortunately, the test was nearly over when this discovery was made.

The results of ammonia testing were not as comprehensive as was planned, however, sixteen separate ammonia injection tests were completed for 100% coal, and coal with 5%, 10%, and 20% weight percent sawdust. The results of these tests are presented in Table 5. In this table, furnace exit oxygen, NO_X emissions data, ammonia injection rate and equivalent fuel nitrogen level (from coal, sawdust, and ammonia) are presented. Also presented for each of the 16 tests are expected NO_X emissions if ammonia was not injected. These estimations were derived from curve fits to NO_X emissions data taken during periods when ammonia was not injected. By comparing estimated NO_X emissions for no ammonia injection with NO_X emissions measured during periods of ammonia injection an estimate can be made of the effect of increasing fuel nitrogen through ammonia injection. As Table 5 shows, with 15% overfire air, NO_X emissions were only slightly increased. That is, NO_X emissions were observed to increase with ammonia injection, but frequently by less that the uncertainty (1 standard deviation) in the measurement of the NO_X concentration. Indeed, with a mixture of 95% coal and 5% sawdust, when 17 lb/h of ammonia was added (equivalent to 6.4% fuel N), NO_X emissions were increased by only 7%, while the uncertainty in the NO_X measurement was 8% of the measurement.

With no overfire air, NO_X emissions were noticeably increased by the addition of ammonia. As Table 5 shows, with the exception of one test period (a short test of less than 0.5 hours), NO_X emissions were increased by an average of 22% while the results in Table 5 show that the average uncertainty on the NO_X

Table 5. Results of increasing fuel nitrogen by ammonia addition

Fuel	Furnace Exit O_2 Avg. S.D. %	NO_X @ 3% O_2 Avg. S.D. ppmv	NO_X @ 3% O_2 Calc., No NH_3[1] ppmv	Δ %	Ammonia Feed Rate lb/h	Fuel Nitrogen %
0% OFA						
100% Coal					0.0	1.70
	3.08 ± 0.14	632 ± 59	515	**19**	6.1	3.49
	2.88 ± 0.14	618 ± 80	503	**19**	13.1	5.46
5% Sawdust					0.0	1.62
	3.27 ± 0.13	715 ± 67	523	**27**	9.6	4.35
10% Sawdust					0.0	1.53
	3.33 ± 0.15	741 ± 59	553	**25**	7.0	3.51
	3.02 ± 0.09	550 ± 45	529	**4**	10.2	4.37
	3.11 ± 0.17	728 ± 70	536	**26**	13.4	5.20
20% Sawdust					0.0	1.43
	3.13 ± 0.14	578 ± 47	469	**19**	7.2	3.38
	2.89 ± 0.15	586 ± 41	457	**22**	10.8	4.31
			Average[2]	**22**		
15% OFA						
5% Sawdust					0.0	1.70
	3.64 ± 0.16	359 ± 21	319	**11**	2.2	2.25
	3.39 ± 0.20	328 ± 16	304	**7**	11.4	4.82
	3.63 ± 0.17	342 ± 27	319	**7**	17.2	6.36
10% Sawdust					0.0	1.62
	3.44 ± 0.13	299 ± 17	292	**3**	0.8	1.77
	3.05 ± 0.22	286 ± 23	263	**8**	10.3	4.42
20% Sawdust					0.0	1.43
	4.14 ± 0.17	355 ± 12	321	**9**	0.9	1.68
	3.29 ± 0.13	282 ± 19	267	**5**	2.5	2.13
	3.50 ± 0.18	332 ± 21	280	**16**	12.0	4.63
			Average	**8**		

[1] From curve fits to test data taken with no NH_3 injection
[2] Excluding low value of 4%

measurements was 9% of the measurement. The increase in NO_X emissions does not necessarily correlate with the rate of ammonia injection which may be due, in part, to variations in the amount of ammonia injected from moment to moment. However, there is no doubt that in the absence of overfire air NO_X emissions are increased by the addition of ammonia.

With respect to test data acquired during periods of no ammonia injection, Figure 2 presents NO_X emissions for 100% Galatia coal firing for the single-register burner when Galatia coal was burned during Tests 12 and 13. For comparison, Figure 3 presents the NO_X emissions for 100% Galatia coal firing for the single-register burner when Galatia coal was burned during Tests 6and 7. Figures 4 through 6 present average NO_X emissions measured during Tests 12 for 5%, 10%, and 20% by weight sawdust comilled with Galatia coal.

Comparison of Figures 2 and 3 suggest that either the Galatia coal burned for Tests 6 and 7 and the Galatia coal burned in Tests 12 and 13 differ in some respect or the combustion conditions were different for the two series of tests. Because Figure 2 contains closely grouped results for two sequential tests with the same fuel and, likewise, Figure 3 contains similarly closely grouped results for two sequential tests with the same fuel, the possibility that combustion conditions differ for the two test series is a reasonable explanation. Indeed, the coal burned in Tests 6 and 7 was exhausted after Test 7 and a new shipment of Galatia coal was received to burn in Tests 12 and 13. While both shipments were taken from the same mine approximately ten months apart, Table 6 shows that proximate and ultimate analyses of coal feeder discharge samples taken for both shipments are similar. However, suction pyrometry measurements reveal significant differences. Figure 4 shows the results of lower furnace suction pyrometry measurements made for 100% Galatia coal firing during Tests 7 and 12 for 15% overfire air and 3.5% furnace exit oxygen. Unfortunately, suction pyrometry data are not available from Test 6 or Test 7 to compare with Test 12 for the condition where the results are most different: at 0% overfire air.

Suction pyrometry data are available from Tests 12 and 13 for the same conditions shown in Figure 4. Figure 5 presents these data and shows that while slight differences exist between furnace temperature measurements made for the two tests the results are quite similar and compared with Figure 4, these results suggest that differences in furnace temperature are responsible for the differences in NO_X emissions recorded in Figures 2 and 3. Finally, all four tests were conducted at statistically the same energy input to the furnace. This

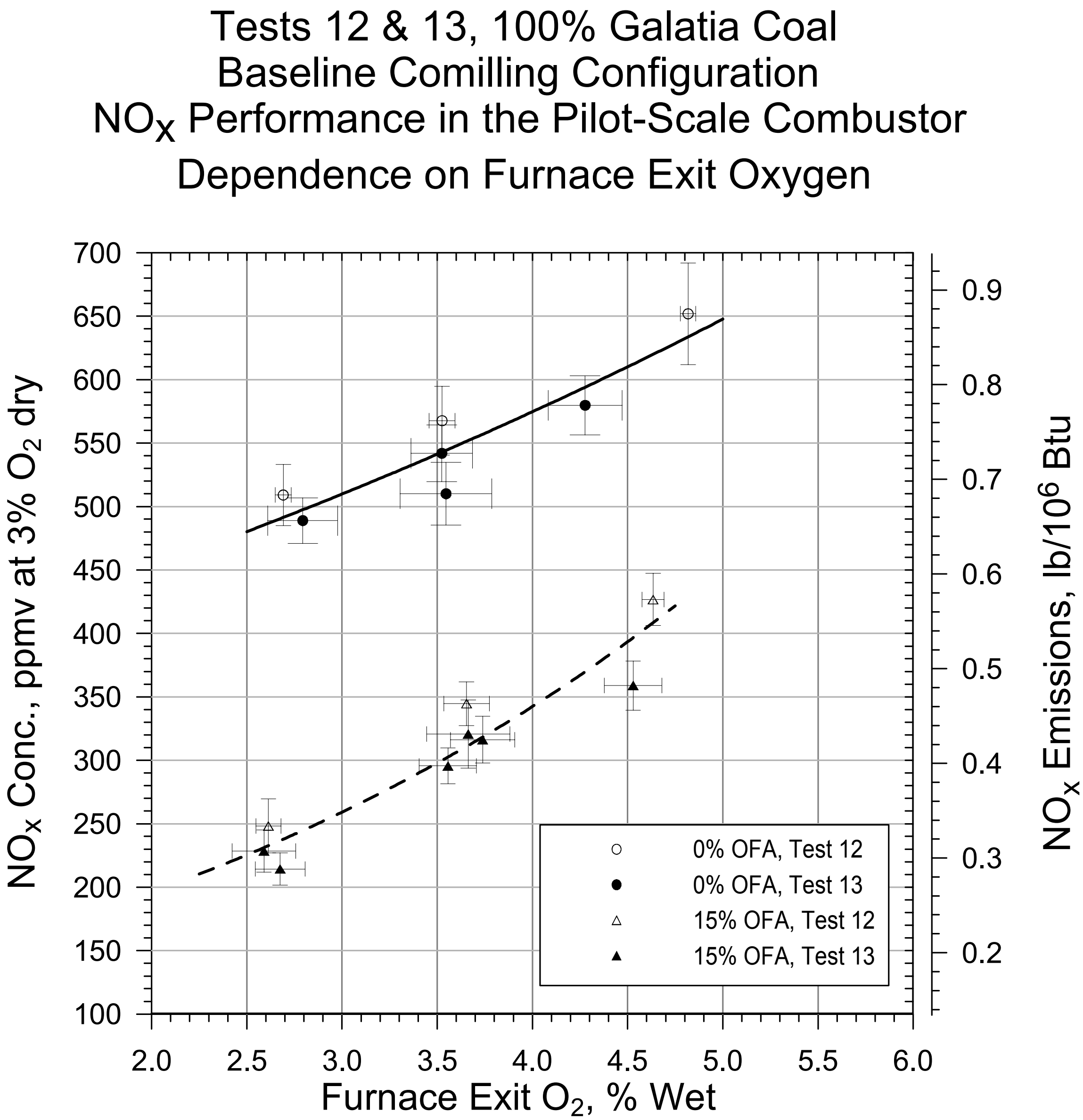

Figure 2. NO_X emissions measured for Galatia coal burned in Tests 12 and 13. Single register burner with 0% and 15% overfire air.

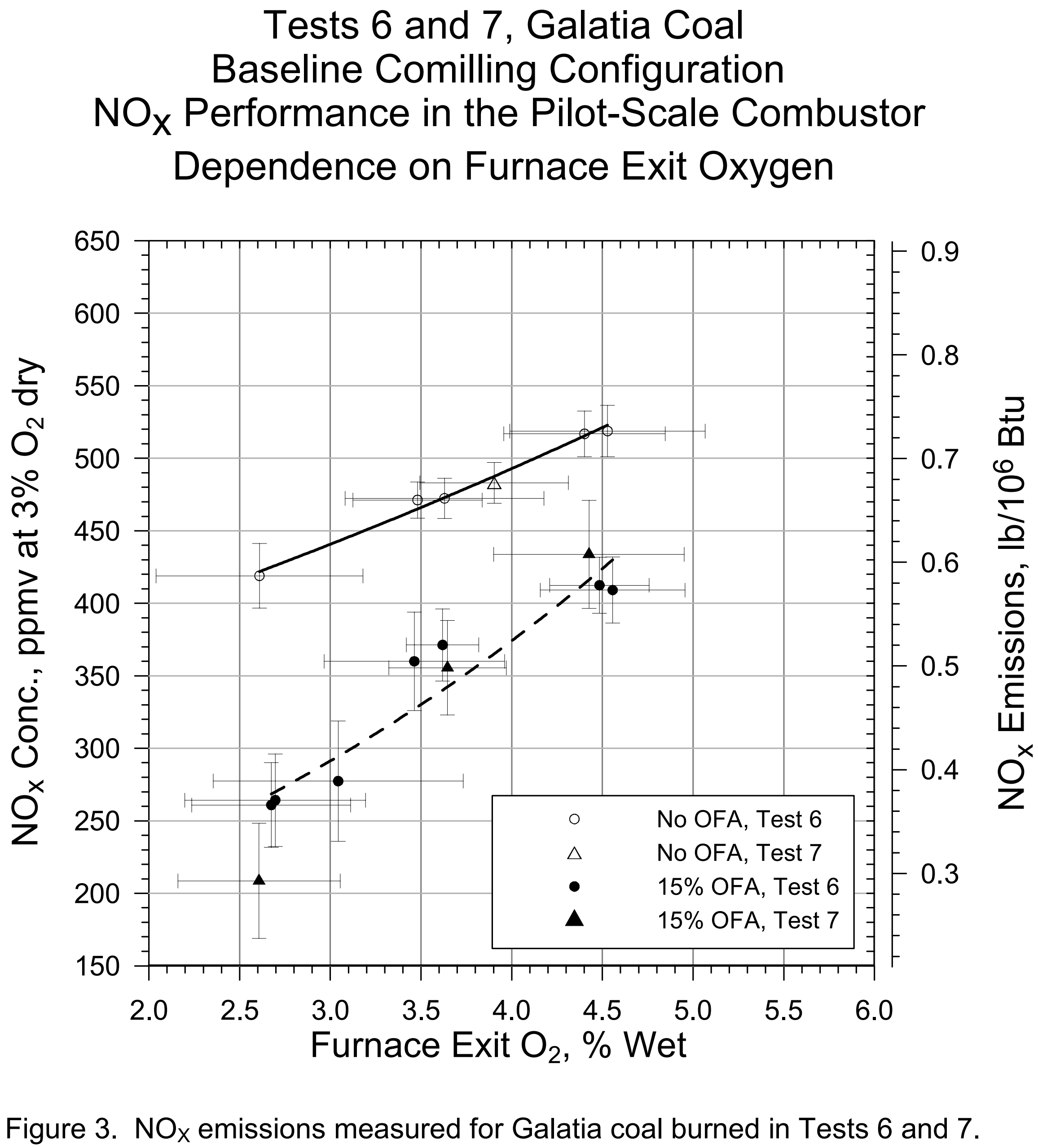

Figure 3. NO_X emissions measured for Galatia coal burned in Tests 6 and 7. Single register burner with 0% and 15% overfire air.

