Enhanced Combustion Low NOx Pulverized Coal Burner

Final Report

Submitted By

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Public Abstract

For more than two decades, Alstom Power Inc. (Alstom) has developed a range of low cost, in-furnace technologies for NOx emissions control for the domestic U.S. pulverized coal fired boiler market. This includes Alstom's internally developed TFS 2000™ firing system, and various enhancements to it developed in concert with the U.S. Department of Energy. As of the date of this report, more than 270 units representing approximately 80,000 MWe of domestic coal fired capacity have been retrofit with Alstom low NOx technology. Best of class emissions range from 0.18 lb/MMBtu for bituminous coal to 0.10 lb/MMBtu for subbituminous coal, with typical levels at 0.24 lb/MMBtu and 0.13 lb/MMBtu, respectively.

Despite these gains, NOx emissions limits in the U.S. continue to ratchet down for new and existing boiler equipment. On March 10, 2005, the Environmental Protection Agency (EPA) announced the Clean Air Interstate Rule (CAIR). CAIR requires 25 Eastern states to reduce NOx emissions from the power generation sector by 1.7 million tons in 2009 and 2.0 million tons by 2015. Low cost solutions to meet such regulations, and in particular those that can avoid the need for a costly selective catalytic reduction system (SCR), provide a strong incentive to continue to improve low NOx firing system technology to meet current and anticipated NOx control regulations.

The overall objective of the work is to develop an enhanced combustion, low NOx pulverized coal burner, which, when integrated with Alstom's state-of-the-art, globally air staged low NOx firing systems will provide a means to achieve:

- Less than 0.15 lb/MMBtu NOx emissions when firing a high volatile Eastern or Western bituminous coal,
- Less than 0.10 lb/MMBtu NOx emissions when firing a subbituminous coal,
- NOx reduction costs at least 25% lower than the costs of an SCR,
- Validation of the NOx control technology developed through large (15 MWt) pilot scale demonstration, and
- Documentation required for economic evaluation and commercial application

During the project performance period, Alstom performed computational fluid dynamics (CFD) modeling and large pilot scale combustion testing in its Industrial Scale Burner Facility (ISBF) at its U.S. Power Plant Laboratories facility in Windsor, Connecticut in support of these objectives. The NOx reduction approach was to optimize near-field combustion to ensure that minimum NOx emissions are achieved with minimal impact on unburned carbon in ash, slagging and fouling, corrosion, and flame stability / turn-down. Several iterations of CFD and combustion testing on a Midwest coal led to an optimized design, which was extensively combustion tested on a range of coals. The data from these tests were then used to validate system costs and benefits versus SCR.

Three coals were evaluated during the bench-scale and large pilot-scale testing tasks. The three coals ranged from a very reactive subbituminous coal to a moderately reactive Western bituminous coal to a much less reactive Midwest bituminous coal. Bench-scale testing was comprised of

standard ASTM properties evaluation, plus more detailed characterization of fuel properties through drop tube furnace testing and thermogravimetric analysis.

Bench-scale characterization of the three test coals showed that both NOx emissions and combustion performance are a strong function of coal properties. The more reactive coals evolved more of their fuel bound nitrogen in the substoichiometric main burner zone than less reactive coal, resulting in the potential for lower NOx emissions. From a combustion point of view, the more reactive coals also showed lower carbon in ash and CO values than the less reactive coal at any given main burner zone stoichiometry. According to bench-scale results, the subbituminous coal was found to be the most amenable to both low NOx, and acceptably low combustibles in the flue gas, in an air staged low NOx system. The Midwest bituminous coal, by contrast, was predicted to be the most challenging of the three coals, with the Western bituminous coal predicted to behave in-between the subbituminous coal and the Midwest bituminous coal.

CFD modeling was used to gain insight into the mechanisms governing nozzle tip performance with respect to NOx emissions. The CFD simulations were run as steady state, turbulent, non-reacting flow with heat transfer and focused on predicting the near field mixing and particle dispersion rates. CFD results were used to refine the proposed tip concepts before they were built, as well as to help identify and evaluate possible improvements to the tips for subsequent test weeks.

CFD models were generated of the baseline shear bar / air deflector and LNCFS™ P2 tips. Four new coal nozzle tip ideas and an earlier Alstom-conceived idea were selected for evaluation in the first week of ISBF testing. A final nozzle tip concept, the Vane Tip, was conceived after examining the results of the first ISBF test week and the available CFD results. The CFD modeling suggested that concentrating the coal particles towards the outside of the coal stream is advantageous for reducing NOx emissions.

The ISBF test program was performed in a series of three test campaigns over a 15 month period. During Campaign one, 72 tests were performed on baseline and new nozzle tip designs from the modeling program, using the Midwest bituminous coal. The second campaign demonstrated that the new Vane Tip successfully combined low NOx and operability, while the flow improvements to the other tips were only modestly successful. Campaign three proved the robust performance of the new tip over a range of design variants (needed for scale-up to the range of commercial equipment sizes), coal types, and over some longer tests. Comparison data with the conventional P2 tip was also taken over the range of coals and stoichiometries.

During the ISBF test program, the new Vane Tip with subcompartmentalized air achieved the NOx emissions goals of the project for all three fuels evaluated in the ISBF:

- The Midwestern bituminous coal gave NOx emissions of 0.14 lb/MMBtu with 10.0% fly ash unburned carbon
- The Western bituminous coal gave NOx emissions of 0.10 lb/MMBtu with 1.9% fly ash unburned carbon
- The subbituminous coal gave NOx emissions of 0.09 lb/MMBtu with 2.8% fly ash unburned carbon

An economic evaluation of the technology was performed. Capital costs for retrofit with TFS 2000™ plus the new technology are well under the target of "25% less than an SCR-only" installation based on commercial costing information. For the bituminous coal cases, the capital cost of retrofit is about 86-89% less than an SCR-only case; for the subbituminous coal case is on the order of 83% less than an SCR-only case. Results from the economic analysis showed that switching to a subbituminous coal, in concert with combustion system modifications, was the most cost effective option if the cost of shipping the subbituminous coal to a particular site was not prohibitive. However, it was recognized that the optimum NOx reduction strategy is, of course, unit, site, and system specific.

The performance of this work has given Alstom sufficient data to design, estimate costs and benefits, construct and demonstrate a commercial version of the final system. The first commercial demonstration is scheduled for the Spring of 2008.

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Executive Summary

Background

For more than two decades, Alstom Power Inc. (Alstom) has developed a range of low cost, in-furnace technologies for NOx emissions control for the domestic U.S. pulverized coal fired boiler market. This includes Alstom's internally developed TFS 2000™ firing system, and various enhancements to it developed in concert with the U.S. Department of Energy. As of the date of this report, more than 270 units representing approximately 80,000 MWe of domestic coal fired capacity have been retrofit with Alstom low NOx technology. Best of class emissions range from 0.18 lb/MMBtu for bituminous coal to 0.10 lb/MMBtu for subbituminous coal, with typical levels at 0.24 lb/MMBtu and 0.13 lb/MMBtu, respectively.

Despite these gains, NOx emissions limits in the U.S. continue to ratchet down for new and existing boiler equipment. On March 10, 2005, the Environmental Protection Agency (EPA) announced the Clean Air Interstate Rule (CAIR). CAIR requires 25 Eastern states to reduce NOx emissions from the power generation sector by 1.7 million tons in 2009 and 2.0 million tons by 2015. Low cost solutions to meet such regulations, and, in particular, those that can avoid the need for a costly selective catalytic reduction system (SCR), provide a strong incentive to continue to improve low NOx firing system technology to meet current and anticipated NOx control regulations.

Objectives

The overall objective of this project is to develop an enhanced combustion, low NOx pulverized coal burner, which, when integrated with Alstom's state-of-the-art, globally air staged low NOx firing systems will provide a means to achieve:

- less than 0.15 lb/MMBtu NOx emissions at less than ¾ the cost of an SCR with low to no impact on balance of plant issues when firing a high volatile Eastern or Western bituminous coal, and
- less than 0.10 lb/MMBtu NOx emissions at less than ¾ the cost of an SCR with low to no impact on balance of plant issues when firing a subbituminous coal.

Further objectives include:

- Validation of the NOx control technology developed through large (15 MWt) pilot scale demonstration
- Evaluation of the engineering feasibility and economics for representative plant cases

Work Scope

Several low NOx coal nozzle tip modifications were developed and evaluated under this project. Alstom utilized CFD to evaluate a series of coal nozzle tip and/or near field stoichiometry controls in order to screen promising design concepts for large pilot scale testing. Following this screening work, Alstom performed large pilot scale combustion testing in its Industrial Scale Burner Facility (ISBF).

A series of three large pilot scale combustion tests were performed in the ISBF. During the first two test series, promising design concepts were evaluated to determine which coal nozzle tip features or combinations thereof provided the best NOx and unburned carbon performance versus operating condition on a high volatile bituminous coal. During the third and final test series, the performance of the best design(s) as determined from the prior two test periods was characterized and optimized on three coals including the same high volatile bituminous coal used during periods one and two. In addition, subbituminous and Western bituminous coals were tested during the third series in an effort to demonstrate a means to achieve NOx emissions below 0.10 lb/MMBtu and 0.15 Lb/MMBtu, respectively, on these fuels.

Upon completion of the large pilot testing, a final cost/performance analysis utilizing the test results was performed to ensure the project objectives were met.

Key tasks within the project were:

- Preliminary coal nozzle tip concept design and performance evaluation
- Large pilot scale test preparations
- Firing system design and fabrication
- Fuel procurement and characterization
- Large pilot scale testing
- Cost and performance analyses

Preliminary coal nozzle tip concepts were evaluated using CFD modeling to assess candidate enhanced-combustion low NOx coal nozzle tip modifications for large pilot scale combustion testing. Screening was done mainly from the CFD modeling results, coupled with existing field and laboratory data and additional, proprietary, in-house performance predictive tools and algorithms.

The ISBF was configured with a single, tangentially fired coal burner, including associated auxiliary air compartments, and two levels of overfire air, consistent with the design of Alstom's TFS 2000™ low NOx firing system. Design and fabrication of appropriate global firing system components included a new main burner windbox, required primary and secondary air systems, and burner parts fabrication. An appropriate refractory configuration and firing rate was determined to best match the time-temperature-stoichiometry history of a typical pulverized coal fired utility boiler. The three coals selected and characterized included an Illinois #6 Midwestern bituminous coal, a lower sulfur Western bituminous coal, and a very low sulfur Indonesian subbituminous coal.

Large pilot combustion testing was performed in the ISBF to estimate system performance at a commercial scale. The ISBF is a balanced draft; front wall fired combustion test facility designed to replicate the time-temperature-stoichiometry history of a typical industrial or utility steam generator. All major combustion-side aspects of a commercial boiler are duplicated in the ISBF, including the radiative furnace cavity and simulated convective heat transfer surfaces. The ISBF was operated with a single tangential-design coal and air admission assembly and up to two levels of overfire air, consistent with present low NOx firing system design practice.

Cost and performance analyses were performed to determine the ability of enhanced combustion burner concepts developed in the project to reduce NOx emissions. The performance and economics of individual, enhanced combustion technologies were considered alone and in appropriate combination (addition of selective catalytic reduction, purchase of NOx allowances, etc.) to optimize overall cost / performance behavior. Various NOx reduction options were evaluated as retrofit cases for the following tangential-fired utility boiler/fuel combinations:

- 400 MW boiler on the East coast firing an Eastern bituminous sulfur compliance coal,
- 400 MW boiler on the East coast switching to Powder River Basin (PRB) subbituminous coal,
- 500 MW boiler in the Midwestern US firing a local bituminous coal,
- 500 MW boiler in the Midwestern US switching to PRB subbituminous coal, and
- 330 MW boiler in the Western US firing a PRB subbituminous coal.

For each unit and fuel combination, seven NOx control options were evaluated: Economic analyses included calculation of the Net Present Value (NPV) of each retrofit option, capital costs for each retrofit option, and the sensitivity of NPV to input economic parameters.

Coal Nozzle Tip Design Screening and Modeling Results

CFD modeling was used to gain insight into the mechanisms governing nozzle tip performance with respect to NOx emissions. The CFD modeling was focused on predicting the near field mixing and particle dispersion rates and the simulations were run as steady state, turbulent, non-reacting flow with heat transfer. The simulations were run in an approximated ISBF geometry, including the coal and air nozzle tips, the windbox, two levels of overfire air, and a simulated convective section. CFD results were used to refine the proposed tip concepts before they were built, as well as to help identify and evaluate possible improvements to the tips for subsequent test weeks. CFD models were generated of the baseline shear bar / air deflector and LNCFS™ P2 tips. From project team discussions and initial modeling, four new coal nozzle tip ideas were selected for detailed modeling and evaluation in the first week of ISBF testing. These are referred to in this report as the center bluff, the recessed center bluff, the X-tip and the diverging hybrid tip. After the first test series, improvements to the week one tips and a newly designed vane tip, conceived after examining the results of the first ISBF test week and the CFD results, were modeled and tested.

The CFD modeling and ISBF combustion testing suggest that concentrating the coal particles towards the outside of the coal stream is advantageous for reducing NOx emissions while minimizing unburned carbon levels.

Pilot-Scale Test Results

The ISBF test program was performed in a series of three test campaigns over a 15 month period. During campaign one, 72 tests were performed on baseline and new nozzle tip designs from the modeling program, using the Midwest bituminous coal. Based on the first series of tests, as well as subsequent CFD modeling, design improvements and a new concept were chosen for analysis and combustion tested during a second test series. The second campaign was 5 days of testing, which produced 81 test points. This series demonstrated that the new tip concept, known as the Vane Tip, successfully combined low NOx and operability, while the improvements to the other tips were only modestly successful.

Campaign three took place over 8 days of testing, which produced 83 test points. This series proved the robust performance of the new Vane Tip over a range of design variants, coal types, and over some longer tests. Comparison data with the conventional P2 tip was also taken over the range of coals and stoichiometries. Specific, key findings from the pilot-scale testing were as follows:

- Vane Tip with subcompartmental air achieved the NOx emissions goals of the project for all three fuels evaluated in the ISBF:
    - The Midwestern bituminous coal tested (Illinois #6) gave NOx emissions of 0.14 lb/MMBtu with 10.0% fly ash unburned carbon
    - The Western bituminous coal tested (Sufco) gave NOx emissions of 0.10 lb/MMBtu with 1.9% fly ash unburned carbon
    - The subbituminous coal tested (Adaro) gave NOx emissions of 0.09 lb/MMBtu with 2.8% fly ash unburned carbon
- NOx decreased with reduced main burner zone stoichiometry down to an optimum point. . The subbituminous and Western bituminous coals gave lower NOx (at optimum stoichiometry) than the Midwestern coal.
- All tips and all coals generally showed substantial increases in unburned carbon at reduced stoichiometry conditions. However the Western bituminous and subbituminous coals generally maintained unburned carbon below the five percent level required for many ash recycling processes.
- CO emissions with the Vane Tips were generally higher than the baseline P2 tips, but this is typically “tunable” at utility boilers where the full range of tangential firing system adjustments are available.
- Front and rear furnace temperature indications showed that the Vane Tips created combustion conditions where the initial heat release was significantly greater than the baseline P2 tip. This accentuated the NOx reduction characteristics of all the coals tested at low main burner zone stoichiometry conditions. However when more oxygen was available at high stoichiometries these combustion conditions naturally led to greater NOx production. It is these high initial heat release, low stoichiometry combustion conditions that are believed to be the primary contributor to the superior performance of the Vane Tip.
- Comparing optimum tested conditions for the baseline P2 tip versus the Vane Tip variants, the Vane Tips produced overall lower NOx and unburned carbon emissions. At these conditions with Vane Tip D, Midwestern bituminous coal NOx emissions were reduced 44%, Western bituminous coal NOx emissions were reduced 36%, and subbituminous coal NOx emissions were reduced 50%.

Engineering System Analysis and Economics

An economic evaluation was performed in order to update prior studies with respect to NOx reduction options, particularly in view of the recent increases in commodity and labor costs for both fuels and materials, and the recent decrease in NOx allowance prices. Various NOx reduction options were evaluated as retrofit cases for 3 tangential-fired utility boilers in the US: (1) a 400 MW boiler on the East coast firing an Eastern bituminous compliance coal, (2) a 500 MW boiler in the Midwestern US firing a local bituminous coal, and (3) a 330 MW boiler in the Western US firing a subbituminous coal from the Powder River Basin (PRB). In addition, for the first two units, a PRB fuel switch and NOx retrofit were also evaluated. The units were selected as being representative of a large number of pulverized coal fired, utility boilers in the US.

Cost estimates and limited sensitivity analyses were carried out for each of the units. For this study, the units were assumed to be flexible with regard to buying and selling NOx allowances. These allowances could be bought and sold without limits and with no additional local constraints applied. A 15 year project life was assumed and a net present value of the retrofit option was calculated. The results of these calculations were plotted and compared to give an indication of the best choice for any given unit, provided that the assumptions on delivered fuel price and allowance price prevailed. However, it must be recognized that the optimum NOx reduction strategy is unit, site, coal, and system specific.

The key findings from this study are

- Low NOx burner retrofits show positive NPV values for most of the cases studied.
- Cases Lta (**L**NCFS™ level III with new **t**ips and subcompartmental **a**ir) and Tta (**T**FS 2000™ with new **t**ips and subcompartmental **a**ir) have at least a $30 million NPV advantage over SCR at the current NOx allowance price of $1000/ton for both bituminous and PRB coal.
- The capital cost for Case Tta is 83-89% less than the SCR-only case for both bituminous and PRB coal.
- The economic results are dependent upon the fuel and the allowance price level.
- For the allowance price levels and emissions standards used in this study, the SCR option did not provide the optimum economic result. However, there may be other reasons to justify SCR retrofits, such as local regulations, over-control with emission averaging for another unit, higher allowance prices, etc.
- Additional opportunities exist for time-varying over-control, depending upon the current value of NOx allowances.
- Lower NOx allowance prices strongly favor firing system modification economics.

1 Introduction

For more than two decades, Alstom Power Inc. (Alstom) has developed a range of low cost, in-furnace technologies for NOx emissions control for the domestic U.S. pulverized coal fired boiler market. This includes Alstom's internally developed TFS 2000™ firing system, and various enhancements to it developed in concert with the U.S. Department of Energy (DOE). To date, more than 270 units, representing more than 80,000 MWe of domestic coal fired capacity, have been retrofit with Alstom low NOx technology. Best of class emissions range from 0.18 lb/MMBtu for bituminous coals to 0.10 lb/MMBtu for subbituminous coals, with typical levels at 0.24 lb/MMBtu and 0.13 lb/MMBtu, respectively.

NOx emissions from pulverized coal-fired power plants in the United States have dropped significantly since the Clean Air Act Amendments (CAAA) were passed in 1990. NOx emissions data in 2003 showed a 29% reduction over 1990 levels, even though coal usage increased by almost 30% over the same period [1]. On March 10, 2005, the Environmental Protection Agency (EPA) announced the Clean Air Interstate Rule (CAIR). CAIR requires 25 eastern states to reduce NOx emissions from the power generation sector by 1.7 million tons in 2009 and 2.0 million tons by 2015. Low cost solutions to meet such regulations, and in particular those that can avoid the need for a costly selective catalytic reduction system (SCR), provide a strong incentive to continue to improve low NOx firing system technology to meet current and anticipated NOx control regulations.

To develop low cost solutions, the U.S. Department of Energy Office of Fossil Energy's National Energy Technology Laboratory (DOE/NETL) funded programs for the development of advanced NOx control technologies for the existing fleet of coal-fired utility boilers. Under one of these programs Alstom, in cooperation with the DOE, has developed an enhanced combustion, low NOx pulverized coal fired burner. This project builds upon a previous DOE co-funded project where Alstom developed an Ultra Low NOx Integrated System for NOx emission control from pulverized coal-fired utility boilers [2]. That research effort utilized a scaled version of Alstom's LNCFS™-P2 low NOx coal nozzle tip and focused on global air staging, windbox air distribution, and fuel air balancing. In contrast, the current project focuses on the near field aerodynamics and a new low NOx coal nozzle tip.

Alstom believes this enhanced combustion, low NOx pulverized coal fired burner will, when integrated with Alstom's state-of-the-art, globally air staged low NOx air systems, provide a means to achieve less than 0.15 lb/MMBtu NO_x at less than ¾ the cost of an SCR with low to no impact on balance of plant issues when firing a high volatile bituminous coal. High volatile bituminous coals are universally more problematic from a NO_x control standpoint than subbituminous PRB coals. Because many of the tangentially-fired units in this country that have not yet received low NOx retrofits currently fire PRB or western bituminous coals, Alstom has extended the scope of this project to also include achieving less than 0.10 lb/MMBtu NOx on subbituminous and below 0.15 Lb/MMbtu NOx on Western bituminous coals.

Under this program Alstom Power Plant Laboratories (Alstom-PPL) has performed three test campaigns of large pilot scale combustion testing in its Industrial Scale Burner Facility (ISBF) to help optimize the near-field combustion environment in order to maximize NOx reduction, while minimizing the impact on unburned carbon in ash, slagging and fouling, corrosion, and flame stability / turn-down under globally reducing conditions. Alstom has also utilized computational fluid dynamic modeling to help evaluate and understand coal nozzle tip performance and to help refine promising nozzle tip concepts. Also part of the program are preliminary (issued Sept 2006) and final cost / performance analyses of the developed enhanced combustion low NOx burner as applied to Alstom's state-of-the-art TFS 2000™ firing system. The performance of this work has given Alstom sufficient data to design, evaluate costs and benefits, construct and demonstrate a commercial version of the enhanced combustion low NOx pulverized coal burner. The first commercial demonstration is scheduled for the Spring of 2008.

1.1 Background

This section will describe Alstom's traditional approach for addressing customer environmental compliance needs, specifically NOx reduction. Knowledge of Alstom's traditional approach will provide a useful foundation for understanding how this project was conceived.

Alstom's approach for solving environmental compliance needs has been to create a total environmental solutions team that utilizes the full range of specific product resources and talents throughout the company. This team begins evaluating a compliance strategy by considering all of the potential places within the steam generating system where NOx can be affected and controlled. An analysis is made of the fuel selected, and its preparation, pulverization, and combustion. All feasible options for in-furnace NOx control are reviewed for reduction efficiency and potential impact on steam generator performance. Post-combustion technologies are also a major component of the evaluation. Alstom has expertise in post combustion systems including SCR, SNCR and hybrid technologies. A total approach to integrated controls and measurement is an integral part of this evaluation. This approach provides the flexibility to invest capital on equipment that provides the most cost-effective NOx reduction strategy, thus minimizing the total capital and operating costs for compliance.

Alstom has supported customer requirements to address CAAA of 1990 rules by offering a broad line of low NOx firing system products. Customer requirements have been met in many cases with in-furnace solutions alone. With the wide variety of tangential fired boiler designs of varying vintage, along with a broad range of coals being fired, Alstom developed and provides a family of low NOx firing system products which includes Level I, II, and III LNCFS™, LNCFS™-P2, TFS XP™, and TFS2000™ technology for retrofit. Figure 1.1-1 shows the relative costs and reduction efficiencies of Alstom's Low NOx solutions, all based on a typical single furnace 200 MW boiler[3]. Figure 1.1-2 presents a schematic of the firing systems available with the LNCFS™ family.

Each of these low NOx firing system products utilizes related design features of air-staged combustion, early fuel devolatilization, and local combustion air staging. The differences among the options available occur in the tradeoffs between coal properties, the extent of NOx emissions reduction and the complexity and cost of material modification and retrofit requirements. The percent decrease in NOx emissions from baseline is unit and fuel specific.

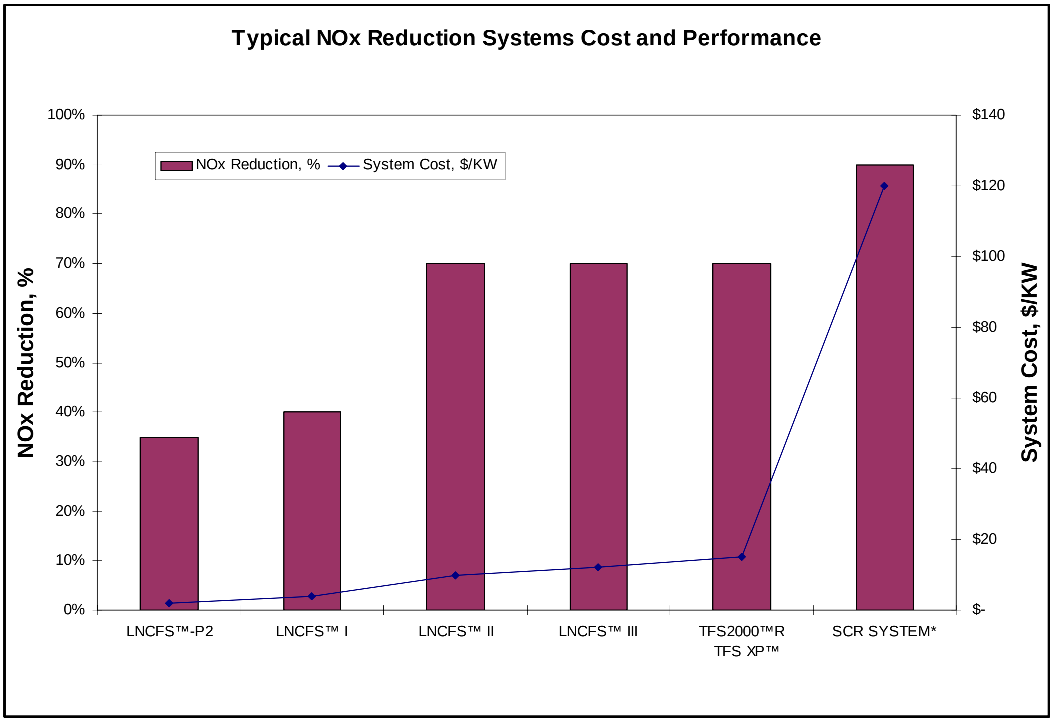


Figure 1.1-1 NOx Reduction System Cost vs. Performance

Standard Windbox	LNCFS™ P2	LNCFS™ Level I	LNCFS™ Level II	LNCFS™ Level III	TFS2000™R TFS XP™
			SOFA	SOFA	SOFA
			SOFA	SOFA	SOFA
					SOFA
					SOFA
AIR	VCCOFA	CCOFA	CCOFA	CCOFA	CCOFA
COAL	P2 COAL	CCOFA	COAL	CCOFA	COAL
AIR	CFS™ AIR	COAL	CFS™ AIR	COAL	CFS™ AIR
COAL	P2 COAL	COAL	COAL	COAL	COAL
AIR	CFS™ AIR	CFS™ AIR	CFS™ AIR	CFS™ AIR	CFS™ AIR
COAL	P2 COAL	COAL	COAL	COAL	COAL
AIR	CFS™ AIR	CFS™ AIR	CFS™ AIR	CFS™ AIR	CFS™ AIR
COAL	P2 COAL	COAL	COAL	COAL	COAL
AIR	CFS™ AIR	CFS™ AIR	CFS™ AIR	CFS™ AIR	CFS™ AIR
COAL	P2 COAL	COAL	COAL	COAL	COAL
AIR	AIR	AIR	AIR	AIR	AIR

Figure 1.1-2 Schematic of Firing System Arrangements for LNCFS™ Family of Low NOx Technology

Alstom has been supplying overfire air-based NOx reduction systems since 1970 and has been supplying its family of LNCFS™ NOx control firing systems since 1980. Over 270 coal-fired tangential boilers have incorporated these systems, representing over 80,000 MWe of generating capacity. These unit retrofits range in size from 44 MWe industrial to a 900 MWe supercritical, divided unit. The retrofit experience covers an extensive range of coal types from lignites to bituminous.

TFS 2000™ represents the most aggressive NOx reduction firing system technology available that includes features to mitigate increases in unburned carbon in fly ash and increases in carbon monoxide emissions from units firing high and low rank coals, respectively. NOx emissions levels below 0.15 lb/10^6 Btu are currently achieved and maintained on a continuous basis in many units firing lower ranked coals.

Prior to the demonstrated success of Alstom's technology to achieve this low level of NOx emissions, it was universally thought that installation of an SCR would be required. The success of low NOx firing technology used in concert with high reactivity low rank coals represents an order of magnitude of potential cost savings available by avoiding an SCR installation while maintaining acceptable NOx emission.

Of the over 80,000 MWe and more than 270 units retrofitted with low NOx technology, over 20,000 MWe and forty-seven (47) units include the use of low rank high reactivity coals. Of these forty-seven (47) units, only seventeen (17) were originally designed for PRB or lignite coal. The remaining thirty (30) units have been converted from their original design for firing bituminous coals.

<u>TFS 2000™ System Design</u>

The TFS2000™ firing system is the most aggressive example of LNCFS™ technology. The design philosophy of the TFS 2000™ firing system (Figure 1.1-3) is based on the integration of precise furnace stoichiometry control, pulverized coal fineness control, initial combustion process control, and concentric firing via CFS™. This represents the most advanced in-furnace combustion NOx control system. Multiple levels of separated over-fire air (SOFA) are used to maximize NOx reductions while limiting CO emissions or increases in unburned carbon. Depending on the type of coal, DYNAMIC™ Classifiers may be added to the pulverizers to control coal fineness and further limit unburned carbon or to increase pulverizer capacity for low rank coal conversions.

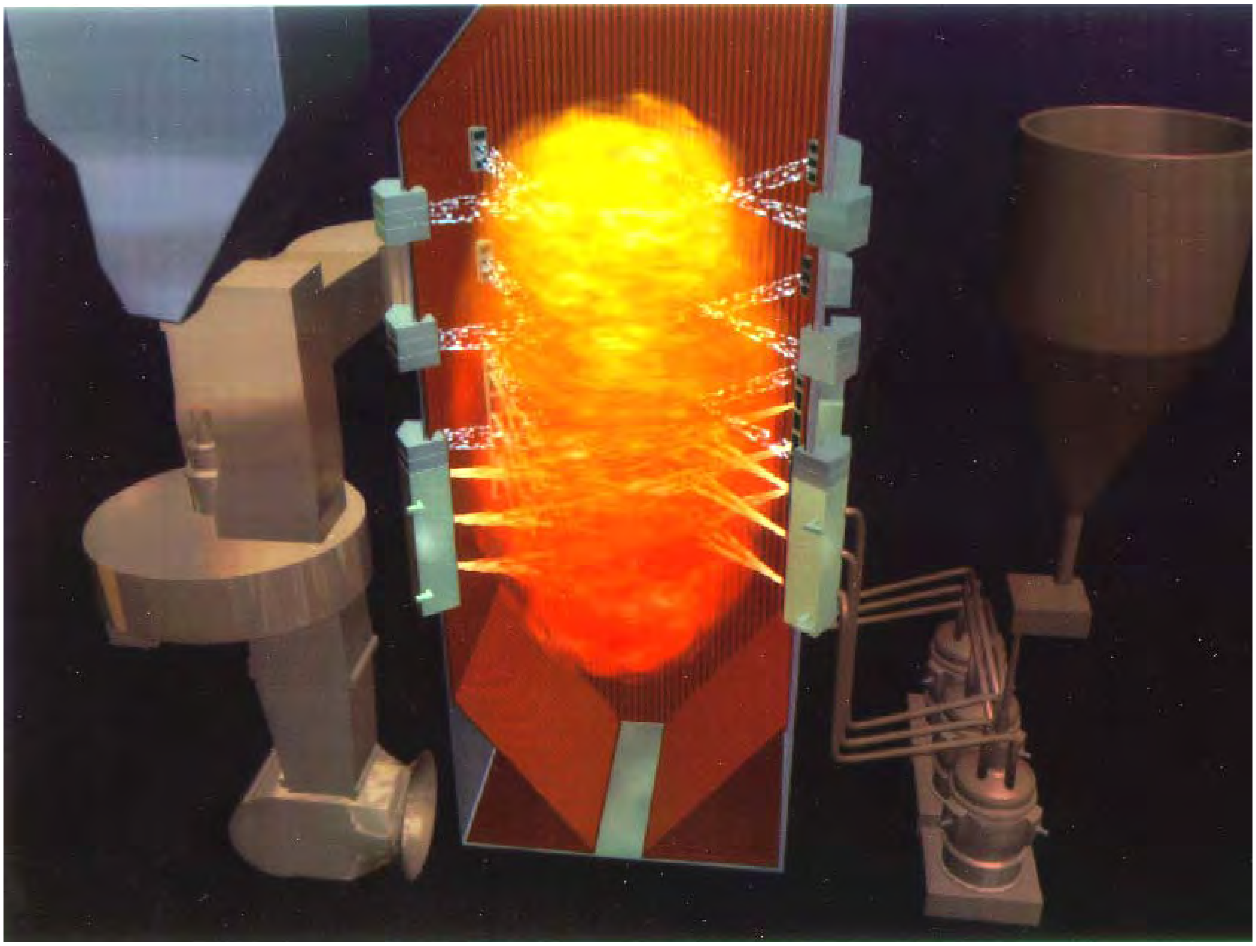


Figure 1.1-3 TFS 2000™ Low NOx Firing System

Table 1.1-1 lists the top 50 pulverized coal-fired generating power plants in the US with lowest average NOx emissions (no SCR) for the 1st Quarter 2006 based on U.S. EPA reporting criteria. Alstom tangential firing technology and subbituminous coals dominate the list.

Table 1.1-1 Alstom Low NOx System Retrofits Firing High Reactivity Coal

No.	Generating Station	Unit No.	NOx, lb/mm Btu	Boiler Supplier	Fuel	No.	Generating Station	Unit No.	NOx, lb/mm Btu	Boiler Supplier	Fuel
1	Baldwin Energy	3	0.092	ALSTOM	PRB	26	J T Deely	1	0.126	ALSTOM	PRB
2	Rush Island	1	0.099	ALSTOM	PRB	27	J T Deely	2	0.126	ALSTOM	PRB
3	Rush Island	2	0.104	ALSTOM	PRB	28	South Oak Creek	7	0.126	ALSTOM	PRB
4	Sam Seymour/Fayette	1	0.104	ALSTOM	PRB	29	Scherer	3	0.128	ALSTOM	PRB
5	Sam Seymour/Fayette	2	0.105	ALSTOM	PRB	30	Scherer	4	0.129	ALSTOM	PRB
6	Labadie	4	0.106	ALSTOM	PRB	31	Joppa Steam	5	0.129	ALSTOM	PRB
7	Labadie	1	0.112	ALSTOM	PRB	32	Big Brown	2	0.129	ALSTOM	Lignite
8	Labadie	3	0.112	ALSTOM	PRB	33	Shiras	3	0.132	ALSTOM	PRB
9	Hennepin Station	1	0.113	ALSTOM	PRB	34	Wood River	4	0.133	ALSTOM	PRB
10	Hennepin Station	2	0.113	ALSTOM	PRB	35	Bridgeport Harbor	3	0.135	ALSTOM	Indonesian
11	Sam Seymour/Fayette	3	0.113	ALSTOM	PRB	36	Joppa Steam	1	0.135	ALSTOM	PRB
12	Labadie	2	0.117	ALSTOM	PRB	37	Meramec	1	0.135	ALSTOM	PRB
13	Milton L Kapp	2	0.119	ALSTOM	PRB	38	Scherer	2	0.136	ALSTOM	PRB
14	Scherer	1	0.122	ALSTOM	PRB	39	Joppa Steam	2	0.136	ALSTOM	PRB
15	Joliet 29	71	0.122	ALSTOM	PRB	40	Gibbons Creek	1	0.137	ALSTOM	PRB
16	Meramec	2	0.122	ALSTOM	PRB	41	Big Brown	1	0.138	ALSTOM	Lignite
17	Joliet 29	72	0.123	ALSTOM	PRB	42	Joppa Steam	3	0.140	ALSTOM	PRB
18	Newton	2	0.123	ALSTOM	PRB	43	Columbia	1	0.140	ALSTOM	PRB
19	Columbia	2	0.123	ALSTOM	PRB	44	Joppa Steam	4	0.142	ALSTOM	PRB
20	Joliet 29	82	0.124	ALSTOM	PRB	45	Will County	3	0.142	ALSTOM	PRB
21	South Oak Creek	8	0.125	ALSTOM	PRB	46	Monticello	1	0.144	ALSTOM	Lignite
22	Fisk	19	0.126	ALSTOM	PRB	47	Will County	4	0.145	ALSTOM	PRB
23	Joliet 29	81	0.126	ALSTOM	PRB	48	Coleto Creek	1	0.145	ALSTOM	PRB
24	Joppa Steam	6	0.126	ALSTOM	PRB	49	Jeffrey Energy	3	0.146	ALSTOM	PRB
25	Newton	1	0.126	ALSTOM	PRB	50	Monticello	2	0.146	ALSTOM	Lignite

1.2 Project Overview

Alstom has been an industry leader in research and development on low NOx firing techniques and modifications to achieve NOx emissions below 0.15 lb/MMBtu emissions rate through combustion modifications and without the use of add-on technologies such as SCR or SNCR. Alstom performed the DOE funded project "Ultra Low NOx Integrated System for NOx Emissions Control from Coal-Fired Boilers" (Cooperative Agreement DE-FC26-00NT40754) that investigated improvements in subsystems to achieve NOx emissions below 0.15 lb/MMBtu. Areas investigated included enhancements to the milling system for high fineness coal and coal/primary air flow balancing, low NOx oxidizing pyrolysis burners for near field stoichiometry control, high velocity overfire air for carbon/CO burnout, and advanced control concepts such as adaptive neural networks for global stoichiometry control.

Coal nozzle tip near field stoichiometry control was investigated systematically and thoroughly in the current DOE funded project, "Enhanced Combustion Low NOx Pulverized Coal Burner" (Cooperative Agreement DE-FC26-04NT42300). Multiple coal nozzle tip designs were evaluated both by computational fluid dynamics modeling (CFD) and by combustion testing at large pilot scale. Coal nozzle tip component changes to optimize near field stoichiometry were designed to promote higher fuel-bound nitrogen release through more rapid heating of coal particles in the near-burner zone, coupled with the generation of additional near-burner turbulence to create a more uniform, high intensity, fuel rich zone.

Several low NOx coal nozzle tip modifications were developed and evaluated under this project. Alstom utilized CFD to evaluate a series of coal nozzle tip and/or near field stoichiometry controls in order to screen promising design concepts for large pilot scale testing. Following this screening work, Alstom performed large pilot scale combustion testing in its Industrial Scale Burner Facility (ISBF). Promising design concepts were evaluated to determine which coal nozzle tip features or combinations thereof provided the best NOx and unburned carbon performance versus operating condition. During the final test series, the performance of the best design(s) as determined from the prior two test periods was characterized and optimized. In addition, subbituminous and Western bituminous coals were tested during the third series in an effort to demonstrate means to achieve NOx emissions below 0.10 lb/MMBtu and 0.15 Lb/MMBtu, respectively, for these two coal types..

An engineering systems analysis and economic evaluation was performed to evaluate various NOx reduction options including the commercially available TFS 2000™ firing system, the Enhanced Combustion Low NOx Pulverizer Coal Burner developed in this project, and selective catalytic reduction (SCR). The various NOx reduction alternatives were evaluated as retrofit options for 3 tangential-fired utility boilers in the U.S.: (1) a 400 MW boiler on the East coast firing an Eastern bituminous compliance coal, (2) a 500 MW boiler in the Midwestern US firing a local bituminous coal, and (3) a 330 MW boiler in the Western US firing a subbituminous coal from the Powder River Basin (PRB). In addition, for the first two units, a PRB fuel switch and NOx retrofit were also evaluated. The units were selected as being representative of a large number of pulverized coal fired, utility boilers in the US.

In order to assure the success and commercial applicability of results from this project, Alstom Power assembled a project team of cognizant members from several Alstom Power groups. Alstom Power Plant Laboratories (PPL) in Windsor, CT, led this team in conjunction with the following project team members:

- Alstom Power Performance Projects
- Alstom Power New Boilers

Alstom Power Performance Projects provides engineered boiler products and services to the electric power industry, including the low NOx firing system equipment proposed herein. Alstom Power New Boilers designs and builds new utility boilers.

2 Objectives

NOx emissions limits in the U.S. continue to ratchet down for new and existing (retrofit) boiler equipment. On March 10, 2005, the Environmental Protection Agency (EPA) announced the Clean Air Interstate Rule (CAIR). CAIR requires 25 eastern states to reduce NOx emissions from the power generation sector by 1.7 million tons in 2009 and 2.0 million tons by 2015. Low cost solutions to meet such regulations, and in particular those that can avoid the need for a costly SCR, provide a strong incentive to continue to improve low NOx firing system technology to meet current and anticipated NOx control regulations.

The overall objective of this project is to develop an enhanced combustion, low NOx pulverized coal burner, which, when integrated with Alstom's state-of-the-art, globally air staged low NOx firing systems will provide a means to achieve:

- less than 0.15 lb/MMBtu NOx emissions at less than ¾ the cost of an SCR with low to no impact on balance of plant issues when firing a high volatile Eastern or Western bituminous coal, and
- less than 0.10 lb/MMBtu NOx emissions at less than ¾ the cost of an SCR with low to no impact on balance of plant issues when firing a subbituminous coal.

High volatile bituminous coals are more problematic from a NOx control standpoint as existing firing system technologies do not provide a means to meet current or anticipated regulations absent the use of an SCR. Further objectives include:

- Validation of the NOx control technology developed through large (15 MWt) pilot scale demonstration
- Evaluation of the engineering feasibility and economics for representative plant cases

Among the novel attributes of the enhanced combustion burner will be means to optimize the local (near-field) time-temperature-stoichiometry (mixing) history of combustion. Such optimization will ensure that minimum NOx emissions are achieved with minimal impact on unburned carbon in ash, slagging and fouling, corrosion, flame stability, turndown capability, and other balance of plant impacts.

3 Statement of Work

Several low NOx coal nozzle tip modifications were developed and evaluated under this project. Alstom utilized CFD to evaluate a series of coal nozzle tip and/or near field stoichiometry controls in order to screen promising design concepts for large pilot scale testing. In concert with the CFD work, Alstom set-up preliminary economic models to determine the cost/performance of such coal nozzle tips applied to Alstom's state-of-the-art TFS 2000™ firing system product compared to SCR.

Following this screening work, Alstom performed large pilot scale combustion testing in its Industrial Scale Burner Facility (ISBF). A series of three large pilot scale combustion tests were performed in the ISBF. During the first two test series, promising design concepts were evaluated to determine which coal nozzle tip features or combinations thereof provided the best NOx and unburned carbon performance versus operating condition on at least one high volatile bituminous coal. As required, iterations on and/or improvements to these designs were made between the first and second test period. During the third and final test series, the performance of the best design(s) as determined from the prior two test periods was characterized and optimized on three coals including the same high volatile bituminous coal used during periods one and two. In addition, subbituminous and Western bituminous coals were tested during the third series in an effort to demonstrate means to achieve NOx emissions below 0.10 lb/MMBtu and 0.15 Lb/MMBtu, respectively, on these coal types as well. The performance of this work at large pilot scale provided sufficient data to allow Alstom to design, construct and demonstrate a first of a kind commercial version of the final system upon completion of the subject work.

Upon completion of the large pilot testing, a final cost/performance analysis utilizing the test results was performed to ensure the project objectives were met.

3.1 Tasks Performed

A series of six tasks were performed to take the enhanced combustion low NOx pulverized coal burner from concept to commercial design. These tasks are briefly described as follows.

<u>Task 1</u> – Preliminary Coal Nozzle Tip Concept Design & Performance Evaluation

Under this task, candidate enhanced-combustion low NOx coal burner components were screened to identify favorable designs and combinations thereof for large pilot scale combustion testing. CFD modeling was used as the principle performance screening tool, coupled with existing field and laboratory data and additional, proprietary, in-house performance predictive tools and algorithms. Performance estimates for NOx, CO, and unburned carbon in the fly ash were included as part of this work.

<u>Task 2</u> – Large Pilot Scale Test Preparations

Preparations of Alstom's ISBF for large pilot testing of promising, low NOx coal nozzle tip concepts was performed under this task. This included design, fabrication and installation of appropriate firing system components, including proposed test coal nozzle tip designs; procurement, characterization and pulverization of test fuels; and general test facility preparation and equipment calibration in support of performance of the subject work.

<u>Subtask 2.1</u> – Firing System Design & Fabrication

Under this task, the ISBF was configured with a single, tangentially fired coal burner, including associated auxiliary air compartments, and two levels of overfire air, consistent with the design of Alstom's state-of-the-art TFS 2000™ low NOx firing system. Design and fabrication of appropriate global firing system components included:

- a new main burner windbox capable of holding the enhanced burner components,
- required primary and secondary air feed systems,
- drawings of promising, candidate coal nozzle tip concepts for large pilot testing, and
- coal nozzle tip parts fabrication.

Finally, an appropriate refractory configuration and firing rate (MMBtu/hr) for performance of the subject work was determined under this task to best match the time-temperature-stoichiometry history of a typical pulverized coal fired utility boiler in support of the program objectives.

<u>Subtask 2.2</u> – Fuel Procurement & Characterization

Three coals were selected and procured under this task. The coals included an Illinois #6 Midwestern bituminous coal, a lower sulfur Western bituminous coal, and a very low sulfur Indonesian subbituminous coal. (The Indonesian subituminous coal was selected with DOE input for the convenience and cost of the test program. The Indonesian subituminous coal has properties similar to Western U.S. Powder River Basin (PRB) type coals.) All of these coals are in use now at major US power generation facilities.

Prior to their use in the large pilot testing, each of these fuels was characterized using standard ASTM (ultimate, proximate, HHV) and petrographic analyses. In addition, Drop Tube Furnace System (DTFS) high temperature pyrolysis, and Thermogravimetric Analysis (TGA) char reactivity testing were performed to characterize the combustion behavior of the test fuels in support of extrapolation of the test results to alternate coals and commercial boiler installations.

Pulverization of the ISBF test fuels was also performed under this task in Alstom's Pulverizer Development Facility (PDF). Typical current commercial coal grinds for each fuel were prepared for ISBF test use.

<u>Subtask 2.3</u> – General Test Facility Preparations

In concert with the design and fabrication of the required coal nozzle tip equipment, general test facility preparations including refractory installation, and overall coal and air supply system configuration and installation were performed under this subtask. As design and fabrication were completed, initial enhanced-combustion burner components including the test burner windbox, auxiliary air nozzles, and initial stationary coal nozzle and tip, were installed.

In addition, facility instrumentation and data acquisition system (DAS) set-up and calibration was performed under this task. This included preparation and calibration of the ISBF's gas analysis system (GAS) to continually measure O_2, CO, CO_2, SO_2, NOx and THC in the boiler effluent gas in advance of flue gas clean-up equipment. It also included the set-up of a semi-isokinetic fly ash sampling system for capture of coal ash samples for eventual, post-test carbon content analysis.

Finally, this task culminated with a shakedown of all installed facility and combustion test equipment to prove operability in advance of the planned combustion testing.

Task 3 – Large Pilot Scale Testing

Large pilot combustion testing was performed in Alstom's Industrial Scale Burner Facility (ISBF) to quantify system performance at a commercial scale. The ISBF is a balanced draft; front wall fired combustion test facility designed to replicate the time-temperature-stoichiometry (mixing) history of a typical industrial or utility steam generator. All major aspects of a commercial boiler are duplicated in the ISBF, including the radiative furnace cavity and simulated convective heat transfer surfaces. For this work, the ISBF was operated with a single pulverized coal burner assembly and up to two levels of overfire air, consistent with present generation, state-of-the-art low NOx firing system design practice.

Subtask 3.1 – Test Series 1

After completion of initial test facility preparation activities, the first of three test series was conducted. This test series consisted of 9 days of testing during November and December 2005. During this period, six coal nozzle tips were fired on the Illinois #6 coal, including four new tip designs and two current Alstom commercial products used here as a reference baseline. A total of 72 tests were performed on baseline and new nozzle tip designs from the modeling/screening task.

Following this work, preliminary data reduction and analysis of the series 1 results were performed. Recommendations for coal nozzle tip component testing during the second combustion test period, including any suggested modifications to the test coal nozzle tip designs and/or installed facility equipment, were made.

Subtask 3.2 – Test Series 2

Following completion of the first combustion test series, including associated data reduction and analysis, the second of three combustion test series was begun. The second series of ISBF testing was completed in March 2006. Modifications were made to several of the coal nozzle tips tested in series 1 with the aim of improving their performance. Two additional coal nozzle tip concepts were also tested during series 2. This test series was performed while firing the same high volatile bituminous coal tested during series 1.

Some additional tests were performed for each coal nozzle tip in an attempt to optimize the performance of each tip. Parameters that were adjusted for each tip included the quantity of fuel air, the distribution of auxiliary air between the various compartments, and the overfire air configuration.

Following the performance of the combustion testing, preliminary data reduction and analysis of the series 2 results was performed. Recommendations for coal nozzle tip component testing during the third combustion test period, including any suggested modifications to the test coal nozzle tip designs and/or installed facility equipment were aimed at achieving the project goals. Two of the eight tip configurations tested during test series 2 achieved a 0.15 lb/MMBtu NOx emissions rate.

Subtask 3.3 – Test Series 3

Following completion of the second combustion test series, including associated data reduction and analysis, the third of three combustion test series was begun. This test series consisted of 8 days of testing in January 2007. During this series, one baseline and four enhanced low NOx coal nozzle tip designs were evaluated on three fuels to determine the optimum arrangement and operating conditions versus fuel type. Selected fuels included the same high volatile bituminous coal fired during test series 1 and 2, a lower sulfur western bituminous coal, and a very low sulfur subbituminous coal from Indonesia.

Again, additional tests were performed for each coal nozzle tip in an attempt to optimize the performance of each tip. Parameters that were adjusted for each tip included the quantity of fuel air, the distribution of auxiliary air between the various compartments, and the overfire air configuration.

Results from this testing span a range of fuel ranks encountered in the domestic U.S. market, which assists in predicting performance for a different commercial fuels. In addition, through testing of the subbituminous coal, this work demonstrated the potential to achieve less than 0.10 lb/MMBtu NOx for pulverized coal fired utility boilers.

Following series 3 combustion testing, final data reduction and analysis of all the test results was performed. In addition, facility and test equipment dismantling and storage occurred. As an outcome of the series 3 data analysis, recommendations for the design of a commercial enhanced combustion low NOx system were made.

Task 4 – Cost / Performance Analysis

Under this task, a series of economic analyses were performed to determine the ability of promising enhanced combustion coal nozzle tip concepts to achieving less than 0.15 lb/MMBtu NOx emissions at less than ¾ the cost of SCR for a high volatile bituminous coal. In support of this target, the performance and economics of individual, enhanced combustion technologies were considered alone and in appropriate combination (addition of selective catalytic reduction, purchase of NOx allowances, etc.) to optimize overall cost / performance behavior. Various NOx reduction options were evaluated as retrofit cases for the following tangential-fired utility boiler/fuel combinations:

- 400 MW boiler on the East coast firing an Eastern bituminous sulfur compliance coal,
- 400 MW boiler on the East coast switching to Powder River Basin (PRB) subbituminous coal,
- 500 MW boiler in the Midwestern US firing a local bituminous coal,
- 500 MW boiler in the Midwestern US switching to PRB subbituminous coal, and
- 330 MW boiler in the Western US firing a PRB subbituminous coal.

For each unit and fuel combination, seven NOx control options were evaluated:

- No low NOx features
- Firing system retrofit with LNCFS™ level III
- LNCFS™ level III with new coal nozzle tips
- LNCFS™ level III with new tips and subcompartmental air
- Firing system retrofit with TFS 2000™
- TFS 2000™ with new tips and subcompartmental air
- SCR retrofit

Then, budget hardware and O&M cost estimates were made, and mass and energy balances developed. Finally, boiler and plant performance impacts, including any changes in unburned carbon in the ash, were estimated with proprietary performance models, and economic analysis conducted with the resultant data. Economic analyses included calculation of the Net Present Value (NPV) of each retrofit option, capital costs for each retrofit option, and the sensitivity of NPV to input economic parameters.

Subtask 4.1 – Initial Cost/Performance Analysis

Two levels of economic evaluation were part of Task 4. The first was an initial economic evaluation that was used to validate economic assumptions and set-up preliminary economic models in advance of the performance of the large pilot scale testing. Performance input for this subtask was derived from the outcome of Task 1 – Preliminary Coal Nozzle Tip Concept Design & Performance Evaluation. Final plans for the large pilot scale testing were prepared to be consistent with these results.

Subtask 4.2 – Final Cost/Performance Analysis

Upon completion of the large pilot combustion testing, a final cost/performance analysis was performed to ensure the overall results were consistent with project goals, namely the achievement of less than 0.15 lb/MMBtu at ¾ the cost of SCR when firing a high volatile bituminous coal. For this work, large pilot scale performance data for select, tested design concepts and combinations thereof were input into the economic models developed under Subtask 4.1. An output of this subtask was a recommendation for the design of an enhanced combustion low NOx coal nozzle tip designs for commercial application.

Task 5 – Reporting

The reporting task includes required quarterly technical and financial progress reports and informal updates as well as the project final report. This final report provides a detailed discussion of the coal nozzle tip evaluation effort, including CFD modeling results, as well as the large pilot testing, including a description of tested technologies and performance results. The report also contains a discussion of the final cost/performance analysis, culminating in a recommendation for the design of a commercial, enhanced combustion low NOx pulverized coal burner.

Task 6 – Project Management

Under this task, the project manager has tracked and maintained the overall project scope and budget, prepared required periodic reports, and represented Alstom to the DOE. Presentations of technical papers covering the results of this work were made at the Clearwater Coal Conference in both 2006 and 2007.

Task 7 – Water Table Tests

After completion of the Task 3.3 testing, it was realized that one potential performance problem had not been addressed: possible leakage of coal into the burner windbox where the coal nozzle tip pivots on the coal nozzle. A series of water table tests (physical flow model) were conducted to observe the following issues:

determine if excessive coal can leak from gaps at the coal nozzle pivot points,

- determine if there are any wear or flow issued on the nozzle tip vanes, and

if an issue is found, determine a design modification to resolve the problem.

Cross sectional models of the nozzles and nozzle tips were fabricated. The water table test consisted of flowing colored water through the nozzles in a clear wall water tank and observing the flow patterns. The advantage of this method is the ability to easily and inexpensively make geometry changes to the system and quickly see the result of these changes.

This additional work required a contract extension but was completed within the available budget.

