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 eighth 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. The final biomass co-firing test burn was conducted during this quarter. In this test (Test 14), up to 20% by weight dry 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 this test 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 REI Configurable Fireside Simulator (CFS) is now in regular use. Presently, the CFS is being used to generate CFD calculations for completed tests with Powder River Basin coal and low-volatility (Jim Walters #7 Mine) coal. Niksa Energy Associates will use the results of these CFD simulations to complete their validation of the NOx/LOI predictive model. Work has started on the project final report.

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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, with an approved time extension, continues through December 31, 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 1-9.

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 Tests 1-9. *In this way, these Test series were simulated with the detailed chemical reaction mechanisms, based on CFD simulations from REI and CFD simulations carried out with the REI's Configurable Fireside Simulator.*

NEA is in the process of making comparisons with tests involving Powder River Basin (PRB) coal. Comparisons for cofiring tests with low volatility coal must wait until CFD simulations are completed.

CFD Simulations

REI's Configurable Fireside Simulator for the Pilot-Scale Combustion Research Facility is now operational and CFD simulations for PRB coals have been completed. Work is underway on completing CFD simulations with low volatility coal.

Pilot-Scale Combustor Testing

Furnace Testing Fourteen furnace tests have been completed through the end of September, 2002. Tests 1 through 13 have been reviewed in previous quarterly progress reports. Test 14 (conducted in July, 2002) is reviewed below. Table 1 summarizes the tests that have been completed to date. 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 Test 14. In this test, 5%, 10%, and 20% by weight finely-divided, dry switchgrass 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 (~20% volatiles, ~ 0.7% S). In an earlier companion test (Test 13), 5%, 10%, and 20% by weight finely-divided, dry sawdust was comilled with Jim Walters #7 mine coal and injected through the single-register burner. The results from Test 13 were presented in the last Quarterly Progress Report. As with previous tests, the biomass used in Test 14 was processed by MESA Reduction Engineering and Processing, Inc. in a collision mill of their design.

Test 14 For this test, from July 14-19, 2002, Jim Walter #7 mine low-volatility coal was burned by itself and comilled with switchgrass and injected into the furnace at injection location 1 as shown in Figure 1. As with Test 13, this coal was obtained locally from a portion of the Blue Creek seam known to have a lower than normal volatile matter content (~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

Table 1. Tests Completed Through September, 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)

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

Test 14 Jim Walters #7 coal – Comilled Biomass, single register burner (Location 1), 5%, 10%, 20% Switchgrass. 0%, 15%, overfire air. Char sampling below overfire air ports. 7/14-19/02

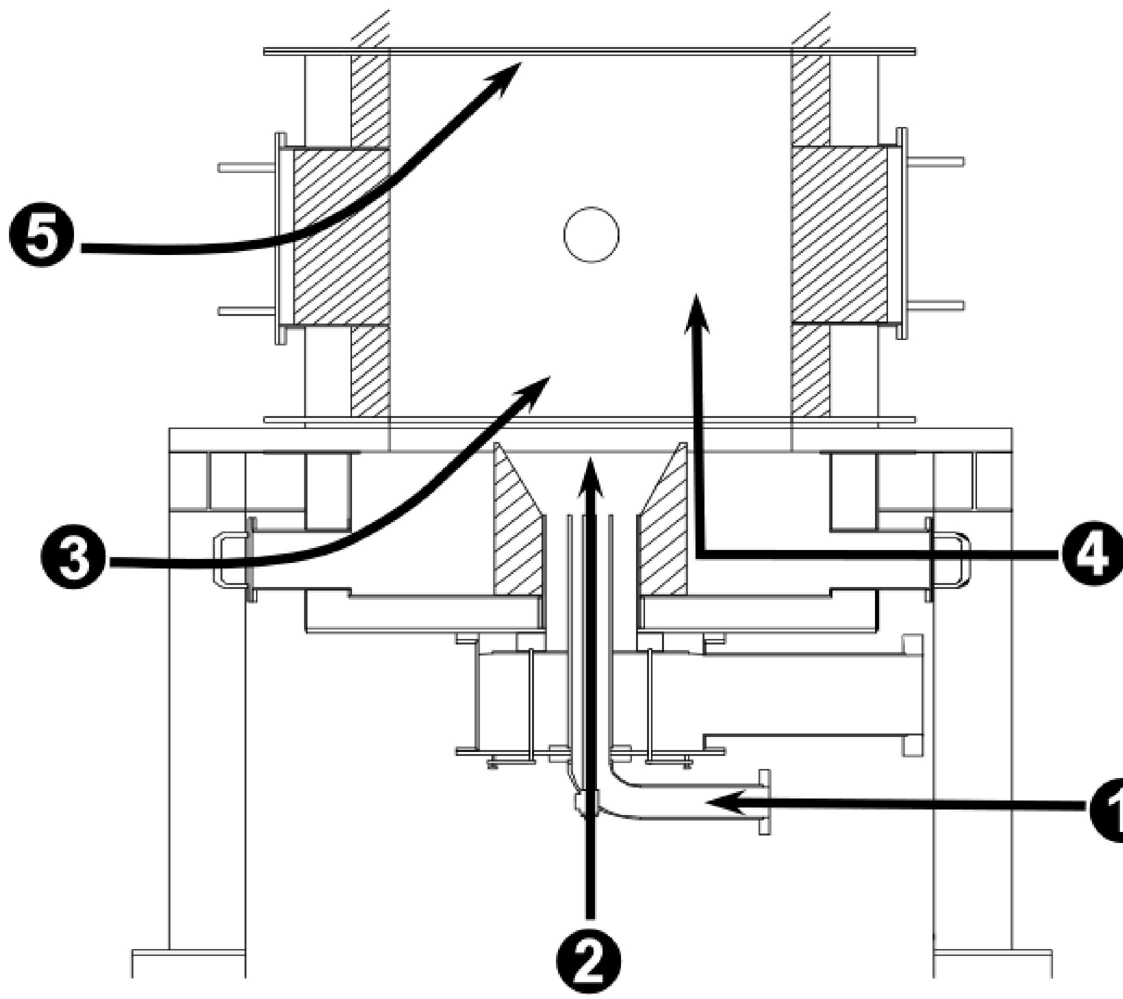

Figure 1. Locations for biomass injection in the SRI/SCS furnace equipped with the single-register burner.

Table 2. Typical Proximate and Ultimate analyses of Coal and Biomass Fuel Samples from Test 14.