Table 6. Proximate and Ultimate analyses of coal feeder discharge samples of Galatia (Illinois Basin) coal from Tests 7 and 12.

Sample I.D. Galatia Coal	J858-20-CFDC-12 Test 7		J947-93-CFD-1 Test 12	
Proximate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	5.0	---	4.53	---
Ash, %	7.52	7.92	7.46	7.81
Volatile, %	33.19	34.94	35.44	37.12
Fixed Carbon, %	54.29	57.14	52.57	55.07
Sum	100.00	100.00	100.00	100.00
Heat Content, Btu/lb	12703	13372	12786	13393
Sulfur, %	1.0	1.05	1.24	1.30
MAF Btu/lb	---	14522	---	14528
Ultimate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	5.00	---	4.53	---
Carbon, %	71.69	75.46	72.88	76.34
Hydrogen, %	4.46	4.70	4.50	4.71
Nitrogen, %	1.78	1.87	1.70	1.78
Sulfur, %	1.00	1.05	1.24	1.30
Ash, %	7.52	7.92	7.46	7.81
Oxygen (diff.), %	8.55	9.00	7.69	8.06
Sum	100.00	100.00	100.00	100.00
Chlorine, %	0.33	0.35	0.48	0.50
Ash Fusion	Reducing	Oxidizing	Reducing	Oxidizing
Initial Deformation, °F	2335	2460	2090	2550
Softening, °F	2405	2540	2180	2600
Hemispherical, °F	2490	2610	2275	2645
Fluid, °F	2550	2655	2350	2690

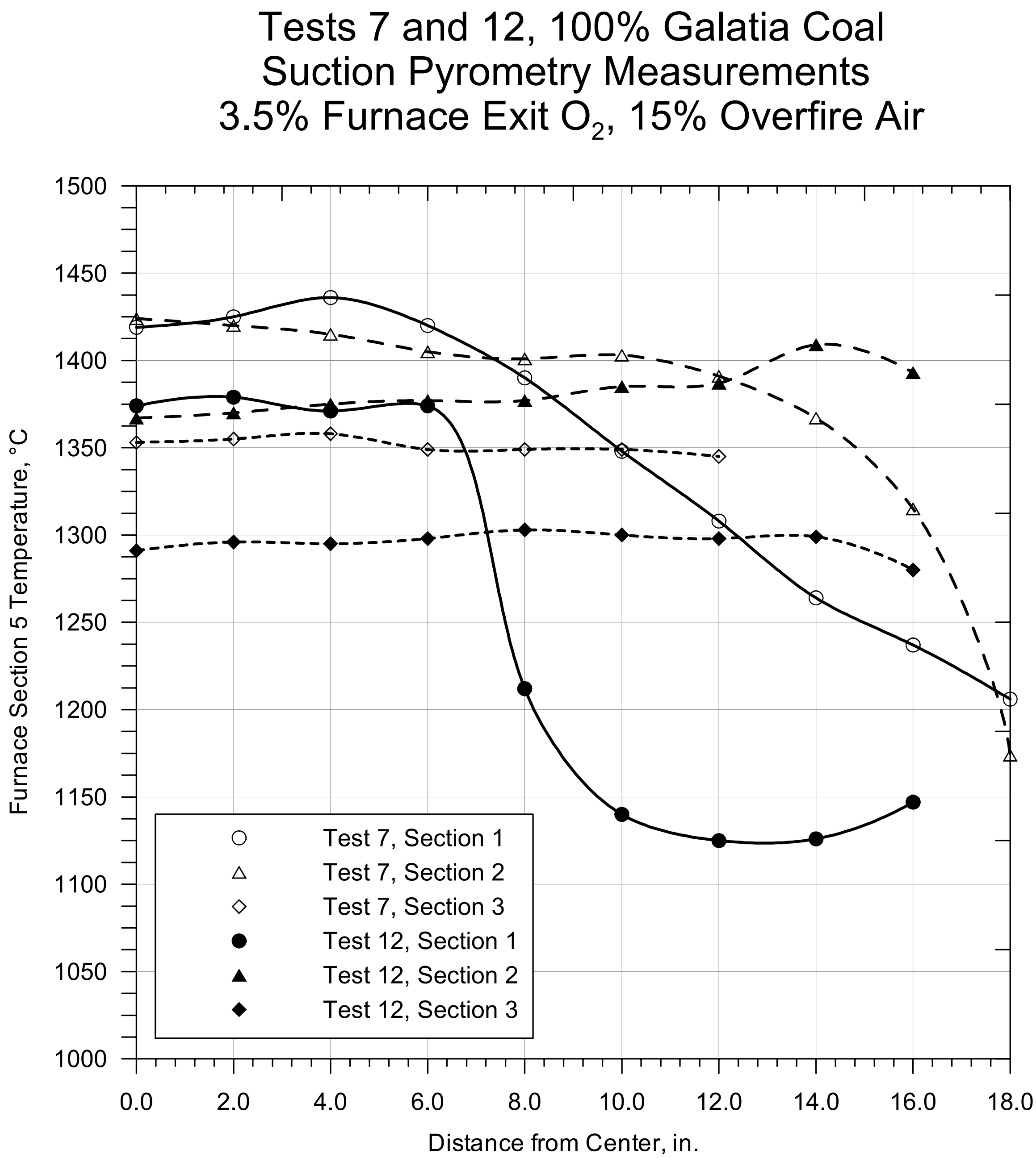

Figure 4. Lower furnace suction pyrometry measurements for 100% Galatia coal from Tests 7 and 12. 3.5% furnace exit oxygen and 15% overfire air.

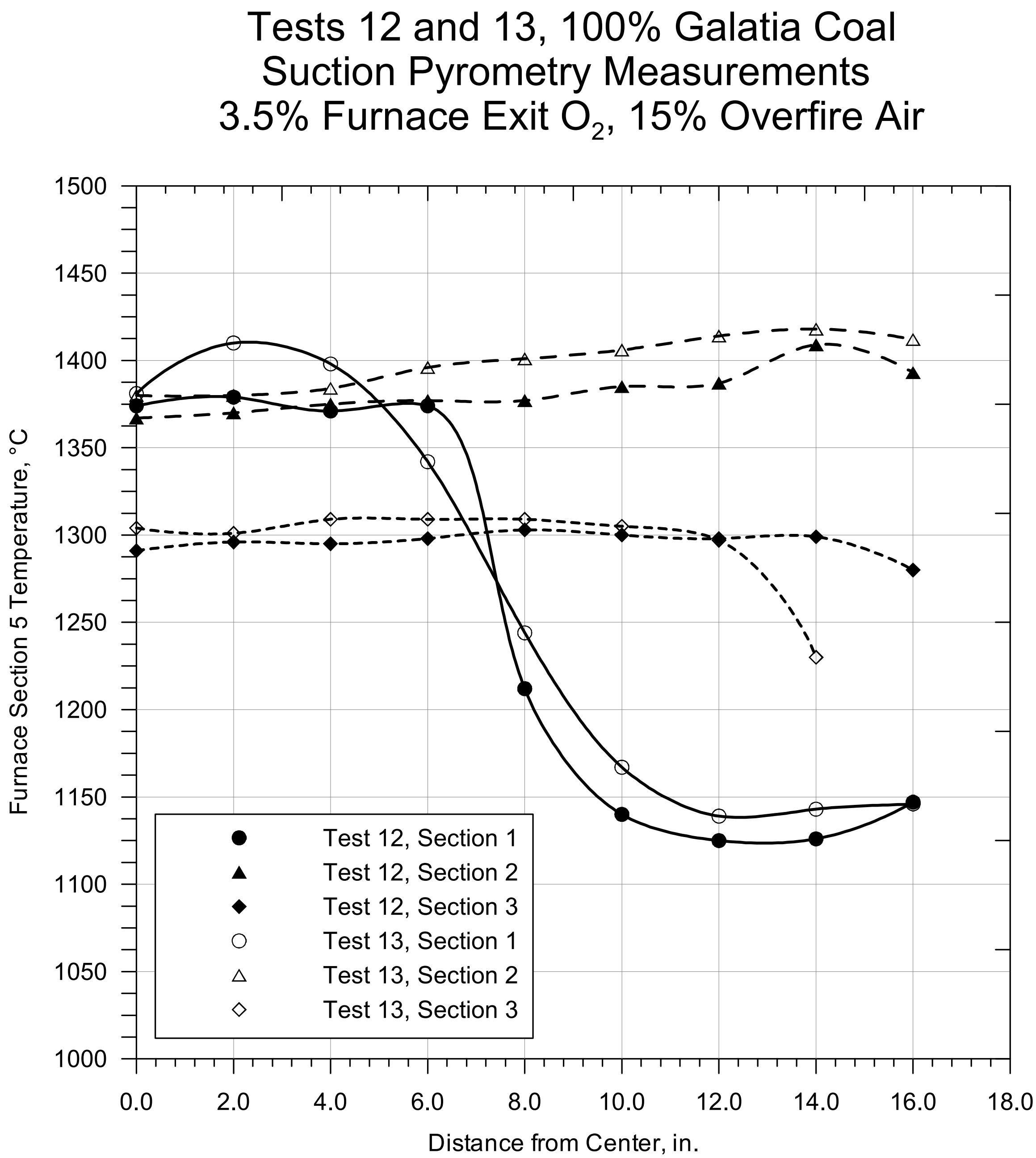

Figure 5. Lower furnace suction pyrometry measurements for 100% Galatia coal from Tests 12 and 13. 3.5% furnace exit oxygen and 15% overfire air.

suggests that the slight fuel differences recorded in Table 6 may be responsible for the differences in NO_X emissions evident in Figures 2 and 3.

Figures 6 through 9, and Table 7 summarize the results of NO_X emission measurements taken during Test 12 when 5%, 10%, and 15% sawdust was cofired with Galatia coal during periods when ammonia was not injected. Finally, Figures 10 and 11 present the results of unburned carbon (UBC) measurements carried out on fly ash obtained by isokinetically sampling the furnace effluent at various values of furnace exit oxygen.

Figure 9 shows that for either 5% or 10% by weight sawdust mixed with coal, the addition of biomass does not appreciably alter NO_X emissions. Only at a 20% level of addition, and for that amount of sawdust, only for 0% overfire air, are NO_X emissions significantly reduced (by ~10%) for the range of furnace exit oxygen levels that were tested. Figures 10 and 11 show that where there is overlap with Test 6 and 7, the values of unburned carbon measured in Test 12 are substantially in agreement.

Test 13 For this test, from May 19-24, 2002, two coals were burned. On the first day of testing, the same Galatia coal burned in Test 12 was burned so that a specially designed char sampling probe could be used to obtain char samples from section three of the furnace, just below the overfire air ports. Galatia coal normally produces unburned carbon levels up to 7% for low values of furnace exit oxygen. Char measurements on ash samples obtained from Galatia coal combusted under these conditions will provide useful information for the modeling effort.

For the remaining days of testing, Jim Walter #7 mine low-volatility coal was burned by itself and comilled with sawdust and injected into the furnace at injection location 1 as shown in Figure 1. This coal was obtained locally from a portion of the Blue Creek seam known to have a lower than normal volatility (~20%). Lower furnace char sampling was also performed while Jim Walter #7 mine coal was burned. Typical proximate and ultimate analyses for the base coal and the sawdust used in this test are presented in Tables 2 and 3. Table 8 presents the results of proximate and ultimate analyses of pulverized (comilled) mixtures of Jim Walter #7 mine coal and sawdust.