4 Coal Nozzle Tip Design Screening and Modeling

This section documents the Computational Fluid Dynamics (CFD) modeling work performed as part of the overall project to develop an enhanced combustion low NOx pulverized coal burner. The CFD modeling scope includes simulations of roping in coal piping, which was used to determine the model parameters for use in the coal nozzle simulations, as well as non-reacting flow through the various coal nozzle tips. The tip CFD work was performed in several iterations in conjunction with the three combustion test series

4.1 Coal Rope Simulations

Transport of pulverized coal particles in typical coal piping is a complex phenomenon, as elbows can concentrate the particles and cause the formation of coal ropes (non-uniform distribution of coal across the pipe cross-section). As the distribution of the particles at the coal nozzle tip can affect the combustion and emissions performance of the tip, a model validation study was executed to determine the discrete phase parameters that should be used to adequately simulate the transport of pulverized coal particles. Fluent CFD predictions of particle concentrations after an elbow were compared with available data from the literature [4] with respect to coal rope magnitude, circumferential location, and circumferential and radial spread.

The comparative experimental configuration was a simple duct flow (80 mm ID duct) with a single 90 degree turn that was in either a horizontal or vertical orientation with either a short radius (100 mm) or long radius (200 mm) bend. Particle concentration distributions were measured optically.

The geometries modeled with Fluent are shown in Figure 4.1-1. The operating conditions used in both the experiments and simulations are given in Table 4.1-1. A particle distribution of glass beads was used in the testing with a mean diameter of 38 microns as shown in Figure 4.1-2. The particle size data was fit with a Rosin-Rammler size distribution that was used in the CFD modeling work. The 80 °F air was injected at velocities from 14 - 24 m/s with primary air to fuel ratios of approximately 1.5 - 3.3.

The CFD simulations were performed with Fluent version 6.2. The isothermal 3D simulations were run using the $\kappa-\varepsilon$ model for turbulence with the particles fully coupled with the continuous phase. The configuration of Fluent's discrete phase model (DPM) which best matched measured particle rope concentrations in cylindrical ducts was found to be as follows:

- Default wall reflection coefficients, (both normal and tangential settings at unity)
- Saffman lift force activated
- Rosin Rammler particle distribution with flow rate scaled by area
- Stochastic particle tracking with 5 tries

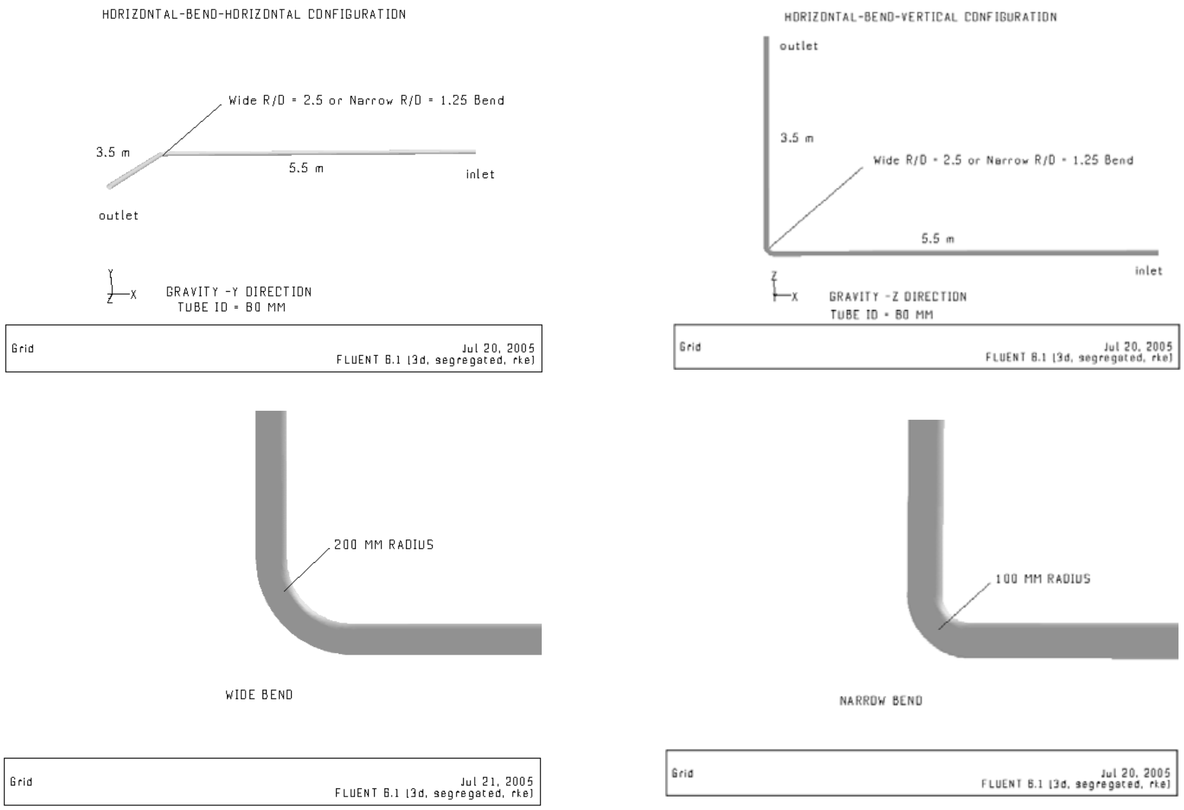


Figure 4.1-1 Geometry modeled to validate coal flow predictions

Table 4.1-1 Experimental and CFD test conditions

Air Speed m/s	14-24
Pipe Roughness (smooth or rough)	0.0 or 0.001
Air Temperature	80 F
Inlet turbulence (realizable k-e)	5%
Outlet Pressure (gage)	0
Rosin Rammler Mean Particle Size	38 microns
Rosin Rammler Slope	2.46
Inlet Particle Distribution	Uniform
Particle Density kg/m^3	2500
Particle Shape	spherical
mu=Particle Flowrate/Air Flowrate	0.3, 0.5, 0.7

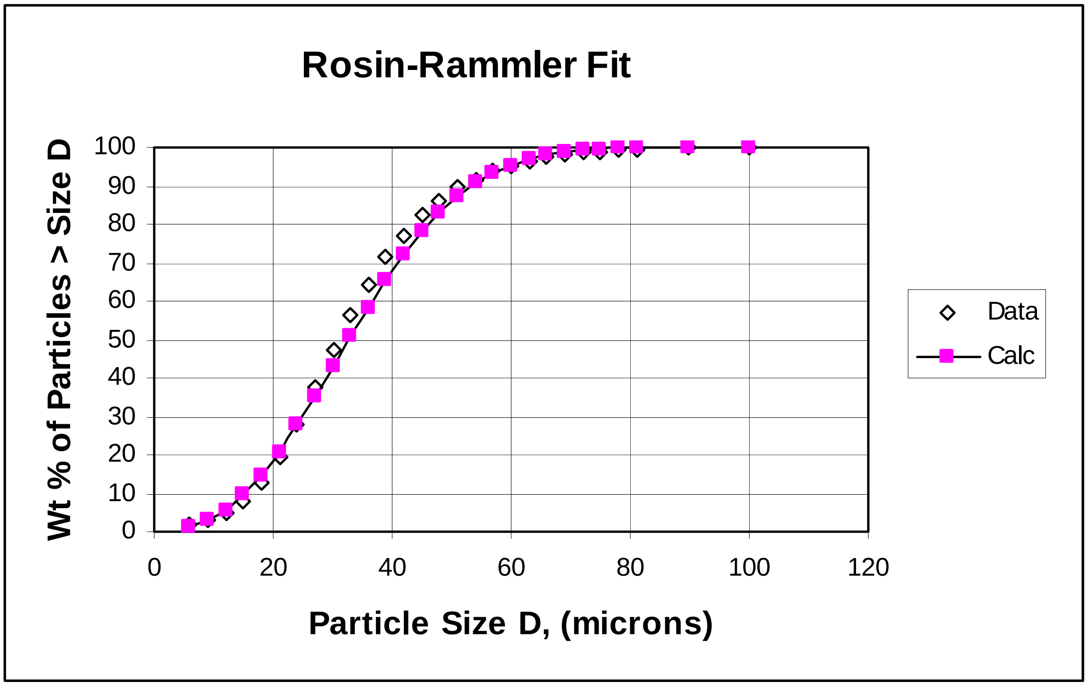


Figure 4.1-2 Particle size distribution used for CFD model validation

Two typical results showing a good match of concentration magnitude, circumferential location and spread are shown in Figure 4.1-3 and Figure 4.1-4 The first comparison is in a horizontal section of pipe, and the second in a vertical section. There are a total of 12 such comparisons.

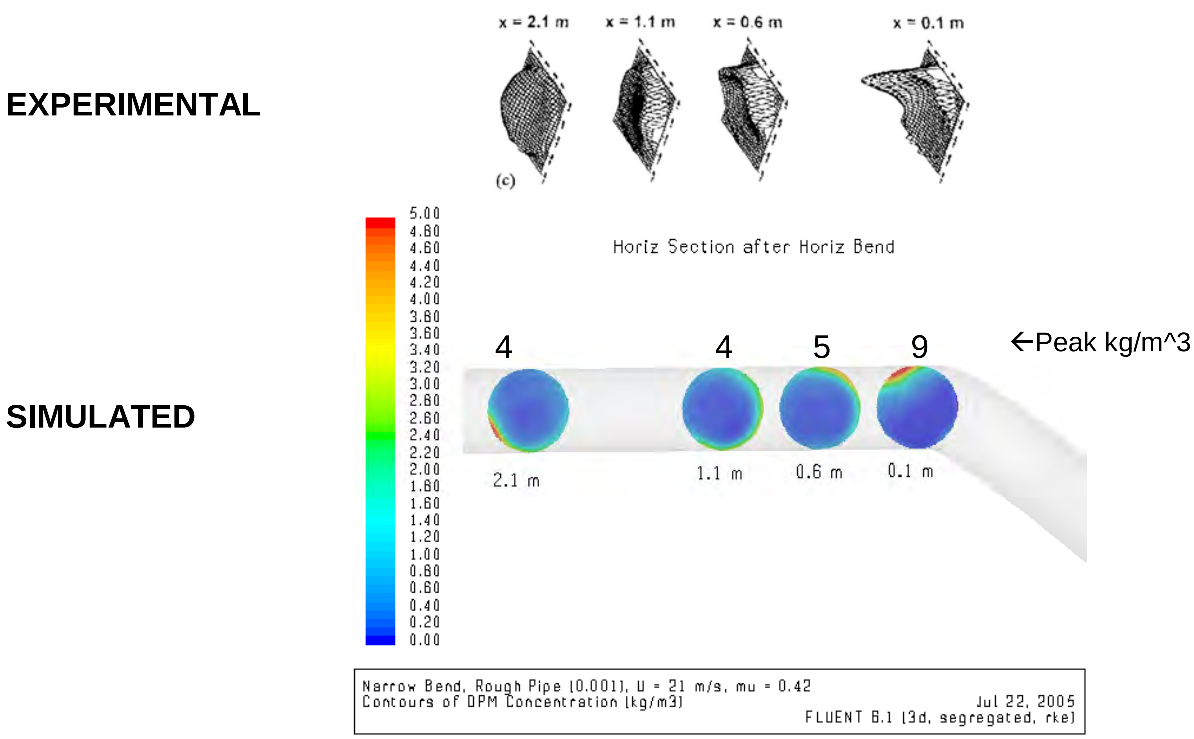


Figure 4.1-3 Comparison between predicted and measured particle concentrations in the horizontal section

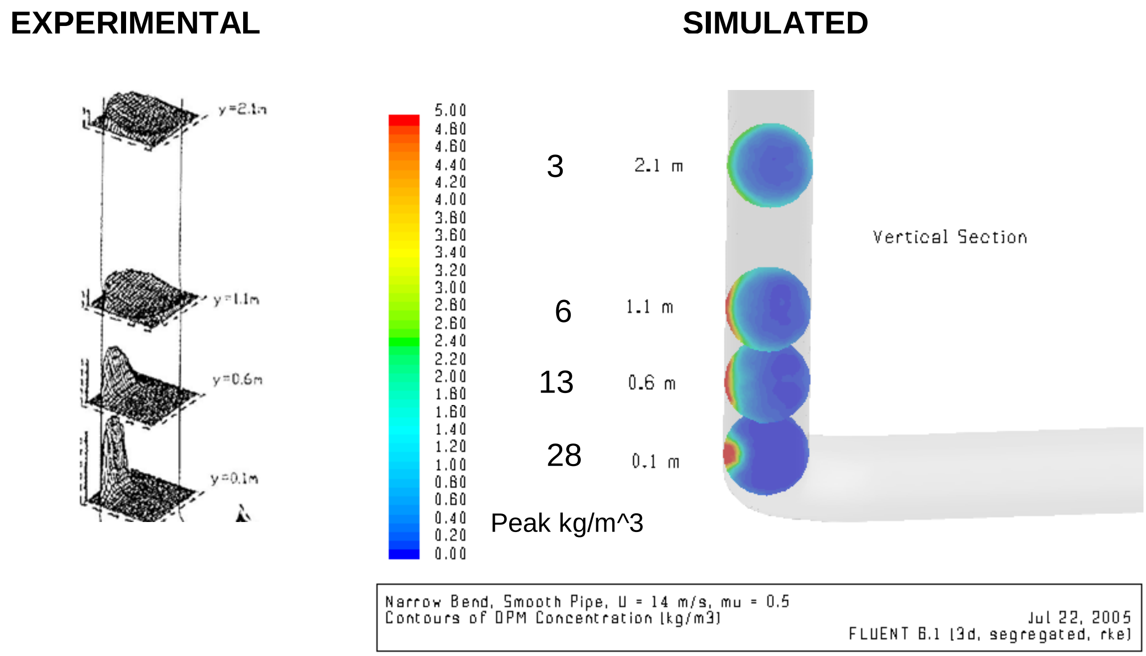


Figure 4.1-4 Comparison between predicted and measured particle concentrations in the vertical section

Typical results showing the match of concentration radial distribution are in Figure 4.1-5, taken just downstream of a vertical bend. This illustrates the lack of the model's ability to match the measured concentration behavior at the wall. The predictions show the maximum particle concentration at the wall, while the experiments show the peak to be just off the wall.

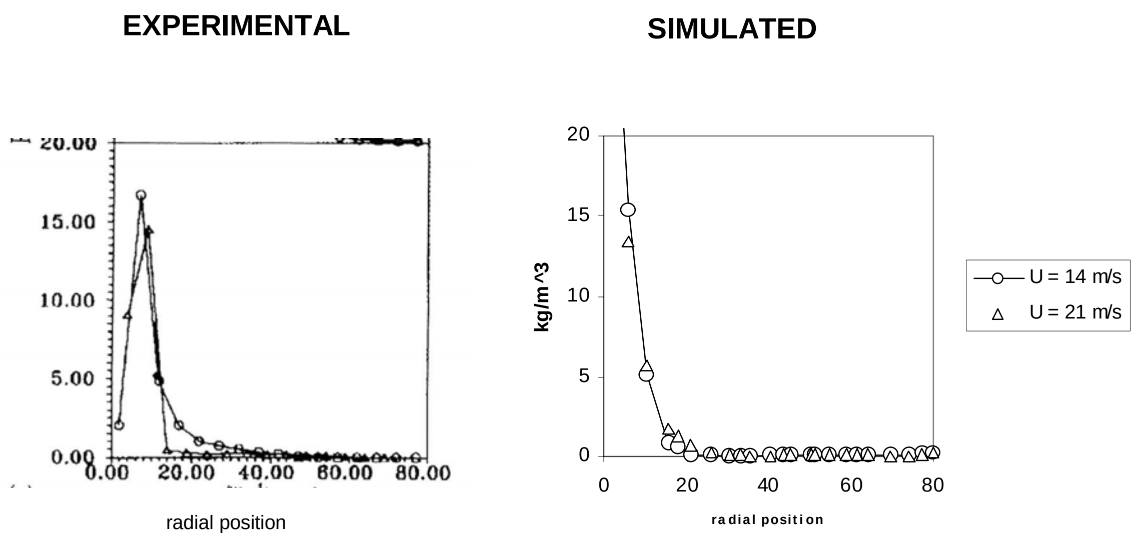


Figure 4.1-5 Comparison between predicted and measured particle concentrations

Figure 4.1-6 shows contours in a horizontal section of the pipe in which the predictions don't agree as well with the experiments. In the top simulation an attempt was made to separate the particles from the pipe wall by artificially increasing the wall normal reflection coefficient to values greater than 1.0. The bottom contour in Figure 4.1-6 shows the predicted particle concentration with a normal wall reflection coefficient of 1.5. This artificially moved more of the particles from the wall, but resulted in an unstable model and still leaves the maximum concentration at the wall.

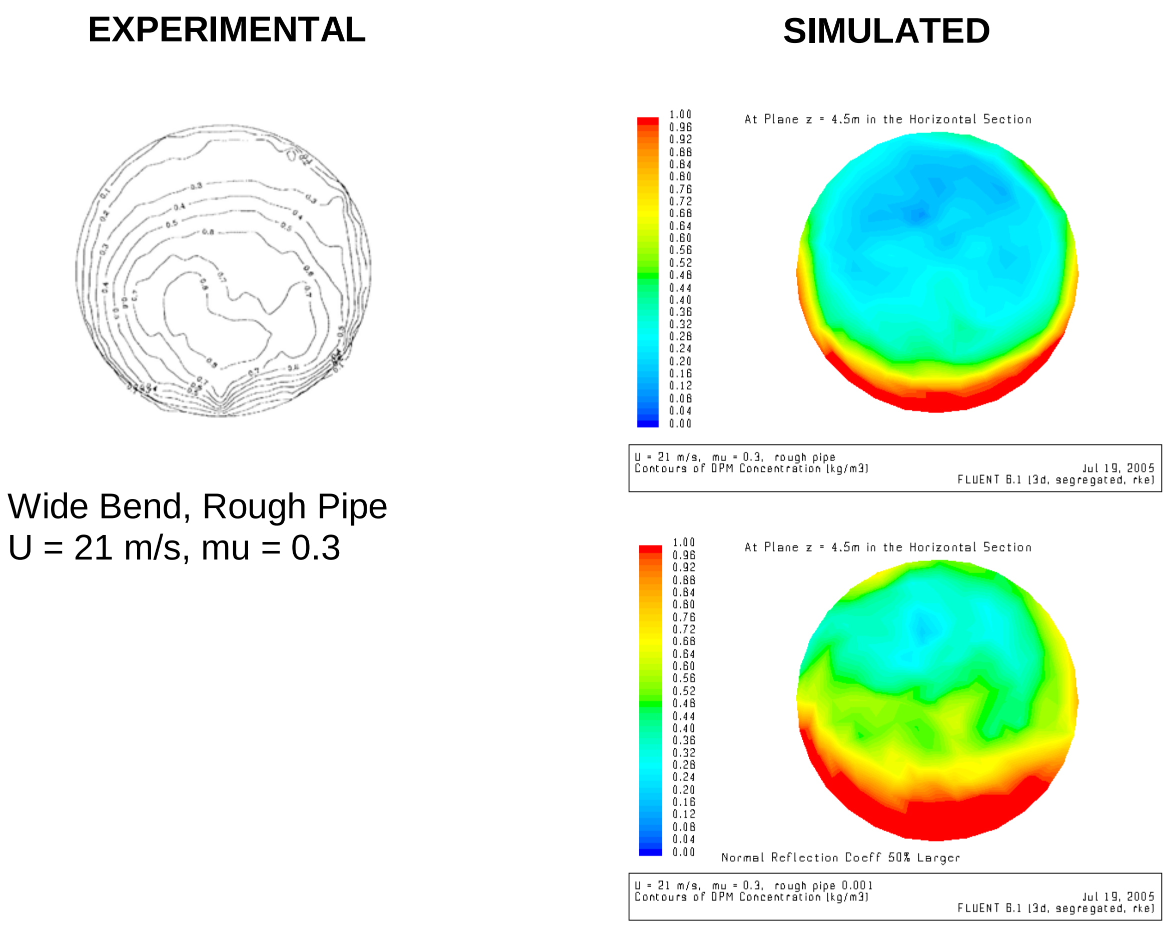


Figure 4.1-6 Comparison between predicted and measured particle concentrations

The following conclusions were made from the coal rope validation exercise:

- The relative ratios of the peak particle concentration throughout the tube compare well between simulation and experiment.
- The amount of circumferential spread and location compare well between simulation and experiment.
- The actual concentration magnitudes in kg/m^3 compare well except at the wall. Simulations show the maximum particle concentration is at the walls. Experiments show it is separated from the walls.
- Modifying the wall reflection coefficients (Normal, Tangential) from (1.0,1.0) to (1.5,1.0) moved some particles away from the wall, but the calculated peak concentration was still at the wall. Increasing the normal reflection coefficient also resulted in unstable DPM tracking and difficulty in convergence.

The recommended DPM settings for any coal piping simulations are as follows:

- Stochastic particle tracking
- Default wall reflection coefficients, (both normal and tangential settings at unity)
- Saffman lift force activated

It should be noted that the coal nozzle tip simulations included in the following section of this report included the settings recommended by the previous validation exercise. However, all of the coal nozzle / tip simulations started after the final elbow in the coal transport line and assumed a uniform coal particle distribution coming into the coal nozzle.

4.2 Coal Nozzle Tip Simulations

As part of the coal nozzle tip development project, CFD modeling was used with the goal of gaining insight into the mechanisms governing nozzle tip performance with respect to NOx emissions. CFD models were generated of the baseline coal nozzle tips, as well as the new tip concepts and one existing concept that were tested as part of this program. The CFD results were used to refine the proposed tip concepts before they were built, as well as to help identify and evaluate possible improvements to the tips for subsequent testing. This meant that the CFD work took place in two primary phases, one before the first series of combustion tests and the second between the first and second series.

Two coal nozzle tips were selected for testing as a baseline of current Alstom firing system technology, a standard shear bar / air deflector tip and an LNCFS™ P2 tip. From project team discussions and initial modeling, four new coal nozzle tip ideas were selected for evaluation in the first week of ISBF testing. These are referred to in this report as the center bluff, the recessed center bluff, the X-tip and the diverging hybrid tip. The new coal nozzle tip concepts were selected based on different theories for obtaining lower NOx emissions which built upon past combustion test experience at Alstom and new ideas. These concepts were then developed further based on the results of the first combustion series and some additional CFD work. In the same timeframe another nozzle tip concept, the vane tip, was conceived, also based on the results of the first ISBF test week and CFD studies. During the second combustion series all the modified tips and the new tip were evaluated, and a tip selection made for the third test series on multiple coals.

This section will document the CFD modeling approach that was used to simulate both the baseline and new coal nozzle tip designs and describe each tip that was modeled. A selection of plots illustrating the CFD results will be presented for each tip.

4.3 ISBF Geometry

The CFD modeling was focused on predicting the near field mixing and particle dispersion rates and the simulations were run as steady state, turbulent, non-reacting flow with heat transfer. The coal nozzle tip simulations were run in an approximated ISBF geometry as illustrated in Figure 4.3-1. As shown in the figure, the model includes the coal nozzle, the windbox, two levels of overfire air, and a simulated convective section. As the simulations were focused on mixing and particle dispersion in the near burner region, a simplification was made to the ISBF exit geometry. The furnace outlet in the model was assumed to be after the convective section as shown, instead of the flow turning upwards after the convective section, transitioning from a rectangular to round cross section, etc.

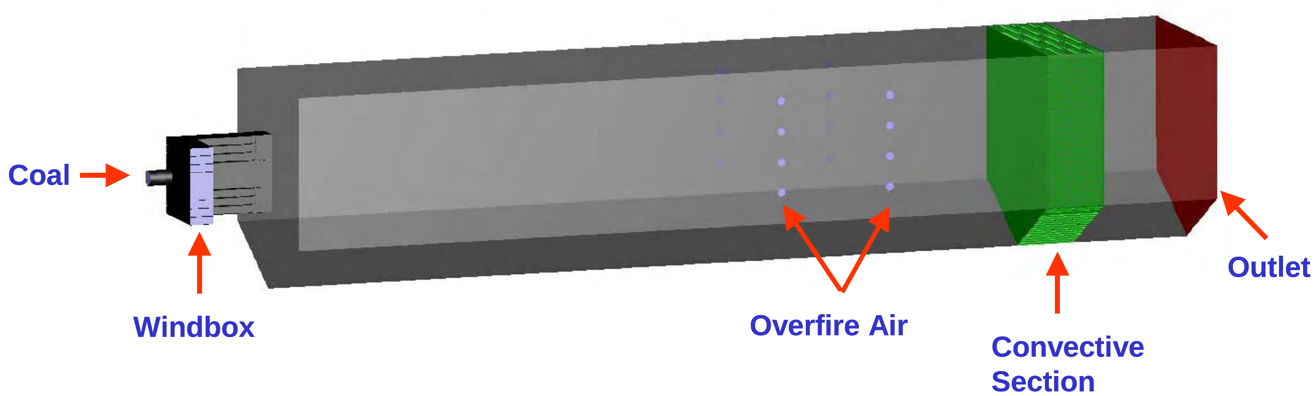


Figure 4.3-1 ISBF geometry for CFD simulations

For comparison, the actual windbox installed in the ISBF with the shear bar/air deflector tip is shown in Figure 4.3-2. As seen in the picture, the windbox contains a single coal nozzle tip with three auxiliary air compartments above and below the coal compartment, with cooling leakage around each tip. The gas ignitor pipe shown on the right side of the windbox was not included in the CFD model.

Figure 4.3-2 Front wall of ISBF with newly installed windbox

The as-modeled geometry of the ISBF windbox is shown in more detail in Figure 4.3-3. As illustrated in the figure, the model included the three auxiliary air compartments above and below the coal nozzle compartment, the fuel air, and leakage around the tips. The geometry of the coal nozzle and auxiliary air compartments is shown in more detail in Figure 4.3-4. The CFD geometry did not attempt to resolve the dampers that controlled the air flow rate to each of the compartments, or include the transition from the vertical air supply ductwork to the horizontal windbox compartments. Instead, the mass flow rate of air for each compartment was specified at the blue inlet boundaries, assuming a uniform velocity profile for each inlet.

The CFD models did not include the effects of the elbow in the coal transport line that was attached to the coal nozzle. A uniform coal particle distribution was assumed at the inlet to the coal nozzle. The coal transport line was 8 inch flexible hose which was attached to a 90 degree elbow at the coal nozzle. The 8 inch diameter coal nozzle (inlet area 50.3 square inches) transitioned to a rectangular coal nozzle choke area of 43 square inches, for an 85% choke. The choke area was the same for all nozzle tips evaluated in this project; however, the choke flare angle used was set by and equal to Alstom design standards. The center fin on the top of the coal nozzle (to break up any coal rope) was included in both cases.

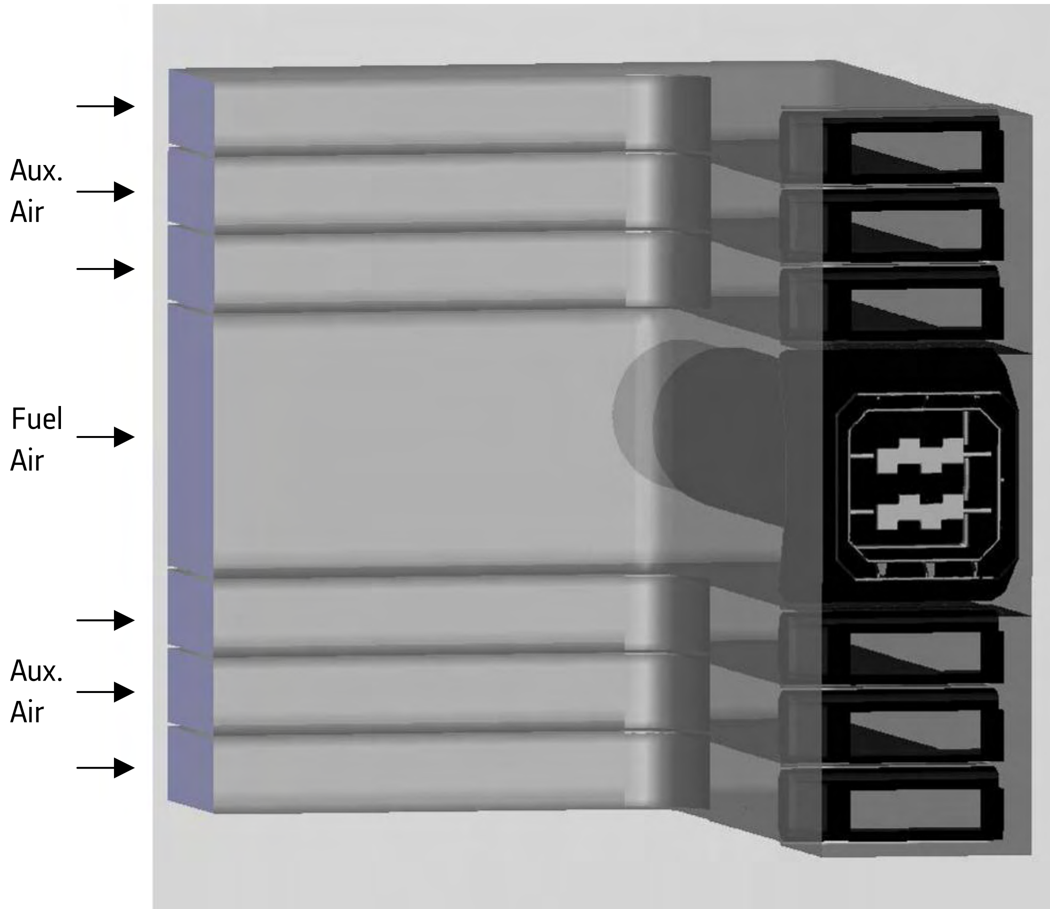


Figure 4.3-3 ISBF windbox geometry and auxiliary air nozzles

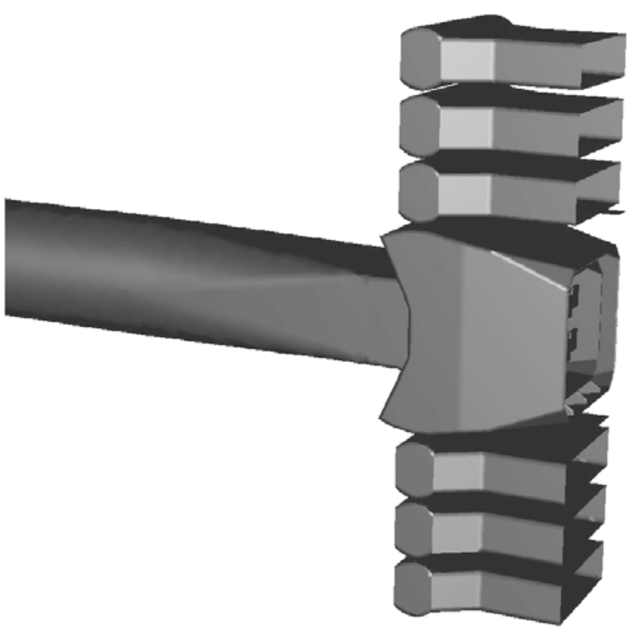


Figure 4.3-4 ISBF coal nozzle, nozzle tip, and auxiliary air nozzle geometries

A picture looking towards the rear of the ISBF before testing can be seen in Figure 4.3-5. At the rear of the ISBF are cooling tubes, which simulate the tubes in the convective pass of a utility boiler. The convective section of the ISBF was simulated using a porous media region for simulating pressure drop, but did not include heat transfer. This porous media convective region was shown in green in Figure 4.3-1. Some of the round SOFA ports on the ISBF walls can also be seen in Figure 4.3-5. The SOFA system had 4 opposing ports on each side wall at both near and far (from the burner front) SOFA locations.

Figure 4.3-5 Looking towards the rear of the ISBF at the convective section

4.4 CFD Modeling Approach

The CFD modeling task was performed with Fluent version 6.2 and focused on predicting the near field mixing and particle dispersion rates. The simulations were run as steady state, turbulent, non-reacting flow with heat transfer. Initial simulations attempted to run full combustion simulations with reacting flow, heat transfer, and radiation. However, it quickly became apparent that it would not be possible to evaluate a range of coal nozzle tips with combustion, NOx, etc. The main reason for this was the uncertain location of the combustion stabilization point for a tangentially-fired coal nozzle tip.

In a swirl burner, the strong swirl creates recirculation zones that act to stabilize the flame. The stabilization point allows the CFD to calculate a reasonable ignition point without having the complex ignition phenomenon included in the physics of the CFD code. In most tangentially-fired coal nozzle tips, there really is no strong aerodynamic stabilization point for the flame. Hence, the burner relies upon the entrainment of hot combustion products, radiation from combusting particles, impingement of upstream coal flames, etc., to ignite the coal jet. The ignition location can vary from attached to the tip to several burner diameters off of the nozzle tip.

Not all of the appropriate physics are included in the Fluent combustion model, so it is difficult to predict the correct ignition location for a single T-fired nozzle tip. The lack of a strong flame stabilization point makes it problematic to converge to a reasonable single nozzle solution. If the solution was initialized with high temperatures near the burner tip, the model could predict a reasonable ignition point and flame structure. However, running additional iterations in an attempt to fully converge the simulation would typically allow the flame front to move further away from the tip, resulting in significant amounts of relatively cold primary air and coal particles extending far off of the coal nozzle tip.

The predicted ignition point could be stabilized closer to the tip by artificially increasing the coal devolatilization rate by orders of magnitude, for example, but this could artificially mask real differences in the tip ignition and performance. In a real tangentially-fired boiler with multiple burners, on the other hand, the burners are often ignited via flames from the upstream corners, and if the ignition location is not accurately predicted, there probably isn't a large impact on the overall furnace aerodynamics and heat transfer.

With the limitations imposed on the evaluation of the different coal nozzle tip design to predict stable ignition profiles, the modeling tool was instead used to characterize the detailed flow patterns generated by the various coal nozzle tip configurations. Using a very detailed geometric treatment of the coal and adjacent air compartments, the jet penetration, recirculation zones and coal particle dispersion patterns were analyzed and compared to the observed flame patterns and resulting emissions measured. The goal was to determine how the flow profiles correlated with measurement to better understand the important aerodynamic features and how they impacted combustion performance and NOx emissions.

The typical grid sizes for the various coal nozzle tip simulations ranged from 2.5 - 3 million cells. The grids were largely hexahedral cells, with a few tetrahedral cells in regions of complex geometry or transition regions from a fine grid at the nozzle exit to the coarser grid of the main furnace. Attempts were made to use small enough cells in the coal nozzle tip to resolve all of the fine geometric features, including shear bars, air deflectors, and bluff bodies. The grid in the windbox, coal nozzle, and furnace, with the exception of the coal nozzle tip exit, was essentially the same for all cases.

The mass flow rates for the various air compartments as modeled with CFD are shown in Table 4.4-1. The primary air was 17.9% of the total air flow rate, for a primary air to fuel ratio of 2.0 at a heat input of approximately 45 MMBtu/hr. The fuel air was 13.6 % of the total air flow, while each of the six auxiliary air compartments had 8% of the total air flow. Approximately 10.3% of the total air was injected at each of the two SOFA injection locations or "elevations." Note that there are four SOFA ports on each side of the furnace at each injection elevation and the SOFA flow was split uniformly between all ports. Separate air species were used for the primary air, fuel air, and

Table 4.4-1 Air flow distribution used in the CFD simulations

Air Compartment	**Mass Flow, lb/hr**	**% of Total Air**	*Temperature, F*
Primary Air	7008	17.9	150
Fuel Air	5306	13.6	450
Aux 1 (bottom)	3125	8.0	450
Aux 2	3125	8.0	450
Aux 3	3125	8.0	450
Aux 4	3125	8.0	450
Aux 5	3125	8.0	450
Aux 6 (top)	3125	8.0	450
SOFA - Near	4009	10.3	450
SOFA - Far	4009	10.3	450
Total Air Flow	39080	100.0	

auxiliary air, and the SOFA compartments to facilitate looking at the mixing of the various air streams. The primary air was injected at a temperature of 150 °F, while the combustion air was injected at 450 °F. The air properties were assumed to be a function of temperature due to the mixing of the hot combustion air and the cold primary air. Radiation was not included in the CFD models. The models used the realizable k-e turbulence model with standard wall functions.

The CFD models utilized Fluent's discrete phase model with LaGrangian stochastic particle tracking with coupled gas and particle phase momentum. The coal properties and DPM settings are shown in Table 4.4-2.

Table 4.4-2 Particle parameters used in the CFD simulations

Particle Parameters	Values	*Units*
Coal Feed Rate	3504	lb/hr
Particle Density	1550	lb/ft^3
Particle Temperature	150	F
Particle Specific Heat	0.4013	Btu/lb-R
Rosin-Rammler Size Distribution	Yes	
Min Diameter	1	micron
Max Diameter	200	micron
Mean Diameter	46.4	micron
Spread	0.7818	
Number of Diameters	10	
Stochastic Model Parameters		
Number of Tries	40	
Random Eddy Lifetime	yes	
Time Scale Constant	0.15	
Wall Reflection Coefficients		
Coal Nozzle and Tip	1.0	(normal and tangential)
Furnace Walls	Trap	

The coal particles were assumed to be inert with a Rosin-Rammler size distribution with a top size of 200 microns, consistent with a DYNAMIC™ classifier grind. The model tracked 10 particle sizes, with 40 stochastic tries, using a surface injection at the inlet of the coal nozzle. This resulted in a total of approximately 150,000 particles that were tracked during the discrete phase iterations. The discrete phase was recalculated every 20 gas phase iterations. The walls of the coal nozzle and nozzle tip were assumed to reflect the particles with reflection coefficients of 1.0 in both the normal and tangential directions, while the furnace walls were assumed to trap the particles in order to reduce the time required for particle tracking as the modeling was interested mainly in the flow patterns near the nozzle tip exit.

The simulations were run in parallel on a Linux cluster and typically required approximately 2 days runtime on 4 processors.

4.5 Baseline Coal Nozzle Tips

Two coal nozzle tips were selected for testing as a baseline of current Alstom firing system technology, a standard shear bar / air deflector tip and an LNCFS™ P2 tip. Two baseline tips were selected as the Alstom new boiler and boiler retrofit groups use a variety of coal nozzle tips in their product offerings.

4.5.1 Shear Bar / Air Deflector Tip

The baseline shear bar/air defector tip as represented in CFD is shown in Figure 4.5-1. For comparison, the shear bar/air deflector coal nozzle tip that was fabricated and installed in the ISBF is shown in Figure 4.5-2. All aspects of the actual nozzle tip design were modeled in the CFD configuration.

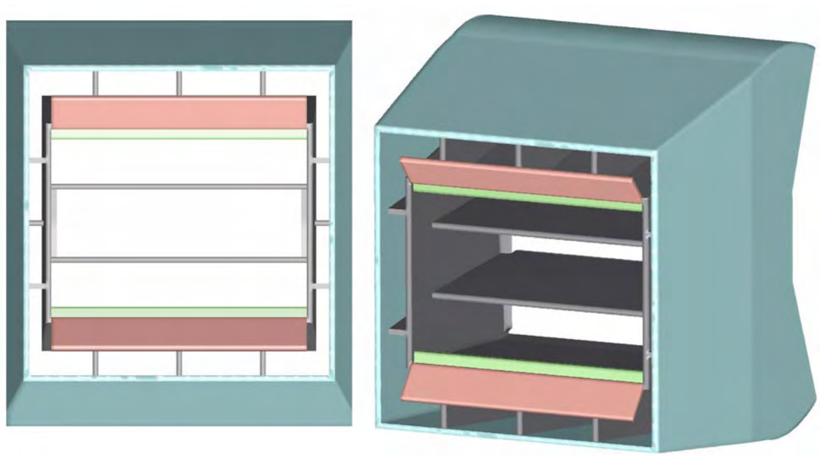


Figure 4.5-1 Shear bar / air deflector coal nozzle tip as represented by CFD

Figure 4.5-2 Shear bar / air deflector coal nozzle tip installed in ISBF before testing

The predicted gas velocity distribution at the center plane for the shear bar / air deflector tip is shown in Figure 4.5-3. Note that all of the gas velocity contour plots shown in this report were created on the same 0 -150 ft/s scale, with yellow the highest velocity to dark blue at zero velocity. The recirculation zones that form behind the air deflectors are evident in the figure. The air deflectors are designed to promote early ignition and to help the flame attach to the top and bottom of the coal nozzle tip. The shear bars tend to increase the turbulence in the shear layer between the primary air and the fuel air, which may also help the coal to ignite.

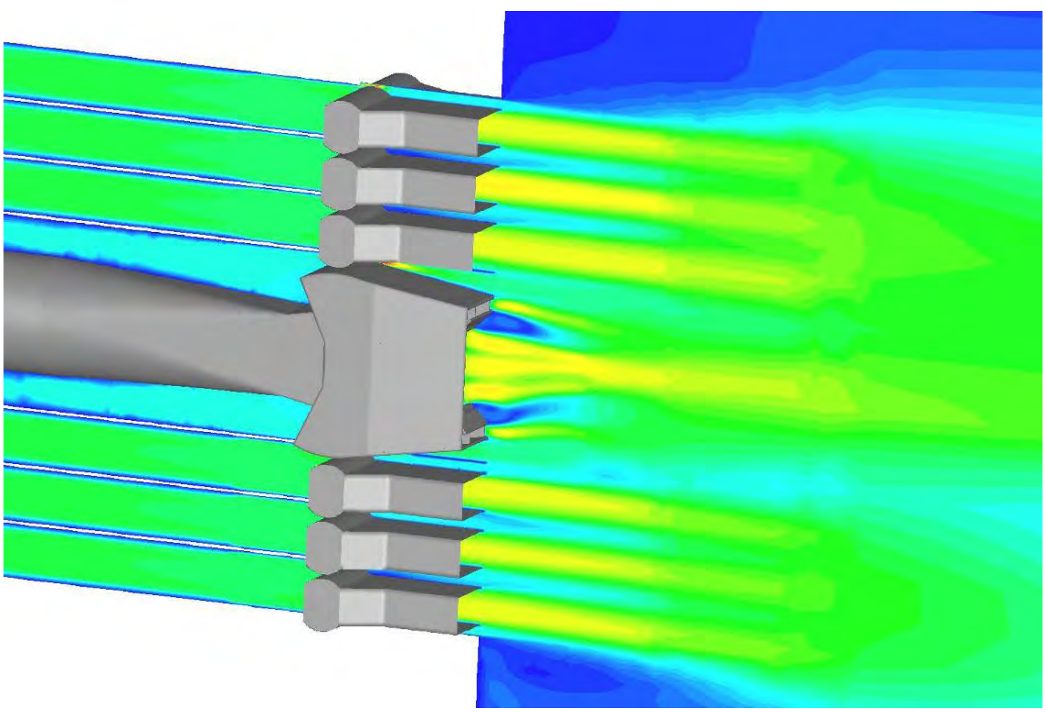


Figure 4.5-3 Predicted air velocity magnitude for shear bar/air deflector tip

The converging shape of the coal nozzle tip tends to concentrate the gas flow into a single jet approximately one tip diameter downstream of the exit. As shown in the figure, there is little interaction between the auxiliary air jets and the primary air jet for several burner diameters. This may be exaggerated somewhat due to the non-reacting nature of the simulations. In reality, once the coal jet ignites there will be an increase in temperature and velocity, which may impact the rate of expansion of the coal jet and the mixing characteristics.

The predicted particle phase concentration at the tip center plane is shown in Figure 4.5-4. The scale of the particle concentration plots is 0-0.125 lb/ft^3, again with yellow as the maximum concentration and dark blue as zero. As seen in the figure, the shear bar/air deflector tip tends to concentrate the coal particles in the center of the tip. A few of the smaller diameter coal particles become entrained in the recirculation zones behind the air deflectors, but the majority of the coal particles are concentrated in a single jet at the center of the coal nozzle tip.

Of the tips tested during Week 1 in the ISBF on an Illinois #6 coal, the shear bar / air deflector tip tended to have the highest NOx emissions, and the flame was not strongly attached to the tip. The flame was weakly attached to the bottom of the tip for some test conditions and generally not attached at the top of the tip. It was the design goal of this tip to have a strongly attached flame, via turbulence generation, giving early ignition of the coal jet.

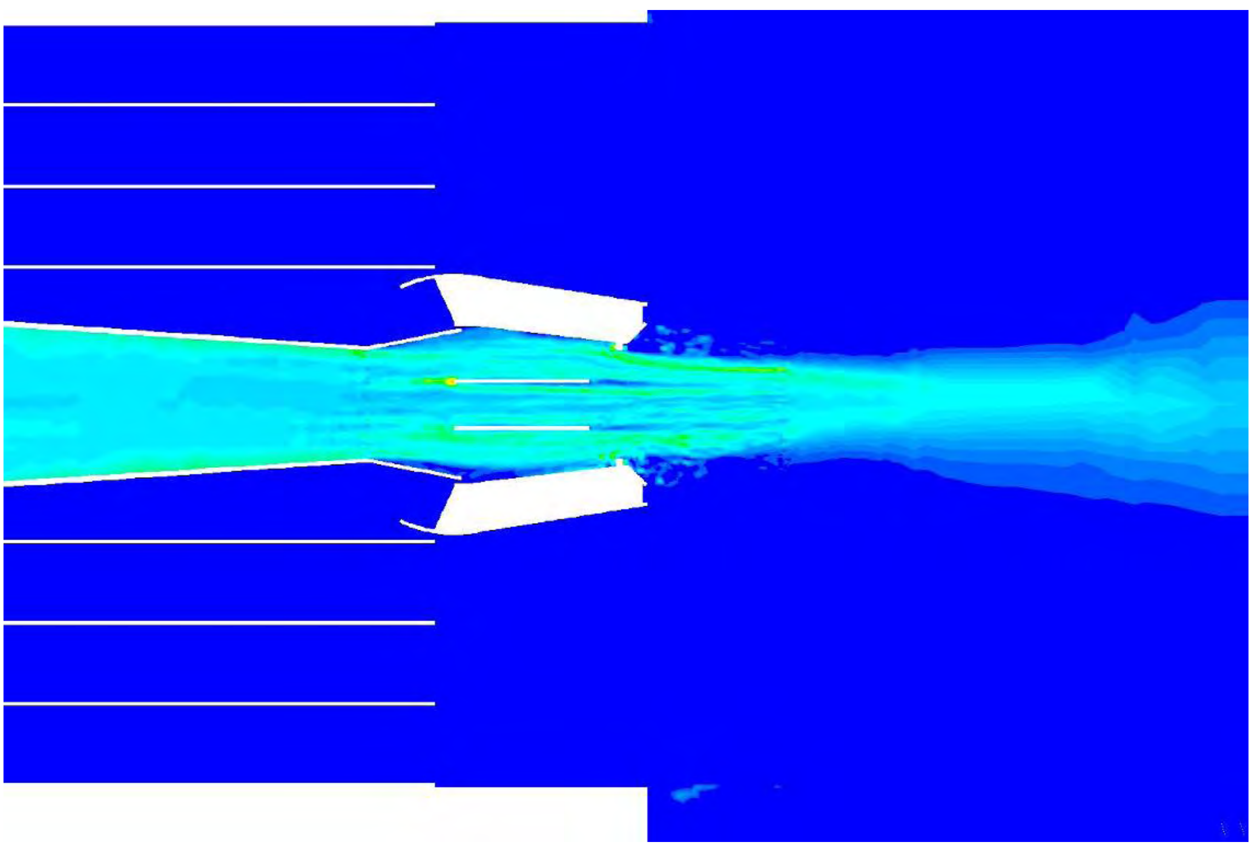


Figure 4.5-4 Predicted particle concentration for shear bar/air deflector tip

4.5.2 LNCFS™ P2 Tip

The baseline LNCFS™ P2 coal nozzle tip as represented in CFD is shown in Figure 4.5-5. Again, all aspects of the actual nozzle tip design, including free areas, and bluff body recirculation configurations were used for the CFD modeled nozzle tip. The predicted gas velocity distribution at the center plane for the LNCFS™ P2 tip is shown in Figure 4.5-6. Recirculation zones form behind the pumpkin teeth on the LNCFS™ P2 tip, which increase the local turbulence levels in the primary air stream. As the inner shroud of the LNCFS™ P2 tip doesn't converge to the extent that it does for the shear bar / air deflector tip, the gas flow is not concentrated to the center of the tip as much.

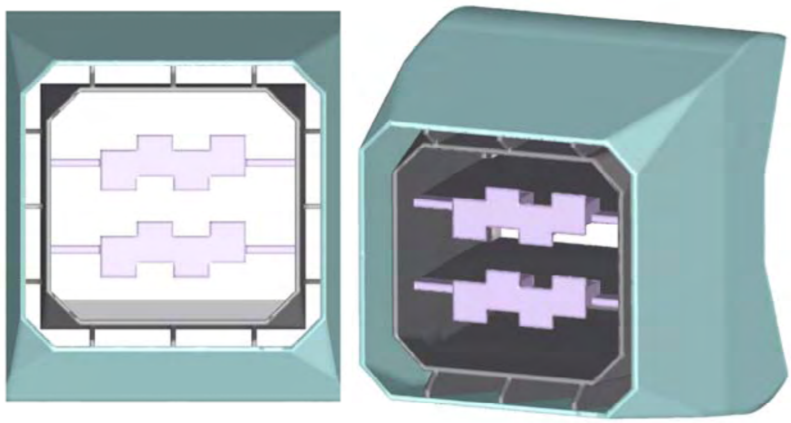


Figure 4.5-5 LNCFS™ P2 coal nozzle tip as represented by CFD

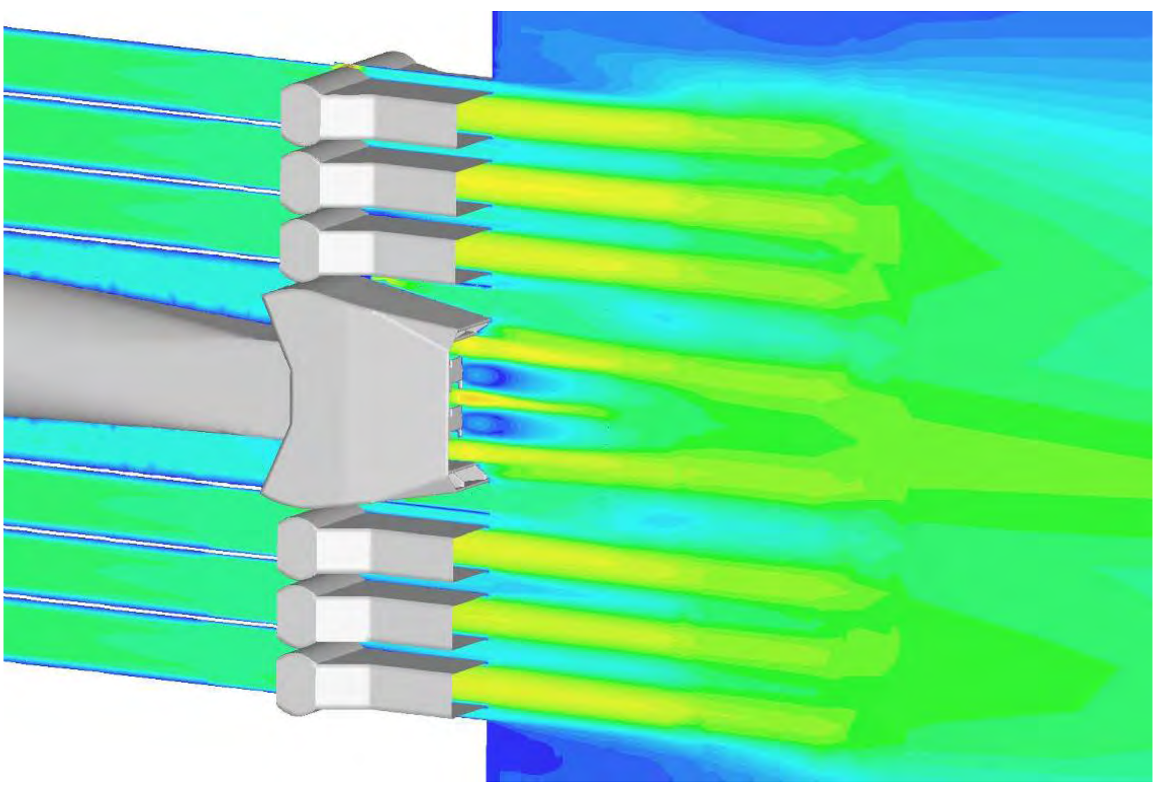


Figure 4.5-6 Predicted air velocity magnitude for LNCFS™ P2 tip

Similarly, the particles are not concentrated to the center as much in the LNCFS™ P2 tip (see Figure 4.5-7). The two rows of pumpkin teeth tend to stratify the particles into alternating rich and lean regions. As there is nothing on the outside of the tip to promote mixing between the secondary and primary air, the particles tend to reform into a single larger jet before combustion would be completed.

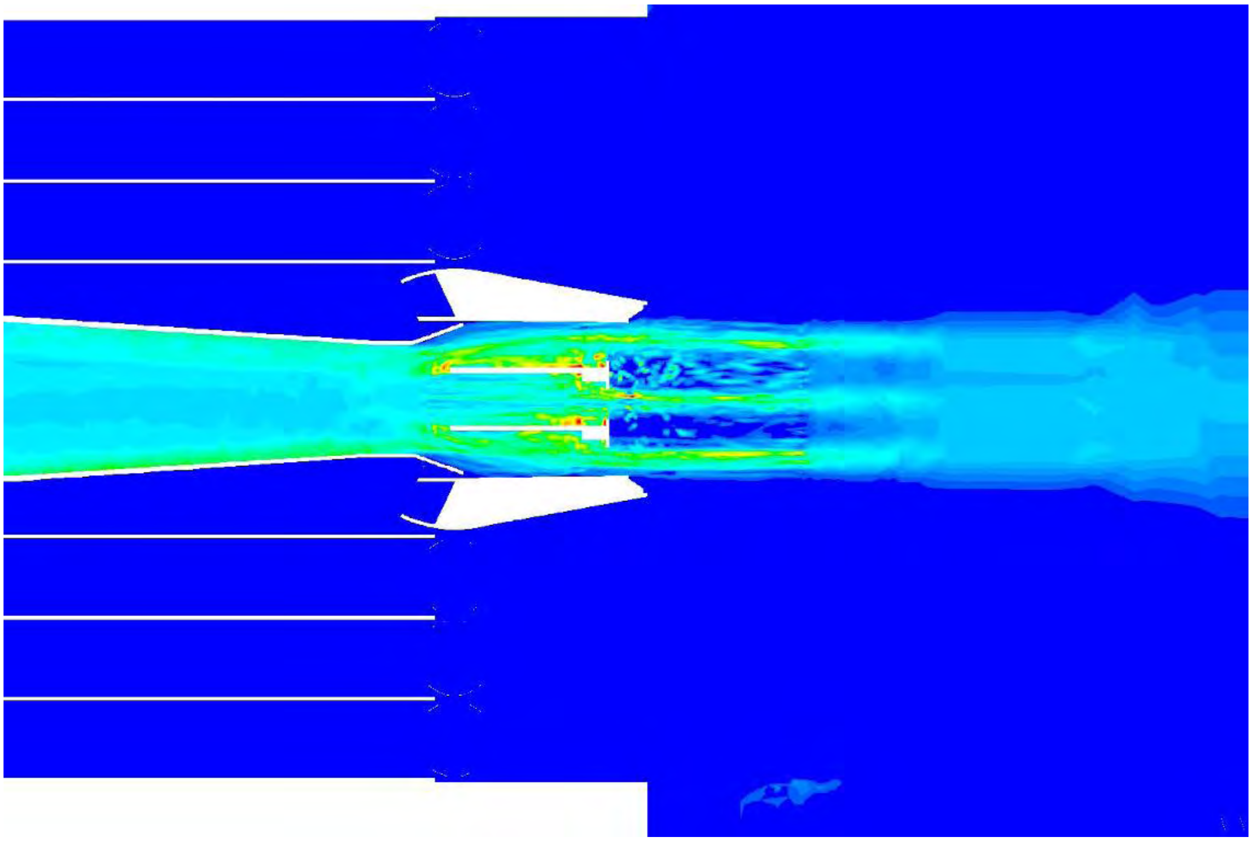


Figure 4.5-7 Predicted particle concentration for LNCFS™ P2 tip

The LNCFS™ P2 coal nozzle tip gave slightly lower NOx emissions than the shear bar / air deflector tip in the week 1 ISBF testing on an Illinois #6 coal. The flame ignition location for the LNCFS™ P2 coal nozzle tip was typically more than two burner diameters off the tip.