Sample I.D. Fuel	J947-142-CC-1 JW #7 Crushed Coal		E-1035-142-8 Switchgrass	
Proximate Analysis	As Rec.	Dry Basis.	As Rec.	Dry Basis
Moisture, %	1.36	---	7.72	---
Ash, %	15.01	15.22	6.74	7.30
Volatile, %	21.53	21.83	62.76	68.01
Fixed Carbon, %	62.10	62.95	22.78	24.69
Sum	100.00	100.00	100.00	100.00
Heat Content, Btu/lb	12607	12781	6556	7104
Sulfur, %	0.68	0.69	0.05	0.05
MAF Btu/lb	---	15075	---	7663
Ultimate Analysis	As Rec.	As Rec.	As Rec.	Dry Basis
Moisture, %	1.36	---	7.72	---
Carbon, %	73.56	74.57	42.90	46.49
Hydrogen, %	3.76	3.81	5.17	5.60
Nitrogen, %	1.42	1.44	1.07	1.16
Sulfur, %	0.68	0.69	0.05	0.05
Ash, %	15.01	15.22	6.74	7.30
Oxygen (diff.), %	4.21	4.27	36.35	39.40
Sum	100.00	100.00	100.00	100.00
Chlorine, %	0.01	0.01	0.34	0.36
Hardgrove Grindability	---	79	---	

Table 3. Proximate and Ultimate analyses of coal feeder discharge samples of Jim Walters #7 Mine (low volatility Eastern bituminous) coal from Tests 13 and 14.

Sample I.D. Fuel Test Number	J947-143-CFD-1 Jim Walters #7 Test 14		J-947-128-CFD-1 Jim Walters #7 Test 13	
Proximate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	0.91	---	0.75	---
Ash, %	14.60	14.73	14.61	14.72
Volatile, %	19.47	19.65	20.00	20.15
Fixed Carbon, %	65.02	65.62	64.64	65.13
Sum	100.00	100.00	100.00	100.00
Heat Content, Btu/lb	13114	13234	13215	13315
Sulfur, %	0.74	0.75	0.72	0.73
MAF Btu/lb	---	15520	---	15613
Ultimate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	0.91	---	0.75	---
Carbon, %	75.35	76.04	75.72	76.29
Hydrogen, %	3.84	3.88	3.91	3.94
Nitrogen, %	1.37	1.38	1.48	1.49
Sulfur, %	0.74	0.75	0.72	0.73
Ash, %	14.60	14.73	14.61	14.72
Oxygen (diff.), %	3.19	3.22	2.81	2.83
Sum	100.00	100.00	100.00	100.00
Chlorine, %	0.0.01	0.0.01	0.01	0.01
Ash Fusion	Reducing	Oxidizing	Oxidizing	Oxidizing
Initial Deformation, °F	2500	2675	2520	2695
Softening, °F	2570	2725	2590	2725
Hemispherical, °F	2610	2750	2665	2765
Fluid, °F	2695	2790	2730	2790

Table 4. Proximate and Ultimate analyses of coal feeder discharge samples of Jim Walter #7 mine coal comilled with dry switchgrass from Test 14.

Sample I.D. / Fuel	J947-148-CFD-1 5% Switchgrass		J947-151-CFD-3 10% Switchgrass		J947-155-CFD-1 20% Switchgrass	
Proximate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	1.04	---	1.16	---	1.74	---
Ash, %	14.45	14.60	13.97	14.13	13.13	13.36
Volatile, %	22.91	22.14	23.38	23.65	35.94*	36.58*
Fixed Carbon, %	62.60	63.26	61.49	62.22	49.19*	50.06*
Sum	100.00	100.00	100.00	100.00	100.00	100.00
Heat Content, Btu/lb	12760	12894	12725	12874	12134	12349
Sulfur, %	0.72	0.73	0.69	0.70	0.55	0.56
MAF Btu/lb	---	15098	---	14992	---	14253
Ultimate Analysis	As Rec.	Dry Basis	As Rec.	Dry Basis	As Rec.	Dry Basis
Moisture, %	1.04	---	1.16	---	1.74	---
Carbon, %	73.09	73.86	72.50	73.35	69.72	70.95
Hydrogen, %	3.92	3.96	3.89	3.94	4.20	4.27
Nitrogen, %	1.57	1.59	1.42	1.44	1.40	1.42
Sulfur, %	0.72	0.73	0.69	0.70	0.55	0.56
Ash, %	14.45	14.60	13.97	14.13	13.13	13.36
Oxygen (diff.), %	5.21	5.26	6.37	6.44	9.26	9.44
Sum	100.00	100.00	100.00	100.00	100.00	100.00
Chlorine, %	0.01	0.01	0.02	0.02	0.05	0.05
Ash Fusion	Reducing	Oxidizing	Reducing	Oxidizing	Oxidizing	Oxidizing
Initial Deformation, °F	2510	2680	2505	2660	2335	2450
Softening, °F	2590	2730	2570	2710	2400	2510
Hemispherical, °F	2650	2765	2615	2735	2440	2555
Fluid, °F	2735	2800+	2675	2770+	2490	2605

* Volatile content higher than expected – possible instrument error. Fixed carbon is obtained by difference and is therefore lower than expected.

the sawdust used in this test are presented in Tables 2 and 3. Table 4 presents the results of proximate and ultimate analyses of pulverized (comilled) mixtures of Jim Walter #7 mine coal and switchgrass.

As was also observed in Test 13, because of the low volatility of this coal, the pure coal flame was not well defined. As biomass was added and as fuel volatility was increased from ~20% (100% coal) to over 30% (20% switchgrass, 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 more lower furnace slag than was seen with Galatia or PRB coals. 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 switchgrass.

Figure 2 presents NO_X emissions for 100% Jim Walter #7 coal firing for the single-register burner. In this figure, the results of 100% coal firing for Tests 13 and 14 are combined. Figures 3 through 5 present average NO_X emissions measured for the combustion of 5%, 10%, and 20% by weight switchgrass comilled with Jim Walter #7 coal. Figure 6 summarizes Figures 2 through 5, placing all NO_X emissions trends within one graph. Figure 7 and Table 5 summarize the effect of switchgrass addition on NO_X emissions. Finally, Figures 8 and 9 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 Test 13, sawdust was comilled with Jim Walters #7 mine low-volatility coal. Figure 10 summarizes the results of NO_X emissions trends from that test. This figure can be directly compared with Figure 6 so that differences in NO_X emissions trends as a function of the cofired biomass will be readily apparent. Figure 10 shows that compared to 100% coal firing, NO_X emissions were either unaffected or reduced by the addition of sawdust. Indeed, with or without overfire air, a minimum in NO_X emissions was observed at a 10% level of sawdust addition. When Jim Walters #7 mine coal was cofired with switchgrass, with or without overfire air, adding a small amount of switchgrass (5 weight %) tended to increase NO_X emissions above those measured for 100% coal firing. Adding more switchgrass (10 weight %) produced mixed results with NO_X emissions being reduced below those measured for 100% coal firing for values of furnace exit oxygen (FEO) lower than ~3 to 3.5%, but increased above those measured for 100% coal firing for greater values of FEO. At the highest level of switchgrass

