Dense Phase Reburn Combustion System (DPRCS) Demonstration On a 154 MWe Tangential Furnace: Additional Area of Interest - To Develop and Demonstrate an In-Furnace Multi-Pollutant Reduction Technology to Reduce NO_x, SO_2 & *Hg*

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Abstract

Semi-dense phase pneumatic delivery and injection of calcium and sodium sorbents, and microfine powdered coal, at various sidewall elevations of an online operating coal-fired power plant, was investigated for the express purpose of developing an in-furnace, economic multi-pollutant reduction methodology for NO_x, SO_2 & Hg. The 154 MWe tangentially-fired furnace that was selected for a full-scale demonstration, was recently retrofitted for NO_x reduction with a high velocity rotating-opposed over-fire air system. The ROFA system, a Mobotec USA technology, has a proven track record of breaking up laminar flow along furnace walls, thereby enhancing the mix of all constituents of combustion. The knowledge gained from injecting sorbents and micronized coal into well mixed combustion gasses with significant improvement in particulate retention time, should serve well the goals of an in-furnace multi-pollutant reduction technology; that of reducing back-end cleanup costs on a wide variety of pollutants, on a cost per ton basis, by first accomplishing significant in-furnace reductions of all pollutants.

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Introduction

The Dense Phase Reburn Combustion System (Pilot Scale Project) was originally designed around development of a CentroFloat milling system, MC-coal reburning by pneumatic delivery of micronized coal at a high coal/air ratio, in conjunction with an existing NO_x reduction technology [ROFA/ ROTOMIX a design of Mobotec USA]. The goal was to combine these two known NO_x reduction technologies into a single in-furnace technology that would reduce NO_x to below 0.15 lbs/mmbtu at (3/4 -1/2) the cost of an SCR. Due to some initial success by Mobotec AB in Sweden, furnace sorbent injection (FSI) was added to the project resulting in a FULL SCALE EVALUATION OF AN IN-FURNACE, MULTI-POLLUTANT REDUCTION TECHNOLOGY. The bulk of the work associated with these trials centered around FSI and the most positive results were from the sorbent injection trials. Chronologically the FSI trials were completed first and correspondingly this cumulative test data and methods will be described first.

Executive Summary

Sorbent Injection Trials

Furnace sorbent injection (FSI), using finely powdered limestone and Trona, was examined in combination with the existing Rotating Opposed Overfire Air system [ROFA™ by Mobotec USA] installed on Unit 5 at the Cape Fear Generating Station, for the purpose of obtaining substantial SO_2 and mercury reductions at low capital and operating costs. These two sorbents were chosen to compare the impact of calcium carbonate versus sodium carbonate in a highly reactive environment. Significant SO_2 reductions of 69% were achieved with Trona and 64% with limestone. Surprising mercury reductions of 89% were achieved with limestone and 67% with Trona. Slagging in the superheater section was however, a major operational concern and will be described in detail later in the report. Summarized test results as provided by URS are presented in Table 1.

- Demonstration Site location
  - Carolina Power & Light Div: Progress Energy
  - Cape Fear #5 Power Plant Moncure, NC
  - 154 MWe 4-Corner tangential furnace Built in 1957

- Principle Team Members
  - Wiley & Associates Developer of micronized coal reburn technology
  - Mobotec USA (ROFA/ROTOMIX) Developer of rotating opposed fired air systems
  - Progress Energy Host Utility

- Primary sub-contractors
  - Reaction Engineering International (REI) Computational Fluid Dynamic Modeling
  - URS Third party engineering firm (data collection for FSI trials)

Micronized Coal Trials

The Micronized coal (MC-coal) trials were completed in March of 2003 with mixed results. Cape Fear #5, was in a deeply staged operating condition with the ROFA system in place, and was already at .17-.26 lbs/mmbtu NO_x. Conventional reburn technologies call for injection between an overfire air system (OFA) and the primary combustion zone. However, Computational Fluid Dynamic (CFD) modeling indicated that conventional reburn would increase the exit NO_x. This modeling analysis was confirmed with full-scale testing results. CFD modeling of the furnace concluded that the core of the furnace contained the highest NO_x, therefore MC-coal injection very low in the furnace would drive the core fuel rich and consume NO_x. Methods and results will be discussed later in the micronized coal injection part of this report.

Results and Discussion

URS - Sorbent Injection Test Results

Prepared For: Mobotec, USA Inc. Raleigh, NC

Prepared By: URS Corporation, 1600 Perimeter Park Dr., Morrisville, NC

Introduction (URS)

During November and December 2002, URS performed tests for emissions of mercury (Hg), sulfur dioxide (SO_2), sulfuric acid mist (SO_3), hydrogen chloride (HC1) and particulate matter (PM) on Unit 5 at Progress Energy's Cape Fear Plant. Tests for Hg, SO_2 and SO, were conducted at the exhaust stack, downstream of the electrostatic precipitator (ESP). Tests for HCl and PM were conducted at the inlet of the ESP. All appropriate notices prior to testing were submitted to the North Carolina Division of Air Quality (DAQ).

The exhaust is a circular stack, with four test ports located at right angles to each other for traversing the exhaust. At the test location the measured inside diameter is 144 inches. The test ports are located >8 diameters downstream of the breaching from the ESP and >2 diameters upstream of the outlet of the stack. Only two test ports were fully accessible during testing, because of other probes that were in the stack.

The ESP inlet testing location consists of two identical, parallel rectangular ducts, 171 inches wide and 83 inches deep. Each rectangular duct is equipped with eight test ports. Due to physical obstructions, testing was conducted in four ports in each of the two ducts.

A five-person URS test team, under the direction of Ron McCulloch performed the emissions testing. Steve Castagnero of Progress Energy provided oversight to the sampling.

Table 1 shows a summary of the calculated emission reduction performance of the sorbents based on comparison of stack concentrations during the sorbent injection tests to the baseline tests. Discussion of factors that may influence of bias these values is included in Results.

Table 1 - Summary of Emission Reduction Performance

(SO_2 *Reductions are measured in lbs/hr)*

Pollutant	Limestone	Trona
SO_2	69%	64%
SO_3	88%	93%
Hg (total)	89%	67%
HCl	12%	78%

RESULTS

This test series was performed to evaluate SO_2 and Hg reduction potential of two sorbent materials. Emissions were tested under three conditions. Baseline tests were conducted, during which no sorbents were injected. Limestone and Trona sorbents were injected at two feed rates each. The boiler was operated at 75% load during all tests.

Each test run included measurements for velocity (U.S. EPA RM 1, 2), molecular weight (U.S. EPA RM 3) and moisture (U.S. EPA RM 4).

Tests for Hg and HCl/PM were conducted by employing the appropriate isokinetic sampling methods, as indicated in the test plan (Hg: Ontario Hydro Test Method; HCl/PM: U.S. EPA RM 5/26A). Testing for SO_2 /SO_3 was conducted using the controlled condensation system (CCS) method.

Rates of HCl and PM mass flow into the ESP measured during the test program are shown in Table 2. Limestone feed rates were 5,800 lb/hr during the first run and 8,700 lb/hr during the second run. Trona feed rates were 3,606 lb/hr during the first run and 7,212 lb/hr during the second run. Emission rates of Hg, SO_2 and SO_3 from the exhaust stack, measured during the test program are shown in Table 3.

Velocity of the exhaust gas was measured using RM 2. Both isokinetic sampling methods used in this test series (Ontario Hydro and U.S. EPA RM 5/26) employ a Type -S pitot tube conforming to the geometric design requirements of RM 2. Twelve traverse points, six on each of two perpendicular traverse lines, were measured in the stack (Table 4), as indicated by U.S. EPA RM 1. At the ESP inlet, measurements were made using a 4 x 3 matrix (Table 5). Temperature was also determined at each point with a Type K thermocouple. The dimensions of the sampling location met U.S. EPA RM 2 requirements for a stable, fully developed flow pattern (RM 2, Section 10.1.2.2) . Pitot tube configuration was checked after the completion of the test to insure that the sampling tips were not damaged during use.

Oxygen (0_2) and carbon dioxide ($C0_2$) were measured during the testing program to calculate the molecular weight of the exhaust gas. These molecular weights were used to determine volumetric flow at standard conditions for calculations of mass emission rates. The 0_2 and CO_2 measurements were made with a Fyrite system (U.S. EPA RM 3).

Moisture in the exhaust gas was measured using U.S. EPA RM 4. RM 4 determines moisture by condensing the water from a known volume of sample and measuring the collected water gravimetrically, and is an integral part of the Ontario Hydro method, CCS, and RM 5/26A.

Table 2 - Location of Velocity Sampling Points
(Exhaust Stack**)**

Inside Stack Diameter – 144”		
Point Number	**% of Diameter From Wall**	**Distance From Wall (inches)**
1	4.4	6.3
2	14.6	21.0
3	29.6	42.6
4	70.4	101.4
5	85.4	123.0
6	95.6	137.7

Table 3 – Location of Velocity Sampling Points
(ESP Inlet)

Inside Stack Depth – 83”		
Point Number	**% of Depth From Wall**	**Distance From Wall (inches)**
1	16.7	14.0
2	50.0	41.5
3	83.3	69.0

Table 4 - HCI and PM Mass Flow into ESP

Condition	Units	**Baseline**			Limestone				**Trona**			
Run	'		2	Avg		2	Avg	%Red*			Avg	%Red
Date		11/12/02			12/10/02				12/13/02			
Start Time		10:10	14:02		12:29	16:20			9:45	14:10		
End Time		12:19	16:10		14:43	18:32			12:01	16:22		
Flow	dscfm	282,609	322,967	302,788	256,095	262,486	259,291		243,832	224,469	234,150	
Temp	°F	243	243	243	246	245	245		262	271	267	
02	% dry	4.3	4.3	4.3	5.5	5.4	5.4		4.6	3.9	4.3	
H20	% Vol	8.0	7.5	7.8	5.3	6.3	5.8		6.6	7.4	7.0	
HCl	ppmVd	64.8	67.5	66.2	53.3	62.8	58.1	12.3%	16.1	12.4	14.3	78.4%
	lb/MMBtu	0.13	0.14	0.14	0.12	0.14	0.13	5.8%	0.03	0.02	0.03	78.4%
	lb/hr	104.2	124.0	114.1	77.7	93.7	85.7	24.9%	22.3	15.9	19.1	83.3%
PM	gr/dscf	5.01	4.84	4.92	3.95	4.12	4.03	18.0%	1.23	0 75	0.99	799%
	lb/MMBtu	8.8	8.5	8.7	7.5	7.8	7.6	1 1.9%	2.2	1.3	1.7	79.8%
	lb/hr	12,127	13,392	12,760	8,660	9,280	8,970	29.7%	2,577	1,441	2,009	84.3%

Table 5 – Hg, SO_2, and SO_3 Emission Rates at Exhaust Stack

Condition	Units	**Baseline**			Limestone				Trona			
Run		1	2	Avg	I	2	Avg	%Rcd*	1	2	Avg	%Red
Date		11/12/02			12/10/02				12/13/02			
Start Time		10:10	14:02		12:29	16:20			9:45	14:10		
End Time		12:19	16:10		14:43	18:32			12:01	16:22		
Flow	dsctm	271,890	237,852	254,871	234,814	234,010	234,412		234,860	229,637	232,248	
Temp	°F	246	245	245	274	287	281		248	261	254	
0_2	% dry	7.5	6.5	7.0	9.3	10.5	9.9		8.0	6.3	7.1	
H_2O	% Vol	8.5	7.7	8.1	6.7	7.1	6.9		6.5	7.1	6.8	
SO_2	ppmVd	729.9	706.2	718.1	324.3	356.0	340.2	52.6%	296.1	291.0	293.5	59.1%
	lb/MMBtu	1.9	1.7	1.8	0.9	1.2	1.1	40.0%	0.8	0.7	0.7	58.6%
	lb/hr	2,742	1,675	2,208	759	831	795.1	64.0%	694	666	679.9	69.2%
SO_3	ppmVd	0.47	0.54	0.51	0.06	0.06	0.06	87.5%	0.04	0.03	0.03	93.1%
	lb/MMBtu	0.0015	0.0016	0.0015	0.0002	0.0003	0.0002	84.2%	0.0001	0.0001	0.0001	93.0%
	lb/hr	0.0042	0.0047	0.0044	0.0006	0.0006	0.0006	86.9%	0.0003	0.0003	0.0003	93.0%
Hg ^{PM}	pg/Nm^3	0.10	0.01	0.05	0.18	0.01	0.09	-79.1%	0.04	0.11	0.08	*-52.1*
	lb/MMBtu	8.6E-08	6.6x 10^{-9}	4.6x 10^{-8}	1.8x 10^{-7}	8.2x 10"9	9.6x 10-'	-108.1 %	4. 1 x 10"8	9.3x 10^{-8}	6.7x 10-'	-45.2%
	lb/hr	9.2E-05	6.6x 10"6	4.9x 10^{-5}	0.00015	5.8x 10^{-6}	7.7x *10-5*	-56.2%	3.7x 10^{-5}	92x 10^{-5}	6.4x 10"5	-30.5%
Hg ^{2*}	µg/Nm^3	7.95	8.16	8.06	0.90	1.04	0.97	87.9%	2.07	2.15	2.11	73.8%
	lb/MMBtu	7.1 E-06	6.7x 10"6	6.9x 10^{-6}	9.2x 10^{-7}	1.2x 10^{-6}	1.1 X10^{-6}	84.7%	I .9x 10^{-6}	1.7x 10-"	I .8x 10^{-6}	73.5%
	lb/hr	0.0075	0.0068	0.0072	0.0007	0.0009	0.0008	88.9%	0.0017	0.0017	0.0017	76.1
Hg °	pg/Nm^3	2.50	3.14	2.82	0.09	0.07	0.08	97.1%	1.54	1.28	1.41	50.1
	lb/MMBtu	2.2E-06	2.6x 10^{-6}	2.4x 10"6	9.2x 10^{-8}	8.5x 10^{-8}	8.9x 10^{-8}	96.3%	1.4x 10^{-6}	1.0x 10^{-6}	1.2x 10^{-6}	49.0%
	lb/hr	0.0024	0.0026	0.0025	0.0001	0.0001	0.0001	97.3%	0.0013	0.0010	0.0011	54.2%
Hg ^{Total}	pg/Nm^3	10.54	11.31	10.93	1.18	1.12	1.15	89.5%	3.65	3.54	3.60	67.1%
	lb/MMBtu	9.4E-06	9.3x10^{-6}	9.3x10^{-6}	1.2x10^{-6}	1.3x10^{-6}	1.2x10^{-6}	86.7%	3.4x10^{-6}	2.9x10^{-6}	3.1x10^{-6}	66.6%
	lb/hr	0.0100	0.0094	0.0097	0.0010	0.0009	0.0009	90.3%	0.0030	0.0028	0.0029	69.9%

Observations Regarding the Operating Processes and the Test Results Include:

1. The measured exhaust gas flow rates during the baseline testing were higher than during the limestone and Trona injection tests. Also, measured flow rates were higher at the ESP inlet than at the exhaust stack; this could be due to erroneous cross-sectional dimensions.