4.6 New Coal Nozzle Tips

Four new coal nozzle tip ideas were selected for evaluation in the first week of ISBF testing, referred to in this report as the center bluff tip, the recessed center bluff tip, the X-tip, and the diverging hybrid tip. The new coal nozzle tip concepts were selected based on different theories for obtaining lower NOx emissions which built upon past combustion test experience at Alstom and new ideas.

This section briefly describes each of the new tip ideas and presents gas velocity and particle concentration plots similar to those presented in the previous section for the two baseline tips. The scales on all of the color contour plots in this report are the same; velocity 0 - 150 ft/s and particle concentration 0 - 0.125 lb/ft^3. For some of the tips, more than one geometry variation was modeled. The geometry first tested in the ISBF will be presented with the tip name. Variations to the coal nozzle tip geometries, simulated either before or after the initial combustion testing, will be referred to with a revision number, e.g., recessed center bluff rev. 1. The tip variations modeled with CFD will be listed in the following sections. However, if the modifications did not result in any significant variations to the results, the color contour plots will not be presented in the report.

4.6.1 Center Bluff Tip

The CFD representation of the center bluff coal nozzle tip is shown in Figure 4.6-1. The CFD model for this tip design mirrored all aspects of the nozzle tip used during the combustion testing. The design philosophy behind this tip was to have shear bars and air deflectors to help attach the flame to the top and bottom of the coal nozzle tip. The flame ladders would then provide a path to ignite the center of the coal jet in the recirculation zone in front of the center bluff body. Igniting the coal jet from both the inside and outside would result in strong ignition of the coal jet and release more of the coal bound nitrogen in the fuel rich zone in the furnace for reduced NOx emissions.

The predicted gas velocity distribution at the center plane for the center bluff tip is shown in Figure 4.6-2. A large recirculation zone forms behind the center bluff body and the flame ladders. The corresponding particle concentration on the tip centerline is shown in Figure 4.6-3. The center bluff tip tends to spread out the coal particles more than the baseline tips. There also seems to be more particles in the recirculation zones behind the air deflectors than for the shear bar / air deflector tip.

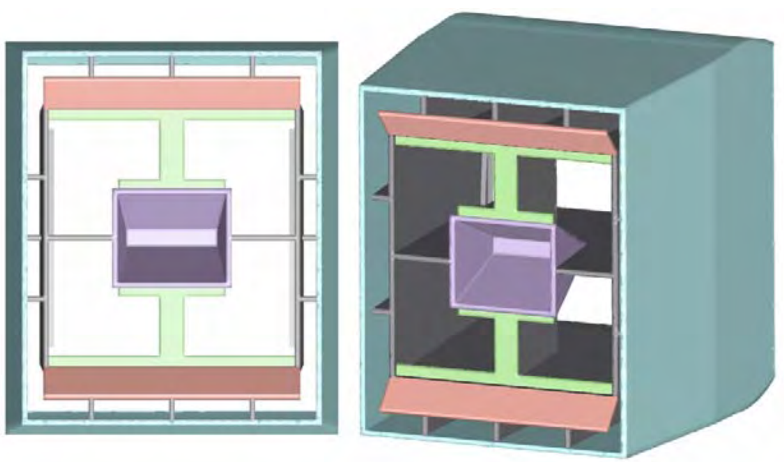


Figure 4.6-1 Center bluff coal nozzle tip as represented by CFD

The predicted gas velocity and particle concentrations at a plane one inch from the centerline are shown in Figure 4.6-4 and Figure 4.6-5. This location is just past the flame ladders that are in the center of the tip. The small high velocity spot on the upper side of the center bluff body is not physical, but due to incomplete convergence of the solution. The particle concentration plot shows enriched particles above and below the bluff body. The predicted particle concentration at the outlet plane (see Figure 4.6-6) also shows increased particle concentrations on the side of the bluff body.

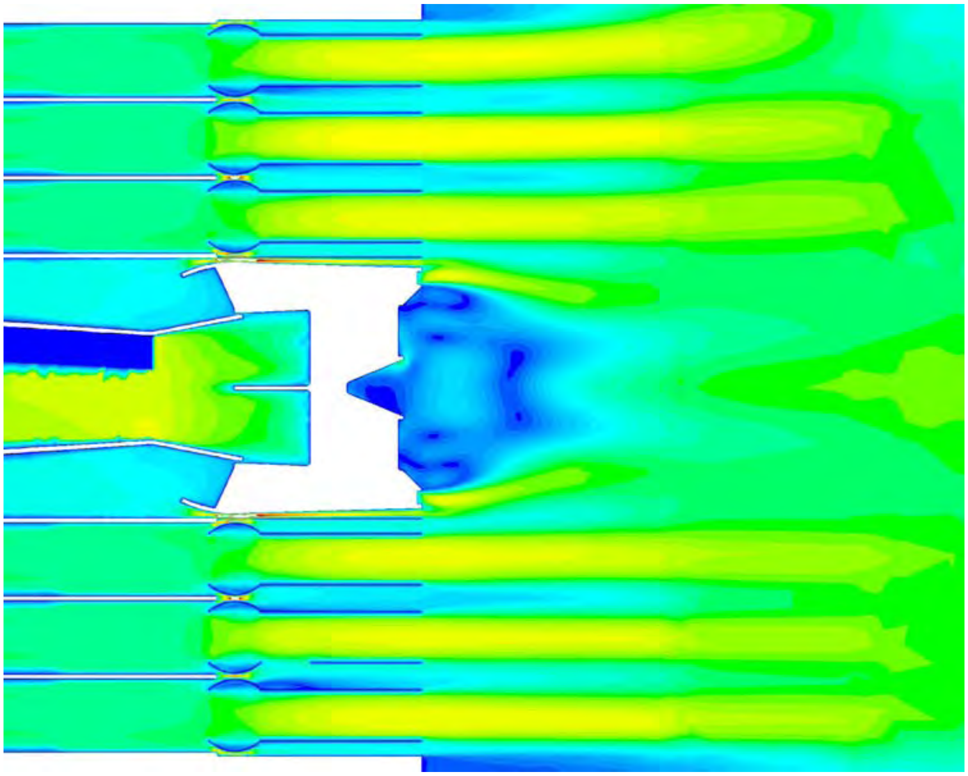


Figure 4.6-2 Predicted air velocity magnitude for center bluff tip

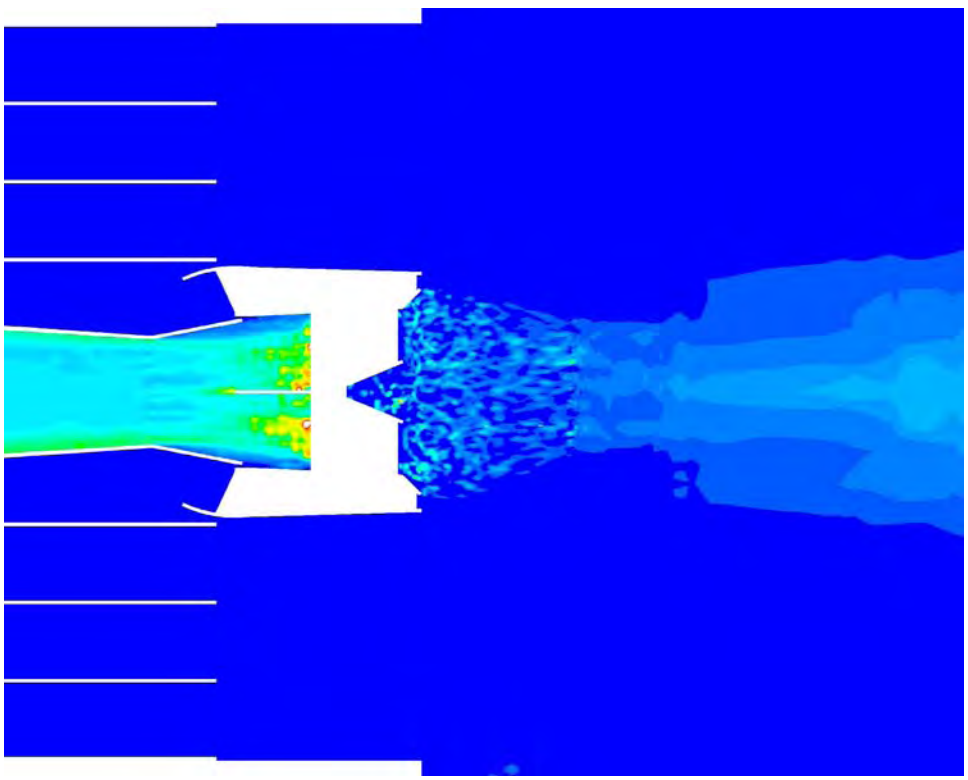


Figure 4.6-3 Predicted particle concentration for center bluff tip

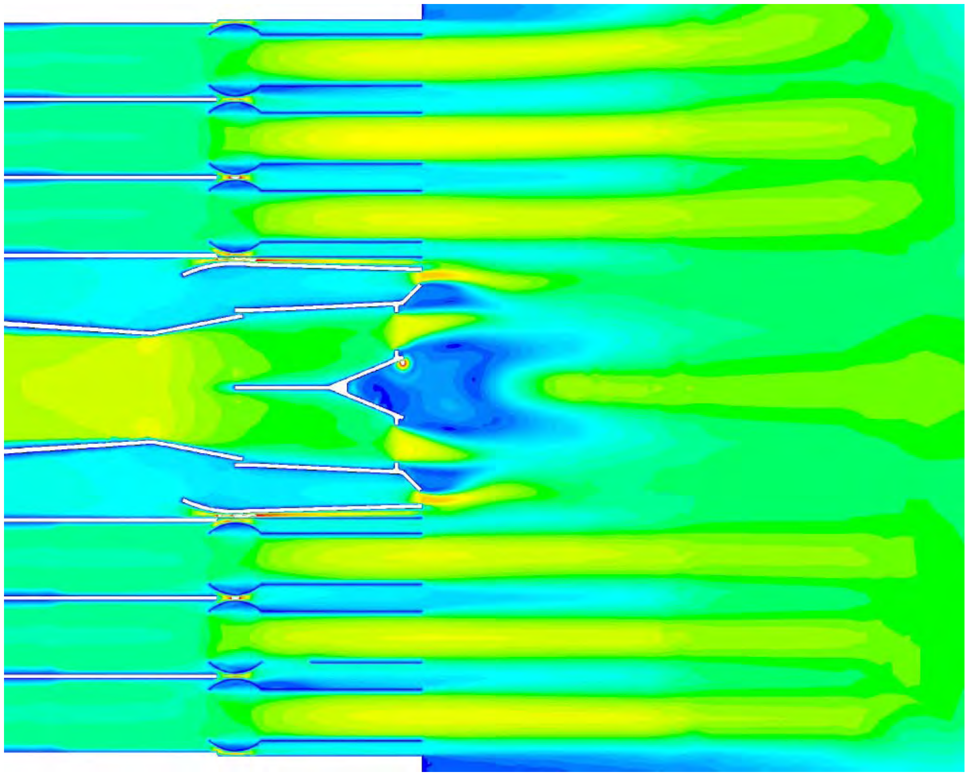


Figure 4.6-4 Predicted air velocity magnitude for center bluff tip (+1 in)

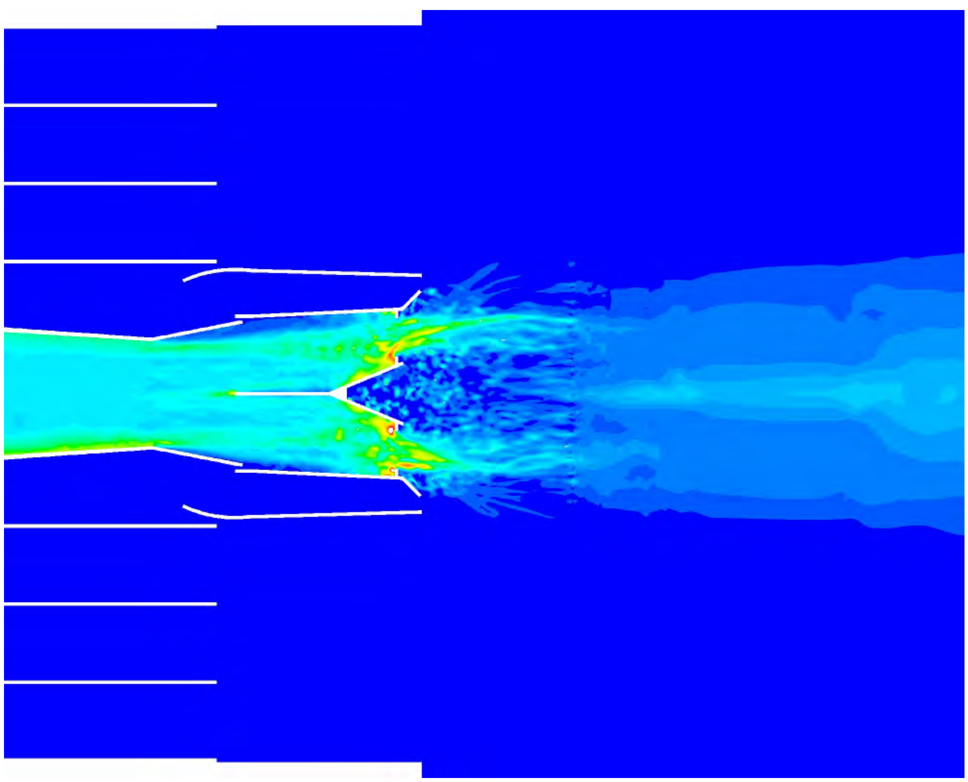


Figure 4.6-5 Predicted particle concentration for center bluff tip (+1 in)

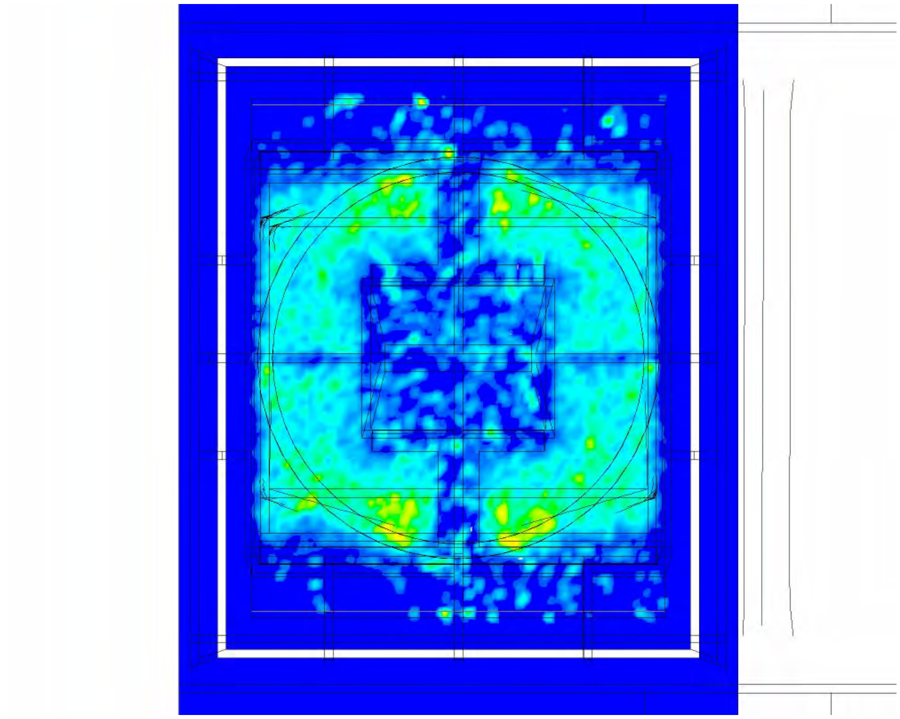


Figure 4.6-6 Predicted particle concentration at the center bluff tip outlet plane

The center bluff tip had the lowest NOx emissions of the tips tested in the ISBF in week 1. The NOx values for the center bluff tip were approximately 30 ppm lower than the LNCFS™ P2 tip across the range of stoichiometries tested.

One revision of the center bluff body tip was modeled and tested in week 2 in the ISBF in an attempt to draw the flame into the recirculation zone behind the center bluff body. The bluff body assembly from the center bluff tip was inserted into the diverging hybrid tip shell (larger available flow area). The height of the shear bars was increased and the width of the flame ladders was increased as well. This tip revision is shown in Figure 4.6-7. (Note there should be a horizontal division plate to help secure the bluff body to the inner shroud).

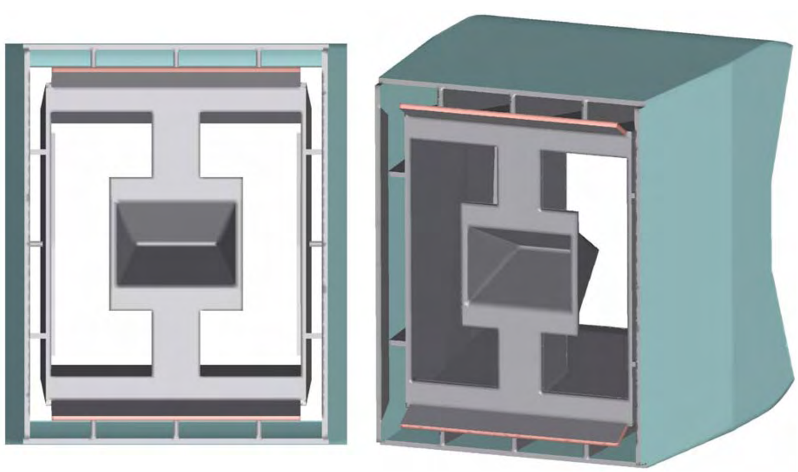


Figure 4.6-7 Center bluff rev. 1 coal nozzle tip as represented by CFD

The predicted velocity field at the center plane was similar to the baseline, as shown in Figure 4.6-8, only stretched in the vertical direction with a bigger separation between the two sides of the tip due to the larger flame ladder. The particles were separated into two distinct areas as shown in Figure 4.6-9, resulting in fuel rich and fuel lean regions. The rev. 1 tip modification resulted in an experimental NOx reduction of approximately 15 ppm over the range of stoichiometries tested as compared to the original center bluff tip.

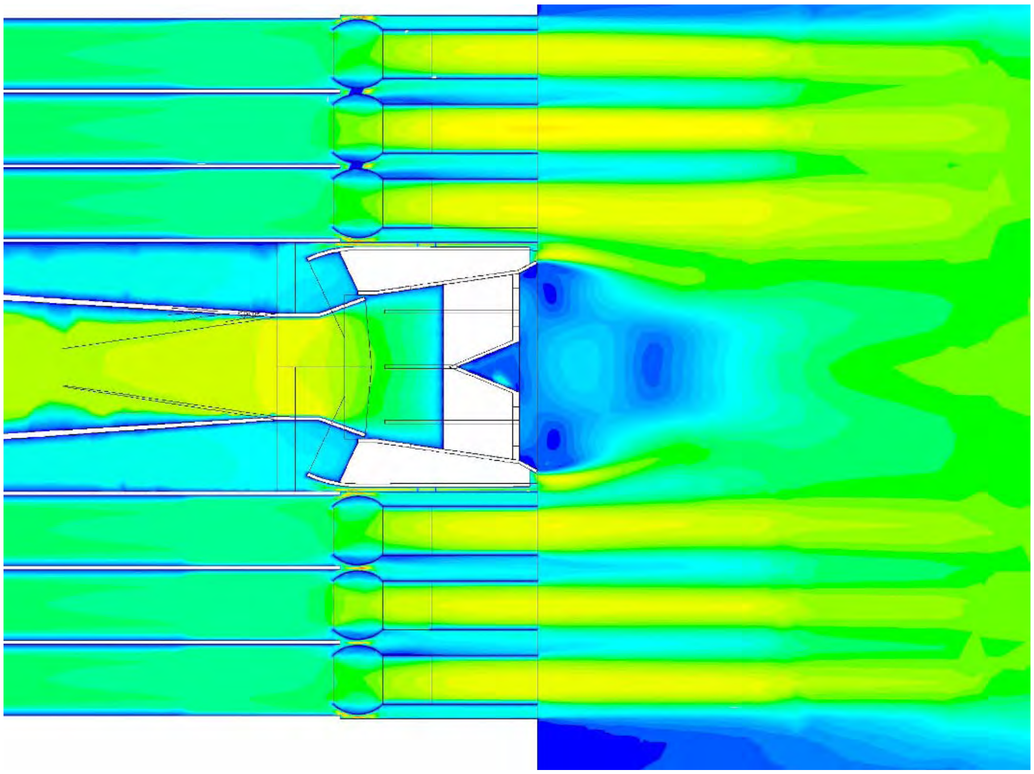


Figure 4.6-8 Predicted air velocity magnitude for center bluff rev. 1 tip

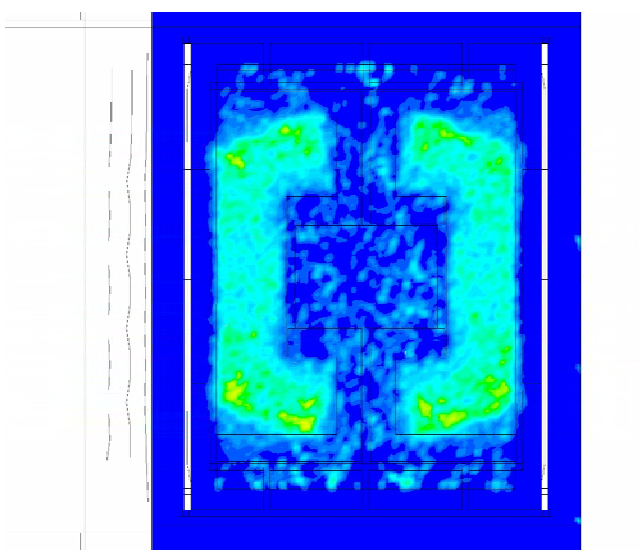


Figure 4.6-9 Predicted particle concentration at the center bluff tip rev. 1 outlet plane

4.6.2 Recessed Center Bluff Tip

The CFD representation of the recessed center bluff coal nozzle tip is shown in Figure 4.6-10. The design philosophy behind this tip was similar to that of the center bluff tip, to have flame attachment on the top and bottom shear bars / air deflectors which then propagates to the recirculation zone behind the bluff body in the center of the tip. For the recessed center bluff body tip, however, a portion of the coal and air proceeds straight through the tip through the three compartments on either side of the center bluff body. The coal and air in the center of the tip flows over a bluff body that has been recessed back into the tip. Angled flame ladders on each corner of the tip were added to help bring the flame back into the recirculation zone in front of the bluff body. The same primary and secondary air free areas were used as on the original center bluff tip.

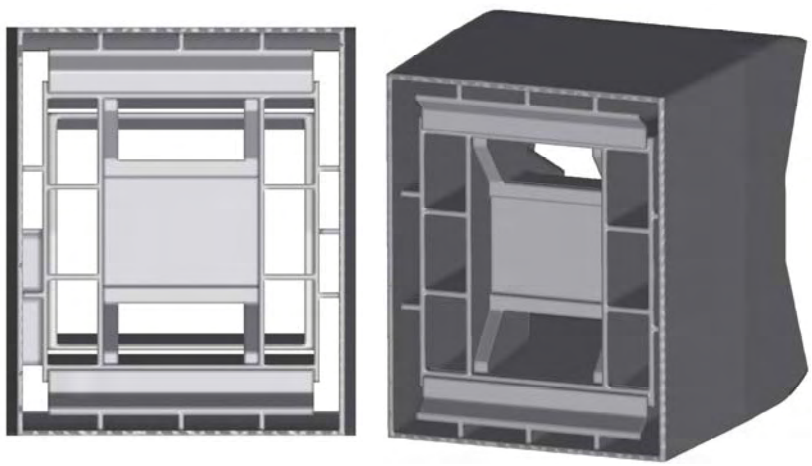


Figure 4.6-10 Recessed center bluff coal nozzle tip as represented by CFD

The predicted gas velocity distribution at the center plane for the recessed center bluff tip is shown in Figure 4.6-11. Recirculation zones form after the center bluff body and the air deflectors. However, the center recirculation zone behind the recessed bluff body is much smaller than that behind the center bluff body tip described in the previous section. The gas flow field quickly closes together behind the bluff body. The predicted particle concentrations (see Figure 4.6-12) follow the same trend as the gas. The bluff body causes separation into two fuel rich streams at the top and bottom of the tip, but they quickly merge back together into a single zone just downstream of the bluff body.

The following revisions of the recessed center bluff body tip were simulated with CFD:

- Rev. 1: 22 deg. Air deflector, side shear bars, shear bars on top and bottom, no shear bars on bluff body.
- Rev. 2: Tapered bluff body.
- Rev. 3: No side shear bar on middle section.
- Rev. 4: Rev. 3 with side windows cut out.
- Rev. 5: Extended bluff body.
- Rev. 6: Extended bluff body, no top & bottom shear bars.

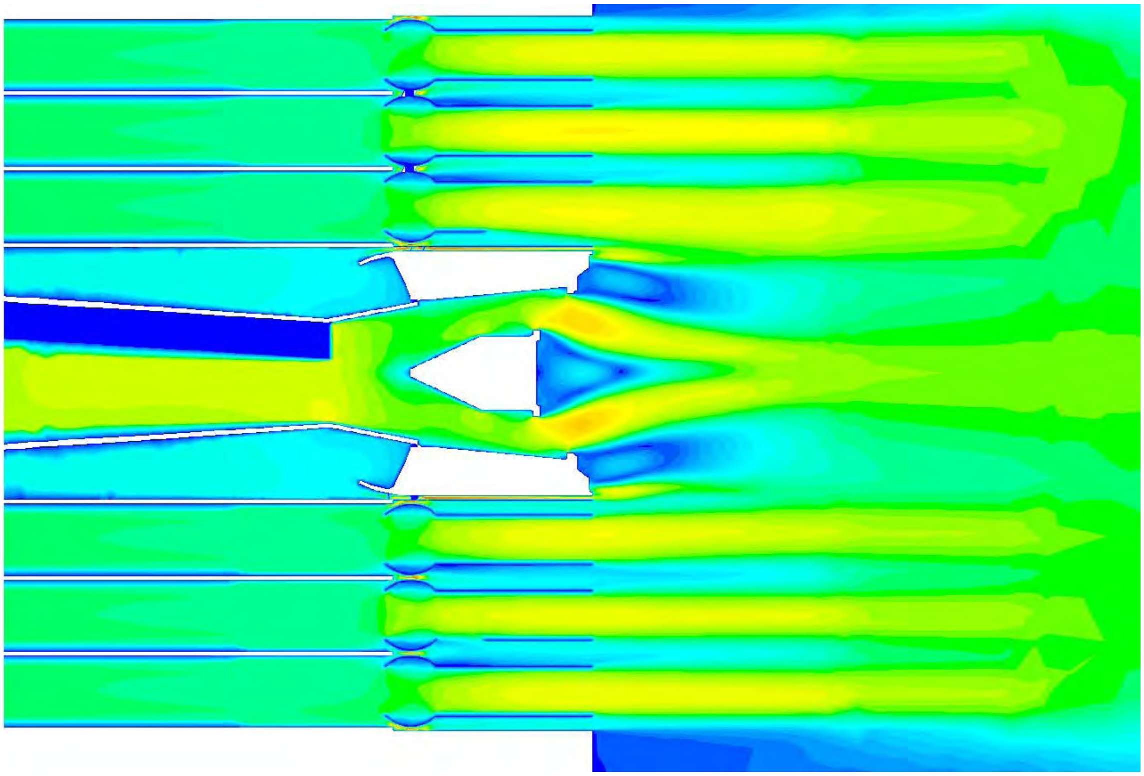


Figure 4.6-11 Predicted air velocity magnitude for recessed center bluff tip

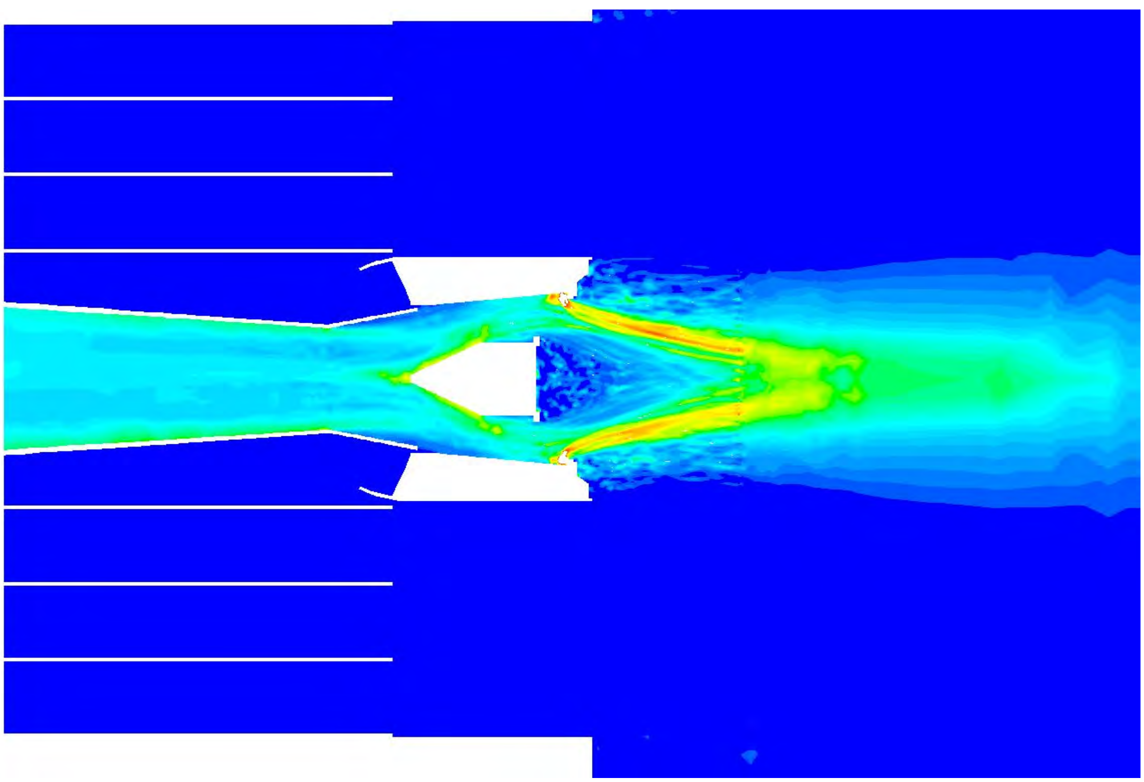


Figure 4.6-12 Predicted particle concentration for recessed center bluff tip

Most of the revisions had only small impacts on the predicted near field gas and particle distributions. The modification that was most different was rev. 6. Figure 4.6-13 illustrates the rev. 6 geometry. The extended center bluff body results in a somewhat larger recirculation zone behind the bluff body and prevents the gas and particle streams from closing together as quickly as shown in Figure 4.6-14 and Figure 4.6-15. Note, however, that a significant fraction of the particles pass through the side windows and are not affected by the bluff body at all (see Figure 4.6-16).

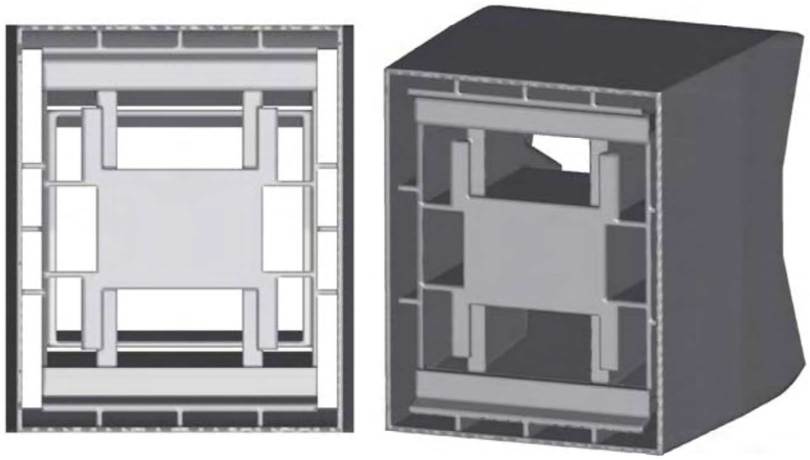


Figure 4.6-13 Recessed center bluff coal nozzle tip rev. 6 as represented by CFD

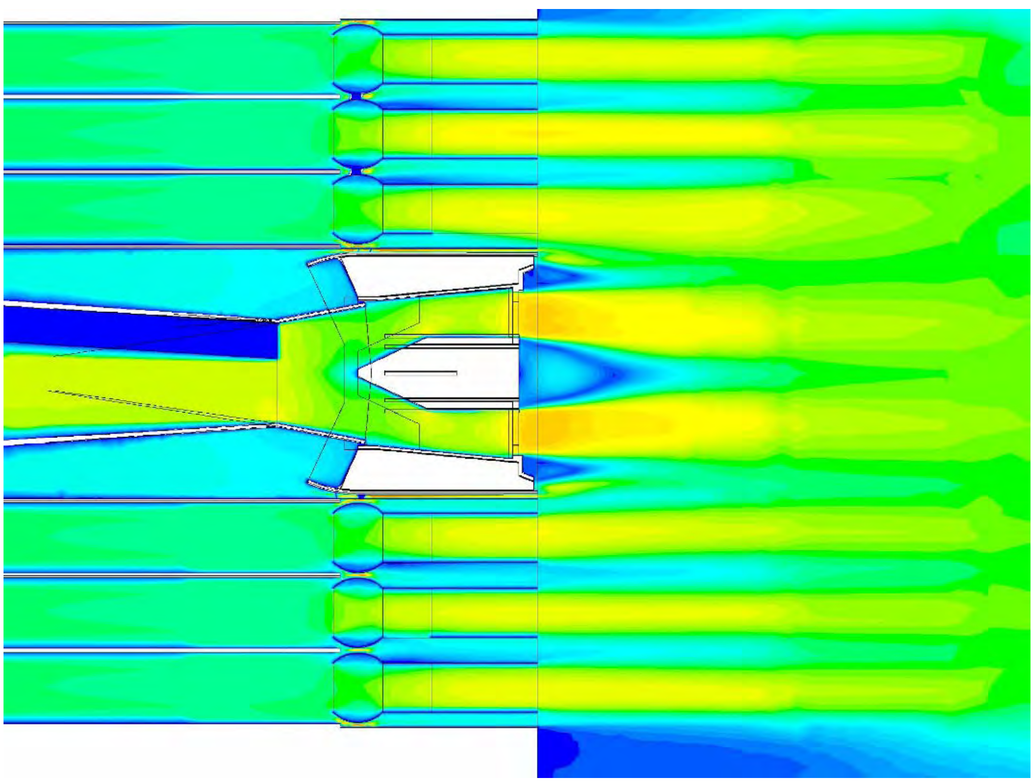


Figure 4.6-14 Predicted air velocity magnitude for recessed center bluff rev. 6 tip

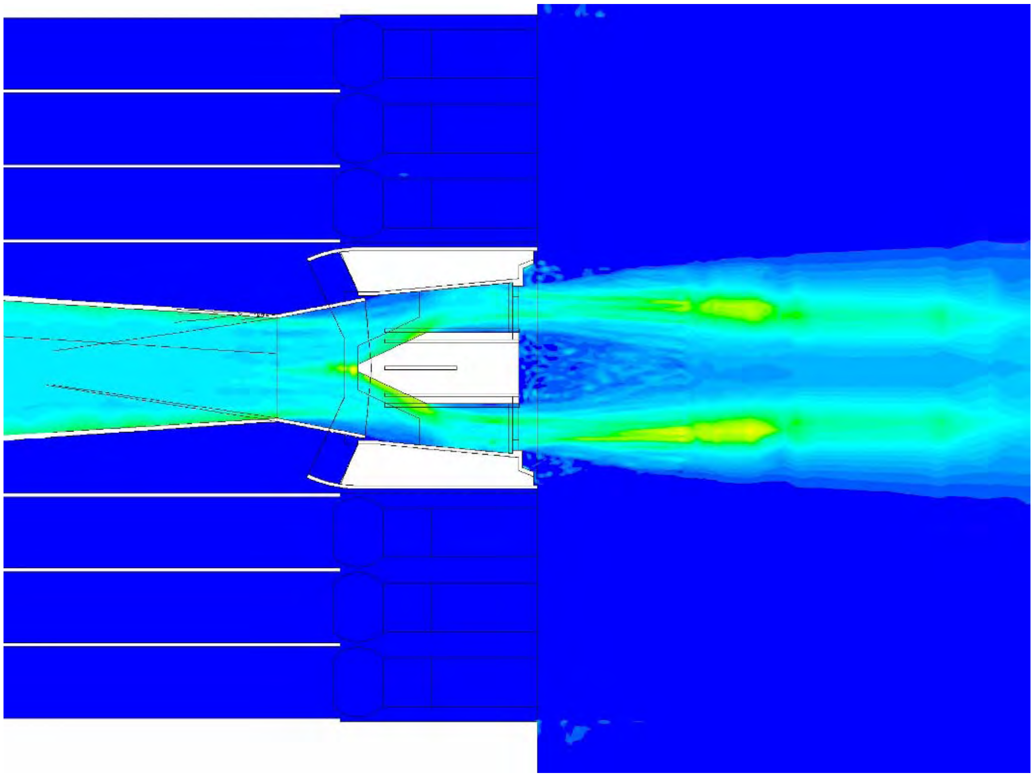


Figure 4.6-15 Predicted particle concentration for recessed center bluff rev. 6 tip

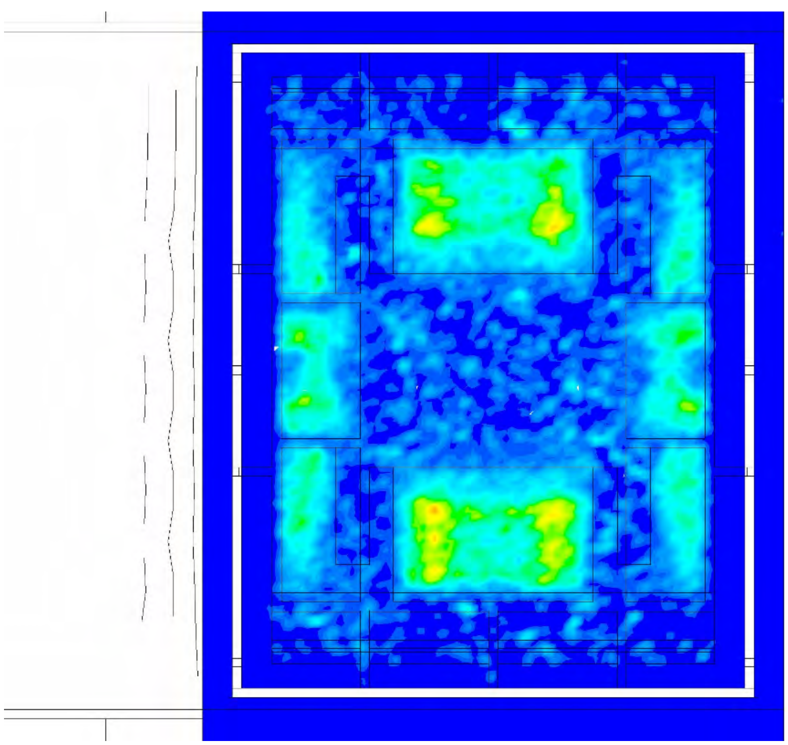


Figure 4.6-16 Particle concentration at the recessed center bluff tip rev. 6 outlet plane

The recessed center bluff tip had NOx emissions similar to the LNCFS™ P2 tip tested in week one on the Illinois #6 coal. Similar to the center bluff tip, this tip did not achieve strong flame attachment on the top and bottom of the tip and there was no evidence of flame in the recirculation zone after the center bluff body. Two additional modifications to the recessed center bluff tip were made (including an extended bluff body) and tested in week 2 of the ISBF testing in an attempt to get flame attachment and early ignition. Neither modification was successful in changing the ignition point and had little impact on the measured NOx emissions.

4.6.3 X Tip

The CFD representation of the X tip is shown in Figure 4.6-17. The design philosophy behind this tip was to increase the surface area of the flame by generating four lobes of fuel instead of a single coal jet. The increased surface area of the flame would result in faster combustion and more of the fuel nitrogen being released in the substoichiometric region of the boiler. Shear bars were added around the outside surface of the X tip to help promote early ignition. The bluff body was added to help deflect particles to the four lobes of the tip. Similar primary and secondary air free areas were used as on the original center bluff tip.

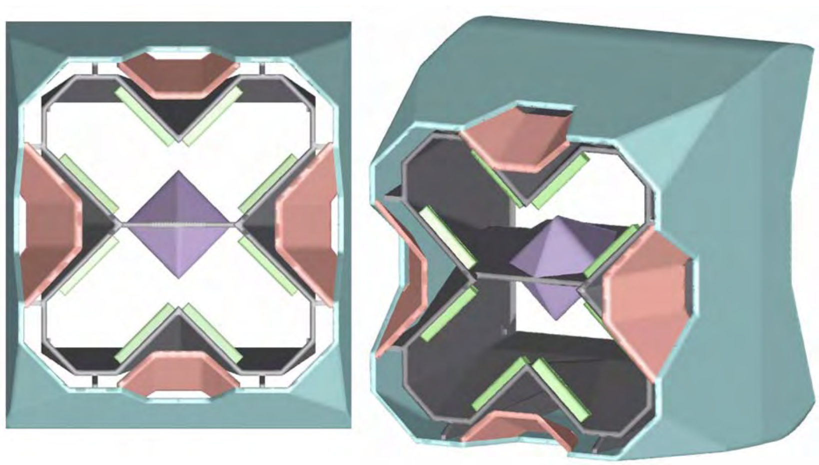


Figure 4.6-17 X tip as represented by CFD

The predicted gas velocity and particle distributions at the center plane of the X tip are shown in Figure 4.6-18 and Figure 4.6-19. The center plane view shows no significant recirculation zones downstream of the bluff body, with all the streams converging to form a single jet at the center of the tip. The particles are pushed outward by the bluff body and tend to reflect off the inner shroud. The particle concentration at the burner outlet plane (see Figure 4.6-20) shows that the particles actually form the four lobes as intended, with a small lean region directly behind the bluff body.

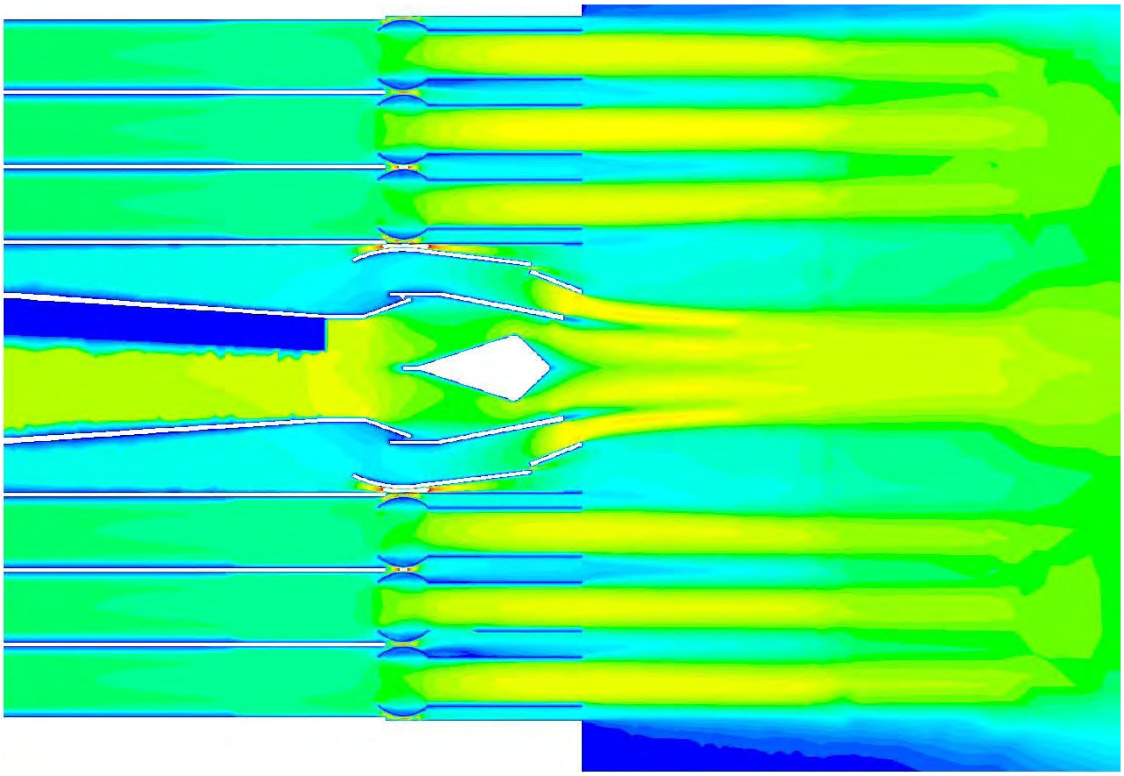


Figure 4.6-18 Predicted air velocity magnitude for X tip

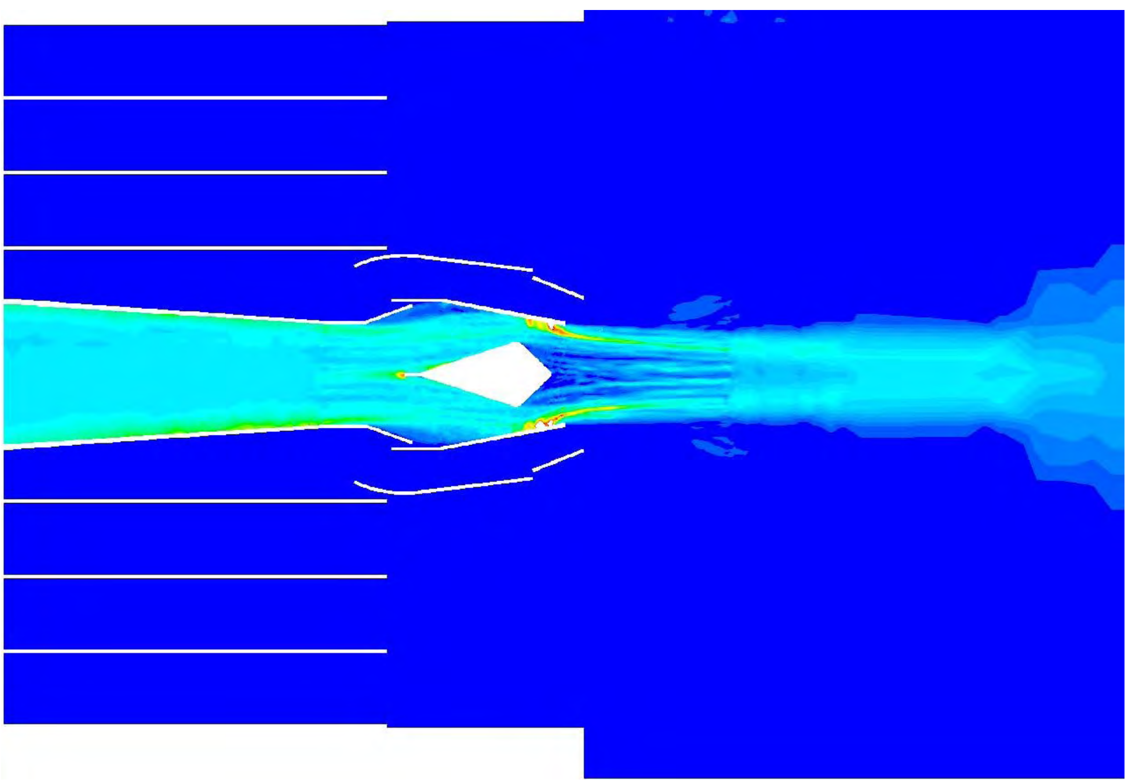


Figure 4.6-19 Predicted particle concentration for X tip

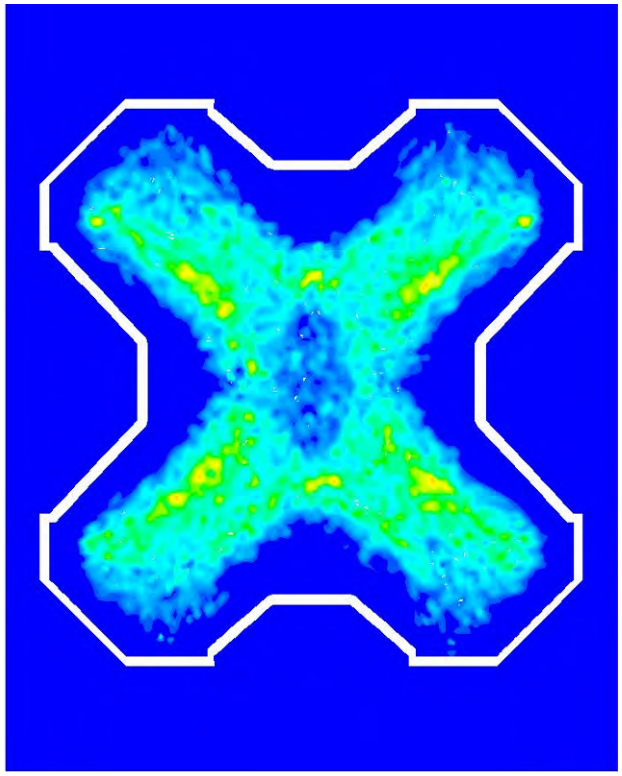


Figure 4.6-20 Predicted particle concentration at the X tip outlet plane

In the week 1 ISBF testing, NOx emissions from the X tip were second best of the new tips tested, showing a reduction in NOx of approximately 20 ppm as compared to the LNCFS™ P2 tip.

The following revisions to the X tip were simulated with CFD:

- Rev. 1: No bluff body.
- Rev. 2: Teardrop bluff body, ½ inch shear bars.
- Rev. 3: Larger teardrop bluff body, increased ramp angles.
- Rev. 4: Larger teardrop bluff body, same ramp angles as baseline.
- Rev. 5: No bluff body with 35 degree recessed swirler.
- Rev. 6: No fixed bluff body with ice cream cone movable bluff body at recessed position.

Most of the X tip revisions simulated with CFD had minimal impact on the results. The swirl generated by rev. 5 did tend to throw more particles to the outside of the lobes, but the swirl tended to wash out the four fuel rich lobes generated by the X tip.

4.6.4 Diverging Hybrid Tip

The CFD representation of the diverging hybrid coal nozzle tip is shown in Figure 4.6-21. This tip had a larger flow area than the others. The larger flow area was tested to assess reduced jet velocity. All other aspects of the nozzle tip design were similar to a standard commercially offered coal nozzle tip design.

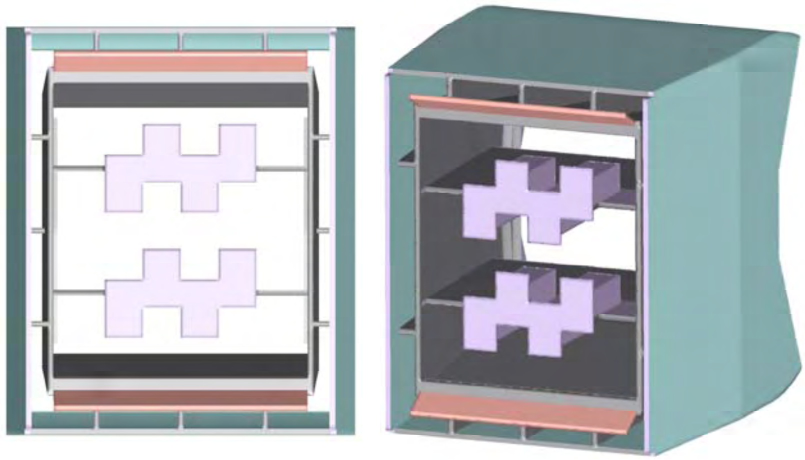


Figure 4.6-21 Diverging hybrid coal nozzle tip as represented by CFD

The design philosophy behind this tip was to have a hybrid between the LNCFS™ P2 tip and the shear bar / air deflector style tip, while opening up the tip at the exit to reduce the axial velocity of the fuel and air. The shear bars and air deflectors were used to help attach the flame to the top and bottom of the coal nozzle tip. The pumpkin teeth were used to generate turbulence and promote mixing and combustion. One significant difference between this tip and the others was the divergence of the inner shroud. The inner shrouds of the other tips all converged, consistent with current / past Alstom tip design philosophy.

The predicted gas velocity distribution at the center plane for the diverging hybrid tip is shown in Figure 4.6-22. As expected, recirculation zones form behind the air deflectors and the pumpkin teeth. The average axial velocity exiting the tip is lower than that of the other tips, consistent with the increased primary air free area of the diverging tip. Figure 4.6-23 shows the predicted particle distribution for the diverging hybrid tip. The pattern is similar to the LNCFS™ P2 tip, with the pumpkin teeth dividing the particles into distinct rich and lean zones. The diverging nature of this tip, however, allows the particles to spread out more in the vertical direction than the other tips examined so far. The measured week 1 NOx emissions for the diverging hybrid tip were approximately 10 ppm lower than the LNCFS™ P2 tip at all stoichiometries when firing the Illinois #6 coal.