Testing was uneventful, however, because of the low volatility of this coal, the pure coal flame was not well defined and additional time was required to achieve the best possible flame shape. As more biomass was added (and as the

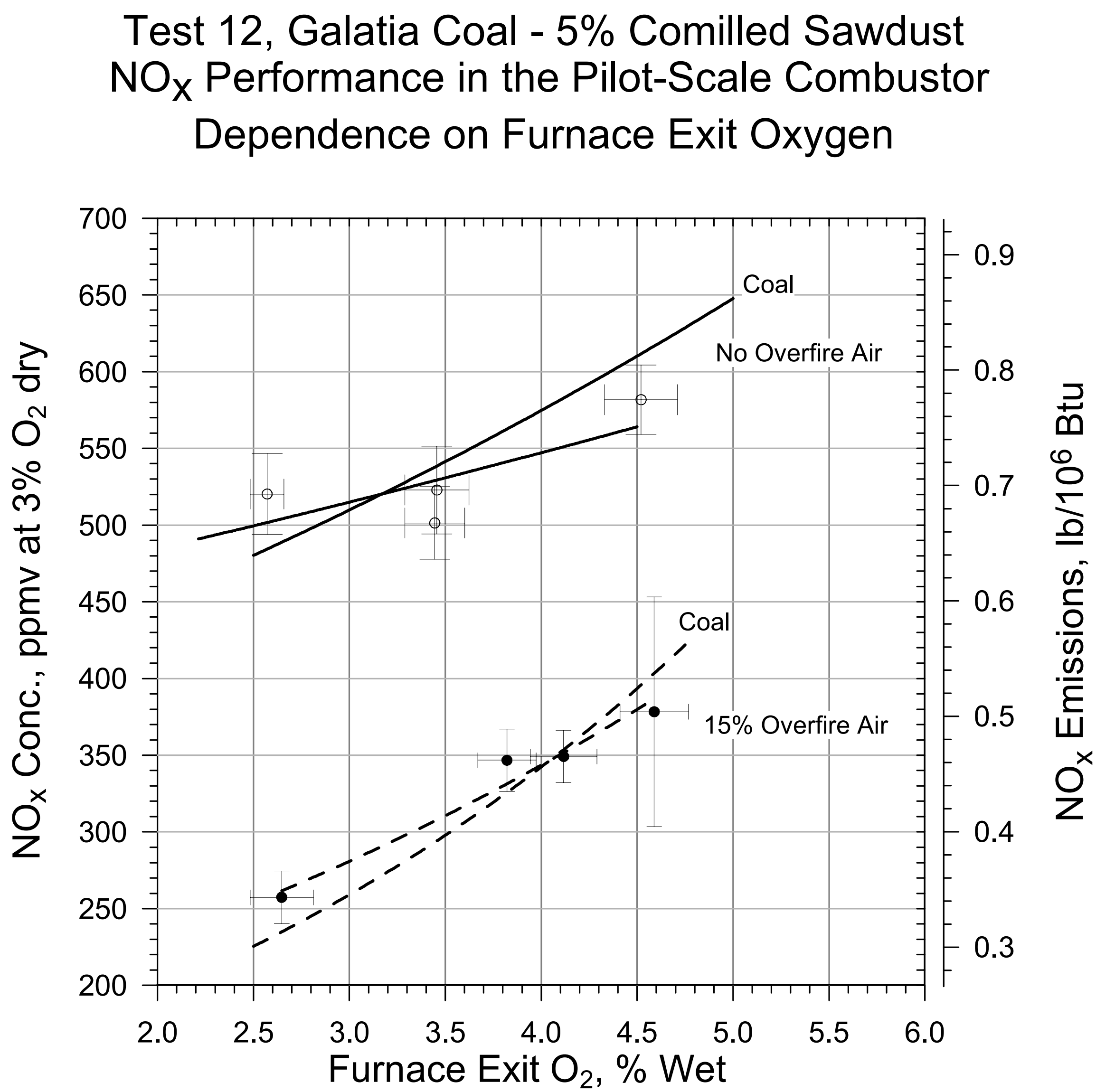

Figure 6. NO_X emissions measured for Galatia coal comilled with 5% by weight dry hardwood sawdust. Single register burner with 0% and 15% overfire air.

Test 12, Galatia Coal - 10% Comilled Sawdust
NO_X Performance in the Pilot-Scale Combustor
Dependence on Furnace Exit Oxygen

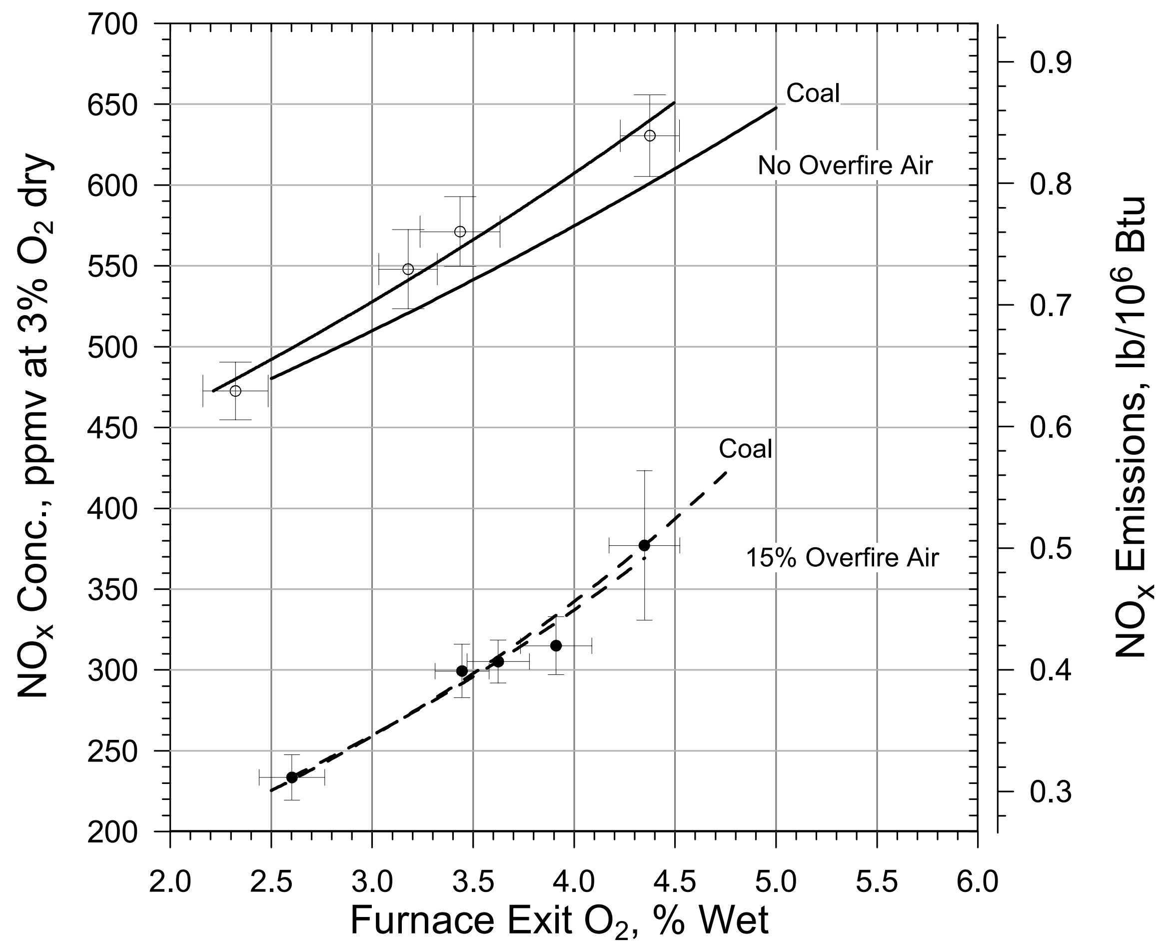

Figure 7. NO_X emissions measured for Galatia coal comilled with 10% by weight dry hardwood sawdust. Single register burner with 0% and 15% overfire air.

Test 12, Galatia Coal - 20% Comilled Sawdust
NO_X Performance in the Pilot-Scale Combustor
Dependence on Furnace Exit Oxygen

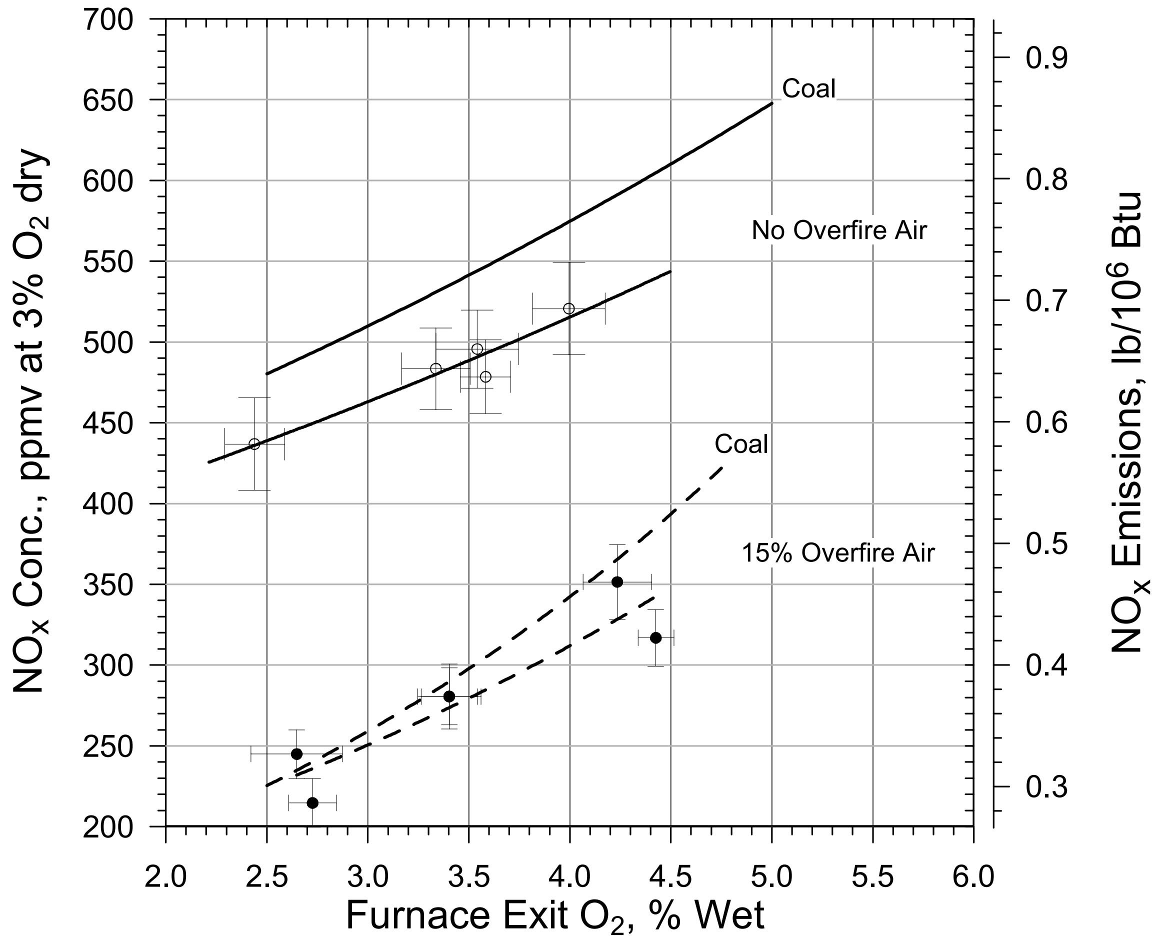

Figure 8. NO_X emissions measured for Galatia coal comilled with 20% by weight dry hardwood sawdust. Single register burner with 0% and 15% overfire air.

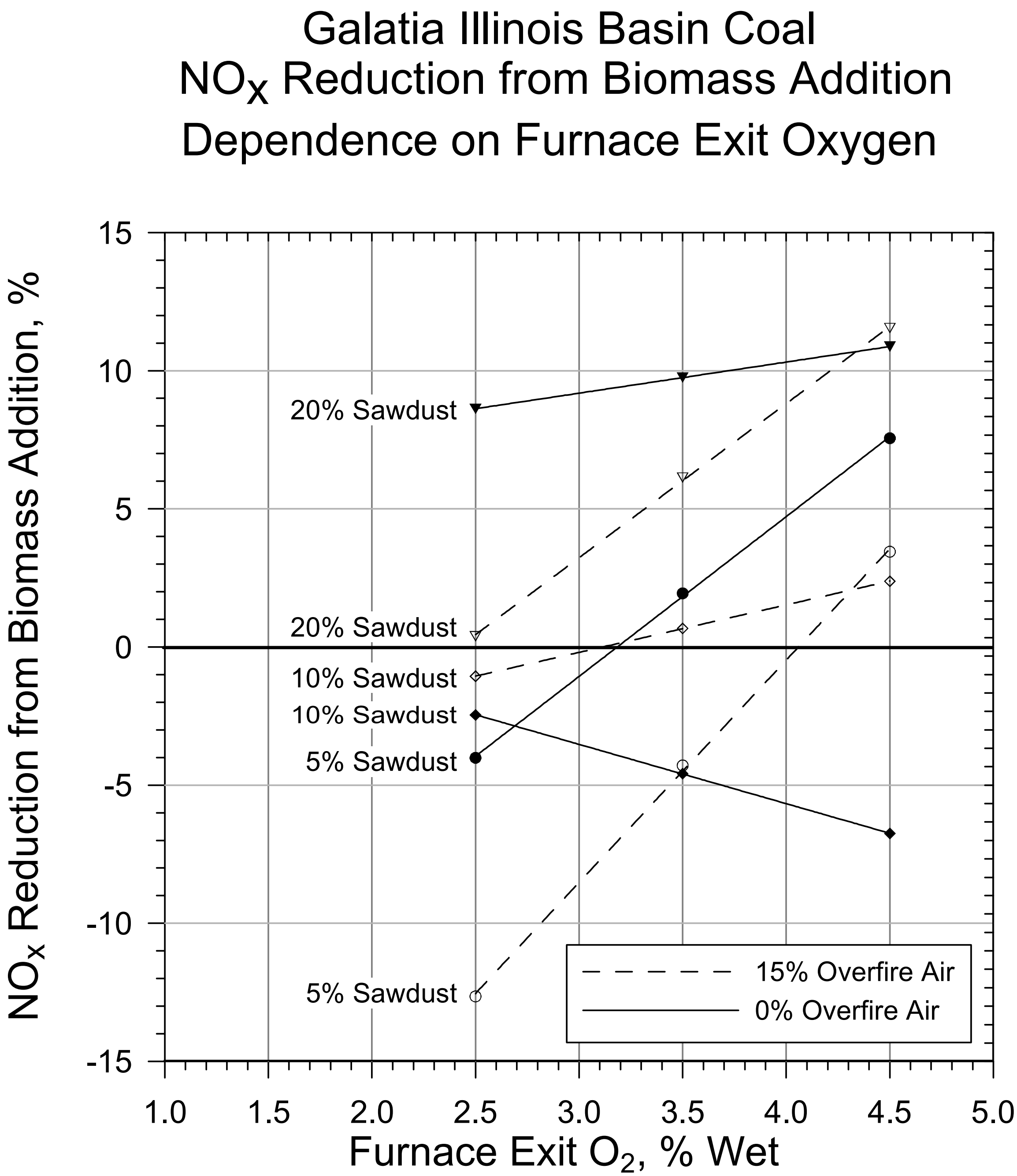

Figure 9. NO_X reductions measured for 5%, 10% and 20% sawdust comilled with Galatia coal. Single register burner with 0% and 15% overfire air.