2. Due to apparent ambient air dilution of the $0_2/C0_2$ samples that were collected at the ESP inlet (these ports are under significant negative pressure of ˜-9" w.c.), the plant's 0_2 readings were used to estimate 0_2 levels at the ESP. The difference in plant readings and test-site readings did not have a significant impact on calculated emission concentrations or mass emissions, but the plant readings were considered more reliable.

3. No significant differences were observed between the emissions during first and second runs with each sorbent. Given the different sorbent injection rates during the two tests, this would indicate that the higher sorbent injection rate provided very little additional emission reduction, and that a lower sorbent injection rate may be able to achieve similar emission reductions.

4. The PM measurements at the ESP inlet are consistent with the buildup of sorbent and flyash upstream of the ESP inlet. The PM loading at the ESP inlet was ~20% lower during the limestone injection tests than during the baseline and was ~80% lower during the Trona tests. The ESP inlet temperature during the Trona test was ~20°F higher than during the baseline and limestone tests, also indicating fouling of heat transfer surfaces during the Trona tests.

5. The SO_2 performance levels as measured with CCS were similar to those indicated by the plant's CEM measurements during the Trona testing. Differences in percent reduction observed during the limestone tests appear to be mainly related to differences in methodology. Sorbent injection data were compared to the baseline data, while the plant had CEM data with and without sorbent injection on the same day. Furthermore, the plant data are based on SO_2 in units of lb/MMBtu while the Tables 4 and 5 are based on ppm readings. The CCS data converted to lb/MMBtu show an SO_2 reduction of ~40% during the limestone tests (similar to the CEM data) and a higher outlet level. The reason for the lower SO_2 level measured by the CEM is uncertain, but could be due to measurement variability or other factors. The difference in percent reductions based on ppm vs. lb/MMBTU is caused by the increase in stack O_2 levels during the limestone testing compared to the baseline and Trona tests. *Therefore,* SO_2 *reductions have been presented in absolute terms (lbs/hr), and are not dependent upon excess* O_2 *or differences in methodology*.

6. Although the data indicates high SO_3 reductions during injection tests, the SO_3 concentration at baseline was very low (~0.5 ppm; <1% of the SO_2 concentration).

7. Based upon review of the data and the background literature, the Hg reduction data are interesting from several perspectives and appear to reflect both changes in Hg speciation and variations in collection efficiency of individual species. No significant differences were observed between the results from the initial analysis and the reanalysis of the samples.

Sampling and Analytical Procedures

The sampling and analytical procedures used for these tests are described in the Test Protocol (Appendix A) of the original URS report. The test plan was reviewed and approved by DAQ prior to conducting the test on site.

The test methods used to perform the sampling and analysis are provided in Table 6. Additional details regarding the methods are described in the test protocol. The sampling locations and sampling ports are also described in the protocol.

Table 6. Test Methods

Parameter Measured	Method Number
Velocity	EPA Reference Methods I and 2
Oxygen and Carbon Dioxide	EPA Reference Method 3
Mercury (Hg)	Ontario Hydro (ASTM D6784-02)
Sulfur Dioxide/Sulfuric Acid Mist a	Controlled Condensation System (CCS)
Hydrogen Chloride	EPA Reference Method 26A
Particulate Matter	EPA Reference Method 5/26A

* Sulfate and chloride content of samples was analyzed by ion chromatograph

Documentation

Complete Field Data Sheets are provided in Appendix B of the original URS report. Appendix B also includes sampling summaries, equipment calibration sheets, and pitot tube inspection sheets. Analytical data is included in Appendix C. The original report is available through the URS office in Morrisville, NC.

Quality Assurance/Quality Control

Specific QA/QC procedures that were identified in the test plan and reference methods were followed to ensure data quality suitable for determining compliance status. Method-specific QC checks and corresponding results are shown in Table 7. Analytical QA/QC measures for sulfate and chloride analysis, including calibrations, are detailed in the complete laboratory report in Appendix C.2. (Available through URS)

Table 7. Method-Specific QA/QC Results

QA/QC Parameter		Requirement	Result
Method 2	Manometer Leak Check	No leaks at >3" water column	Passed
	Passing Pilot Tube Inspection	See Appendix B.3	Passed
Method 5/26A & Ontario Hydro	Manometer Leak Check	No leaks at 5-7" water column	Passed
	Sampling System Leak Check'	<4% of sampling rate (or < 0.02 cfm); >_ 15" Hg vacuum	Passed
	% Isokinetic	90-110%	100.0 - 108.1
	Dry Gas Meter Calibration Factor (Y_d), Initial [a]	0.95- 1.02	1.001-1.019
	Dry Gas Meter Calibration Factor (Yd), Final [a]	Initial Y_d ± 5%	± 1.7%
	Nozzle Diameter Measurements	Within 0.004"	Passed
	Repeat Weighing Precision	± 0.5 mg (0.0005g)	± 0.4 mg

a) Leak check and calibration requirements also apply to CCS sampling

Performance Audit Samples

No performance audit samples were provided for this test program.

Progress Energy Executive Summary (Furnace Sorbent Injection Trials)

One of the goals of Progress Energy's Strategic Engineering Unit is to identify and assess new environmental technologies to meet current and future air emission regulations, while maintaining the competitiveness of Progress Energy's generation fleet.

In 2000, MobotecUSA successfully installed ROFA and reduced NO_x, air emissions at Progress Energy's Cape Fear Unit 5 by 55%. Mobotec has also been successful in Sweden coupling ROFA with FSI (Furnace Sorbent Injection) to reduce SO_2 air emissions by 90%. FSI is considered a multi-pollutant technology, reducing SO_2, mercury, and HCI. FSI injects sorbent material into the upper region of a coal-fired furnace to reduce pollutants. The solids are then subsequently removed by a particulate removal device. Sorbent materials can include limestone, lime, and sodium bicarbonate.

In March 2002, Progress Energy, Mobotec USA, Wiley & Associates, and the Department of Energy formed a team to evaluate the effectiveness of the FSI technology with ROFA The project goal was to achieve greater than 75% SO_2 air emissions reduction and greater than 50% mercury reduction Additionally, the trial was to obtain operational knowledge to determine if a long term trial was worthwhile. Cape Fear Unit 5 was chosen as the test site. Cape Fear Unit 5 is a 153MWe corner fired unit, currently burning .88% sulfur coal. Sorbent materials for the short term trial included limestone and Trona. Trona is a sodium based product mined in Wyoming.

On December 8, 2002, the FSI trials commenced by injecting limestone at a low rate to determine safety and operational issues. Official testing was conducted for limestone and Trona on December 10 and 13 respectively. URS, an engineering firm, provided both baseline air emissions testing data and the data resulting from the sorbent injection trials. (See Table 1) Both limestone and Trona provided only moderate SO_2 reduction results. Mercury reductions were significantly higher than expected, especially with limestone. Detailed mercury reduction data reflect a change in speciation from elemental mercury to oxidized mercury, improving capture rate.

During the sorbent trials, excessive slagging occurred on the pendant superheat tubes. Cape Fear Unit 5 required a shutdown to remove the slag. A root cause analysis was performed and showed both limestone and Trona lowered the ash fusion temperature. Cape Fear Unit 5 air soot blowers proved to be inadequate to minimize ash deposition. The addition of limestone and Trona reduced the ash fusion temperature so that the ash quality resembles PRB coal (Powder River Basin). Electric utilities who have switched to PRB coal have similar problems and operate successfully with severe duty steam soot blowers. The economic assessment includes capital dollars for a severe duty steam soot blower system.

Economic Assessment

An economic assessment of the FSI technology produces SO_2 removal costs of $500 to $600 per ton. The limestone sorbent has the lower removal cost due to its lower purchase price. Traditional SO_2 removal methods are low sulfur coal at $100 to $200 per SO_2 ton and wet scrubbers at approximately $500 to $700 per SO_2 ton. FSI is comparable to wet scrubbers in cost per ton, however can only remove 53% to 59% versus greater than 90`%o with wet scrubbers. FSI should be considered a "niche" technology for moderate SO_2 reduction with limited U.S. market potential. An example of a "niche" application would be a generation site that has a local inexpensive limestone supply and requires only moderate reductions.

Mercury

Proposed mercury air emissions regulations are scheduled to be issued by December 2003 with final regulations in 2004. Mercury emissions may be site specific and not system averaged like NO_x, and SO_2 emissions. If this occurs, generation units not designated to receive a wet or dry scrubber technology may require a mercury removal system. Activated carbon injection, a commercially available technology, can reduce mercury at a cost of $30,000 to $60.000 per lb removed. In comparison. FSI mercury removal costs are estimated at $20,000 to $40,000 per lb removed. FSI would have the added benefit of SO_2 emission reductions.

Progress Energy Conclusions and Recommendations

In conclusion, FSI is a cost competitive SO_2 reduction technology for sites requiring modest reductions. FSI is a competitive mercury removal technology for units not designated to receive wet or dry scrubber installations. Operational issues such as furnace slagging would have to be minimized by new a soot blowing system. Following are recommendations if FSI is to be considered a part of Progress Energy's mercury and SO_2 air emissions compliance plan.

- Capital and O&M costs are budgetary numbers. Detailed engineering cost estimates should be performed to develop more accurate capital and operating costs.

- Due to the short term nature of the trial, ESP and ash pond effects could not be ascertained. A detailed study to understand the long term impact to ESP performance, ash pond life and ash pond chemistry should be performed before proceeding with the technology.

- Critical to FSI's commercial operation is to minimize furnace slagging. Site visits to PRB coal users should be planned to gain extensive operational and maintenance knowledge. In addition, intelligent soot blowing systems should be investigated, including the possibility of obtaining a system for evaluation

Sorbent Injection Procedure

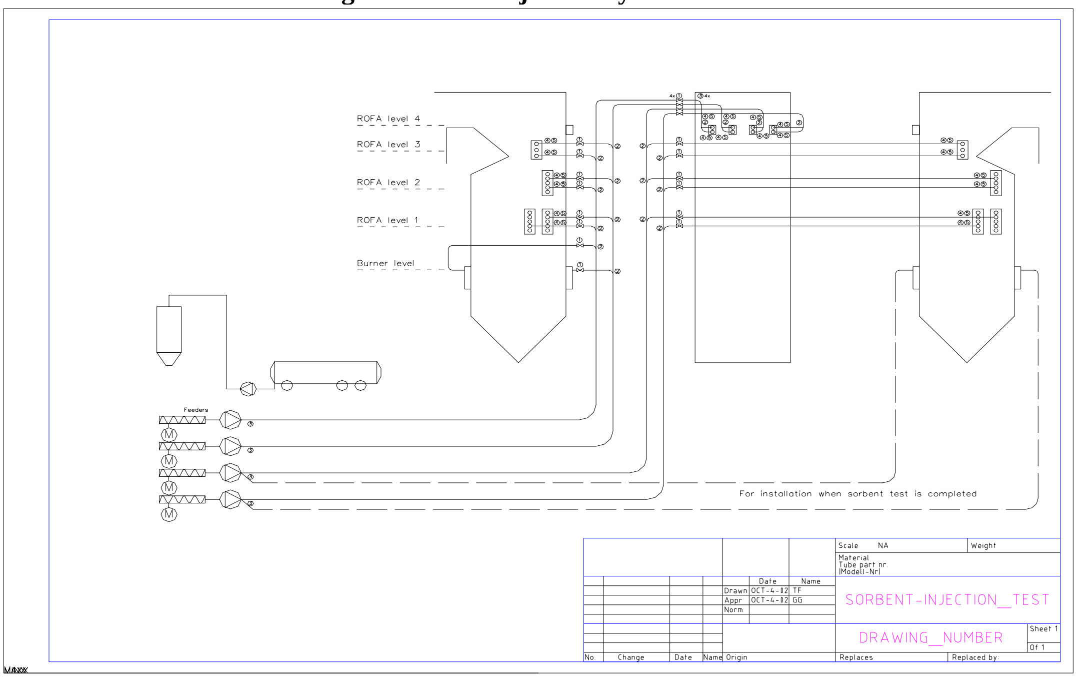
The objective of evaluating furnace sorbent injection (FSI) at the Cape Fear Generating Station was to demonstrate a cost efficient way to reduce SO_2 and mercury with the advantage of the turbulent mixing created by the ROFA™ and ROTAMIX™ system. The project goal was to achieve greater than a 60% reduction in SO_2 emissions with the use of Trona and/or limestone. No projections were made as to the level of mercury reduction. A contractor for EPA was conducting mercury emission tests during our first day of limestone injection and was the first to notice a very significant drop in Hg levels. Data collected by URS confirmed this finding.

FSI was evaluated because of its potential to reduce $SO_{2,}$ Hg, and HCl air emissions on a low cost per kilowatt basis. The advantages of FSI are primarily the simplicity of the process and its low capital cost. Past FSI demonstrations in the U.S. have produced a range of 25-75% SO_2 reduction. However, FSI coupled with ROFA (rotating opposed fire air) has produced a 90% SO_2 reduction at a 78 MW and 150 MW unit in Sweden. ROFA creates excellent turbulence and mixing in the furnace which improves FSI’s ability to capture sulfur.

ROFA/ROTAMIX boxes are mounted at four different levels, and Fig. 1 depicts both sides of the furnace profile and indicates the location of ROFA boxes relative to the burner elevation and the nose of the furnace. Sorbents were injected through 2 inch lances located in each ROFA box. Eight hour baselines were taken by URS and test duration was scheduled for two 8 hour periods. The purpose of the first 8 hour test was to determine the best location and operational performance. The second 8 hour time period was allotted for the official test. Each sorbent was injected at a low sorbent to sulfur ratio to check safety and operational performance. Next a moderate sorbent to sulfur ratio was injected at different elevations to determine maximum SO_2 reduction. These initial trials were to last six to eight hours. If no safety or operational concerns were identified, then an official trial was conducted the next day. The official trial required an eight hour period beginning with the moderate ratio and increasing to a higher ratio. Test data was collected by URS Corporation and the plants distributed control system (DCS). The test program for analysis included the following:

<u>Sorbent Injection System</u>

Fig 1 - Sorbent Injection System



<u>Equipment Utilized for Sorbent Injection Trials</u>

The following equipment was used for the trials:

1. 1 - 4,100 cu ft. possum belly cement trailer with a 75 hp PD blower.
2. 1 - Feed bin hopper with baghouse (6’x8’x30’) ~600 cu ft. capacity.
3. 1 – Distribution hopper with four 2” variable speed screw conveyors
4. 4 – 8” rotary vane feeders
5. 4 – Fox Valve venting eductors (1 ½”)
6. 4 – Positive displacement (PD) blowers with 10hp motors. (0-6 psi)
7. Electrical control panels with motor-starters, AC drives, and PLC controller.
8. All piping was schedule 40 PVC (4” from supply trailer – feed bin, and four 3” lines from rotary valve outlets to ROFA boxes.
9. 3”x2” PVC reducers at the ends of all PVC piping.
10. 3” PVC ball valves were installed in each of the four PVC lines at each ROFA level.
11. ROFA box injection lances - 6’ sections of 2” schedule 40 steel pipe (ROFA levels 1-3) with 1.5” pipe at ROFA level 4.
12. 2.5” ID flexible hose connected PVC piping to steel injection lances.

