MODULATING CONTROL OF LOW NO_X BURNERS

ABSTRACT

Manufacturers of today's wall-fired low NO_X burners (LNB) recommend a single-position secondary air volume control for in-service burners. Air register modulation is avoided. This paper documents a successful effort to progress beyond conventional practices of contemporary LNB applications by continuously modulating LNB air registers and overfire air (OFA) registers. The paper asserts a hypothesis that burner front combustion would be better controlled by modulating burner air registers to follow burner fuel flow, while OFA responds to NO_X. The authors conducted extensive parametric tests to support the hypothesis. A control system was subsequently developed and implemented to confirm the results.

INTRODUCTION

The PSI Energy, Inc., Gibson Generating Station is located in southwestern Indiana on the Wabash River. The station is composed of five Foster Wheeler opposed-fired supercritical steam generators and five 650-MW General Electric turbine generators. The Foster Wheeler steam generators are rated at 4,588,000 lbs/hr main steam at 1,005 degrees. This papers addresses NO_X reduction work conducted on Units 1 through 4 which went commercial in 1975 through 1979. In response to the Clean Air Act Amendment of 1990 (CAAA-90), PSI implemented NO_X reduction modifications to Units 1 through 4 during the years 1991 through 1994. Highlights of the specific technical details were presented at this conference in 1993.

NO_X REDUCTION DESIGN PARAMETERS

The objective of the NO_X reduction effort at the Gibson Generating Station was to meet the NO_X compliance limit mandated by the CAAA-90 at the lowest evaluated cost while producing the least impact on the PSI system. The evaluated cost included the projected impacts on boiler performance, including but not limited to, thermal efficiency, availability, and maintenance costs. The project team endeavored to produce a NO_X capability of less than .50 lb/MMBtu with no increase entries in unburned carbon and no loss in unit operability. The equipment was also required to have sufficient adjustability to accommodate as many as 45 different fuels.

NO_X REDUCTION EQUIPMENT, CONFIGURATIONS, AND CONTRIBUTORS

Each Foster Wheeler boiler is fitted with six Foster Wheeler MB-series mills. The chosen low NO_X burner supplier was Phoenix Combustion, using their Atlas air register and Atlas burner. Phoenix Combustion also supplied all overfire air equipment. Energy Systems Associates (ESA) was chosen to supply a computer model describing combustion and heat transfer processes occurring in the furnace. A majority of the tuning and adjustment was also aided by a sample and analysis system provided by ESA. All control and monitoring was implemented through a Westinghouse WDPF control system. Burns & McDonnell Engineering Company provided all engineering for evaluation, specification, installation, and tuning.

Units 1 and 2 employ a dual-level overfire air system with 16 ports per wall. Units 3 and 4 employ a single-level overfire air system with four ports per wall. The four ports per wall used on Units 3 and 4 took advantage of existing burner openings made available by alteration of the former Foster Wheeler interstage air system. Thus, the lower pre-modification NO_X levels and the higher post-modification NO_X levels.

NO_X REDUCTION RESULTS

Units 1 and 2 NO_X emissions was originally 1.30 lb/MMBtu. Through the use of the Phoenix Combustion low NO_X burners, the Phoenix dual-level overfire air system, and configuration optimization using the ESA model, NO_X emissions at full load were reduced to .32 lb/MMBtu. Similarly, Units 3 and 4 NO_X emissions were reduced from .80 to .42 lb/MMBtu. In both instances, unburned carbon was increased minimally, and unit operability was not noticeably changed. This over compliance capability allowed PSI to target a NO_X emissions level of .45 lb/MMBtu at all loads.

CONVENTIONAL WISDOM

Almost all low NO_X burner manufacturers recommend a single position operation for secondary air volume control. Although not always true, NO_X on wall-fired units is usually at its peak at full load. For that reason, low NO_X burners are typically optimized for maximum performance and NO_X reduction at full load. Those positions remain unchanged at lower loads, resulting in compromised, but adequate performance. Modulation of OFA is usually accomplished in discrete steps based on unit load. There is typically no modulation of the secondary air inner or outer registers, or of the overfire air dampers.

THE GIBSON APPROACH

PSI Energy chose to approach Gibson's NO_X reduction project from a perspective which more closely integrates emissions levels with unit operability and efficiency. The Gibson approach was to intentionally design the NO_X reduction revisions for over compliance. The over compliance capability would allow latitude in burner, air register, and overfire air adjustments. Parametric relationships were then developed for implementation in a control system to result in adequate NO_X compliance with minimal impact on performance.

The advantages of this approach are numerous. The generating station remains responsive to the CAAA-90 legislated NO_X emissions limit of .50 lb/MMBtu. This is an environmentally responsible position, taking the attitude that legislators had properly evaluated appropriate emissions levels and determined that anything under.50 lb/MMBtu was acceptable. This position is also environmentally responsible toward non-renewable natural resources. Adjusting for a NOX emission level of .45 lb/MMBtu instead of .32 lb/MMBtu would probably result in lower unburned carbon, which translates into more economical use of coal as a fuel.

Minimizing the depth of combustion staging (through OFA) also results in less reducing atmosphere in the lower furnace, less lower furnace corrosion, less tendency for slagging in the lower furnace, and lower unburned carbon.