Table 7. NO_X Emissions for 0% and 15% overfire air at 2.5%, 3.5%, and 4.5% furnace exit O_2, (wet) for sawdust comilled with Galatia coal with the single-register burner.

Biomass	Weight%	Tertiary Air, %	NO_X Emissions at 3% O_2, dry ppmv	Reduction of NO_X Emissions, %
2.5% Furnace Exit Oxygen				
None	0	0	480	0
		15	225	0
Sawdust	5	0	500	-4.0
		15	254	-12.7
	10	0	492	-2.5
		15	228	-1.1
	20	0	439	8.6
		15	225	0.4
3.5% Furnace Exit Oxygen				
None	0	0	541	0
		15	298	0
Sawdust	5	0	531	1.9
		15	311	-4.3
	10	0	566	-4.6
		15	296	0.7
	20	0	488	9.7
		15	280	6.1
4.5% Furnace Exit Oxygen				
None	0	0	610	0
		15	393	0
Sawdust	5	0	564	7.5
		15	380	3.4
	10	0	651	-6.7
		15	384	2.4
	20	0	544	10.9
		15	348	11.5

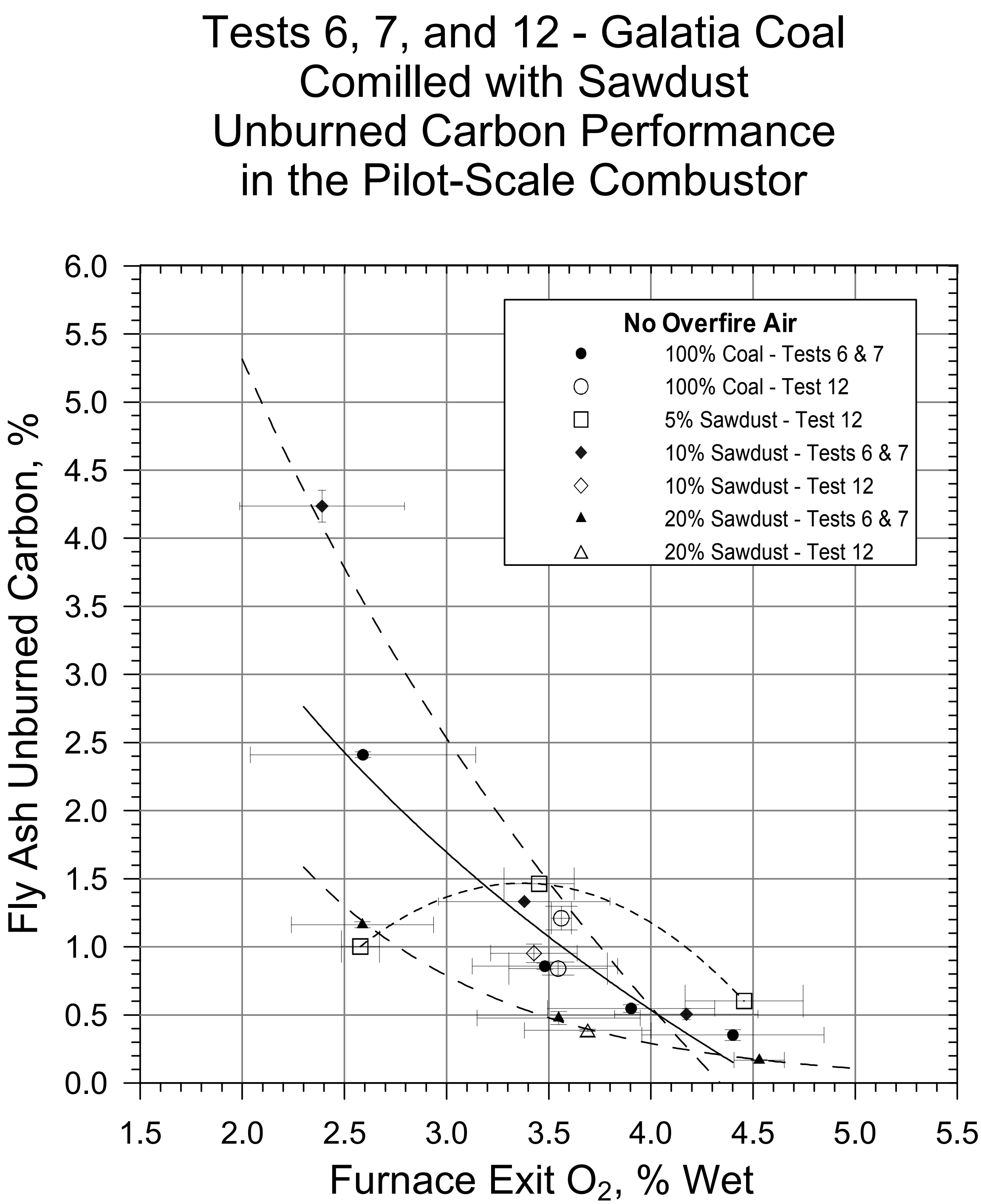

Figure 10. Unburned carbon emissions for the comilling of sawdust with Galatia coal. Single register burner with 0% overfire air.

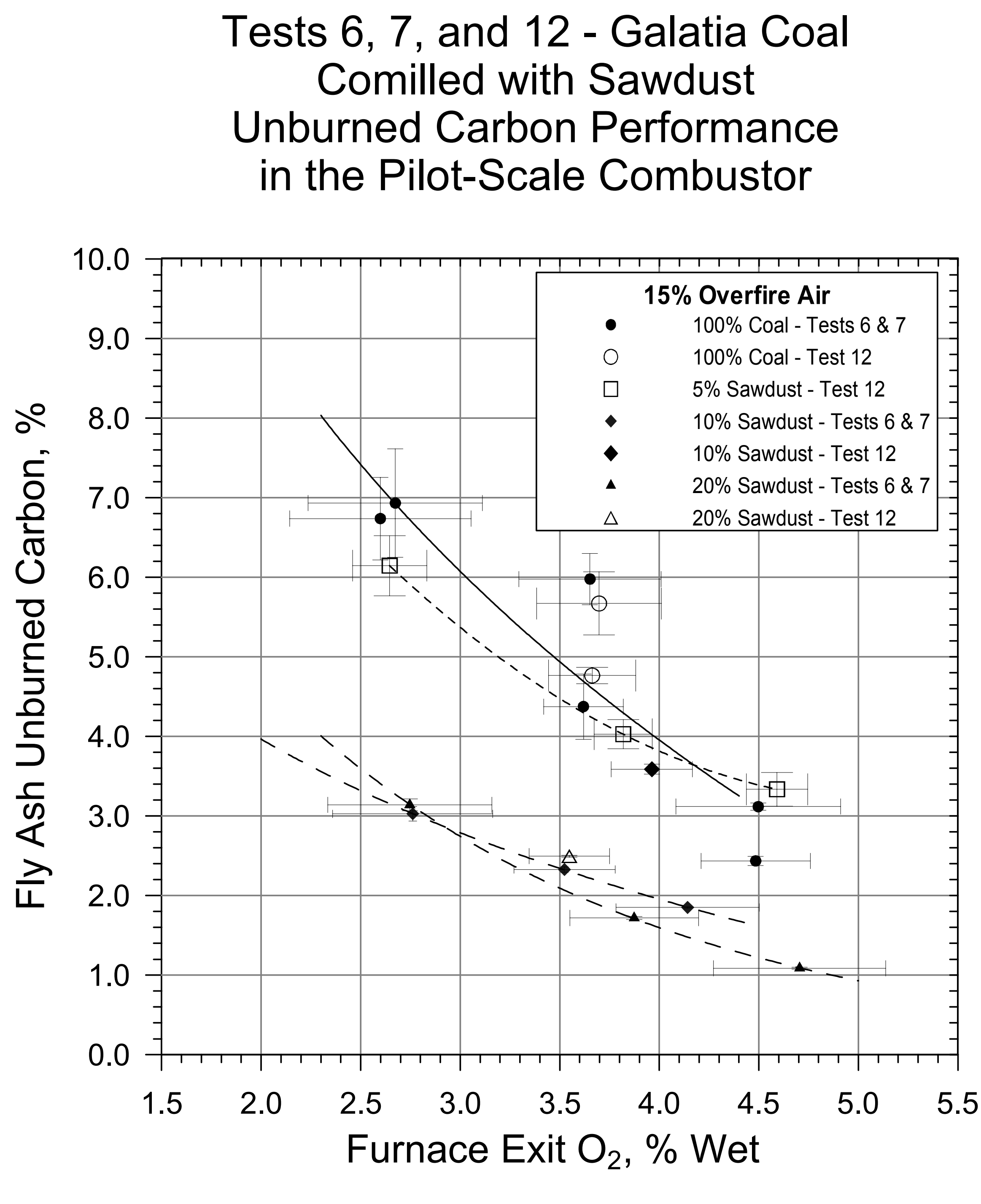

Figure 11. Unburned carbon emissions for the comilling of sawdust with Galatia coal. Single register burner with 15% overfire air.

Table 8. Proximate and Ultimate analyses of coal feeder discharge samples of Jim Walter #7 mine coal and dry hardwood sawdust from Test 13.

Sample I.D. Fuel	J947-132-CFD-1 5% Sawdust		J947-135-CFD-3 10% Sawdust		J947-139-CFD-1 20% Sawdust	
Proximate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	0.76	---	0.94	---	1.08	---
Ash, %	14.21	14.32	12.97	13.09	12.14	12.27
Volatile, %	22.11	22.28	25.64	25.88	30.09	30.42
Fixed Carbon, %	62.92	63.40	60.45	61.03	56.69	57.31
Sum	100.00	100.00	100.00	100.00	100.00	100.00
Heat Content, Btu/lb	12641	12738	12594	12714	12260	12394
Sulfur, %	0.68	0.69	0.66	0.67	0.60	0.61
MAF Btu/lb	---	14867	---	14629	---	14127
Ultimate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	0.76	---	0.94	---	1.08	---
Carbon, %	73.28	73.84	72.98	73.67	70.20	70.97
Hydrogen, %	4.03	4.06	4.01	4.05	4.18	4.23
Nitrogen, %	1.51	1.52	1.31	1.32	1.37	1.38
Sulfur, %	0.68	0.69	0.66	0.67	0.60	0.61
Ash, %	14.21	14.32	12.97	13.09	12.14	12.27
Oxygen (diff.), %	5.53	5.57	7.13	7.20	10.43	10.54
Sum	100.00	100.00	100.00	100.00	100.00	100.00
Chlorine, %	0.01	0.01	0.01	0.01	0.01	0.01
Ash Fusion	Reducing	Oxidizing	Reducing	Oxidizing	Oxidizing	Oxidizing
Initial Deformation, °F	2535	2700	2525	2700	2540	2705
Softening, °F	2620	2745	2600	2730	2600	2740
Hemispherical, °F	2675	2775	2670	2770	2680	2775
Fluid, °F	2740	2800+	2735	2800+	2745	2800+

volatility was increased from 20% (100% coal) to 30% (20% sawdust) the flame was observed to become much more stable and defined. As might be expected with an ash content of ~14%, this coal tended to produce much more lower furnace slag than was seen with either Galatia or Pratt seam coal. Slag frequently accumulated on the two flame scanner ports low in the furnace, another indicator of slagging behavior for a coal.

Three levels of furnace exit oxygen were tested (2.5%, 3.5%, and 4.5%) with overfire air levels of 0% (high NO_X) and 15% (low NO_X). Three levels of biomass addition were tested: 5%, 10% and 20% weight content for the dry hardwood sawdust.