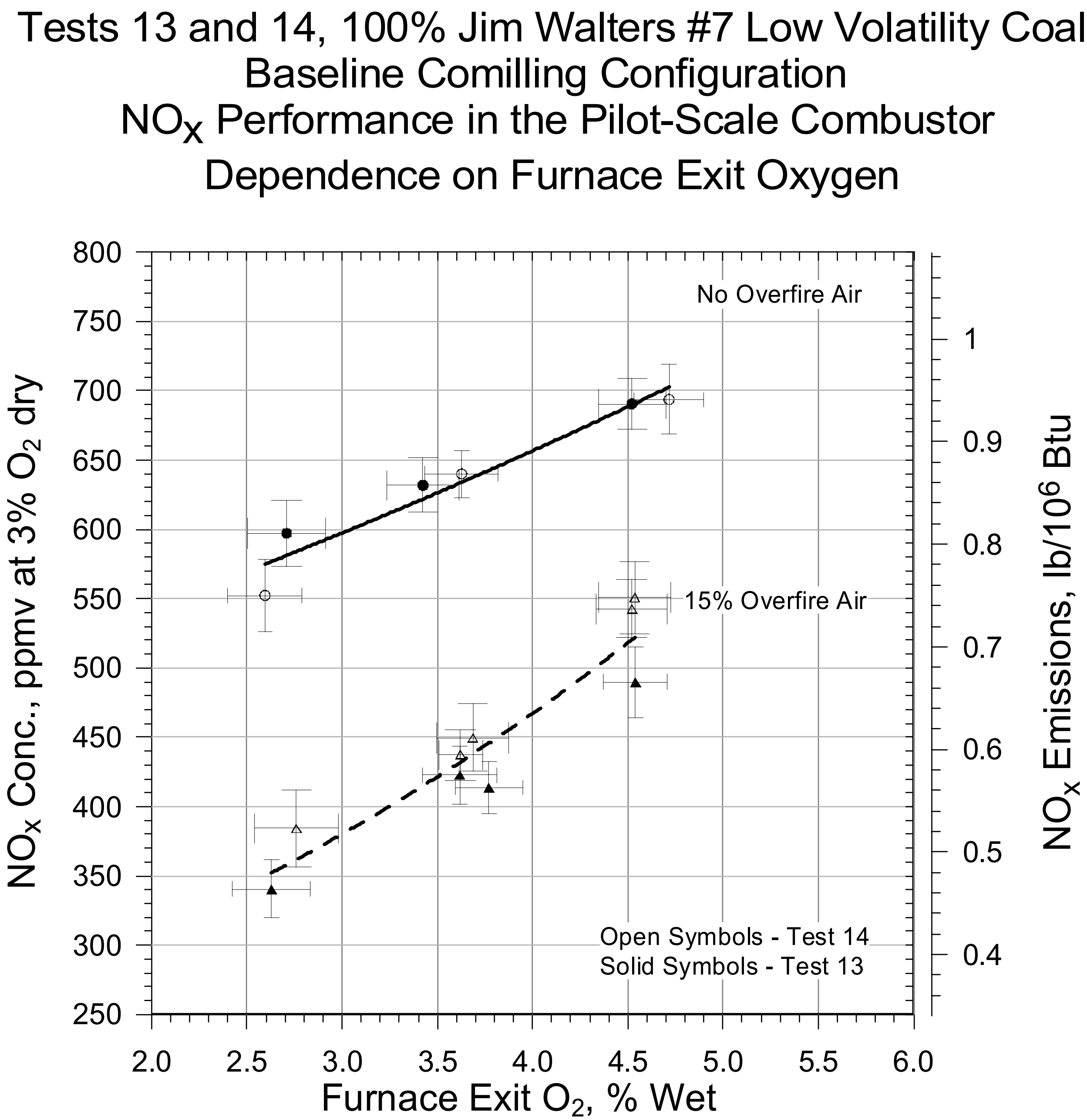

Figure 2. NO_X emissions measured for Jim Walter #7 Mine coal comilled with 5% by weight dry switchgrass. Combined results for Tests 13 and 14. Single-register burner with 0% and 15% overfire air.