WHY CHALLENGE THE CONVENTIONAL WISDOM?

It was the project team's opinion that the conventional approach of not modulating air registers is optimized only at full load. All other combinations of loads, mills in service, fuel flow, etc. are then a compromise resulting in less than optimum performance. Operation at lower loads depends solely on lower windbox pressure to reduce the air flow. This, of course, also results in less overfire air.

PARAMETRIC DATA

The following data was taken at controlled conditions for development of parametric relationships for each furnace:

- NO_X
- LOI
- Load
- Outer air register position
- Inner air register position
- Burner tip position
- OFA position
- O_2
- Quantity of mills in service

The original intent was to develop detailed parametric relationships for each variable. Initial testing illustrated just how complicated and unnecessary some of those relationships were going to be. For example, burner tip position was a relatively labor-intensive adjustment that yielded only minor changes in emissions and LOI. The burner tip position adjustment was provided by

Phoenix Combustion as a means to adjust primary air exit velocity to account for a variety of different fuels. We also found that the quantity of mills in service did influence emissions, but not significantly. This is most likely due to the design of the Phoenix Atlas air register, which required only 8 percent cooling air flow. Thus, the cooling air flow does not significantly impact burner front stoichiometry or overfire air flow. The relationship between O_2 and other performance parameters proved to be elusive. With the overfire air registers throttled down to 70 percent or less and secondary air registers relatively open, NO_X would increase as O_2 increased. However, with 100 percent open overfire air registers, NO_X would actually be reduced at higher O_2. The latter inverse relationship resulted from the relatively large overfire air openings on Units 3 and 4. In effect, reducing O_2 reduced windbox pressure, which had a much larger effect on the overfire air registers than on the throttled-down burner air registers.

After initial testing, parametric development work focused on the following six parameters:

- NO_X
- LOI
- Load
- Outer air register position
- Inner air register position
- OFA position

PARAMETRIC TESTING

All testing was conducted at full load on one fuel at 3.4 percent O_2 with the overfire air closed, except for specific series of tests conducted to develop relationships identifying the effects of those particular parameters. A 24-point sample grid was permanently installed immediately after the economizer and tubed to a sample analysis system in the control equipment room. The sample analysis system, provided by ESA, included two sample vacuum pumps to simultaneously pull a sample for analysis and a sample to be subsequently analyzed. This significantly reduced the amount of time required to purge an old sample out of the sample line and a new sample into the sample line. The sample system also included the capability to manifold several sample points together for one analysis. Sampling all 24 points one at a time required approximately 30 to 45 minutes. Manifolding certain groups of samples could be accomplished in much less. The analysis system was able to indicate NO_X, CO, CO_2, SO_2, and O_2.

A Cegrit isokinetic ash sampler was installed on one air heater gas inlet duct. The sample jar was emptied before each test and samples manually retrieved during or at the end of each test. The unburned carbon was burned off in Gibson's laboratory.

The Phoenix Atlas burner air registers and overfire air registers included pitot tubes for measurement of inner air flow, outer air flow, and overfire air flow at each register. The project team specified these devices in hopes of monitoring air flow in engineering units. However, this proved impractical. Several unsuccessful attempts were made at relating pitot tube d/p to air flow. At best, these air flow measurements were relative indicators. The burners and air registers also included seven thermocouples each to monitor temperatures. All indications and control were accomplished through the Westinghouse WDPF system. The system included numerous graphics and a graphic printer for documentation.

Most of the parametric tests were run as rapidly as possible. If adjusting an air register or overfire air setting, stabilization period was minimal, at approximately 15 to 20 minutes. Test duration was usually determined by the sampling system at about 45 minutes. If adjusting O_2 however, a longer stabilization period of possibly 30 to 60 minutes was allowed.

Parametric Results

The following significant parametric relationships were developed:

- Figure 1 - NO_X and LOI vs. outer air register position.
- Figure 2 - NO_X and LOI vs. inner air register position.
- Figure 3 - NO_X and LOI vs. outer/inner position ratio.
- Figure 4 - NO_X and LOI vs. OFA position.
- Figure 5 - NO_X and LOI vs. percent O_2.
- Figure 6 - Outer air vs. mill load for a resultant .45 lb/MMBtu.
- Figure 7 - OFA vs. air flow for a resultant .45 lb/MMBtu.

The resultant parametric relationships are illustrated on the attached Figures 1 through 7. It should be noted that most of the NO_X and LOI scales on Figures 1 through 5 exceed .50 lb/MMBtu. This is because most of the tests were conducted with overfire air closed in an effort to eliminate overfire air effects on the performance of the burner itself. The data was taken solely to identify trends, not to optimize the settings during the test.

The outer air register position (Figure 1) was found to be the most influential and fortunately, the most predictable adjustment at the burner front. Predictably, opening the outer air register increases NO_X and decreases LOI. The same figure indicates a NO_X increase as O_2 is increased. The inner air register (Figure 2) adjustment exhibited a similar relationship with NO_X but an inverse relationship with LOI. Hence, the ratio of outer-to-inner air register position became an area of focus.