Application and Operational Issues

Powdered limestone and Trona were delivered in dry bulk delivery trailers and pneumatically conveyed into the main supply trailer. Material was then pneumatically transferred to the feed bin on an as needed basis. A large pulsejet baghouse mounted on top of the feed bin captured fugitive dust during dry powder transfer. The distribution hopper, with four small screw conveyors, metered dry chemical through the rotary valves and into the 3” PVC lines. The PD blowers provided the motive energy to deliver the dry chemical to each injection lance. The sorbents were then injected into the furnace with the added air velocity from the ROFA/ROTOMIX system. A significant negative suction on the injection lances also aided in the injection process.

Trona and limestone were chosen as test sorbents. In the furnace, the sorbent first undergoes calcination to form highly reactive oxides that readily react with the SO_2 in the combustion gas. Depending on the injected sorbent the reaction produces either sodium or calcium sulfate which is picked up by particulate control devices. The “popcorn-like” decomposition or calcination of the sorbent creates a large and reactive surface by bringing unreacted sodium or calcium carbonate to the particle surface for Hg, HC1, and SO_2 neutralization. Trona was supplied by Solvay Minerals and limestone was supplied by Chemical Lime.

This project was beset by several mechanical and weather related problems that radically increased both cost and time. With all equipment located outside, rain and ice storms played havoc with normal operations and maintenance. Even a very small water leak into a dry powder handling system is very problematic. Some of these small leaks turned limestone powder into concrete in a few of the PVC ball valves; blocking flow to ROFA boxes.

Backpressure through the rotary valves and into the screw feeders also created substantial problems. Blowback through the rotary valves deposited dry powder chemicals in the bearings of the screw feeders resulting in bearing failure, and disrupted uniform flow of material into the feed lines. Much time and money was spent correcting this problem with a myriad of advice from experts in the field of powder & bulk solid handling. Some of the corrections included:

- Installing venturies under the rotary valves.
- Venting the rotary valves into the baghouse.
- Replacing the rotors in the rotary valves.
- Installing new rotary valves with tighter clearances.
- Adding venting eductors to the new rotary valves with the outlet from the eductors injected into the line downstream of the rotary valves.
- Injecting into two ROFA levels at once to minimize back pressure caused by the 3”x2” reduction and splitting wyes at each set of injection lances.
    - Each ROFA box contained 2 – 2” injection lances for a total area of discharge of 6.28 sq. inches.
    - Opening valves to two ROFA levels simultaneously doubled the discharge area and lowered back pressure, as measured at the PD blowers, from 4.5 psi to 1.5 psi.

- In hindsight, 3" lances with 14.14 sq. inches of discharge area would have been the preferred method of injection. Back pressure would have remained low minimizing feeding problems.

In spite of these difficulties the combination of new rotary valves with venting eductors overcame much of the backpressure issue and delivered a consistent controlled feed rate into the furnace.

Sorbent Injection Application

On December 8th 2002, the sorbent injection trials commenced to determine the potential of furnace sorbent injection (FSI) to reduce SO_2, Hg, and HCl pollutants. Limestone and then Trona were injected at several furnace elevations using the existing Cape Fear Unit 5 ROFA and ROTAMIX boxes. The effluents were monitored during the test to determine the effectiveness of each sorbent. The ratio of sorbent to sulfur was established prior to testing and intentionally varied during the trials.

Limestone was initially setup and tested for approximately 8 hours to determine optimum injection location and check for any safety or operational issues. No issues were uncovered at this point. Limestone was then injected at a ratio of 2:1 (calcium to sulfur) simultaneously into furnace levels 5-1/2 and 6 for a period of 6 hours. An official limestone injection trial was conducted on December 10th. Limestone was once again injected into the same two elevations for a period of 4 hours at a 2:1 ratio, and then 4 hours at a 3:1 ratio. Upon completion of this trial, the system was purged and prepared for the next sorbent injection trial.

On December 12th, Trona was injected at a 1:1 ratio (sodium to sulfur) into several locations, and then at a 2:1 ratio into levels 5-1/2 and 6. An official Trona injection trial was conducted on Friday, December 13th. Trona was injected at elevations 5-1/2 and 6 first for a period of 4 hours at a 2:1 ratio, and then finally for 4 hours at a 3:1 ratio. Tilts were held constant at 75% through the testing period. Excess O_2 was held relatively constant between 3.7 and 4.1 %.

The mercury reduction achieved for both Trona and limestone was very promising. The accuracy of the particulate matter (PM) reduction is somewhat unclear due to upper furnace slagging; i.e. the percentage of PM captured by the slag was not determined.

Another noteworthy result was the reduction in NO_x obtained with the Trona injection. URS was not asked to measure NO_x reduction, but the DCS printouts reflected NO_x reductions of 4% for limestone and 11% for Trona. The Trona supplier maintains that Trona will react with NO_x the before it will react with the SO_2. Additional NO_x reduction achieved with sorbent injection is potentially an added benefit of the Mobotec USA multi pollutant reduction technology.

It may be noted that the SO_2 reduction does not significantly change for increased molar feed ratios of 2:1 and 3:1, sorbent to sulfur. The stoichiometric feed rate comparison suggests the flue gas and sorbent were well mixed and that ROFA and ROTAMIX may decrease the amount of sorbent needed to achieve the desired SO_2 and Hg reductions. Figure 2 and 3 are graphical representations of data collected from the DCS.

Figure 2. Limestone Injection - 12/10/2002. Data Collected Through Plant Instrumentation.

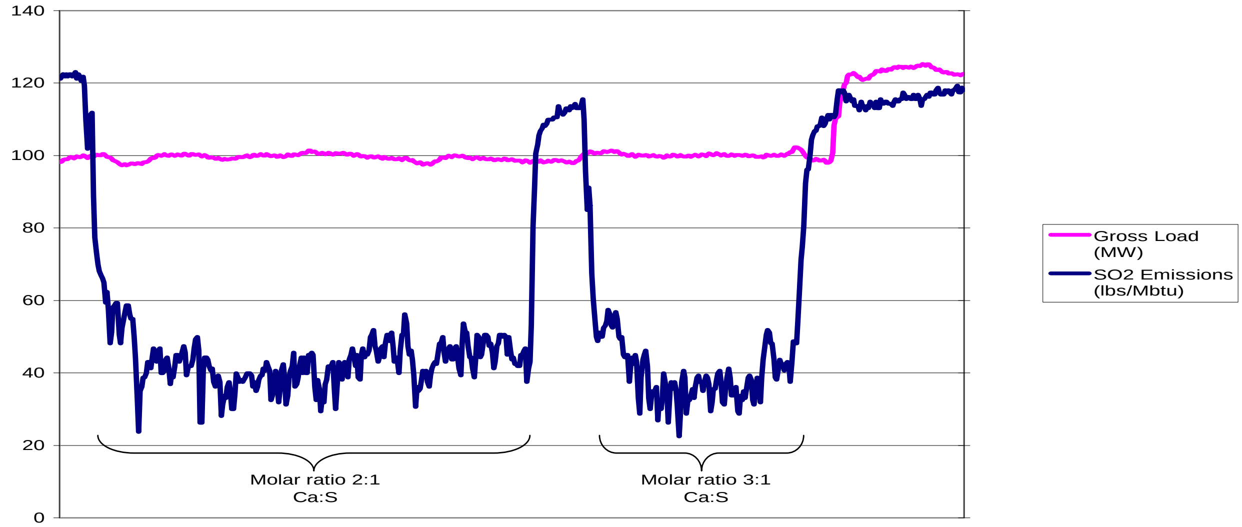
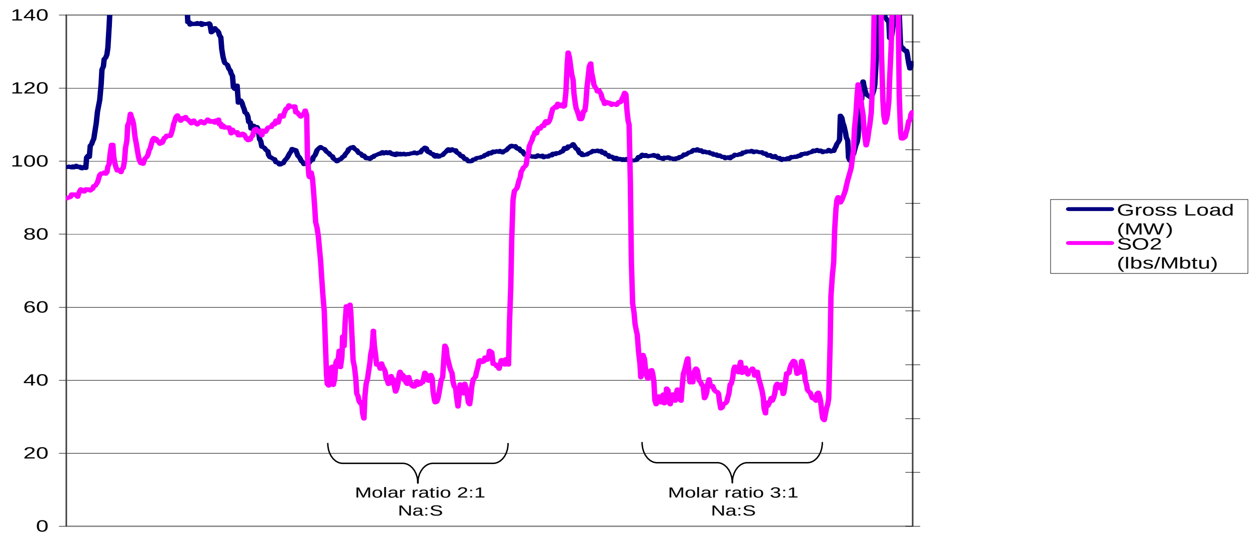


Table 8. Sorbent Particle Size as Received by Supplier.

Limestone	
% < 74 micron	92
% < 44 micron	80
Trona	
% < 70 micron	75
% < 28 micron	50
% < 6 micron	10

Figure 3. Trona Injection - 12/13/2002. Data Collected Through Plant Instrumentation.



Upper Furnace Slagging

Concerns raised in planning sessions about the potential for slagging proved to be legitimate concerns. During the sorbent trials, excessive slagging occurred on the superheater tubes. Cape Fear 5 required a shut down to remove the slag with high pressure water and explosive blasting. The furnace had normal soot blowing capacity but had at least one critical soot blower out of service adjacent to the superheater. Analysis of the slag indicates that the bottom layer adhered to the superheater tubes was primarily calcium sulfate with an over layer of sodium sulfate. Depending on the sorbent concentration, it was determined limestone lowers the ash fusion temperature of the coal by approximately 500ºF and Trona by 300ºF. Although limestone has a lower ash fusion temperature, Trona sticks more tenaciously due to the nature of the chemical bond.

To determine the underlying nature of the slag material and its formation several lab analysis were performed. Several slag samples were taken directly from affected superheater tubes and sent for analysis. The lab information provides sufficient information to determine that limestone injection provided a base deposition on the pendent tubes. This base deposition over time allowed a slagging environment to cultivate. Tables 9 and 10 provide a lab analysis showing a high percentage of calcium based products in the slag material. Typical coal burned at Cape Fear has on average .9% calcium oxide in the ash mineral analysis.

Table 9 Slag Layer Analysis - January 27, 2003 – Auburn Analytic Labs

Note: Method is x-ray diffraction. Light elements such as Na and K may be less than actual.

	Inside Layer	Mid Layer	Mid Layer	Outside Layer	Main Source
SiO2	30.8%	31.1%	32.4%	36.1%	Coal
Al2O3	18.1%	15.3%	17.0%	23.6%	Coal
FeO	12.2%	12.7%	20.0%	19.7%	Coal
CaSO4	12.0%	15.8%	11.0%	12.2%	Reacted Sorbent
CaO	7.0%	1.5%	1.3%	1.0%	Unreacted Sorbent
NaSO4	0.0%	0.0%	3.0%	0.0%	Reacted Sorbent
Na2O	0.0%	0.0%	1.0%	0.0%	Unreacted Sorbent
K2O	2.0%	2.9%	2.2%	3.0%	Coal
TiO2	3.0%	2.6%	2.7%	2.6%	Coal

Table 10. Total Slag Analysis - January 3, 2003 – Solvay Minerals

Note: Method is ICP atomic emission

	All Layers	Main Source
Si	15.7%	Coal
Na	11.3%	Sorbent
Al	10.0%	Coal
S	6.7%	Coal
Ca	5.6%	Sorbent
Fe	3.2%	Coal

A mixtures of coal and sorbent was sent for ash fusion and mineral analysis to determine the effect of sorbent on ash chemistry, Table 11 displays that limestone, even at a moderate 2:1 calcium to sulfur ratio, has a major impact on ash fusion temperature and slagging index. As reference, typical Cape Fear coal has an ash fusion temperature of 2700+ F and a low slagging index.

Table 11. Coal/Sorbent Analysis – February 4, 2003 – Commercial Testing & Engineering

Sorbent	Ratio	Fusion Temp	Slagging Index	Fouling Index
Limestone	2:1	2170 F	High	Low
Limestone	3:1	2180 F	High	Low
Trona	1:1	2322 F	Low	Low
Trona	2:1	2374 F	Med	Low
Trona	3:1	2397 F	Med	Low

Limestone lowered the ash fusion temperature to 2170F. Sorbents were mainly injected into ROFA levels 2 and 3 where furnace temperatures on average were 2200F and 1950F respectively. When the furnace temperature is above the ash fusion temperature, ash softening occurs changing the state of the ash particles. It is logical to conclude that particles did not have enough time to solidify before reaching the superheater pendent. Particles were still in a molten or in the plastic state upon reaching the pendent tubes allowing for adhesion.

Sorbent Trials Conclusions and Recommendations

Mobotec USA's multi pollutant reduction technology successfully reduced SO_2, SO_3, mercury, and HCl, emissions at the Cape Fear Power Station. SO_2 reductions of 69% were achieved with Trona and 64% with limestone. SO_3 reductions were 93% with Trona and 88% with limestone. Mercury reductions of 89% were achieved with limestone and 67% with Trona. HCl was reduced by 78% with Trona and 12% by limestone. ROFA/ ROTAMIX™ can be used efficiently for sorbent furnace injection creating an economical way to reduce SO_2, SO_3, HCl, and mercury. In combination with the turbulent mixing inherent with the ROTAMIX and ROFA Mobotec Systems, and mercury reductions at low capital and operating costs, furnace sorbent injection is quite economical compared to traditional scrubbers.

When performing separate injection of the sorbent, the opportunity for sorbent and ash particles to interact on-the-fly is limited. It might be interesting to look at the ash fusion temperature of the straight sorbents. A low-melting-point sodium or calcium carbonate decomposition product could catch substantial amounts of flyash in a slag/ash coating on the pendants/panels. A simple comparison (equilibrium calculation) between the decomposition products of the two might explain why you see more fouling with Trona

Mobotec USA seeks to enhance and commercialize the technology by performing another full scale evaluation using Trona as the sorbent. Operational issues such as pendant section slagging may be overcome by controlling sorbent injection rate based on upper furnace temperature, a more aggressive and efficient soot blowing scheme, humidification of sorbents in the backpass, and sorbent particle size optimization.