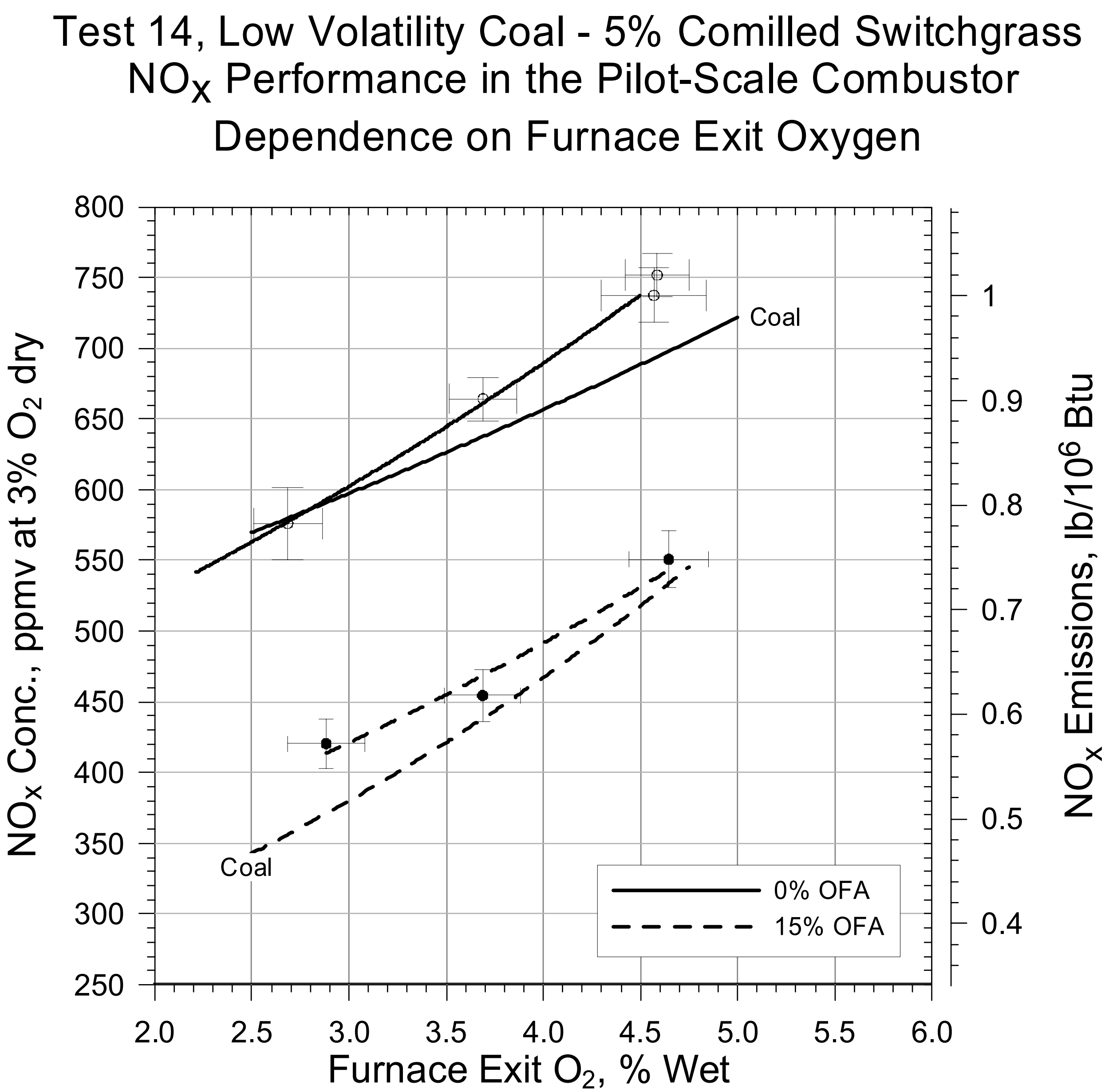

Figure 3. NO_X emissions measured for Jim Walter #7 coal comilled with 5% by weight dry switchgrass. Single-register burner with 0% and 15% overfire air.

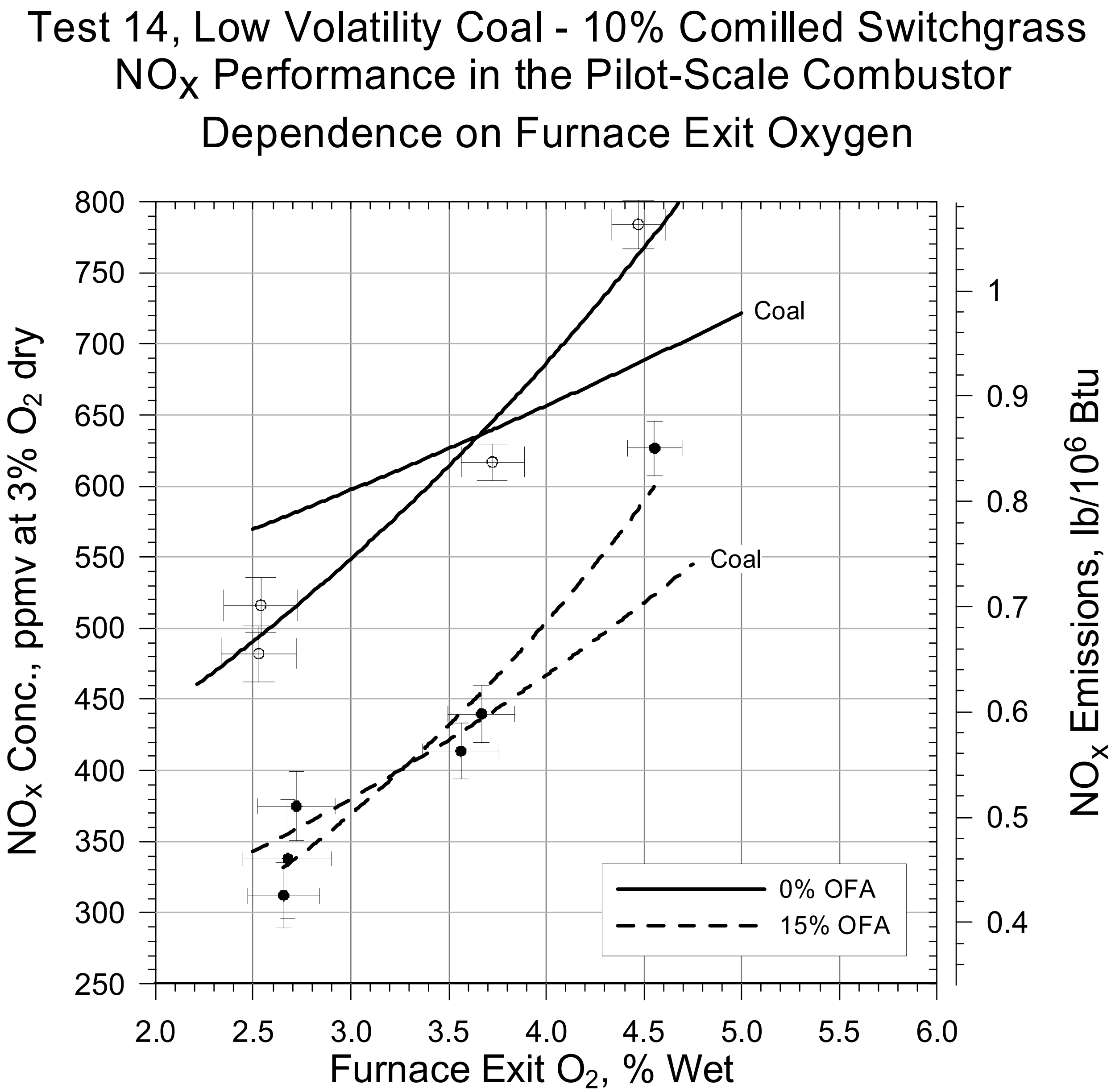

Figure 4. NO_X emissions measured for Jim Walter #7 coal comilled with 10% by weight dry switchgrass. Single-register burner with 0% and 15% overfire air.

