PRACTICAL DIAGNOSTIC TESTS TO IDENTIFY OPPORTUNITIES TO IMPROVE HEAT RATE, RELIABILITY, AND CAPACITY VARIABLES ON LARGE P.C. FIRED BOILERS

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Our intention in preparing and presenting this paper is to show the benefits to performance improvement of a coal fired generating unit, by applying the Thirteen Essentials to optimize combustion. The key to the STORM approach to combustion optimization is a focus on the furnace "inputs." Successful implementation of a regular performance preservation program is necessary and a pre-requisite to obtaining optimum performance.

Currently, discussion concerning the reduction of greenhouse gases is prevalent in the world. When taking a practical approach to addressing this problem, the best and nearly only short-term solution to reduce greenhouse gases on coal-fired power plants is to improve heat rates. This approach has proven to be effective and implemented with minimal cost.

A typical 2400 Psi/1005/1005ºF 500MW coal fired boiler in operation today will be capable of a heat rate of about 9,500 BTU/kWh. The authors have experience with boilers, turbines, and feedwater cycles, at different plants that were designed for similar heat rate. In actual day-to-day operation, however, the heat rates may vary from 200 BTU to 1,000 BTU's above the design or best achievable heat rates. This variation from optimum, in our experience, has been attributed to excellence in boiler and combustion systems, operation and maintenance.

Storm Technologies, Inc. has taken pride in seriously addressing the furnace inputs and applying the "Thirteen Essentials of Optimum Combustion." Often, the application of relatively simple tests can identify opportunities to approach the optimum operational efficiency. Some of the tests to achieve optimum combustion are:

- Fuel line clean air tests
- Fuel line fineness and distribution
- Primary airflow calibrations
- Representative Flyash Sampling
- Secondary airflow measurement
- Overfire airflow measurement
- Total boiler air in-leakage tests from the furnace to the stack
- Furnace water-cooled probe traverses for oxygen stratifications, CO and temperatures.

The combination of all the tests listed above, except clean air tests, in a simultaneous operation, is what Storm Technologies, Inc. refers to as a "Comprehensive Diagnostic Test." Once completed for several load points, opportunities for improvement can be identified, and corrective action applied.

It has been the authors experience that true controllable opportunities for improvement in unit performance, are most likely to be found on the boiler side of the cycle. Nineteen operations and maintenance controllable variables are listed below:

- Superheater steam outlet temperature
- Reheater steam outlet temperature
- Air heater leakage
- Superheater desuperheating spray water flows

- Reheater desuperheating spray water flows
- High primary airflows
- Pulverizer coal rejects or spillage
- High carbon content in the flyash
- High carbon content of bottom ash
- Furnace exit gas temperature
- Boiler (economizer) exit gas temperature
- Airheater exit gas temperature (corrected to no-leakage)
- Boiler air in-leakage
- Auxiliary power consumption of fans, pulverizers, and sootblowers
- Excess oxygen in flue gas higher than necessary when combustion is optimum and air in-leakage is zero
- Cycle losses due to leaking vent and drain valves
- Sootblowing optimization
- Pulverizer air in-leakage on exhauster equipped pulverizers
- Steam purity problems that result in turbine deposits resulting in either load restrictions or cycle efficiency losses

A "Comprehensive Diagnostic Test" is the method recommended by the authors to identify the opportunities for improvement. Corrections can only be completed after the root causes are identified. The testing equipment, procedures and corrective measures used to improve performance will be described. Fundamental improvements include: pulverizer and fuel line modifications to improve fineness and distribution, design and installation of airflow measuring venturis and flow nozzles for airflow measurement and control, and installation of a STORM designed high momentum overfire air system. Case Studies of a 440MW pulverized coal fired boiler that was plagued by tube failures, a 440MW boiler that had a slagging problem, two 72MW boilers with poor furnace combustion, and optimization of a 90MW pulverized coal fired boiler which included NOx reductions by installing a high momentum overfire air injection system are covered within this document.

1.0 BACKGROUND

Since the 1980s STORM has been interested in the beneficial results to coal fired power plant efficiency improvements by the implementation of relatively low cost improvement to the fuel and combustion air inputs to the furnace. Interestingly, the same improvements have been practiced by STORM for many years for different reasons. Six of the main reasons to implement a combustion improvement program are reduction of upper furnace slagging, reduction of flyash carbon content, improving overall efficiency, reliability factors, such as hot gas lanes overheating superheater tubes, and to improve the capability to utilize different coal (particularly ash) qualities. A number of reference publications are listed in the reference section. The first list of input optimizations was called the "Ten Pre-Requisites for Optimum Combustion."[1,2,3] After gaining further experiences, and the passage of the US Clean Air Act Amendment, becoming the law of the land, requiring low NOx burners on virtually all American coal plants, our list of "Ten Pre-Requisites for Optimum Combustion" was expanded to the "Thirteen Essentials of Optimum Combustion." In the next section, the Thirteen Essentials will be described. [4,5,6,7]

2.0 THE THIRTEEN ESSENTIALS FOR OPTIMUM COMBUSTION: HOW TO ACHIEVE

By R.S. Stone and J.A. Brewer[8]

13 Essentials of Optimum Combustion for Low NO_x Burners

Fuel Preparation

1. Fuel feed quality and size shall be consistent.
2. Fuel feed shall be measured and controlled as accurately as possible. Load cell equipped gravimetric feeders are preferred.
3. Fuel line fineness shall be 75% or more passing a 200-mesh screen, and 50 mesh particles shall be less than 0.1%.

Distribution to Burners

4. Primary airflow shall be accurately measured and controlled to ±3% accuracy.
5. Primary air to fuel ratio shall be accurately controlled when above minimum.
6. Fuel line minimum velocities shall be 3,300 ft/min.
7. Fuel lines shall be balanced by "Clean Air" test to within 2% of average.
8. Fuel lines shall be balanced by "Dirty Air" test to within 5% of average.

9. Fuel lines shall be balanced in fuel flow to within 10% of average.

Combustion

10. Over-fire air shall be accurately measured and controlled to ±3% accuracy.
11. Furnace exit shall be oxidizing; 3% oxygen is preferable.
12. Mechanical tolerances of burners and dampers shall be ±1/4?.
13. Secondary air distribution to burners shall be within 5-10% of average.

1. **Fuel feed quality shall be consistent.**
2. **Fuel feed shall be measured and controlled as accurately as possible. Load cell equipped gravimetric feeders are preferred.**

Consistent feed to the pulverizers prevents irregularities in output and keeps the load on the pulverizer steady. Sudden changes in quantity or fuel size will change the amount of duty on the mill and make it difficult to grind the coal consistently. For this reason, the importance of crushers should not be overlooked. Stock gravimetric feeders consistently regulate the fuel feed through the use of a microprocessor load cell.

Figure 1
A typical "pocket feeder." The fuel feed rates may vary by as much as 100% per revolution accuracy on these volumetric style feeders.

Figure 2
A "Stock" gravimetric feeder, equipped with load cells for fuel metering within 1% or better

3. **Fuel line fineness shall be 75% or more passing a 200-mesh screen, and 50 mesh particles shall be less than 0.1%.**
5. **Primary air to fuel ratio shall be accurately controlled when above minimum. The preferred ratio is 1.7-1.8.**
9. **Fuel lines shall be balanced in fuel flow to within 10% of average.**

After determination of the dirty air velocities in a given fuel line, isokinetic coal samples are extracted. To ensure that the proper amount of sample is obtained, the sampler orifice differential pressure is calculated from the dirty air velocity pressures using the following formula:

$$Orifice\,\Delta P = 1.573 \times \left(\sqrt{VP}_{avg} \times Probe\ "K"\ Factor \right)^2$$

The desired differential pressure is monitored and maintained at all times while the probe is in the fuel line. A needle valve is placed on the air supply to manipulate the differential.

Using a coal-sampling probe marked identically to the dirty air probe, the same points are traversed. The probe is used to collect a sample for ten seconds at each point for a total of two minutes per port and four minutes per pipe. The proper sampling time is critical and great care should be taken to ensure the proper amount of sample is obtained.

Once the traverse is completed, the collected sample is weighed and sieved for fineness analysis.

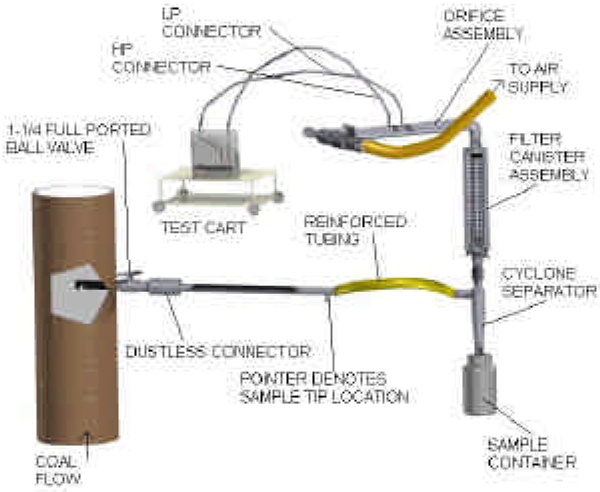


Figure 3

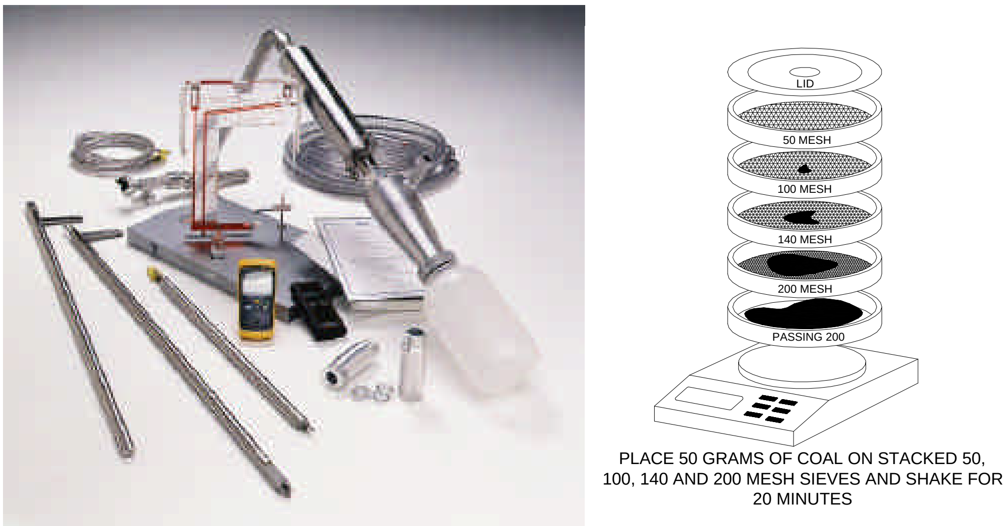


Figure 4

4. **Primary airflow shall be accurately measured and controlled to ±3% accuracy.**
10. **Over-fire air shall be accurately measured and controlled to ±3% accuracy.**

Accurate measurement of airflow is necessary to achieve these two essentials. Venturis are the preferred flow-measuring devices, but flow nozzles have also been successfully used by STORM.

Once installed, the flow-measuring device must be calibrated as follows:

The flow is held steady during the testing traverse. The differential pressure is recorded across the flow-measuring element at regular intervals determined by the test tap layout and the size of the duct. The calibration is performed at normal operating temperatures and conditions. During the tests, all related flow control devices should be locked in "manual".

The following data is measured and used to compute the "K" factor.