Micronized Coal Injection Trials

The Micronized Coal Reburn Process

Reburning is a process by which NO_x compounds, produced in the primary combustion system, are decomposed to molecular nitrogen by the addition of a secondary fuel to the main furnace. This secondary fuel, called the reburn fuel, can be PC-coal, MC-coal, oil, or natural gas depending on unit configuration and furnace dynamics. In the case of Cape Fear #5 MC-coal was the logical choice to demonstrate the economic viability of NOx reduction with the same fuel used in primary combustion. A conventional reburn process employs multiple combustion zones in the furnace defined as, the primary fuel combustion, the reburn zone, and the burnout zone. The furnace would then be retrofitted with fuel injectors located as close to primary fuel combustion zone as furnace conditions will permit. The DPRCS injectors are designed to operate with an extremely low stoichiometry utilizing high velocity conveying air to provide momentum and initial mixing in the furnace. Only 30% to 40% of the required theoretical air necessary for the reburn fuel is supplied to the injector (ie. reburn input stoichiometry is (.30 to .40) thus extremely fuel rich). The combustion gases from the fuel rich reburn mixture combine with the combustion products from the primary combustion zone to obtain a furnace reburn zone stoichiometry of .85 to .95. At this point the total air delivered to the boiler is 85 to 95% of that required for the theoretical combustion of the primary and reburn fuel. The fuel rich reburn zone creates an environment where free hydrocarbon radicals react with NO_x compounds to form nitrogen gas (N_2) and water vapor. The surface area of MC-coal (31 sq. meters/gram) provide sufficient residence time in the reburn zone to allow the chemical reactions to occur.

The balance of air required to complete the combustion process is added through the ROFA ports in the burn-out zone bringing the final stoichiometry to between 1.1 and 1.2. Like the reburn zone, the burnout zone requires sufficient time and turbulence to complete the combustion process and produce minimal CO. The gross amount of NO_x reduction achieved, as measured in exiting flue gas, is a set of intensively complex equations that takes into account the stoichiometric relationship between main burner levels, the reburn level, ROFA level, and final combustion gas stoichiometry. As the project moved forward REI began to develop CFD models of the furnace with MC-coal injection. (REI report page 22) The models predicted that NOx would actually increase if MC-coal was injected in a classic or conventional reburn mode between the primary zone and the overfire air system.

The 1957 vintage tangential furnace did not have modern low NO_x burners with concentric firing, which meant the core of the furnace had very high NO_x levels. It was impractical if not impossible to deliver MC-coal with enough velocity to breakup the high NO_x core of the furnace. Secondly the Mobotec ROFA/ROTOMIX system installed on the furnace, had already reduced NO_x by over 50%, to a normal operating level of (.17 - .26 lbs/mmbtu). Our original goal was to utilize the technique of MC-coal reburning, in conjunction with the ROFA system, to drop NO_x levels below 0.15. CFD modeling indicated that the best injection locations were low in the furnace, perhaps as low as the furnace hopper, driving MC-coal into the center core to lower NO_x. The following data and information represents the application of the MC-coal injection system and the Tests 1-4 essentially confirmed the CFD models veracity.

<u>Micronized Coal Injection System</u>

The following components constitute the MC-coal injection system: (Fig. 4.)

1. A 4,100 cu. ft. bulk storage trailer with a 75 HP PD blower
    a. Coal was micronized off site and shipped to Cape Fear in super-sacks. A Lull was used to raise the super-sacks over the hatches of the bulk storage trailer where they were dumped into the trailer by ripping open the bottom of the sacks.
2. A 4” sch 10 steel pneumatic line connected the bulk storage trailer to a day bin.
    a. The four inch line also serves as a vent line to the baghouse when the trailer is being filled.
3. The day bin consists of a 6,000 acfm pulsejet baghouse, feed bin extension 6’x8’x10’h, and 68^o hopper. Total capacity is approximately 600 cu. ft.
    a. When material is transferred to the day bin, the baghouse collects all fugitive dust and Bindicators are used to determine a filled or low level condition.
4. A distribution box attaches below the feed hopper and contains four 2” variable speed feed screws. Each feed screw is driven by a one HP motor with a 480 vac AC drive. This method provided very accurate material feed control.

    a. Manual butterfly dampers were installed on the feed screw outlet to prevent fluidized MC-coal from spilling from the feed screws.
5. Vented 60^o hoppers were then installed below each of the four feed screw outlets to capture and direct the MC-coal into 3" eductors.
    a. Fox Valve 3" eductors and 200 scfm of 70 psig air were used to provide motive force to the dry powdered coal; delivering the material through 3.5" OD sch 10 steel pipe, to furnace inspection doors on the furnace wall. All steel pipe elbows have a long 36" radius.
6. Furnace door injection lances consisted of a ¼" steel plate sized for each door opening and a 36" section of the sch 10 feed line welded in the center of the plate.
    a. Approximately 6" of pipe protruded into the furnace and this section was heated and flattened to form an oval injection nozzle.
    b. The steel plate was then bolted in place in the inspection door opening. An infrared thermometer was used to check plate and line temps. Plate temps ranged from 150^o - 330^{oF} while line temps within 12" of the furnace never exceeded 180^o. Furnace draft provided cooling to the mounting plate and injection lance.
7. In tests 1,3&4 feed lines were run to NE and SW furnace inspection doors at elevations 217' and 231'.
    a. In test 2 feed lines were extended to four furnace inspection doors on the east and west sides of the furnace at elevation 245'.
8. A PLC controller was installed and programmed to regulate flow, control motors and valves and provide safety. The control room had the ability to shut down the system during an emergency.

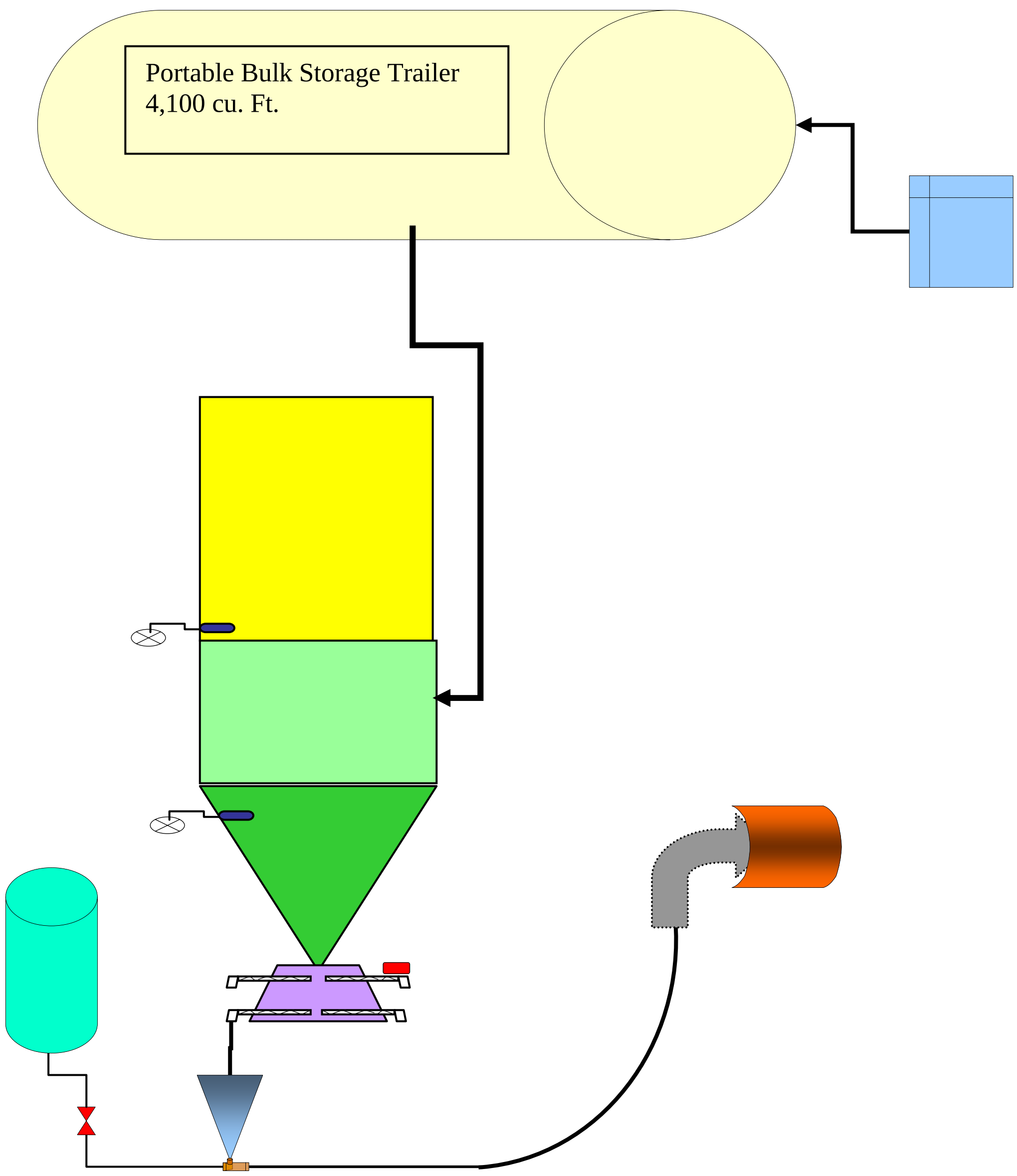
<u>Changes to Equipment and Injection Locations</u>

Three inch pvc piping with pvc ball valves at each ROFA level was installed and utilized for the sorbent trials. Leaking hose connections and arching from static electric fields were major safety concerns prior to the MC-coal trials. High back pressure at the rotary valves, creating back-flow through the valves, was also a concern regarding uniform feed rate of MC-coal at each of four furnace injection locations. Much of the back pressure was attributed to the 3" to 2" reductions at the point of injection. A material handling expert was brought in to analyze our system and make recommendations. The changes suggested included sch. 10 - 4" steel pipe from the bulk storage trailer to the day bin, and 3.5" OD steel piping from the day bin/baghouse to each furnace injection point. No reductions in pipe size at the point of injection and the use of eductors and compressed air as the motive force to uniformly feed MC-coal in each of four feed lines.

Due to weather delays and equipment problems, CFD modeling work by Reaction Engineering (REI) was performed concurrent with steel pipe routing. When modeling was finally completed in early March the CFD model indicated that MC-coal injection should take place much lower in the furnace and act as a deep staging fuel to breakup high NOx in the core of the furnace. Micronized coal injection locations were run both to the traditional reburn location, above the primary combustion zone, and to lower locations adjacent to both top and bottom burner elevations.

Bearings went out in the ROFA fan in late December and were not replaced and the fan made operational until the week of March 17th. In combination, all of these various changes and delays added three months to the project, and substantial cost increases over the budget.

Fig. 4. MC-coal Process Flow Diagram



Coal Analysis and Percent of MC-coal Input

The coal analysis is of an eastern bituminous West Virginia coal (Table 12). The percent of MC-coal to total fuel input is depicted in Table 13. MC-coal input ranged from 8,400 lbs/hr - 8,640 lbs/hr in all four tests, or approximately 13% of total fuel input at a 75% load.

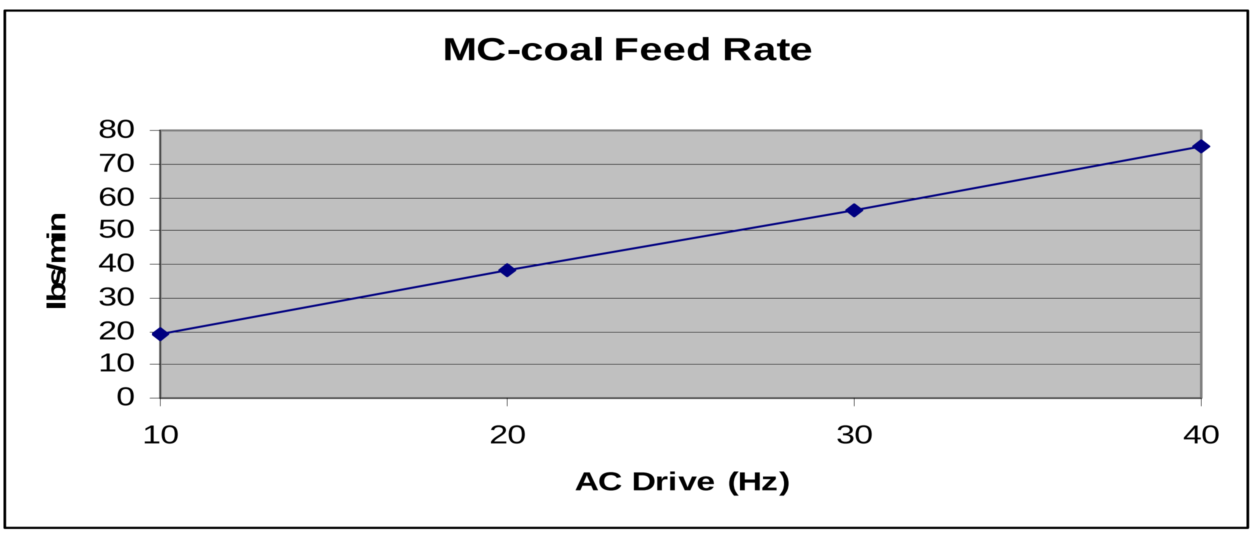
Table 12. Coal Analysis.

	As Received	Dry Basis
% Moisture	1.65	-
% Carbon	70.19	71.37
% Hydrogen	4.67	4.75
% Nitrogen	1.41	1.43
% Sulfur	0.87	0.88
% Ash	12.64	12.85
% Oxygen	8.57	8.72
Sum	100	100

Table 13. MC-coal Fuel Percentage of Total Fuel Input

MC-coal % to total fuel btu	10%	12%	14%	16%
MC-coal rate in lbs/hr @ 75% MDC	6,219	7,463	8,707	9,951
MC-coal rate in lbs/hr @ 100% MDC	8,292	9,951	11,609	13,268
Full load in kw	110,000			
heat rate in btu/kwh	9,800			
MC-coal in btu/lb	13,000			

Fig 5. Calibration chart for MC-coal Feed Rate



Reaction Engineering International Report

Prepared for Mobotec USA
May 7, 2003

Background
Staging of fuel and air mixing has been shown to be one of the most cost effective means to reduce NOx emissions from a coal-fired boiler. Staging occurs through multiple mechanisms including low NOx burners, overfire air, and reburn. The staging process that occurs in each of these three approaches creates reducing regions that can prevent fuel-bound nitrogen from being oxidized as well as reduce or “reburn” NOx that has been formed at other locations. In addition, staging the combustion process can reduce peak temperatures and consequently thermal NOx formation. The objective of this trial was to evaluate the combination of micronized coal reburn injection with ROFA.

During the last decade Computational Fluid Dynamic (CFD) simulations have developed into a practical tool for the purpose of evaluating potential NOx control technologies in coal-fired boilers. CFD tools not only provide qualitative insight useful for development and design purposes, but also can be used a quantitative indicator of gas temperature, flow field patterns, and emissions concentrations.

Micronized Coal Injection Strategies

Several fuel injections strategies have been applied in coal-fired boilers. Conventional gas reburn relies upon injection immediately downstream of the coal flames and attempts to insure adequate residence time for the reburning chemistry to take place prior to the addition of the burnout air. Placement of the overfire air ports is generally done to achieve a residence time of approximately 0.5 seconds. However, Unit #5 at the Cape Fear station has previously been retrofit with an advanced Rotating Opposed Fire Air (ROFA) system developed by Mobotec USA. This technology uses carefully arranged, high velocity air injection to rapidly create a well-mixed upper furnace, which consequently allows the lower furnace to be operated under reducing conditions while improving CO emissions and without significant effect on unburned carbon in flyash. ROFA creates low NO_x emissions in the lower furnace and a challenging baseline condition for further reduction in a traditional reburn zone.