Figure 3 indicates an approximation of the outer-to-inner air register position ratio. The relationship is believed to be representative, if not accurate. It proved difficult to accommodate the economics of the utility and the needs of the dispatcher while trying to retrieve meaningful data. The test log did indicate however, that identical tests could be repeated after a few days,

with repeatable results. Figure 3 indicates theat best NO_X performance occurs almost simultaneously with the worst LOI performance. Thus, the effort to choose a compromise setting focused on optimizing the NO_X/LOI tradeoff while finding an area without a steep slope to the curve. The steeper the slope, the less predictable the performance results will be for any particular setting. For the Gibson Station, an outer-to-inner ratio of 5 was chosen.
Figure 4 indicates the relationship between overfire air position, and NO_X and LOI performance parameters. The overfire air register design is simply a single-stage version of the burner outer air register. The tests indicated that little is gained in performance beyond 60 percent open.

Figure 5 indicates the relationship between NO_X and LOI, and the economizer exit O_2. This data was taken after fuel and air balancing was completed and air register settings were determined. Thus, low LOI was achievable down to approximately 2.5 percent O_2.

Development of these relationships aided PSI in identifying optimum performance settings. The final tests focused on using those settings in a closed loop control system for NO_X compliance. The final tests operated the unit at various loads to achieve a NO_X emissions value of .45 lb/MMBtu. The tests began at full load with overfire air full open and air registers at the optimized settings. Air registers were then adjusted to achieve the desired NO_X setting of .45 lb/MMBtu. Unit load was then dropped 50 MW. At the new, lower load, air registers were adjusted according to the previously developed parametric relationships to match pulverize fuel flow. This adjustment raised windbox pressure, which provided additional overfire air. Any final adjustment to NO_X was made using the overfire air. This procedure was repeated from 600 MW down to 250 MW. Figures 6 and 7 indicate the results. Figures 6 and 7 were then programmed into a NO_X control system.

NO_X CONTROL CONFIGURATION

The NO_X control scheme is composed of two major subloops as shown in Figure 8. The NO subloop uses the established parametric relationships to program and position overfire and dampers. The secondary air subloop similarly positions the air registers, and both loops are subsequently trimmed by the NO_X controller. The system uses the burner air registers to control burner air flow and velocity, while keeping burner front stoichiometry within reasonable limits. Maintaining adequate windbox pressure becomes an incidental issue, and is accomplished via air register positioning only because the two relationships were developed concurrently. The OFA position characterization curve (Figure 7) was developed as that which resulted in a NO_X emission of approximately .45 lb/MMBtu. Thus, only minor trimming by the NO_X trim controller should be required. This approach was chosen because it would maintain NOX compliance while maintaining unit operability and minimum LOI.

System gains are such that the NO_X controller (Item 1.2) is an off-line controller with relatively limited contribution to summer 1.3. The basic OFA positioning is accomplished by function generator 1.5, which uses total air flow for its programming input. In this manner, the relatively unreliable NO_X analyzer (Item 1.1) can fail and the OFA dampers will still be driven approximately to the correct position by the function generator.

Total air flow is used as the program base instead of steam flow, firing rate master or fuel flow. Total air flow incorporates the effect of excess air (O_2), which can significantly affect NO_X emission and thus the need for OFA.

Manual loader 1.4 provides an adjustable OFA set point for the trim. It also artificially adjusts measured total air flow in an attempt to approximate a revised OFA program to match the revised OFA set point.

Outer air registers are positioned by function generator 2.14. Optimum outer-to-inner air register position ratio has been determined to be approximately 5:1. Thus, the inner air positions is programmed to be 20 percent of the outer air position program. This arrangement maintains proper outer/inner air relationship and also maintains similarly matched air/fuel ratio.

The configuration also recognizes that there may be conditions under which this system cannot maintain NO_X at set point because of equipment condition changes or weather conditions. The NO_X trim control loop was incorporated to compare measured NO_X to set point and adjust both overfire air position and air register position, thus affecting windbox pressure and required OFA position. Multiplier 3.11 and high/low limiter 3.12 work together to allow a variable maximum trim influence. Multiplier 3.11 ratios the error to establish a very small trim limitation at low loads and a larger trim limitation at high loads. For example, if measured NO_X is higher than set point, then the NO_X trim subloop would attempt to close down on the air registers within limits, which would raise windbox pressure. The increased windbox pressure would force additional overfire air and deeper furnace combustion staging. Simultaneously the NO_X trim would try to increase the OFA damper opening.

CONCLUSION

The examples in this paper were derived from Gibson Station Unit No. 3. Similar configurations have been implemented in Units 1, 2 and 4. As expected, Units 1 and 2, with their modified overfire air system, required minor revisions. This control system has operated at Gibson for approximately 2 years in Unit 3 with very good results. The unit maintains NO_X at approximately .45 lb/MMBtu at all loads and during most upset conditions and ramp rates. The project proved that modulation of air registers is feasible, responsible and effective.