1. Velocity pressure (VP "w.c.) for each test point measured using calibrated velocity probe for a multipoint traverse.
2. Differential pressure (? P "w.c.) from primary element sensing lines.
3. Area (ft^2) of duct at traverse plane.

$$"K"\ Factor = \frac{MassFlowRate}{\sqrt{(r)(\Delta P)}}$$

The "K" factor along with the density (ρ) is then used to convert the differential pressure (? P) measured at the test taps into the mass airflow rate shown in the control room.

$$MassFlowRate = "K"\ Factor\sqrt{(r)(\Delta P)}$$

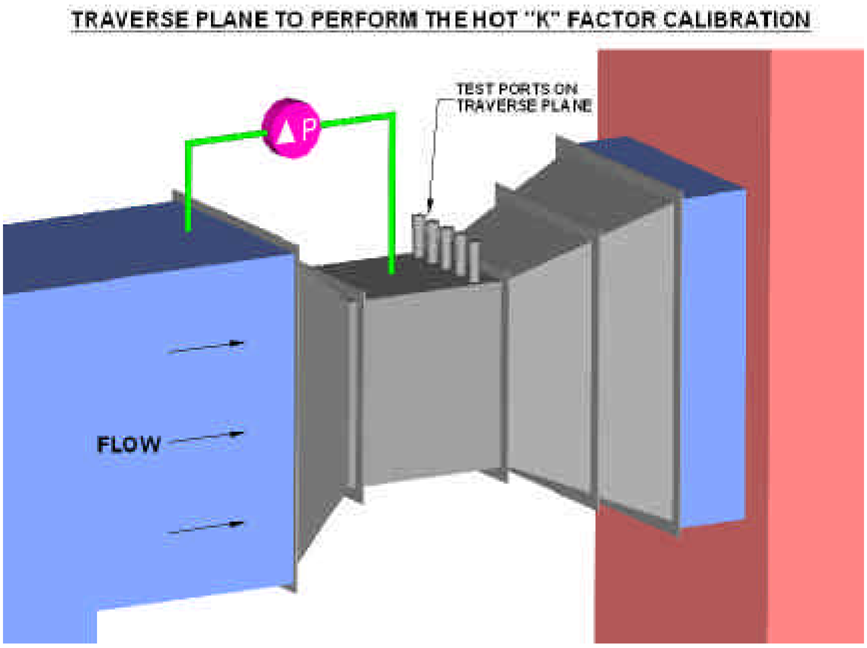


Figure 5

6. **Fuel line minimum velocities shall be 3,300 ft/min.**
8. **Fuel lines shall be balanced by "Dirty Air" test to within 5% of average.**

Figure 6

Fuel line velocities are measured and balanced using a dirty air probe. The dirty air probe is a proven device, which allows the measurement of airflow in a dust-laden environment with minimum risk of probe stoppage.

The traverse is accomplished in accordance with the ASME performance test code for circular ducts. Coal line test taps, which facilitate the insertion of dirty air probes and use of dustless connectors, require 1.25" full ported ball valves.

In the same fashion that a clean air test is conducted, the pipe is traversed to obtain velocity pressures at each point. When recorded along with static pressure and temperature, the velocity of the coal/air mixture in each pipe is determined using the following equation:

$$Velocity = 1096 \times \frac{\sqrt{VP}_{avg}}{\sqrt{Density}} \times Probe\ "K"\ Factor$$

$$Volumetric\ Flow = Area \times Velocity$$
$$Mass\ Flow = Density \times Volumetric\ Flow$$

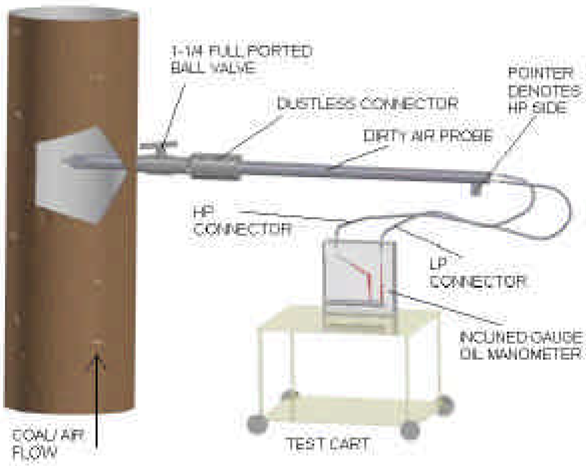


Figure 7

7. Fuel lines shall be balanced by "Clean Air" test to within 2% of average.

The "clean air" traverse is the first step in balancing fuel lines to individual burners. Balancing each individual pipe's airflow establishes a similar system resistance that should help maintain equal amounts of "dirty airflow" once coal is put back in the pipes.

The clean air velocity traverse is very similar to a dirty air traverse. However, since coal is absent from the pipes, the use of an industry standard ninety degree Pitot tube is permitted.

The test is accomplished in accordance with the industry accepted equal areas method of determining test points. This is shown in the ASME performance test codes as well as other standards. Usually two ports ninety degrees apart are utilized. Then, twelve sample points representing equal areas are traversed. Drilling two 0.5" NPT holes and using a threaded plug is all that is necessary to install clean air test ports.

The test itself should be performed while maintaining a steady fuel line velocity similar to normal operating conditions. Primary air temperatures must be set at a very steady temperature and flow. Two sets of data, from two complete clean air traverses must compare within 1% for the clean air test to be considered valid, which is very important. Steady state conditions are absolutely mandatory for the period of time it takes to conduct a clean air test. As a test quality assurance step, STORM recommends that two test teams measure the velocities of each coal pipe on back-to-back tests. STORM refers to this method as the "Two Team, Dual Traverse Method of

Clean Air Testing." The most common problem in correctly measuring clean air flows in fuel lines is obtaining absolutely steady flows and temperatures for the time it takes to conduct careful and accurate clean air traverses of all of the burner lines from each pulverizer.   By recording the velocity pressure (VP "w.c.) at each point and the static pressure (SP "w.c.) and temperatures (ºF) for each pipe, a determination of the velocity in each pipe is made using the following equation:

$$Velocity = 1096 \times \frac{\sqrt{VP}_{avg}}{\sqrt{Density}}$$

$$Volumetric\ Flow = Area \times Velocity$$
$$Mass\ Flow = Density \times Volumetric\ Flow$$

Fixed fuel line orifices are changed as required to establish the ±2% balance for all the fuel pipes from each coal pulverizer.

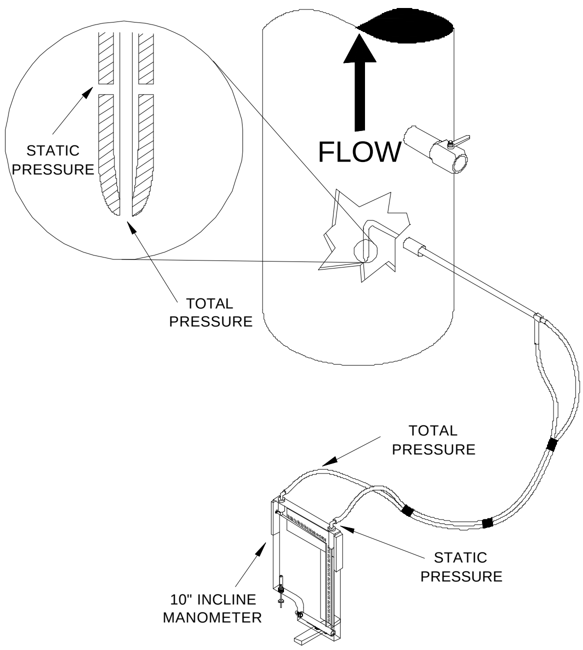


Figure 8

11. Furnace exit shall be oxidizing; 3% oxygen is preferable.

Oxygen levels at the furnace exit are measured using a water-cooled High Velocity probe, (or HVT test probes). Some excess oxygen at all points is necessary for complete combustion. As long as there is excess oxygen at the furnace exit, unburned products of combustion, such as CO and carbon in ash, are minimized.

Typically, excess oxygen is measured and controlled by an oxygen analyzer at the economizer exit. High levels of air in-leakage dilute the flue gas with tramp air prior to its measurement at the economizer exit. The oxygen analyzers will not be able to distinguish excess oxygen that entered the boiler convection pass as "tramp air," or combustion air. It is not uncommon to find total leakage between the furnace exit and the economizer exit in the 10% to 20% range. Water-cooled gas analyses traverses using a HVT probe, on boilers older than ten years, provide an accurate grid of oxygen levels across the furnace exit to ensure accurate data is used. The carbon char and CO of the products of combustion must be completely combusted before the flue gases are quenched below 1400°F(760ºC).

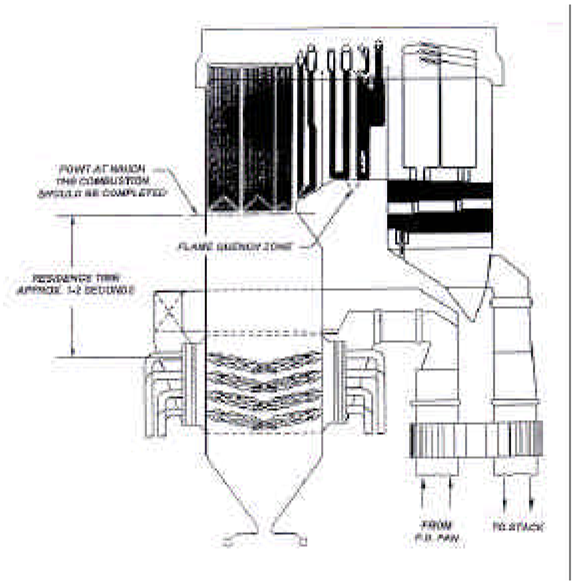


Figure 9

To operate the HVT probe make sure the water supply and discharge hoses are connected and that both lines are free of restrictions. Adequate water-flow must be maintained to keep the HVT probe at no more than 110ºF (43ºC). Mark the probe at two-foot increments starting from the tip of the radiation shield. Once the thermocouple is connected, turn on the aspirating air and insert the probe into the boiler. Record the temperatures at two-foot intervals. Complete the traverse by turning off the aspirator and connecting the gas conditioner and ECOM gas analyzer. Record the oxygen, carbon monoxide and NOx levels at two-foot intervals on the way out.

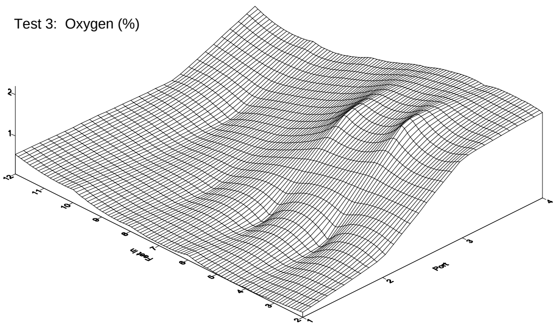


Figure 10

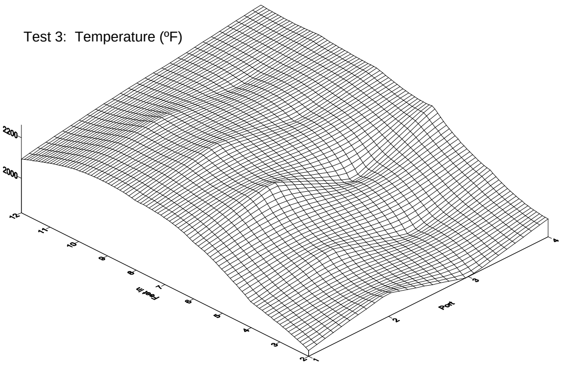


Figure 11

Given that enough points are measured, 3D graphs can be generated to show how temperature and gas concentrations are distributed throughout the boiler exit. Note the extreme differences in excess oxygen from the center of the front wall, almost zero, to over 2% in the far right rear. Also note the reciprocal effects of excess oxygen on temperature.

Figure 12
An HVT probe in use

Figure 13
A STORM HVT kit, including a HVT probe, gas sample pump/conditioner and ECOM gas analyzer

12. Mechanical tolerances of burners and dampers shall be ±1/4".
13. Secondary air distribution to burners shall be within 5-10% of average.

Making sure that all burners and dampers are free to operate as designed is important to controlling combustion. Taking a heat damaged burner like the one seen below and returning it to its original dimensions will increase the chances of proper coal flame development. Making these corrections, along with installing a venturi to measure airflow to the windbox, is a good way to measure and control secondary air.