In order to explore other potential avenues for using “reburn” chemistry in this boiler, several additional injection locations were investigated. The cost of (1) hardware modifications and (2) micronized coal to evaluate each of these possibilities would be prohibitive under the current project. Therefore, CFD modeling was used as a scoping tool and to better understand the details of the fluid mechanics and chemistry taking place in this boiler. The injection locations evaluated also took into account the practical access limitations. Based on these considerations the following injection locations were evaluated (see Figures 6 & 7):

- Within the ROFA injection system (MC in ROFA)
- "Traditional" injection between the upper pulverized coal (pc) injector and the ROFA ports (MC mid) - Elevation 245'
- Near the upper pc injection elevation fed by the "A" mill (Elevation 231')
- Near the lower pc injection elevation fed by the "D" mill (Elevation 217')

Fig 6. Location of Furnace Inspection Doors

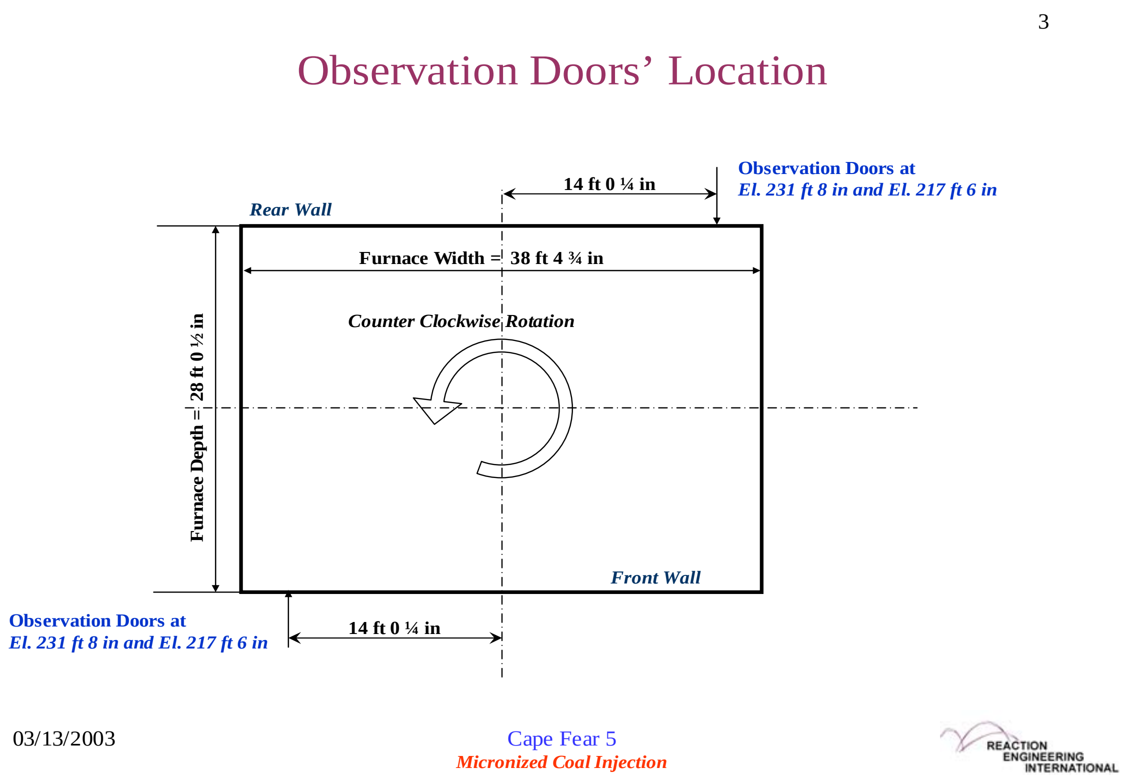
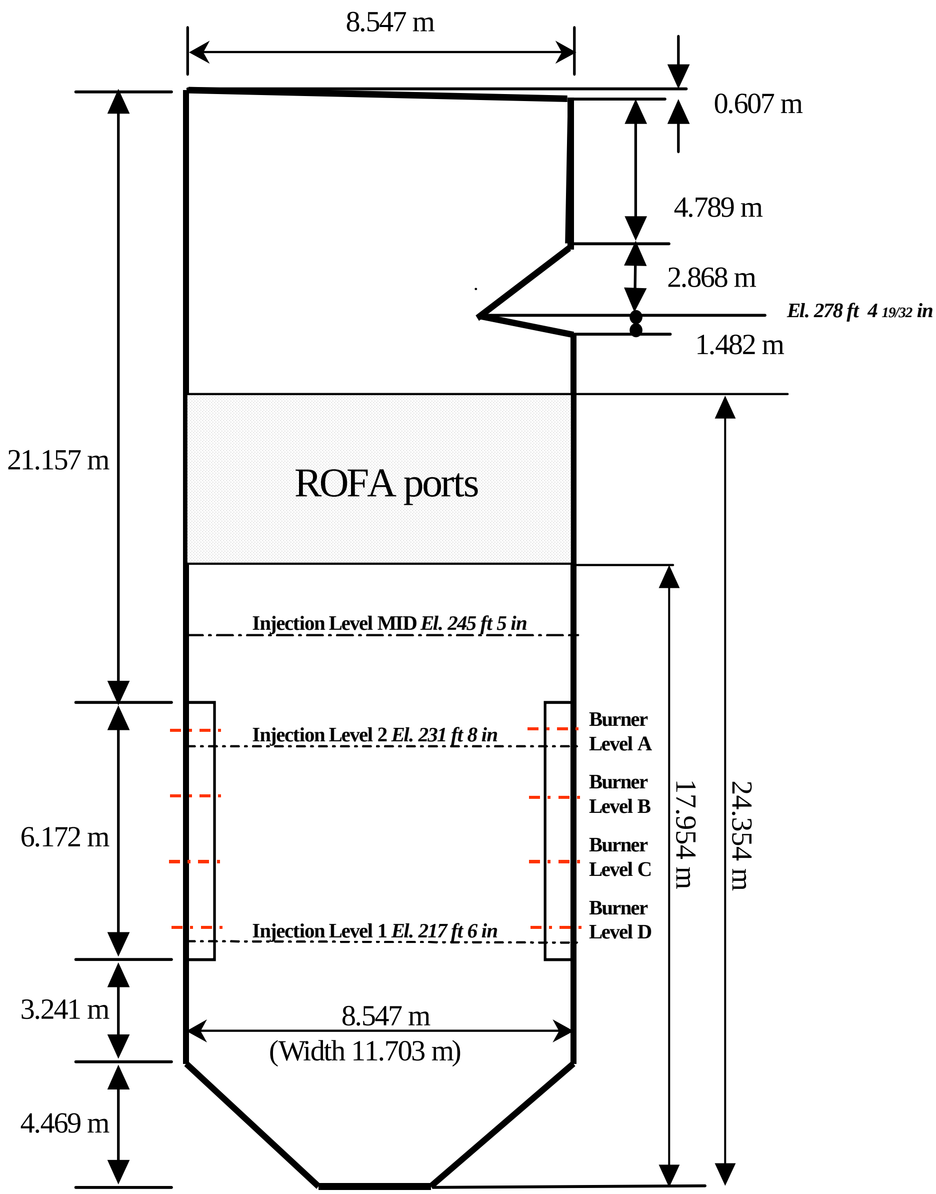


Fig 7. Furnace Cross Section With Injection Locations



Waterwall penetrations were not required for any of these locations as existing observation doors were used. Multiple injection schemes were evaluated for the two lower injector elevations:

- 2 front & 2 rear wall locations near each fuel injector at "A" elevation (231') (4MC@A)
- 2 front & 2 rear wall locations near each fuel injector at "D" elevation (217') (4MC@D)
- 4 front & 4 rear wall locations near each fuel injector at "A" and "D" elevations (231' & 217') (8MC@A&D)
-

Results

Operating conditions of coal-fired boilers are often difficult to define with precision. Therefore, educated assumptions were made in several areas (e.g., ideal coal and air distribution) to simplify the task at hand. Some fine-tuning of the model inputs based on comparisons with observed NO_x emissions and carbon-in-ash was performed. It was determined that the simulation inputs were adequate when the predictions for a number of key elements were within the range of observations made during performance testing and typical operation of the unit. For example, the initial tuning of the unit led to NO_x emissions of 0.28 lb/MMBtu. This was very similar to emissions observed during the period following the installation of the ROFA system, but not as low as was achieved subsequently following a more rigorous tuning of the system/boiler. With ROFA alone during NO_x season, Cape Fear 5 currently operates at NO_x levels of (0.17 - 0.26) lbs/MMBtu.

The CFD results of the different micronized coal injection strategies mentioned previously are summarized in Table 14.

Operating Conditions

	ROFA Only	MC in ROFA	MC mid	4MC @ A	4MC @ D	8MC @ A&D
Injection Level (Elevation in **ft**)	Biased Burners		245 ft 5 in	231 ft 8 in	217 ft 6 in	231 ft 8 in & 217 ft 6 in
Injection location		ROFA ports	Side Walls	Front and Rear Walls	Front and Rear Walls	Front and Rear Walls
Levels			1	1	1	2
Doors		0	4	4	4	8
% Reburn	NA	16	16	16	16	16
Burner SR	**0.8**	0.952	0.952	**0.8**	**0.8**	**0.8**
Furnace SR	**1.03**	1.156	1.156	**1.03**	**1.03**	**1.03**
% ROFA air (% of baseline airflow)	30	30	30	30	30	30

Results

	ROFA Only Biased Burners	MC in ROFA	MC mid	4MC @ A	4MC @ D	8MC @ A&D
Horizontal Nose Temp (°F)	2149	1988	2009	2136	2148	2213
Horizontal Nose CO (dry, ppm)	1470	107	16	2800	697	1082
NO_x (lb/MMBtu)	0.28	0.44	0.32	0.29	0.26	0.25
LOI (%)	3	2	2	13	11	-----

Table 14. CFD Simulation Results for Selected Micronized Coal Injector Configurations.

Each of these simulations provided insight in identifying more promising strategies. Color images presenting cross sections of key properties including gas temperature, CO concentration, NO_x concentration, and NO_x formation/destruction rates are included in Appendix 1.

Conventional installations of a reburning system assume that the lower furnace is operating under lean conditions (e.g. a stoichiometric ratio of 1.2) and that the reburn fuel will be added such that the overall stoichiometry is decreased to a slightly rich level (e.g., SR=0.9) in the reburn zone before overfire air injection returns the overall stoichiometric ratio to its exit level.

This approach can be applied locally without creating overall rich conditions if high NOx areas can be accessed effectively. The key parameters controlling the chemistry of reburning include stoichiometric ratio, temperature, residence time and reburn fuel composition. However, for unit #5 at the Cape Fear power plant, two atypical characteristics must be considered; (1) reburn is being applied to a unit that has a staged lower furnace (i.e. the burner belt SR <1.0); (2) Some early low NO_x firing systems for T-fired boilers, such as that at Cape Fear 5, do not include concentric firing (i.e. air injection angled more toward the boiler wall). Without concentric firing, the fireball can have a less rich core and therefore substantial NO_x at the center of the furnace.

Due to the effectiveness of reducing furnace stoichiometry in controlling NO_x emissions, one should not expect a typical reburn installation to be particularly effective for this unit. Removing fuel from the lower furnace to use as a reburn fuel reduces the staging of the lower furnace in a stoichiometry range where NO_x emissions are a strong function of stoichiometric ratio (i.e., in the 0.8 to 1.0 range). As shown in Table 14, the NO_x emissions actually increase for the MC in ROFA and the MC-mid injection strategies. In order to use the micronized fuel in a more effective manner, the results of the baseline simulation and the boiler drawings were evaluated to identify access points that would deliver the micronized fuel to local regions (1) that contained substantial NO_x concentrations and (2) that could be made rich with the micronized fuel injection.

In order to target the NO_x more effectively, lower furnace injection strategies were employed. Injection through access doors near the upper fuel injection elevation mixes the reburn fuel directly into the NO_x formed at the outer fringe of the fireball. The rapid heating and pyrolysis of the micronized fuel makes it possible for fuel rich gases to be quickly produced and allows for adequate residence time for the reburn chemistry (generally thought to be about 0.5 sec). However, NO_x emissions did not change significantly from the baseline simulation. The results indicated that the fuel removed from the firing system led to a leaner fireball interior as fuel-lean gases are recirculated up through the fireball. This was in part due to the nature of the firing system. Newer low-NO_x T-fired designs inject the air with an offset angle from the fuel such that the walls are protected by the air and the center of the fireball is fuel-rich.

Considering the constraints of the current firing system, another approach to create rich gases that can be entrained into the fireball is to provide separate injection of fuel in the hopper. Evaluation of the baseline modeling results indicated that the streamlines in the neighborhood of the lowest fuel injectors would be carried into the bottom of the furnace and up through the center of the fireball. Injection of the fuel through the lowest available access locations (in this case near the bottom row of fuel injectors) was therefore simulated. This was very effective and resulted in lower NO_x levels not only in the fireball but also at the furnace exit. The results of this simulation indicated that there was also potential for complementary effects while using both the A & D level injection elevations such that the A level injection reduced NO_x at the outer edge of the fireball and the D level injection reduced NO_x in the center of the fireball.

Summary

These modeling efforts were performed with the objective of providing design guidance and reassurance that the concept to be field tested would provide effective NO_x reduction. The modeling served as an effective scoping tool for conceptual injection configurations and indications that the reduction, although significant, was not expected to be as substantial as observed in earlier micronized coal reburn demonstrations. Post-testing modeling based on best estimates of the as-installed inputs estimated 18% reduction. However, the difficulty in obtaining exact descriptions of a utility boiler made this number less certain than is typically the case as indicated by a comparison of baseline NO_x data (.185 – .262 actual vs. 0.28 predicted). Typically potential emissions reductions are observed to be somewhat larger when starting from a higher NO_x baseline.