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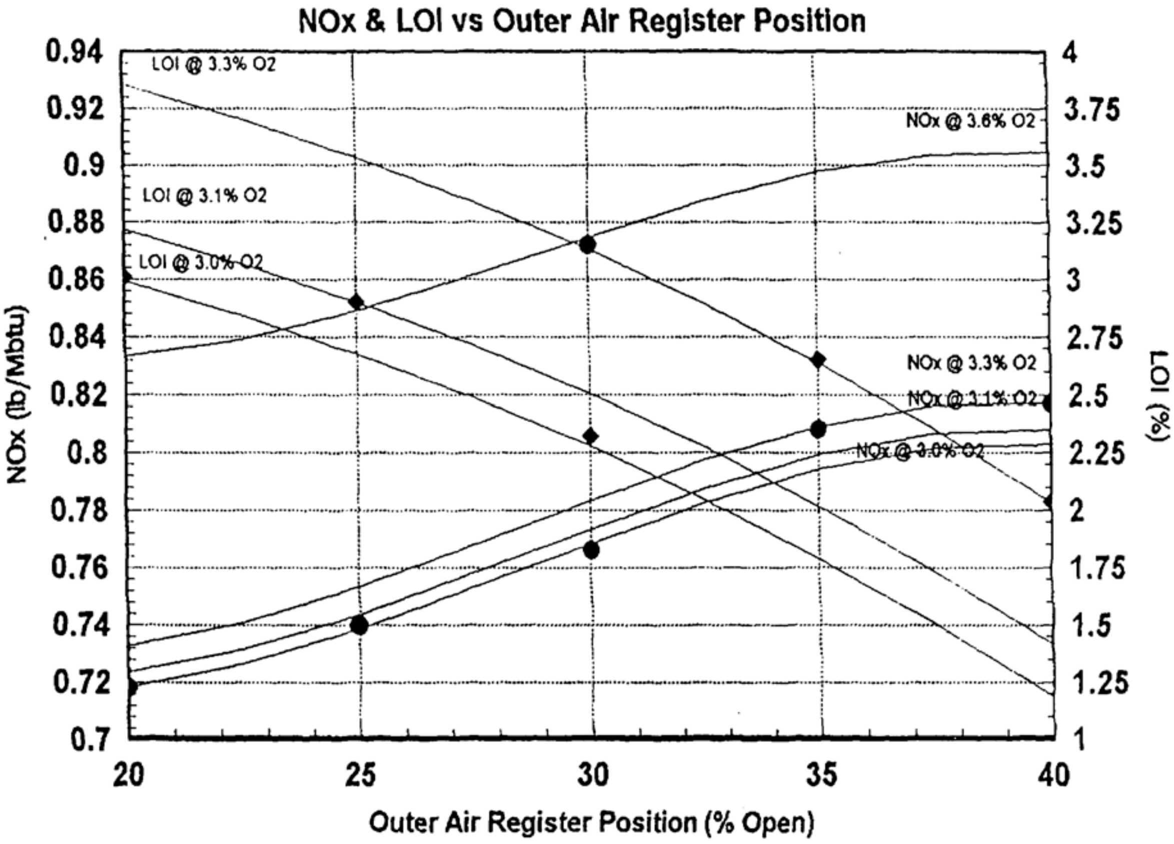