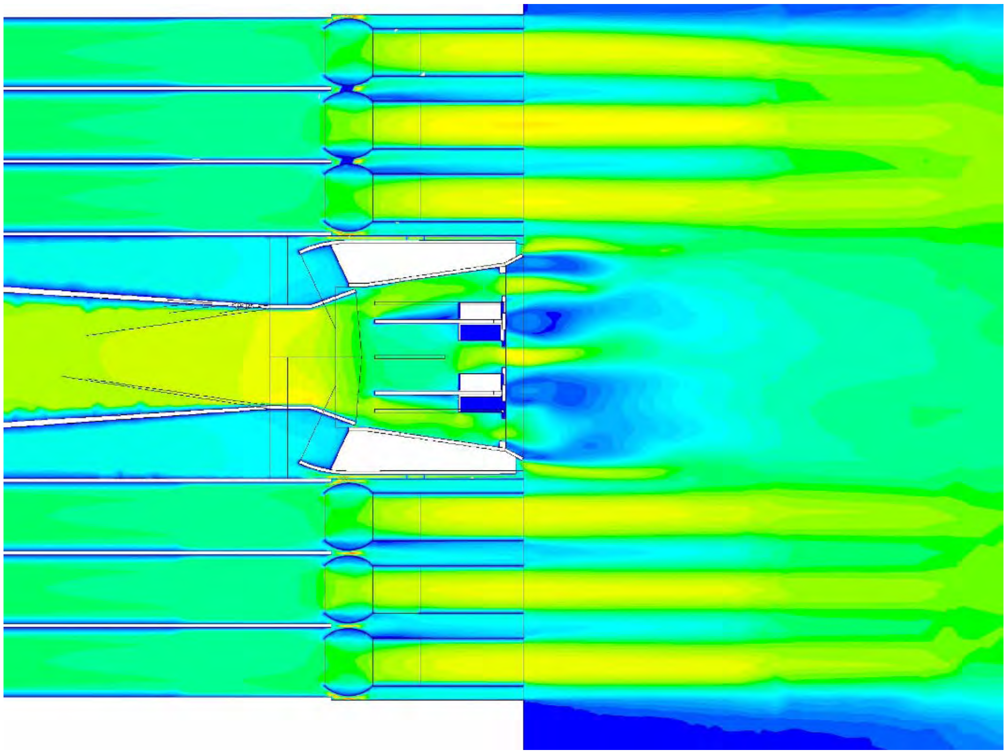


Figure 4.6-22 Predicted air velocity magnitude for diverging hybrid tip

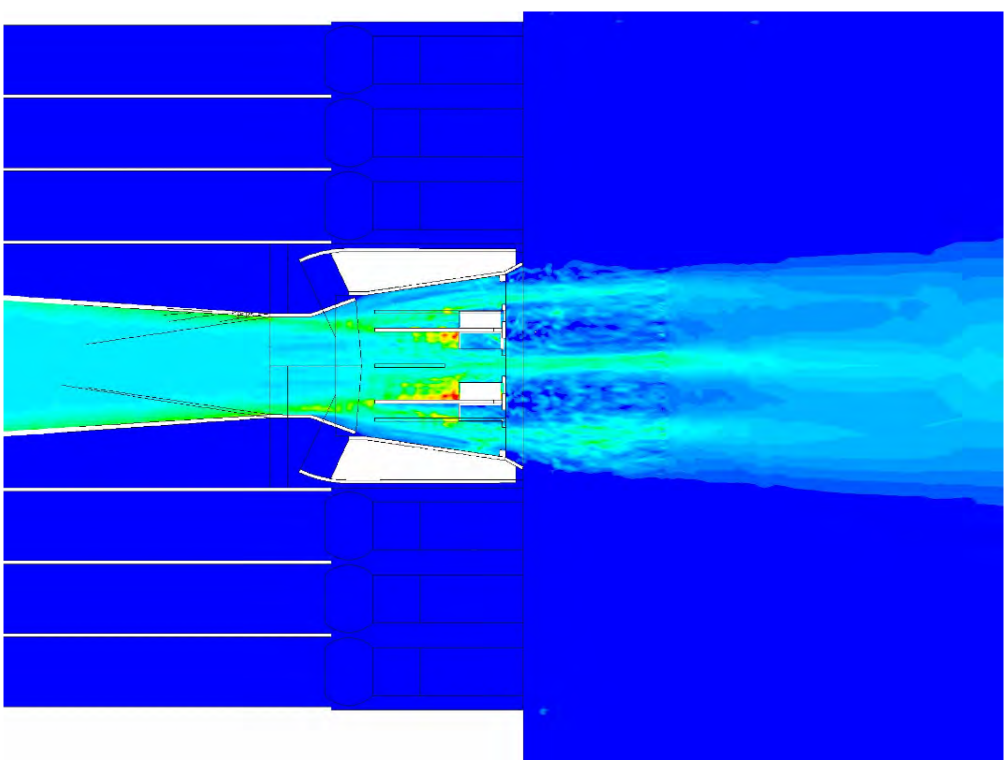


Figure 4.6-23 Predicted particle concentration for diverging hybrid tip

4.6.5 Round Tip

An alternative tip concept was brought into the test program for comparison and concept development purposes, despite its unconventional design for tangential firing applications. The round coal nozzle tip was originally conceived, designed, and modeled outside of this test program by another Alstom group. However it was felt that for comparison to and development of the other tips this tip could be helpful, so it was included in some modeling studies and the second combustion test series. All work shown here took place after the primary Alstom funded round tip design and development. CFD results will be presented for cases with swirler A flush with the nozzle tip exit, swirler A recessed into the coal nozzle (rev. 1), and swirler B recessed into the coal nozzle (rev 2.).

Swirler A

The CFD representation of the round coal nozzle tip with swirler A is shown in Figure 4.6-24. The swirler, shown in detail in Figure 4.6-25, had four swirl vanes on a bluff body that was attached to a rod which allowed the swirler to be moved to different axial locations for testing. The baseline swirler A case had the end of the swirler flush with the outlet plane of the coal nozzle tip.

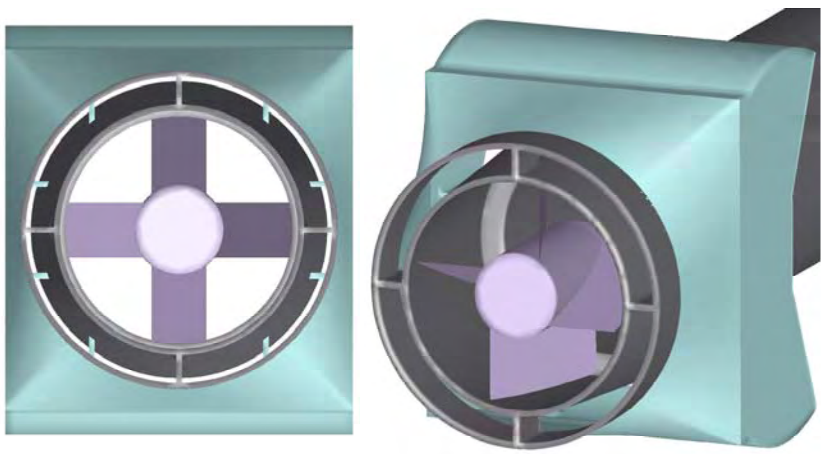


Figure 4.6-24 Round coal nozzle tip with swirler A as represented by CFD

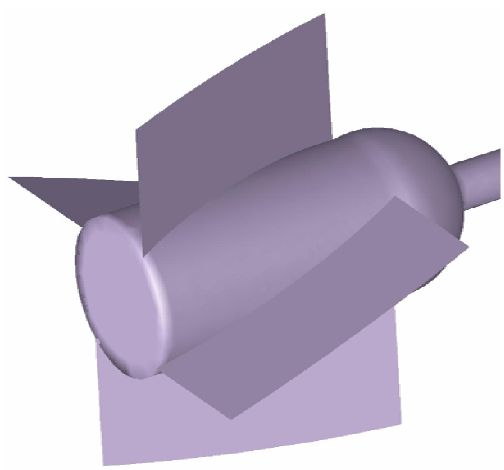


Figure 4.6-25 Swirler A as represented by CFD

The predicted gas velocity field is shown in Figure 4.6-26. The swirling flow exiting the nozzle tip has a low velocity region downstream of the bluff body. The swirl helps slow the air as it converges back into a single jet after it exits the tip. The predicted particle concentration, shown in Figure 4.6-27, shows an annular region of increased particle concentration as the swirl tends to throw the particles outward.

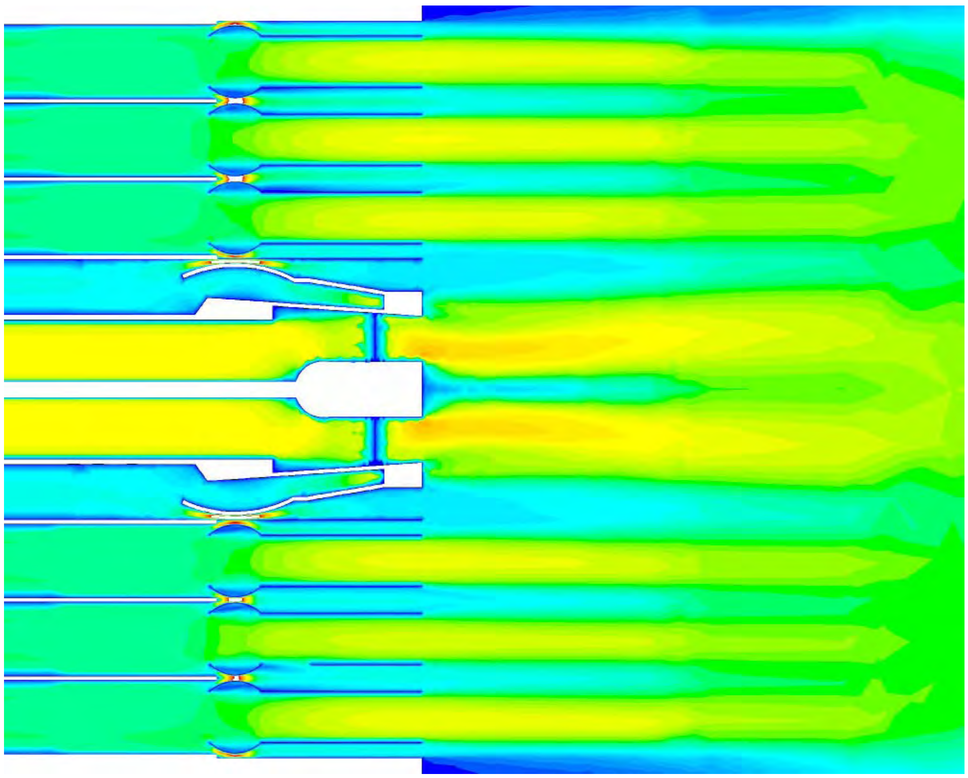


Figure 4.6-26 Predicted air velocity magnitude for round tip, 20° swirler

In the ISBF testing, the round tip with swirler A at the tip exit plane had NOx emissions similar to the center bluff tip, which was the best performing tip of the new ideas tested in week 1 in the IBSF.

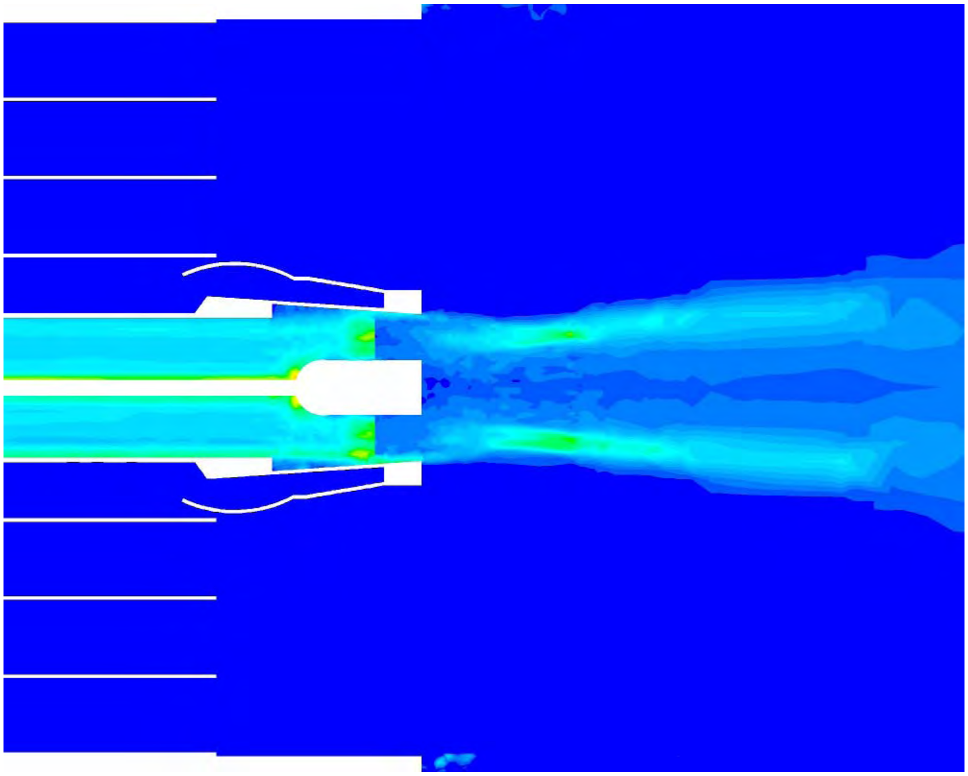


Figure 4.6-27 Predicted particle concentration for round tip, swirler A

Swirler A Recessed

In the ISBF testing, moving swirler A back from the round tip exit plane resulted in a reduction in NOx emissions of approximately 20 ppm. As seen in Figure 4.6-28, in the recessed position the swirler sits inside the coal nozzle instead of the coal nozzle tip. The swirler fits tighter at this location, which results in less fuel and air bypassing around the outside of the swirler. In addition, the axial velocity is higher with the bluff body at this location, which also results in additional swirl velocity for the gas and coal particles.

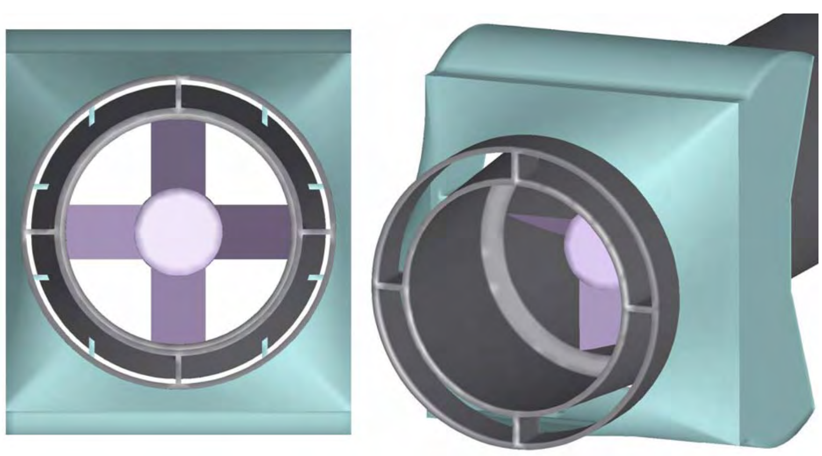


Figure 4.6-28 Round coal nozzle tip with recessed swirler A as represented by CFD

The predicted gas velocity field for the recessed swirler A case is presented in Figure 4.6-29. The additional swirl helps to lengthen the low velocity region in the center of the tip and prevents the gas flow from closing back in to form a single jet. The low velocity region on the bottom right side of the figure that impacts the lower auxiliary air compartments was probably due to incomplete convergence of the case. The additional swirl also helps to even further concentrate the coal particles in an annulus as shown in Figure 4.6-30.

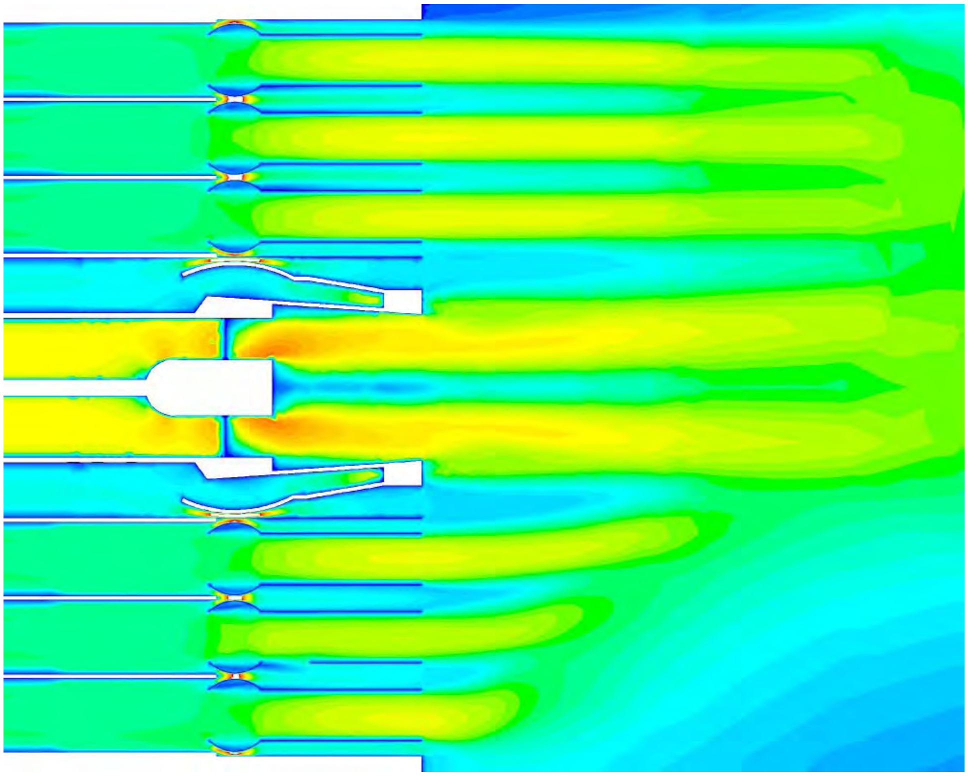


Figure 4.6-29 Predicted air velocity magnitude for round tip, recessed swirler A

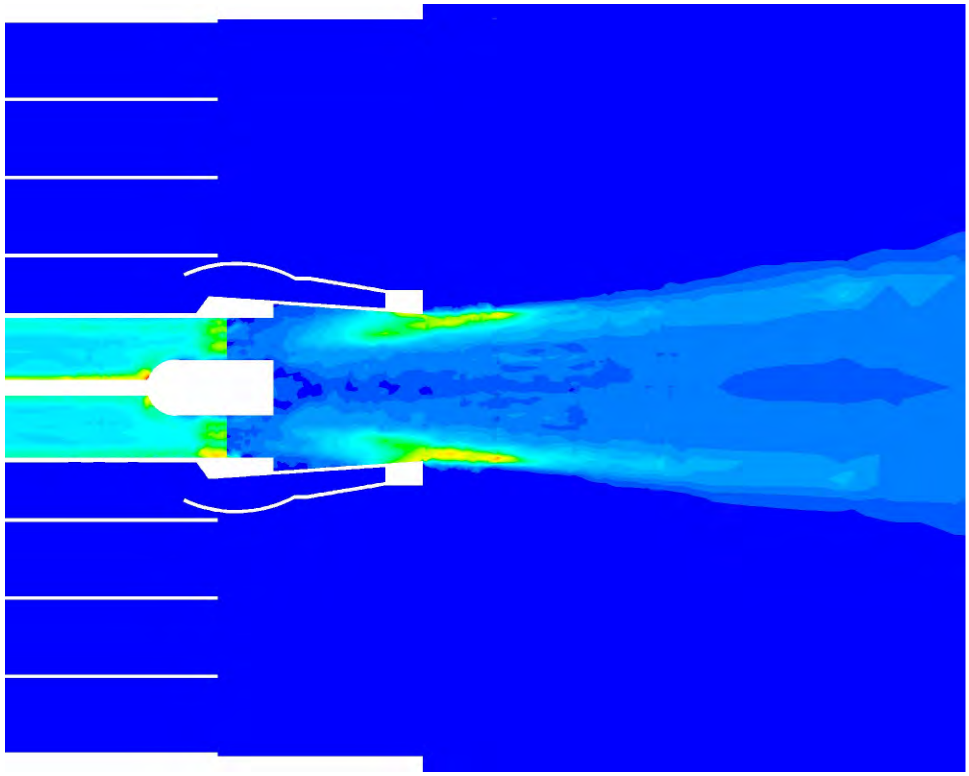


Figure 4.6-30 Predicted particle concentration for round tip, recessed swirler A

Swirler B Recessed

CFD and ISBF runs were made with swirler A modified to a steeper angle as shown in Figure 4.6-31. The round tip was tested with this swirler B in the recessed position as shown in Figure 4.6-32. This change resulted in a reduction in NOx emissions of 50 ppm as compared to swirler A in this position, which was significantly lower than any of the tips previously discussed.

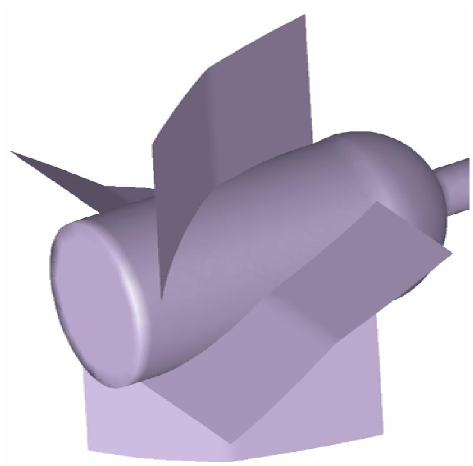


Figure 4.6-31 Swirler B as represented by CFD

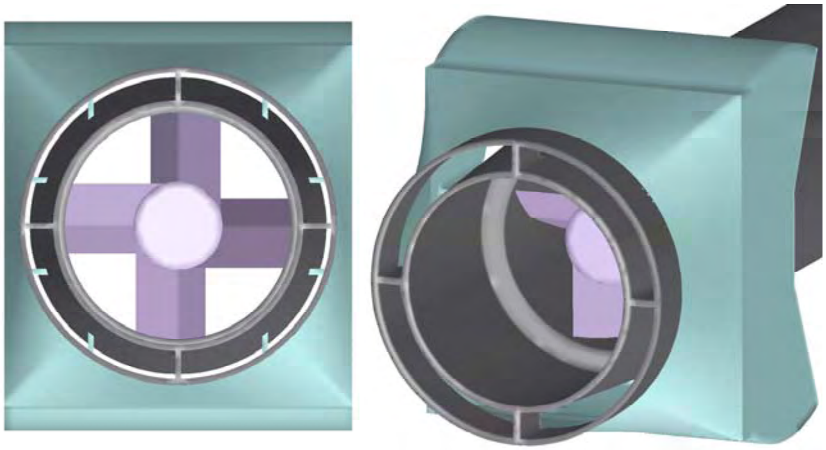


Figure 4.6-32 Round coal nozzle tip with swirler B as represented by CFD

The predicted gas velocity distribution (see Figure 4.6-33) shows that the increased swirl velocity generated by swirler B causes the gases exiting the nozzle tip to expand slightly as compared to swirler A. The higher swirl also concentrates the particles even more in an annulus at the outer edge of the coal nozzle tip as shown in Figure 4.6-34. Figure 4.6-35, which shows the particle distribution at the exit plane of the round coal nozzle tip, reveals that the four vanes actually concentrate the particles into four distinct fuel rich zones in this annulus of coal.

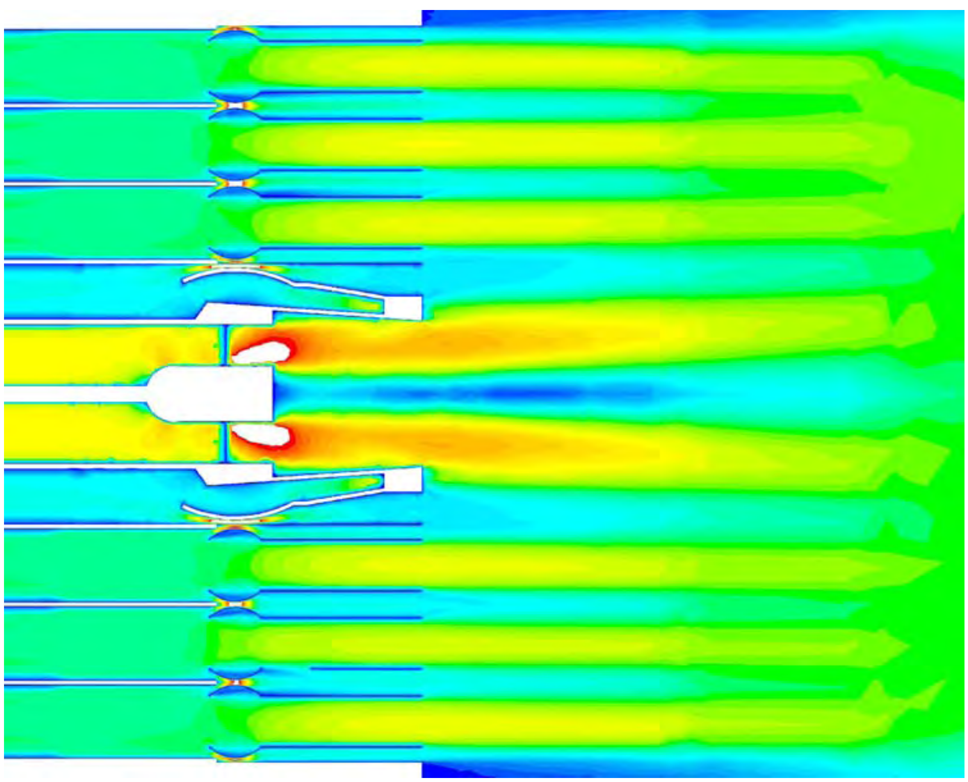


Figure 4.6-33 Predicted air velocity magnitude for round tip, recessed swirler B

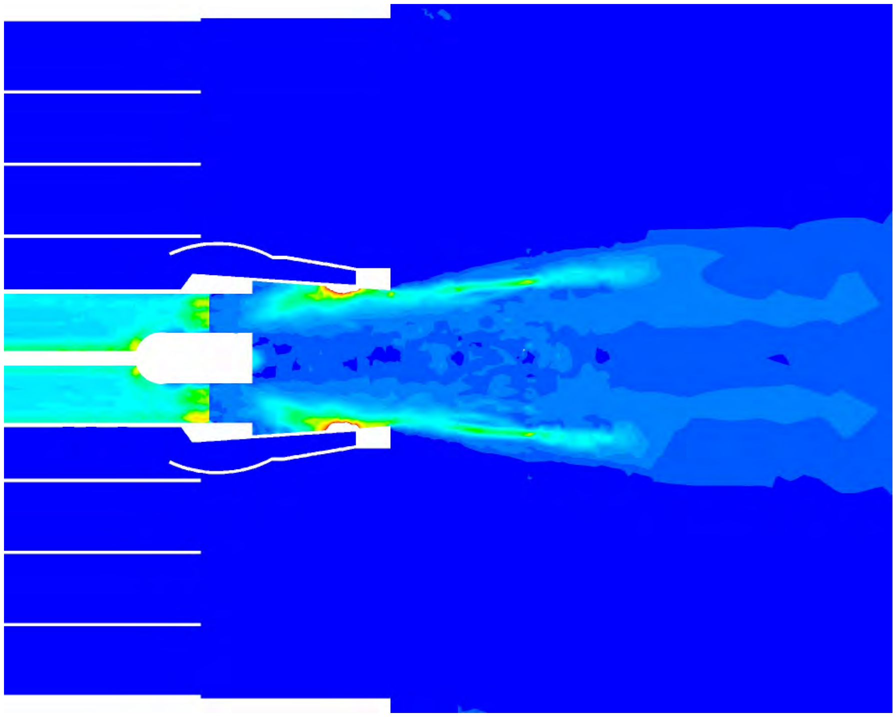


Figure 4.6-34 Predicted particle concentration for round tip, recessed swirler B

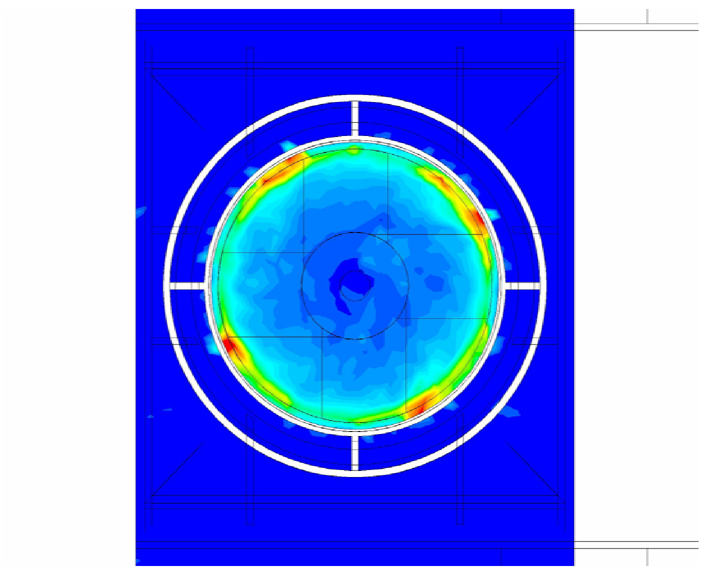


Figure 4.6-35 Particle concentration at the round tip, recessed swirler B outlet plane

The swirl that is imparted to the primary air and fuel is better shown in Figure 4.6-36, which presents gas pathlines flowing from the inlet of the coal nozzle. The strong swirl also throws some of the coal particles outward in a radial direction as seen in Figure 4.6-37. Concentrating the particles on the outside of the tip reduced the time / distance required for the majority of the coal particles to come in contact with the hot flue gas that is entrained in the outside of the jet. Also, once the coal jet ignited, having the coal concentrated in an annulus tended to create more intense combustion adjacent to the burner, even for coal in lean zones.

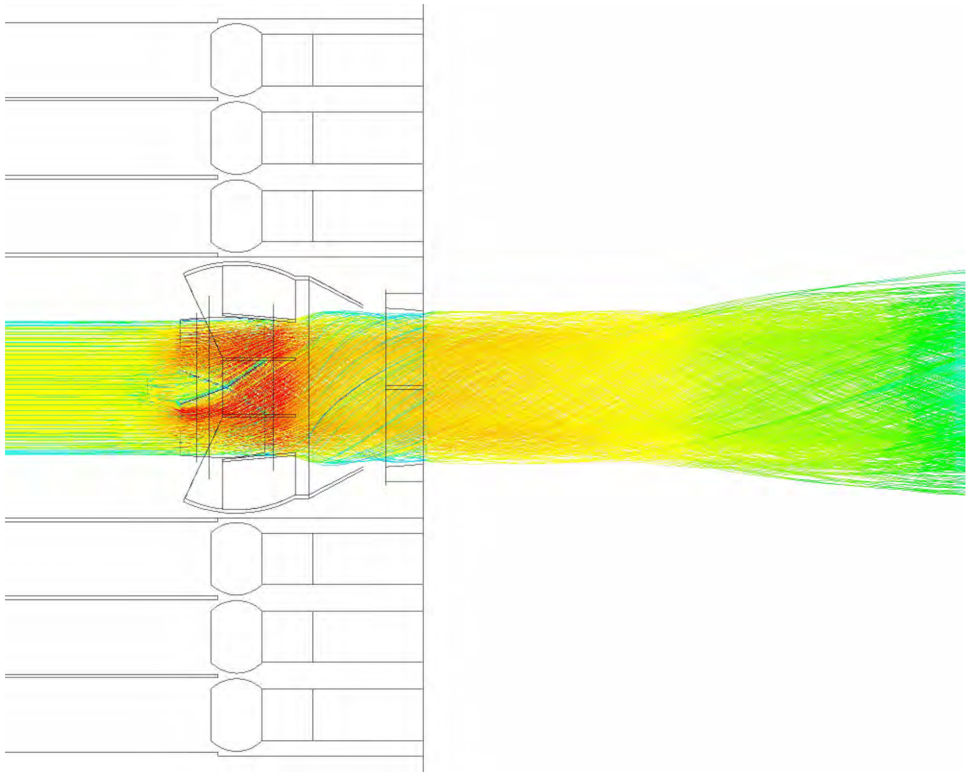


Figure 4.6-36 Gas pathlines from coal inlet for the round tip, recessed swirler B tip

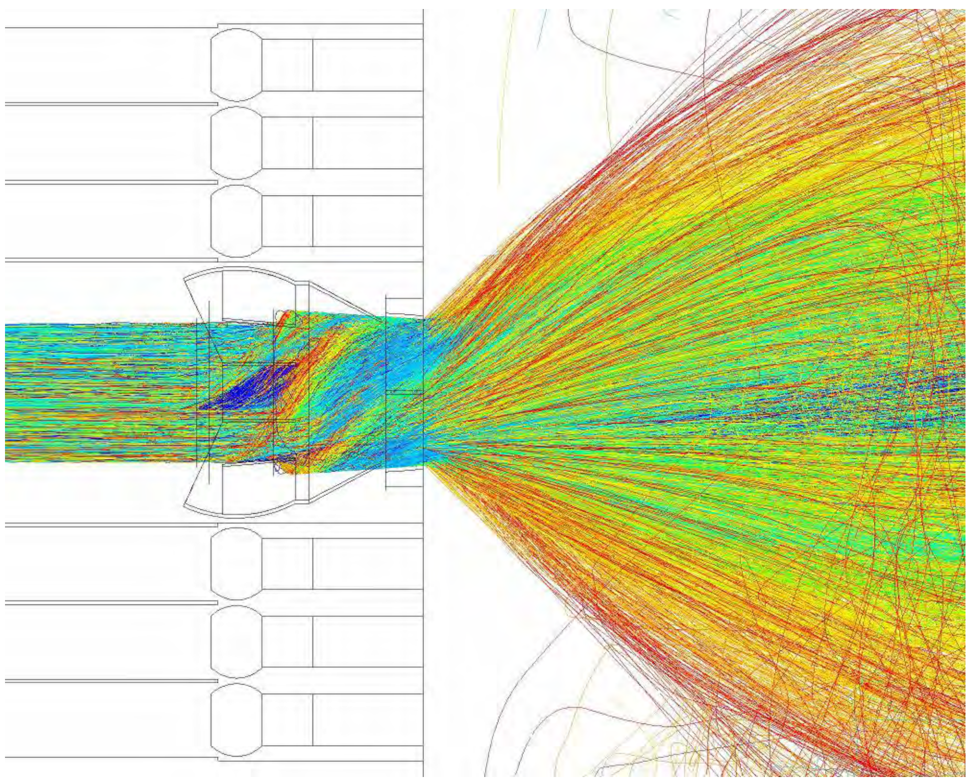


Figure 4.6-37 Particle tracks from coal inlet for the round tip, recessed swirler B

4.6.6 Vane Tip

Based on the results of the first series of tests as well as the CFD modeling, another tip design was proposed and developed for the second series of tests. This tip design is called the vane tip.

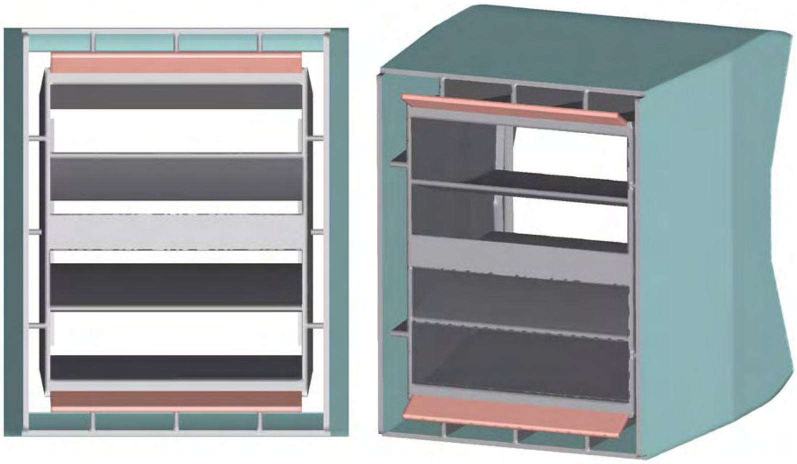


Figure 4.6-38 Vane coal nozzle tip as represented by CFD

The vane tip added a set of vanes to the shell of the diverging hybrid tip shell to concentrate the coal particles towards the top and bottom of the coal nozzle. A small bluff body was added to the center of the tip to give an anchor point for the recirculation zone that would form in the center of the tip as shown in Figure 4.6-39 The shear bars and air deflectors were retained to promote flame attachment on the top and bottom of the tip.

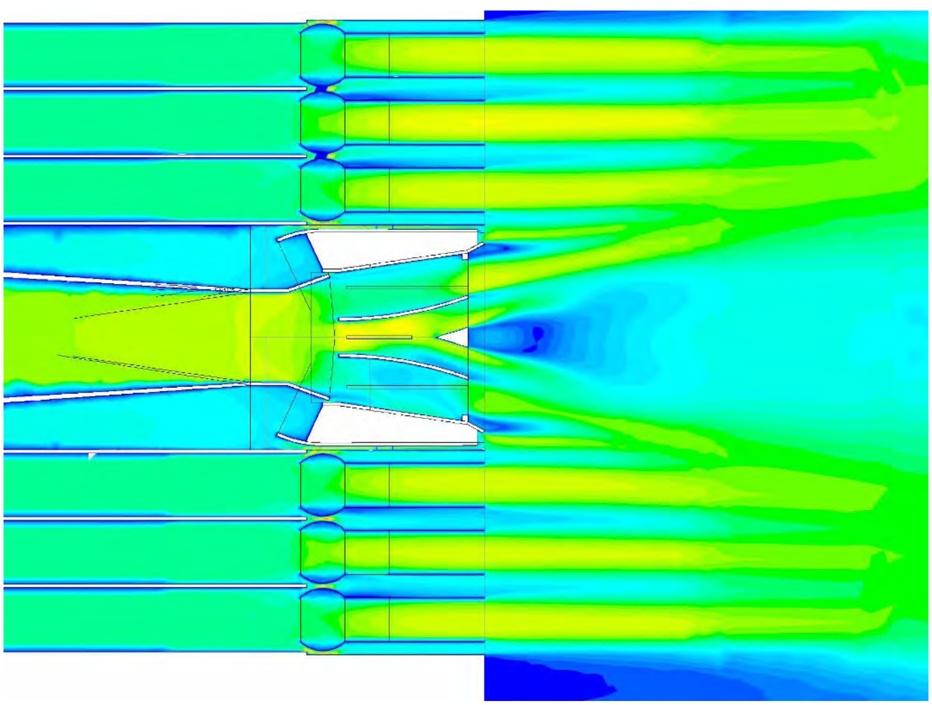


Figure 4.6-39 Predicted air velocity magnitude for vane tip

The predicted coal particle distribution is shown in Figure 4.6-40. As expected, the vanes direct most of the coal particles towards the top and bottom of the tip. This can also be seen in the particle concentration at the outlet plane (see Figure 4.6-41).

Seven variations of this basic design were also modeled with CFD to evaluate design sensitivity to geometry permutations.

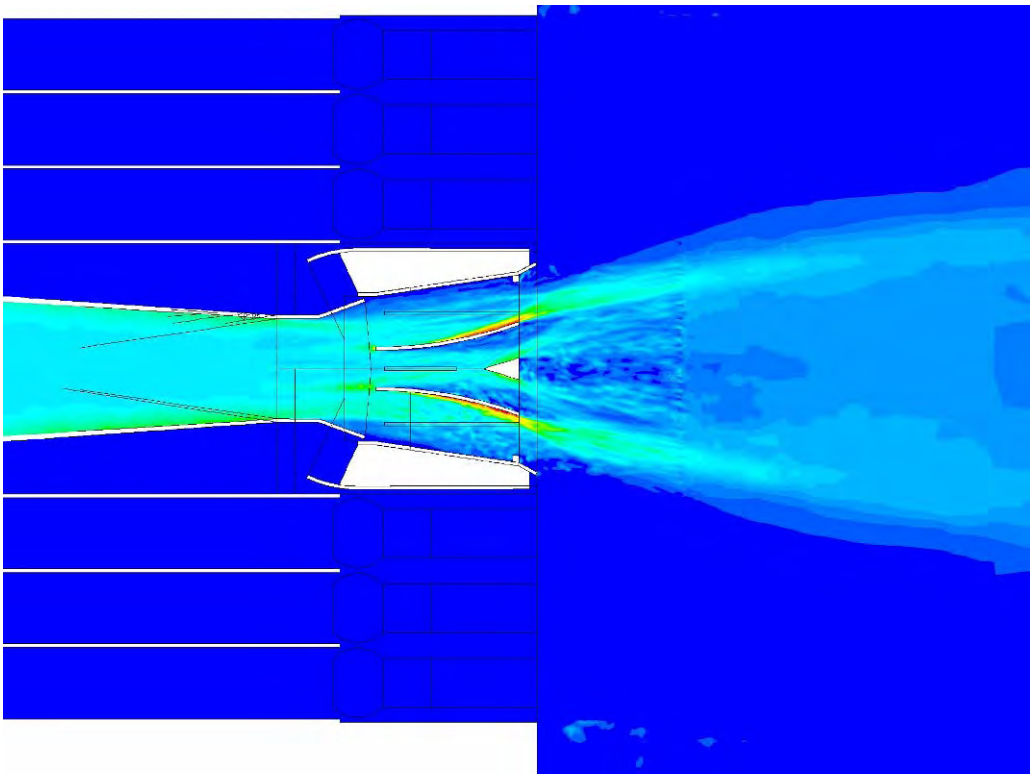


Figure 4.6-40 Predicted particle concentration for vane tip

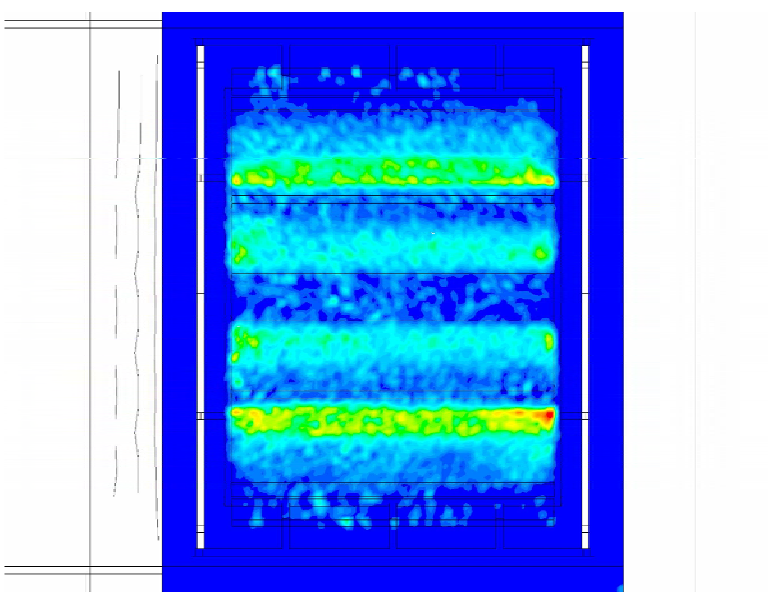


Figure 4.6-41 Predicted particle concentration at the vane tip outlet plane

The first four revisions to the vane tip examined variables such as the vane angle, bluff body size, adding shear bars, and removing the air deflectors. All of theses variations used the diverging hybrid tip shell as a basis. The last three revisions attempted to evaluate the impact of adding the vane tip ideas to an LNCFS™ P2 tip shell. In contrast to the diverging hybrid shell of the original vane tip, the LNCFS™ P2 tip shell actually converges.

Most of the revisions had modest impacts on the predicted near field gas and particle distributions. Increasing the vane angle tended to concentrate the particles a bit more towards the top and bottom, however, the added flow blockage of the bent vanes tended to push a little more of the flow through the center of the tip.

The basic vane tip design and some of the permutations discussed above were tested in week 2 of the ISBF testing. The NOx emissions of the best vane tip design were below all of the other tips tested. Permutations with the vane angle, bluff body size and shear bar configuration all had an impact on NOx emissions performance. It is interesting to note that for some test conditions, the coal actually ignited first in the center of the tip. There was an inner flame anchored to the center bluff body, while the flame was not strongly attached to the shear bars and air deflectors on the top and bottom of the tip.

For coal compartments that may not be able to accommodate the increased height of the diverging tip, the vane and bluff body components were added to an LNCFS™ P2 shell for vane tip revs 5-7. The LNCFS™ P2 shell has a converging inner shroud without shear bars and air deflectors as shown in Figure 4.6-42.

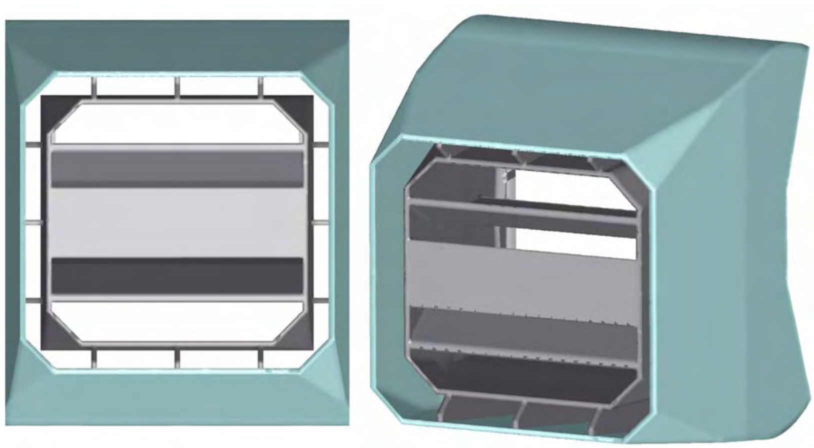


Figure 4.6-42 Vane tip rev. 6 as represented by CFD

Figure 4.6-43 and Figure 4.6-44 present the predicted gas velocity and particle concentration on the center plane for the vane tip rev. 6 case. The gas and particle distributions are similar to the vane tip rev. 2 results at higher velocities. Whether or not the vanes would work as well in the converging shell would require combustion testing to be sure; since test time was of course limited this variant was never combustion tested.

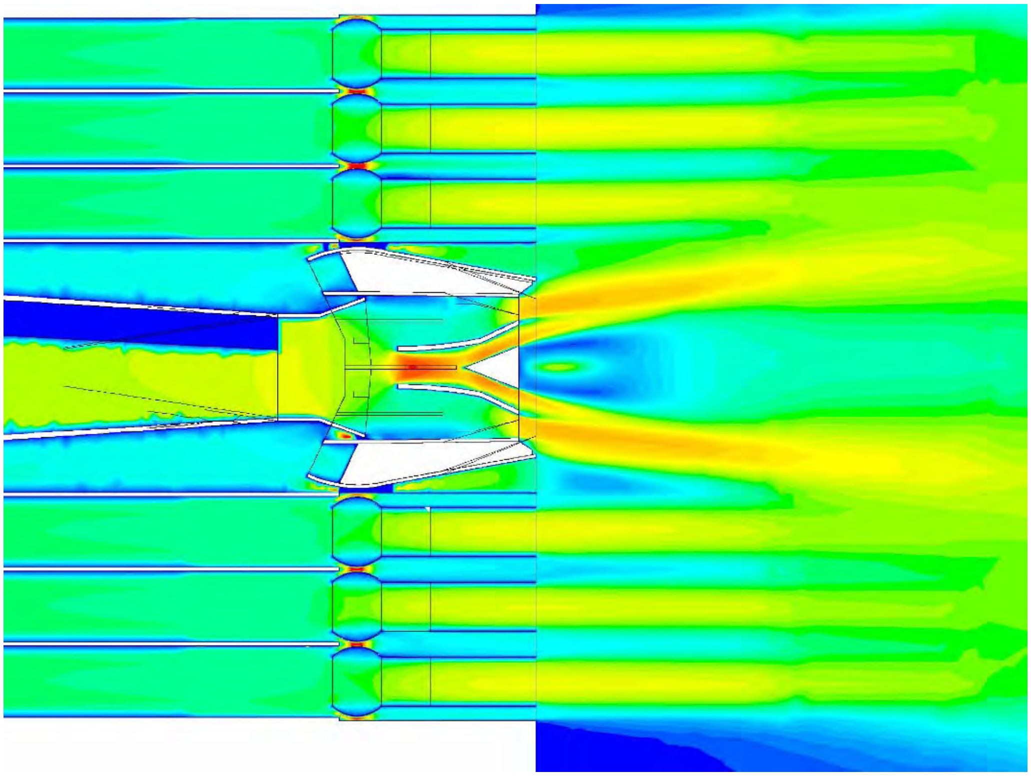


Figure 4.6-43 Predicted air velocity magnitude for vane tip rev. 6

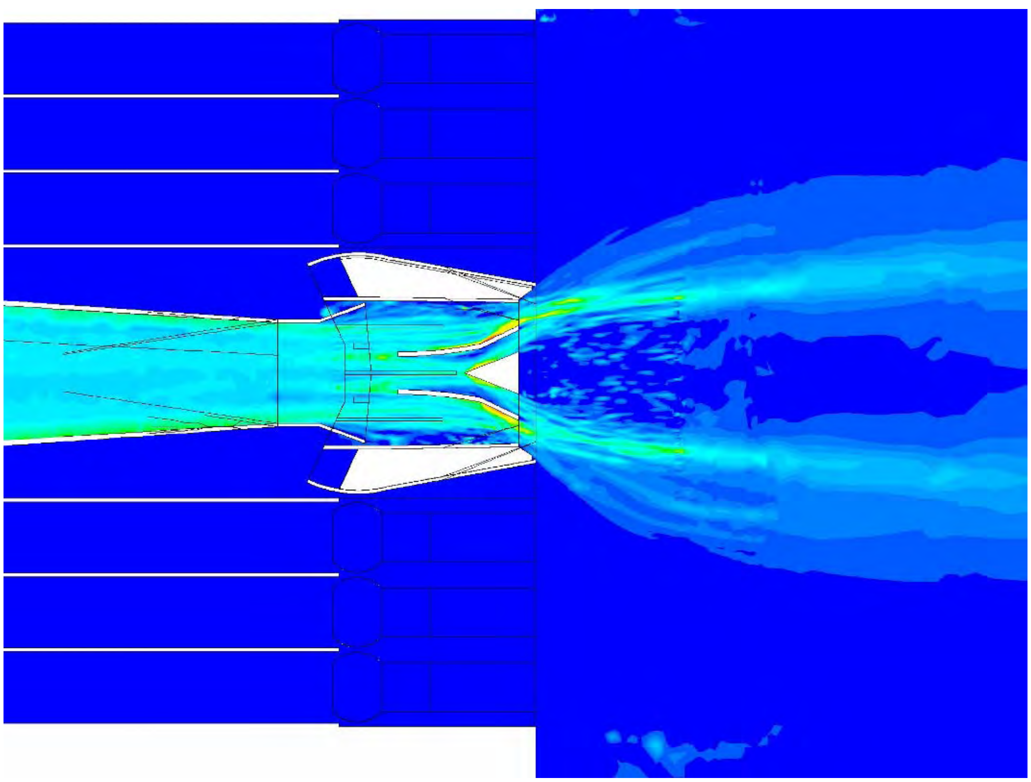


Figure 4.6-44 Predicted particle concentration for vane tip rev. 6

4.7 Modeling Summary

As part of the DOE sponsored coal nozzle tip development project, CFD modeling was used to gain insight into the mechanisms governing nozzle tip performance with respect to NOx emissions. The CFD simulations were run as steady state, turbulent, non-reacting flow with heat transfer and focused on predicting the near field mixing and particle dispersion rates. CFD results were used to refine the proposed tip concepts before they were built, as well as to help identify and evaluate possible improvements to the tips for subsequent test weeks.

CFD models were generated of the baseline shear bar / air deflector and LNCFS™ P2 tips. From project team discussions and initial modeling, four new coal nozzle tip ideas were selected for detailed modeling and evaluation in the first week of ISBF testing. These are referred to in this report as the center bluff, the recessed center bluff, the X-tip and the diverging hybrid tip. After the first test series, improvements to the week one tips and a newly designed vane tip, conceived after examining the results of the first ISBF test week and the CFD results, were modeled and tested.

The CFD modeling and ISBF combustion testing suggest that concentrating the coal particles towards the outside of the coal stream is advantageous for reducing NOx emissions.

5 Test Fuels

Emissions results from a range of coals are critical in determining the expected emissions in a commercial boiler. Coal properties vary and result in significant variations in NOx and unburned carbon emissions. To represent the US market, one coal was selected for the two initial test series, and two more were added for the final test series. These were a Midwestern bituminous (Illinois #6) used for all the test series, a lower sulfur Western bituminous (Sufco), and a very low sulfur Indonesian subbituminous (Adaro). All of these coals are in use now at major US power generation facilities.

5.1 Test Fuel Analyses

The analyses of the "as fired" coals from all the test series are shown in Table 5.1-1. There were some minor variations in the Illinois #6 coal over the series, but nothing unexpected. Note the range of heating values, ash, sulfur, etc of the 3 coals. The ISBF is not direct fired, so the moisture that is removed from the coal during the grinding process is lost. A grind of approximately 83% -200 mesh was used for all of the tests. The coal ash properties in Table 5.1-2 show the range of slag properties of the tested coals.

Table 5.1-1 Analyses of the Coals Fired in the ISBF

Fuel Properties - As Fired	Series 1 Illinois 6 Midwest Bit	Series 2 Illinois 6 Midwest Bit	Series 3 Illinois 6 Midwest Bit	Series 3 Sufco Western Bit	Series 3 Adaro Sub Bit
% Total Moisture	9.30	8.3	10.26	5.95	20.92
% Volatile Matter	32.60	32.50	30.75	37.05	37.37
% Fixed Carbon	50.00	50.40	49.42	45.16	39.50
% Ash	8.20	8.90	9.57	11.84	2.21
HHV Btu/lb	12084	12047	11498	11399	9543
% Moisture	9.00	8.30	10.26	5.95	20.92
% Hydrogen	4.60	4.50	4.19	4.39	3.82
% Carbon	67.00	67.20	63.90	63.93	56.59
% Sulfur	1.70	1.90	1.65	0.45	0.09
% Nitrogen	1.40	1.40	1.50	1.23	1.00
% Oxygen (difference)	8.10	7.80	8.93	12.21	15.37
% Ash	8.20	8.90	9.57	11.84	2.21
% Total	100.00	100.00	100.00	100.00	100.00

Table 5.1-2 Coal Ash Analyses of the Coals Fired in the ISBF

	Series 3 Illinois 6 Midwest Bit	Series 3 Sufco Western Bit	Series 3 Adaro Sub Bit
Coal Ash Properties			
Ash Fusibility (reducing atmosphere)			
I.D. (deg F)	2120	2105	1995
S.T. (deg F)	2140	2125	2010
H.T. (deg F)	2160	2140	2035
F.T. (deg F)	2180	2160	2050
F.T. - I.D.	60	55	55
Ash Elemental Analysis			
% SiO_2	41.44	44.38	27.46
% Al_2O_3	19.99	10.30	13.63
% Fe_2O_3	15.02	4.55	24.08
% CaO	7.70	22.30	14.36
% MgO	0.72	4.96	5.23
% Na_2O	1.90	1.79	0.46
% K_2O	1.74	1.01	0.74
% TiO_2	1.06	0.62	1.15
% P_2O_5	0.12	0.09	0.20
% SO_3	7.96	5.82	10.65
% Mn_3O_4	0.12	0.07	0.27
% BaO	0.04	0.06	0.21
% SrO	0.04	0.07	0.05
% Total	97.85	96.02	98.49

5.2 Fuel Selection

Although much of the project testing was performed with Illinois #6 coal, a screening of several Western U.S. bituminous and subbituminous coals was performed to help identify appropriate coals for the large pilot-scale testing. As much of the near term market for low NOx retrofits is in the Western U.S., it is appropriate to select a suitable coal from this region for testing in the ISBF. The Western U.S. coals evaluated include subbituminous and bituminous coals from New Mexico, Utah, Wyoming, Montana, and Colorado (Coals A-E, respectively). The Adaro Indonesian subbituminous coal (Coal F) was evaluated at a later date.