Figure 14
Burner before repairs

Figure 15
Burner after repairs

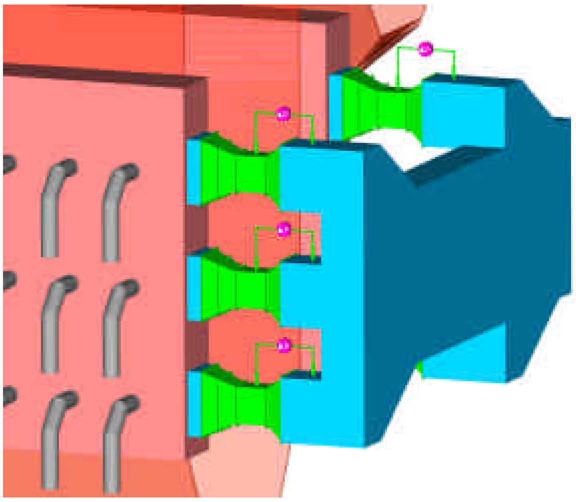


Figure 16
The use of STORM designed venturis to measure and control secondary airflow to the windbox of a 600MW coal fueled boiler

3.0 THE NINETEEN OPERATIONS AND MAINTENANCE CONTROLLABLE FACTORS AFFECTING UNIT HEAT RATE

A typical 500MW coal fired large utility boiler, whether it be a corner fired or wall-fired, will have a furnace size of about 60 feet wide, 50 feet deep and the top burners will be about 60 feet below the superheater. A typical 500MW utility boiler is shown in the following figure.

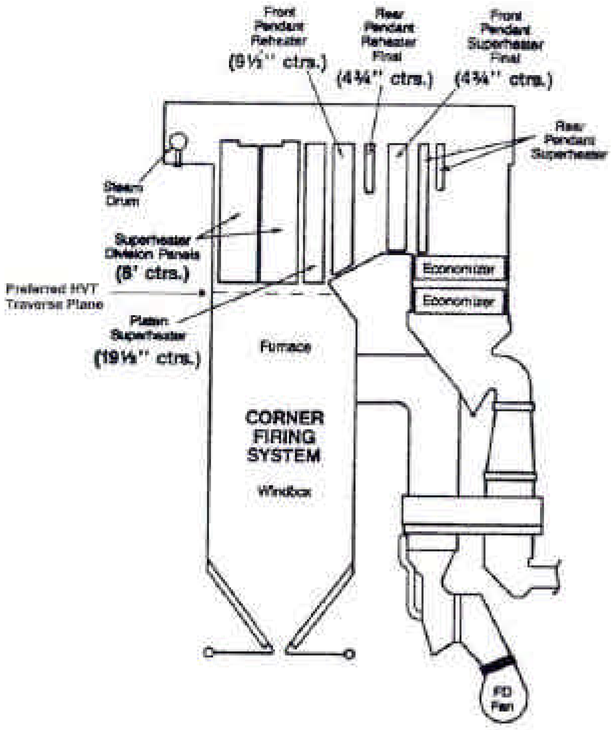
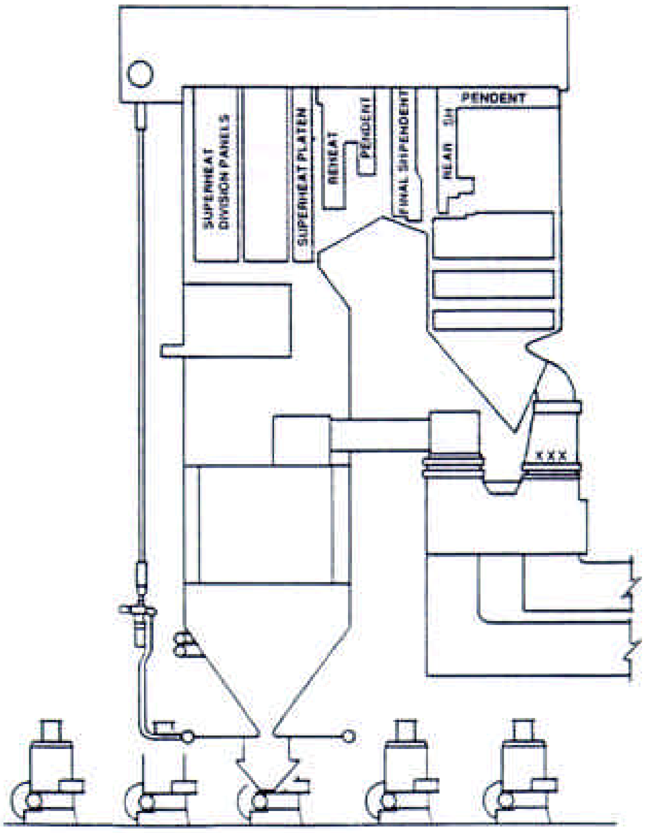


Figure 17

Four controllable heat rate factors are directly related with furnace performance and furnace flue gas uniformity. These are: superheater temperature, reheater temperature, desuperheating spray water flow to the superheater, and desuperheating spray water flow to the reheater. Balancing of the fuel and air to each burner has much to do with furnace combustion efficiency, and the completeness of combustion at the furnace exit. The residence time of the products of combustion from the burners to the superheater flue gas inlet is about one or two seconds. Not very long for furnace mixing of fuel rich and air rich lanes of combustion products. Optimized combustion at the superheater inlet can be quantified by use of a water-cooled high velocity thermocouple probe. Although they are called "HVT" probes, some of their greatest usefulness is in using them as a water-cooled gas-sampling probe, as described earlier.

Slagging at the superheater flue gas inlet has been a problem in a number of boilers due to stratified flue gas. Also, slagging at the lower furnace, which results in large boulder sized clinkers blocking the lower ash hopper. Tube spacing becomes ever closer as the heat transfer changes from radiant in the furnace, to convective in the back pass. Please note Figure 17, which shows the typical tube spacing of pendant superheater and reheater tubes. If lanes in the furnace outlet flue gas approach the ash softening or even the ash fluid temperature, upper furnace slagging and blockage can result in a very short time.

The determination of root causes of such stratifications is the subject of applying the Thirteen Essentials and the use of water-cooled HVT probes at the upper furnace. Several cases studies will be reviewed to show how the application of the Thirteen Essentials have improved slagging, heat-rate, capacity factor, reliability, NOx and/or flyash carbon content.



Furnace Volume	-274,000 ft^3
Pulverizers	-5 Raymond #823
Burners	-20
Design Fuel	-59 HGI / 11.9% Ash / 11,000 Btu per Lb / 10%Moisture
Ash Fusion	-2,000 °F

Figure 18

4.0 AIRFLOW AND FUEL FLOW OPTIMIZATIONS ON A 440MW CORNER FIRED BOILER

4.1 BACKGROUND AND DESCRIPTION OF UNIT

Figure 18 is a nominal 440 MW pulverized coal fueled unit. The steam generator is a four corner, corner-fired boiler designed by Combustion Engineering Company. Pertinent design data for the boiler are shown on Figure 18.[9]

Proximate Analysis			Ultimate Analysis		
	As Received	Dry Basis		As Received	Dry Basis
# Moisture	6.09	xxxxxxxx	# Moisture	6.09	xxxxxxxxx
% Ash	15.63	16.64	% Carbon	63.25	67.35
% Volatile	31.71	33.77	% Hydrogen	4.32	4.6
% Fixed Carbon	46.57	49.59	% Nitrogen	1.37	1.46
	100	100	% Ash	15.63	16.64
			% Oxygen (difference)	5.53	5.89
Btu/Lb.	11376	12114			
MAF Btu		14532			
Alk. As Sodium Oxide	0.25	0.27			
GRINDABILITY INDEX = 45 at 1.50% Moisture					

Figure 19

	Fusion Temperature of Ash, °F	
	Reducing	Oxidizing
Initial Deformation (IT)	1955	2440
Softening (ST)	2180	2515
Hemisperical (HT)	2290	2585
Fluid (FT)	2400	2660

Analysis of Ash	Weight %, Ignited Basis
Silicon dioxide	45.9
Aluminum oxide	20.5
Titanium oxide	0.96
Iron oxide	26.94
Calcium oxide	1.36
Magnesium oxide	0.73
Potassium oxide	2.13
Sodium oxide	0.21
Sulfur trioxide	0.91
Phosphorous pentaoxide	0.3
Strontium oxide	0.02
Barium oxide	0
Undetermined	0.04
	0
	100

Silica Value =	61.26	Fouling Index =	0.1
Base: Acid Ratio =	0.47	Slagging Index =	1.91
T_{250} Temperature =	2340°F		

Figure 20

Based on the on going problems of erratic performance and severe slagging problems in both the upper furnace and the lower ash hopper, it was concluded that the furnace exit gas temperature was varying from non-uniform products of combustion entering the superheater gas side.

Ash fusion temperatures are often lower in a reducing atmosphere than in an oxidizing atmosphere. Since many of the opportunities for improvement that were experienced on this boiler were slagging related, this was a significant factor. Typical fusion temperatures of the ash are shown on Figure 20, and coal analyses are shown on Figure 19.

The furnace exit, excess oxygen and temperature stratifications were found to be the result of a non-homogeneous mixing of the combustion air and fuel in the burner belt zone. Zero oxygen points at the furnace exit could be due to either an abundance of fuel, or a shortage of combustion air. The Comprehensive Diagnostic Test technique was utilized to quantify the opportunities for each. Upon completion of the Comprehensive Diagnostic Tests, the following changes were implemented:

- Fuel lines were balanced
- Flow nozzles were installed for primary airflow measurement and control
- Pulverizer classifier changes
- Secondary air duct changes to balance combustion airflows to each of the four corners.

Figures 22 and 32 show the basic application of the combustion pre-requisites.

The data summary is shown on Figure 21 of pre-outage data and post-outage, which outlines opportunities for improvement.

Parameter	**Pre-Outage**	**Comprehensive Pre-Outage Testing**	**Comprehensive Post-Outage Testing**
Economizer Exit Gas Temperature °F		729 to 748	701-716
Final Reheat Split Side to Side, °F, East to West		20-41°F	0-5°F
Secondary Air Distribution to Corners		±30%	±11-14%
Air Heater Exit Gas Temperature °F	287.3 to 305	303-304°F at 5% O_2	305
Full Load Reheat Spray Flow #s/hr	40,000	0 to 45,000	0 to 20,000
Full Load-Superheater Spray Flow #s/hr	180,000	210,000	145,000
Coal Fineness		62% Passing 200 mesh	70-80% Passing 200 mesh
Maximum Pulverizer Capacity with 70% Min. Passing 200 Mesh		Approx. 75,000#/hr @50 HGI	Approx. 95,000#/hr @50HGI
Pulverizer Spillage #/hr		Up to 500#/hr	Approx. 50#/hr
Furnace Exit Gas Temperature by HVT Probe °F		2325 Avg. Peak Temperatures above 2472°F	2,306°F Avg. Peaks not above 2325°

Figure 21

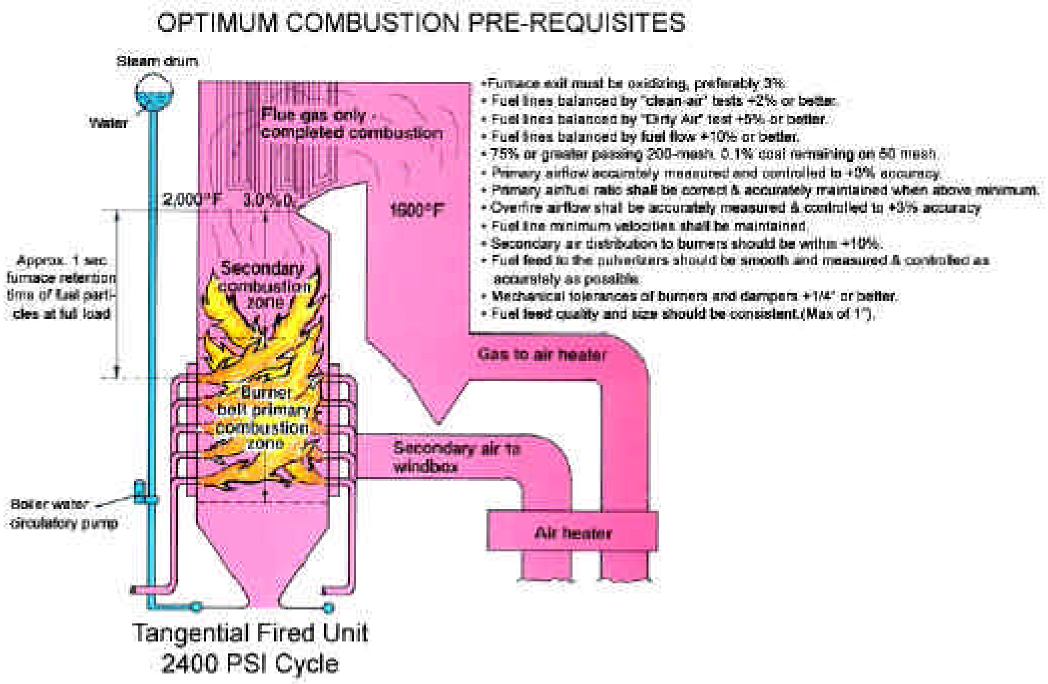


Figure 22

The primary airflow measurement by round cross-sectional area venturis (or flow nozzles) has provided the capability to measure and control primary airflow to improve accuracy (shown in Figure 23).