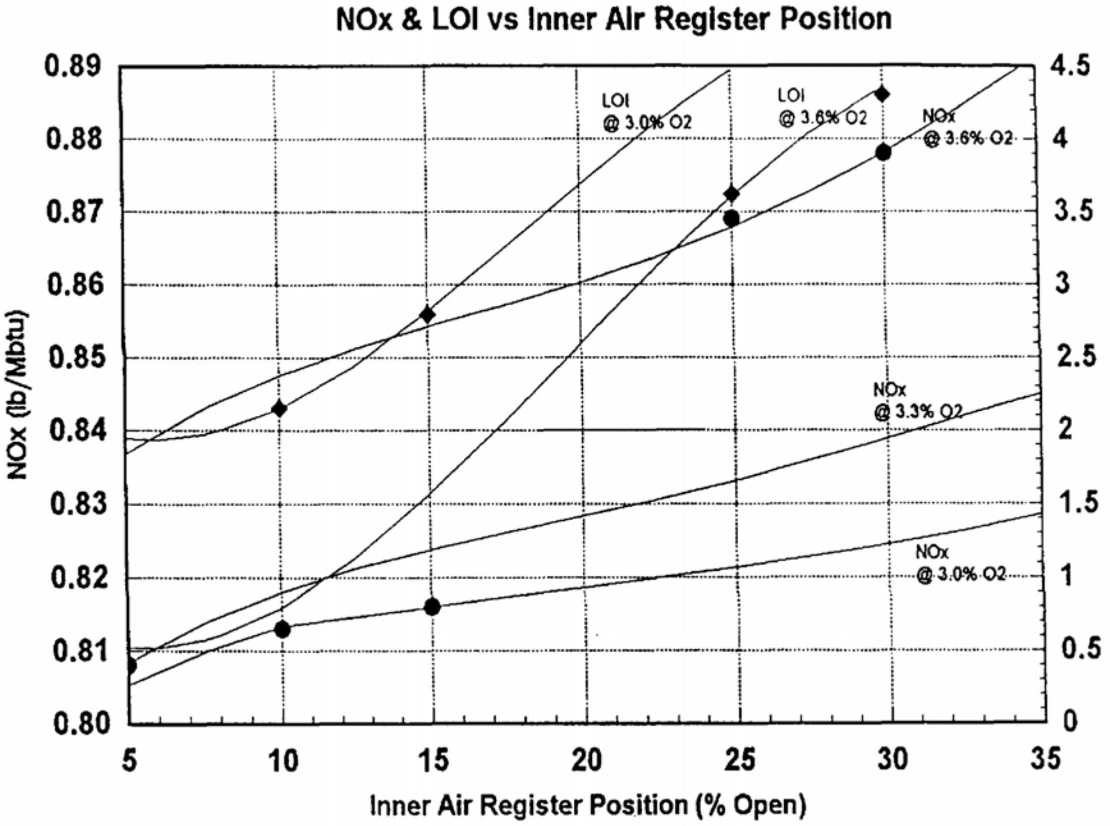
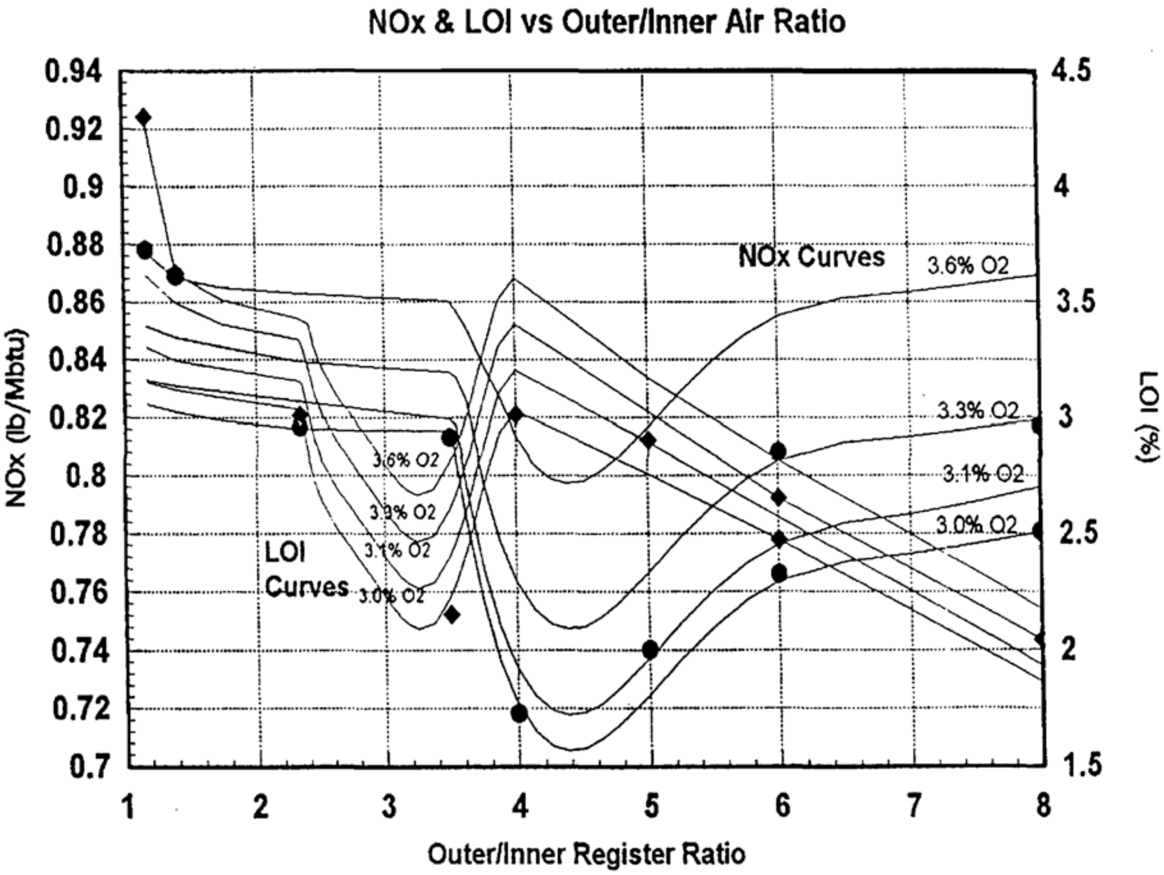