ASTM analyses of the Western U.S. coals are provided in Table 5.2-1. The moisture in the coals ranges from 9.4 to 23.7% and the ash content varies from 3.5 to 15.3% by weight. The as received heating values range from 8,816 to 11,136 Btu/lb. The fixed carbon to volatile matter ratios vary from 1.16 to 1.57, while the oxygen / nitrogen ratios vary from 6.3 to 15.5. The differences in the coal analyses suggest variations in the potential NOx emission levels in units firing the various fuels.

In addition to the standard ASTM analyses, drop tube furnace testing was also used to help characterize the fuels. Alstom Power's Drop Tube Furnace System 1 (DTFS 1) is comprised of a one inch inner diameter horizontal tube gas preheater and a two inch inner diameter vertical tube test furnace for providing controlled temperature conditions to study devolatilization, gasification and/or combustion phenomena. This entrained flow reactor, which is electrically heated with silicon carbide elements, is capable of heating reacting particles to temperatures of up to 2650°F with particle residence times of up to about one second. These conditions simulate the rapid combustion that occurs under suspension firing conditions in commercial pulverized coal fired boilers.

Table 5.2-1 ASTM Analyses of Western Coals

	Coal A	Coal B	Coal C	Coal D	Coal E	Coal F
Fuel Properties - As Received						
% Total Moisture	19.5	23.7	15.7	19.4	9.4	9.1
% Volatile Matter	27.9	29.1	31.9	33.0	32.9	34.2
% Fixed Carbon	43.8	39.5	37.1	41.9	47.0	41.9
% Ash	8.8	7.7	15.3	5.7	10.7	14.8
HHV Btu/lb	9,546	8,816	9,526	10,098	11,136	10,717
% Moisture	19.5	23.7	15.7	19.4	9.4	9.1
% Hydrogen	3.6	3.5	3.8	4.1	4.5	4.3
% Carbon	55.4	51.4	53.4	56.9	62.4	60.7
% Sulfur	0.5	0.5	0.8	1.0	0.6	0.4
% Nitrogen	1.2	0.8	1.0	1.1	1.7	1.1
% Oxygen (diff)	11.0	12.4	10.0	11.8	10.7	9.5
% Ash	8.8	7.7	15.3	5.7	10.7	14.8
FC/VM Ratio	1.57	1.36	1.16	1.27	1.43	1.22
O/N	9.2	15.5	10.0	10.7	6.3	8.5

The DTFS 1 testing procedure entails the following:

- the fuel is fed at a precisely known rate through a water cooled injector into the test furnace reaction zone,
- the fuel and its carrier gas are allowed to rapidly mix with a preheated down flowing secondary gas stream,
- devolatilization, gasification or combustion is allowed to occur for a specific time (dictated by the transit distance),
- reactions are rapidly quenched by aspirating the gas/particulate stream into a water cooled sampling probe,
- the solids are separated from gaseous products in a filter medium, and,
- an aliquot of the effluent gas stream is sent to a dedicated Gas Analysis System for on line determination of NOx, SO_2, O_2, CO_2, CO, and THC (total hydrocarbons) concentrations.

A data acquisition system records, on demand, all relevant test data for subsequent retrieval and processing.

An ash tracer technique is used in conjunction with the proximate analyses of feed samples and chars subsequently generated in the DTFS-1 to calculate the devolatilization, gasification or combustion efficiency as a function of operational parameters (particle temperature, particle residence time, fuel fineness, reaction medium, etc.).

Each of the Western coals was tested in the DTFS-1 at a particle size of 200x400-mesh. Prepared samples of the coals were fed through the DTFS-1 in 100% nitrogen for measurement of high temperature devolatilization (pyrolysis testing). The chars were collected for further reactivity characterization by TGA and the BET surface area was measured. Additional pyrolysis testing was performed in an argon environment to examine the fuel nitrogen release.

To further characterize the coal reactivity, each of the coals was tested in a thermogravimetric analyzer (TGA). Non-isothermal TGA reactivity was performed on a 200 x 400 mesh coal sample and an isothermal reactivity test on chars generated in the DTFS-1 (200 x 400 mesh samples). These results are shown in Figure 5.2-1 through Figure 5.2-4, which illustrate significant variations in reactivity between the various western coals.

When it came time to purchase coals for testing, more than a year after the coal screening, practical considerations controlled the final coal selection. None of the screened Western coals was both available for small truck sales as required for our test program, and of significant commercial interest to Alstom. Because of this, a coal not tested in the original screening, Sufco, was chosen for the pilot scale combustion testing. Similar considerations influenced the selection of the subbituminous coal. Adaro Indonesian subbituminous coal was available from a nearby utility, giving advantages including a) lower project costs, b) greater project security since more could be quickly obtained in the event of equipment failure, and c) lower environmental impact since leftover coal could be easily returned.

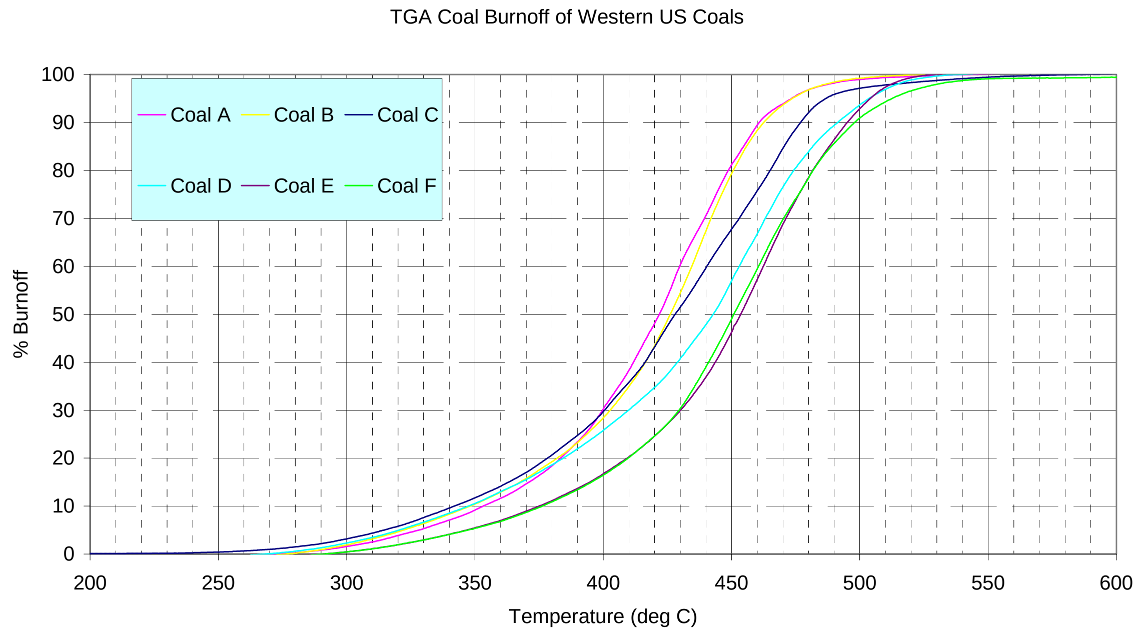


Figure 5.2-1 TGA Burnoff Rate of 6 Western U.S. Coals

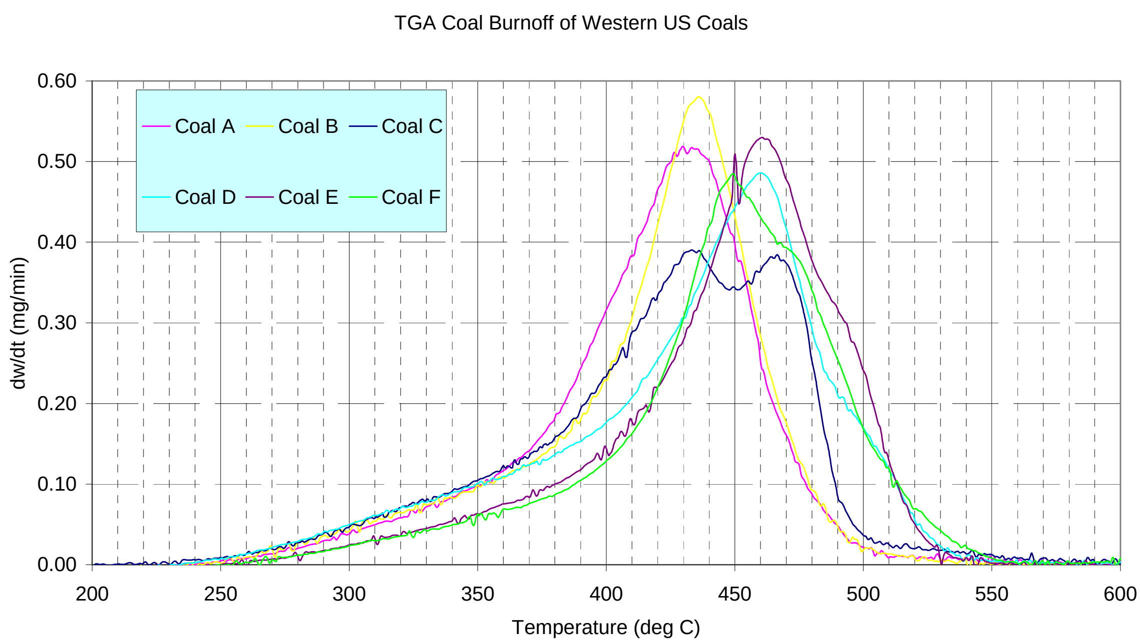


Figure 5.2-2 TGA Burnoff Rate of 6 Western U.S. Coals

Figure 5.2-3 TGA Burnoff Rate of 6 Western U.S. Chars

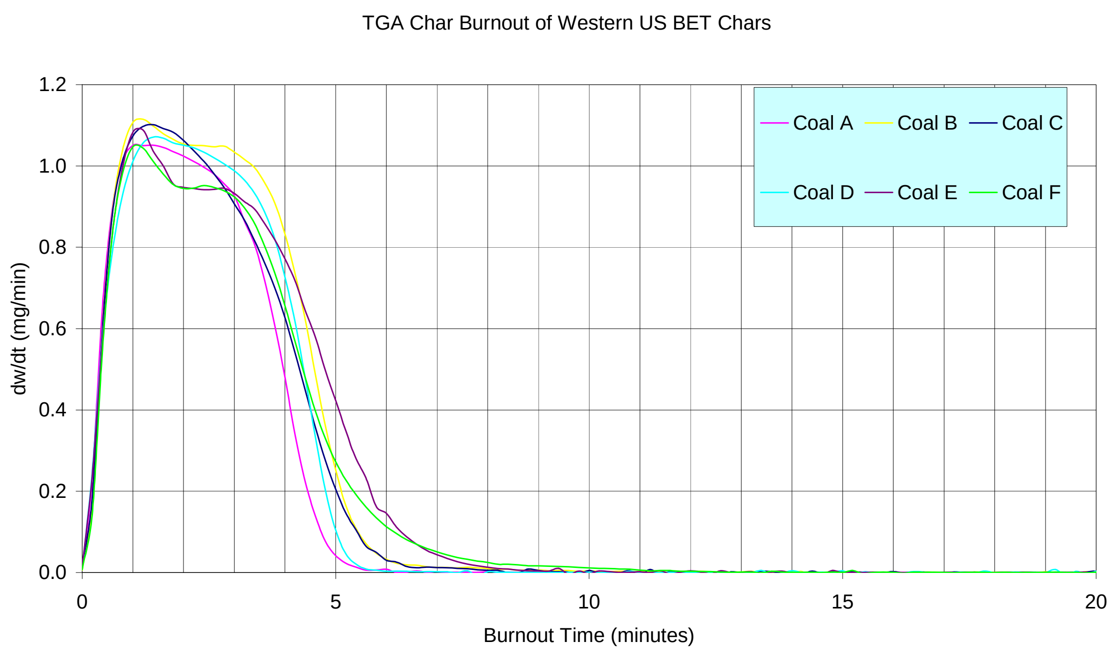


Figure 5.2-4 TGA Burnoff Rate of 6 Western U.S. Chars

So the three coals selected for large pilot scale testing were Illinois #6 bituminous, Sufco Western bituminous, and Adaro Indonesian subbituminous. These coals represent a broad range of the coals currently used in the US utility boiler market. Figure 5.2-5 and Figure 5.2-6 show the TGA burnoff rates for the three selected coals, and a typical Eastern bituminous coal is shown as a reference.

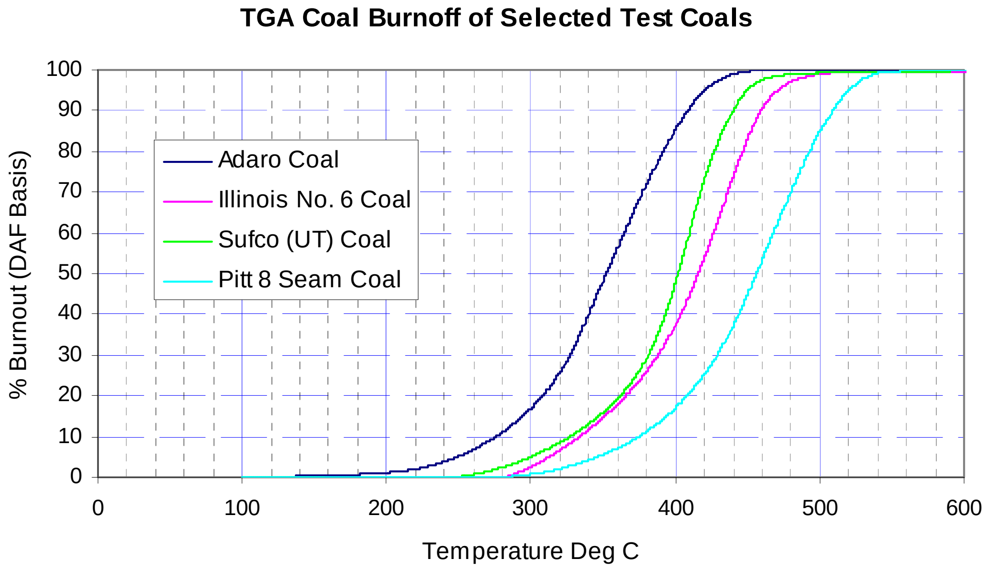


Figure 5.2-5 TGA Burnoff Rate of 3 Coals Selected and Reference Eastern Bituminous Coal

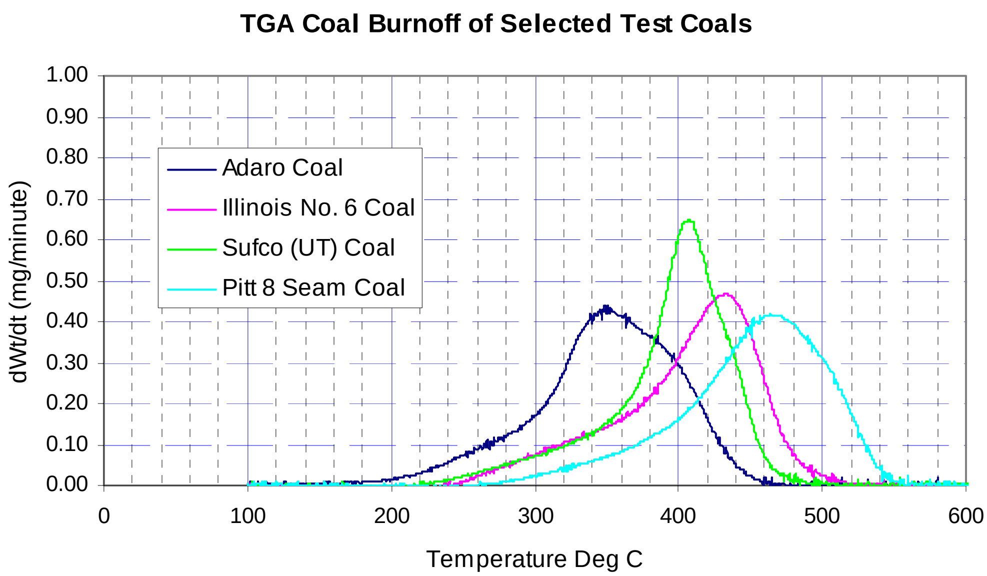


Figure 5.2-6 TGA Burnoff Rate of 3 Coals Selected and Reference Eastern Bituminous Coal

Each of these coals presents specific operational challenges in a low NOx firing configuration, both in their combustion characteristics and in the balance of plant impacts inherent to each coal type. These criteria are discussed briefly for each coal selected for testing at large pilot scale.

In general, bench-scale characterization of the three test coals showed that both NOx and combustion performance are a strong function of coal properties. The more reactive Adaro and Sufco coals evolved more of their fuel bound nitrogen in the substoichiometric main burner zone than the less reactive Illinois #6 coal, resulting in lower NOx emissions. From a combustion point of view, the Adaro and Sufco coals also showed lower carbon in ash and CO values than the less reactive coals at any given main burner zone stoichiometry. According to bench-scale results, the Adaro and Sufco coals were found to be relatively amenable to both low NOx, and acceptably low combustibles in the flue gas, in an air staged low NOx system. The Illinois #6 coal, by contrast, was predicted to be the most challenging of the three coals.

5.2.1 Illinois #6

Midwest bituminous coals often experience high fly ash carbon levels when fired in a low NOx configuration. These coals have a high propensity to slag the furnace as demonstrated by low ash fusion temperatures under reducing conditions, and can also exhibit significantly increased waterwall corrosion rates when fired in a low NOx configuration. The Illinois #6 coal was expected to give the highest NOx emissions and unburned carbon over the stoichiometry range.

5.2.2 Sufco

The Sufco coal chosen was expected to offer significantly lower NOx and unburned carbon than the Illinois #6 coal. Western bituminous coals are more reactive than midwest bituminous, so their fly ash carbon formation potential is lower. Also, Western coal ash is much higher in alkali constituents such as calcium and magnesium than Midwest coal ash. The Western coals will tend to foul convective heat transfer surfaces more than Midwest coals. This ash, when deposited on furnace walls, is typically reflective in nature, reducing furnace heat adsorption and resulting in high furnace exit gas temperatures.

5.2.3 Adaro

Subbituminous coals are much more reactive than either Midwest or Western bituminous coals, and they typically exhibit fly ash carbon levels under 0.5% even when fired in a deeply staged, very low NOx configuration. Also, subbituminous coal ash is higher in alkali constituents such as calcium and magnesium than Midwest coal ash, yet is also often higher in iron content as well. The subbituminous coals tend to foul convective heat transfer surfaces more than bituminous coals. As with Western bituminous coal, these ash deposits on furnace walls are typically reflective in nature, reducing furnace heat adsorption and resulting in high furnace exit gas temperatures. Although Adaro coal does vary from typical US subbituminous coals, it was chosen because its properties are not that different, and was available locally from a plant that was willing to take back any unused coal. This reduced project transport and disposal costs, but more importantly reduced coal landfilling required at the test completion.

5.3 Fuel Preparation

Approximately 300 tons of Illinois #6 coal, 80 tons of Sufco coal, and 120 tons of Adaro coal were purchased for the ISBF testing. The crushed coal, with a top size of 2 inches, was stored in covered bunkers prior to pulverization in Alstom's Pulverizer Development Facility (PDF).

A process flow diagram of the PDF is seen in Figure 5.3-1. The heart of the facility is an HP 323 pulverizer; a 3-journal, 32 inch-bowl near-commercial mill. Its design and location allow for easy interchange of various mill components (e.g. DYNAMIC™ classifiers or grinding rolls). Mill performance results from the PDF are readily scaleable to larger industrial and utility size pulverizers.

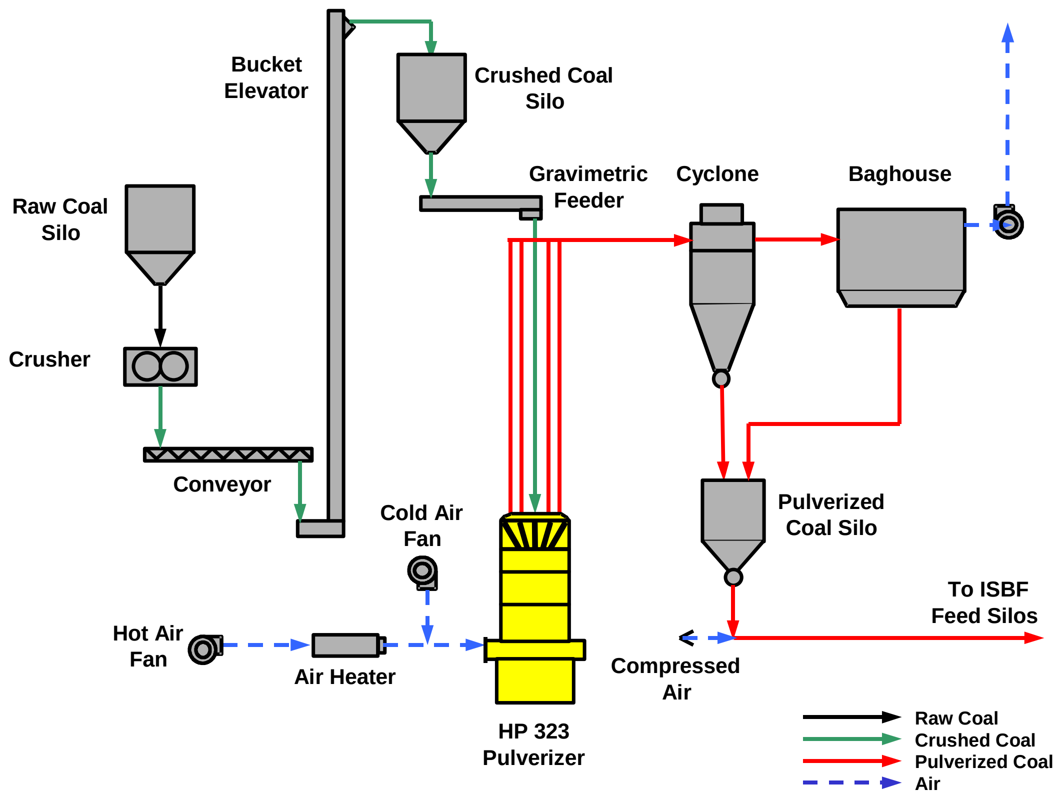


Figure 5.3-1 Pulverizer Development Facility (PDF) Process Flow Diagram

All material flows to the HP323 mill are automatically controlled. A Thayer gravimetric coal feeder (maximum capacity of 8 ton/hr) is used to feed crushed coal (nominal ¾ in x 0) to the mill. Crushed coal is supplied to the coal feeder from a 10 ton crushed coal silo. Coal is supplied to the feed silo using a combination of typical coal handling equipment (crusher, screw conveyors, bucket elevator, etc.) having a maximum transport feed rate of 6 tons per hour.

Hot air (250 to 500 °F as appropriate) is supplied to the mill using a 200 HP Lamson fan with cold (ambient) tempering air being supplied by a 100 hp Lamson fan. The air is heated using a 3.5 MMbtu/hr indirect fired air heater. Both airflow rate and temperature are automatically controlled to maintain the mill at constant operating conditions.

Pulverized coal product leaves the classifier section of the mill through four fuel pipes and is pneumatically conveyed to a collection cyclone where the solids are separated from the air. The cyclone discharges the product into a 20 ton storage silo from where it is pneumatically conveyed to the pulverized coal storage silos at the ISBF complex. Air from the cyclone is discharged to a baghouse where any remaining coal dust is removed and sent to the product silo prior to discharging the air to the atmosphere.

All mill operating parameters are controlled using a programmable computer based control system. Data identifying mill operating conditions, such as mill inlet/outlet temperatures, mill differential pressures, mill power consumption, etc., are continually monitored and recorded using a computer based data acquisition system. In total, there are over 48 different measurements, which are recorded in a format that is readily imported into an Excel spreadsheet for later data analysis.

Establishing proper coal flow rates and fineness requirements is done by performing a classifier "sweep" at rates likely to be employed for product generation. A classifier sweep consists of incrementally closing the classifier inlet vanes (in the case of the static classifiers) or incrementally increasing the speed of the classifier (in the case of the DYNAMIC™ classifier). At each classifier setting, mill performance data is recorded and a mill product sample is aspirated from the fuel lines using a cyclone collector for particle size analysis. The DYNAMIC™ classifier was used for fuel preparation for this project as it provides the most consistent control of product properties.

Pulverized coal samples were obtained periodically during the first test series to determine the variation in the size and composition of the coal that was being fired. As shown in Table 5.3-1, there was a variation of approximately ± 1% on the amount of coal passing through a 200 mesh sieve during the testing.

Table 5.3-1 Variation in Illinois #6 Pulverized Coal Size Distributions

	11/15/05	11/16/05	11/17/05	11/18/05
Sieve Sizing				
+ 50 mesh	0.07	0.11	0.06	0.04
+ 100 mesh	1.49	1.24	1.46	1.66
+ 200 mesh	14.93	13.93	15.56	15.91
Pan	83.46	84.65	82.86	82.40
% Recovery	99.95	99.93	99.94	100.01

A consistent sizing of all the pulverized coals was desired to best compare the differences in coal properties. The varied grinding properties of each of the three coals tested required that a pulverization test sweep be run for each, to determine the relationship between mill parameters (such as classifier speed and feed rate) and the resultant coal fineness. Actual average coal grinds achieved during series 3 are shown below in Table 5.3-2.

Table 5.3-2 Variation in Pulverized Coal Size Distributions in Coals Fired in the ISBF

	Illinois #6	Sufco	Adaro
Sieve Opening	Average % Retained		
+ 50 mesh	0.09	0.10	0.12
+ 70 mesh	0.27	0.25	0.35
+ 100 mesh	1.31	1.30	1.43
+ 140 mesh	3.68	3.80	4.24
+ 200 mesh	8.81	9.16	10.79
Pan (-200 mesh)	85.84	85.39	83.08

At the completion of the project, only a minor amount of coal that had become contaminated had to be landfilled. All of the Illinois #6 and Sufco fuel was burned, and one partial truckload of Adaro fuel was returned to the nearby utility that had originally supplied the Adaro coal.

6 Industrial Scale Burner Facility

6.1 ISBF Description

Alstom Power - Power Plant Laboratories' (PPL) Industrial Scale Burner Facility (ISBF) is a balanced draft, front wall fired combustion test facility designed to replicate the time-temperature-stoichiometry (mixing) history of a typical industrial steam generator. All major aspects of an industrial boiler are duplicated in the ISBF including the radiative furnace cavity, and simulated superheat / reheat and convective (economizer) heat transfer surfaces. The ISBF has a nominal firing rate of 15 MWt (50 MMBtu/hr) in a pulverized coal design furnace configuration, and a maximum permitted firing rate of 26 MWt (90 MMBtu/hr) for gas and oil designed furnace arrangements. The ISBF is pictured in Figure 6.1-1; a side view schematic is shown in Figure 6.1-2.

Figure 6.1-1 ISBF Firing Front

The furnace walls and heat transfer surfaces of the ISBF are cooled by a surrounding, atmospheric pressure, water jacket. Selective refractory lining of the inside furnace walls, and control over the fuel firing rate are utilized to maintain an appropriate furnace gas time-temperature history as compared to that of the commercial furnace or process being evaluated.

The ISBF is part of PPL's Firing Systems Development Complex (FSDC). The FSDC includes equipment to support the firing of all types of solid, liquid and gaseous fuels ranging from crushed and pulverized coal to No. 2 distillate and heavy residual oils, coal-oil, coal-water, or petroleum coke-oil slurries, and natural and bottled gases (etc). FD, ID, and PA fans are provided to control the feed of air to the unit. Solid, liquid, and gaseous fuel flow are monitored. A wet venturi-rod, sodium hydroxide scrubber is provided in the FSDC for SO_2 and particulate emissions control, allowing the ISBF to be operated in compliance with all emissions regulations.

The ISBF is fully instrumented to monitor combustion phenomena. Critical furnace operation and control information are measured, metered, and recorded by a state-of-the-art data acquisition and control system. Operational information such as combustion air and fuel input mass flow rates, air preheat temperatures, furnace exit gas temperatures, and fan damper positions, etc., are reduced, stored and displayed on-line for facility operation and post test data reduction use. Over 20 access ports are located throughout the radiative furnace and convective sections of the ISBF for gas temperature and velocity measurement, and in-furnace particulate and gaseous species sampling utilizing water-cooled suction probes.

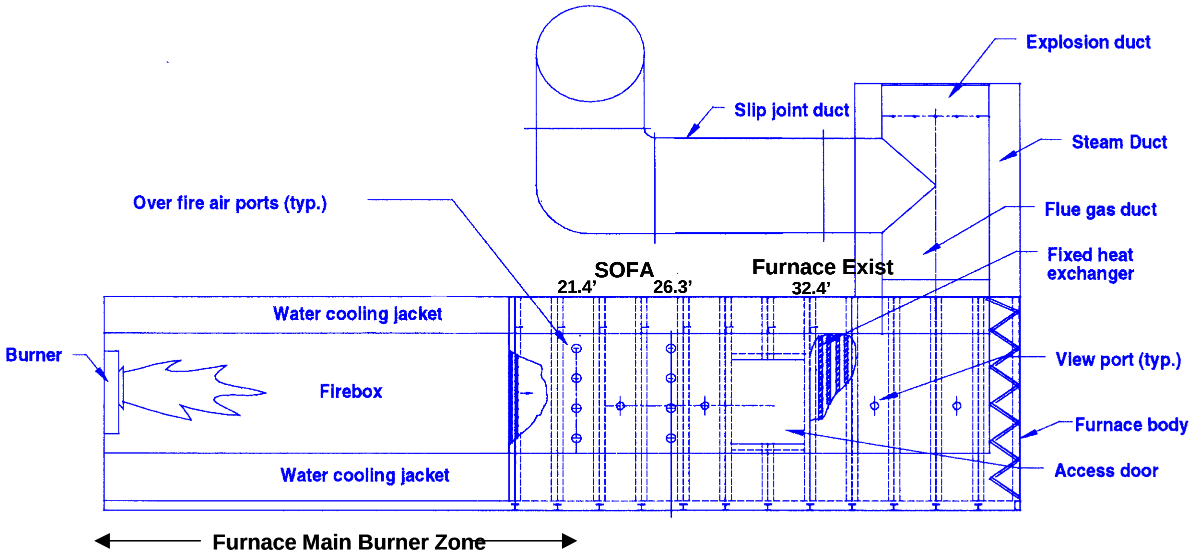


Figure 6.1-2 ISBF Side View

A continuous sampling Gas Analysis System (GAS) is used to precisely measure the gaseous species concentrations in the furnace effluent gas stream prior to the scrubber. The GAS utilizes state-of-the-art instrumental gas species analyzers for O_2, CO, CO_2, SO_2, NO / NOx and THC following the requirements of EPA 40 CFR 60 (Appendix A - Methods 3A, 10, 3A, 6C, 7E, and 25A, respectively). Opacity and smoke number measurement, and particulate sampling for post-test determination of unburned carbon in the fly-ash levels can also be performed.

6.2 General Test Facility Preparation

The primary facility preparation occurred before the first test, but each test campaign did require significant efforts to ready both the facility itself and the test firing system hardware. During preparations for the first series, the ISBF was configured with a single, tangentially fired coal burner, including associated auxiliary air compartments, and two levels of overfire air, consistent with the design of Alstom's state-of-the-art TFS 2000™ low NOx firing system. The design of the coal burner and auxiliary air compartments conformed to general

Figure 6.2-1 ISBF Firing Front During Series 1 Test Preparations

size and velocity standards for a single corner, single elevation section of an Alstom commercial coal fired boiler. Several coal nozzle variants were designed to fit the compartments while allowing for a wide range of nozzle tip designs. Figure 6.2-1 shows the firing front of the ISBF during construction, the round pipe in the middle is the coal nozzle and the individual compartment dampers are to the right. Figure 6.2-2 shows a close up of the dampers after installation.

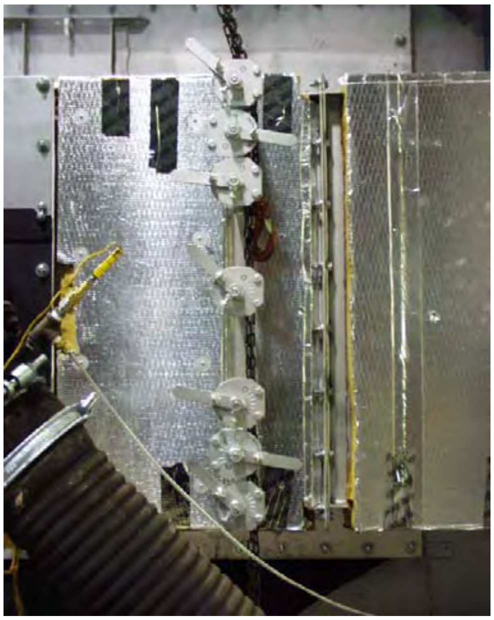


Figure 6.2-2 Firing Front Dampers and Coal Hose

Fuel firing rate, fuel properties, and insulation levels determine the combustion temperatures in the ISBF. For this program temperatures nominally in the range of 2300 to 2500°F at the furnace outlet plane (shortly after the overfire air location) were desired to mimic typical coal fired utility boiler conditions. Calculation routines to determine resultant temperatures from furnace conditions have been developed and were used to set the initial furnace conditions; however, the exact local properties of the refractory and ash can cause actual results to differ substantially from calculated. This is especially true when part of the refractory is used and its thickness and properties vary. For this program the calculations indicated that fresh insulation on the walls while leaving the floor and ceiling alone would result in the correct temperatures.

The walls were cleaned and restudded and fresh insulation installed. Figure 6.2-3 shows the fresh insulation on the facility walls, with the coal nozzle tip, air compartments and gas ignitor inlet in the center. During the initial facility shakedown, that level of insulation proved to be excessive, with temperatures in the range of 2500-2700°F. Removing a strip of the new wall insulation proved to be the correct solution, bringing the temperatures back to the desired range. Figure 6.2-4 shows the inside of the front of the facility with the strip of insulation removed.

Figure 6.2-3 Inside the ISBF Before Test Series 1

Figure 6.2-4 Inside the ISBF After Series 1 Testing

Figure 6.2-5 shows the back of the facility at the same time, these are typical of conditions after each of the three series. The pointy slag covered objects where the refractory was removed are the anchors that originally held the refractory in place.

The Separated OverFire Air system (SOFA) was modified to provide both increased airflow and increased control of the overfire airflow. The preexisting overfire air system had a total of eight air ports, four (two on each side of the furnace) at 21.4 ft from the burner, and four at 26.3 ft as shown in

Figure 6.2-5 Back End (Convective Section) of the ISBF After Series 1 Testing

Figure 6.1-2. In order to attain higher levels of overfire air flow, and be able to direct air flow between the two overfire air locations at moderate overfire airflows, eight more total ports were added in line with the existing ports. Flow measurement equipment was upgraded to match. Each of the final sixteen ports was equipped with a manual damper, permitting any distribution of overfire airflows desired. One side of the final overfire air system is shown in Figure 6.2-6.

Two types of temperature measurement devices were prepared for the combustion testing. A water cooled suction pyrometer with a single type B thermocouple was set up for taking multi point horizontal traverses perpendicular to the gas flow at the furnace outlet just beyond the overfire air ports. Glass viewports with air-cooling and protective blast gates were set up at 6 locations parallel to the furnace centerline axis. A Raytek infrared thermometer was used to take flame temperature measurements at each port to provide a heat release profile.

Other test preparations performed before series 1 included calibration of the facility instrumentation, and checkout and upgrade as required of all the mechanical and electrical systems.

For series 2 and 3 the test preparations were more modest. The non-water cooled firing front of the ISBF required repairs to the blanket refractory after each series, as well as the windbox that becomes

Figure 6.2-6 One Side of the Overfire Air System

exposed to the furnace radiation as the blanket refractory wears away. Additional calibrations and checkouts were performed as appropriate. Liquid and solid scrubber waste, ash, coal waste, etc. were cleaned out of the facility components after each test campaign and disposed of in an environmentally sound manner. Before series 3 several upgrades were performed, not utilizing DOE support, which included redoing the ceiling refractory, replacing a manually inserted and rotated sootblower (for ash buildup removal) with an automatic one, installing a new state of the art NOx analyzer, and adding additional water cooled quenching tubes to the back of the ISBF. The latter change brought furnace exit temperatures down by approximately 300°F, near fully quenching combustion, but as a result substantially increasing CO under most conditions. The new configuration clearly is a more realistic combustion scenario given the CO issues seen with some fuels even in tangentially fired field boilers.

The nozzle tips tested through the three test campaigns in most instances paralleled those tested during the CFD modeling phase, although some additional modifications were made on the fly. The combustion-tested tips are listed in Table 6.2-1, refer back to Section 4 for tip descriptions.

Table 6.2-1 Combustion Tested Coal Nozzle Tips

Test Campaign	Nozzle Tips Tested
1. Nov-Dec 2005	Shear Bar/Air Deflector, LNCFS™ P2, X, Recessed Center Bluff Body, Center Bluff Body, Diverging Hybrid.
2. March 2006	Center Bluff Body, Center Bluff/Diverging Hybrid/Large Shear Bars, Recessed Center Bluff with Shear Bars, Vane, Round, Vane with Reduced Shear Bars, X with Teardrop Bluff Body, Vane with Steep Vane Angle, Round with Adj. Swirler, Vane with Large Bluff Body, Recessed Extended Center Bluff , Vane with Small Bluff & Shear Bars Moved.
3. January 2007	LNCFS™ P2, Vane Series 2 Best (W2B), Vane W2B with Wide Vane Spacing, Vane W2B with Narrow Vane Spacing, Vane W2B No Bluff Body, Vane W2B with Vane Shear Bars (not all done on all three coals).

During the first campaign several of the nozzle tips were equipped with surface thermocouples, in an attempt to better understand the local thermal environment created by the different nozzle tips. However for the most part the data gave no additional insight, with the thermocouples and their lead wires acting as a magnet for coal ash deposits, which interfered with both the temperature readings and the tip aerodynamics. Therefore this approach was abandoned for the remainder of the test program.

7 Combustion Testing

The ISBF test program was performed in a series of three test campaigns over a 15 month period. Campaign one was 9 days of testing during November and December of 2005. During this period 72 tests were performed on baseline and new nozzle tip designs from the modeling program, using the Midwest bituminous coal. The second campaign was 5 days of testing during March 2006 which produced 81 test points. This series demonstrated that the new vane tip successfully combined low NOx and operability, while the flow improvements to the other tips were only modestly successful. Campaign three took place over 8 days of testing during January 2007 which produced 83 test points. This series proved the robust performance of the new vane tip over a range of design variants (needed for scale-up to the range of commercial equipment sizes), and coal types. Comparison data with the conventional P2 tip was also taken over the range of coals and stoichiometries.

As the goal of this test program is development of a lower NOx firing system, and that system was primarily documented and proven in the final campaign, the analysis of results presented will emphasize the final test campaign.

The combustion test procedure in the ISBF was as follows: after a cold facility start-up, several hours were allowed for the ISBF to reach desired load and the refractory lining to reach operating temperatures/thermal equilibrium. Then, test conditions (firing system configuration, furnace stoichiometry history, firing rate, excess air level, etc.) were set to the desired level based on the test matrix specification. Testing then began 24 hours per day to avoid significant changes in the thermal environment in the furnace, with stable test periods alternating with test condition changes leading to the next matrix point. A gas ignitor was used to help maintain furnace temperature when changing out a coal nozzle tip, a task which at the start of the program took about an hour, but was brought down to as little as 20 minutes in the final test series.

The ISBF DCS continually monitors system variables, and the desired data (over 200 system variables) were logged at 1-minute intervals with a Labview data acquisition system. The data for a particular matrix test point was extracted from the continuous data log from the actual start and stop times of the test point. Some of the variables logged for each data point included the global air and fuel input mass flow information, associated temperature data, main burner region windbox air flow rates and total separated overfire air (SOFA) flow rates, which allowed for on-line calculation and control of bulk furnace stoichiometry history. Additional, pertinent operational data such as individual windbox compartment pressures and main windbox and SOFA windbox damper positions were manually recorded as test board data.

Acquisition of data for each matrix test point typically consisted of 15-30 minutes of steady state furnace operation, for which configuration and operational variables were monitored and held constant. At the end of a test point, furnace operation and/or configuration were modified and, after the necessary time for conditions to equilibrate had elapsed, the process was started again.

The ISBF utilized a continuous sampling gas analysis system to measure the gaseous species concentrations in the furnace effluent gas stream, prior to the post-combustion, flue gas conditioning equipment. The gas analysis system utilized gas species analyzers meeting the requirements of 40 CFR methods 7E, 6C, 3A, 10, and 3A for NO/NOx, SO_2, CO_2, CO, and O_2, respectively. This system was calibrated against certified bottled gas standards at least every twelve hours when taking test matrix data.

Carbon loss data was obtained through a pseudo-isokinetic sampling of fly ash with a water-cooled sampling probe, which is inserted in the furnace gas duct downstream of the simulated convective pass. The fly ash was sampled at six locations across the approximately 5ft diameter outlet duct. The flow-rate through the sampling system was measured/controlled during the entire sample time to ensure that the ash system was operated at approximately isokinetic conditions. A water-cooled, suction pyrometer with a single Type B thermocouple was utilized to measure in-furnace gas temperatures (furnace outlet plane temperature) perpendicular to the gas flow. Additionally a Raytek infrared thermometer was used to take non-intrusive flame/thermal environment temperature measurements at 6 glass viewports arranged axially along the flame length.

7.1 Test Series 1

During the first series of ISBF testing, six coal nozzle tips were fired on the Illinois #6 coal. The tip designs and names were explained in the modeling section. Both the shear bar/air deflector and LNCFS™ P2 tips are current Alstom commercial products used here as a reference baseline to compare versus the performance of other tips. The firing rate was nominally 45 MMBtu/hr for each of the tests, with 20% excess air. All furnace and operating conditions were repeated as closely as possible for the testing on each coal nozzle tip. Furnace outlet temperatures were taken at a variety of test conditions, including before and after sootblowing, and the traverse averages ranged from 2321 to 2511°F.

NOx results are presented in Figure 7.1-1. A reduction in NOx emissions of approximately 20% was achieved with the center bluff body tip as compared to the shear bar/air deflector tip and 10% versus the LNCFS™ P2 tip. Note that for some of the new design tips that did well at low stoichiometry, such as the center bluff, the NOx at high stoichiometry is actually greater than the baseline tips. This is explored further in the series 2 results.

Unburned carbon results are shown in Figure 7.1-2. Note there is no data here for the shear bar/air deflector tip due to a sampling problem at the start of the test series. Typically unburned carbon results are much less consistent than most other emissions due to non-steady movement of ash solids in the furnace ducting, so it is more difficult to make conclusions comparing one specific test condition to another. This can be seen in the percent carbon variation for alternate points at similar stoichiometries. However the results in the figure show that compared to the LNCFS™ P2 baseline tests, all the tips had overall fairly similar carbon in ash performance, including a typical rise in carbon in ash at reduced stoichiometry.

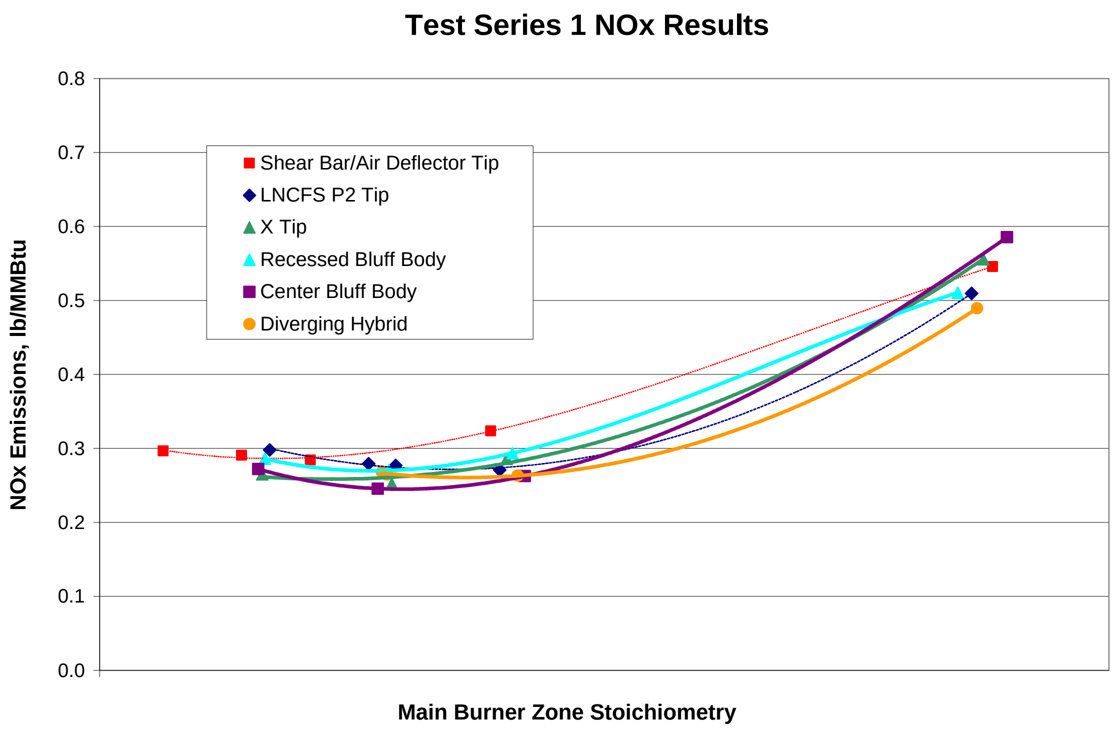


Figure 7.1-1 Series 1 NOx Emissions vs Main Burner Zone Stoichiometry

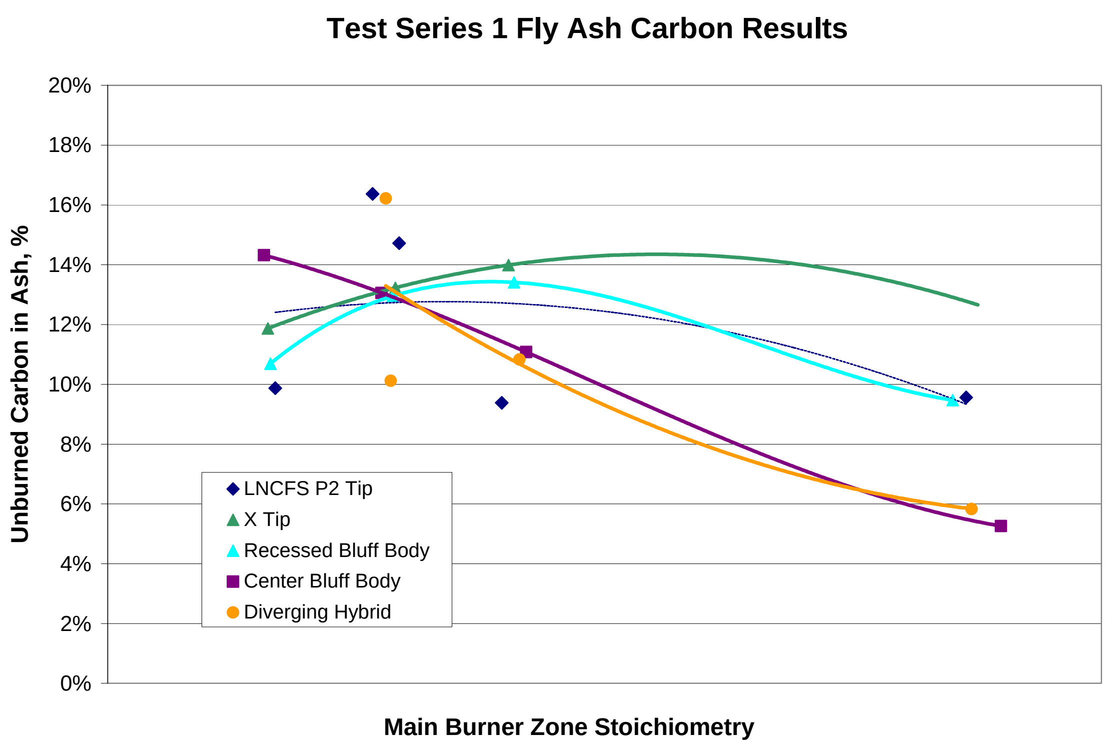


Figure 7.1-2 Series 1 Carbon in Ash vs Main Burner Zone Stoichiometry

In order to achieve the minimum NOx emissions, biasing of the air supply is typically required. The basic goal is to delay combustion as much as possible without triggering excessive CO or unburned carbon, by supplying the fuel with just enough air to keep a minimum level of combustion ongoing. This can be done throughout the combustion process, by 1) transferring fuel air flow (adjacent to the tip) to the auxiliary compartments, 2) moving flow to the furthest auxiliary nozzle from the coal tip, and 3) moving overfire air to the furthest downstream OFA location. Because the ISBF is a "tunnel" single burner furnace, versus Alstom's commercial boilers with multiple tangentially fired burners creating a central fireball, the optimum arrangement of air biasing is different than that for a commercial boiler. However the levels of additional reduction are comparable.

Figure 7.1-3 shows the variation in NOx emissions for a narrow stoichiometry range by tip and by air configuration. Configuration 1 is all OFA ports open with no windbox air subcompartmentalization. Configurations 2 and 3 both have windbox air subcompartmentalization; 2 has a bias towards the far OFA ports while 3 has only the far OFA ports open. Clearly the varying combustion characteristics of the tip designs interact differently with the range of air system configurations tested.

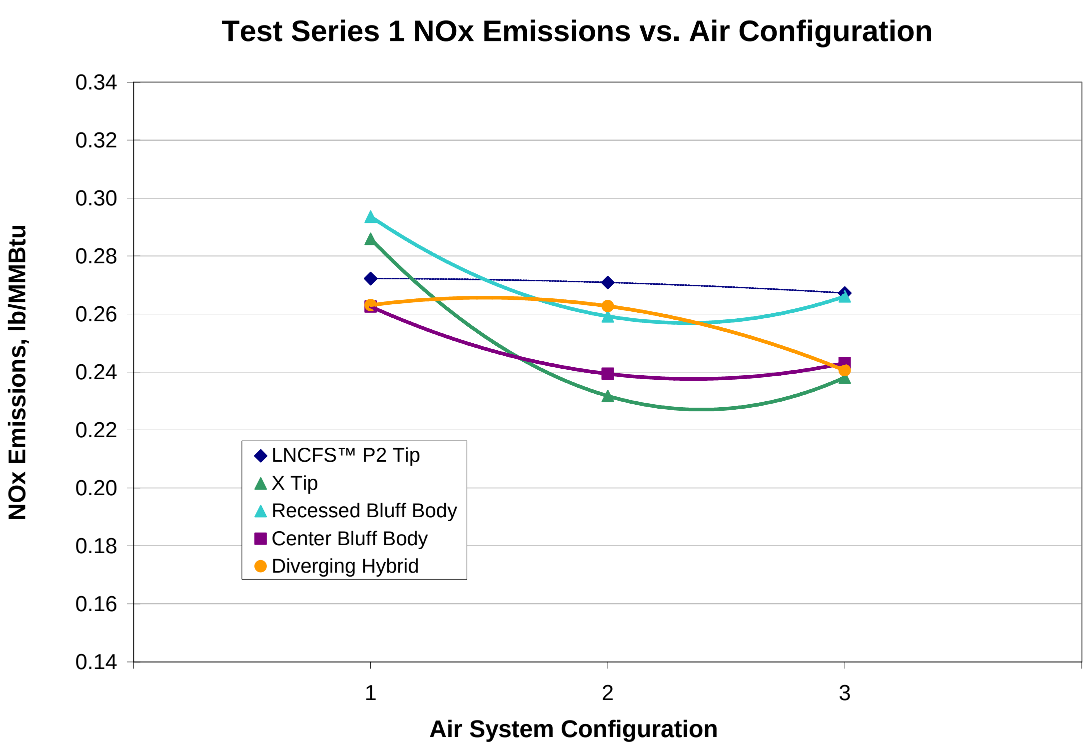


Figure 7.1-3 Series 1 NOx Emissions vs Air System Configuration

The corresponding carbon in ash data is presented in Figure 7.1-4. It appears the LNCFS™ P2 tip may have had a slight advantage in carbon in ash at most of these conditions, but again there is significant uncertainty in these measurements, so the reasonable conclusion is that any changes in carbon in ash are small versus the baseline.