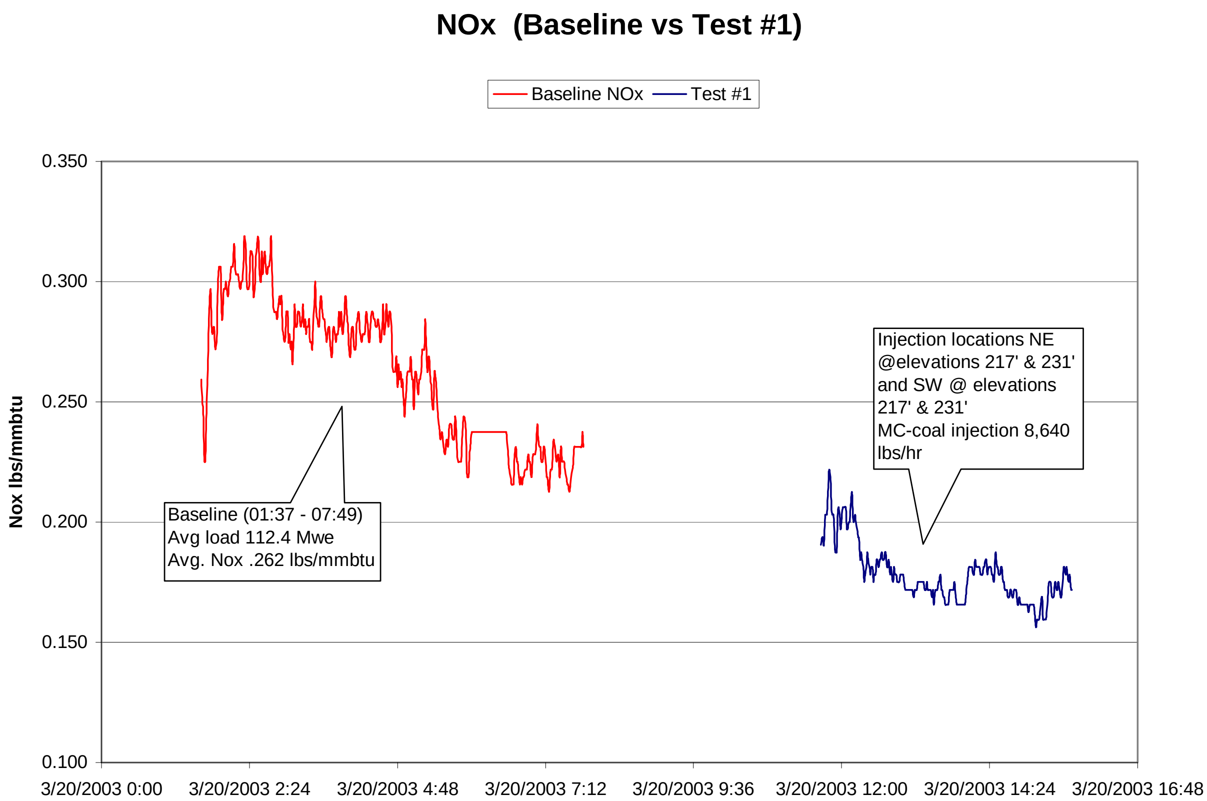
Results of Tests 1-4

Results of Test 1

With the ROFA fan in service under standard operating conditions and a 75% load (110-115 MWe), NO_x levels typically range from .17 - .26 lbs/mmbtu, depending on excess air, burner tilts, and coal quality. Baseline testing prior to Test 1 was conducted from [01:37am to 07:49am] 3/20/03 (Table 15). Average NO_x was .262 lbs/mmbtu with an average load of 112.4 Mwe, an average O_2 of 4.6% and 31.7 ppm CO. Burner fuel and secondary air was not biased during the baseline period of Test 1 period.

During Test 1 [11:40am – 15:44pm] MC-coal was injected in both the NE and SW corner of the furnace at elevation (A -231') and elevation (D – 217'). Feed rate per line was 2,160 lbs/hr for a total feed rate of 8,640 lbs/hr. MC-coal input represented ~13% of total fuel input. Average load was 110.1 MWe and average NO_x was .178 lbs/mmbtu with an O_2 of 3.7%, for a 32% NO_x reduction. Originally Test 1 was to begin at 07:50 while material was being transferred from the trailer to the day bin. During the transfer the fluidized MC-coal flowed through the feed screws with little or no control. The test was stopped within 15 minutes and material was no longer transferred when feed screws were turning.

Fig 8. Test 1

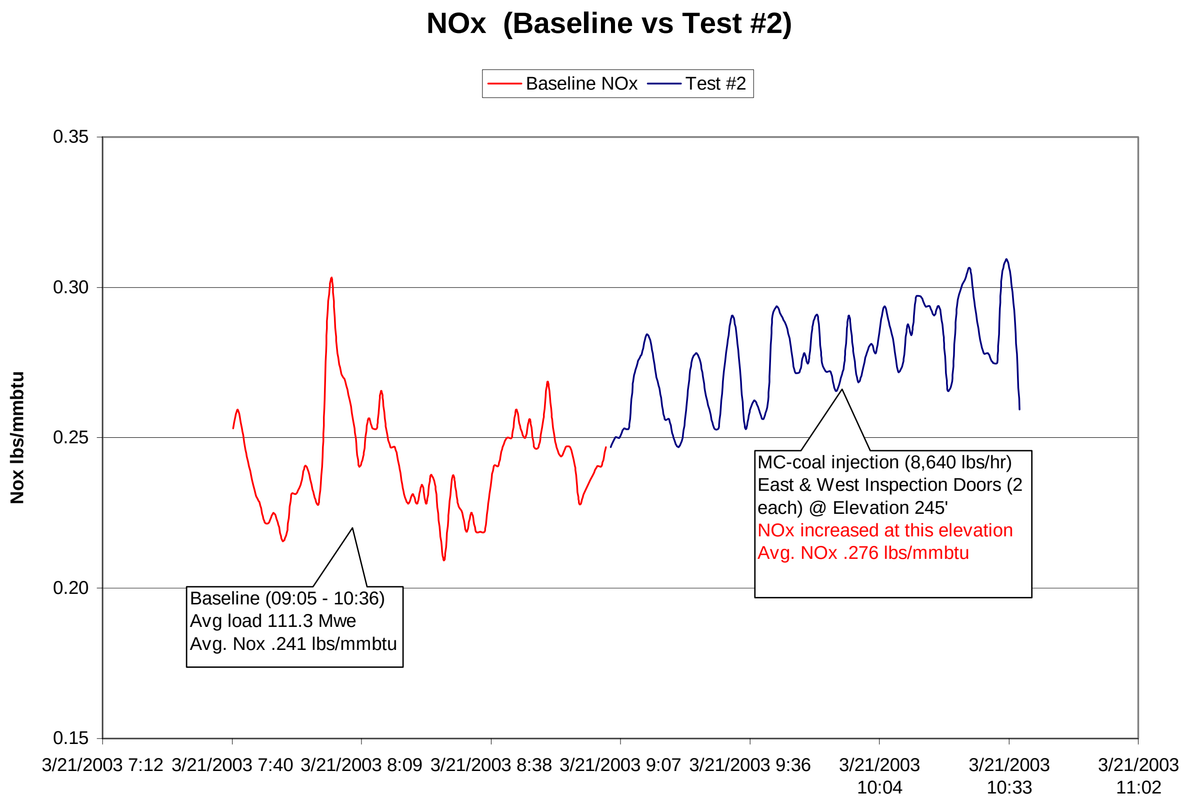


Results of Test 2

In consultation with power plant engineers operating Mc-coal reburn systems there was still a strong belief that the fuel should be injected above the primary zone and below ROFA. Because all the piping was first extended from the ground to elevation 245' it was a fairly simple matter to connect this piping to inspection doors on both the East and West sides of the furnace. This work was completed the afternoon of 3/20 and Test 2 was conducted the morning of 3/21. Some fine tuning of the ROFA system took place before a new baseline was taken. Baseline testing prior to Test 2, was conducted from [07:41 - 09:04] 3/21/03 (Table 15). Average NOx was .241 lbs/mmbtu with an average load of 111.3 Mwe and an O_2 of 4.6%. Fine tuning ROFA and secondary air dampers appeared to also lower NO_x somewhat.

During Test 2 [09:05 – 10:36] MC-coal was injected in both inspection doors on the East and West sides of the furnace at mid-elevation (245'). Feed rate per line was 2,160 lbs/hr for a total feed rate of 8,640 lbs/hr, representing ~13% of total fuel input. Average load was 108.5 Mwe, and an O_2 of 3.8%, and average NO_x was .276 lbs/mmbtu, for a 12.6% NO_x increase. Coal flow to the upper row of burners was biased 30%. The CFD model prediction was correct, NO_x did increase. (Fig. 9)

Fig 9. Test 2



<u>Results of tests 3&4</u>

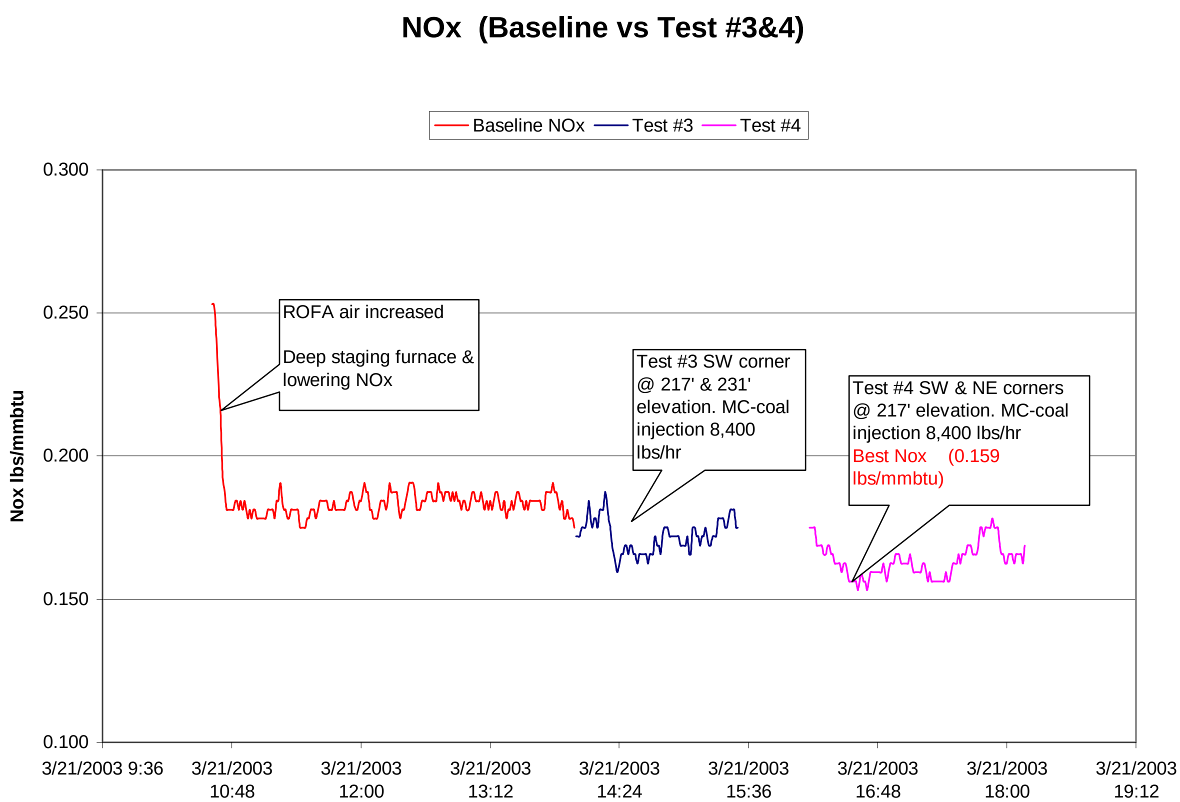
Piping connections were rerouted to NE and SW corners of the furnace at elevation (A -231') and elevation (D – 217'). During this period ROFA air was increased to 27% with a higher percentage of ROFA air directed to ROFA levels 2 & 3. Secondary air dampers were adjusted resulting in an increase in windbox pressure and a significant drop in NO_x. Baseline testing prior to Tests 3&4, were conducted on 3/21 from [10:37 – 13:59] (Table 15). Average NO_x was .185 lbs/mmbtu with an average load of 113.5 MWe. Burner biasing (bottom to top) was -20%, 5%, 0%, and 0% during tests 3&4. Operators were not comfortable with windbox pressures over 1.5" w.c. and with tight tolerances on dampers. Immediately after tests 3&4 were concluded, ROFA air and damper positions were returned to normal operating conditions and NO_x levels returned to a normal range of (.18 - .26)

Note – As the bottom of super-sacks were cut open with a utility knife to decrease unloading time, pieces of super-sack were dropped into the bulk storage trailer and pneumatically transferred to the day bin as the day bin was filled. No one realized pieces of super-sack were in the trailer until they began plugging feed screws. This was a problem during all of the tests but *most evident during tests 3&4. Plugging screw feeders often determined test length and which lines were available to transport material.*

Test 3 (14:00 – 15:30) SW corner only; elevations 231’ and 217’. Screw speeds were increased to 37.5 Hz (4,200 lbs/hr/line) for a total feed rate of 8,400 lbs/hr in the two lines feeding the SW corner, representing ~12.5% of total fuel input. Average load was 116.4 Mwe, and an O_2 of 3.4%, and average NO_x was .172 lbs/mmbtu, for a 7.02% NO_x reduction. (Fig. 8 & Table 15)

Test 4 (16:10 – 18:10) SW and NE corner; elevation 217’. Screw speeds remained at 37.5 Hz (4,200 lbs/hr/line) for a total feed rate of 8,400 lbs/hr in the two lines feeding both lower corners, representing ~12.5% of total fuel input. Average load was 112.1 Mwe, and an O_2 of 3.14% and average NO_x was .164 lbs/mmbtu, for an 11.35% NO_x reduction. (Fig. 8 & Table 15)

Fig 10. Tests 3&4



<u>DCS Data Averages During Baseline and Tests 1-4</u>

Tables 15 & 16 reflect the averages for each baseline period and each test period of data compiled by the DCS in operations. Best NO_x data, as shown on the bottom of Table 15, compares the average of three baseline NO_x readings to the best average NO_x readings from (16:15 – 17:45) 3/21/2003. The average NO_x improvement was 29.6% during this period. Other critical data on Table 15 include CO, O_2, and opacity. All three average data points were well within the parameters of good and reasonable set points. CO did increase to 41 ppm in Tests 3&4 as O_2 was decreased to 3.1%.