Figure 12 presents NO_X emissions for 100% Jim Walter #7 coal firing for the single-register burner and Figures 13 through 15 present average NO_X emissions measured for the combustion of 5%, 10%, and 20% by weight sawdust comilled with Jim Walter #7 coal. Figure 16 and Table 9 summarize the effect of sawdust addition on NO_X emissions. Finally, Figures 17 and 18 present the results of unburned carbon (UBC) measurements carried out on fly ash obtained by isokinetically sampling the furnace effluent at various values of furnace exit oxygen.

In contrast to the results of Test 12, where NO_X emissions were not substantially affected by the addition of sawdust to Galatia coal, with Jim Walter #7 low-volatility coal, in every case except for one (5% sawdust at 15% overfire air) NO_X emissions were not increased or substantially reduced by the addition of sawdust. UBC, however, was not as low as have been measured with high volatility Eastern bituminous coal (Pratt seam coal), but at a maximum of 4% (at 15% overfire air), were closer to the range measured for the Illinois Basin coal (Galatia). On the other hand, with no overfire air, the maximum UBC measured was less than 2%.

Presentations

A paper describing this project that included preliminary results from the first four cofiring tests was presented at the 12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection in Amsterdam, The Netherlands, in June, 2002. This paper is entitled “Development of a validated model for use in minimizing NO_X emissions and maximizing carbon utilization when cofiring biomass with coal” and it is reproduced in Appendix A of this Progress Narrative

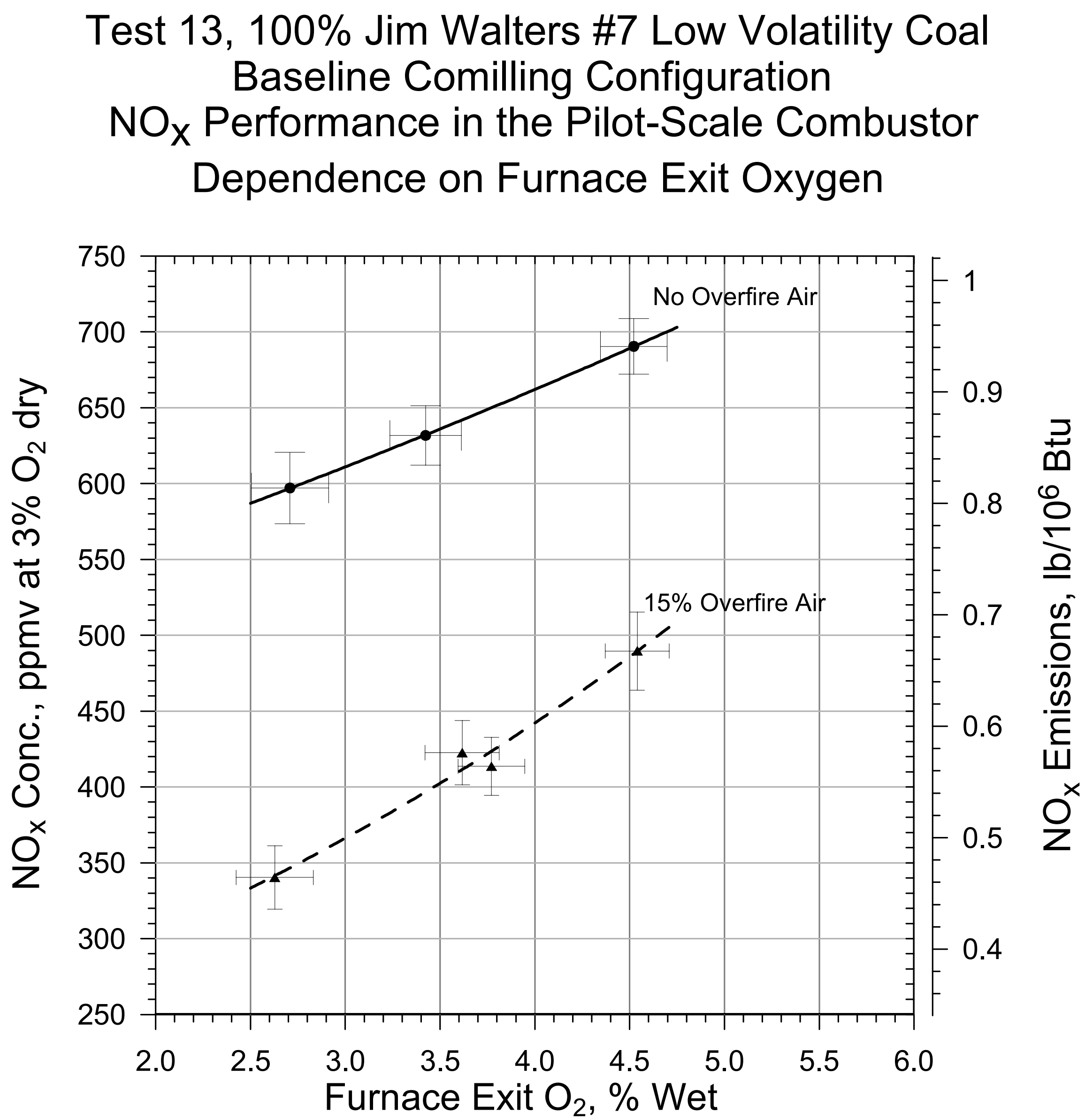

Figure 12. NO_X emissions measured for Jim Walter #7 mine coal burned in Test 13. Single register burner with 0% and 15% overfire air.

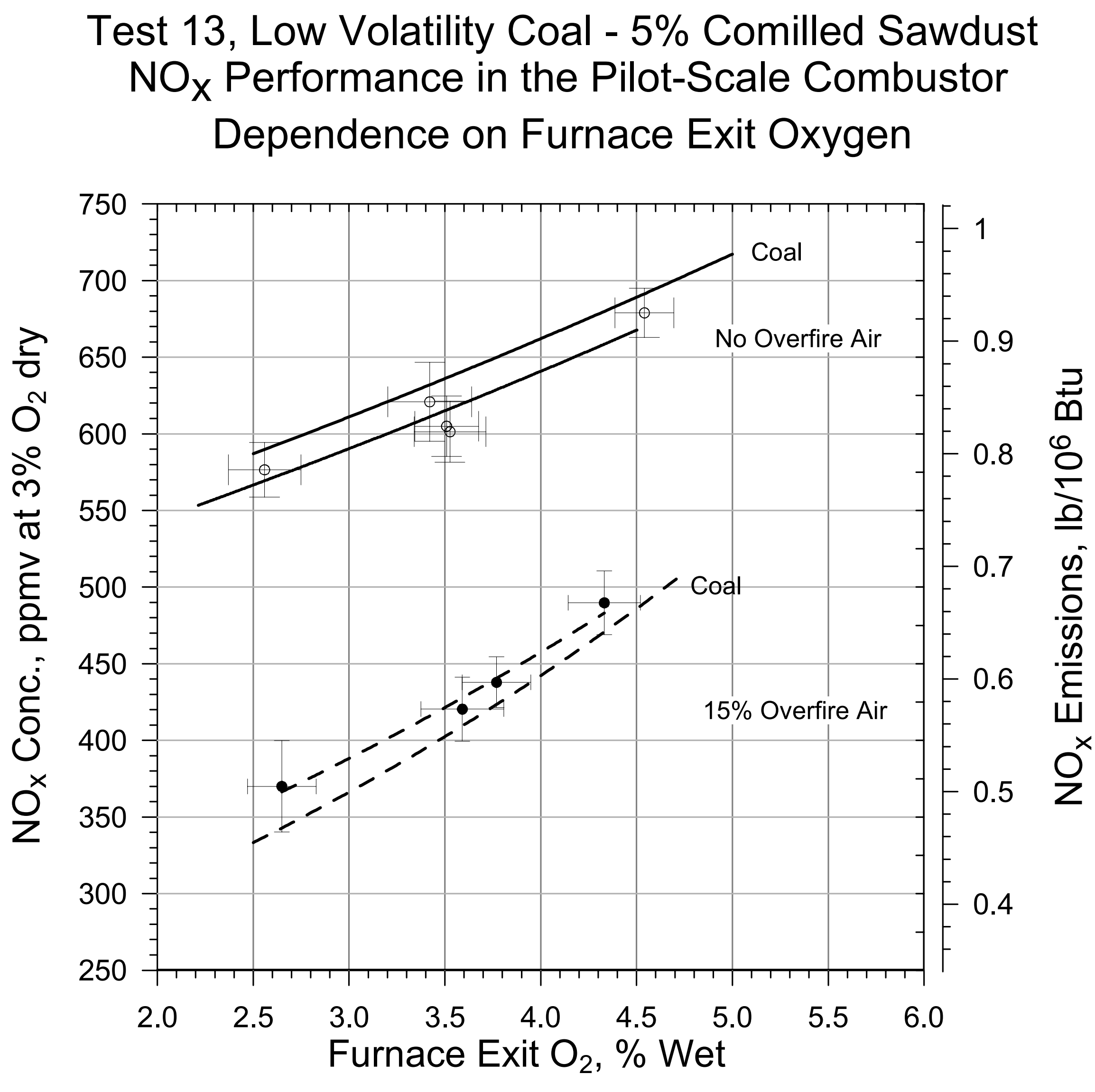

Figure 13. NO_X emissions measured for Jim Walter #7 coal comilled with 5% by weight dry hardwood sawdust. Single register burner with 0% and 15% overfire air.

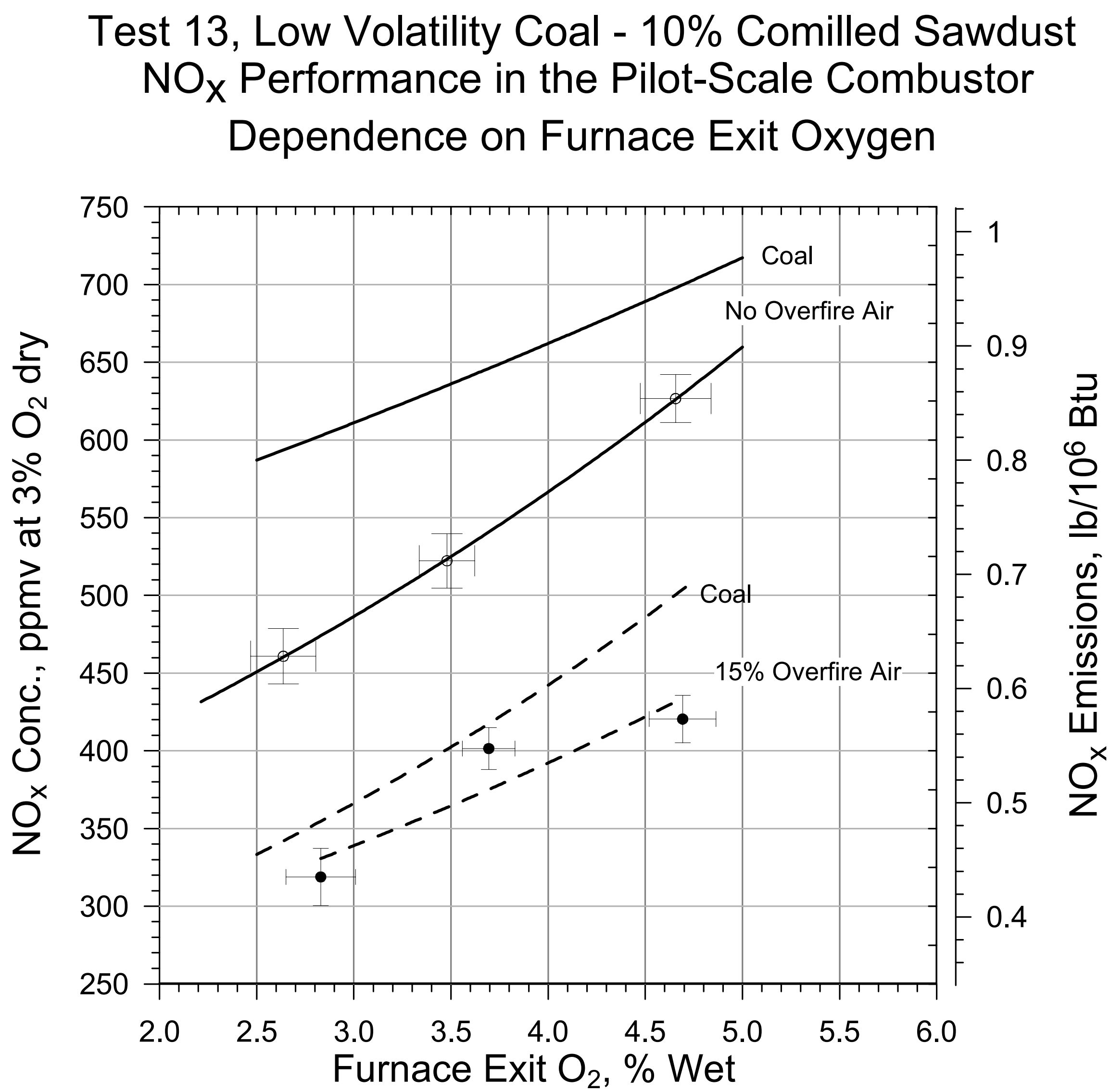

Figure 14. NO_X emissions measured for Jim Walter #7 coal comilled with 10% by weight dry hardwood sawdust. Single register burner with 0% and 15% overfire air.