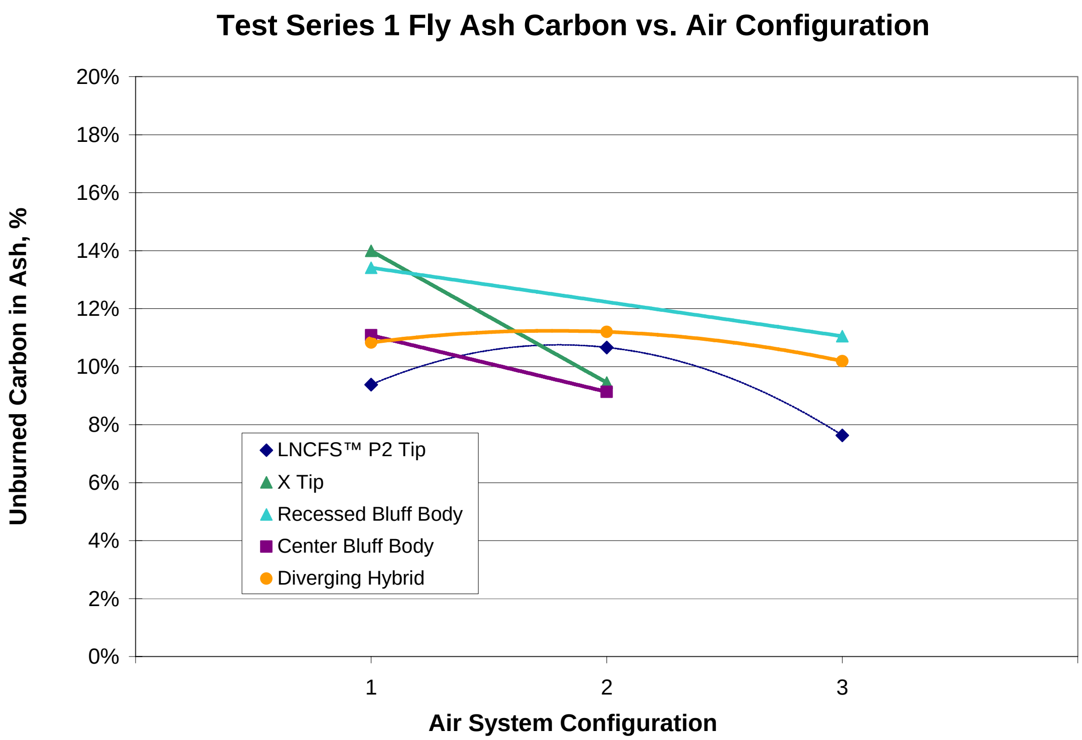


Figure 7.1-4 Series 1 Carbon in Ash vs Air System Configuration

7.2 Test Series 2

The second series of ISBF testing was completed in March 2006. Modifications were made to several of the coal nozzle tips tested in series 1 with the aim of improving their performance. Two additional coal nozzle tip concepts were also tested during series 2. Examples of modifications that were made during the series include increasing the size of shear bars, changing the size of the bluff body, or modifying vane shapes. Facility conditions were as similar as possible to series 1, with the measured furnace outlet temperature averages ranging from 2344 to 2514°F. The same nominal firing rate of 45 MMBtu/hr, excess air of 20%, and Illinois #6 coal were used for each of the tests.

The series 2 NOx results are presented in Figure 7.2-1. As shown in the figure, significant NOx reductions were achieved with the new tip concepts. The modifications made to the center bluff body and recessed bluff body tips show a modest improvement over their series 1 performance. The new tip concepts including the vane tips, achieved significantly lower NOx emissions than any of the series 1 tip concepts. Prior to this testing it was not clear that additional NOx reductions of this magnitude would be possible for deeply staged systems with only coal nozzle tip modifications. These results indicate that significant NOx reductions are indeed possible through coal nozzle tip modifications. It remains to be seen, however, if similar reductions can be achieved in multi-burner utility boilers.

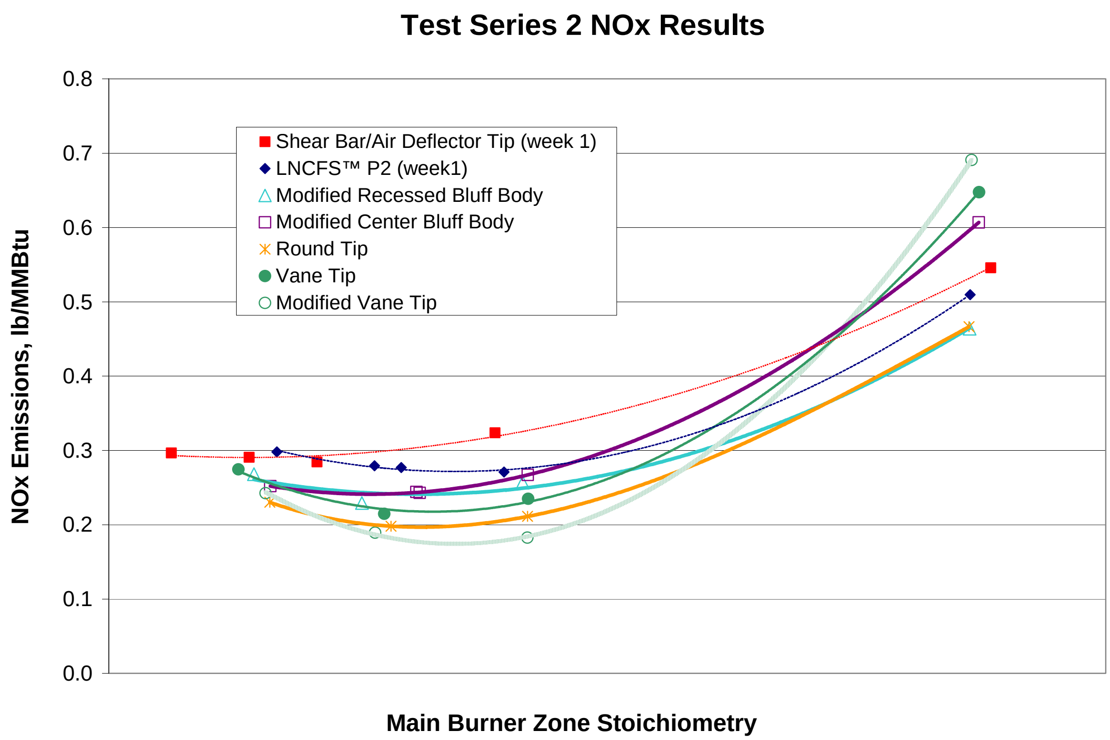


Figure 7.2-1 Series 2 NOx Emissions vs Main Burner Zone Stoichiometry

There are several other interesting results on this graph. The vane tips had low NOx emissions at low main burner zone stoichiometries compared to other tip designs but higher NOx emissions at high MBZ stoichiometries. This may be due to the enhanced ignition and early stage devolatilization exhibited by the vane tip design. At high MBZ stoichiometries this enhanced ignition may produce higher NOx in this air rich environment. The new tip designs had very bright, well-attached flames at all conditions. This is seen in the comparison of Figures 7.2-2 (baseline tip) to7.2-3 (vane tip).

Figure 7.2-2 Typical Baseline Tip Coal Flame

Figure 7.2-3 Typical Vane Tip Coal Flame

The unburned carbon in the fly ash results for the same tests are shown in Figure 7.2-4. Again these results are expected to be less precise than gaseous emissions. There is a general increase in unburned carbon in the fly ash at the lower main burner zone stoichiometries, although there is no clear trend in unburned carbon emissions with the different coal nozzle tips. The carbon loss values are typical of those seen in most utility boilers firing similar fuels. The unburned carbon values for the series 2 tip concepts were generally lower than those achieved with the baseline LNCFS™ P2 tip.

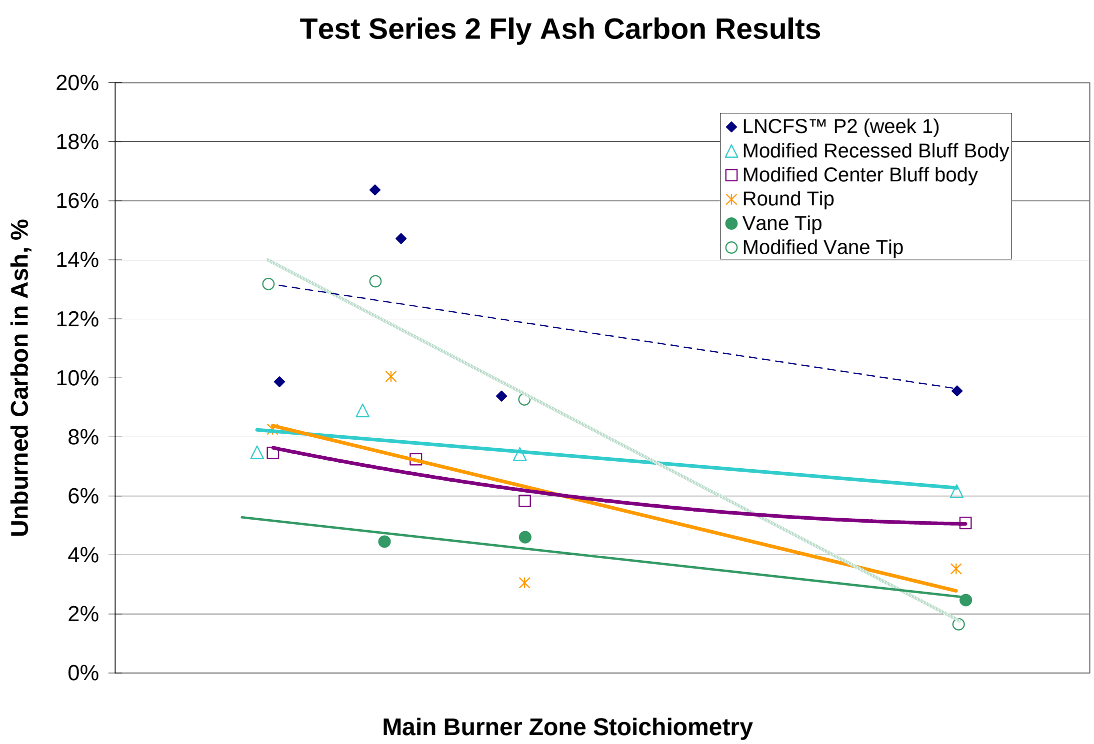


Figure 7.2-4 Series 2 Unburned Carbon in Ash vs Main Burner Zone Stoichiometry

Furnace temperatures were measured via several methods. The furnace outlet temperature (FOT) was measured via a multi point traverse two feet downstream of the final overfire air port, using a conventional thermocouple/suction pyrometer probe system. The 2344 to 2514°F FOTs mentioned earlier were measured in this fashion. The furnace also has two permanently installed wall thermocouples, one near the front of the furnace and one at the rear; however, these are unshielded and unprotected from furnace slag so the readings can be inconsistent. Estimated temperatures were also measured with a hand held Raytek optical pyrometer at ports along the furnace axis.

The wall-mounted thermocouples see radiation from the flame and are partially influenced by the water-cooled furnace walls, so their readings are only meaningful in relative rather than absolute terms. However, the tips with the lowest NOx emissions tended to have the highest near-wall temperatures near the front of the furnace (see Figure 7.2-5). Similar although less consistent results were seen with the optical pyrometer data. These data appear to be indicative of earlier or more intense ignition of the coal stream and more rapid devolatilization, resulting in lower NOx emissions.

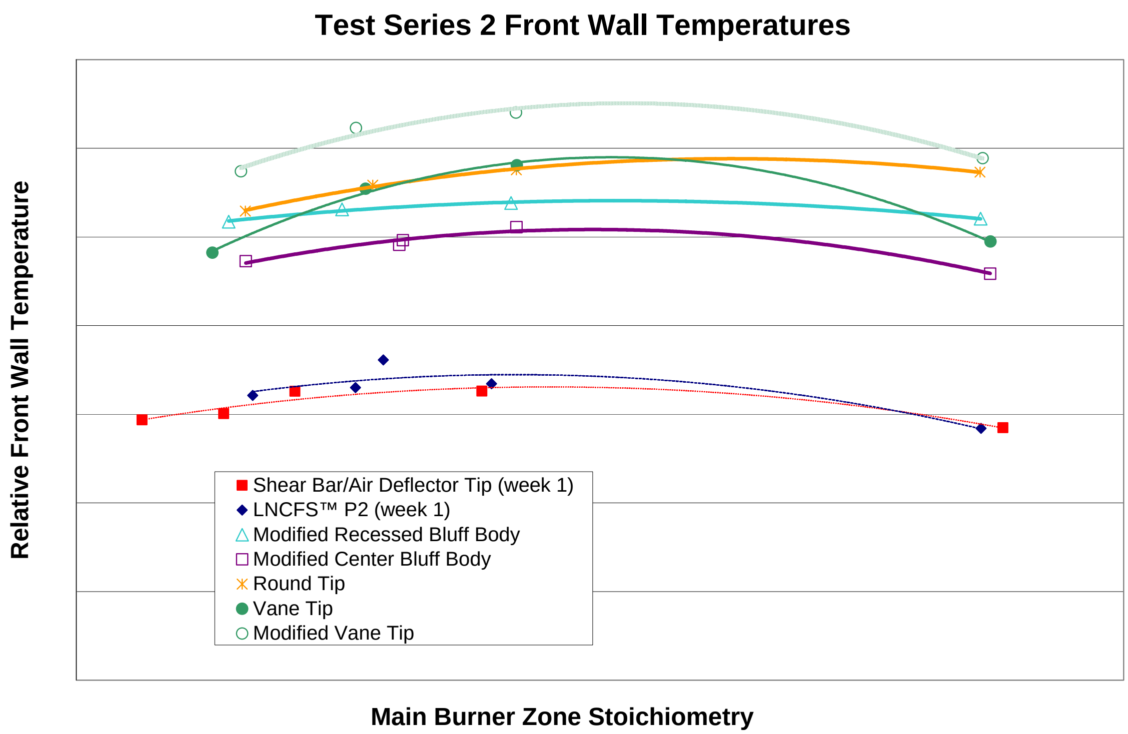


Figure 7.2-5 Front Wall TC vs Main Burner Zone Stoichiometry

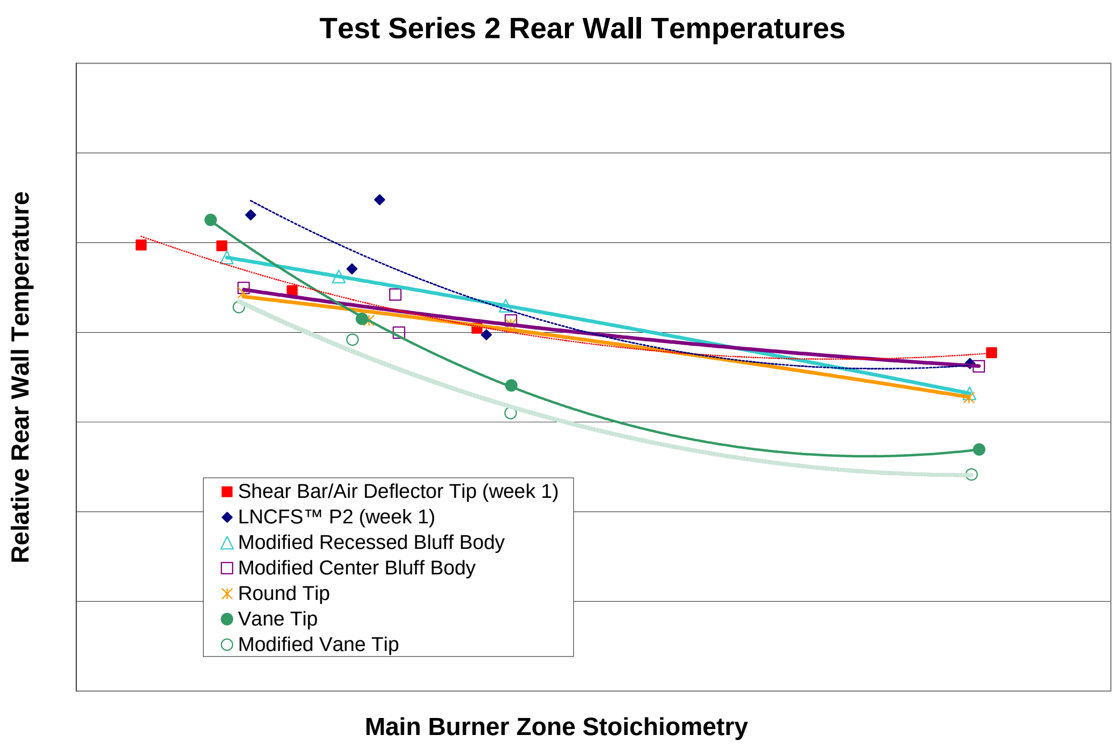


Figure 7.2-6 Rear Wall TC vs Main Burner Zone Stoichiometry

Similarly, Figure 7.2-6 shows that the tips with the highest temperatures towards the front of the furnace had the lowest temperatures near the exit of the furnace. This is not unexpected as more of the heat is transferred to the furnace walls in the front of the facility.

Some additional tests were performed for each coal nozzle tip in an attempt to optimize the performance of each tip. Parameters that were adjusted for each tip included the quantity of fuel air, the distribution of auxiliary air between the various compartments, and the overfire air configuration. These tests were only performed for some of the tips as time permitted. NOx emissions for the optimized condition for each tip are shown in Figure 7.2-7 as a percent reduction from the LNCFS™ P2 tip. The same results are presented in Figure 7.2-8 as the actual measured NOx emissions (lb/MMBtu) for the various tips tested. As shown in the figures, maximum NOx reductions of approximately 45% over the LNCFS™ P2 tip were achieved. NOx emissions less than 0.15 lb/MMBtu were measured for two of the vane tip variations.

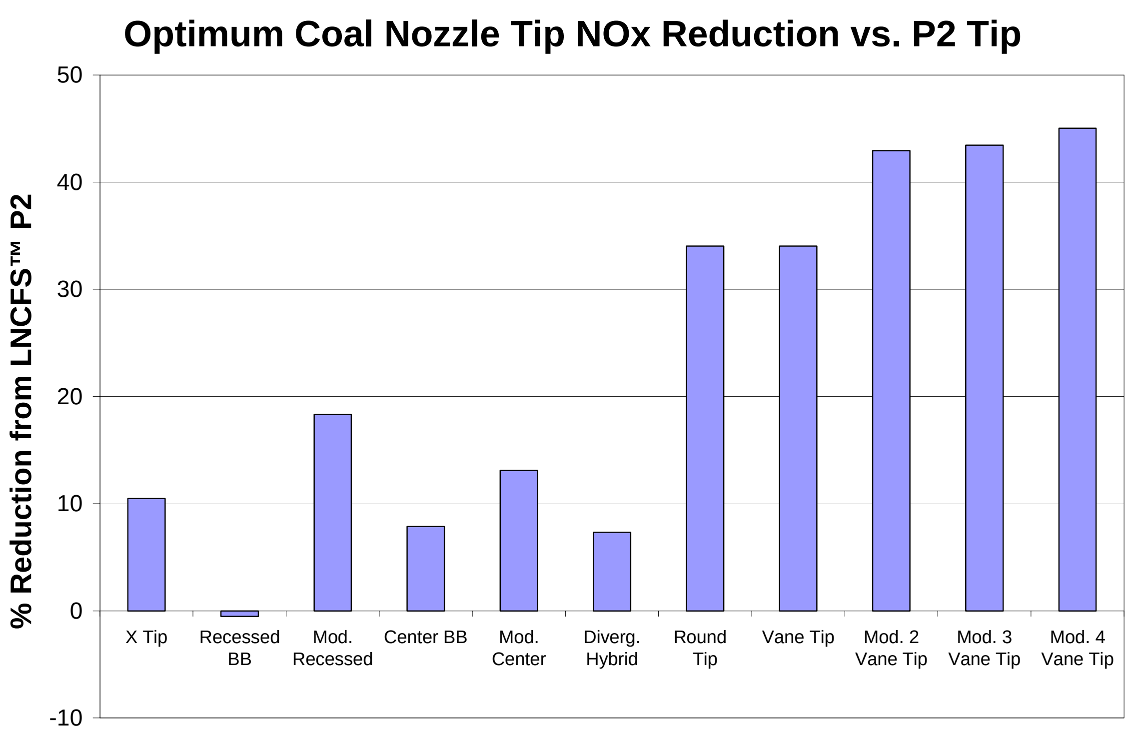


Figure 7.2-7 Optimized NOx Emissions for Each Tip, % Reduction over LNCFS™ P2 Tip

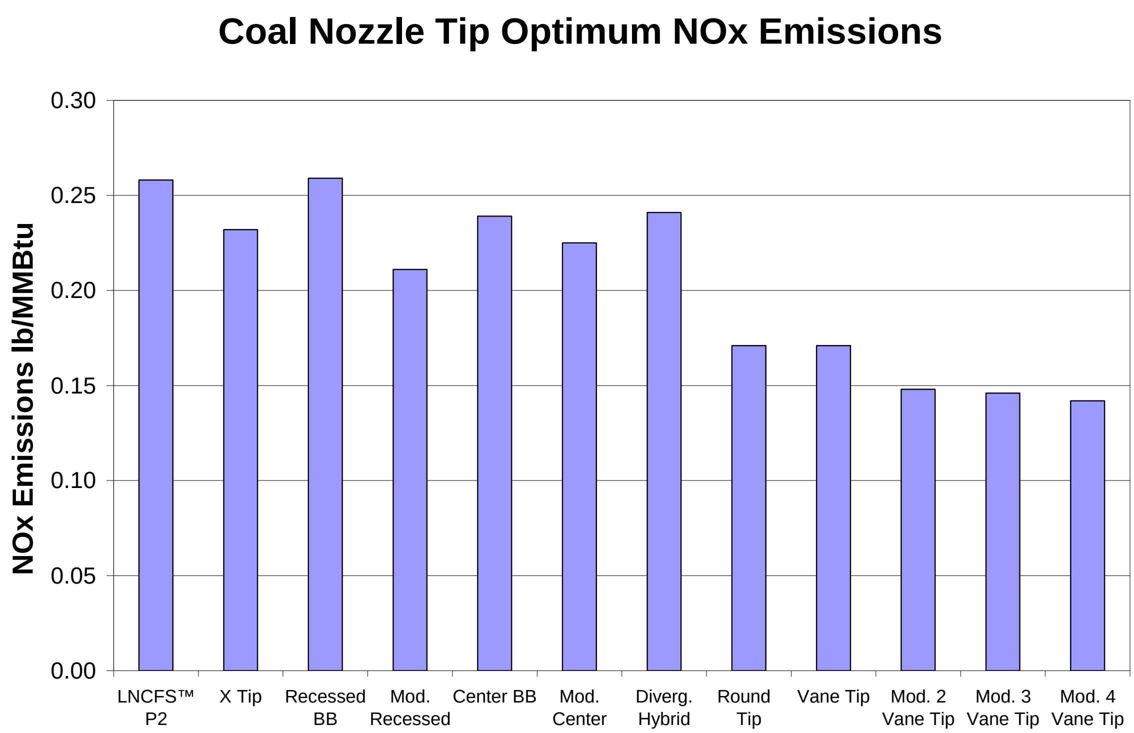


Figure 7.2-8 Optimized NOx Emissions for Each Tip, lb/MMbtu

7.3 Test Series 3

Test Series 3 was run with 3 coals - Illinois #6, Sufco, and Adaro - and a total of 5 coal nozzle tip designs plus the baseline:

- A P2 baseline
- B Optimum from series 2 (vane tip mod 4)
- C B with no bluff body
- D B with larger vane spacing
- E B with smaller vane spacing (Illinois #6)
- E1 B with shear bars on the bluff body (Sufco, Adaro)

For each combination of coal and nozzle, there was this standard series of test conditions:

1. Base case - no staging, nominal 20% excess air, all introduced at the main burner zone.
2. Low overfire air
3. Medium overfire air
4. High overfire air
5. Medium overfire air with windbox air biased away from the coal nozzle
6. Low overfire air with windbox air biased away from the coal nozzle and the overfire air biased to the far location
7. Low overfire air with windbox air biased away from the coal nozzle and the overfire air only to the far location

Test condition 7 was run only for limited tests. Test Series 3 conditions tested and test numbers are shown in Table 7.3-1.

Table 7.3-1 Test Points Conducted in Test Series 3

Test Cond.	1	2	3	4	5	6	7
Overfire Air	None	Low	Med	High	Med	Low	Low
Illinois #6							
A	001,A[1]	002	003	004	005	006	--
B	011	012	013	--	015	016	--
C	021	022	023	024	025	026	--
D	031	032	033	034	035	036	--
E	041	042	043	044	045	--	--
Sufco							
A	101,A	102	103	104	105	106	--
B	111	112	113	114	115,A	116	--
C	--	--	--	--	--	--	--
D	131	132	133	--	135	--	--
E1	121	122	123	124	125	126	--
Adaro							
A	201	202	203	204	205	206	--
B	211	212	213	214	215,A	216	217
C	--	--	--	--	--	--	--
D	231	232	233	234	235	236	237
E1	241	242,A	243	244	245	246	--

[1] "A" indicates a repeat was run.

The test conditions and results are summarized in Table 7.4-1 through Table 7.4-3 by test condition and number. Of particular interest is comparing the test conditions and the results of the base P2 coal nozzle design (A) with the new designs. The following data are shown in the tables:

- Nozzle
- Test Number
- Test Cond'n - Test Condition, see Table 7.3-1
- Start Time - Start of steady test conditions
- End Time - End of steady test conditions
- Duration - Duration of steady test conditions.
- O_2 - Measured oxygen content in the flue gas, ppm dry
- XSA - Calculated overall excess air, %
- OFA - Relative flow rate of overfire air
- FOT - Average of furnace outlet temperature traverse with suction pyrometer, °F
- NOx ppm - Measured NOx in ppm, dry @3% O_2

- NOx lb/MM - Measured NOx in lb/MMBtu HHV fired
- CO ppm - Measured CO in ppm, dry @3% O_2
- C in Ash - % unburned carbon in flyash

The gaseous emissions shown were taken with a conventional gas analysis system using certified calibration gases. Air flows were measured via calibrated orifices. Furnace outlet temperature measurements were discussed in 7.2. Carbon in ash measurements were taken non-isokinetically (to reduce test time permitting a significantly greater number of points per test series) in the furnace outlet duct. Carbon in ash of the samples was measured via ASTM D6316 combustion-infrared detection.

Facility conditions for series 3 were as similar as possible to series 1 and 2. Furnace outlet temperatures, taken with the suction pyrometer thermocouple system, averaged slightly cooler than series 1 and 2 tests, with ranges of 2054-2423°F for Illinois #6 coal, 2165-2472°F for Sufco coal, and 2180-2453°F for Adaro coal. However this is due at least in part to the much greater number of tests taken with variations of the vane tip; as discussed in section 7.2 these tips showed much greater initial heat release, leading to lower temperatures at the furnace outlet. Convective section sootblowing was performed as necessary to maintain furnace temperatures with the different coals (every 3-4 points with Illinois #6 and Sufco, only twice with low ash Adaro). The same nominal firing rate of 45 MMBtu/hr, and normal excess air of 20% were used for each of the tests.

7.4 Test Results Summary

Figure 7.4-1 through Figure 7.4-3 show the NOx emissions for the three coals under test conditions one through seven. For all coals, all the vane tip variants produced consistently less NOx than the baseline P2 tips at reduced main burner zone stoichiometry. Tests of variant C without a bluff body, and E1 with shear bars on the bluff body showed less NOx improvement than the other vane tips. All the other tip variants performed fairly similarly across the range of overfire air flows tested, producing much lower NOx than the baseline P2 nozzle A at reduced stoichiometry.

The previously discussed (Section 7.2) effect of the vane tips producing higher NOx at high stoichiometry conditions appeared consistently for all three coals tested, although for the lower rank coals the effect was significant down to a lower stoichiometry than for the Illinois coal. For the Sufco coal the tested low overfire air flow rate condition is clearly the crossover point as shown above.

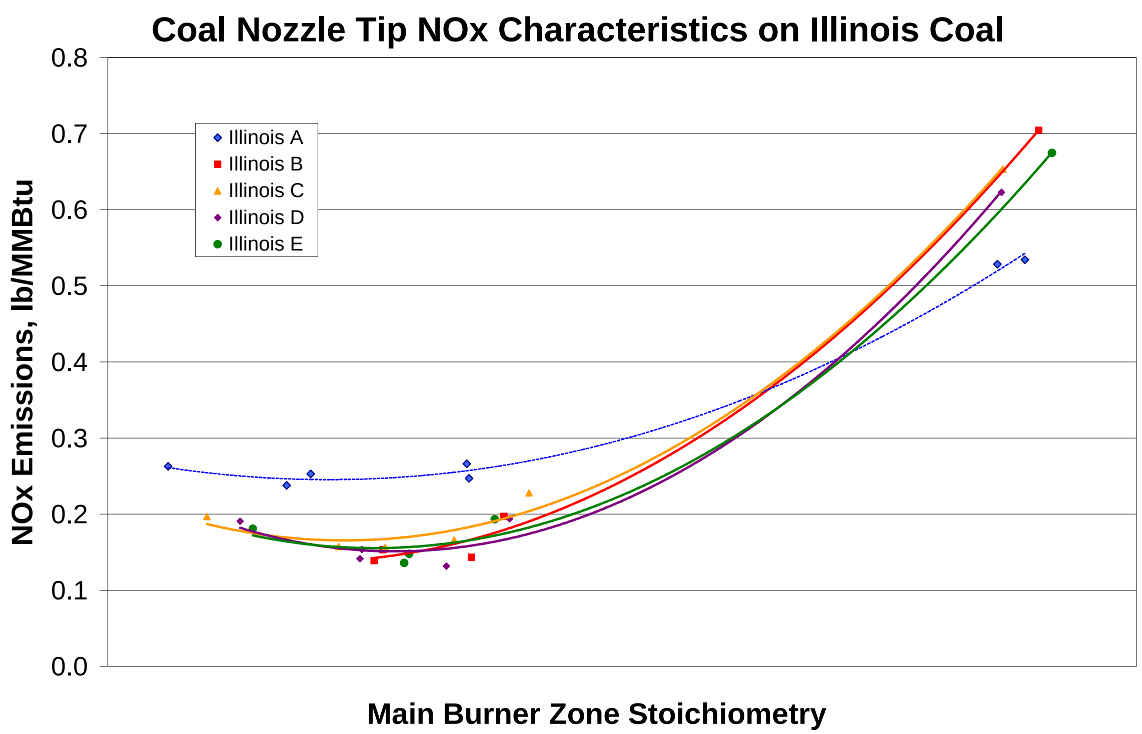


Figure 7.4-1 NOx Emissions vs Main Burner Zone Stoichiometry, Vane Tip Variants on Illinois Coal

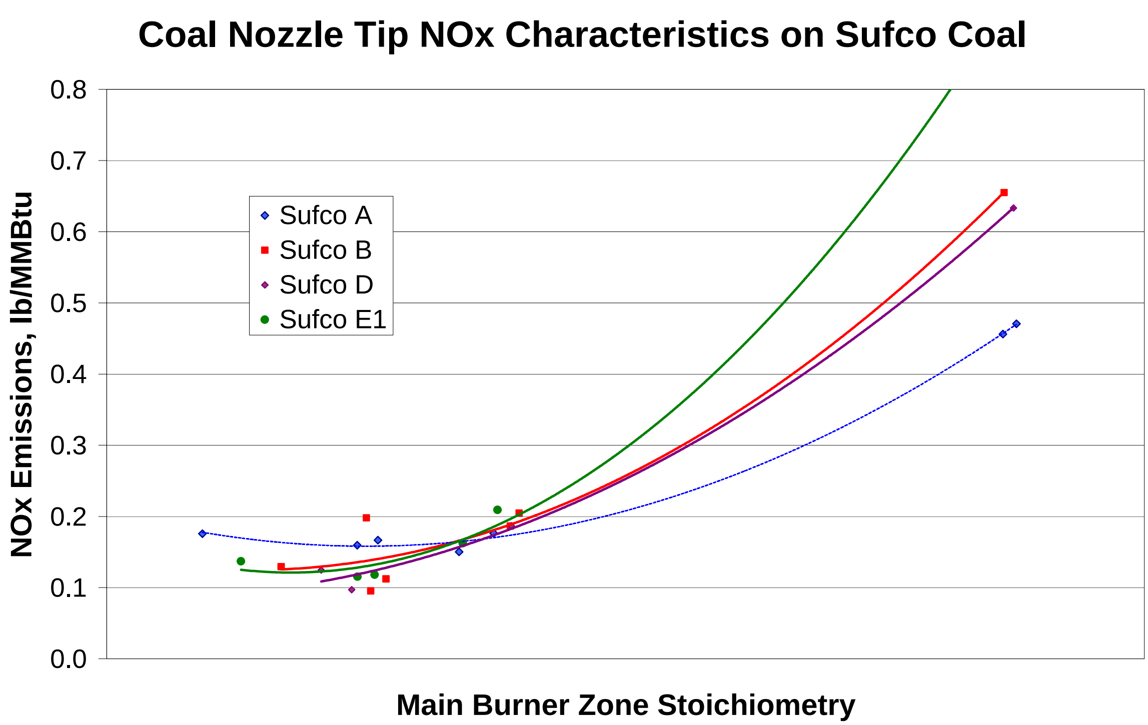


Figure 7.4-2 NOx Emissions vs Main Burner Zone Stoichiometry, Vane Tip Variants on Sufco Coal

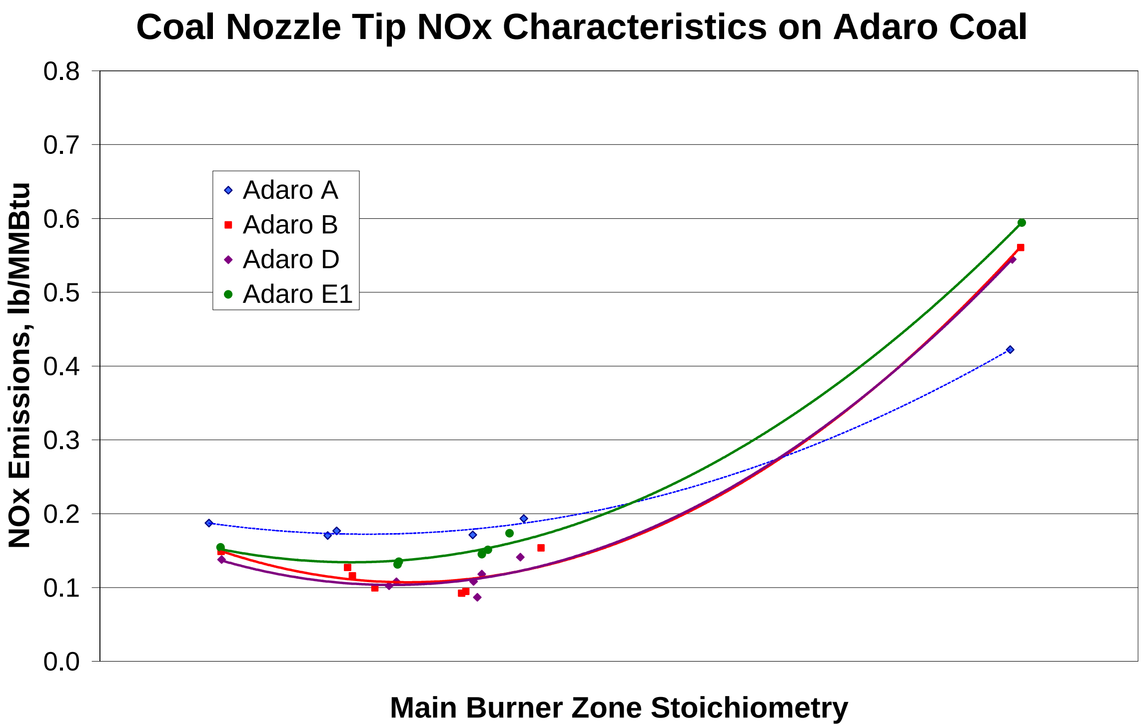


Figure 7.4-3 NOx Emissions vs Main Burner Zone Stoichiometry, Vane Tip Variants on Adaro Coal

Figure 7.4-4 through Figure 7.4-6 show the carbon in ash results for the three coals for all the test conditions. Again there is inherently greater variation in carbon measurements than in most gaseous emissions (Section 7.1). Unburned carbon results again show the vane tips performing similar to or better than the baseline P2 tip. One exception to this is the Adaro coal tip E1 results at low stoichiometry; however, this particular variant was also the worst vane tip NOx performer.

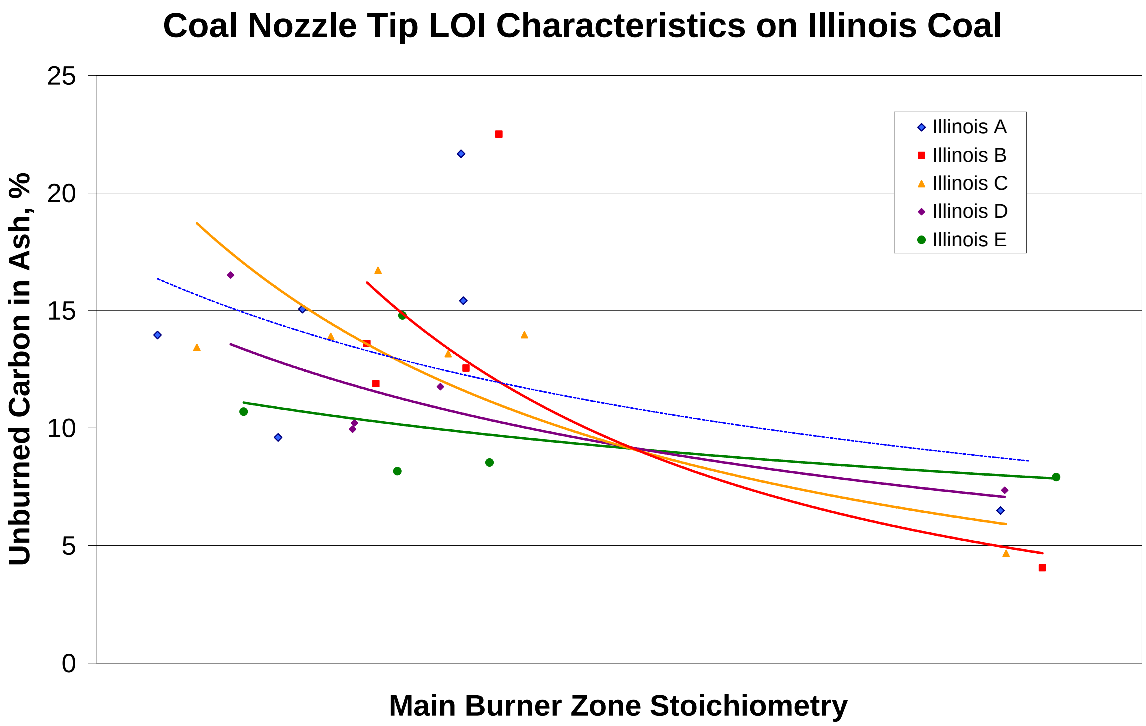


Figure 7.4-4 Unburned Carbon in Ash vs Main Burner Zone Stoichiometry, Vane Tip Variants on Illinois Coal

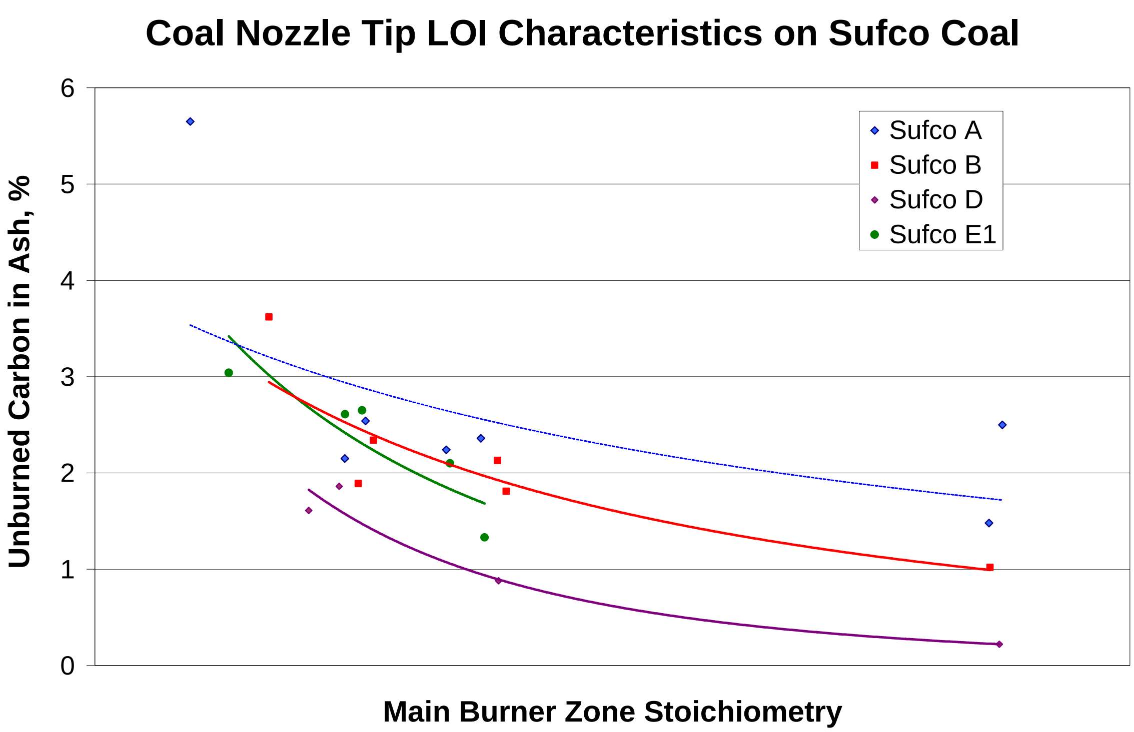


Figure 7.4-5 Unburned Carbon in Ash vs Main Burner Zone Stoichiometry, Vane Tip Variants on Sufco Coal

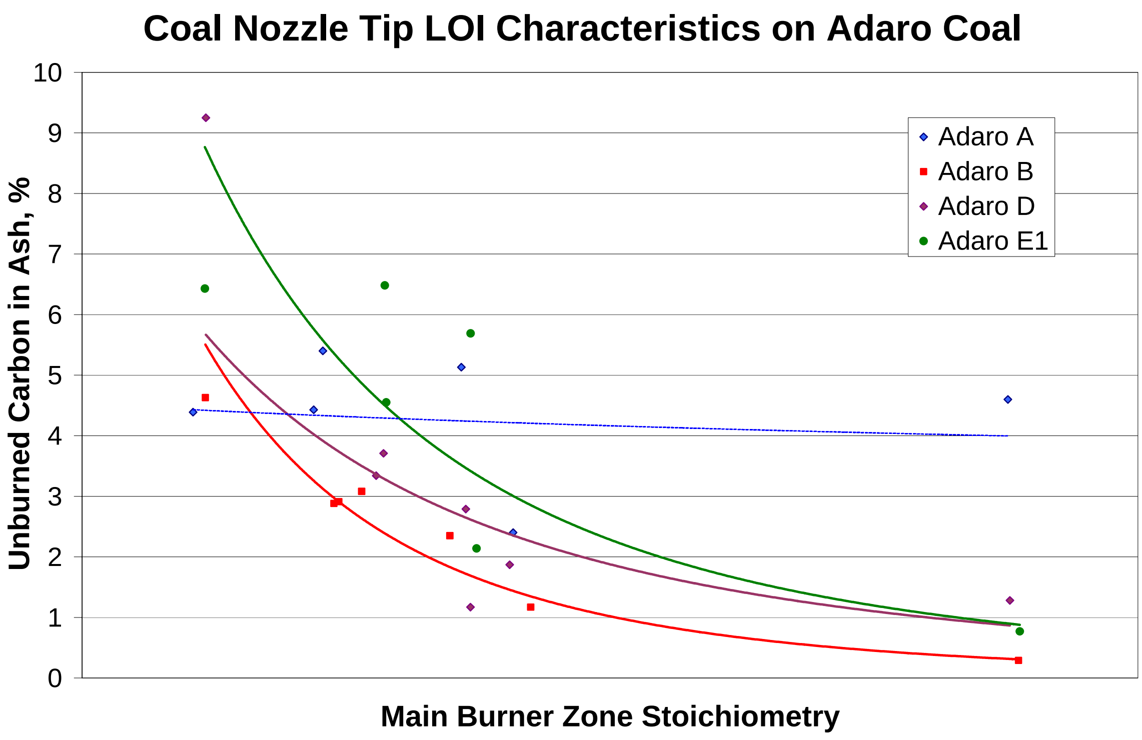


Figure 7.4-6 Unburned Carbon in Ash vs Main Burner Zone Stoichiometry, Vane Tip Variants on Adaro Coal

CO emissions are shown in Figure 7.4-7 through Figure 7.4-9 for the coal/tip combinations tested during Test Series 3. On some of the graphs the trendlines of CO levels extend above any CO emissions actually measured, this is only an artifact of the software used. Air staging level is clearly the most significant factor influencing the CO emissions, but the tip designs also played a major role at low stoichiometry, where CO emissions were almost universally higher for the vane tips. CO emissions are very sensitive to furnace mixing conditions, so in the field it is likely that any excess CO can be tuned out with air redistribution (which wasn't expressly tried here) and tangential firing parameters.

Differences in CO emissions for the vane tip variants staged test conditions are not very consistent, although tip D looked best for two of the three coals. CO levels depend strongly on conditions in the convective pass, including the sootblowing history.

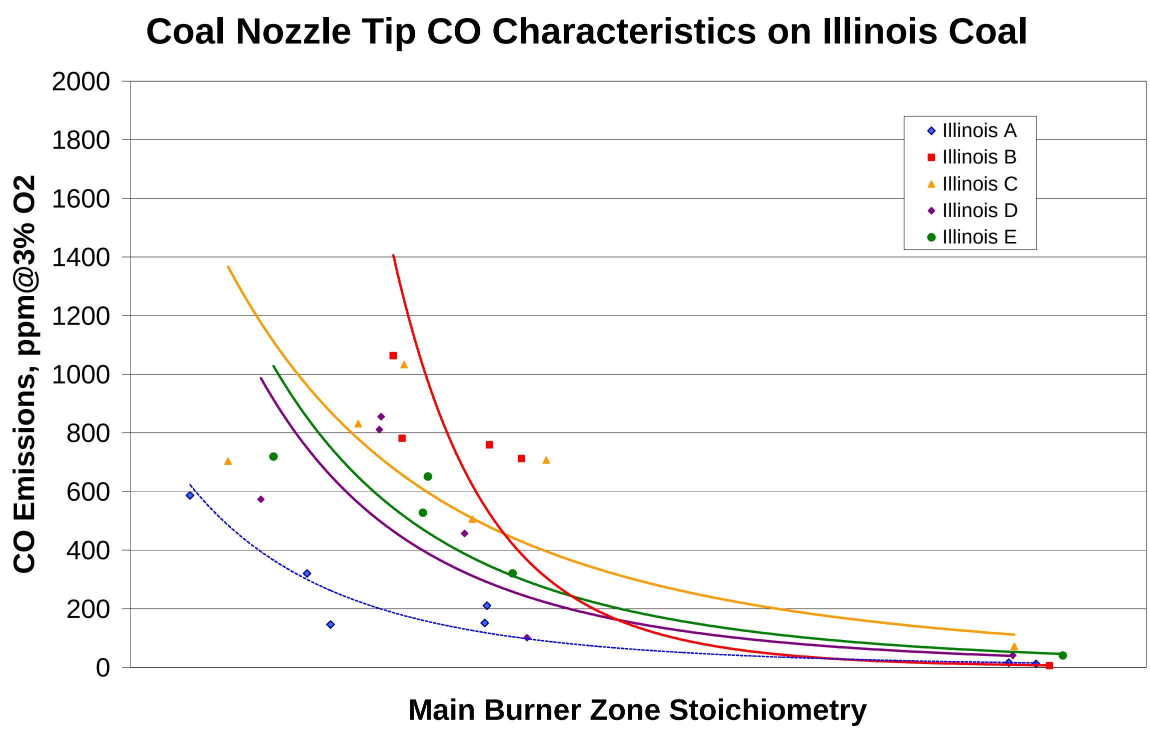


Figure 7.4-7 CO Emissions vs Main Burner Zone Stoichiometry, Vane Tip Variants on Illinois Coal

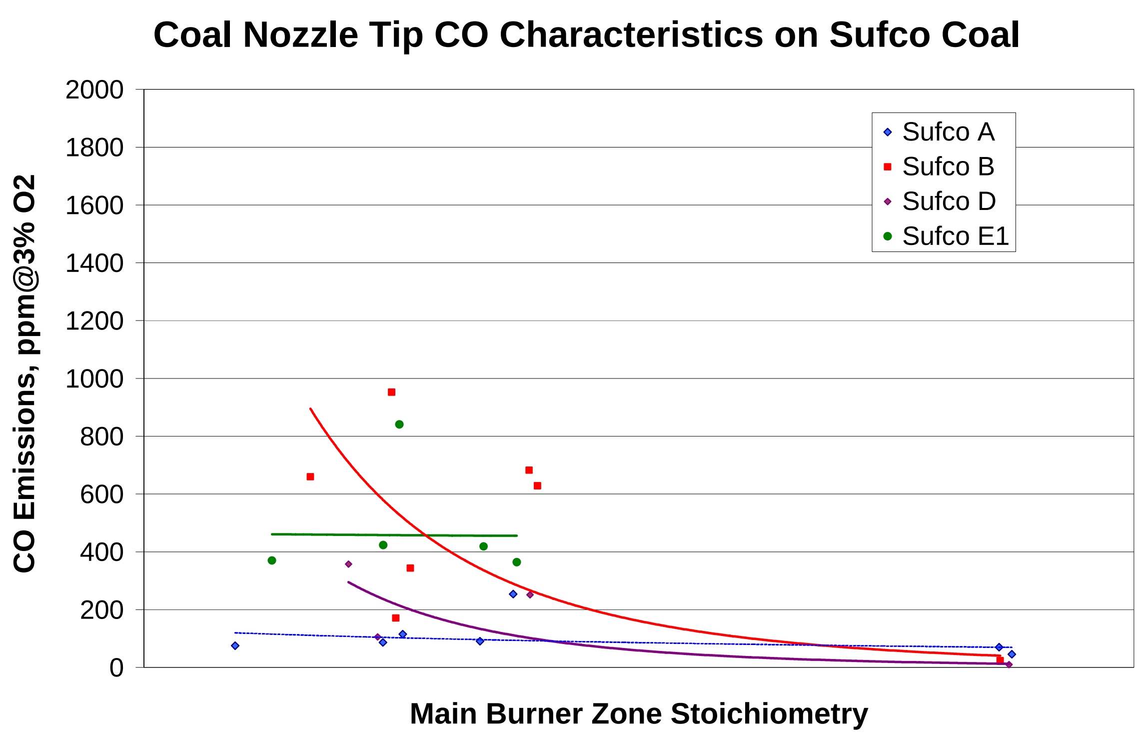


Figure 7.4-8 CO Emissions vs Main Burner Zone Stoichiometry, Vane Tip Variants on Sufco Coal

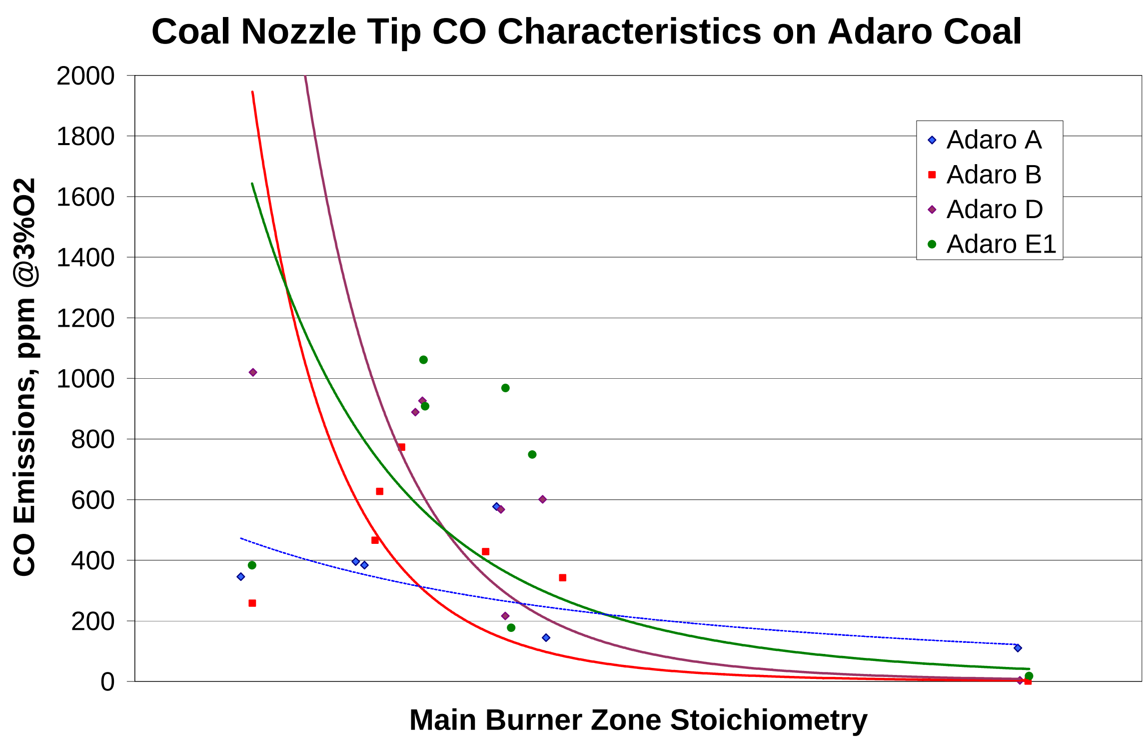


Figure 7.4-9 CO Emissions vs Main Burner Zone Stoichiometry, Vane Tip Variants on Adaro Coal

There appears to be a trend for higher CO emissions with lower main burner zone stoichiometry that is especially pronounced for the Adaro coal as can be seen in Figure 7.4-9. In comparison, the CO emissions from the new nozzles are closer to those from the base P2 nozzle A for the Illinois and Sufco coals under comparable test conditions, and are less sensitive to low main burner zone stoichiometry.

The effect of nozzle/air configuration during Test Series 3 on furnace temperature was documented. The furnace outlet temperature (FOT) was measured via a multi point traverse two feet downstream of the final overfire air port, using a conventional thermocouple/suction pyrometer probe system. The average value of each temperature traverse is given in Table 7.4-1 through Table 7.4-3. In most cases, the average FOT measured beyond the overfire air was higher for nozzle A than for the comparable points with the other nozzles.

The furnace also has two permanently installed wall thermocouples, one near the front of the furnace and one at the rear. These thermocouples are unshielded; they see radiation from the flame and can be influenced by the water-cooled furnace walls, so their readings are only meaningful in relative rather than absolute terms. All of the vane tip variations (tips B through E1 in the figures) had higher wall temperatures near the front of the furnace than the base P2 tip A (see Figure 7.4-10 through Figure 7.4-12).