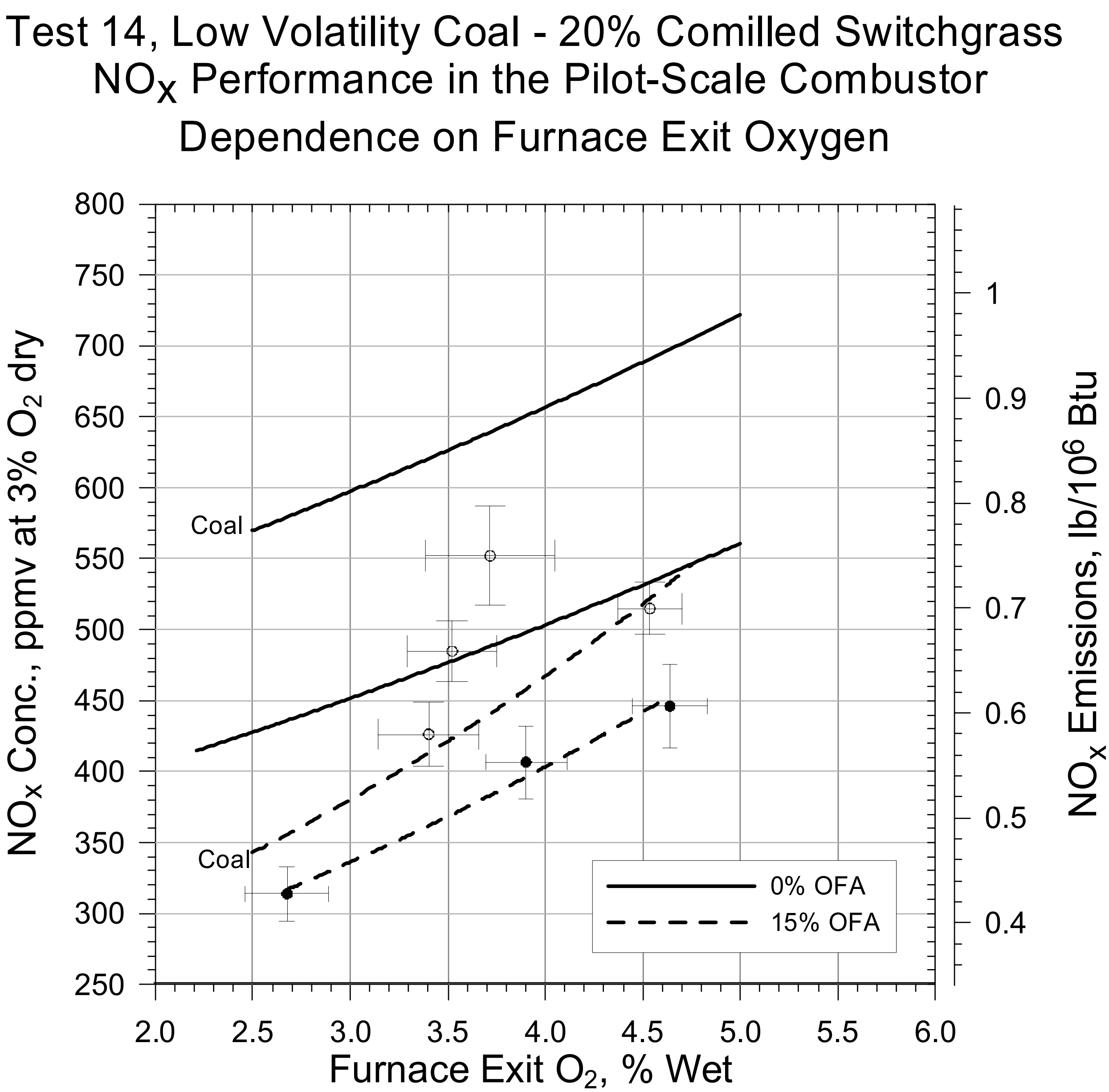

Figure 5. NO_X emissions measured for Jim Walter #7 coal comilled with 20% by weight dry switchgrass. Single-register burner with 0% and 15% overfire air.

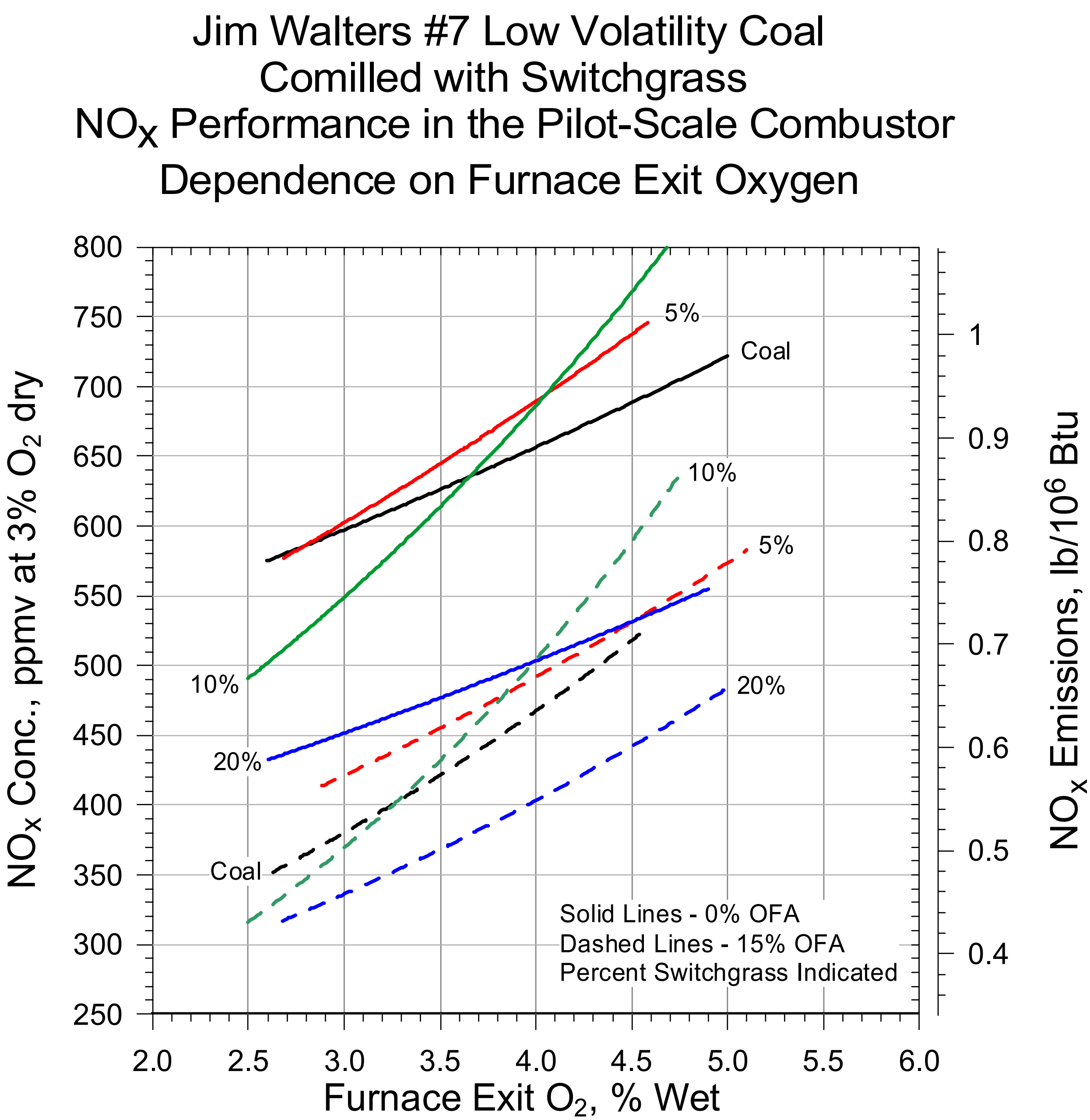

Figure 6. Summary of NO_X emissions measured for 100% coal and for 5%, 10%, and 20% switchgrass comilled with Jim Walter #7 coal. Single register burner with 0% and 15% overfire air.