The columns of throttle pressure and furnace pressure have, for space considerations, been removed from Table 16. Furnace pressure was unchanged at -0.40" w.c. and throttle pressure only varied from (1889 – 1892 psi). Of all the average data points only windbox pressure increases during Tests 3&4 are noticeable. Furnace operation remained very consistent during the micronized coal injection trials. (Table 16)

When injecting auxiliary solid fuel into any furnace, loss of ignition (LOI) is often a concern. Cyclone samplers on the East and West sides of the ESP were check for functionality and collected samples during baseline and test periods. Duration of these periods was short and therefore the LOI samples may not be reflective of a longer test period, however, the low LOI numbers certainly do not indicate any carbon loss issues. (Table 17)

Table 15. Average Mwe, NO_x,CO,O_2,SO_2, & Opacity During Test Periods

Description	Injection location	Start Date	End date	Mwe	NO_x	CO	O_2	SO_2	Opacity
Baseline		3/20/2003 1:37	3/20/2003 7:49	112.4	0.262	31.7	4.6	1.3	10.6
Test 1	1NE top and 1SW bottom	3/20/2003 11:40	3/20/2003 15:44	110.1	**0.178**	18.2	3.7	1.2	10.3
	Lowered tilts due to high temp. tubes, 77-80%								
	ROFA damper LL2 found to be inoperable	**NO_x reduction**	**32.0%**						
	At 14:00 increased ROFA air to 27%								
	MC-coal injection 20 hz (4 lines) = 8,640 lbs/hr								
Baseline		3/21/2003 7:41	3/21/2003 9:04	111.3	0.241	31.6	4.6	1.3	13.8
Test 2	Injection Locations above burners (elevation 245')	3/21/2003 9:05	3/21/2003 10:36	108.5	**0.276**	34.3	3.8	1.3	11.2
	Tilts 100% - high NO_x								
	MC-coal injection east side (2 inspection doors)	**NO_x increase**	**12.6%**						
	and west side (2 inspection doors)								
	ROFA air bias @ 10:00, 10:25								
Baseline		3/21/2003 10:37	3/21/2003 13:59	113.5	0.185	33.2	3.4	1.3	9.9
Test 3	Injection location SW top and bottom	3/21/2003 14:00	3/21/2003 15:30	116.4	**0.172**	34.3	3.4	1.3	11
	Increase rate to 37.5 hz (2 lines) = 8,400 lbs/hr								
Test 4	Injection location SW bottom and NE bottom	3/21/2003 16:10	3/21/2003 18:10	112.1	**0.164**	41.7	3.1	1.3	12
	Increase rate to 37.5 hz								
	Increase windbox pressure	**NO_x reduction**	**9.2%**						
Best data	Injection location SW bottom and NE bottom	3/21/2003 16:15	3/21/2003 17:45	112.1	**0.161**	41.4	3.1	1.3	11
	Increase rate to 37.5 hz								
	Increase windbox pressure	**NO_x reduction**	**29.6%**						

Table 16 Average DCS Data per Baseline and Test Periods

Description	Drum P	Steam Flow	Superheat T	Reheat T	Mill Master	Feeder A	Feeder B	Feeder C	Feeder D	Air Flow	Sec Air T	Windbox P	Stack T
Baseline	1943	816	947	947	52.6	6.3	6.3	6.3	6.4	771	523	1.5	235
Test 1	1939	785	982	982	49.9	5.9	6.0	6.0	6.1	666	532	1.4	236
Baseline	1943	807	945	943	52.8	5.6	6.5	6.6	6.6	744	529	1.4	239
Test 2	1939	786	937	936	46.3	4.2	6.0	6.0	6.1	674	524	1.4	236
Baseline	1942	816	974	974	57.0	6.8	6.8	6.9	6.9	694	531	1.5	240
Test 3	1948	841	967	966	52.6	6.2	6.3	6.3	6.4	710	535	1.49	247
Test 4	1942	805	970	970	51.8	5.1	6.3	6.7	6.8	658	533	1.62	249
Best data	1942	805	970	970	51.8	5.3	6.3	6.6	6.7	656	533	1.52	250

Table 17 LOI Samples

Location & Date of Cyclone collector	LOI
3/20 E	2.9%
3/20 W	3.2%
3/21 E	3.5%
3/21 W	3.6%

Economic & Environmental Considerations

A FULL SCALE EVALUATION OF A MULTI-POLLUTANT REDUCTION TECHNOLOGY has potential economic benefit for many coal-fired power plant operators. A lot was accomplished, for very little funding, at Cape Fear #5. The effect of turbulence and good mixing generated by ROFA/ROTOMIX has an obvious positive impact on sorbent injection, when it comes to SO_2 and Hg capture. A longer full scale evaluation needs to be completed on a furnace properly prepared for sorbent injection, so the process of injection can be closely monitored and the effect of molar ratio and good soot blowing can control slagging. Back-end cleanup with scrubbers is a very costly process with many environmental disposal issues to deal with. Sorbent injection with good furnace mixing may not reduce SO_2 and Hg to EPA mandated levels alone, but substantial in-furnace reduction would always mean less back-end cleanup with a correspondent drop in disposables.

NO_x reduction is a major component in any MULTI-POLLUTANT REDUCTION TECHNOLOGY and the MC-coal injection trials at Cape Fear #5 showed some promise in driving NO_x below .15 lbs/mmbtu. A more extensive trial with on-site coal micronizing, higher injection rates, and an accurate CFD study prior to injection setup, would likely result in a controlled in-furnace NO_x reduction below .15 lbs/mmbtu. Compared to SCR, deep staging a furnace and injecting MC-coal is a hands down economic and environmental winner in the NO_x reduction wars. As EPA considers even lower NO_x mandates, the first step by any and all coal-fired plant owners, should be in-furnace reduction before backend cleanup. The in-furnace cost per ton of NO_x removed is approximately ¼ the cost of removal by SCR, and should a SCR still be required to meet new lower standards, the size (capital cost) and operating cost (fan power, ammonia & catalyst) of the SCR would be much less. Ammonia slip and blue haze is giving some utilities fits from large SCR installations. The conversion of high priced natural gas to ammonia use for NO_x reduction is not only an environmental issue but this application of high priced natural gas would be better served in a home heating application.

Conclusions

Very high mercury reductions (89% with limestone and 67% with Trona) was the pleasant surprise during these injection trials. As reported by URS “the Hg reduction data are interesting from several perspectives and appear to reflect both changes in Hg speciation and variations in collection efficiency of individual species”. It was difficult to believe these very substantial mercury reduction numbers at first, but URS confirmed the initial analysis with a reanalysis of the data. Sulphur reduction numbers experienced in Sweden (90%) were not replicated at Cape Fear, but US coal-fired generating plants operate at higher furnace temperatures than small Scandinavian district heating boilers. Higher furnace temps also accounted for much of the slagging in the superheater. Mobotec USA is quite interested in a more extensive full scale test using Trona for SO_2 and Hg capture.

Weather played a major role in conducting these tests in an outdoor environment. North Carolina experienced crippling ice storms and repeat periods of rain all during the fall and spring of 2002 – 2003. Incessant rain hampered operations and implementation of equipment changes throughout the project. Water invaded PVC connections causing some plugging problems and finally leaked into the bulk storage trailer containing micronized coal. Water in the MC-coal created a hot spot due to spontaneous combustion, and stopped the MC-coal injection trials before their natural conclusion. Attempting a FULL SCALE EVALUATION OF A MULTI-POLLUTANT REDUCTION TECHNOLOGY on a very small budget was also a significant contributing factor to the length of the project and certainly the end results of the micronized coal trials. Three months had passed between the sorbent injection trials, plugging and subsequent cleaning of the superheater, and the MC-coal trials. By this time plant personnel had run out of patience and wanted the MC-coal injection trials over and done with so the site could be restored to normal operation. The trials were to begin on 3/17/03 but bearings were still out on the ROFA fan delaying the trials to the last two days of the week. Much was accomplished in that two day period but realistically, a full week of trials would have made more sense and potentially shown better results.

With the illumination of hindsite we would have made the following changes in our approach to the project.

1. Use sch 10 steel piping from the beginning.
2. Eliminate line valving and carry full diameter piping to the point of injection.
3. Micronize coal and sorbents on site eliminating the bulk storage trailer
4. Set the day bin higher in the furnace structure to minimize piping lengths
5. Use eductors and compressed air in lieu of PD blowers and rotary valves
6. Place a higher emphasis on understanding the complexities of the furnace before injection.
7. Use experienced material handling contractors.
8. Provide more manpower to ensure adequate support for the project.

In spite of aforementioned difficulties many positive aspects ie, (89% Hg reduction and the low cost and environmental impact of in-furnace capture versus backend cleanup) came out of the sorbent and micronized coal trials. A natural next step is development of the CentroFloat Mill to be utilized in future full scale tests. Progress Energy and other utilities have expressed interest in more extensive testing and the application of biomass processing for co-firing.

Acknowledgements

We would like to express our collective gratitude and patience for the plant personnel at Cape Fear Power Plant, Moncure, NC. In particular the yeoman effort put forth by Steve Castagnero of the Strategic Engineering Group. We would also like to thank Bruno Morabito, Trigen-Cinergy Solutions of Rochester, NY, and Dr. Jamal Mereb DTE Energy, Detroit, MI, for their experience and expertise on micronized coal reburn.

Listing of Pertinent Publications

- *Micronized Coal Reburning for NO_x Control on a 175 MWe Unit*, D T. Bradshaw, J.U. Watts, T.F. Butler,
- A.C. Wiley, R.E. Sommerlad, presented at Power-Gen 91', December 4-6, 1991,Tampa, FL.
- *Critical Design Issues In The Utility Retrofit Application of Selective Catalytic Reduction System (SCR) Technology,* K.C. Hopkins, F. Massi, presented at American Power Conference, April 9-11,2001, Chicago, IL.
- *Mercury Emissions and Removal During Co-firing of Coal Wood Wastes,* P. Kouvo, T. Korelin, T. Savola, presented at The US EPA-DOE-EPRI Combined Power Plant Air Pollutant Control Symposium: (The Mega Symposium), August, 20-23,2001, Chicago, IL.
- *Micronized Coal For Boiler Upgrade/Retrofit,* M. Beam, T. Rogers, L. Berry, A. C. Wiley, presented at Gen-Upgrade 90, April, 1990, Washington. DC.
- *Co-firing Coal-Water Slurry Fuel with Pulverized Coal as a NO_x Reduction Strategy,* Bruce G. Miller, Sharon F. Miller, Joel L. Morrison, and Alan Scaroni, presented at the 14^{th} International Pittsburgh Coal Conference, Taiyun, China, Sep. 23-27, 1997.
- *Comparison of NOx Control Parameters Using Pulverized Coal Reburning In Wall and Tangential Firing Configurations,* Jamal B. Mereb and Murray F. Abbott, proceedings of the 1998 International Joint Power Generation Coneference, Vol. I, pp. 139-146, 1998
- *Dense Phase Reburn Combustion System (DPRCS^{Tm}),* Bruno Morabito, Robert Hochstetler, and Allen C. Wiley, presented at PowerGen 2001, Dec. 11-13, 2001, Las Vegas, NV.
- *Micronized Coal Reburning Demonstration for NO_x Control: A DOE Assessment*, DOE/NETL-2001/1148 June 2001.
- *New Developments and Application Experience with Combustion and Post Combustion NOx Control Technologies*, Edwin Haddad and John Ralston; Mobotec USA; Mark Shilling, Progress Energy, presented at PowerGen 2001, Dec. 11-13, 2001, Las Vegas, NV.
- *Use of CFD Modeling to Evaluate NOx Reduction in Utility Boilers,* Brad Adams, Marc Cremer and Dave Wang, Reaction engineering Int., presented at PowerGen 2001, Dec. 11-13, 2001, Las Vegas, NV.
- *Design and Testing of A Retrofit Dry Sorbent Injection System on a 300 MWe Pulverized Fuel Boiler*, D. Cameron and J.A. Arnott, Ontario Hydro Power Equipment Department, Toronto, Ontario, Canada.

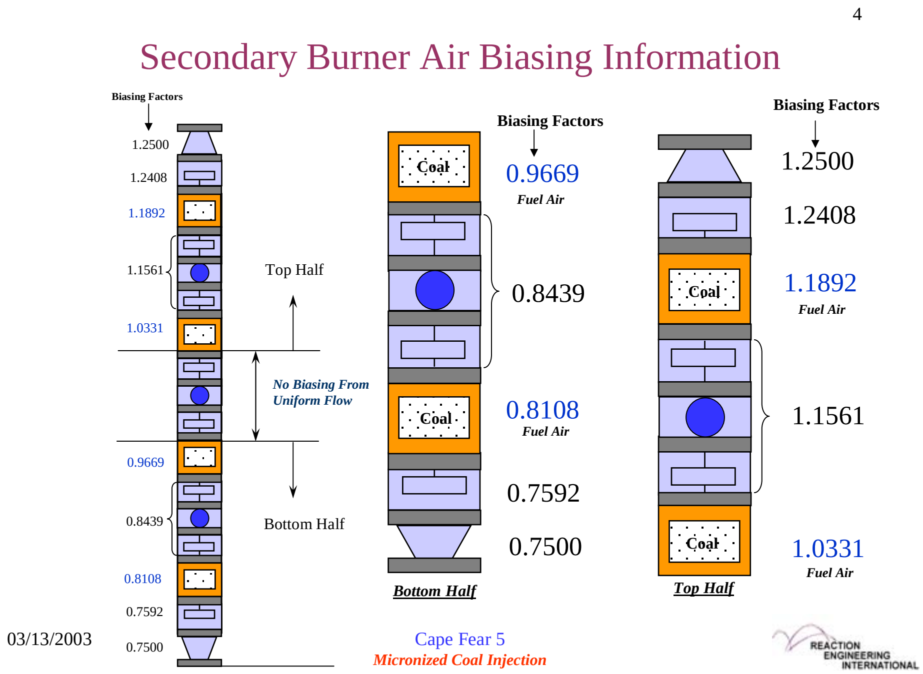
Acronyms and Abbreviations

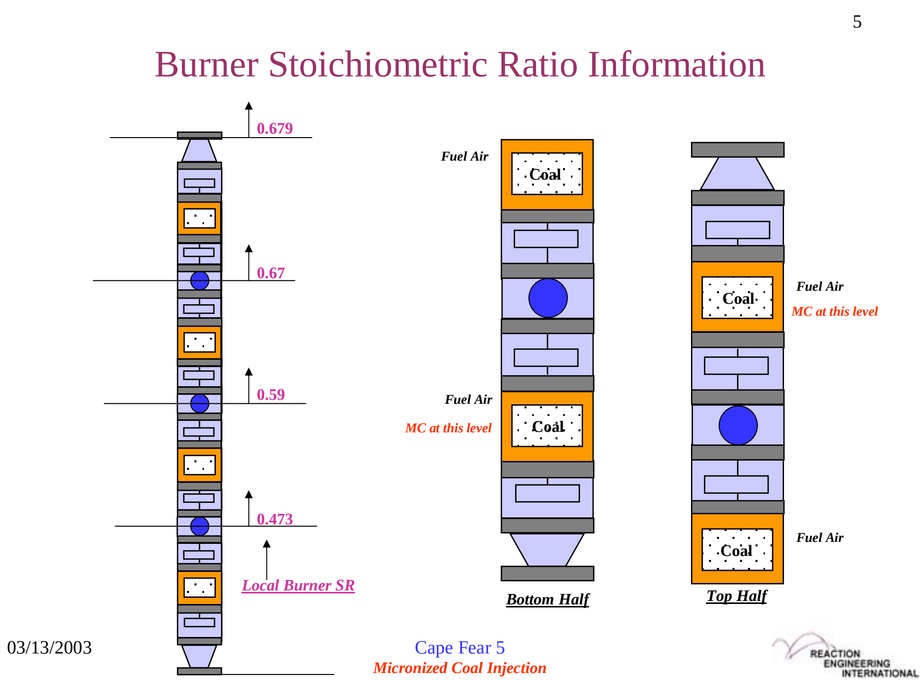
ABS	Ammonia bi-sulfate	MC	Micronized coal
ACFM	Actual cubic feet per minute	MC-coal	Micronized coal
AEFLGR	Amine enhanced flue gas reburn	MCR	Maximum combustion rating
ASTM	American Society of Testing Materials	Mg	Miligram
Avg.	Average	MWe	Mega-watt electric
$CaCO_3$	Calcium carbonate	N_2	Nitrogen gas
CCT	Clean Coal Technology	NO_x	Nitrogen oxide
CCS	Controlled Condensation System	O_2	Oxygen
CFD	Computational fluid dynamics	OFA	Over-fire air
CO	Carbon monoxide	O&M	Operation & maintenance
CO_2	Carbon dioxide	PC	Pulverized coal
CP&L	Carolina Power & Light	PC-coal	Pulverized coal
CWS	Coal water slurry	PM	Particulate matter
DCS	Distributed Control System	PPM	Parts per million
DOE	United States Department of Energy	PVC	Poly vinyl chloride plastic
DPCT	Dense Phase Coal Torch	QA	Quality Assurance
DPRCS	Dense Phase Reburn Combustion System	QC	Quality control
DSCFM	Dry standard cubic feet per minute	% Red	Percent reduced
ESP	Electrostatic precipitator	RDF	Refuse derived fuel
FD	Forced draft	REI	Reaction Engineering International
FSI	Furnace sorbent injection	ROFA	Rotating opposed-fired air
Gr	Grains	ROTAMIX	Rotary mixing of chemicals & sorbents
GWe	Giga-watt	SCR	Selective catalytic reduction
H_2O	Water	SEM	Scanning electron microscope
HCl	Hydrogen cloride	SIP	State Implementation Plan
ID	Induced draft	SNCR	Selective non-catalytic reduction
KW	Kilo-watt	SO_2	Sulfur dioxide
Lb/mmbtu	Pounds per million btu	SO_3	Sulfuric gas
Lbs/hr	Pounds per hour	SR	Stoichiometric ratio
LNB	Low NOx burner	T-fired	Tangentially-fired
LOI	Loss of ignition	Ug/Nm^3	Micro-grams per cubic meter (nitrogen)
		WIR	Russian NOx technology