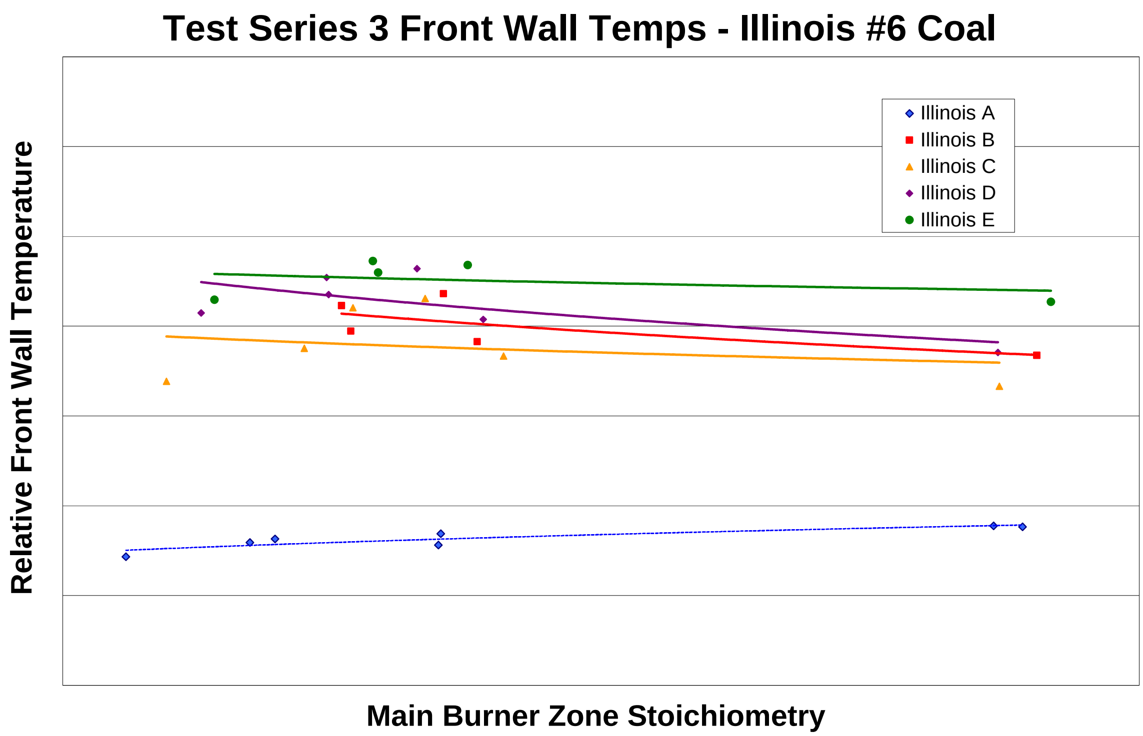


Figure 7.4-10 Front Wall TC vs Main Burner Zone Stoichiometry, Vane Tip Variants on Illinois Coal

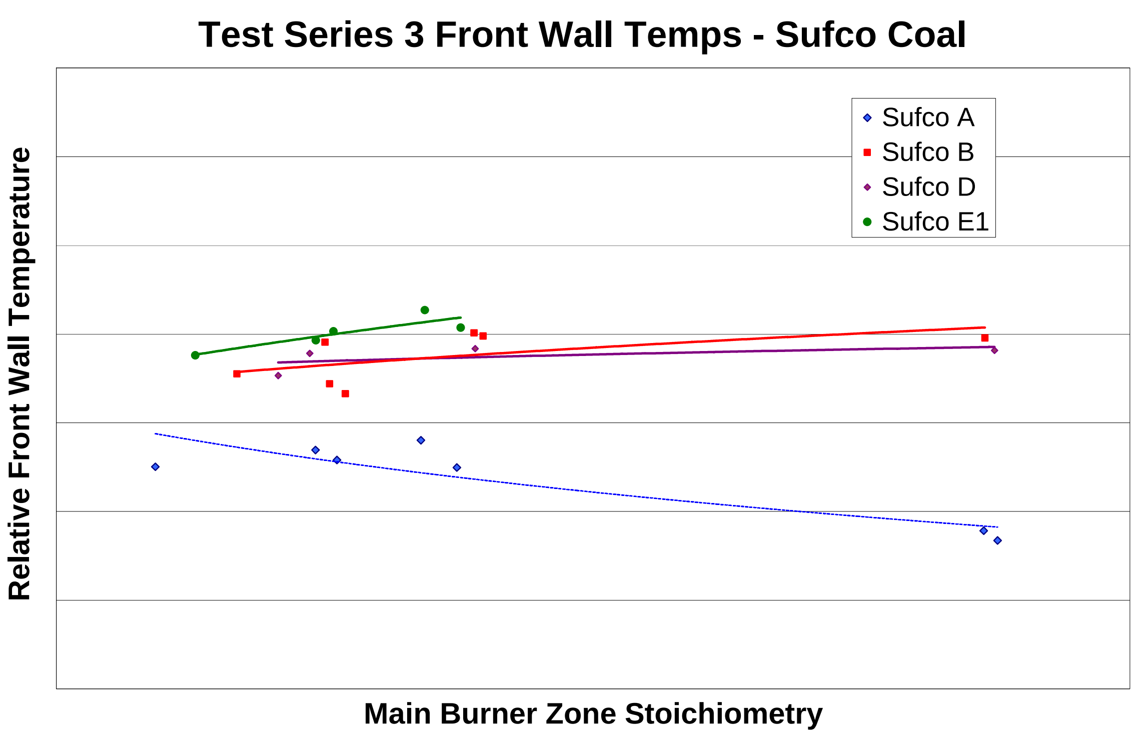


Figure 7.4-11 Front Wall TC vs Main Burner Zone Stoichiometry, Vane Tip Variants on Sufco Coal

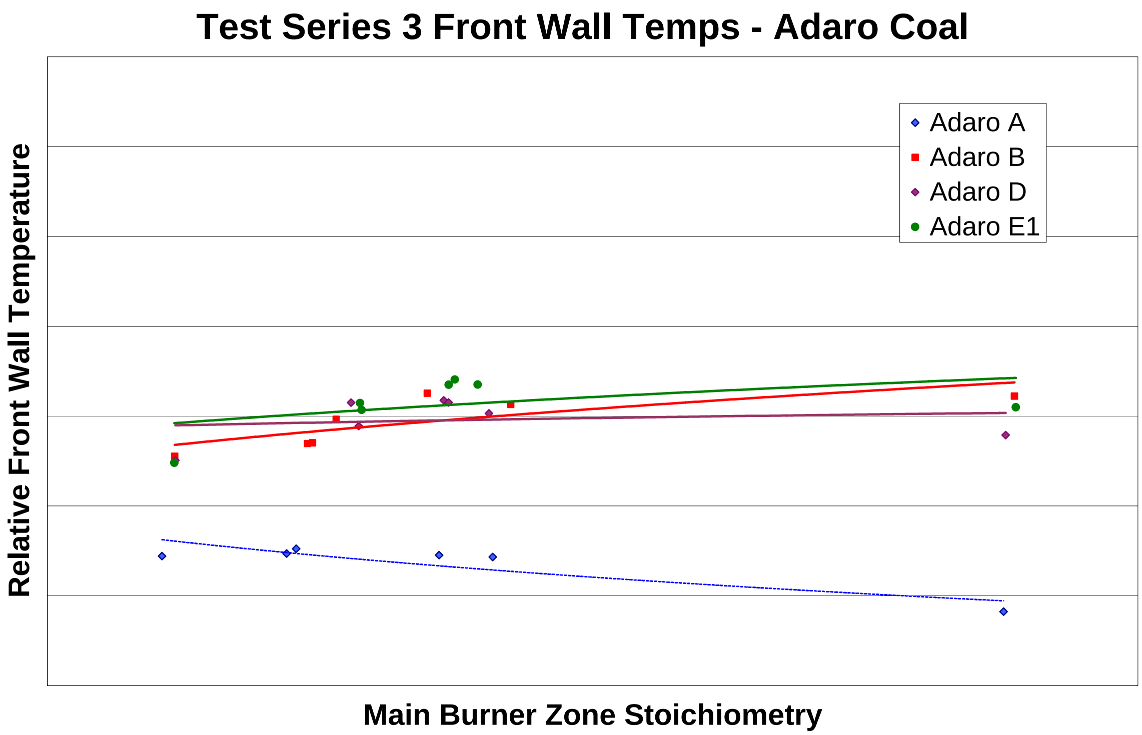


Figure 7.4-12 Front Wall TC vs Main Burner Zone Stoichiometry, Vane Tip Variants on Adaro Coal

To a large extent, it appears these temperature and performance differences are a consequence of different heat release profiles with the vane tips versus the baseline coal nozzle tips. How these heat release profile changes affect firing in a tangential configuration in a utility boiler is unknown until field tests are performed. However previous design changes to increase early heat release, such as additions of shear bars and pumpkin tooth splitters, have shown reduced NOx emissions both in earlier ISBF tests and in hundreds of field applications.

One goal of the coal nozzle tip design evaluation was to determine the ease with which the enhanced combustion low NOx coal nozzle tips could be transferred to the existing fleet in the field. The vane tip clearly was the most promising concept from the Test Series 2 evaluation, now the challenge was to determine the flexibility of vane tip design parameters to meet existing coal pipe nozzle and windbox geometries for a wide range of existing tangentially-fired boilers. Some of the vane tip variations involved changing the hardware design of the tip, while others involved changing the geometry of the tip. The coal nozzle tips tested in Test Series 3 can be grouped as follows:

Baseline	A	Existing P2 coal nozzle tip
Tip Geometry Changes	B	Vane tip mod 4
	D	Vane tip B with larger vane spacing
	E	Vane tip B with smaller vane spacing (Illinois #6)
Tip Hardware Changes	C	Vane tip B with no bluff body
	E1	Vane tip B with shear bars on the bluff body (Sufco, Adaro)

The NOx reduction performance of all the vane tip variants in comparison to the baseline P2 tip is shown in Figure 7.4-13, Figure 7.4-14 and Figure 7.4-15 for the Illinois #6, Sufco, and Adaro coals, respectively. These figures show that the B, D and E vane tip variants all performed nearly the same as far as NOx reduction performance goes for all three coals, while the C and E1 variants were not as successful. This is significant – the relatively major geometry changes between the B, D and E tips did not change their overall NOx reduction performance, indicating that the vane tip coal nozzle tip has a great deal of flexibility to fit a range of existing windbox geometries in the field.

The "optimal" operating configuration for the Illinois #6 and Sufco coals was generally test condition 5, with medium overfire air and with windbox air biased away from the coal nozzle. The "optimal" operating configuration for the Adaro coal was generally test condition 6, with low overfire air, windbox air biased away from the coal nozzle, and overfire air biased to the far location. Test condition 5 was a moderately staged configuration and attempted to achieve low NOx while maintaining acceptable carbon in ash and CO emissions performance with the bituminous coals.

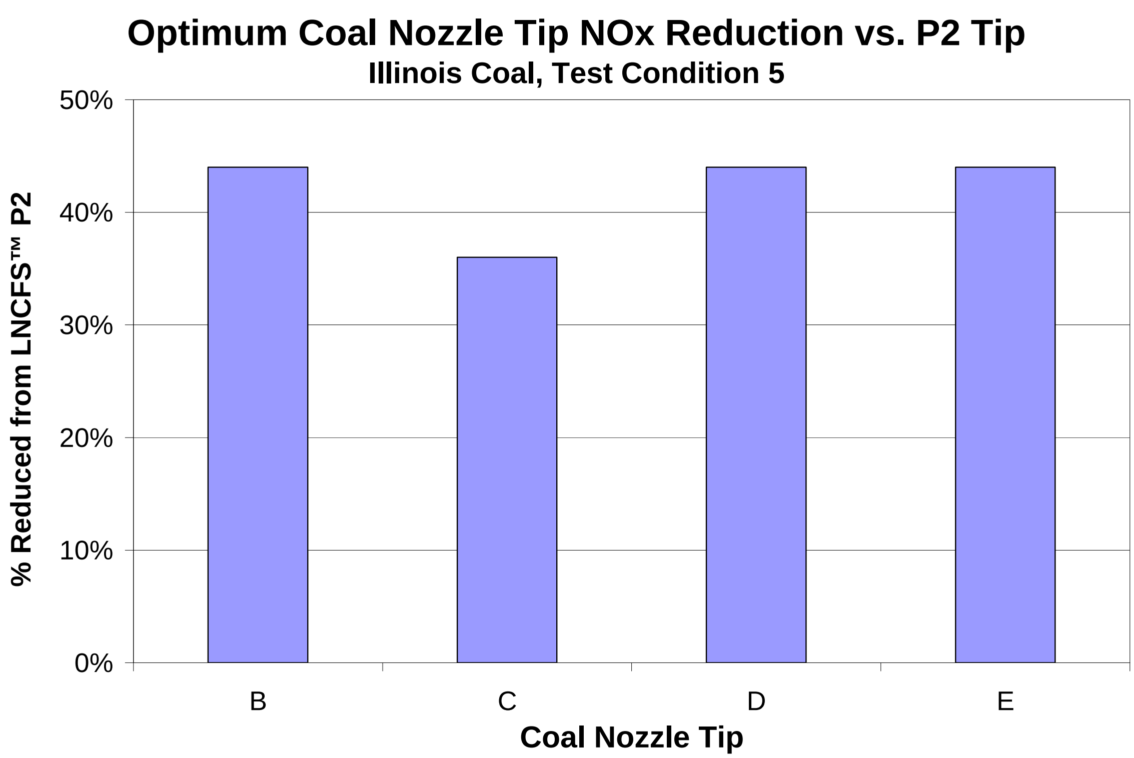


Figure 7.4-13 Optimized NOx Emissions for Each Vane Tip Variant on Illinois Coal, % Reduction over LNCFS™ P2 Tip

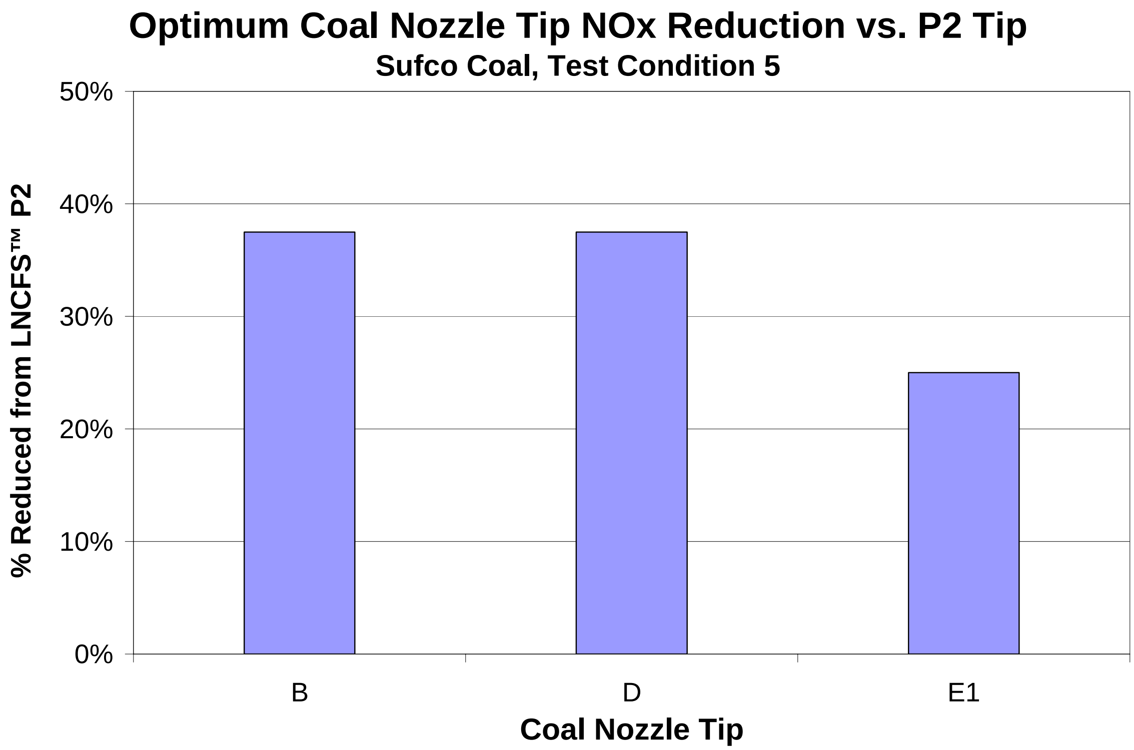


Figure 7.4-14 Optimized NOx Emissions for Each Vane Tip Variant on Sufco Coal, % Reduction over LNCFS™ P2 Tip

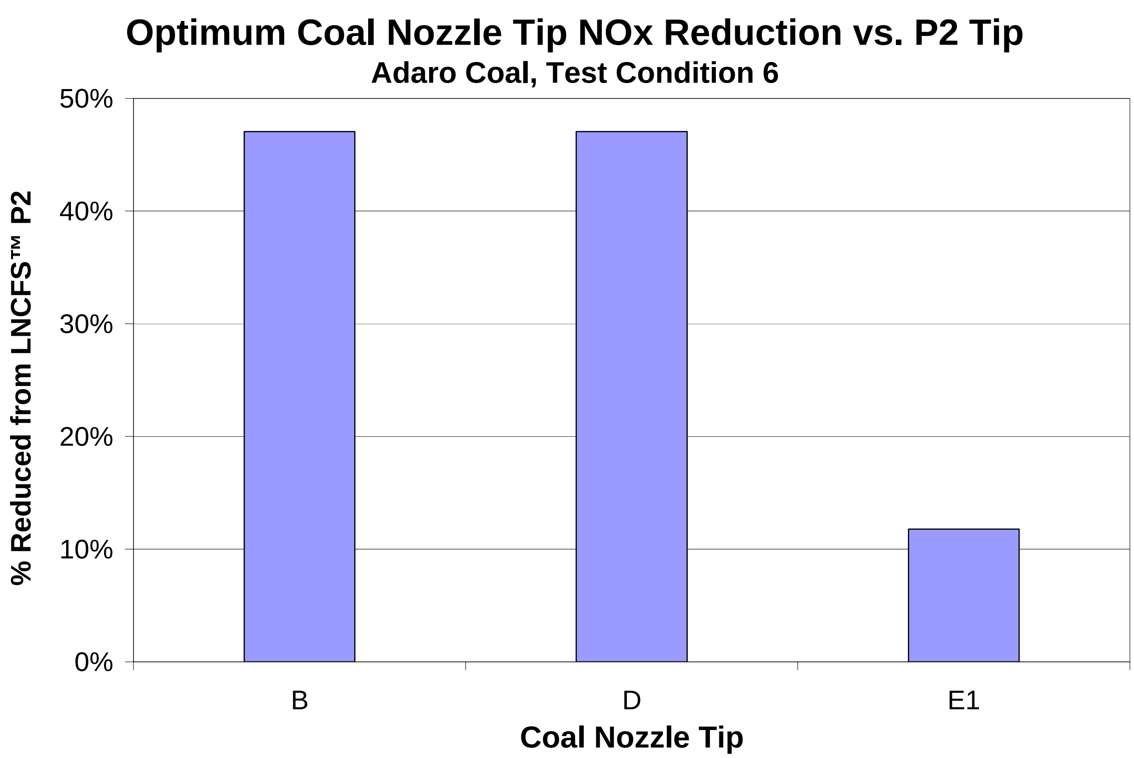


Figure 7.4-15 Optimized NOx Emissions for Each Vane Tip Variant on Adaro Coal, % Reduction over LNCFS™ P2 Tip

Again, the past three figures show that the B, D and E vane tip variants all performed nearly the same as far as NOx reduction performance goes for all three coals. The relatively major geometry changes between the B, D and E tips did not change their overall NOx reduction performance, indicating that the vane tip coal nozzle tip has the flexibility to fit existing windbox geometries in the field. As shown in the figures, maximum NOx reductions of 38 to 48% in comparison to the LNCFS™ P2 tip at the same firing conditions were achieved.

NOx emissions and unburned carbon results for the tests shown in previous three figures are presented in Figure 7.4-16 through Figure 7.4-18. These figures show the actual measured NOx emissions in lb/MMBtu and the unburned carbon in ash levels for the various vane tip mod 4 variants tested on Illinois, Sufco and Adaro coals. NOx emissions less than 0.15 lb/MMBtu were measured for three of the vane tip variations on the Illinois coal. NOx emissions at or below 0.10 lb/MMBtu were measured for two of the vane tip variations on both the Sufco and Adaro coals.

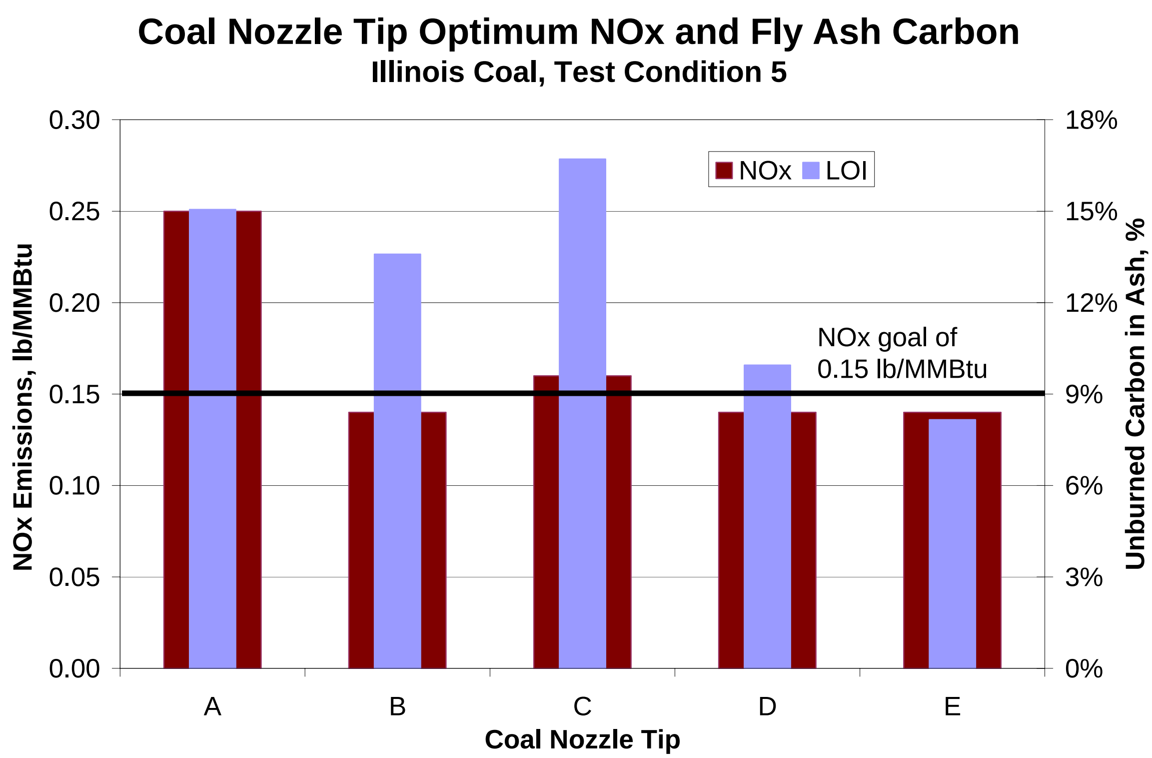


Figure 7.4-16 Optimized NOx and Unburned Carbon Emissions for P2 (A) and Vane Tip Variants on Illinois Coal

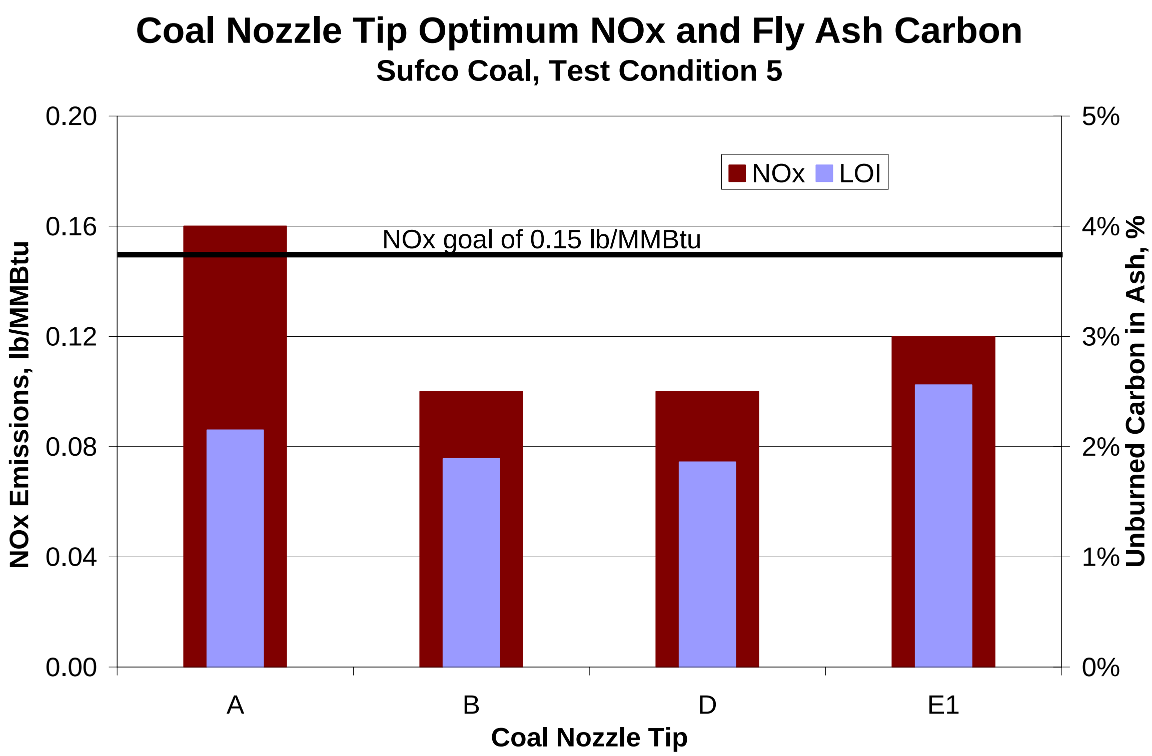


Figure 7.4-17 Optimized NOx and Unburned Carbon Emissions for P2 (A) and Vane Tip Variants on Sufco Coal

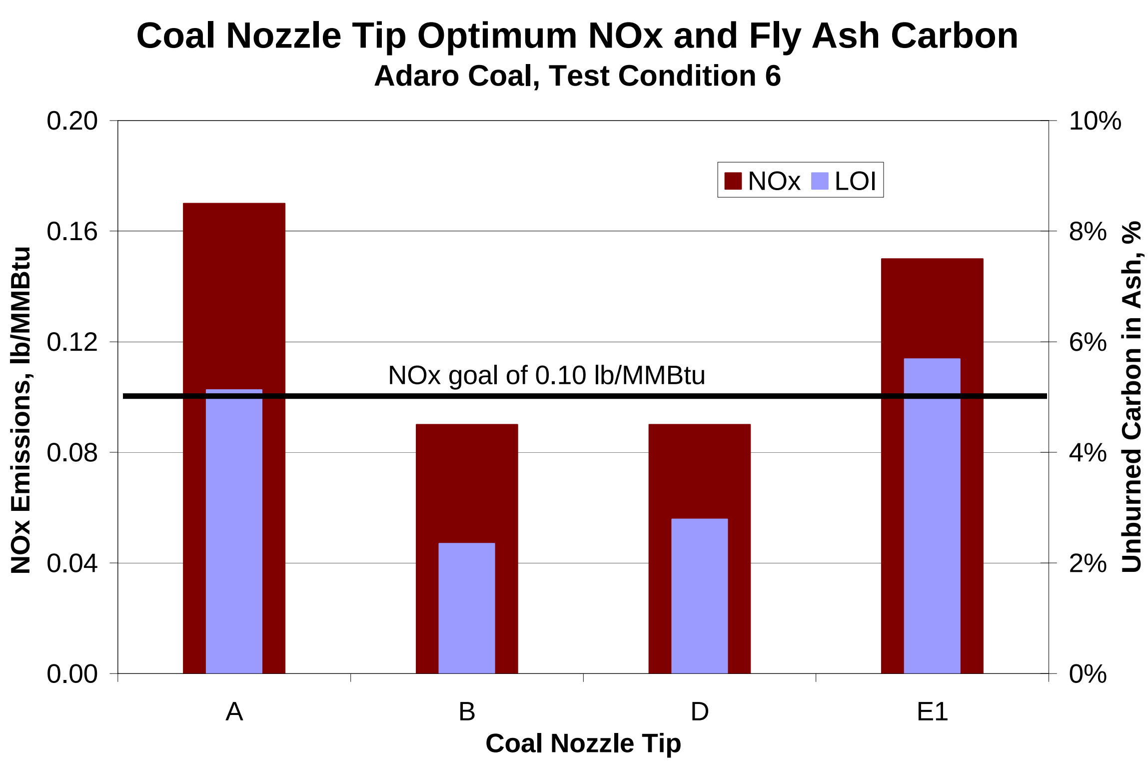


Figure 7.4-18 Optimized NOx and Unburned Carbon Emissions for P2 (A) and Vane Tip Variants on Adaro Coal

The previous three figures show that Vane Tip variants B and D both met the NOx performance goals for all three coals tested. Figure 7.4-16 shows that variants B and D both achieved 0.14 lb/MMBtu NOx emissions rate on the Illinois #6 Midwestern bituminous coal. The results for D had better unburned carbon performance of 10% LOI compared to 14% LOI for B, both of which were better than the P2 at 15%.

Figure 7.4-17 shows that variants B and D both achieved 0.10 lb/MMBtu NOx emissions rate on the Sufco Western bituminous coal. Tips B and D had essentially the same unburned carbon performance of 1.9% LOI compared to 2.1% for the P2 baseline.

Figure 7.4-18 shows shows that variants B and D both achieved 0.09 lb/MMBtu NOx emissions rate on the Adaro subbituminous coal. D showed unburned carbon performance of 2.8% LOI compared to 2.4% LOI for B, and 5.1% for the P2 baseline.

Table 7.4-1 Summary of Illinois #6 Test Points in Test Series 3

Burner	Test Number	Test Cond'n	Start Time	End Time	Duration	O_2	XSA	OFA	FOT	NOx ppm	NOx lb/MM	CO ppm	C in Ash
A	1	1	1/15 08:55	1/15 09:49	00:54	3.38	1.19	None	2591	384	0.53	16	6.49
A	1A	1	1/15 11:06	1/15 11:21	00:15	3.69	1.21	None	2388	382	0.53	12	
A	2	2	1/15 12:05	1/15 12:26	00:21	3.57	1.21	Low	2293	191	0.27	151	21.67
A	3	3	1/15 14:03	1/15 14:12	00:09	3.48	1.20	Med	2362	173	0.24	321	9.60
A	4	4	1/15 15:12	1/15 15:27	00:15	3.44	1.20	High	2412	191	0.26	586	13.96
A	5	5	1/15 16:27	1/15 16:53	00:26	3.66	1.21	Med	2354	182	0.25	146	15.06
A	6	6	1/15 17:51	1/15 18:07	00:16	4.36	1.26	Low	2328	170	0.25	210	15.42
B	11	1	1/15 21:31	1/15 21:57	00:26	3.84	1.22	None	2272	498	0.70	6	4.05
B	12	2	1/15 22:45	1/15 23:13	00:28	3.71	1.21	Low	2170	141	0.20	712	22.50
B	13	3	1/15 23:53	1/16 00:12	00:19	4.25	1.25	Med		106	0.15	781	11.89
B	15	5	1/16 00:23	1/16 00:46	00:23	4.23	1.25	Med	2200	96	0.14	1063	13.59
B	16	6	1/16 01:44	1/16 02:08	00:24	4.08	1.24	Low	2161	100	0.14	759	12.55
C	21	1	1/16 03:38	1/16 03:58	00:20	3.44	1.20	None	2198	481	0.65	72	4.67
C	22	2	1/16 05:14	1/16 05:32	00:18	4.22	1.25	Low	2065	160	0.23	707	13.97
C	23	3	1/16 06:30	1/16 07:00	00:30	3.83	1.22	Med	2213	113	0.16	832	13.90
C	24	4	1/16 07:52	1/16 08:13	00:21	3.92	1.23	High	2275	142	0.20	703	13.43
C	25	5	1/16 09:32	1/16 09:48	00:16	4.28	1.26	Med	2147	109	0.16	1033	16.71
C	26	6	1/16 10:54	1/16 11:14	00:20	3.76	1.22	Low	2205	119	0.17	506	13.16
D	31	1	1/16 13:53	1/16 14:17	00:24	3.43	1.19	None	2362	461	0.62	41	7.35
D	32	2	1/16 20:57	1/16 21:02	00:05	3.88	1.23	Low	2178	136	0.19	101	
D	33	3	1/16 22:58	1/16 23:21	00:23	4.09	1.24	Med	2308	108	0.15	856	10.22
D	34	4	1/17 00:40	1/17 01:00	00:20	4.35	1.26	High	2315	134	0.19	573	16.51
D	35	5	1/16 23:56	1/17 00:19	00:23	4.00	1.24	Med		100	0.14	811	9.95
D	36	6	1/17 01:40	1/17 02:00	00:20	3.78	1.22	Low	2233	95	0.13	457	11.76
E	41	1	1/17 03:33	1/17 03:52	00:19	3.99	1.23	None	2303	482	0.67	40	7.91
E	42	2	1/17 04:49	1/17 05:14	00:25	3.81	1.22	Low	2313	139	0.19	320	8.53
E	43	3	1/17 06:06	1/17 06:27	00:21	4.37	1.26	Med	2237	102	0.15	651	14.79
E	44	4	1/17 08:33	1/17 09:05	00:32	4.12	1.24	High	2372	129	0.18	719	10.70
E	45	5	1/17 07:06	1/17 07:33	00:27	4.32	1.26	None	2283	94	0.14	527	8.16

Table 7.4-2 Summary of Sufco Test Points in Test Series 3

Burner	Test Number	Test Cond'n	Start Time	End Time	Duration	O_2	XSA	OFA	FOT	NOx ppm	NOx lb/MM	CO ppm	C in Ash
A	101	1	1/17 17:50	1/17 18:26	00:36	3.52	1.20	None	2457	343	0.47	46	2.50
A	101A	1	1/18 02:49	1/18 03:15	00:26	3.37	1.19	None		335	0.46	70	1.48
A	102	2	1/18 04:04	1/18 04:24	00:20	3.20	1.18	Low	2413	131	0.18	254	2.36
A	103	3	1/18 05:11	1/18 05:38	00:27	3.74	1.22	Med	2415	120	0.17	115	2.54
A	104	4	1/18 08:50	1/18 09:21	00:31	3.34	1.19	High	2472	129	0.18	75	5.65
A	105	5	1/18 06:04	1/18 06:29	00:25	3.56	1.20	Med	2455	116	0.16	87	2.15
A	106	6	1/18 07:35	1/18 08:00	00:25	3.42	1.19	Low	2434	110	0.15	91	2.24
B	111	1	1/18 11:30	1/18 11:54	00:24	3.38	1.19	None	2370	480	0.66	23	1.02
B	112	2	1/18 13:20	1/18 13:55	00:35	3.68	1.21	Low	2247	147	0.20	628	1.81
B	113	3	1/18 15:16	1/18 15:32	00:16	3.93	1.23	Med	2248	79	0.11	344	2.34
B	114	4	1/18 19:50	1/18 20:16	00:26	4.32	1.26	High	2335	89	0.13	660	3.62
B	115	5	1/18 16:29	1/18 16:44	00:15	3.74	1.22	Med	2259	68	0.10	171	1.89
B	116	6	1/18 18:15	1/18 18:31	00:16	4.08	1.24	Low	2165	130	0.19	682	2.13
E1	121	1	1/18 22:26	1/18 22:48	00:22	3.50	1.20	None	2367	686	0.94	16	
E1	122	2	1/18 23:28	1/19 00:00	00:32	3.36	1.19	Low	2285	153	0.21	364	1.33
E1	123	3	1/19 00:23	1/19 00:45	00:22	3.70	1.21	Med	2313	83	0.12	423	2.61
E1	124	4	1/19 04:36	1/19 04:56	00:20	3.56	1.20	High	2320	99	0.14	370	3.04
E1	125	5	1/19 01:40	1/19 02:02	00:22	3.96	1.23	Med	2242	83	0.12	841	2.65
E1	126	6	1/19 03:07	1/19 03:28	00:21	3.40	1.19	Low	2240	117	0.16	419	2.10
D	131	1	1/19 07:30	1/19 07:58	00:28	3.49	1.20	None	2247	463	0.63	10	0.22
D	132	2	1/19 08:58	1/19 09:19	00:21	3.47	1.20	Low	2293	137	0.19	251	0.88
D	133	3	1/19 10:24	1/19 10:50	00:26	3.77	1.22	Med	2364	89	0.12	358	1.61
D	135	5	1/19 11:44	1/19 12:15	00:31	3.58	1.21	Med	2378	70	0.10	106	1.86

Table 7.4-3 Summary of Adaro Test Points in Test Series 3

Burner	Test Number	Test Cond'n	Start Time	End Time	Duration	O_2	XSA	OFA	FOT	NOx ppm	NOx lb/MM	CO ppm	C in Ash
A	201	1	1/24 00:14	1/24 00:43	00:29	3.52	1.20	None	2453	301	0.42	110	4.60
A	202	2	1/24 01:29	1/24 01:50	00:21	3.76	1.22	Low	2335	135	0.19	144	2.40
A	203	3	1/24 02:17	1/24 02:48	00:31	3.53	1.20	Med	2390	121	0.17	395	4.43
A	204	4	1/24 05:25	1/24 05:47	00:22	3.67	1.21	High	2422	132	0.19	345	4.39
A	205	5	1/24 03:16	1/24 03:44	00:28	3.57	1.21	Med	2418	125	0.18	384	5.40
A	206	6	1/24 04:28	1/24 04:50	00:22	3.61	1.21	Low	2417	122	0.17	577	5.13
B	211	1	1/24 07:52	1/24 08:20	00:28	3.64	1.21	None	2370	397	0.56	1	0.29
B	212	2	1/24 09:36	1/24 10:08	00:32	3.92	1.23	Low	2183	106	0.15	342	1.17
B	213	3	1/24 11:37	1/24 12:10	00:33	3.76	1.22	Med	2270	81	0.12	627	2.91
B	214	4	1/24 18:50	1/24 19:30	00:40	3.74	1.22	High	2213	105	0.15	258	4.63
B	215	5	1/24 13:06	1/24 13:40	00:34	3.67	1.21	Med	2263	89	0.13	466	2.88
B	215A	5	1/24 14:30	1/24 14:54	00:24	3.97	1.23	Med	2180	69	0.10	773	3.08
B	216	6	1/24 15:53	1/24 16:32	00:39	3.69	1.21	Low	2205	64	0.09	428	2.35
B	217	7	1/24 17:35	1/24 18:05	00:30	3.44	1.20	Low		67	0.09	354	
E1	241	1	1/24 21:05	1/24 21:44	00:39	3.65	1.21	None	2383	420	0.59	18	0.77
E1	242	2	1/24 23:25	1/25 00:04	00:39	3.38	1.19	Low	2355	107	0.15	177	2.14
E1	242A	2	1/25 02:30	1/25 02:45	00:15	3.60	1.21	Low	2383	122	0.17	749	
E1	243	3	1/25 03:20	1/25 04:02	00:42	4.07	1.24	Med		93	0.13	908	4.55
E1	244	4	1/25 06:37	1/25 07:16	00:39	4.10	1.24	High		108	0.15	383	6.43
E1	245	5	1/25 04:12	1/25 04:40	00:28	4.04	1.24	Med	2340	92	0.13	1061	6.48
E1	246	6	1/25 05:19	1/25 05:59	00:40	3.92	1.23	Low	2372	101	0.15	968	5.69
D	231	1	1/25 10:01	1/25 10:32	00:31	3.54	1.20	None	2408	386	0.54	4	1.28
D	232	2	1/25 12:08	1/25 12:25	00:17	3.72	1.22	Low	2233	104	0.14	601	1.87
D	233	3	1/25 13:32	1/25 14:03	00:31	3.81	1.22	Med	2243	75	0.11	926	3.71
D	234	4	1/25 15:40	1/25 16:10	00:30	3.36	1.19	High	2224	101	0.14	1021	9.25
D	235	5	1/25 14:38	1/25 15:14	00:36	3.68	1.21	Med	2264	72	0.10	889	3.34
D	236	6	1/25 16:50	1/25 17:20	00:30	3.50	1.20	Low	2304	61	0.09	568	2.79
D	237	7	1/25 17:50	1/25 18:21	00:31	3.55	1.20	Low	2198	71	0.12	216	1.17

7.5 Analysis and Conclusions

7.5.1 NOx Emissions Relative to Base P2 Nozzle A

The primary objective of the Test Series 3 was to compare the NOx emissions of the new coal nozzle tips with those from the baseline P2 nozzle A. The relative maximum emissions reductions are summarized in Figure 7.5-1. The NOx is shown as a fraction of the NOx level with nozzle A at the optimum test condition shown for each tip/fuel combination in Table 7.4-1.

For the Illinois #6 and Adaro coals, each new nozzle tip reduced NOx compared to nozzle A in every test point except for the unstaged test condition 1. With the Sufco coal, the new tips had higher NOx emissions at the unstaged test condition 1 and at the low overfire air conditions 2 and 6, but at the low NOx conditions 3, 4, and 5 the vane tips clearly reduced NOx emissions.

Table 7.5-1 summarizes the minimum NOx emissions achieved for each fuel with each coal nozzle tip and the corresponding test condition, and the percent reduction from the P2 baseline (A). The test conditions were run according to a fixed test matrix, not as an attempt to minimize the NOx for each fuel and nozzle. Therefore the values in Table 7.5-1 do not represent the lowest achievable NOx with that nozzle, but rather the lowest among the tests run. Despite this, as previously mentioned, the primary program goals of 0.15 lb/MMbtu NOx for Illinois #6 and Sufco and 0.10 lb/MMbtu NOx for Adaro were all achieved.

Table 7.5-1 Lowest NOx Achieved for Each Fuel and Nozzle

	A	B	C	D	E	E1
Illinois #6						
lowest NOx (at test condition)	0.25 (6)	0.14 (5)	0.16 (5)	0.13 (6)	0.14 (5)	
% reduction w.r.t. nozzle A		44	36	44	45	
% C in ash	15.42	13.59	16.71	11.76	8.16	
% O_2 in flue gas	4.36	4.23	4.28	3.78	4.32	
nozzle pressure, in. wg	2.4	2.4	3.5	2.6	2.6	
Sufco						
lowest NOx (at test condition)	0.15 (6)	0.11 (3)		0.10 (5)		0.12 (3,5)
% reduction w.r.t. nozzle A		28		36		25
% C in ash	2.24	2.34		1.86		2.63
% O_2 in flue gas	3.42	3.93		3.58		3.70
nozzle pressure, in. wg	3.8	3.2		3.0		3.7
Adaro						
lowest NOx (at test condition)	0.17 (3)	0.09 (6)		0.09 (6)		0.13 (5)
% reduction w.r.t. nozzle A		47		50		24
% C in ash	4.43	2.35		2.79		6.48
% O_2 in flue gas	3.53	3.44		3.50		4.04
nozzle pressure, in. wg	4.2	3.8		4.2		n/a

NOx values in lb/MMBtu

Nozzle D consistently had the greatest reduction for each fuel. Nozzle E had similar reduction for Illinois #6, but was not tested with the other fuels.

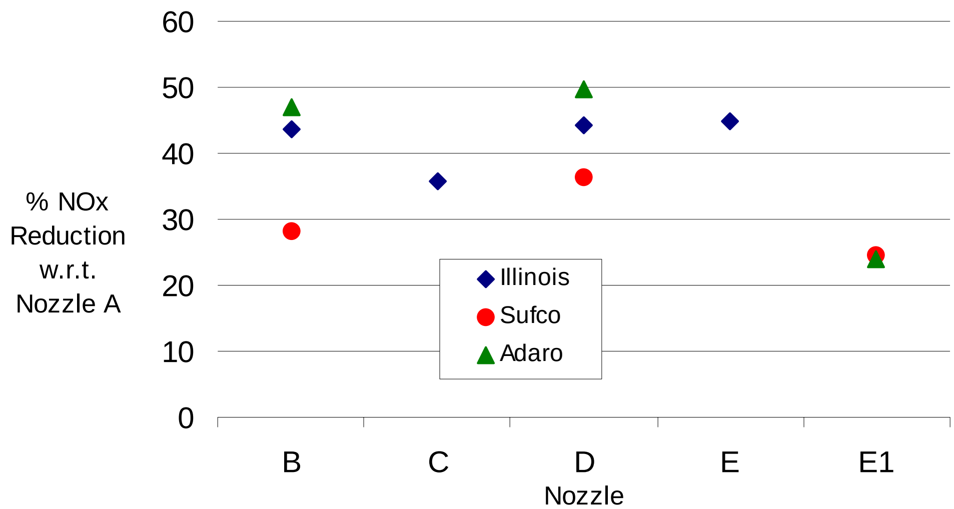


Figure 7.5-1 Percent NOx Reduction with respect to Nozzle Tip A

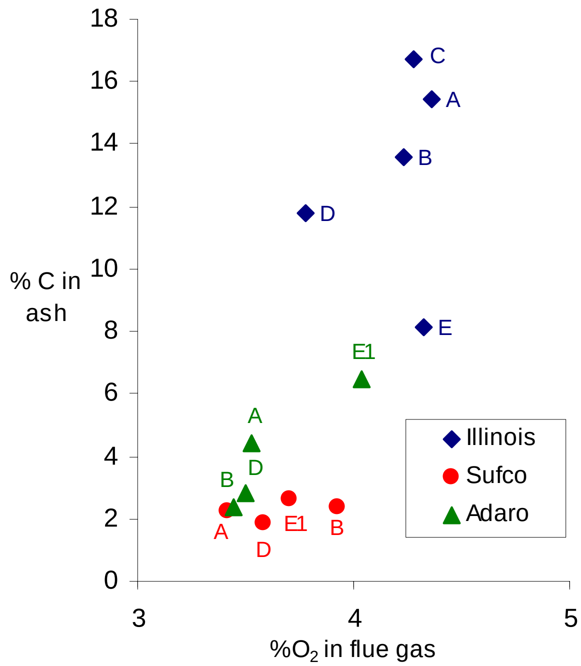


Figure 7.5-2 Percent Carbon in Ash at Minimum NOx Points

7.5.2 Carbon in Ash Relative to Base P2 Nozzle Tip A

The unburned carbon in the flyash for each of the minimum NOx test points is given in Table 7.5-1 and is plotted in Figure 7.4-2. . Recall that there is greater uncertainty in unburned carbon tests than in other tests (Section 7.1). The excess air levels varied somewhat from test to test, due to both natural variation and to maintain permitted CO emissions. A full comparison of unburned carbon in flyash must consider the excess air level, which is also given in Table 7.5-1 as percent O_2 in the flue gas at the minimum NOx condition. In Figure 7.5-2, percent carbon in ash is plotted against percent excess O_2 in the flue gas for each of the optimum test conditions. For all the coals, nozzle tips B and D gave better or equivalent carbon in ash results in comparison to the baseline P2 tip A, and at lower O2 for the Illinois and Adaro coals. This data indicates that there should be no significant detrimental changes to carbon in ash in field applications of the new vane tips.

7.5.3 Coal Nozzle Static Pressure

Table 7.5-1 also lists the coal nozzle static pressure for each of the minimum NOx test points.

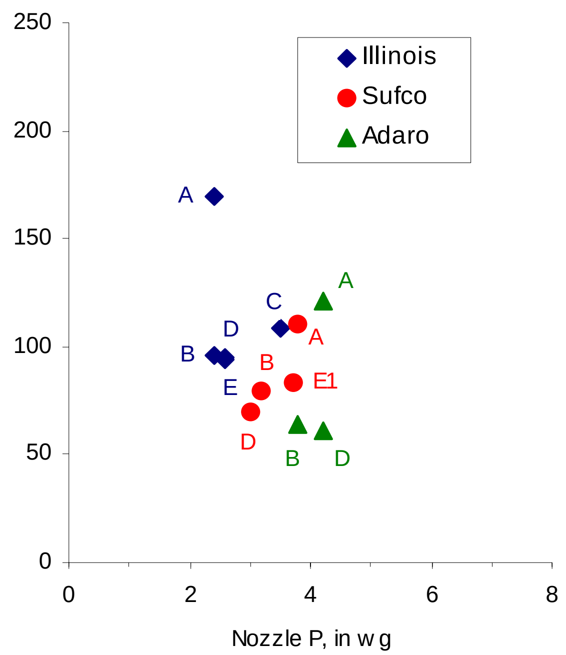


Figure 7.5-3 Minimum NOx Emissions vs. Nozzle Static Pressure

Figure 7.5-3 shows NOx reductions were achieved with the new nozzle tips (B, C, D, E) at minimal to no cost in static pressure versus the baseline A tips.

7.6 Overall Combustion Testing Results

Under staged firing conditions two properties are of paramount importance, as far as NOx reduction and combustion performance are concerned. First, the fuel bound nitrogen must be readily released in the near burner zone to allow the nitrogen to form molecular nitrogen in the region of low oxygen availability. Secondly, the char must be sufficiently reactive and the combustion conditions conducive to completing combustion in the burnout zone. In the case of the three coals evaluated, TGA tests of the subbituminous coal showed the highest percentage of fuel bound nitrogen being released in the near-burner zone and the most reactive char having to be burned in the burnout zone. Conversely, the least reactive coal (Midwestern bituminous) showed the lowest percentage of fuel bound nitrogen being released in the near-burner zone, and the least reactive char having to be burned in the burnout zone. More reactive coals also allow more aggressive conditions to be specified for the staged combustion conditions, i.e., lower stoichiometries and/or longer residence times at reduced stoichiometry. The Western bituminous coal was more reactive and exhibited some combustion characteristics more typical of a subbituminous coal than a bituminous coal.

From the above, it then follows that higher reactivity coals are more amenable to NOx reduction, with acceptable combustion performance, under staged combustion conditions.

Specific, key findings from the pilot-scale testing were as follows:

- The Vane Tip, in several geometry variations and with subcompartmental air, achieved the NOx emissions goals of the project for all three fuels evaluated in the ISBF:
    - The Midwestern bituminous coal tested (Illinois #6) gave NOx emissions of 0.14 lb/MMBtu with 10% fly ash unburned carbon
    - The Western bituminous coal tested (Sufco) gave NOx emissions of 0.10 lb/MMBtu with 1.9% fly ash unburned carbon
    - The subbituminous coal tested (Adaro) gave NOx emissions of 0.09 lb/MMBtu with 2.8% fly ash unburned carbon
- NOx decreased with reduced main burner zone stoichiometry down to an optimum point. The subbituminous and Western bituminous coals gave lower NOx (at optimum stoichiometry) than the Midwestern coal.
- All tips and all coals generally showed substantial increases in unburned carbon at reduced stoichiometry conditions. However the Western bituminous and subbituminous coals generally maintained unburned carbon below the five percent level required for some ash recycling processes.
- CO emissions with the Vane Tips were generally higher than the baseline P2 tips, but this is typically “tunable” at utility boilers where the full range of tangential firing system adjustments are available.
- Front and rear furnace temperature indications showed that the Vane Tips created combustion conditions where the initial heat release was significantly greater than the baseline P2 tip. This accentuated the NOx reduction characteristics of all the coals tested at low main burner zone stoichiometry conditions. However when more oxygen was available at high stoichiometries these combustion conditions naturally led to greater NOx production. It is these combustion conditions that are believed to be the primary contributor to the superior performance of the Vane Tips.

- Comparing optimum tested conditions for the baseline P2 tip versus the Vane Tip variants, the Vane Tips produced overall lower NOx and unburned carbon emissions. At these conditions with Vane Tip D, Midwestern bituminous coal NOx emissions were reduced 44%, Western bituminous coal NOx emissions were reduced 36%, and subbituminous coal NOx emissions were reduced 50%.

8 Coal Nozzle Tip Seal Tests

After the combustion testing, one critical unplanned aspect of the new firing system design had to be addressed, and neither the CFD modeling nor the combustion testing were suitable means to test this operational aspect. Tangential firing requires coal injectors to tilt vertically with minimal complexity. The tilting permits efficient control of steam temperature as load and other conditions vary. This is accomplished via pivoting tips on the end of each coal nozzle.

Pivoting requires a clearance between the nozzle and the pivoting tip, which provides a potential route for coal leakage from the primary coal stream into the secondary air compartment; this leakage can create a fire situation. Typically this issue is addressed through a balance of tip/nozzle design and the use of higher air pressures for the secondary air compartments versus the primary air. However, different backpressure and tilt behavior of a new tip can alter this balance. Because of the different flow characteristics of the new tip, there was a need to analyze its coal leakage potential.

After extensive discussions it was determined that a hydraulic slice (water table) model would be the most effective way to analyze this issue. Water tables allow simple tilt and flow changes; even geometry modifications can be made quickly. The data is qualitative rather than quantitative, but with a comparison to an existing baseline the relative leakage potential of several tip designs can be obtained. In March 2007, design and construction of a suitable test rig was completed, and a few initial tests were performed. In April and May of 2007, the test tips were built and tested on the water table.

8.1 Coal Nozzle Tip Seal Test Rig

The objective of this portion of the project was to investigate coal flow leakage potential due to flow bypass characteristics of the new Vane Tip and compare these to the current P2 tip over a range of operating conditions. The coal nozzle design should allow no flow bypass from the primary air stream to the secondary air passage at normal flow conditions, and minimal bypass at large tilts and reduced secondary airflow conditions. The full range of flow and tilt conditions are all easily simulated with the water table.

Therefore a hydraulic slice model (water table) was constructed for this study. The model consisted of a full scale 1.5" thick slice along the vertical centerline of the coal nozzle assembly (as used in the ISBF combustion testing). The full-scale model was fabricated of Plexiglas acrylic sheets for ease of construction, modification and flow visualization. Water at room temperature was used as the operating fluid. Five inlets were plumbed into the model, one for the primary stream, two each for the secondary and auxiliary streams. Blue dye was injected at selected locations to visualize the flow patterns under various flow conditions. To allow for normal tilting of the system, the tip, nozzle, and seal plates were mounted on separate thin metal plates with a common pivot point.

The water table, made of Plexiglas acrylic sheets, is shown in Figure 8.1-1. Fresh water was pumped into the primary, secondary and auxiliary flow passages. At the end of the water table, water spilled over a weir and was collected in a trough and pumped out to a drainage pipe.

Figure 8.1-1 Water Table Test Rig Setup

The flow rates were controlled by valves and measured by gauges located upstream of the physical model, as shown in Figure 8.1-2. Blue dye was injected into the flow at selected locations by a pressurized dye injector, shown in Figure 8.1-3.

Figure 8.1-2 Inlets to Flow Compartments

Figure 8.1-3 Dye injector

A video camera mounted atop the water table was used to record the flow patterns, with images routed to a TV monitor for ease of viewing in real time, as shown in Figure 8.1-4. This monitor was used to determine the onset of coal leakage into the fuel air compartment.

Figure 8.1-4 Video Monitor Displaying the Flow Pattern in Real Time

Figure 8.1-5 shows the test region of the completed water table with the baseline coal nozzle tip. The blue dye is the primary zone (coal and transport air mix), and the clear flow regions above and below are two levels of secondary air; fuel air adjacent to the primary, and the outer auxiliary air. The marked coal leakage region shows the area of concern where the primary mixture (blue) can leak into the adjacent fuel air compartment.