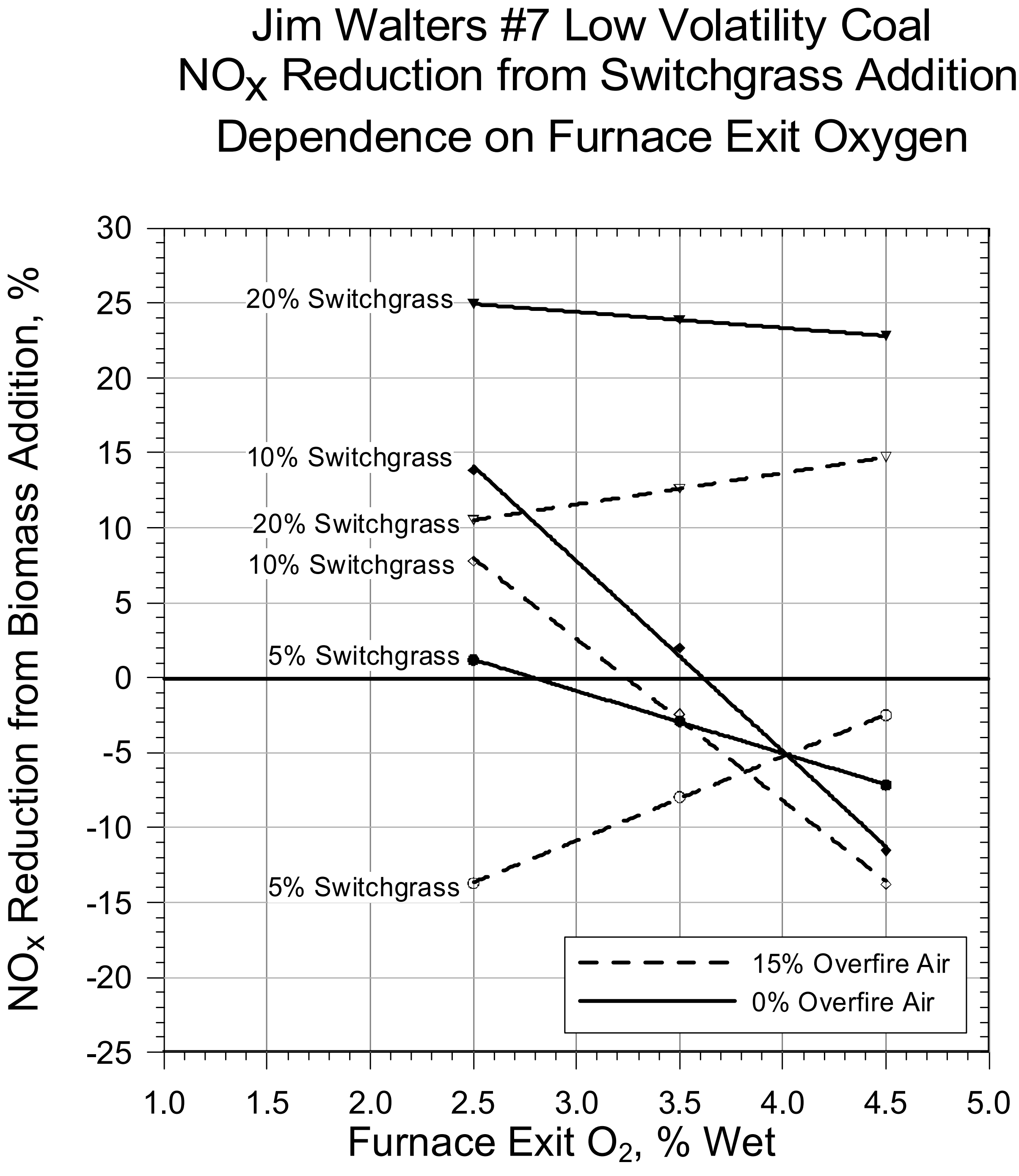

Figure 7. NO_X reductions measured for 5%, 10% and 20% switchgrass comilled with Jim Walter #7 coal. Single-register burner with 0% and 15% overfire air.

Table 5. NO_X emissions for 0% and 15% overfire air at 2.5%, 3.5%, and 4.5% furnace exit O_2, (wet) for switchgrass 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	570	0
		15	343	0
Switchgrass	5	0	563	1.2
		15	390	-13.7
	10	0	491	13.8
		15	316	7.8
	20	0	428	24.9
		15	307	10.5
3.5% Furnace Exit Oxygen				
None	0	0	626	0
		15	421	0
Switchgrass	5	0	645	-2.9
		15	455	-8.0
	10	0	614	2.0
		15	432	-2.4
	20	0	477	23.9
		15	368	12.6
4.5% Furnace Exit Oxygen				
None	0	0	688	0
		15	518	0
Switchgrass	5	0	738	-7.2
		15	531	-2.5
	10	0	768	-11.5
		15	589	-13.8
	20	0	531	22.8
		15	442	14.7