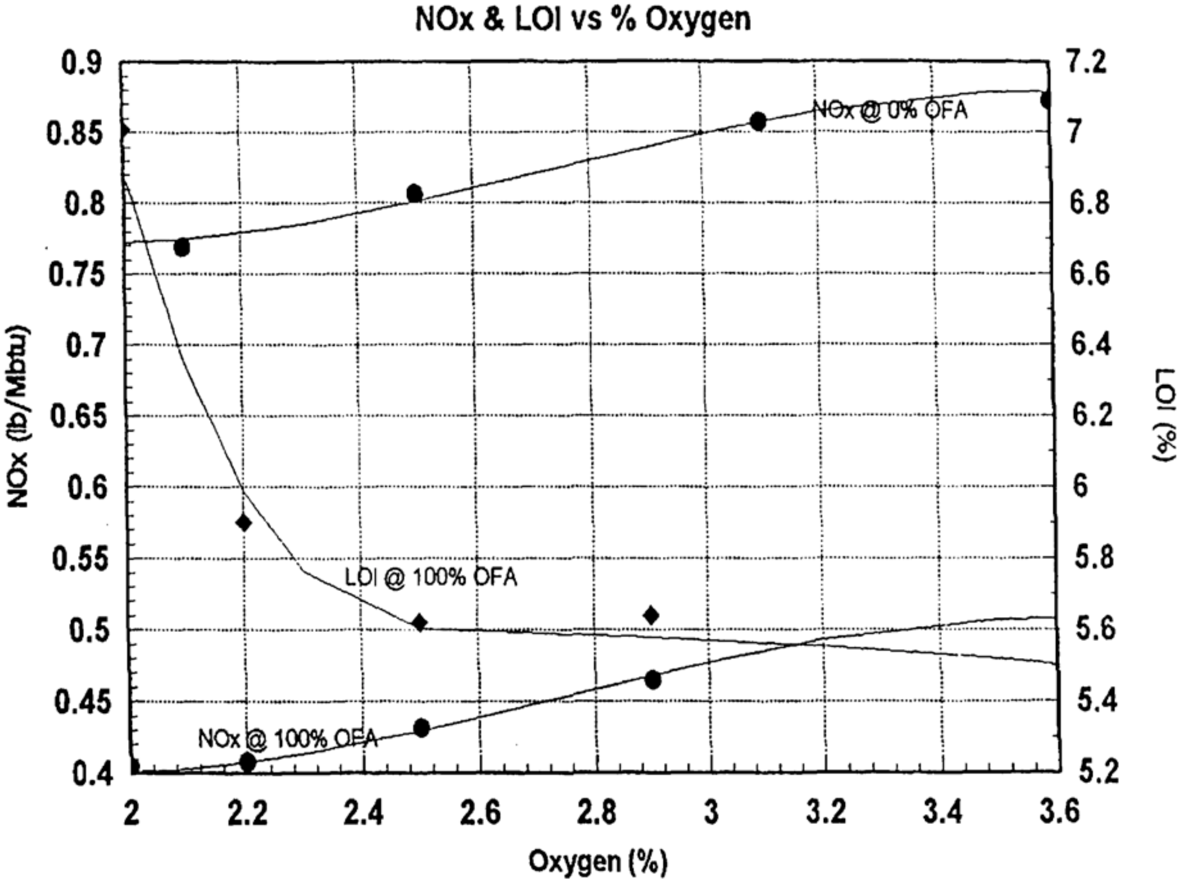
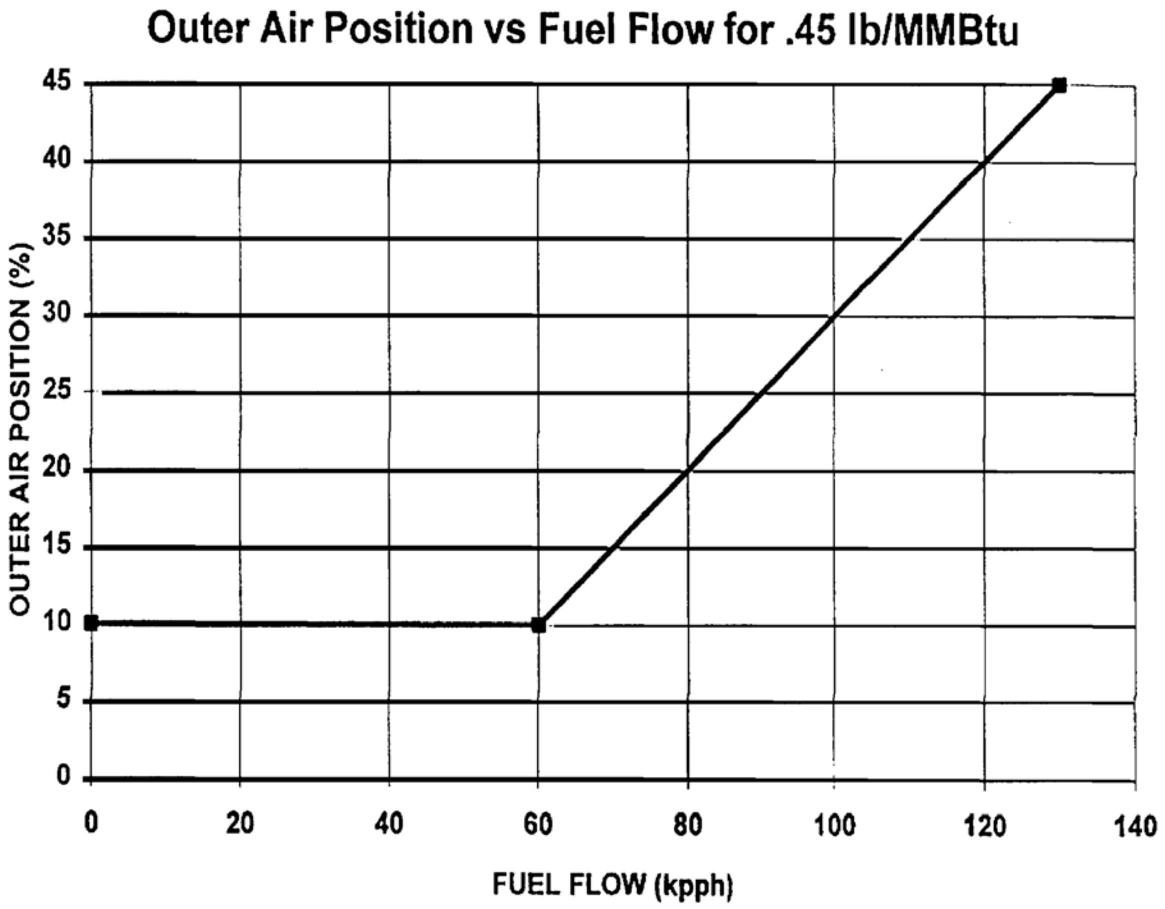