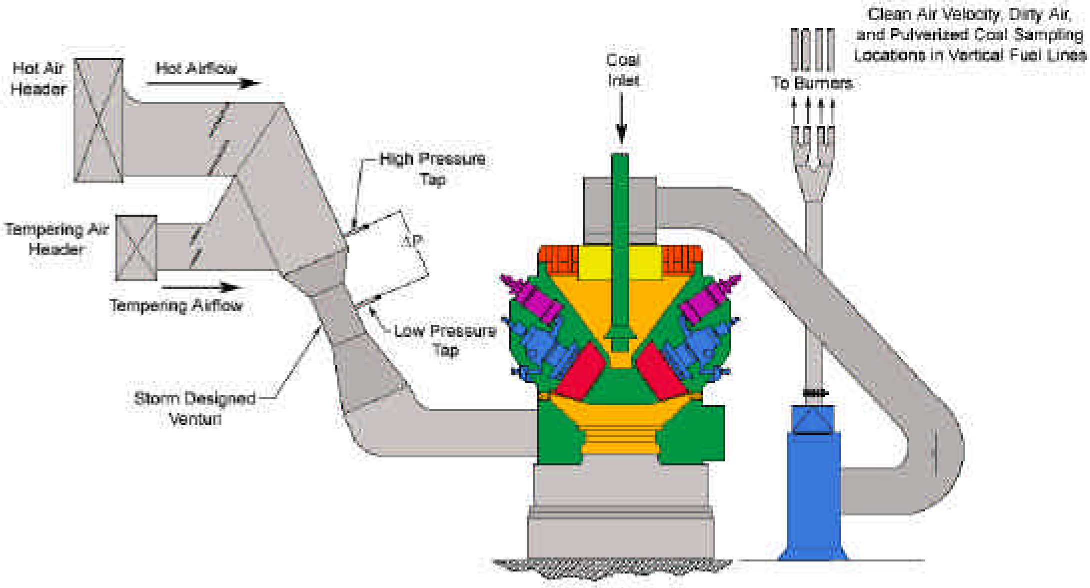


Figure 23

Outage Inspections and Repairs

During a scheduled overhaul outage comprehensive repairs were completed for improvements in the following areas:

- Burner tilt synchronization and adjustable coal tip repairs
- Precision stroking of dampers
- Expansion joint repairs to reduce air in-leakage
- Fan and pulverizer tolerances (blue printing!)
- Coal feeder repairs and calibration

The furnace was scaffolded, and a very comprehensive boiler overhaul was completed. Following the outage repairs, implementation of the modifications and several months of tuning, the unit performed better than it ever had.

As a result of the modifications that were implemented, it was determined that boiler performance improvements were made in the following areas (shown in Figure 24)

- **Reduction of Superheat Spray Flows**
- **Reduction of Reheat Spray Flows**
- **Reduction in Slagging of the Furnace**
- **Reductions of Auxiliary Horsepower Consumption Reductions of Tempering Air Usage**
- **Reductions of Coal Spillage from the Mills**
- **Balanced Air and Fuel Flows**

Figure 24

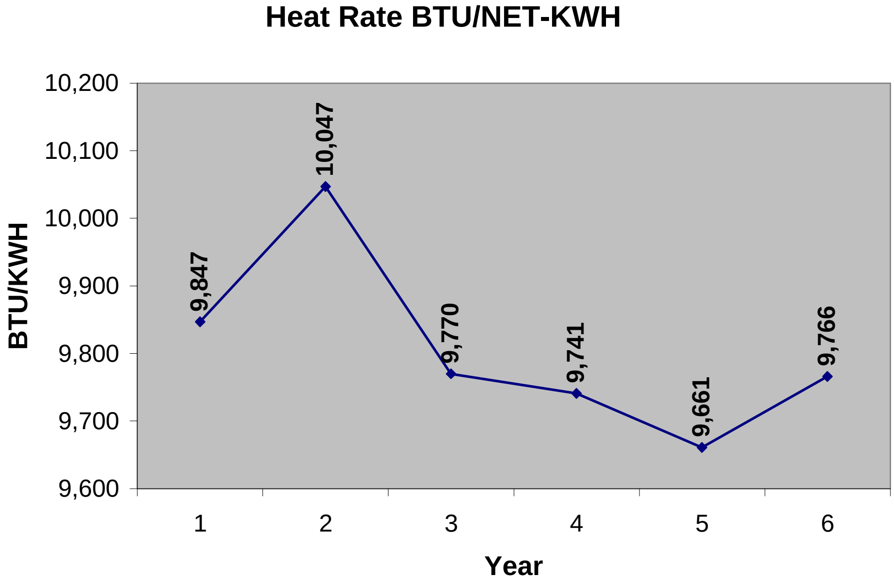


Figure 25

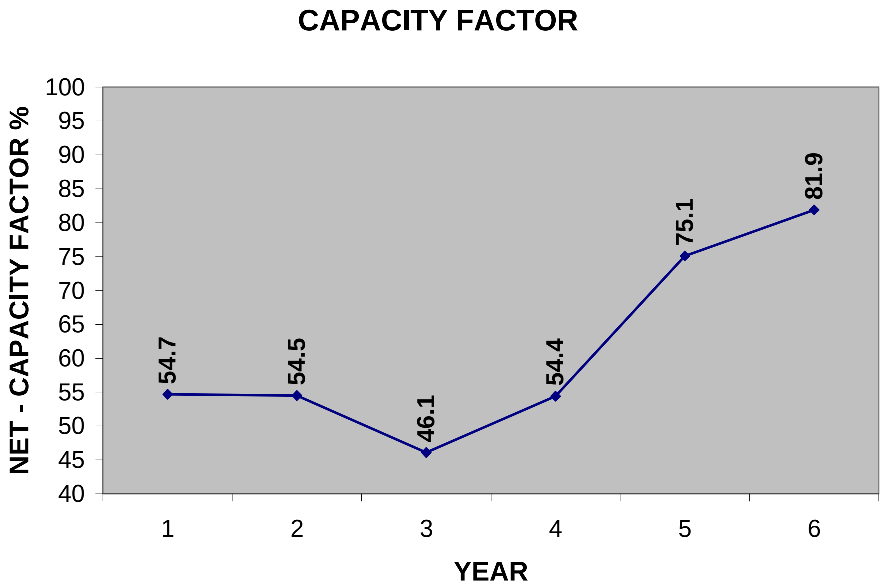


Figure 26

5.0 440 MW, SINGLE WALL FIRED BOILER[10]

This is a nominal 440 MW pulverized coal wall fired unit, designed by the Riley Stoker Corporation. The Unit utilizes seven Attrita pulverizers with volumetric feeders supplying fuel to twenty-eight (28) DRB-XCL® burners.

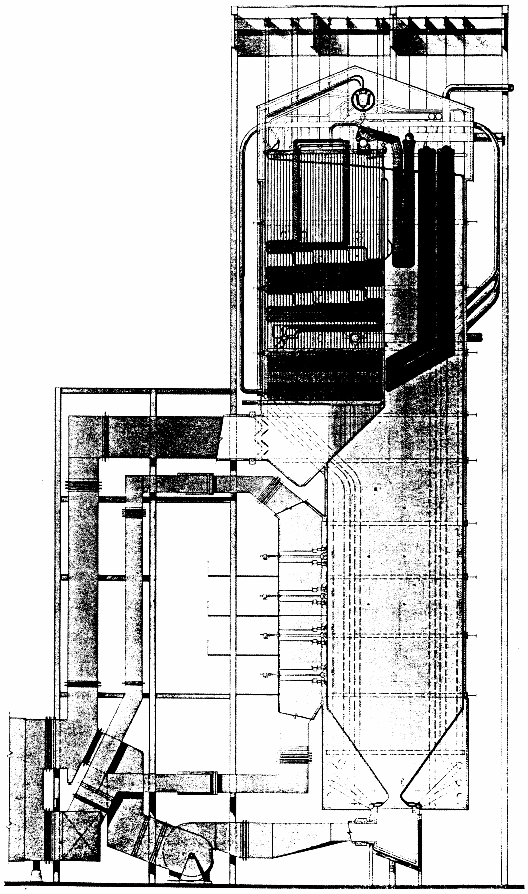


Figure 27

This was an ideal partnering relationship of the utility and Storm Technologies, Inc. It was a seamless commitment, from initial diagnostic base-line testing, through outage inspections, technical direction of the recommendations during the outage, and final testing and tuning (Post-outage).

The approach Storm Technologies, Inc. takes toward optimum combustion continues to relate to the "Thirteen Essentials for Optimum Combustion", which have been discussed in depth previously and outlined later in this section. Pre-Outage testing was first performed in order to discover areas on needed improvement that deal with the opportunities for improvement. Tests completed included:

- Air In-Leakage Testing was performed throughout the unit
- Pulverizer testing:
    - Clean air
    - Dirty Air
    - Isokinetic Coal sampling
    - Fuel Fineness
- Flyash sampling (LOI: Loss On Ignition of the ash)

The main purpose of the testing and tuning was performed to improve reliability. Primary superheater tube failures and forced outages were a serious problem during high load factor operation. Based on the baseline testing, the majority of the performance issues dealt with pulverizer performance and balance to the furnace. In addition to the pulverizer testing, several other tests completed indicated performance opportunities linking pulverizer performance (i.e. Furnace Exit Temperature and Analysis, Flyash LOI, Etc….). Example: The flyash sample was sieved and approx. 85% passed through a standard US 200 mesh sieve. With proper pulverizer performance 92-95% of the flyash should pass a 200-mesh sieve. Based on the original performance and reliability issues, twelve goals were set, which are as follows:

Goals:

- Achieve Maximum Reliability and best tuning to keep superheater outlet tubes to acceptable metallurgical limits

- Achieve satisfactory combustion stability over the full coal load range of 115 MW to 440 MW
- Achieve satisfactory adjustments for optimum thermal performance of the unit (i.e. 1000/1000 degrees F. steam temperatures and less than 10% carbon in ash (LOI)
- While combustion optimization and reliability are of the first priority, the NOx production must also be within allowable limits
- Reduce Slagging
- Improved Availability and Increased Load Factor
- Lower Kilowatt Production Cost/unit heat rate
- Improved Capability to Sell Flyash
- Capability to Fire Lower Cost Fuel
- Improved Life Expectancy of Superheaters and Reheaters
- Decreased Exfoliation of S.H. and R.H. Tubes
- Increased Emphasis on Planned Maintenance

In order to achieve the previous goals, it was agreed that the plant and STORM would work towards achieving Storm Technologies, Inc.'s "Thirteen Essentials for Optimum Combustion". Based on the baseline testing and initial inspection, the following were the main areas to address:

- Pulverizers and Primary Airflow Measurement Control:

Figure 28: "As Found" Averaging Pitot Tubes

Figure 29: STORM Airflow Measurement Devices

	A	B	C	D	E	F	G
Measured Value	70,381	73,646	71,706	73,337	71,682	70,863	72,209
Indicated Value	72,418	71,861	71,554	72,762	72,822	71,861	71,159
% Error	2.89%	-2.42%	-0.21%	-0.78%	1.59%	1.41%	-1.45%

Post Primary Airflow Measurement Accuracy w/STORM Venturi Section

- Burner Line Orifice Plates to Balance by Clean Air Method
- Burners (Mechanical Tolerances)

Figure 30: "As Found" Burner Tolerances

Figure 31: Burner Centering and Tolerances

- Lower Ash Hopper Air In-Leakage
- PSH Tube Metal Thermocouples to Measure and Monitor Temperatures
- Mechanical tolerances of OFA ports, OFA dampers, etc….
- Mechanical tolerances of burner register timing and settings
- Technical Direction and Review of Items

Post outage Testing prove that results were achieved by implementing the "Thirteen Essentials for Optimum Combustion". The clean air was balanced within the recommended 2% deviation pipe to pipe. Significant improvements in fineness and primary airflow management were made. The original fineness was found from up to 4% remaining on a standard US 50 mesh sieve and low 60s% passing a standard US 200 mesh sieve and was improved to 1% remaining on 50 mesh and low 70s% passing a 200 mesh sieve. Further mechanical classifier adjustments have been recommended to improve fineness further and the majority of this improvement can be attributed to clean air balance, pulverizer mechanical tolerances and the capability to accurately lower and control the primary air to fuel (air/fuel) ratio from around a 2.0 Air/Fuel to approximately 1.2 Air/Fuel ratio.