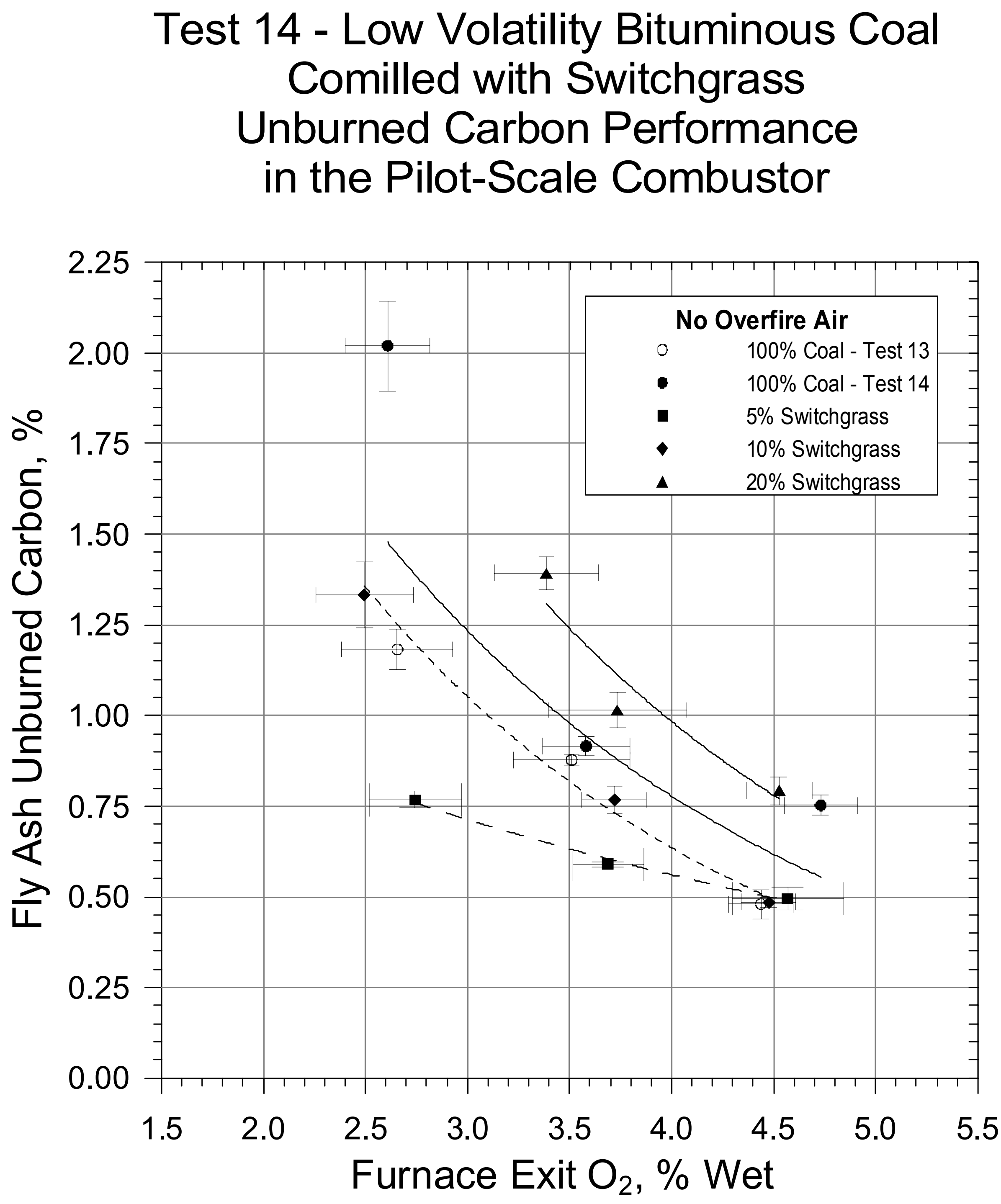

Figure 8. Unburned carbon emissions for the comilling of switchgrass with Jim Walter #7 coal. Single-register burner with 0% overfire air.

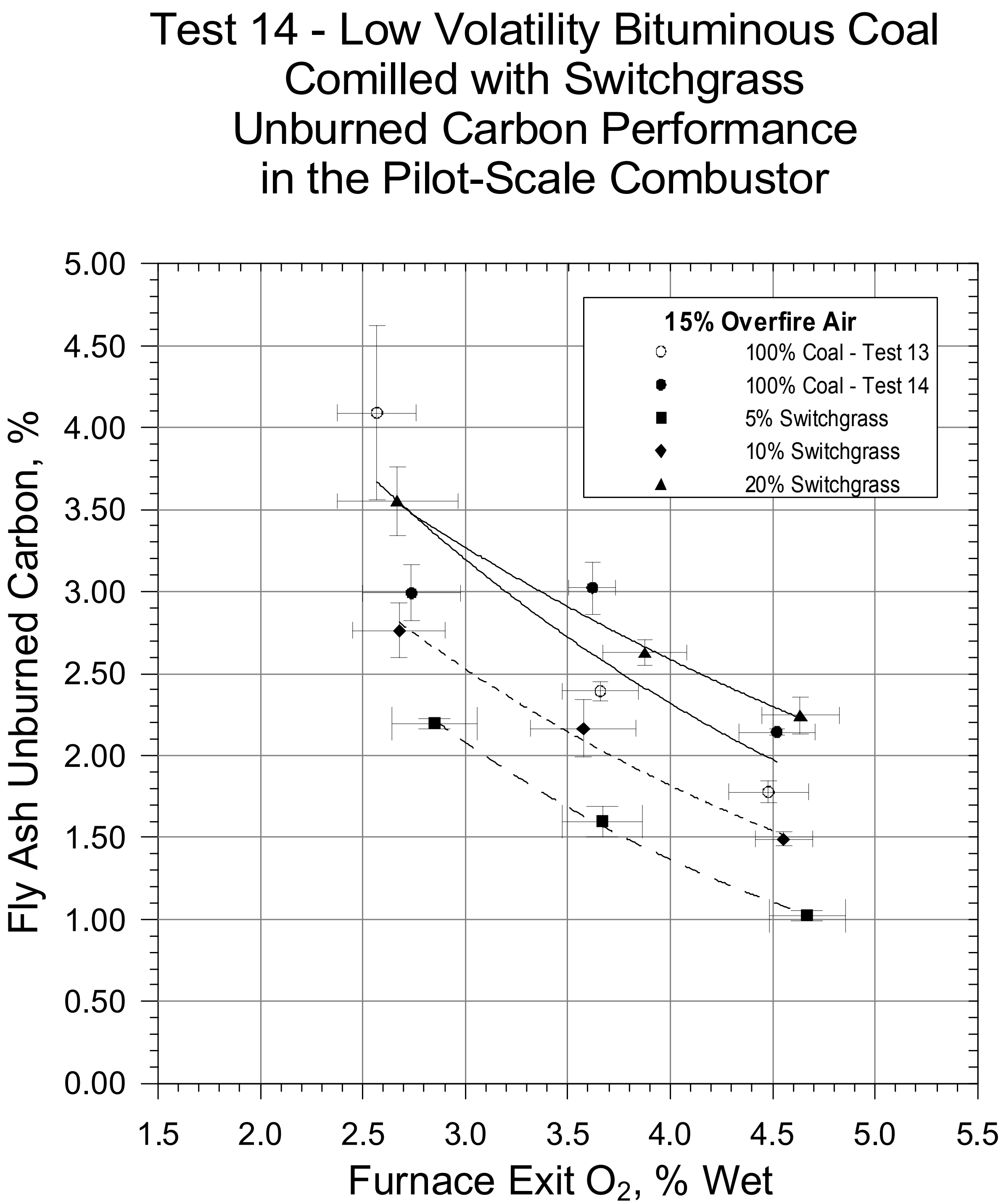

Figure 9. Unburned carbon emissions for the comilling of switchgrass with Jim Walter #7 coal. Single-register burner with 15% overfire air.