NOx & LOI vs Outer Air Register Position
NOx (lb/Mbtu)
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
0.7
LOI (%)
4
3.75
3.5
3.25
3
2.75
2.5
2.25
2
1.75
1.5
1.25
1
20
25
30
35
40
Outer Air Register Position (% Open)
LOI @ 3.3% O2
LOI @ 3.1% O2
LOI @ 3.0% O2
NOx @ 3.6% O2
NOx @ 3.3% O2
NOx @ 3.1% O2
NOx @ 3.0% O2

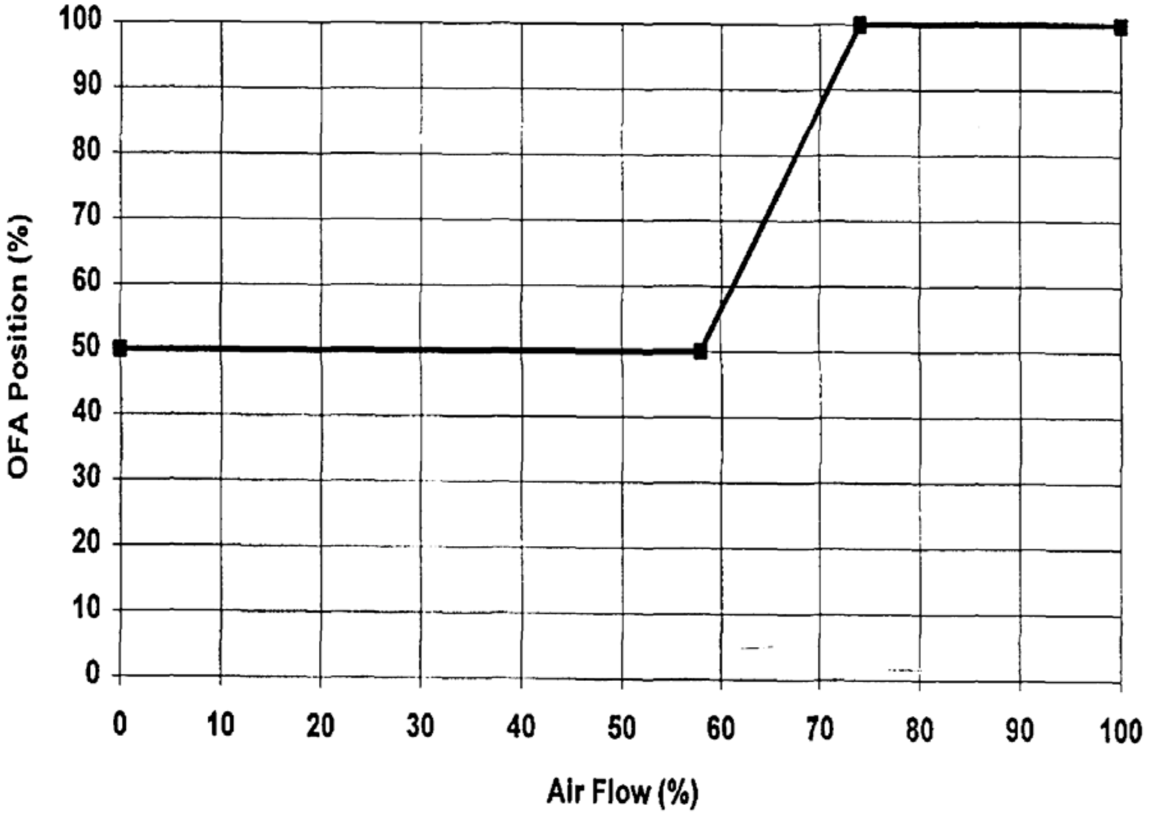

NOx & LOI vs Inner Air Register Position
0.89
0.88
0.87
0.86
0.85
0.84
0.83
0.82
0.81
0.80
NOx (lb/Mbtu)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
LOI (%)
5
10
15
20
25
30
35
Inner Air Register Position (% Open)
LOI
@ 3.0% O2
LOI
@ 3.6% O2
NOx
@ 3.6% O2
NOx
@ 3.3% O2
NOx
@ 3.0% O2