Operational Review and Recommendations:

- Critical Operational Concerns:
  - Selective (smart) Sootblowing needed to be implemented based on the low temperature of the superheater upleg tube metal thermocouple temperatures. The highest tube metal temperature needed to be kept below 900ºF. This is because the furnace heat absorption may be below that required limit the flue gas temperature into the convection pass to an estimated 1,800 degrees F maximum.
  - Recommendations have been made to install 25-degree impellors on one burner level to increase flame stability and flame intensities. Steam temperatures of 1,000/1,000 degrees F could be obtained at 125 MW, and the flames were stable with some air register biasing.
  - The best present indications of satisfactory furnace performance are the local tube metal thermocouples and superheat and reheat spray water flows. In summary, the furnace heat absorption must be optimized by utilization of the water-wall and steam long retractable sootblowers as well as manual operation of the SH and RH by-pass damper.

STORM Performance Recommendations:

- Maintain previous mechanical tolerances (i.e. blue-printing feeders, stroke dampers, burner mechanical tolerances, soot-blowers, etc….).
- Improve pulverizer performance:
  - Fineness >75% passing 200 mesh and 0% on 50 mesh
  - Distribution of fuel and air within acceptable limits previously discussed
  - Review the possibility of upgrading feeders to Gravimetric and/or as a minimum provide Lbs/Hr indication flow based on RPM (volumetric)
  - Optimum crusher performance for raw coal size <3/4"
  - Performance coal for both pulverizer performance and NOx
- Provide new tube metal thermocouple indication to control room to utilize as a tool for furnace and convection pass heat absorption
- Incorporate 25 degree impellors on "E" pulverizer level for flame stabilities at lower loads and maintain proper flame intensities
- Input fuel and air biases into ProVox and Allen Bradley for operations to minimize confusion of biases and control parameters
- Tune reheat and superheat by-pass damper to control in "auto" for temperature control as well as indication of spray flow (RH and SH) in Lbs/Hr versus existing indication of only percent flow
- Provide airflow indication in Lbs/Hr (Secondary and OFA), currently they operate in only percent range and the secondary air indicates approximately a 30% difference, however the testing indicated similar flows for both indications.
- Periodic pulverizer and flyash samples should be monitored to maintain performance preservation
- Six (6) mill operation was capable of achieving 400 MW Gross (feeders are uncontrollable above 85% feeder due to feeder output greater than pulverizer)
- With six- (6) mill operation, acceptable NOx was achieved and tube metal temperatures were approaching 900 degrees F limit, with LOI approximately 20%. The out of service pulverizer (top row) was utilized to simulate OFA with the registers open to reduce the NOx levels. This enforces the recommendation to add OFA ports and a booster fan on the burner wall to provide effective mixing of the OFA with the fireball. The OFA ports and fan will allow for all seven (7) pulverizers to give the operators improved control, fineness improvements, etc… while reducing the NOx to reasonable levels. This would include the modification of existing OFA ports and ductwork.

- Additional mechanical recommendations shall include flame holders on each burner to provide an envelope of fuel and air rich zones for improved NOx control, flame stability, etc…
- Maintain airheater seal clearances and tolerances to minimize air in-leakage. Currently, the airheater has approximately 6%-8% leakage, which is good for a ljungstrum type airheater. The pent-house seals and RH and SH division walls should be in proper condition to minimize by-pass and air in-leakage.

These changes and recommendations were made for high load factor operation over the summer of 2002. The combination of combustion tuning and smart Sootblowing, by monitoring the hot LTSH tubes successfully eliminated the forced outages due to tube failures during the critical period.

6.0 TWO 72MW FRONTWALL FIRED BOILERS EQUIPPED WITH LOW NOX BURNERS OPTIMIZED BY APPLYING THE THIRTEEN ESSENTIALS[11,12]

Growing competition in the power industry has led to many changes in the way O&M organizations are approaching plant operations. Budgetary constraints, performance expectations, reliability concerns, and environmental compliance issues are now the driving forces behind plant operations. As with most new facilities, the focus for the operator of the plant was on reliability improvement during the early post- commercial period. As the "randomness" was eliminated from the facility and reliable operation became the norm, attention was turned to cost savings through performance improvement. At this time the income of the plant had basically been maximized and any profitability improvement could only come from cost reductions. The owners and operator of this facility both recognized the value of boiler performance improvement and committed the resources necessary to make the optimization program successful.

There were obvious opportunities for boiler improvements following start-up and early commercial operation of the plant. Flyash and bottom ash that visually looked like it needed to be run through the boiler again were very obvious signs that combustion was less than ideal. Low NOx burners were new to the operator and while higher levels of carbon in the ash (or loss on ignition) were expected, it was unclear as to how much penalty these burners would cause. Therefore the visibly dark ash was not the "warning flag" it might have been with conventional burners. Reliability concerns were at the top of the priority list, therefore optimizing combustion received little attention during early commercial operation. However, once attention turned to performance improvement the following combustion related problems had been identified:

- Flyash loss on ignition (LOI) levels of 9 to 10 percent.
- High desuperheating spray flows (70 to 80 KLbs./hr)
- Visibly high levels of carbon in the bottom ash
- Sporadic NOx values, but within the permit limit
- Poor flame quality resulting in unstable boiler operation

Because of these problems and the effect they were having on the operator's ability to meet the requirements of the air permit and maximize the profitability of the project, a boiler optimization program was undertaken with the following desired results:

- Flyash LOl's of 3 to 5 percent under all operating loads
- Desuperheat spray flows of 40 to 50Klbs/hr at full load
- "Clean" bottom ash
- Consistent NOx levels of 0.30 to 0.32 Lbs/MMBTU
- Consistent flame quality and stable boiler operation
- Predictable pulverizer performance throughout the wear cycle
- Ability to routinely perform boiler tests and track results

Facility Description:

The 144MW pulverized coal facility consists of two independently operated, identical units. Each unit utilizes a single Foster-Wheeler 600,000 Lb/hr coal boiler. The coal is delivered to the boiler by three Williams Model DF-64 pressurized pulverizers each supplying two burners. The pulverizers employ variable speed drives on both the main drive and the spinner/separator. Stock model 8424 gravimetric feeders control the coal flow to the pulverizers. Primary air is provided to the pulverizers from a single primary air (PA) fan whose discharge is split into a heated and unheated header. This air is mixed at each pulverizer to control outlet temperature. Secondary air is provided to the boiler from one forced draft (FD) fan supplying a non-partitioned wind box, front and rear over fire air ports (4 each), and boundary air at the bottom of the boiler. Each unit is equipped with six Controlled Flow-Split Flame Low NOx burners by Foster-Wheeler. Operation of the plant is controlled by a Bailey INFI 90 DCS. Each unit is dispatchable from 1 8 to 66 MW by the host utility. Export steam is provided to a nearby steam host via General Electric single auto-extraction turbines. Additional design data associated with the boilers is as follows:

- Drum pressure — 1755 psig
- Turbine inlet conditions — 950°F at 1575 psig
- Economizer water inlet temperature — 412°F
- Economizer gas outlet temperature — 290°F
- Furnace exit gas temperature — 1930°F
- FD fan air inlet temperature — 70°F
- Boiler efficiency — 88.42%
- NOx limit — 0.33 Lbs/MMBTU - (30 day roiling average)

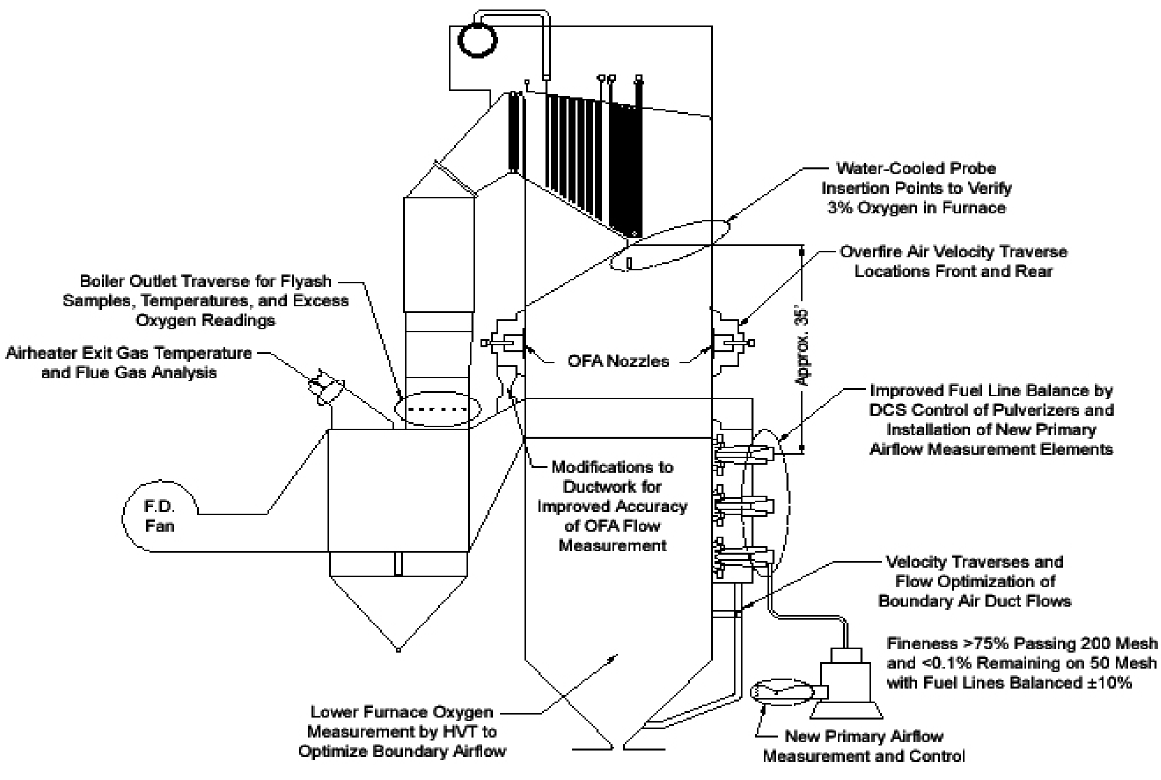


Figure 32: Side Elevation of Boiler & Performance Optimization Factors

Initial Assessment:

Once the desired results were defined it was determined that a combustion consultant would be necessary to help develop the program. The services of STORM TECHNOLOGIES, Inc. ("STORM") of Albemarle, NC were retained to initiate the optimization program. For the program to be successful a comprehensive approach had to be taken to the optimization process (See Figure 32). STORM personnel made an initial assessment of the boilers in June of 1994 and discovered high primary airflow and severe secondary combustion in the upper furnace. They quickly concluded that more air was needed in the burner zone. The low NOx burners are designed to operate at 90% stoichiometry, which both limits maximum combustion temperature and eliminates free O_2 in the combustion zone, both of which contribute to reduced NOx production. However sufficient air must be introduced into the boiler to produce an oxidizing atmosphere at the furnace exit to ensure complete carbon burn out. Excessive secondary combustion in the upper furnace was noted by STORM, which indicated insufficient carbon burn out in the burner zone. The secondary combustion was caused by re-ignition of the remaining unburned carbon as the over fire air (OFA) was introduced.