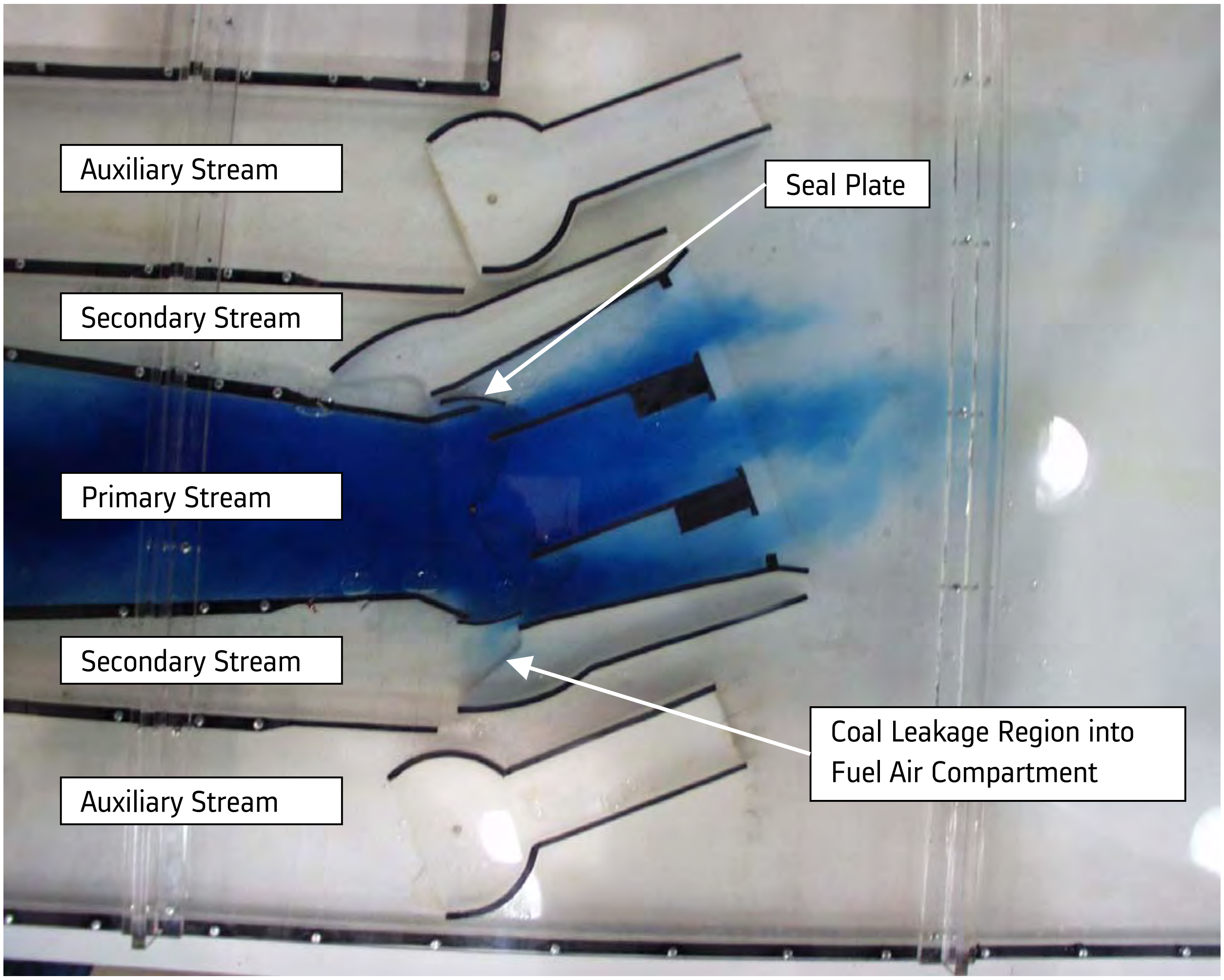


Figure 8.1-5 Baseline P2 Tip Water Table in Maximum Tilted Configuration

8.2 Coal Nozzle Tip Seal Test Results

Bypass between the primary and secondary flow streams is controlled by three factors:

- the pressure difference between the streams at the gaps between the coal nozzle body and the coal nozzle tip;
- the tilt angle of the coal nozzle tip; and
- the geometry of the coal nozzle tip, the seal plate, and the adjacent air nozzles.

For an accurate comparison to full scale burner conditions in the field during the water table experiment, the momentum ratio of the two streams at the tip of the coal nozzle is kept the same as that in the actual gas flow condition. The momentum of the primary stream includes both gas and coal particles. Operation of the model was based on the calculated momentum ratios between the primary, secondary, and auxiliary streams as follows:

$$M_s = \frac{\rho_s A_s V_s^2}{\rho_p A_p V_p^2}$$

and

$$M_a = \frac{\rho_a A_a V_a^2}{\rho_p A_p V_p^2}$$

Where M=Momentum Ratio

ρ = Density of stream

A = Cross Sectional Area at the coal tip location

V = Velocity of stream at the coal tip location

The subscripts “p”, “s”, and “a” refer to the primary, secondary fuel air, and auxiliary streams, respectively. The calculation to convert flows in the water table to equivalent air and coal/primary air flows in a full scale burner in the field has been included in Table 8.2-1.

A range of tilts and flow rates corresponding to field operating conditions were selected for testing. Particular attention was given to the interface area between the primary and secondary flow streams to identify conditions where flow bypassing occurred. Two different flow rates for the primary flow streams corresponding to standard and low load operating conditions were investigated. Secondary and auxiliary flow rates during the tests were representative of low NOx firing conditions.

For each operating condition, the flow rates of primary and auxiliary streams are fixed, while the flow rate of the secondary flow stream is gradually reduced until flow bypass from primary to secondary passage occurs. Results were documented on video.

Tests on the water table were run to show the minimum velocity in the fuel air compartment required to prevent the infiltration of flow from the primary fuel (blue) region. Three different tip arrangements were tested, the baseline P2 tip with a seal plate, Vane Tip B from test series 3 without a seal plate, and Vane Tip B with a seal plate. Alstom typically provides nozzle tips with and without seal plates depending on job requirements such as unit specific geometry and tilt requirements (in general lower tilt requirements means a seal plate is less likely).

Each tip was tested at several flow and tilt conditions as shown in Table 8.2-1. Maximum tilts vary depending on the tip design specifics so are different for each tip. At each test condition, fuel air flow was started at a high level and gradually reduced until blue dye from the primary compartment started to leak into the fuel air compartment. The lower the fuel airflow rate at which the leakage starts, the better the performance of the tip to nozzle seal. The data clearly show, at all the conditions tested, that Vane Tip B performed better than the existing P2 tip design.

Table 8.2-1 Results of Water Table Testing

	Model Condition (gpm)				Equiv. Field Condition (ft/sec)		
Coal Nozzle Type	Primary	Auxiliary	Secondary Fuel Air Leakage Start	Max Tip Tilt (degree)	Primary	Auxiliary	Secondary Fuel Air Leakage Start
Vane Tip w/seal plate	10	8.2	1.6	0	58	129	87
Vane Tip w/seal plate	7	8.2	1.4	0	41	129	82
Vane Tip w/seal plate	10	8.2	1.8	30	58	129	105
Vane Tip w/seal plate	7	8.2	1.2	30	41	129	70
Vane Tip without seal plate	10	8.2	1.8	0	58	129	105
Vane Tip without seal plate	7	8.2	1.4	0	41	129	82
Vane Tip without seal plate	10	8.2	2	20	58	129	117
Vane Tip without seal plate	7	8.2	1	20	41	129	58
P2 Tip	10	8.2	2	0	58	129	117
P2 Tip	7	8.2	1.8	0	41	129	105
P2 Tip	10	8.2	2.9	25	58	129	169
P2 Tip	7	8.2	2	25	41	129	117

These results were separated for full load and low load tests, and the data are presented graphically to compare the performance of the Vane Tip to the P2 Tip. Figure 8.2-1 shows the full load simulation test results, and Figure 8.2-2 shows the reduced load simulation test results. In both cases, the P2 tip requires higher secondary fuel flow to prevent leakage from occurring when compared with results for the Vane Tip mod 4. This clearly shows that the tip to nozzle seal performed better for the optimum low NOx tip (Vane Tip B) than for the existing P2 tip.

For a given nozzle tip, more secondary fuel flow is typically needed to prevent leakage from occurring when the nozzle tip is tilted. However, the Vane Tip exhibits this behavior at full load (Figure 8.2-1) bur not at reduced load (Figure 8.2-2). For the Vane Tip with the seal plate, leakage occurs at a lower secondary fuel flow rate when compared with the results without the seal plate at full load but not for the reduced load simulation. Overall, in all these qualitative tests the Vane Tip performance was found to be superior to the P2 tip and hence there should be no reason to expect tilt operational problems in field installations.

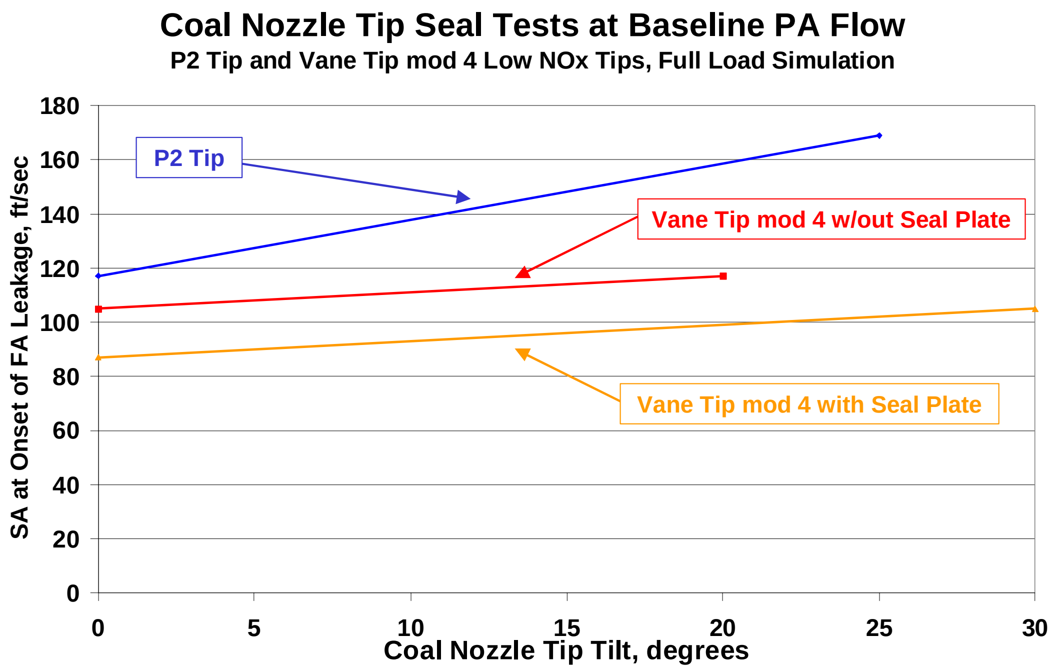


Figure 8.2-1 Full Load Coal Nozzle Tip Seal Test Results

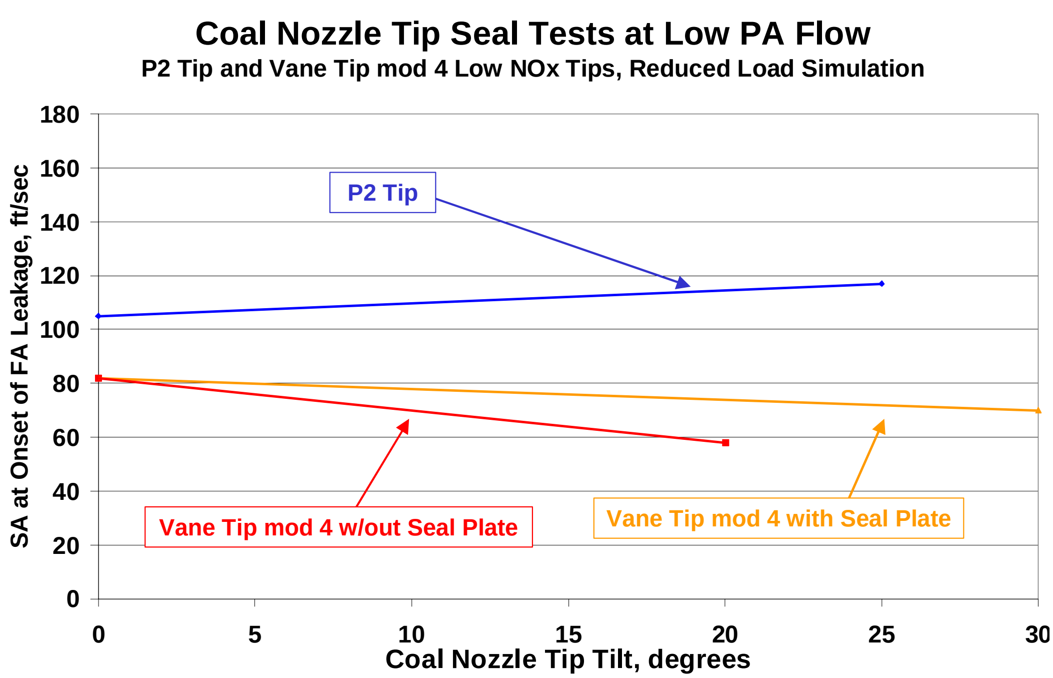


Figure 8.2-2 Reduced Load Coal Nozzle Tip Seal Test Results

9 Economic Analysis

An economic evaluation was performed in order to update prior studies with respect to NOx reduction options, particularly in view of the recent increases in commodity and labor costs for both fuels and materials, and the recent decrease in NOx allowance prices. Various NOx reduction options were evaluated as retrofit cases for 3 tangential-fired utility boilers in the US: (1) a 400 MW boiler on the East coast firing an Eastern bituminous compliance coal, (2) a 500 MW boiler in the Midwestern US firing a local bituminous coal, and (3) a 330 MW boiler in the Western US firing a subbituminous coal from the Powder River Basin (PRB). In addition, for the first two units, a PRB fuel switch and NOx retrofit were also evaluated. The units were selected as being representative of a large number of pulverized coal fired, utility boilers in the US.

9.1 Cost and Sensitivity Analysis

Cost estimates and limited sensitivity analyses were carried out for each of the units. For this study, the units were assumed to be flexible with regard to buying and selling NOx allowances. These allowances could be bought and sold without limits and with no additional local constraints applied. A 15 year project life was assumed and a net present value of the retrofit option was calculated. The results of these calculations were plotted and compared to give an indication of the best choice for any given unit, provided that the assumptions on delivered fuel price and allowance price prevailed. However, it of course must be recognized that the optimum NOx reduction strategy is unit, site, coal, and system specific.

PC Units and Fuels Fired

Five combinations with three fuels and three tangential fired PC units were considered in this study:

- A 400 MW unit on the East coast that typically fires low sulfur, bituminous coal from central Appalachia.
- A 500 MW unit located in the Midwestern US, firing a high volatile bituminous coal with 2.5% sulfur by weight.
- A 330 MW unit firing in the Western US, firing low sulfur Powder River Basin (PRB) subbituminous coal.
- The 400 MW East coast unit switched to firing PRB.
- The 500 MW Midwestern unit switched to PRB.

Assumptions for each case are given in Table 9.1-1. The fuel price for the PRB subbituminous increases with increasing transportation distance from the western mine, as expected. The plant heat rate was assumed to be constant for all cases, regardless of fuel type or NOx control type. The plant's annual NOx allowance is based on an emission level of 0.15 lb/MMBtu fired for 6307 hours per year (a 72% capacity factor).

Table 9.1-1 Assumptions for Economic Analysis

Unit Specific Assumptions

Unit	Fuel	Fuel Price $/MMBtu	Plant Heat Rate Btu/kWh	NOx Allowed TPY
Eastern 400 MW	Eastern Bit PRB	$ 2.29 $ 2.63	10,000 10,000	1894 1894
Mid-Western 500 MW	Mid-Western Bit. PRB	$ 1.11 $ 1.38	10,000 10,000	2367 2367
Western 330 MW	PRB	$ 0.62	10,000	1562

Other Economic Assumptions

Depreciation 15 years	Debt 56%
Analysis horizon 15 years	Interest rate 6.6%
Loan term after construction 15 years	Discount rate 7.5%
Inflation 0%	Corporate tax 20%
Equity 44%	Capacity factor 72%

For each unit and fuel combination, 7 NOx control options were evaluated:

- Case **N** — **N**o low NOx features
- Case **L** — Firing system retrofit with **L**NCFS™ level III
- Case **Lt** — **L**NCFS™ level III with new coal nozzle **t**ips
- Case **Lta** — **L**NCFS™ level III with new **t**ips and subcompartmental **a**ir
- Case **T** — Firing system retrofit with **T**FS 2000™
- Case **Tta** — **T**FS 2000™ with new **t**ips and subcompartmental **a**ir
- Case **S** — **S**CR retrofit

The SCR cases include firing system modification as well:

- Eastern 400 MW unit - TFS 2000™ (Case T) with the SCR providing an additional 80% reduction in NOx.
- Midwestern 500 MW and Western 330 MW units - LNCFS™ level III (Case L) with the SCR providing an additional 80% reduction in NOx.

The NOx emissions assumed for each case are given in Table 9.1-2 and in Figure 9.1-1.

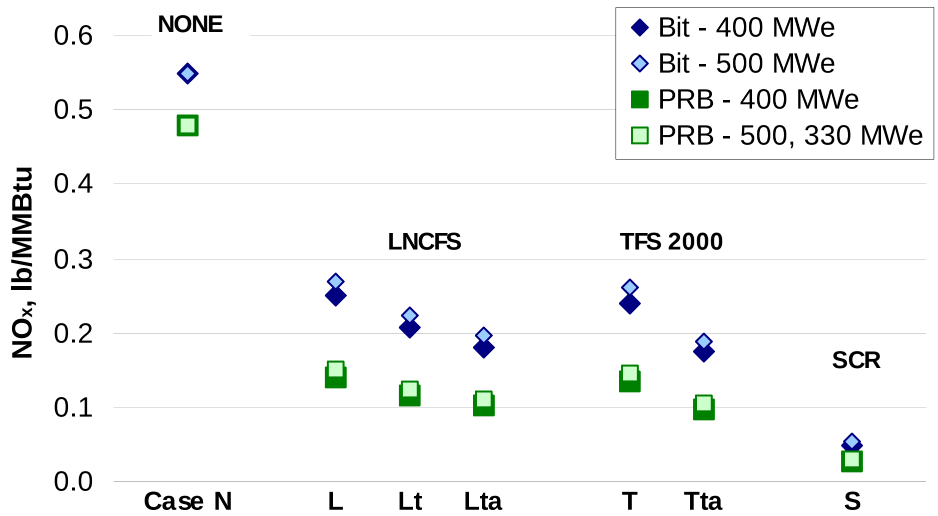


Figure 9.1-1 NOx Emissions Assumed for Economic Analysis

Net Present Value Analysis

For each combination of unit, fuel, and NOx control the net present value (NPV) was calculated for three NOx allowance values: $1,000/ton, $2,000/ton, and $3,000/ton (with $1,000/ton being the approximate current market price). The NPV considers fuel cost, NOx allowance cost or credit, the capital cost of the NOx control technology, and the incremental operating cost for the SCR case. For each unit and fuel combination, the NPV is relative to a base of NPV = 0 for a retrofit to LNCFS™ level III (Case L) with a NOx allowance of $2,000/ton. Thus the NPV's for NOx control for the bituminous units cannot be directly compared to the fuel switching cases.

Sensitivity studies were then performed on Cases Lt and Lta to evaluate the impact of the NOx emissions values being 3% higher or lower than the predicted values.

The results of the analysis are given in Table 9.1-2. The net present values for the base cases are also plotted in Figure 9.1-2 and for the sensitivity cases in Figure 9.1-3.

Since each unit and fuel combination has its own NPV basis, results cannot be compared among them. The final optimum technology results, however, are consistent between the fuel cases.

Bituminous Firing

For this study, firing system modifications with new tips and subcompartmental air are assumed to reduce NOx levels to below 0.2 lb/MMBtu (Cases Lta and Tta), but do not achieve the NOx limit of 0.15 lb/MMBtu (see Figure 9.1-1). NOx allowances must be purchased - thus the NPV decreases with increased allowance price for firing system modification cases (Figure 9.1-2). SCR can of course meet the limit. NOx allowances can be sold - thus the NPV increases with increased allowance price for the SCR case.

Table 9.1-2 Economic Analysis Summary

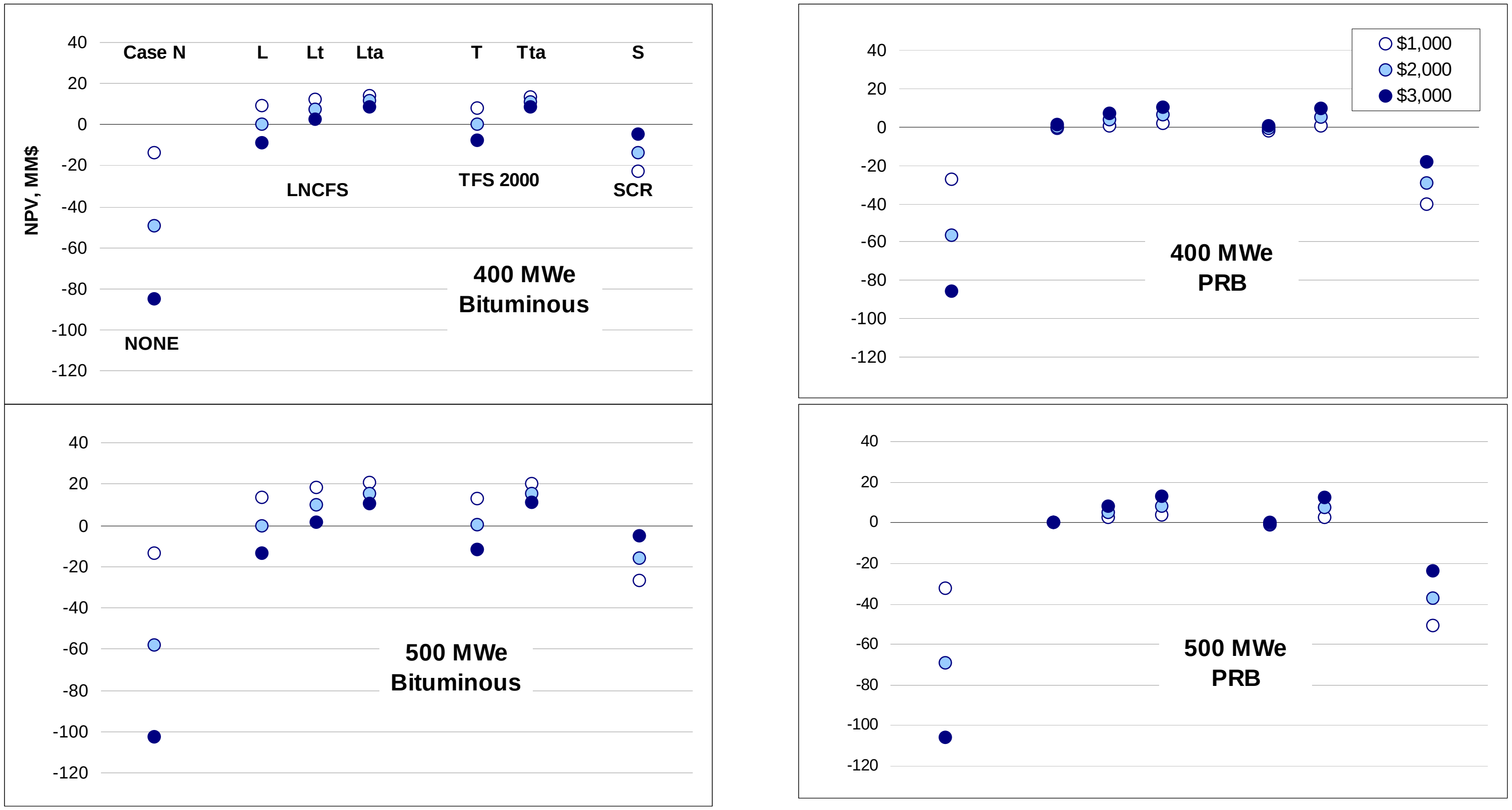
	NOx Emissions			NPV ($MM)			NOx Emissions			NPV ($MM)		
	lb/MMBtu	TPY	relative to Case N	NOx credit, $/Ton: $1,000	$2,000	$3,000	lb/MMBtu	TPY	relative to Case N	NOx credit, $/Ton: $1,000	$2,000	$3,000
	400 MWe - Eastern Bituminous						400 MWe - Powder River Basin					
Case N	0.550	6943	1.00	-13.77	-49.43	-85.09	0.480	6059	1.00	-27.14	-56.56	-85.98
Case L	0.250	3156	0.60	8.91	0.00	-8.92	0.140	1767	0.29	-0.89	0.00	0.89
Case Lt	0.206	2601	0.49	12.30	7.31	2.32	0.115	1452	0.24	0.80	3.92	7.04
Case Lta	0.181	2285	0.43	14.16	11.40	8.64	0.101	1275	0.21	1.68	6.05	10.42
Case T	0.240	3030	0.44	8.13	0.11	-7.91	0.135	1704	0.28	-2.12	-0.78	0.56
Case Tta	0.174	2197	0.40	13.14	11.00	8.86	0.098	1237	0.20	0.30	4.93	9.57
Case S	0.048	606	0.09	-22.60	-13.51	-4.41	0.027	341	0.06	-40.22	-29.25	-18.29
Case Lt, low	0.200	2525	0.48	12.84	8.38	3.92	0.112	1414	0.23	1.07	4.46	7.85
Case Lt, high	0.213	2689	0.51	11.68	6.06	0.45	0.119	1502	0.25	0.45	3.21	5.97
Case Lta, low	0.175	2209	0.42	14.70	12.47	10.24	0.098	1237	0.20	1.95	6.59	11.22
Case Lta, high	0.188	2373	0.45	13.54	10.15	6.77	0.105	1326	0.22	1.33	5.34	9.35

	500 MWe - Midwestern Bituminous						500 MWe - Powder River Basin					
Case N	0.550	8679	1.00	-13.53	-58.10	-102.68	0.480	7574	1.00	-32.47	-69.25	-106.02
Case L	0.270	4261	0.64	13.37	0.00	-13.37	0.150	2367	0.31	0.00	0.00	0.00
Case Lt	0.223	3519	0.53	18.06	9.92	1.79	0.124	1957	0.26	2.35	5.24	8.14
Case Lta	0.196	3093	0.47	20.72	15.59	10.46	0.109	1720	0.23	3.67	8.24	12.80
Case T	0.260	4103	0.47	12.72	0.46	-11.79	0.145	2288	0.30	-1.21	-0.65	-0.09

Case Tta	0.189	2982	0.44	19.86	15.52	11.17	0.105	1657	0.22	2.48	7.49	12.51
Case S	0.054	852	0.13	-26.76	-16.06	-5.36	0.030	473	0.06	-50.48	-37.11	-23.74
Case Lt, low	0.216	3408	0.51	18.84	11.48	4.13	0.120	1894	0.25	2.79	6.13	9.48
Case Lt, high	0.230	3629	0.55	17.28	8.36	-0.55	0.128	2020	0.27	1.90	4.35	6.80
Case Lta, low	0.189	2982	0.45	21.50	17.15	12.80	0.105	1657	0.22	4.11	9.13	14.14
Case Lta, high	0.203	3203	0.48	19.94	14.03	8.12	0.113	1783	0.24	3.22	7.34	11.47

	330 MWe - Powder River Basin					
Case N	0.480	4999	1.00	-20.03	-44.30	-68.57
Case L	0.150	1562	0.31	0.00	0.00	0.00
Case Lt	0.124	1291	0.26	1.40	3.31	5.22
Case Lta	0.109	1135	0.23	2.02	5.04	8.05
Case T	0.145	1510	0.30	-1.30	-0.94	-0.57
Case Tta	0.105	1094	0.22	0.66	3.97	7.28
Case S	0.030	312	0.06	-31.70	-22.87	-14.05
Case Lt, low	0.120	1250	0.25	1.69	3.90	6.10
Case Lt, high	0.128	1333	0.27	1.10	2.72	4.34
Case Lta, low	0.105	1094	0.22	2.32	5.63	8.94
Case Lta, high	0.113	1177	0.24	1.73	4.45	7.17

Underscores in the NOx emission columns indicate where the allowed level of 0.15 lb/MMBtu is met. With higher NOx, allowances must be purchased; with lower NOx, they are sold.



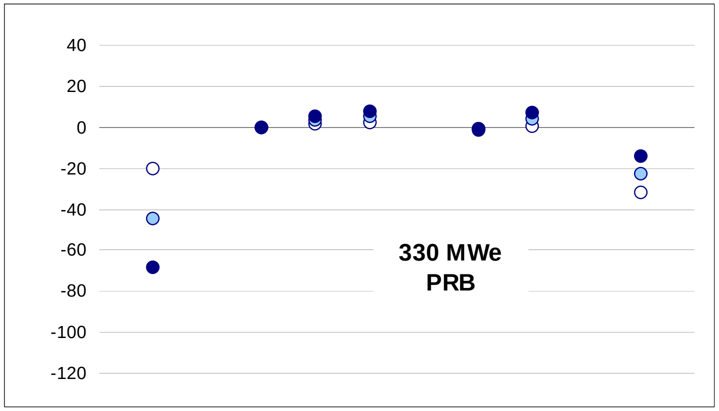
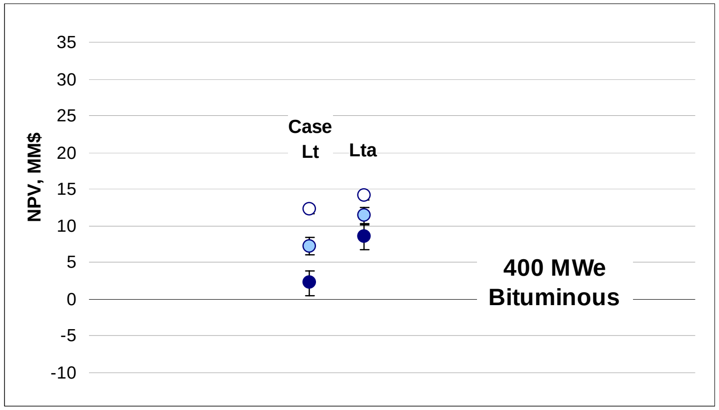
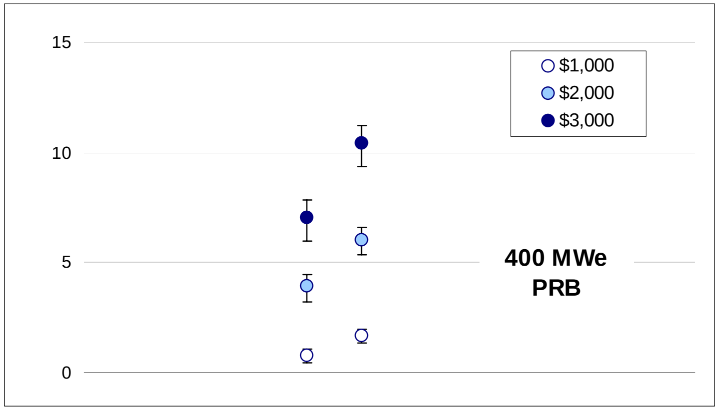
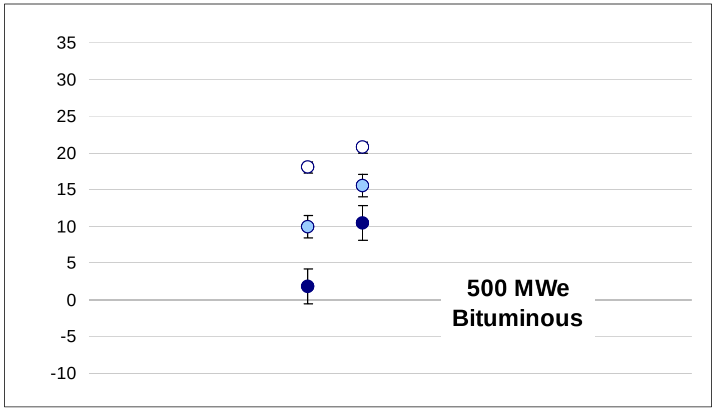


Figure 9.1-2 Net Present Value Results







Bars indicate the sensitivity to variation in NOx emissions:

upper limit - 3% lower NOx

lower limit - 3% higher NOx

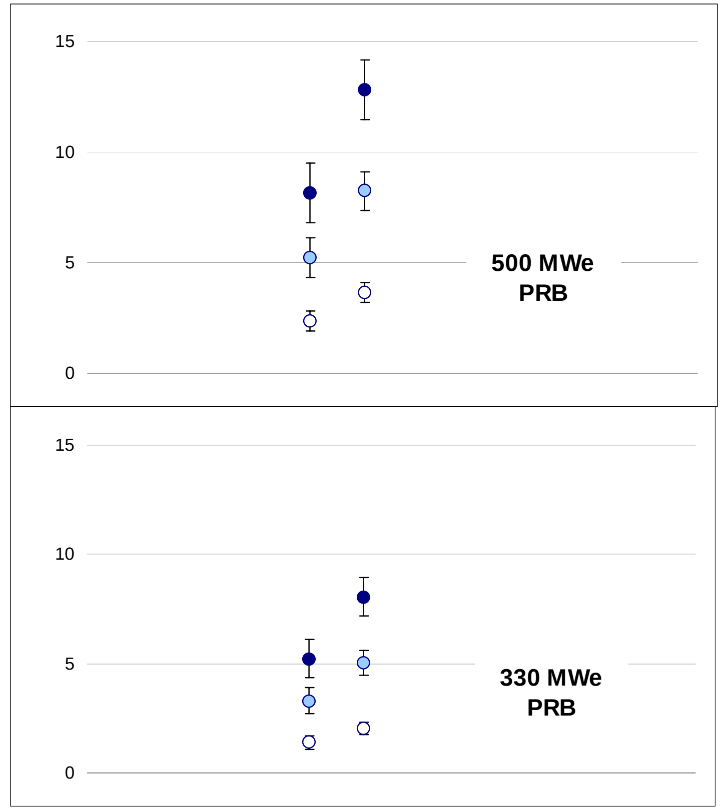


Figure 9.1-3 Net Present Value Sensitivity

Nevertheless, the SCR does not give the highest NPV for bituminous coal firing. The sale of allowances does not offset the high installed and/or operating cost of the SCR, especially at the current NOx allowance price of $1000/ton. At the highest allowance price of $3,000/ton NOx, the SCR option has a slightly higher NPV than the standard firing system modification options L or T.

The highest NPVs result from firing system modifications with new tips and subcompartmental air: Cases Lta and Tta have similar NPV's. The LNCFS™ level III (Lta) has the highest NPV at $1,000 or $2,000/ton allowance price; the TFS 2000™ (Tta) is slightly higher at $3,000/ton. Cases Lta and Tta both have over a $30 million NPV advantage over SCR at the current NOx allowance price of $1000/ton.

Powder River Basin Firing

For PRB firing, all of the firing system modifications are sufficient to achieve the NOx limit of 0.15 lb/MMBtu (see Figure 9.1-1). Only for the uncontrolled Case N must NOx allowances be purchased.

Compared to the low-cost firing system modifications, the high-cost SCR has a negative NPV. It does not provide sufficient incremental allowances for sale.

LNCFS™ level III with new tips and subcompartmental air (Case Lta) has the highest NPV regardless of NOx allowance price. TFS 2000™ with new tips and subcompartmental air (Case Tta) and LNCFS™ level III with new tips only (Case Lt) have NPV's nearly as high in each case. Cases Lta, Tta and Lt all have at least a $30 million NPV advantage over SCR at the current NOx allowance price of $1000/ton.

Sensitivity Analysis

The sensitivity of the NPV to variations of ±3% in NOx emissions for Cases Lt and Lta are given in Table 9.1-2 and Figure 9.1-3. The effect on NPV is obviously greater for a higher NOx allowance credit.

Fuel Switching

Switching from bituminous to PRB firing may be done for reasons other than NOx emissions, such as sulfur emissions. There will be significant economic impacts of fuel switching beyond those considered in this study. These present results do not show how firing system modification on bituminous fired units compares to fuel switching to Powder River Basin. If fuel switching is done, firing system modification to LNCFS™ with new tips and subcompartmental air provides the highest NPV for the conditions of this study.

Capital Cost Summary

The NPV analysis is based on the following estimated capital costs for each of the NOx reduction alternatives, based on Alstom commercial experience. Capital costs are shown in Table 9.1-3. The retrofit capital cost is assumed to be the same whether the unit is firing bituminous coal or has switched to subituminous coal.

Table 9.1-3 Capital Costs of NOx Reduction Options

Case	Cost $1000s	% of Case S	Multiple of Case S
500 MW – L	$5,265	7.0%	14.2
Lt	$5,940	7.9%	12.6
Lta	$6,368	8.5%	11.8
T	$7,425	9.9%	10.1
Tta	$8,370	11.2%	9.0
S	$75,000	100.0%	1.0
400 MW – L	$4,973	8.3%	12.1
Lt	$5,625	9.4%	10.7
Lta	$6,075	10.1%	9.9
T	$7,020	11.7%	8.5
Tta	$8,100	13.5%	7.4
S	$60,000	100.0%	1.0
330 MW – L	$5,198	10.5%	9.5
Lt	$5,828	11.8%	8.5
Lta	$6,413	13.0%	7.7
T	$7,245	14.6%	6.8
Tta	$8,438	17.0%	5.9
S	$49,500	100.0%	1.0

Summary of Economic Analysis

The key findings from this study are

- Low NOx burner retrofits show positive NPVs for most of the cases studied.
- Cases Lta and Tta have at least a $30 million NPV advantage over SCR at the current NOx allowance price of $1000/ton for both bituminous and PRB coal.
- The capital cost for Case Tta is 83-89% less than the SCR-only case for both bituminous and PRB coal. Note that the project goal was only a 25% reduction frome the SCR cost.
- The economic results are dependent upon the fuel and the allowance price level.
- For the allowance price levels and emissions standards used in this study, the SCR option did not provide the optimum economic result. However, there may be other reasons to justify SCR retrofits, such as local regulations, over-control with emission averaging for another unit, higher allowance prices, etc.
- Additional opportunities exist for time-varying over-control, depending upon the current value of NOx allowances.
- Lower NOx allowance prices strongly favor firing system modification economics.

10 Commercialization Plan

The market for retrofit NOx emissions control from existing U.S. coal-fired boilers will be significant for the next several years as plant owners act to comply with Clean Air Act and Ambient Air Quality environmental regulations, and the Clean Air Interstate Rule (CAIR). CAIR requires 25 eastern states to reduce NOx emissions from the power generation sector by 1.7 million tons in 2009 and 2.0 million tons by 2015. This market is highly competitive and plant owners are vigilant in seeking lowest costs. This environment is heightened by craft labor shortages and long equipment supply lead times due to an active global market for new coal power generation.

Today in the United States, existing coal plant owners are generally favorably cost positioned in the deregulated market with paid-down plant capital, low fuel costs, modest O&M, high availability, and a resulting low cost of electricity production, with resulting high capacity factor that further improves electricity production costs. These plant owners seek to maintain this competitive advantage by meeting NOx compliance with the lowest possible levelized costs.

There is generally a range of technically feasible options for a single power plant's unit emissions compliance plan. The challenge is to balance the cost, performance and impact on unit operation for the best overall result. This effort becomes much more complex on a system-wide basis as the matrix of choices expands. However, if this evaluation is done systematically, opportunities exist for the greatest cost savings through the optimization of low-cost firing system modifications combined with strategic utilization of higher-cost SCR systems where necessary.

The in-furnace NOx emission levels that can be achieved are a function of the furnace design, coal properties and the firing system components employed. In general, boilers designed in the nineteen-fifties were conservative in design. The furnaces were typically tall with large cross sectional areas, resulting in lower peak gas temperatures. The generous furnace height can be strategically used in an overfire air retrofit to optimize the staged residence time for maximum NOx reduction. By the mid nineteen-sixties economic pressures dictated reductions in the capital cost of new units, resulting in shorter, hotter furnaces which present a greater challenge for low NOx firing. In addition, as the unit size and electrical output continued to grow, the cross-sectional area of furnace increased. The larger furnace sizes impact the SOFA mixing characteristics that must be optimized for adequate combustion efficiency at optimal low NOx conditions.

As seen in both the large pilot-scale testing performed in this project and in field experience, NOx emissions under low NOx conditions are a strong function of coal rank. The high reactivity, subbituminous and Western bituminous coals are able to achieve lower NOx emissions with air staging than the Midwestern and Eastern bituminous coals that have less reactive chars. These coals also affect many other aspects of boiler operation, from SOx emissions to maximum output to ash quality.

The Alstom Power strategy is to offer plant owners the most cost effective firing system solution to achieve the desired level of NOx reduction for their specific unit. At the start of this project, the TFS 2000™ system was the most aggressive low NOx firing system in the Alstom toolbox for tangentially-fired pulverized coal boilers. With the results of this study, TFS 2000™ and all the other low NOx options may be able to offer significantly improved NOx performance where incorporation of the vane tips is possible, thereby offering some of the most cost effective NOx solutions ever.

The large pilot-scale testing in the ISBF suggested that the combination of vane tips, high set overfire air, and windbox biasing yielded a good compromise between low NOx emissions and acceptable levels of unburned carbon in the fly ash. The testing also showed that the best results varied with coal type and acceptable main burner zone stoichiometry. In the field, results will also vary with specific furnace and firing system geometric characteristics. However, as some of these parameters for improved NOx performance are not possible in some situations, or can result in other negative effects, such as higher levels of unburned carbon in the fly ash, the modifications for a given unit must be carefully selected and engineered. Initial cost, equipment design, operating cost, maintenance, and performance all must be balanced to achieve the customer's goals.

Fuel switching to subbituminous coals is part of both Alstom's and our customer's strategies for decreasing NOx emissions from pulverized coal-fired utility boilers. As was demonstrated in the large pilot-scale testing in this project, the lowest NOx emissions were obtained with the highly reactive subbituminous and Western bituminous coals with minimal impact on the carbon in fly ash. Alstom has significant commercial experience with low NOx firing systems with PRB coals where NOx emissions have been consistently less than 0.15 lb/MMBtu. Where unit requirements warrant, fuel switching will be considered, and incorporated into the overall NOx reduction plan as appropriate.

The first field demonstration of the vane tips is planned for installation during March 2008, utilizing Alstom funding. The unit is a 180MW nineteen-fifties boiler firing PRB in an LNCFS Level II firing system with the P2 coal nozzle tips. Only the tips will be replaced with the vane tip design, there will be no modifications to the overfire air and no internal windbox changes for subcompartmentalization. Therefore the demonstration will provide the most direct comparison of the performance of the P2 coal nozzle tips to the vane tips, similar to the comparative pilot scale tests performed during this development program.

Baseline testing of the unit with the P2 tips will take place as late as possible (February 2008), to minimize the effect of any long term variations in fuel quality. A test matrix will be developed to compare performance over a range of main burner zone stoichiometries, loads, excess airs, tilts, etc. Test data similar to that for the pilot scale testing will be taken with both tip designs. Additionally, longer term tests to look at deposition effects, changes to flame front position, and long term performance changes will also be performed.

The results of this first demonstration will be used to corroborate the results of the pilot scale testing. If the expected significant performance improvement is achieved, a second demonstration at full modern boiler scale (500-900MW) will be arranged and performed. Successful completion of this second demonstration would then lead to commercial offerings. The mechanical designs and the results from the pilot scale testing and the two demonstrations will be utilized to finalize the design standards for use in the commercial offerings.

11 Conclusions and Recommendations

Conclusions

The overall objective of the project is to develop an enhanced combustion, low NOx pulverized coal burner, which, when integrated with Alstom's state-of-the-art, globally air staged low NOx firing systems will provide a means to cost effectively reduce NOx emissions from both existing and new coal fired boilers. Toward that end, Alstom Power set the following specific project objectives for work that was performed in response to the above goal. The first two objectives were "official" in that they were included in the original proposal; Alstom added the remaining supplementary goals after the project start.

- Objective: Develop an enhanced combustion, low NOx pulverized coal burner to achieve less than 0.15 lb/MMBtu NOx emissions with low to no impact on balance of plant issues when firing bituminous coal.

- ❑ Achievement: For the typical Midwestern bituminous coal tested in the ISBF, the specific target was met with emissions as low as 0.14 lb/MMBtu in the pilot scale testing with lower unburned carbon than the baseline. The Sufco Western bituminous coal gave NOx values as low as 0.10 lb/MMBtu. The results suggest that the target is realistic for boilers firing less reactive bituminous coals, although unburned carbon and CO are still potential issues. Given the range and importance of specific coal properties on NOx and combustion performance, as well as the specific boiler designs, it is difficult to project the performance of the new technology over the entire tangentially-fired utility boiler market, but over time the performance capabilities will be quantified.

- Objective: Achieve the above NOx performance with economics that are at least 25% lower cost than SCR-only technology.

- ❑ Achievement: Capital costs for the enhanced combustion, low NOx pulverized coal burner with subcompartmentalized air are well under the target of "25% less than an SCR-only" installation based on commercial costing information. For the bituminous coal cases (taken from Section 9), the capital cost of retrofit with the TFS 2000™ plus the enhanced combustion, low NOx pulverized coal burner with subcompartmental air is about 86-89% less than an SCR-only case; for the subbituminous coal case the TFS 2000™ plus the enhanced combustion, low NOx pulverized coal burner with subcompartmental air is on the order of 83% less than an SCR-only case.

- Objective: Develop an enhanced combustion, low NOx pulverized coal burner to achieve less than 0.10 lb/MMBtu NOx emissions with low to no impact on balance of plant issues when firing subbituminous coals.

- ❑ Achievement: At pilot scale the Adaro subbituminous coal gave NOx values as low as 0.09 lb/MMBtu for the enhanced combustion, low NOx pulverized coal burner. The minimum NOx conditions yielded lower unburned carbon for the new technology than for the baseline tests.

- Objective: Validate the enhanced combustion, low NOx pulverized coal burner with subcompartmentalized air NOx control technology through large (15 MWt) pilot scale demonstration.

- ❑ Achievement: Credible emission results have been obtained from Alstom Power's 15 MWt pilot-scale facility for the many low NOx system variants tested. It is recognized that absolute NOx and carbon in ash emissions levels are a function of the boiler design, including furnace height, furnace cross sectional area, firing zone heat release rates, etc. Since the ISBF was designed to span a range of time-temperature histories of commercial utility and industrial boilers, NOx and carbon in ash levels vary from what might be obtained in commercial utility boilers. However, relative results of the ISBF are broadly applicable and illustrate the effectiveness of firing system modification in lowering NOx emissions and strongly suggest that additional NOx reduction over current commercially available firing systems is possible.

- Objective: Evaluate engineering feasibility and economics for several scenarios of technology components and component integration, for representative plant cases with both bituminous and subbituminous coals

- ❑ Achievement: Engineering and economic evaluations were performed to evaluate various NOx reduction options including the commercially available TFS 2000™ firing system, the enhanced combustion, low NOx pulverized coal burner with subcompartmentalized air developed in this project, and selective catalytic reduction (SCR). Optimum NOx reduction strategy was unit and fuel specific for the three tangential-fired utility boilers evaluated in this study, a 400 MW boiler on the East coast firing an Eastern bituminous compliance coal, a 500 MW boiler in the Midwestern U.S. firing a local bituminous coal, and a 330 MW boiler in the Western U.S. firing a subbituminous coal from the Power River Basin. Of course actual utility NOx reduction strategies must also account for current and anticipated local and national emissions regulations, potential of NOx credit trading, utility deregulation, etc. which may be unit, site, fuel, and system specific.

Results from this project will directly and positively affect Alstom Power's ability to cost effectively reduce NOx emissions from utility boilers.

In addition to the above responses to specific project objectives, key conclusions from Sections 4, 7 and 9 are reiterated here for convenience.

Section 4 – Coal Nozzle Tip Design Screening and Modeling

As part of the DOE sponsored coal nozzle tip development project, CFD modeling was used to gain insight into the mechanisms governing nozzle tip performance with respect to NOx emissions. The CFD simulations were run as steady state, turbulent, non-reacting flow with heat transfer and focused on predicting the near field mixing and particle dispersion rates. CFD results were used to refine the proposed tip concepts before they were built, as well as to help identify and evaluate possible improvements to the tips for subsequent test weeks.

CFD models were generated of the baseline shear bar / air deflector and LNCFS™ P2 tips. From project team discussions and initial modeling, four new coal nozzle tip ideas were selected for detailed modeling and evaluation in the first week of ISBF testing. These are referred to in this report as the center bluff, the recessed center bluff, the X-tip and the diverging hybrid tip. After the first test series, improvements to the week one tips and a newly designed vane tip, conceived after examining the results of the first ISBF test week and the CFD results, were modeled and tested. The CFD modeling and ISBF combustion testing suggest that concentrating the coal particles towards the outside of the coal stream is advantageous for reducing NOx emissions while minimizing unburned carbon levels.

Section 7 - Large Pilot-Scale Combustion Testing

Under staged firing conditions two properties are of paramount importance, as far as NOx reduction and combustion performance are concerned. First the fuel bound nitrogen must be readily released in the near burner zone to allow the nitrogen to form molecular nitrogen in the region of low oxygen availability. Secondly, the char must be sufficiently reactive and the combustion conditions conducive to completing combustion in the burnout zone. In the case of the three coals evaluated, TGA tests of the subbituminous coal showed the highest percentage of fuel bound nitrogen being released in the near-burner zone and the most reactive char having to be burned in the burnout zone. Conversely, the least reactive coal (Midwestern bituminous) showed the lowest percentage of fuel bound nitrogen being released in the near-burner zone, and the least reactive char having to be burned in the burnout zone. More reactive coals also allow more aggressive conditions to be specified for the staged combustion conditions, i.e., lower stoichiometries and/or longer residence times at reduced stoichiometry. The Western bituminous coal was more reactive and exhibited combustion characteristics more typical of a subbituminous coal than a bituminous coal.

From the above, it then follows that higher reactivity coals are more amenable to NOx reduction, with acceptable combustion performance, under staged combustion conditions.

Specific, key findings from the pilot-scale testing were as follows:

- The Vane Tip, in several geometry variations and with subcompartmental air achieved the NOx emissions goals of the project for all three fuels evaluated in the ISBF:
    - The Midwestern bituminous coal tested (Illinois #6) gave NOx emissions of 0.14 lb/MMBtu with 10% fly ash unburned carbon.
    - The western bituminous coal tested (Sufco) gave NOx emissions of 0.10 lb/MMBtu with 1.9% fly ash unburned carbon.
    - The subbituminous coal tested (Adaro) gave NOx emissions of 0.09 lb/MMBtu with 2.8% fly ash unburned carbon.
- NOx decreased with reduced main burner zone stoichiometry down to an optimum point. The subbituminous and Western bituminous coals gave lower NOx (at optimum stoichiometry) than the Midwestern coal.

- All tips and all coals generally showed substantial increases in unburned carbon at reduced stoichiometry conditions. However the Western bituminous and subbituminous coal generally maintained unburned carbon below the five percent level required for many ash recycling processes.
- CO emissions with the Vane Tips were generally higher than the baseline P2 tips, but this is typically "tunable" at utility boilers where the full range of tangential firing system adjustments are available.
- Front and rear furnace temperature indications showed that the Vane Tips created combustion conditions where the initial heat release was significantly greater than the baseline P2 tip. This accentuated the NOx reduction characteristics of all the coals tested at low main burner zone stoichiometry conditions. However when more oxygen was available at high stoichiometries these combustion conditions naturally led to greater NOx production. It is these combustion conditions that are believed to be the primary contributor to the superior performance of the Vane Tips.
- Comparing optimum tested conditions for the baseline P2 tip versus the Vane Tip variants, the Vane Tips produced overall lower NOx and unburned carbon emissions. At these conditions with Vane Tip D, Midwestern bituminous coal NOx emissions were reduced 44%, Western bituminous coal NOx emissions were reduced 36%, and subbituminous coal NOx emissions were reduced 50%.

Section 9 - Engineering Systems Analysis and Economics

An economic evaluation was performed in order to update prior studies with respect to NOx reduction options, particularly in view of the recent increases in commodity and labor costs for both fuels and materials, and the recent decrease in NOx allowance prices. Various NOx reduction options were evaluated as retrofit cases for 3 tangential-fired utility boilers in the US: (1) a 400 MW boiler on the East coast firing an Eastern bituminous compliance coal, (2) a 500 MW boiler in the Midwestern US firing a local bituminous coal, and (3) a 330 MW boiler in the Western US firing a subbituminous coal from the Powder River Basin (PRB). In addition, for the first two units, a PRB fuel switch and NOx retrofit were also evaluated. The units were selected as being representative of a large number of pulverized coal fired, utility boilers in the US.

Cost estimates and limited sensitivity analyses were carried out for each of the units. For this study, the units were assumed to be flexible with regard to buying and selling NOx allowances. These allowances could be bought and sold without limits and with no additional local constraints applied. A 15 year project life was assumed and a net present value of the retrofit option was calculated. The results of these calculations were plotted and compared to give an indication of the best choice for any given unit, provided that the assumptions on delivered fuel price and allowance price prevailed. However, it of course must be recognized that the optimum NOx reduction strategy is unit, site, coal, and system specific.

The key findings from this study are

- Low NOx burner retrofits show positive NPV values for most of the cases studied.
- Cases Lta (**L**NCFS™ level III with new **t**ips and subcompartmental **a**ir) and Tta (**T**FS 2000™ with new **t**ips and subcompartmental **a**ir) have at least a $30 million NPV advantage over SCR at the current NOx allowance price of $1000/ton for both bituminous and PRB coal.
- The capital cost for Case Tta is 83-89% less than the SCR-only case for both bituminous and PRB coal. Note that the project goal was only a 25% reduction from the SCR-only cost.
- The economic results are dependent upon the fuel and the allowance price level.
- For the allowance price levels and emissions standards used in this study, the SCR option did not provide the optimum economic result. However, there may be other reasons to justify SCR retrofits, such as local regulations, over-control with emission averaging for another unit, higher allowance prices, etc.
- Additional opportunities exist for time-varying over-control, depending upon the current value of NOx allowances.
- Lower NOx allowance prices strongly favor firing system modification economics.

Recommendations

1. Pilot scale testing and economic evaluation indicate that the improved firing system hardware developed under this program will likely offer significant NOx reductions at reasonable cost for tangential coal fired boilers. Alstom Power should and will demonstrate, commercialize, and standardize this hardware for deployment to utility boilers as rapidly as possible. The first installation in a utility boiler is scheduled for March 2008.
2. The results of this and earlier programs indicate the sensitivity of emissions performance to firing system design for tangential boilers. Oxy firing, which is likely to play a significant role in the long term control of CO2 emissions, involves many performance design challenges. A significant program to test and optimize firing systems to accommodate the range of coal types should be jointly developed by Alstom and the Department of Energy.

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