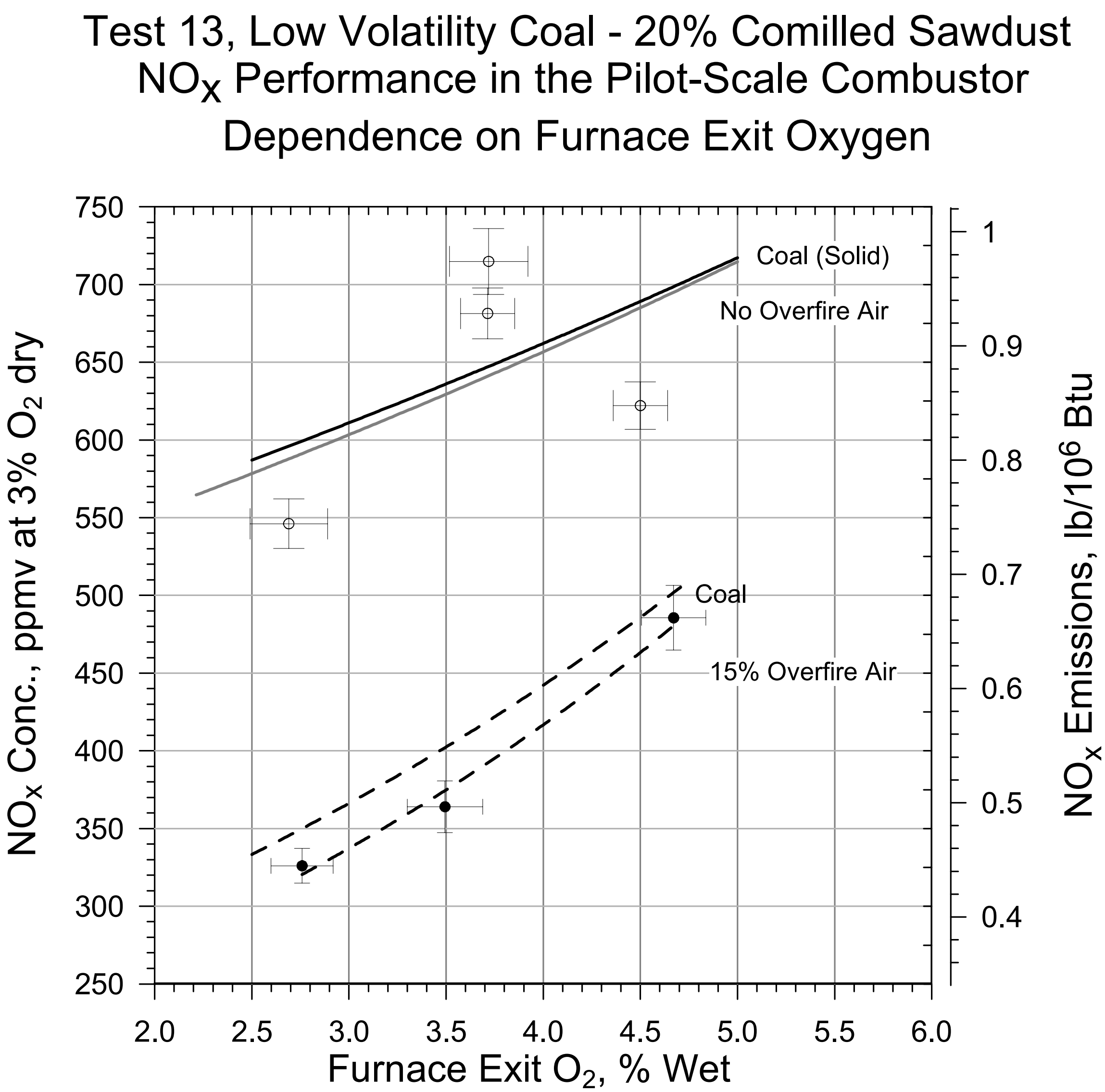

Figure 15. NO_X emissions measured for Jim Walter #7 coal comilled with 20% by weight dry hardwood sawdust. Single register burner with 0% and 15% overfire air.

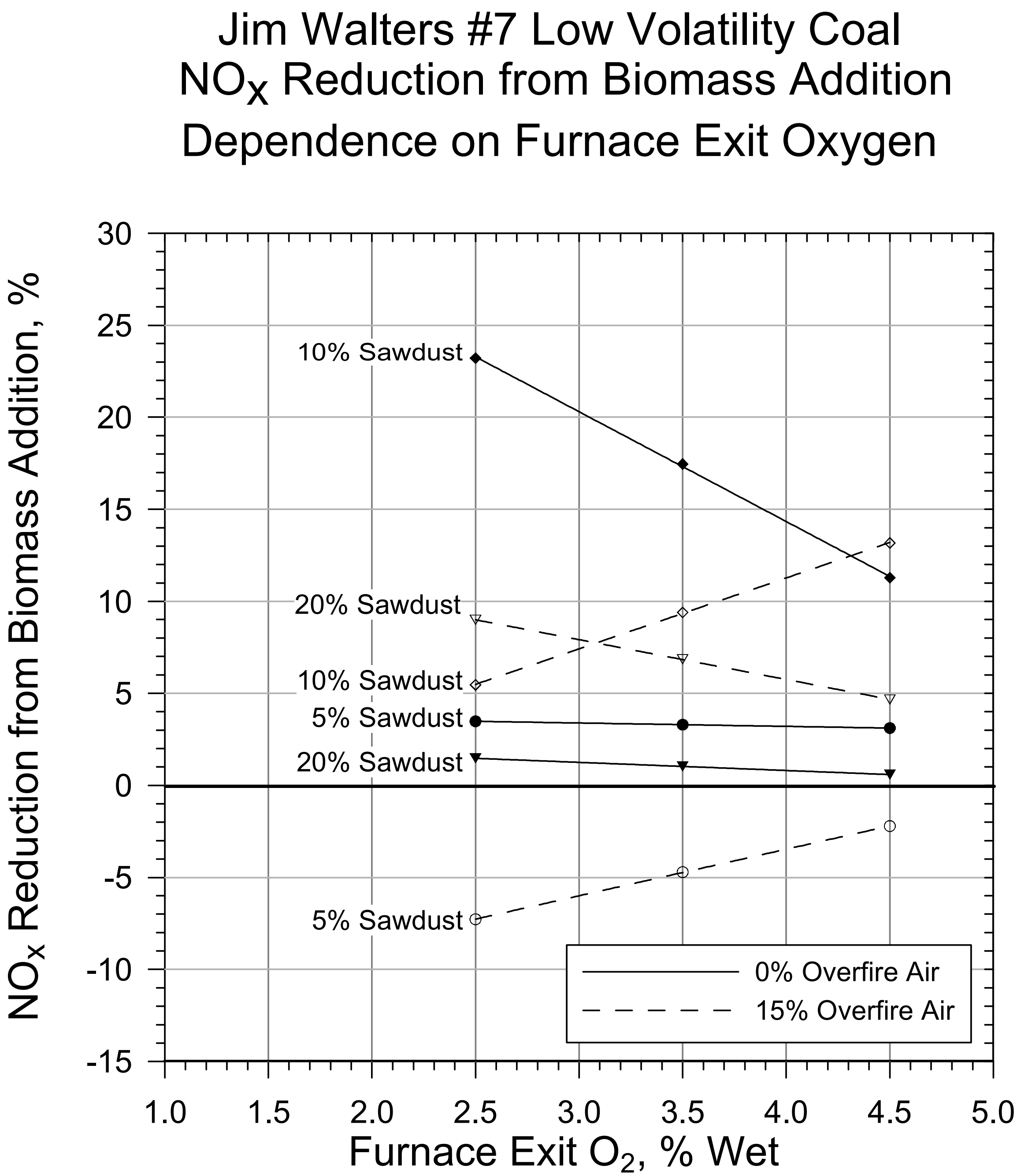

Figure 16. NO_X reductions measured for 5%, 10% and 20% sawdust comilled with Jim Walter #7 coal. Single register burner with 0% and 15% overfire air.

Table 9. NO_X Emissions for 0% and 15% overfire air at 2.5%, 3.5%, and 4.5% furnace exit O_2, (wet) for sawdust comilled with Jim Walter #7 coal with the single-register burner.

Biomass	Weight%	Tertiary Air, %	NO_X Emissions at 3% O_2, dry ppmv	Reduction of NO_X Emissions, %
2.5% Furnace Exit Oxygen				
None	0	0	587	0
		15	333	0
Sawdust	5	0	567	3.5
		15	358	-7.3
	10	0	451	23.2
		15	315	5.5
	20	0	578	1.5
		15	303	9.0
3.5% Furnace Exit Oxygen				
None	0	0	636	0
		15	402	0
Sawdust	5	0	615	3.3
		15	421	-4.7
	10	0	525	47.5
		15	365	9.4
	20	0	630	1.0
		15	375	6.8
4.5% Furnace Exit Oxygen				
None	0	0	689	0
		15	486	0
Sawdust	5	0	668	3.1
		15	497	-2.2
	10	0	611	11.3
		15	422	13.2
	20	0	685	0.6
		15	463	4.7

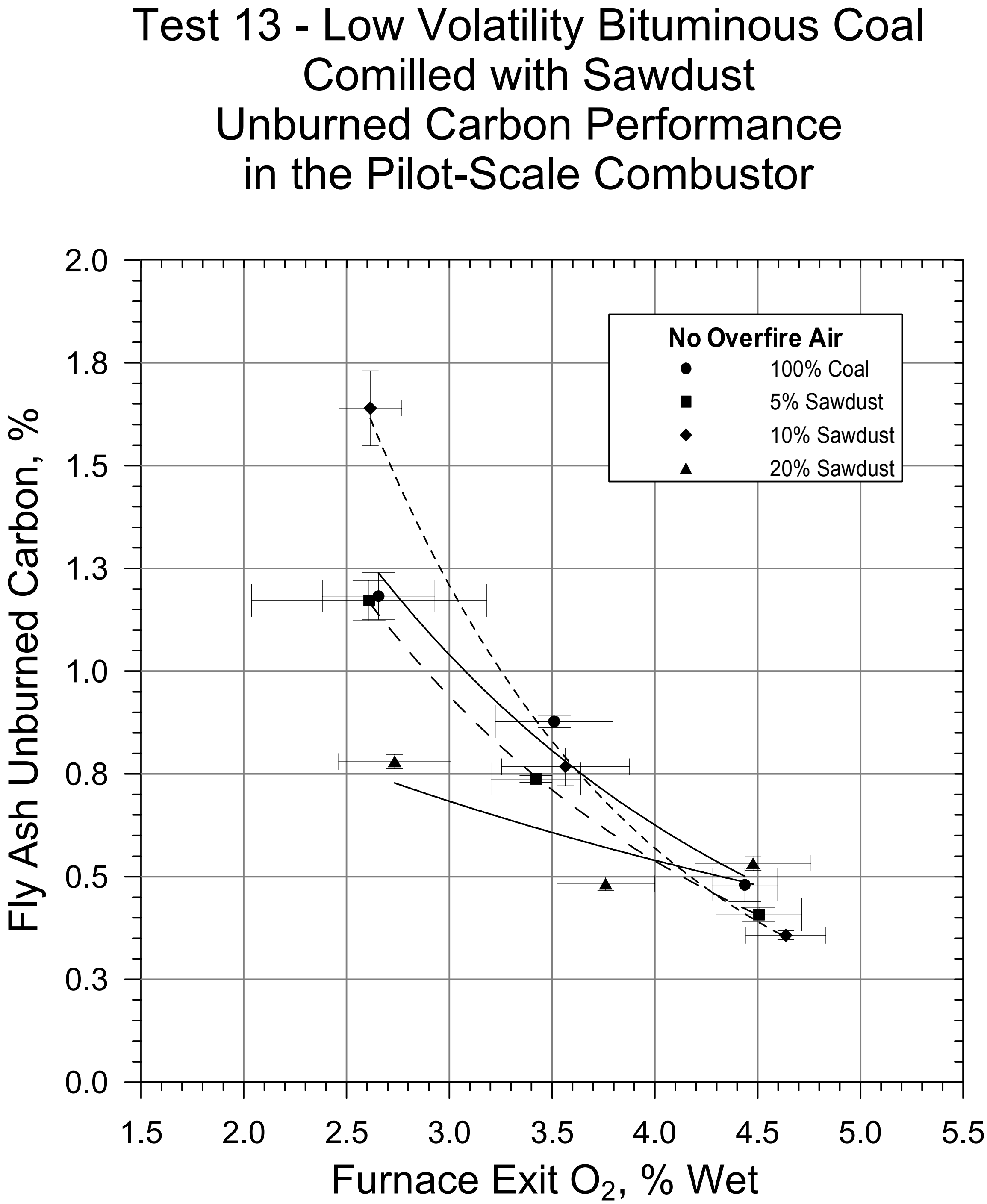

Figure 17. Unburned carbon emissions for the comilling of sawdust with Jim Walter #7 coal. Single register burner with 0% overfire air.