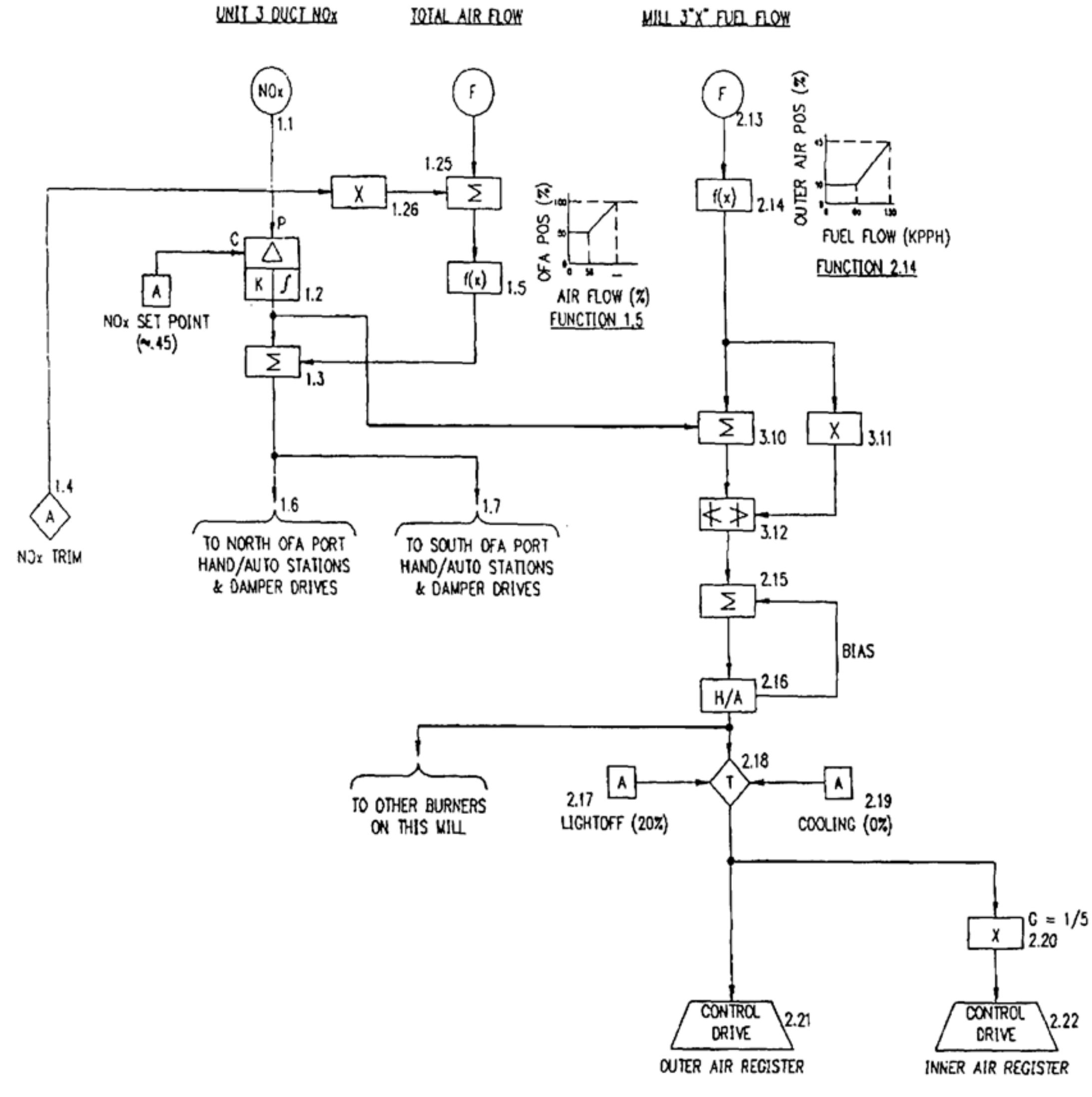

NOx & LOI vs Outer/Inner Air Ratio
NOx (lb/Mbtu)
0.94
0.92
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
0.72
0.7
LOI (%)
4.5
4
3.5
3
2.5
2
1.5
1
2
3
4
5
6
7
8
Outer/Inner Register Ratio
NOx Curves
3.6% O2
3.3% O2
3.1% O2
3.0% O2
LOI
Curves
3.6% O2
3.3% O2
3.1% O2
3.0% O2


NOx & LOI vs % Oxygen
NOx (lb/Mbtu)
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
LOI (%)
7.2
7
6.8
6.6
6.4
6.2
6
5.8
5.6
5.4
5.2
2
2.2
2.4
2.6
2.8
3
3.2
3.4
3.6
Oxygen (%)
NOx @ 0% OFA
LOI @ 100% OFA
NOx @ 100% OFA


Outer Air Position vs Fuel Flow for .45 lb/MMBtu
OUTER AIR POSITION (%)
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
FUEL FLOW (kpph)

OFA Position vs Air Flow for .45 lb/MMBtu




UNIT 3 DUCT NOx
TOTAL AIR FLOW
MILL 3"X" FUEL FLOW
NOx
1.1
F
F
2.13
1.25
X
1.26
Σ
f(x)
2.14
OUTER AIR POS (%)
FUEL FLOW (KPPH)
FUNCTION 2.14
P
C
K
∫
1.2
A
NOx SET POINT
(≈.45)
f(x)
1.5
OFA POS (%)
AIR FLOW (%)
FUNCTION 1.5
Σ
1.3
Σ
3.10
X
3.11
1.4
A
NOx TRIM
1.6
1.7
TO NORTH OFA PORT
HAND/AUTO STATIONS
& DAMPER DRIVES
TO SOUTH OFA PORT
HAND/AUTO STATIONS
& DAMPER DRIVES
3.12
Σ
2.15
BIAS
H/A
2.16
TO OTHER BURNERS
ON THIS MILL
2.18
T
A
2.17
LIGHTOFF (20%)
A
2.19
COOLING (0%)
X
C = 1/5
2.20
CONTROL
DRIVE
2.21
OUTER AIR REGISTER
CONTROL
DRIVE
2.22
INNER AIR REGISTER