Appendix

REI Power Point Slides

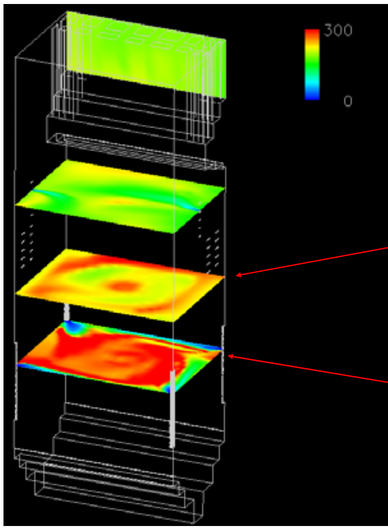
Air biasing & stoichiometric ratio





NOx and temperature cross-sections

NOx Concentration Cross-sections

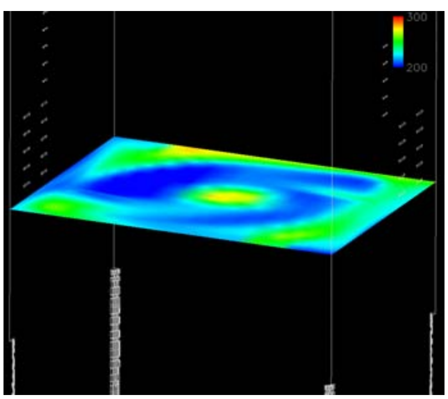


below lowest ROFA ports

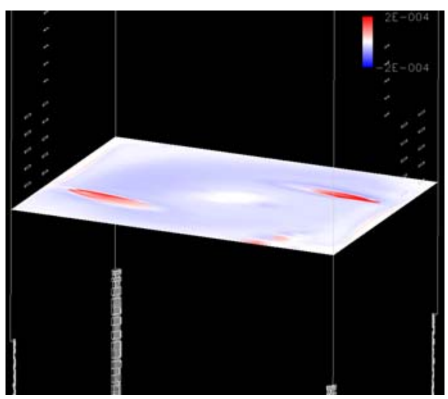
Immediately below top fuel injector

NOx below ROFA Ports

NOx Concentration (ppm)

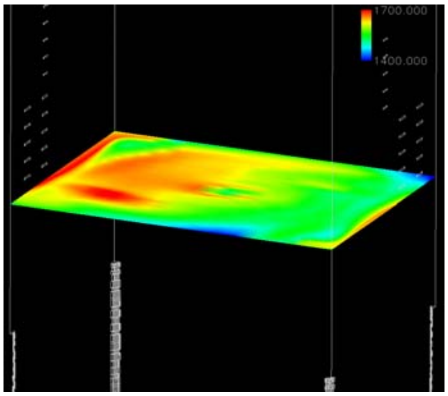


NOx Formation/Destruction Rates

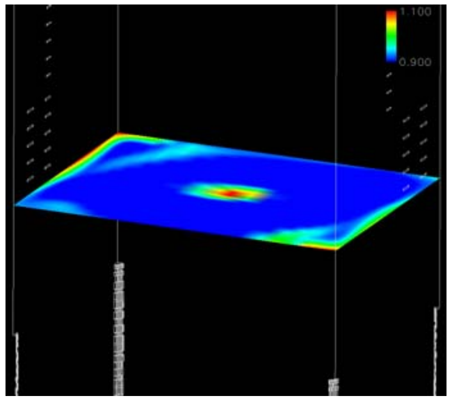


Temperature and SR below ROFA Ports

Gas Temperature (K)



Stoichiometric Ratio



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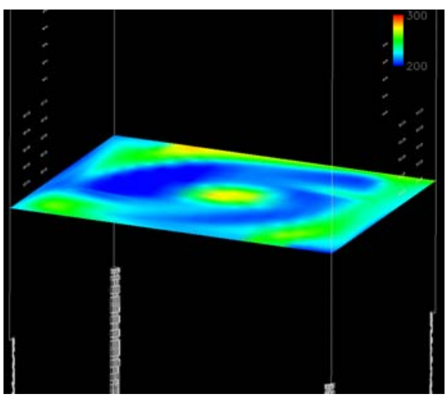
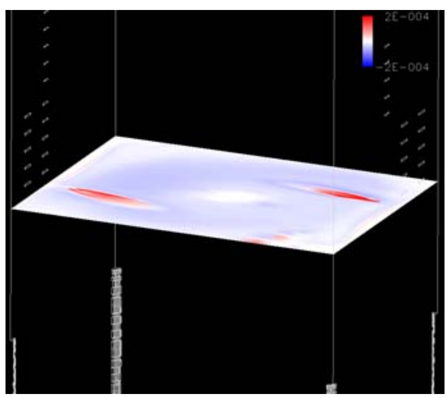
NOx below ROFA Ports

NOx Concentration (ppm)



NOx Formation/Destruction Rates



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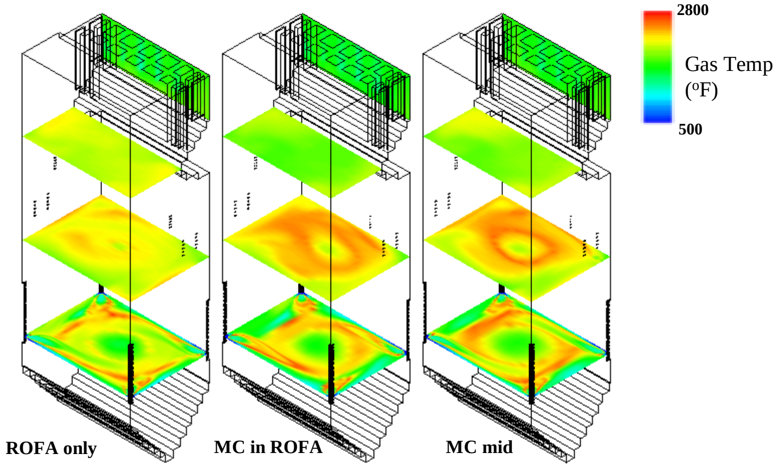
CFD Simulation Cross-Sections

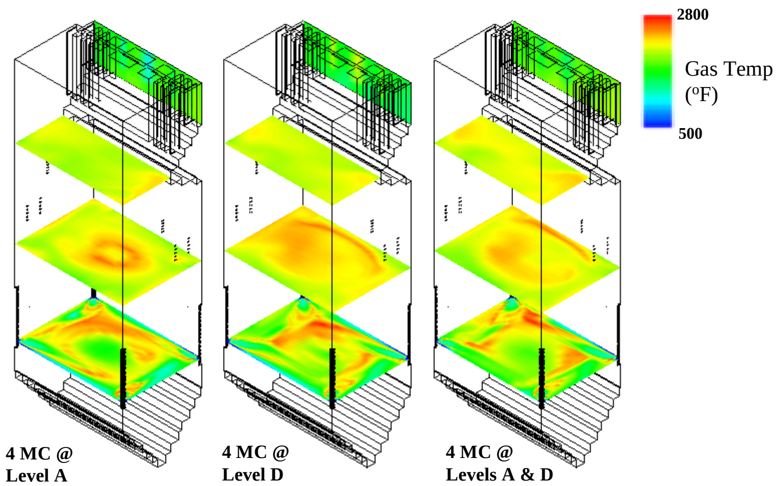
2

Gas Temperature

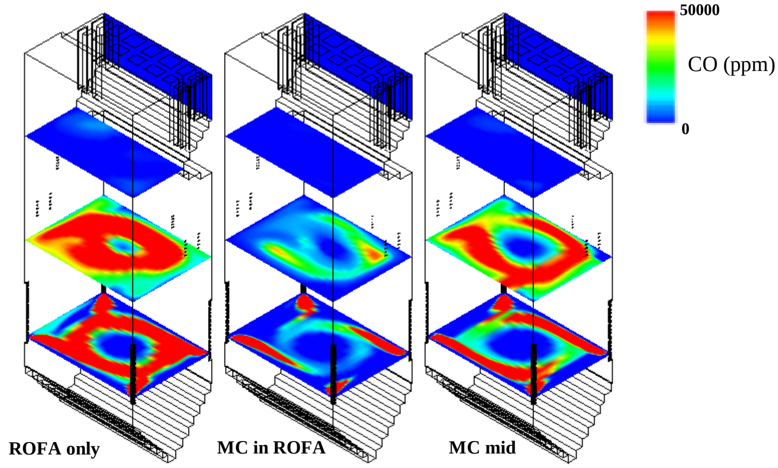


3

Gas Temperature



CO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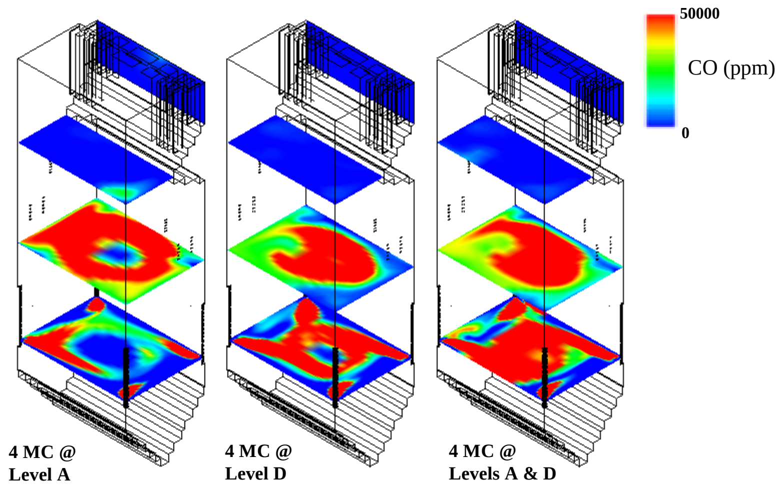
CO (ppm)
0
ROFA only
MC in ROFA
MC mid

CO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CO (ppm)
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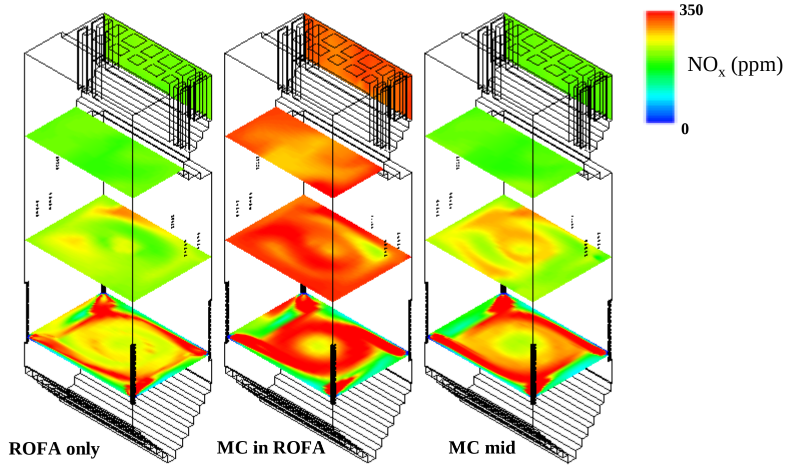
4 MC @
Level A
4 MC @
Level D
4 MC @
Levels A & D

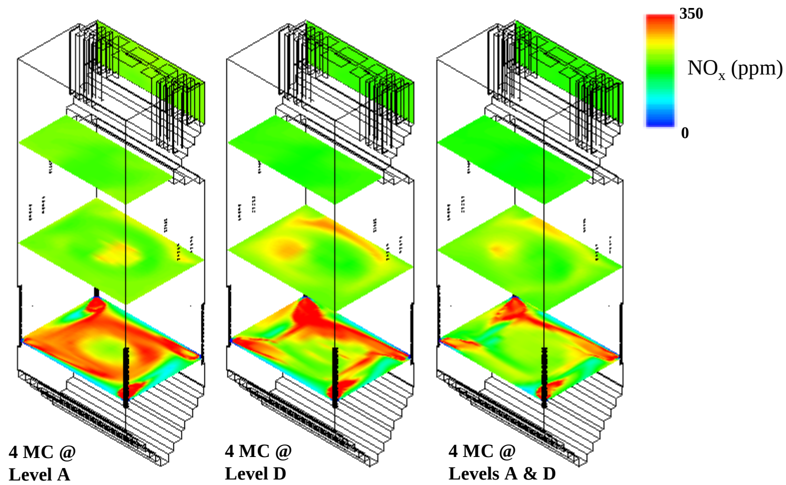
6

NO_x


350
NO_x (ppm)
0
ROFA only
MC in ROFA
MC mid

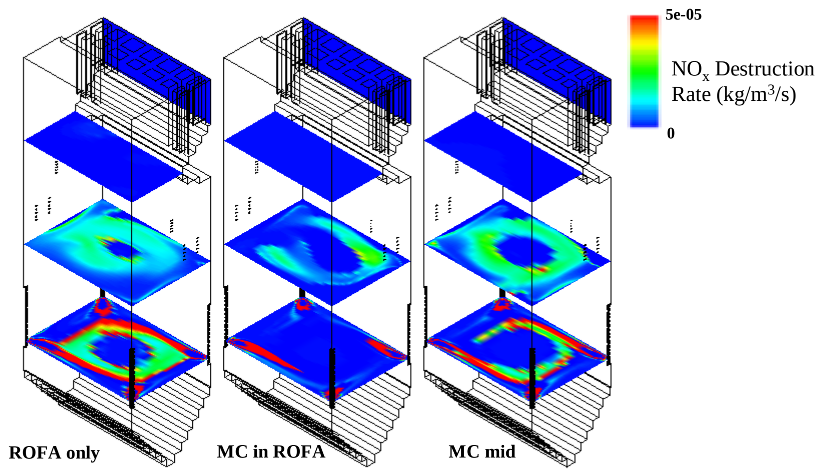
7

NO_x


350
NO_x (ppm)
0
4 MC @
Level A
4 MC @
Level D
4 MC @
Levels A & D

8

NO_x Destruction Rate



9

NO_x Destruction Rate