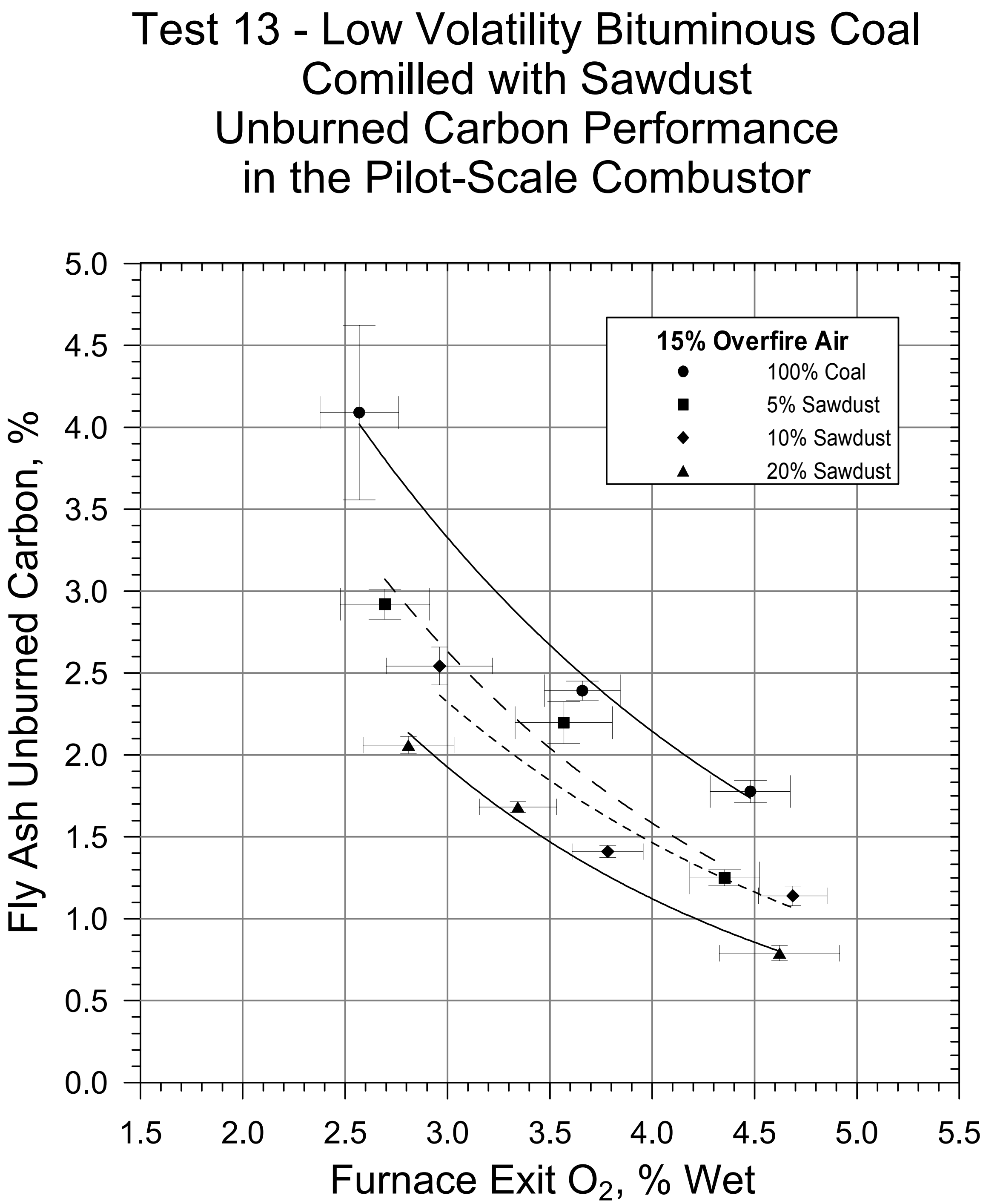

Figure 18. Unburned carbon emissions for the comilling of sawdust with Jim Walter #7 coal. Single register burner with 15% overfire air.

DISCUSSION

REI has delivered the Configurable Fireside Simulator (CFS) and after initial software testing, the additional CFD simulations required by NEA to model Tests 8 and 9 (Powder River Basin coal tests), and Test 13 (low-volatility Eastern bituminous coal) will be completed and the model can then be tested for this coal with the variety of biomasses tested. Because of the delay in receiving the CFS, a no-cost project extension to the end of the calendar year will probably be requested so that the modeling task can be completed.

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 NO_X emission rates and carbon burnout efficiency. Results to date suggest that NO_X emissions can be predicted within experimental uncertainty (for Pratt seam and Galatia coals) and that UBC emissions trends are well characterized but are presently less accurate than are predicted NO_X emissions.

Pilot-scale tests have continued to investigate the comilling of sawdust mixed at three concentrations with an Illinois basin coal and a low-volatility Eastern bituminous coal and fired with the single-register burner. These tests show how strongly coal and biomass properties affect NO_X emissions and carbon burnout. This highlights the importance of characterizing fuel and air mixing in the modeling effort and the overall significance of thorough CFD analysis to the construction of a proper model.

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 proving successful. This development is a generally applicable algorithm that 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 seventh quarter and further testing is proceeding.

Plans for the next quarter include:

- Completing CFD simulations with the Configurable Fireside Simulator

- Continued software development to test the NOX/UBC model against test results with Powder River Basin coal and a low-volatility Eastern bituminous coal cofired with sawdust and switchgrass
- One additional test with low-volatility Eastern bituminous coal cofired with switchgrass with the single-register burner

In the twelfth combustor run, sawdust was comilled with an Illinois Basin coal and injected into the furnace through the single-register burner. Ammonia was also added to increase fuel nitrogen. In the thirteenth combustor run, sawdust was comilled with a low-volatility Eastern Bituminous coal and injected into the furnace through the single-register burner.

APPENDIX A

Development of a validated model for use in minimizing NO_X emissions and maximizing carbon utilization when cofiring biomass with coal

Presented at:

The 12th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection in Amsterdam, The Netherlands, in June17-21, 2002

DEVELOPMENT OF A VALIDATED MODEL FOR USE IN MINIMIZING NOX EMISSIONS AND MAXIMIZING CARBON UTILIZATION WHEN COFIRING BIOMASS WITH COAL

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ABSTRACT: This paper describes the testing phase of a project that will produce a validated predictive model to optimize the cofiring of biomass and coal to minimize NO_X emissions and maximize carbon utilization. The effect of biomass cofiring on NO_X emissions has been site-specific and data are limited so that no basis exists to specify fuel or injection system characteristics to minimize the formation of NO_X. This project is designed to fill a void in the understanding of the interactions of biomass and pulverized coal with a predictive model that can determine optimal energy and environmental benefits from cofiring these two types of fuel. The computer model, based on the EPRI NO_X LOI Predictor, will be validated through an extensive series of tests at a 3.8 GJ/hr combustor at the Southern Company/Southern Research Combustion Research Facility. The model will identify the biomass cofiring injection configuration that minimizes NO_X emissions from burning biomass/coal blends, and predict the NO_X reduction efficiency and loss-on-ignition (LOI) from biomass cofiring. This project is being carried out under DOE Cooperative Agreement DE-FC26-00NT40895, through the U.S. DOE, National Energy Technology Laboratory, in Pittsburgh PA.

Keywords: biomass/coal, combustion, emission reduction

1 INTRODUCTION

This paper describes the testing phase of a project that will produce a validated predictive model designed to optimize the cofiring of biomass and coal to minimize NO_X emissions and maximize carbon utilization. The beneficial effect of biomass cofiring on NO_X emissions has been found to be site-specific and results are so limited in number that there is no basis to specify fuel or injection system characteristics to minimize the formation of NO_X [1,2]. This project is designed to fill a void in the understanding of the interactions of biomass and pulverized coal with a predictive model that can determine optimal energy and environmental benefits from the cofiring of these two types of fuel. The computer model, based on EPRI's NO_X LOI Predictor that Niksa Energy Associates and others successfully developed for coal-fired boilers, will (i) identify the biomass cofiring injection configuration that minimizes NO_X emissions in flames of biomass/coal blends; and (ii) predict the NO_X reduction efficiency and loss-on-ignition (LOI) of biomass cofiring.

The computer model is being validated through an extensive set of tests at the pilot-scale combustor in the Southern Company Services/Southern Research Institute Combustion Research Facility (CRF). For this investigation, the CRF is fired at 3.8 GJ/hr (3.6 MBtu/hr) to emulate the time-temperature profile of a typical pulverized coal-fired boiler in the Southern Company system. Testing has covered a range of biomass materials, coal types, fuel mixing conditions, and burner geometry. The scalable database resulting from these tests will have inherent value as a reference set of data for assessing the impact of biomass cofiring on NOX emissions and carbon utilization. Moreover, this characterization will be considerably strengthened by the connections between the pilot-scale tests and the detailed process model that will be developed in tandem with the testing.

Model predictions are being validated across the entire laboratory database to within useful quantitative tolerances. Once validated, the model will provide a relatively inexpensive means either (1) to identify the most effective cofiring 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, this model becomes an important cost-saving tool, and the modeling effort has the potential to accelerate the widespread adoption of biomass cofiring as a NO_X control strategy in the electric utility industry. The modelling effort has been described in detail elsewhere [3].

Project partners include Southern Research Institute (project management and testing), Southern Company Services, Niksa Energy Associates (modeling), Reaction Engineering International (CFD calculations), and MESA Reduction Engineering & Processing, Inc. (biomass processing).

2 TESTING

2.1 Combustion Research Facility (CRF)

The Southern Company /Southern Research Institute CRF is designed for up to 6.3 GJ/hr firing on natural gas, coal, or mixtures of coals and biomass fuels, which is equivalent to 1.75 MW thermal or about 0.6 MW electric. Because of its size and the time required to reach thermal equilibrium, the facility is operated around the clock during testing. Tests usually last 5-7 days.

The design of the facility was carefully chosen to provide a close simulation of the physical processes that occur in a full-scale utility boiler. The facility, shown in Figure 1, consists of a coal crushing and milling area, a coal feeding system, a 1.07 m internal diameter vertical, refractory-lined, water-cooled furnace, a single up-fired burner (single- and dual-register burners available), a horizontal convective section pass with three air-cooled tube banks, a series of heat exchangers, an electrostatic precipitator, a pulse-jet baghouse, and a packed-column scrubber. The facility is completely instrumented and is controlled and monitored by a networked digital control system that also functions as a dedicated programmable data acquisition system. Typically, about 200 channels of data are logged during testing. The facility includes a CE- Raymond Model 352 bowl mill where candidate fuels are blended and milled. Pulverized fuel is captured in a pulse-

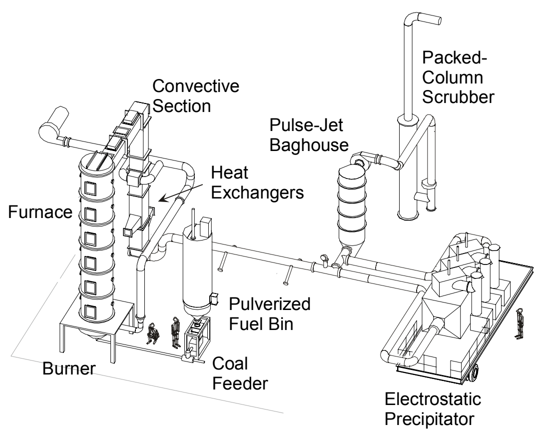

Figure 1: The combustion research facility

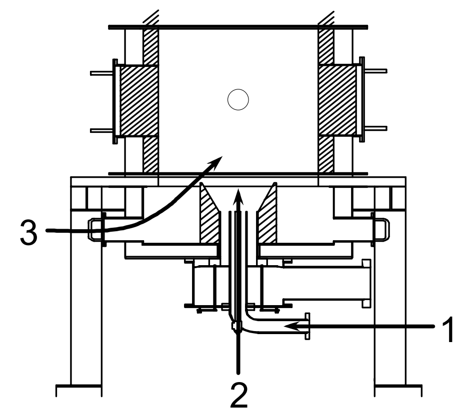

Figure 2: Biomass injection locations

jet baghouse and conveyed via a dense-phase trans-port system to a fuel storage silo near the furnace [4].

The ability to predict the performance of full-scale equipment from pilot-scale experimental results is essential. Hence, the pilot-scale facility was designed to closely replicate the controlling mechanisms that occur in a large boiler. Fortunately, a great deal of previous work on scaling was available to guide the design of the facility. Testing has confirmed that NOX and unburned carbon emissions are very close to that measured for full-scale boilers [5].

2.2 Test Protocol

The test matrix employed for this project includes four types of US coal (Powder River Basin, Eastern bituminous high-volatility, Eastern bituminous low-vol-atility, and Illinois Basin coals). Two burner con-figurations have been tested (single register tangentially-fired burner and generic low-NO_X dual-register burner). Three schemes for biomass cofiring have been tested (biomass comilled with coal, separate biomass injection through the center of the burner, and off-axis direct injection into the flame). Figure 2 illustrates the three locations where biomass has been injected with the single-register burner.