Some quick adjustments to the pulverizers and air registers as well as increasing the total air flow resulted in much better appearing flames, reduced secondary combustion, reduced superheat spray flows, and increased NOx while the hourly NOx levels were intermittently above 0.33 Lbs/MMBTU during testing and optimization, the 30 day rolling average NOx, which is the air permit standard, was never compromised. The initial results were highly encouraging, however it became obvious due to increased NOx levels that a more in-depth approach would be required. STORM recommended a much more comprehensive analysis using sophisticated test equipment. STORM identified the following parameters as mandatory, to achieve optimum combustion:

- Oxidizing conditions at the furnace exit with approximately 3% excess O_2.
- Coal fineness of> 75% passing 200 mesh and <0.1 % remaining on 50 mesh.
- Fuel distribution within: ±10% burner to burner.
- Primary airflow accurate and measurable.
- Primary airflow fit to a curve to insure proper air/fuel ratio (1.8-2.0 lb of air per lb of fuel).
- Pulverizer line velocities above minimum velocity at low loads to prevent coal drop out and to position the ignition point at a distance from the burner tip to avoid coking and burner fires.
- Secondary airflow proportional to total fuel flow and controllable at burners, overfire air ports, and boundary air.
- Fuel flow to the pulverizers must be measured and controlled with smooth feed rates during load changes. A range of ± 1 % actual to indicated fuel flow should be the tolerance on gravimetric feeders as verified by calibration.

Ensuring these parameters were being met would require considerably more personnel and test equipment than were available during the initial assessment. STORM was scheduled to return in July 1994 to begin the detailed optimization work.

Testing and Optimization:

The initial test group consisted of both STORM personnel and plant operations personnel. The operator chose to use plant personnel for the testing; both for educational purposes and to develop the expertise in-house to perform routine testing once the optimization effort was completed.

Air Flow Management:

Ensuring sufficient free oxygen for combustion was the first step of the optimization effort. The challenging part of this step was to provide sufficient air to the burner area for complete combustion without creating excessive NOx. Originally the only available O_2 monitoring was located at the boiler outlet flue prior to the scrubber. Although this provided a reading of boiler exit O_2 concentration it gave little information about the oxygen profile across the boiler. Furnace exit gas traversing was performed immediately in front of the superheater using a water-cooled High Velocity Thermocouple (HVT) probe (shown in Section 2.0) to obtain a detailed profile of the upper furnace O_2. This process was also helpful with side-to-side burner adjustments. Initial O_2 traverses showed 4% on one side of the furnace and 0% on the other. Maintaining 3% excess oxygen with no reading below 2% was achieved with some minor air register and total airflow curve adjustments.

One of the original goals of the program was to maintain the level of NOx consistently below the permit limit of 0.33 Lbs/MMBTU. Unfortunately, good clean burning fires that result in low LOI also tend to produce more NOx. It was quickly discovered that the NOx level could be controlled by controlling excess air. However, how much was LOI being sacrificed when the total air was reduced enough to consistently maintain NOx levels below the permit limit? To monitor the carbon content in the flyash a high volume flyash flue sampler (shown in Section 2.0) was used during each test and the samples were screened through a 200-mesh screen and were then analyzed for fine particle LOI (passing through screen) and coarse particle LOI (remaining on screen). Initial test results showed the fine particle LOI was greater than the targeted 2%, which indicated a need to improve furnace mixing and to introduce more oxygen into the burner area. By balancing the oxygen profile from side to side and bringing more air into the burner zone, the fine particle LOI's were eventually reduced to less than 2%. Coarse particle LOI was also above desired levels of 6% that indicated possible pulverizer related problems.

Pulverizer Testing and Optimization:

Consistent coal fineness of at least 75% passing 200 mesh with no more than 0.1% remaining on 50 mesh was the ultimate performance goal for the pulverizers. During testing, coal samples were taken from each burner transport line using a modified ASME type isokinetic sampler and a dirty air probe (shown in Section 2.0). Test ports were installed on the transport lines so the sampling and velocity measurements could be done on vertical runs from two axes 90° apart. The dirty air velocities were measured first in each fuel line to establish the proper sampling rate and airflow. Once the dirty air velocity traverse was complete, sampler orifice differential pressure was calculated and the ISO kinetic coal samples were taken. The isokinetic samples were then weighed to determine line-to-line coal distribution. After weighing, the samples were then sifted through 50, 100, 140, and 200 mesh screens to establish the coal fineness. Initial testing revealed that very poor and very good fineness results could be achieved with the Williams pulverizers depending on the particular set up of the mill. However, due to pulverizer control limitations the good results could not be consistently repeated. It was also known that some of the mill inconsistencies were due to primary air (PA) flow measurement errors.

The pulverizers are equipped with variable speed mill and spinner drives. The original control of the pulverizers interfaced with the plant DCS for start and stop control only, while all other control functions were handled by a separate PLC. In order to enhance the operation of the pulverizers and achieve the necessary control of the spinner and pulverizer drives, the operator elected to modify and transfer the controls to the DCS. The operator's personnel developed new DCS logic and implemented the control swap-over on one of the pulverizers in December 1994. This modification followed on the remaining five pulverizers in March 1995. These control enhancements allowed the operator to develop new pulverizer drive and spinner drive curves which could be easily biased as operating or fuel conditions changed. These changes provided for finer control of the mills resulting in more consistent coal fineness throughout the load range. The changes also gave the operator more effective control of the pulverizer differential pressure which resulted in more uniform coal delivery to the boiler. Upon completion of these changes and fine-tuning of the pulverizers, the composite LOI (Loss On Ignition) was reduced to less than 3%. To verify uniform fuel distribution within the range of ±10% burner to burner, the sample weights collected from the two burner lines were compared for each pulverizer. The coal sample weighing did verify the close relationship between coal fineness and fuel line distribution. Coal fineness in the targeted range resulted in more uniform distribution to the burners than did poor fineness coal. Based on the clean air test results, it was determined that no mechanical means of fuel line balancing would be necessary. The testing process also included recording all the necessary data to calculate air mass flow rate so the individual burner air to fuel ratio could be determined. A clean airflow test using a standard pitot tube was performed to verify airflow balance and actual primary airflow. The clean air test consisted of multi-point traverses of equal areas. Each line was traversed through two axes and the velocities were averaged. The testing was performed at normal operating conditions. Initial testing revealed no significant pipe-to-pipe differences during clean air testing. The clean air test did however verify that the station PA flow measurements were highly inaccurate.

The PA flow indications were neither accurate nor repeatable enough to provide optimum pulverizer control. STORM emphasized that there were multiple benefits to operating the pulverizers with an ideal air to fuel ratio of 1.8 pounds of air per pound of fuel. <u>They are as follows:</u>

- Stable burner performance
- Improved coal fineness
- Improved fuel distribution
- Reduced furnace exit gas temperature
- At Reduced superheat spray flows
- Reduced flame impingement and increased waterwall life
- More complete combustion in the burner zone resulting in lower LOI
- Improved NOx control

At full load the boiler nominal primary airflow is approximately 16% of total boiler airflow. The fact that the Mecklenburg boilers suffered from excessive primary airflows proved to be one of the major contributing factors to the high superheat spray flows, poor coal fineness and high flyash LOI levels. This discovery was not easily correctable due to excessive pulverizer "rumble" and high differential operating pressures when the PA flow was initially reduced to the desired 1.8 to 1 air to fuel ratio. Improving the pulverizer controls by transferring them to the DCS and improving the PA flow measurement proved successful in overcoming these barriers.

Once it was determined that the primary air flow indication was not nearly accurate enough for precise mill tuning, a recommendation was made by STORM to modify the existing design to achieve a more accurate reading. The original installation used a pressure averaging Pitot tube, which only delivered a total span of 1" of water due to low duct velocities. The small differential pressure range coupled with a multi-leafed flow control damper immediately upstream resulted in the poor accuracy and repeatability that had been noted. STORM designed and fabricated new reduced area primary air duct sections with a pressure averaging pitot tube that provided up to 4" of water differential pressure at full load conditions (see Section 2.0 for figure of Airflow Measurement Device). The increased velocity not only created more range from the Pitot tube but the converging action of the reduced area duct resulted in more uniform velocities at the Pitot tube. A flow distribution plate was designed from field pitot tube measurements to further enhance the uniformity of the air velocity profile at the Pitot tube. The combination of the new duct sections and flow distribution plates resulted in measurements accurate to within ±3% compared to original measurements that were on the order of ±20%.

Accurate primary airflow indication was vital for the development of the primary airflow curves. These curves were developed along with the pulverizer drive speed curves and the spinner drive speed curves to meet the operational requirements of the pulverizers while maintaining the air to fuel ratio as close as possible to the ideal 1.8:1 over the entire pulverizer load range (Figure 33). Below 50% pulverizer capacity, the PA flow was limited by the minimum line velocity to prevent coal drop out and consequently the 1.8:1 air to fuel ratio could not be maintained. Actually mill "rumble" was more often the limiting factor on reducing PA flow to ideal conditions. This typically occurs at about 60% pulverizer capacity depending on the condition of the pulverizer. Below this load the PA flow must be increased somewhat above ideal to keep the coal bed lifted into the grinding zone and avoid excessive "rumble". This has not proven to be a major concern since at lower loads the boiler is more "forgiving" due to increased furnace residence time.

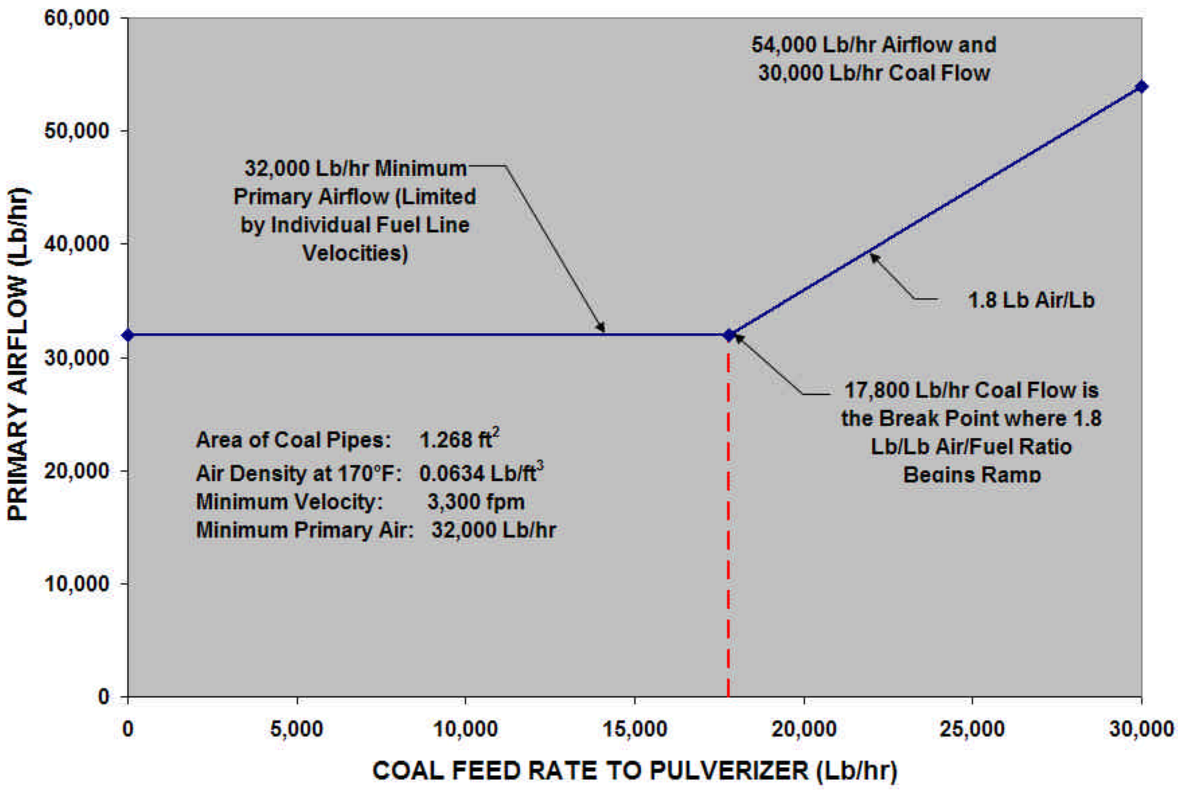


Figure 33

Burner Optimization:

Keeping a uniform and controllable secondary airflow at the burners also proved to be challenging. The initial setup of the burners following start-up only admitted air through the outer register. Consequently, the conditions in the burner area showed signs of “insufficient oxygen and poor flame quality" The burners have a movable sleeve damper and an inner and outer register (Figure 34). The position of the sleeve damper, along with the wind box pressure, dictates the total airflow through the burner. The outer air register divides the secondary air stream into two concentric streams, which independently vary air stream swirl. One air stream regulates the amount of air going to the inner air register and the other is directed by a flow divider to enter the furnace axially.

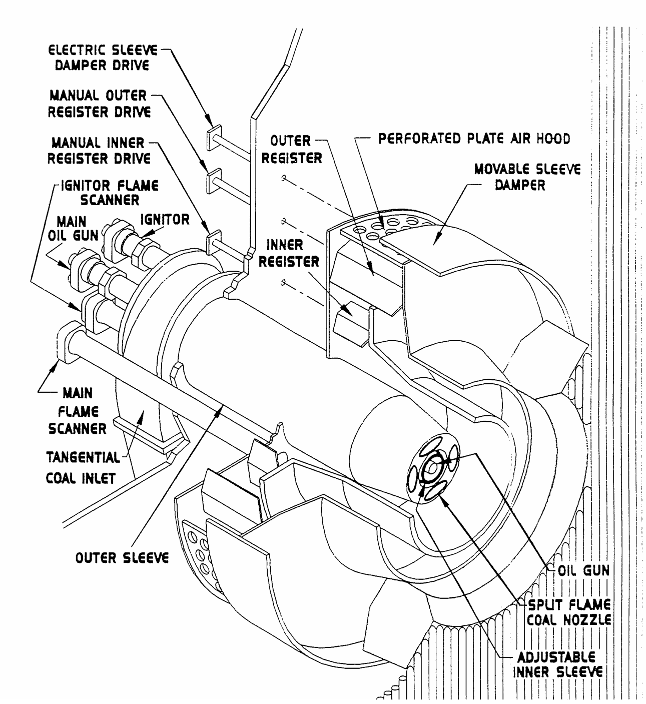


Figure 34

The swirl on the secondary air stream promotes sufficient mixing of the two streams to ensure adequate carbon burnout prior to exiting the flame zone. As the outer register is opened it transforms the flame from a bushy, short flame, to a longer, narrower flame. The inner register regulates the degree of swirl imparted on the coal/air mixture in the near throat area and, in conjunction with the primary airflow, controls the point of ignition of the mixture.

After a series of tests utilizing the HVT probe at the entrance to the superheater and visual observations, adjustments were made to improve the flame quality by positioning the sleeve dampers and air registers. This proved to be a very time consuming process, which required close coordination. Due to a non-compartmented wind box adjustments that were made to any register had a cascade effect on the other registers and burners. The goal was to obtain an oxygen balance from side to side of 3% ±1% and NOx levels near the desired level of 0.32 Lbs/MMBTU. Testing conducted on the overfire airports showed significant airflow with the flow control dampers in the closed position. The original installation of the O.F.A. Pitot tubes resulted in a very small differential pressure span with consequent poor accuracy. The ductwork in the area of the overfire airflow averaging Pitot tube was modified to create a more uniform, repeatable, and accurate overfire airflow measurement. This was necessary for acceptable total airflow measurement and control.

The boilers were also designed with an annulus around the bottom ash area to provide an oxygen blanket (boundary air) on the lower waterwall tube area to minimize reducing atmosphere metal wastage. The annulus is divided into three areas and is maintained at a positive pressure to allow small amounts of airflow through slots cut in the membrane between the lower tube sections. The lines Coming out of the wind box for pressurization initially had no means of throttling and no air flow indication. Dampers, which were designed and constructed on site, were installed in these lines to provide throttling. Testing was then conducted to limit and balance the amount of boundary air to achieve a good O_2 profile from front to back. This effort was intended to limit the amount of the total air entering the boiler at places other than through the burners. The following table will show the results of the testing for the full load tests (Figure 35).

Test No.	Avg Excess Oxygen	Avg. Primary Air/Fuel Ratio	NOx (Lb/mmBtu)	OFA (%)	*LOI (%)	Spray-Flow (Lb/hr)	Peak Temp. (°F)	Efficiency (%)
1	2.59	2.06	0.366	0	2.6	67,000	2,245	88.86
2	3.99	1.96	0.461	0	0.9	67,140	2,175	87.64
6	1.53	1.95	0.308	100	2.6	79,010	2,275	87.78
11	2.74	1.86	0.323	100	2.5	66,880	2,216	88.11

Figure 35

Fuel Flow Verification:

During the optimization process it was also important to verify the tolerances of the feeders and verify smooth feed rates. The calibration of the feeders was verified prior to testing and data was recorded during the test to ensure smooth consistent operation of the feeders and their control. The calibrations were already part of the plants continuing preventive maintenance program, which made this step one of the easiest.

Continued Improvement:

Following the initial testing and optimization phase a significant amount of progress had been made. The furnace exit oxygen had been reduced to an acceptable range of 3% with a good side-to-side balance. The LOI of the flyash was below 5% on a consistent basis. The de-superheater spray flows had been reduced from 79,000 Lbs/hr to 67,000 lbs/hr, flame quality was consistent through the load range of the boiler and maintaining consistent, acceptable NOx levels were also possible.

The de-superheating spray water flows and furnace exit gas temperature tend to increase at high load factor operation. This is due to furnace seasoning, i.e., slagging from continuous operation. The data in Table No.1 was taken on a seasoned furnace. Provisions were made in the original design for waterwall deslaggers to be installed on the rear and side waterwalls. The installations of four are planned in the next year. The purpose of these installations is to increase furnace waterwall heat absorption and further reduce de-superheater spray water flows at high capacity operation. The operator was confident that if testing was conducted on a regular basis the improvements could be maintained and further improvements would follow. STORM recommended a continuing performance preservation program, which included the following:

- Furnace exit excess oxygen and temperature traverses
- Economizer exit oxygen and temperature traverses
- Economizer exit flyash sampling
- Pulverizer burner line clean air test
- Pulverizer coal sampling for line balances and fineness
- Bottom ash observation for carbon content

The core group of operators that was assigned to the initial test group had become quite proficient with the sophisticated test equipment supplied by STORM. The group was able to repeat the testing with enough confidence that the decision was made to purchase the test equipment. Following a brief procedure development period the testing was repeated on both units. The findings from successive testing resulted in the development of detailed procedures and a trouble-shooting guide describing how to operate the units efficiently over the entire load range, with different pulverizer combinations and while continuously maintaining compliance NOx levels. The procedures also outlined actions that could be taken during upset conditions to minimize the effects on plant efficiency while maintaining reliable operations until any such problem could be corrected.

The modifications that were made to the pulverizers and the primary air ducts have given the operators the ability to fine-tune the boilers at all loads. To minimize the turnaround time of fineness results a shaker and the necessary coal fineness testing equipment was purchased. The test procedures that were developed promote testing by any member of the plant staff that may recognize a potential problem. A series of computer spreadsheets and files have been developed to allow for easy storage and retrieval of the test data. Various quality checks have been incorporated into the procedures to flag potential problems and to help ensure reliable results. These quality checks include using computer worksheets with all relevant formulas, to backup manual calculations done during the testing, the use of a proven method of fineness testing and plotting the results on a Rosin and Rammler Chart, and utilizing DCS trending during testing to document test conditions. The integration of the testing program with the current preventive maintenance program will provide improved pulverizer wear tracking and control curve tuning so the desired plant efficiency can be maintained throughout the pulverizer wear life. The advantages of developing and maintaining this history includes extended pulverizer life by not over-grinding the coal, reduced auxiliary loads, reduced maintenance costs and manpower savings.

In conjunction with the program development, the need was identified for more accurate boiler O_2 measurement to ensure proper excess air was maintained. Two Yokogawa oxygen monitors were installed in the boiler before the economizer. One monitor was placed on each side of the boiler (at the same spacing as the burners) so the side-to-side oxygen profile could be taken, averaged and used for the boiler O_2 control signal. The DCS allows for individual monitoring which helps the operator recognize possible problems before they have a major impact on the plant. Aligning the monitors with the burners assists the operator with identifying burner imbalance problems. At the time of this writing O_2 control curves were under development, which will be incorporated into the DCS for precise airflow control over the entire load range.

Summary:

The success of the optimization program was the result of a proactive commitment by the owners and operator. Changes were implemented using a fast track approach so benefits could be realized quickly. The success of the program was related to the implementation of changes in design, early in the operating life of the units. The key factors in the success were:

- Completing a comprehensive combustion system analysis and identifying the optimization program goals to provide focus for all parties.
- Team approach of owners, operator, and consultant to work together for the overall best performance
- Rapid approval of capital expenditures for changes
- Expedited and smoothly coordinated implementation of changes utilizing strong teamwork from all parties involved
- Development of operating personnel's awareness of factors regarding performance, maintainability, load response, capability and reliability
- Establishment of routine follow-up testing and tuning to preserve the performance gains

The capital expenditures which have been implemented so far are:

- DCS control of pulverizers
- Purchase of boiler test equipment
- Installation of new primary airflow measuring duct sections on all pulverizers
- Installation of two new permanent oxygen analyzers per boiler

Capital expenditures planned for next year for continuing performance improvement are:

- Installation of waterwall de-slaggers

Heat rate gains from the optimization program cannot be quantified due to the lack of a complete thermal performance kit for these units at the time of the boiler optimization. The reduction in ash disposal costs from reduced ash production has been significant in itself. Boiler flame stability has been greatly increased through the performance improvement efforts. Plant reliability has been excellent with an Equivalent Forced Outage Rate (EFOR) of 0.7% in 1994 and 0.5% year to date in 1995. The bottom ash now has a consistent light gray color, flyash LOI's are less than 5% at all loads and NOx control is predictable, reliable and comfortably within permit limits. Due to the high level of employee involvement throughout the optimization process, the awareness level is now very high. Most combustion problems are quickly recognized and corrected by operating personnel. The commitment of the owners and operator to actively support a team approach is the primary reason for the success.

7.0 COMBUSTION OPTIMIZATION AND FAN BOOSTED OVER FIRE AIR INCORPORATED ON A 90 MW BOILER[13]

The unit is a 90 MW nominal pulverized coal fired unit designed by Combustion Engineering Company. The unit consist of a four corner, corner fired boiler with four Raymond Bowl 533 pulverizers. Below is a side Elevation of the tangentially fired unit with the OFA ports shown.