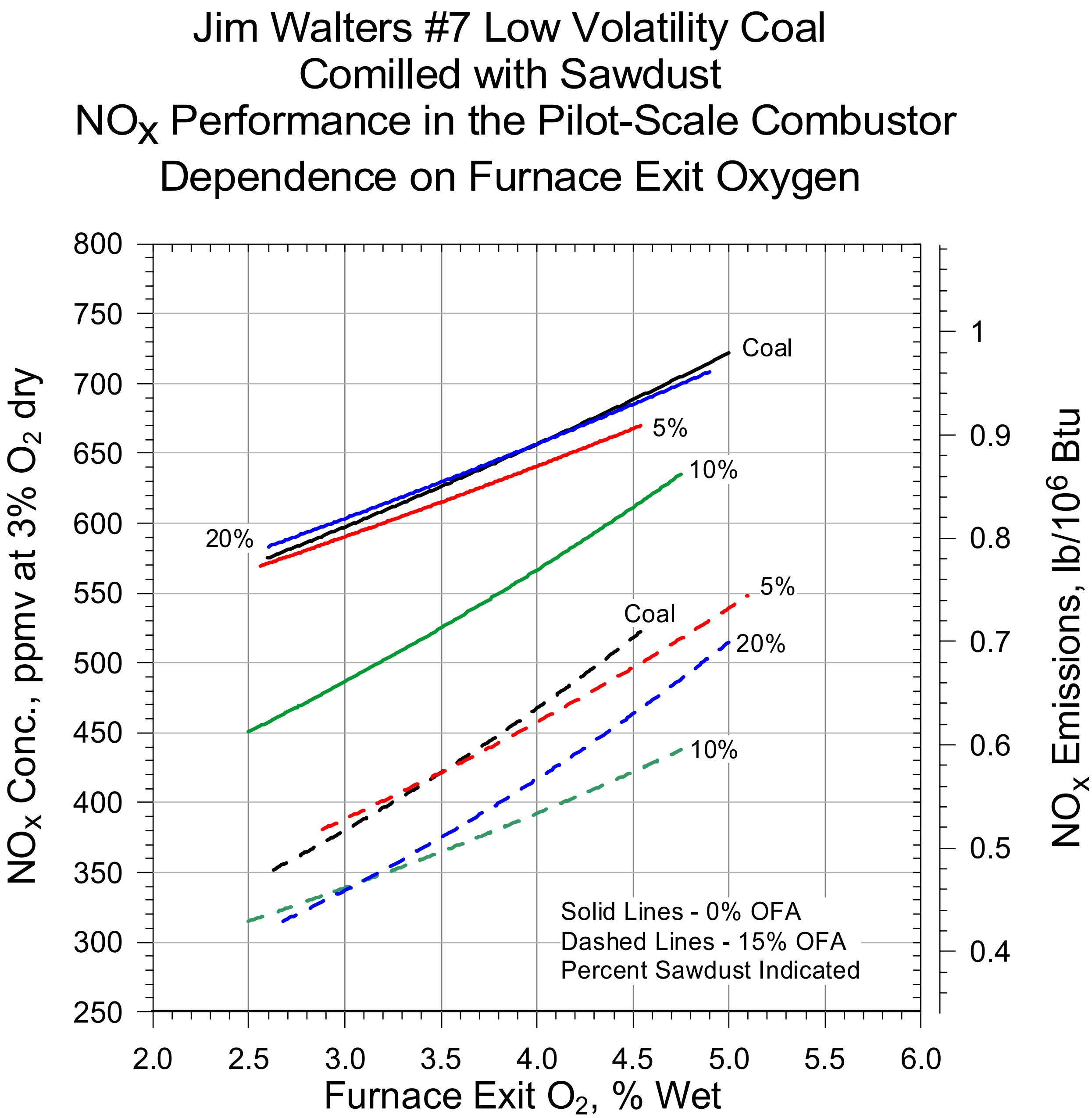

Figure 10. Summary of NO_X emissions measured for 100% coal and for 5%, 10%, and 20% sawdust comilled with Jim Walter #7 coal (Test 13). Single-register burner with 0% and 15% overfire air.

addition (20 weight %), NO_X emissions were decreased by up to 25% compared to NO_X emissions measured for 100% coal firing.

Clearly, the biomasses selected for Tests 13 and 14 are of sufficiently different character so that in cofiring they affect NO_X production in significantly different ways. As such, data from these two tests should provide a proper challenge for the model validation effort.

DISCUSSION

The Configurable Fireside Simulator (CFS) has been used to complete the CFD simulations required by NEA to model Tests 8 and 9 (Powder River Basin coal tests), Work is proceeding on using the CFS to carry out CFD simulations for Tests 13 and 14.

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.

With Test 14 concluded, no further pilot-scale furnace tests are planned. To date four coals and two biomasses have been tested with up to three modes of biomass injection. Combustion of a third biomass (chicken litter) was simulated by adding ammonia to the primary air/fuel feed line. Most testing was conducted with a single-register burner, since budgetary constraints precluded developing CFD simulations (and model validations) for a dual register burner. However, one test was conducted with a dual-register (low-NO_X) burner so that the database of information generated for this project will include NO_X emissions data from a dual-register burner. After initial tests with comilling, center-burner biomass injection, and side injection of biomass into the burner, subsequent tests concentrated on comilling biomass with coal when results from the modeling effort indicated that the model was most stringently tested with emissions data from cofiring tests with comilled biomass.

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. One pilot-scale furnace tests was concluded in the eighth quarter and no further testing is planned.

Plans for the next quarter include:

- Completing CFD simulations with the Configurable Fireside Simulator
- Completion of chemical reaction modeling by NEA to validate NO_X and UBC prediction across the spectrum of coals and biomasses tested in the pilot-scale combustor
- Preparation of the Final Report

In the fourteenth combustor run, switchgrass was comilled with a low-volatility Eastern Bituminous coal and injected into the furnace through the single-register burner. Once again, NO_X emissions were found to be strongly affected by the type and amount of each biomass that was comilled with the same base coal. These results continue to substantiate earlier results: NO_X and UBC emissions resulting from the cofiring of a given coal-biomass mixture are not intuitively related to NO_X and UBC emissions from the cofiring of another coal with the same biomass or for the same coal with another biomass.