Two principal sources of biomass have been utilized (switchgrass and dry hardwood sawdust). Others may be tested, as dictated by the modeling effort. Candidate cofiring fuels include willow, hybrid poplar, rice straw, corn stover, and poultry litter. Finally, three levels of biomass addition have been tested, as a percentage of the total mass fired (0%, 10% or 15%, and 20%).

Testing with a particular fuel or blend of fuels requires one full day of testing. During that day, with the selected fuel and burner combination, the furnace is operated at three levels of furnace exit oxygen or FEO (usually 2.5%, 3.5%, and 4.5%) at up to two levels of separated overfire air or SOFA (usually 0% and 15%). At each level of FEO and SOFA, gaseous and particulate emissions and furnace operating parameters are measured and recorded for a minimum of one hour after the furnace has stabilized. Thus, within one week of testing, a maxi-mum of five major test conditions, each with 12 minor test conditions can be investigated. Up to eighteen separate week-long tests are planned, twelve of which have been completed. As testing proceeds, and the database of test results is compiled, the results of modeling are being compared with the test results obtained to verify and tune the model.

2.3 Test Results

Although four types of coal have been cofired with sawdust and switchgrass, in this paper we present test results from the Eastern bituminous, high-volatility coal, cofired with sawdust and switchgrass in the CRF's single resister burner configured to emulate tangential firing.

Table I presents proximate and ultimate analyses of this coal and the two biomasses that have been tested. As this table shows, fuel nitrogen is reduced when coal is cofired with biomass. At a 10% level of biomass addition, fuel N is reduced by ~ 6% for switchgrass and sawdust. At a 20% level of biomass addition, fuel N is reduced by ~ 12 % for switchgrass and sawdust. Thus, the addition of sawdust or switchgrass could be expected to result in a reduction of NOX in proportion to the reduction in fuel N. When NO_X emissions are different from the net fuel N difference with biomass addition, other NOX reduction mechanisms must be at work.

Figure 3 shows NO_X emissions for 100% pulverized coal as a function of FEO (on a wet basis) for two levels of SOFA for the three biomass cofiring configurations. With 100% coal firing, only biomass transport air is injected through the biomass injection locations. Biomass transport air is ~ 0.85 m3/min, or about 4% of the total air flow to the furnace. Figure 4 presents NO_X reductions measured for 10% and 20% sawdust comilled with coal and for 15% and 20% switchgrass comilled with coal (location 1 in Fig.2). Similar results are presented in Figure 5 for finely ground sawdust and switchgrass injected through the center of the single register burner (location 2 in Fig. 2) and in Figure 6 for finely ground sawdust and switchgrass injected into the flame from the side of the furnace (location 3 in Fig. 2). All NO_X emissions data are corrected to 3% O_2, on a dry basis.

The results shown in these figures suggest a number of complex interactions. First, in Figure 3, in the absence of biomass, increasing total air flow to the furnace by 4% (by injecting room-temperature air into the vicinity of the burner) can increase or decrease NOX emissions. For center-burner cofiring, baseline NOX emissions are increased significantly in the absence of SOFA. With 15% SOFA, the primary effect is to change the shape of the NO_X - FEO relationship. For side injection, baseline NO_X emissions are reduced with or without SOFA, perhaps because the air added at the root of the flame stages combustion by creating a lean-burn zone.

Table I: Typical as received (AR) fuel analyses

Fuel Analysis	Eastern Bituminous (High Vol.)	Switchgrass (Var. Alamo)	Hardwood Sawdust (Red Oak)
Proximate			
Moisture, %	3.03	7.21	4.60
Ash, %	16.47	3.71	0.50
Volatile, %	31.09	73.15	82.25
Fixed C, %	49.41	15.94	12.65
Volatile/FC	0.6292	4.588	6.502
Ultimate			
Moisture, %	3.03	7.21	4.60
Carbon, %	64.40	43.51	46.57
Hydrogen, %	4.54	5.53	5.87
Nitrogen, %	1.47	0.53	0.59
Sulfur,%	1.49	0.07	0.01
Ash, %	16.47	3.71	0.50
Oxygen, %	8.60	39.44	41.86
Heat Value			
AR, kJ/kg	27354	17492	19390
Dry, kJ/kg	28207	18850	20325
Chlorine, %	0.04	0.19	0.01

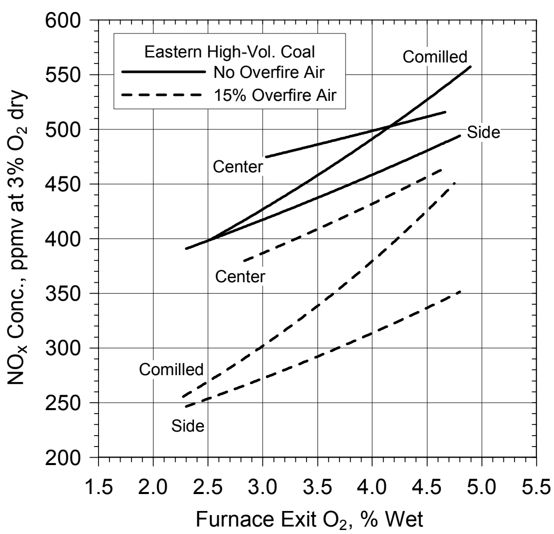

Figure 3: NO_X emissions for 100% coal

When biomass is added, Figures 4 through 6 reveal additional complex relationships that are strongly influenced by the amount and choice of biomass and the manner of cofiring. Though there is not room here to present the data, testing with other coals has shown that for the same biomass and cofiring geometry, coal choice can strongly affect NO_X emissions and levels of unburned carbon (UBC) in the ash.

The greatest levels of NO_X reduction are achieved when biomass is comilled with coal. In most cases, NO_X reductions are far greater than the reductions in fuel nitrogen from the addition of biomass.

When biomass is milled with the coal, the milling criterion is that 70% of the pulverized blend must be finer than 75 μm. This results in coal fraction that is more finely ground than usual (~85-90% < 75 μm). However, testing with coal

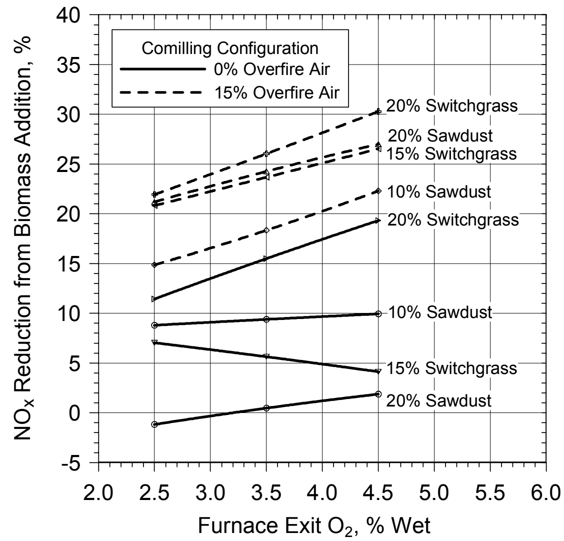

Figure 4: NO_X reductions with comilled biomass

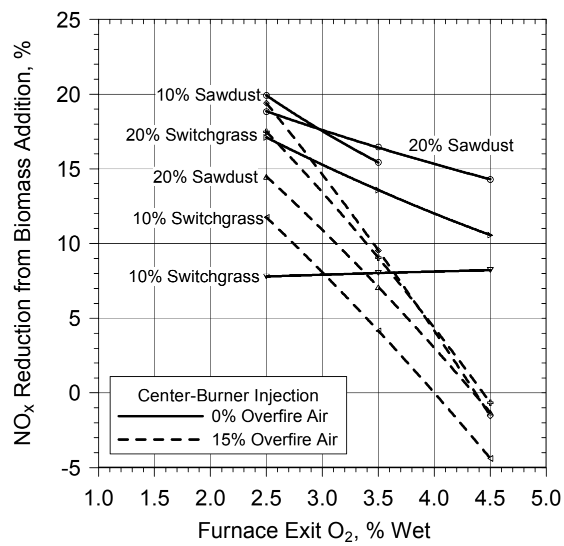

Figure 5: NO_X reductions with core injection of biomass

ground to the fineness of the coal in a comilled mixture of coal and biomass has shown that the finer coal grind did not affect NO_X emissions. Thus, NO_X reductions from cofiring with comilled biomass are not related to the particle size distribution of the coal.

With comilling, NO_X emissions may be lowered because highly volatile biomass burns first, creating a lean-burn environment near the burner. Because the coal and biomass are intimately mixed, less O_2 is generally available for the coal. This is consistent with the results shown in Figure 4 where with no SOFA, NO_X reductions are generally less than with 15% SOFA, when less air is available at the burner. There are, however, other counterintuitive biomass-related interactions. In the absence of SOFA, increasing the amount of comilled switchgrass lowers NO_X emissions while increasing the amount of comilled sawdust increases NO_X emissions. Adding SOFA changes the pattern of NO_X reduction to one where increasing the amount of either biomass decreases NO_X emissions. This latter result

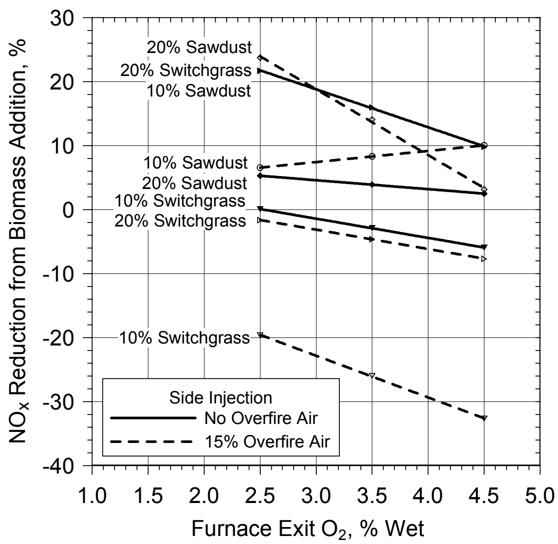

Figure 6: NO_X reductions with side injection of biomass

is an unexpected, but beneficial effect. With Coal, as FEO is increased, NO_X emissions increase. When biomass is comilled with coal, with 15% SOFA, increasing FEO, tends to increase the relative amount of NO_X reduction.

As the location for biomass injection is moved away from the flame, NO_X emissions can increase dramatically. Figures 5 and 6 show when cofired biomass is not comilled, increasing the amount of biomass can increase NO_X emissions, sometimes above those observed for 100% coal firing. In the worst case, for cofiring switch-grass through side injection with 15% SOFA, adding 10% switchgrass increased NO_X emissions by up to 32%. For the same geometry, when 15% SOFA was added, NO_X emissions still were increased over those measured for 100% coal firing, but by a maximum of 6%.

Figures 4-6 also show that some of the behavior seen with comilled sawdust occurs for other cofiring configurations. That is, for a particular cofiring geometry and level of SOFA, increasing the content of one biomass may reduce NO_X emissions, but increasing the content of another biomass may have no effect or increase NO_X emissions. Thus, while such behavior is unexpected, it has been found to occur for three cofiring configurations with two different biomasses.

These seemingly contradictory relationships are real. Shortly after the testing phase of this project began, and results such as the above were observed, selected tests were repeated to verify that the behavior that was observed could be repeated. Thus, perhaps the most important general conclusion that can be drawn from these results is that in order to understand the nature of these interactions, fundamental questions of fuel chemistry and combustion must be addressed. Finally, as a general comment, UBC emissions were low for all combinations of biomass with this coal.

3 MODELING

The goal of the modeling portion of this project is to construct a comprehensive model of biomass cofiring that can predict the body of experimental results that has been observed, without the need for sets of adjustable or arbitrary parameters. The modeling strategy provides an alternative to conventional CFD post-processing to estimate exhaust NOX emissions. The method first analyzes a CFD furnace simulation to specify temperature histories and mixing rates. Then bulk flow patterns are represented by an equivalent network of idealized reactor elements. Detailed reaction mechanisms are then applied over the reactor network, including the most fully validated reaction mechanisms for coal devolatilization and char oxidation and complete elementary reaction mechanisms for chemistry in the gas phase and in soot.

This approach has been able to predict NO_X emissions measured at the CRF for pilot-scale flames of coal and coal/biomass blends within experimental uncertainty over a broad range of FEO concentrations, with and without SOFA. Predicted unburned carbon emissions are qualitatively correct, but char reactivity parameters need to be specified in a one-point calibration for quantitative predictions. This approach also characterizes distinctive chemistry within the flame core, a mixing layer for secondary air entrainment, an overfire air zone, and a char burnout zone. The main practical benefit of the mechanistic complexity is that simulations based on detailed mechanisms require fewer parameter adjustments than CFD simulations whenever different fuels are considered [3].

4 CONCLUSIONS

A large, comprehensive, set of experimental data has been compiled from which a model of biomass cofiring is being constructed. The experimental data were obtained at a pilot-scale furnace that has been shown to be representative of full-scale pulverized coal-fired utility boilers. The experimental matrix has subjected a variety of coals, biomasses, and biomass cofiring geometries, to the same set of combustion conditions and the emissions data obtained in this effort are being used to validate the model development.

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