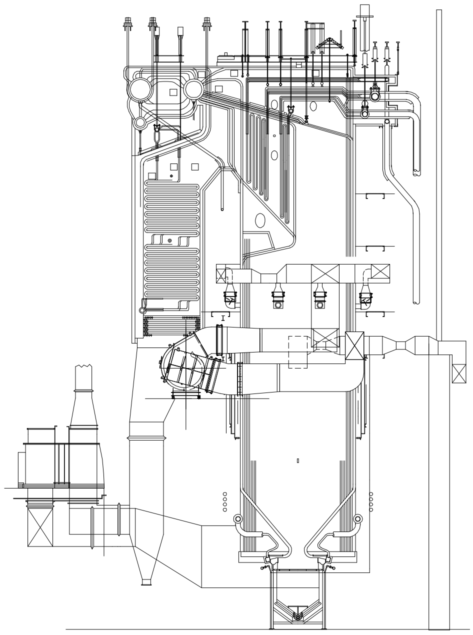


Figure 36

Due to limitations on NOx emissions it was necessary to reduce emissions while maintaining unit performance and reliability. The fan-boosted over-fire air system provides a measured and precise method of injecting up to 25% of the total air supplied for combustion into the upper furnace. The key to the success of this project has been the commitment to performing a comprehensive combustion systems approach. This included, and continues to include the importance of pulverizer performance optimization and accurate airflow management.

Prior to the installation of the Fan Boosted Over-Fire Air System the unit performance and NOx levels at normal operation and 80 Net MW are noted as follows:

- NOx levels 0.51 – 0.53 Lbs/MMBTU
- L.O.I. (Loss On Ignition) or Carbon Loss approximately 20%+
- <2% Oxygen Control Point
- Fuel and Air Biased

The following were the goals of operation following the installation of the over-fire air system:

- A minimum of 2.0% Oxygen level at the furnace exit by traversing a test grid with a HVT probe
- NOx levels ≤0.32 Lbs/MMBTU at 83 Net MW unit load
- LOI 5% - 8% or better at 83 Net MW unit load
- Minimal slagging at full load conditions
- Performance Preservation (STORM 13 Essentials)

The purpose of the Boosted Over-Fire Air is to provide proper staging of air and fuel to the furnace. This staging allows for NOx reduction in the burner belt zone as well as the O.F.A. system allowing oxygen to provide carbon char burn-out prior to exiting the furnace. This will result in an overall NOx reduction as well as improved levels of carbon loss or LOI.

The concept of the eight OFA nozzles (two on each water wall) is to utilize the upper furnace for carbon char burnout. This upper furnace zone is where the flame temperatures are cooled to below the threshold thermal NOx formation temperature of about 2,804ºF. This is shown on the diagram, Figure 37

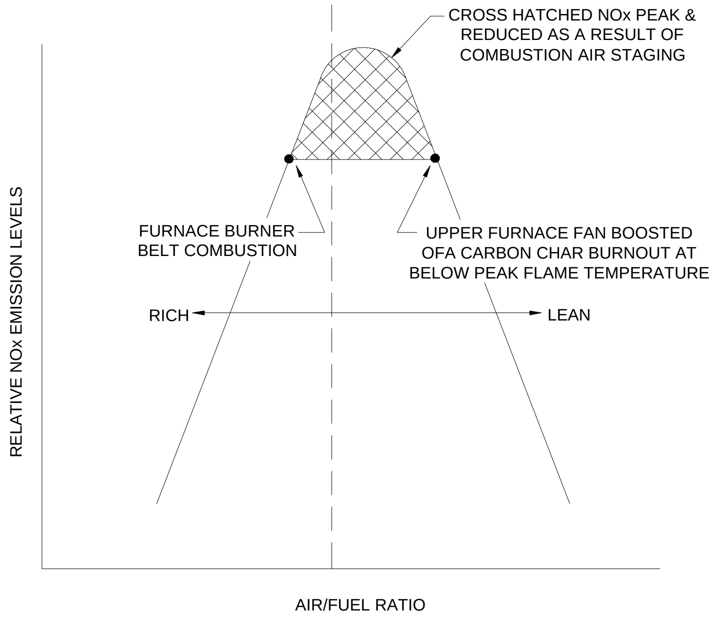


Figure 37

The NOx formation graph above shows the peak NOx production at a slightly oxidizing environment. The principal purpose of the FBOFA system, is to stage combustion, so that most combustion is completed in the burner belt, at a low furnace stoichiometry. The heat energy is released in the burner belt and radiant heat transferred to the waterwalls, the upper furnace products of combustion will be reduced in temperature to below 2,800ºF. It is at this point that the high momentum over-fire air is injected to complete combustion of the carbon char. This final stage of the combustion process is to be completed below 2,800ºF and therefore below the threshold temperature for thermal NOx production.

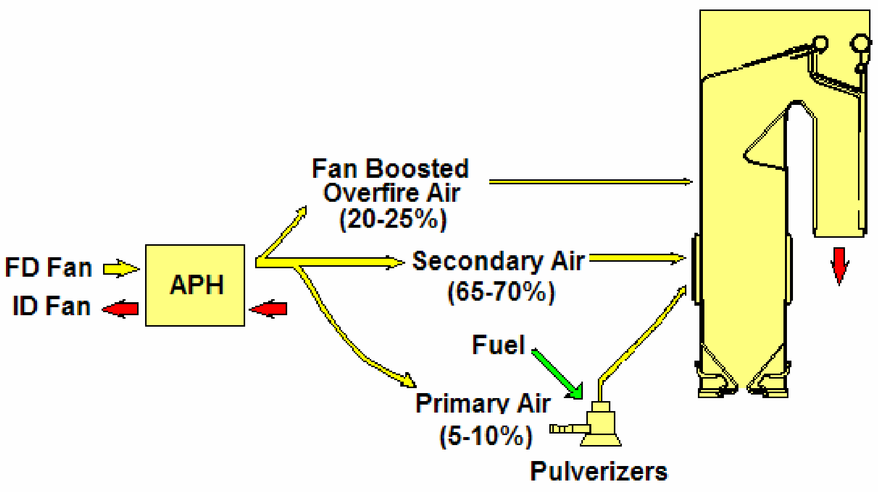


Figure 38: Airflow schematic of OFA

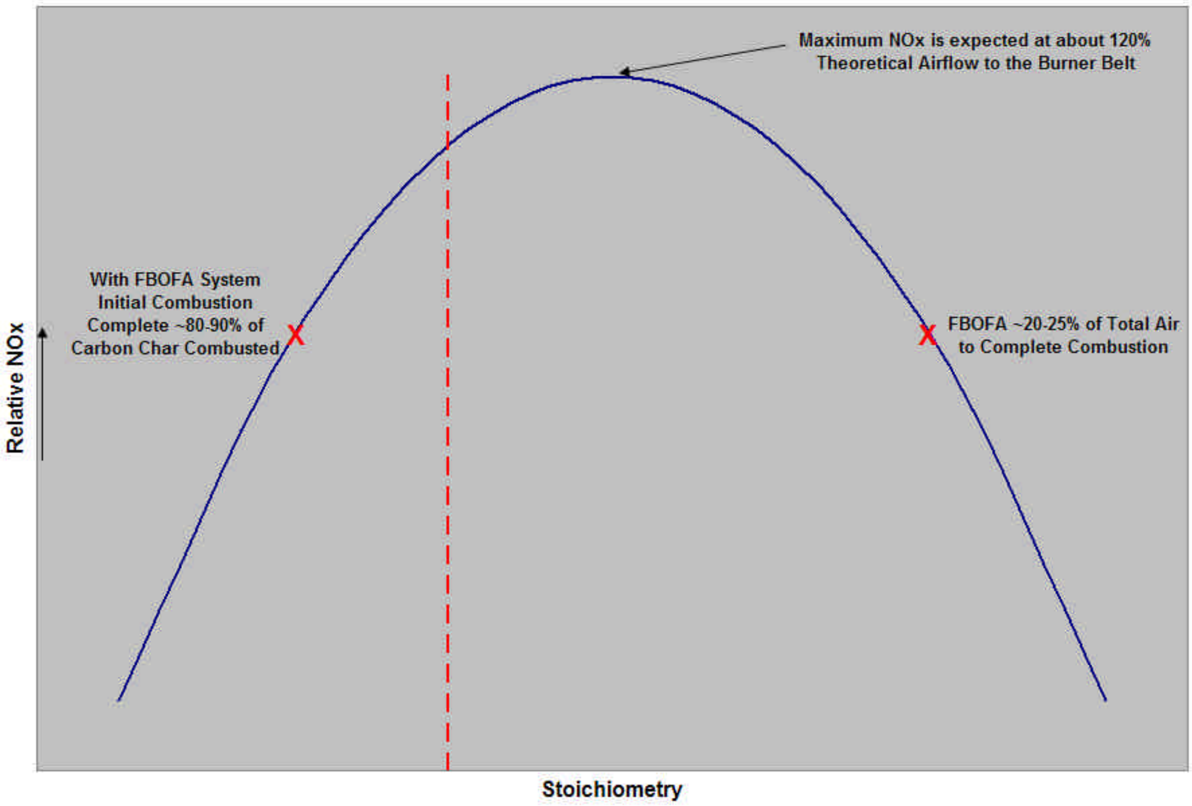


Figure 39

The over-fire air is drawn from the existing 600°F combustion air supply at the air heater exits and is ducted bypassing the burners to the booster fan and to the over-fire air-ports. Two venturis and dampers are provided to precisely measure and control the total over-fire airflow. Manual dampers are provided to control the flow at the individual OFA ports.

The fan-boosted over-fire air system operates at the same design total airflow as original. The difference with the fan-boosted over-fire air system is that combustion is staged and controlled using more of the total furnace volume and height. It is for this fundamental reason that the project is considered a "comprehensive combustion optimization," including significant pulverizer and burner improvements.

The Over-fire air system uses a booster fan to increase the supply pressure of the OFA to approximately 10"-15" w.c. using 600°F+ air so proper penetration velocities can be obtained through each of the eight waterwall openings (shown in Figure 40). This penetration velocity is critical to maintain acceptable flyash LOI and exit gas carbon monoxide (CO) levels.

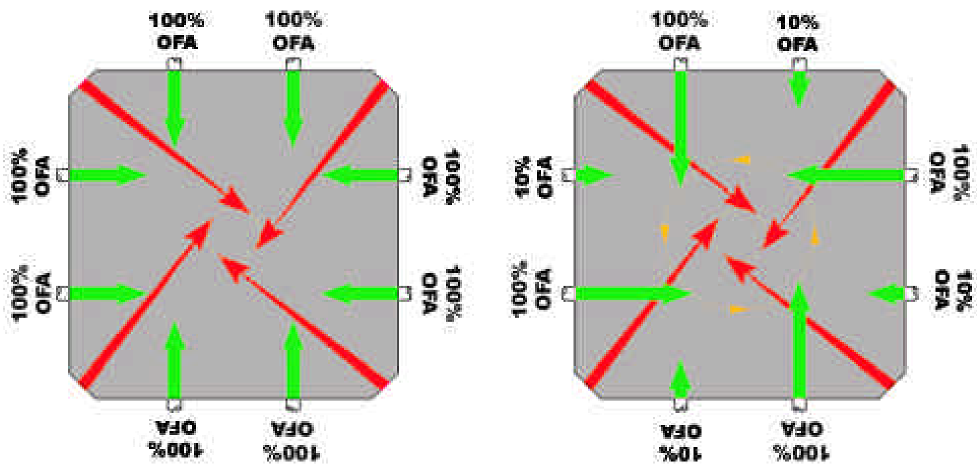


Figure 40

The system uses 170,000 Lb/Hr OFA Flow, at approximately 600ºF combustion air temperature. The basic design, therefore, is for approximately up to 25% of full load airflow to be supplied through the over-fire ports.

Combustion Optimization

Pulverizers
Fuel line fineness must be at least 75% passing 200 mesh and a maximum of 0.1% on 50 mesh. To achieve these results the following mill modifications were performed: extended outlet skirt, extended exhauster blades, and corrected tolerances. Spring tensions were first checked and set to the proper tension ±200 Lbs. journal to journal. Classifier blade settings were checked and properly set to achieve the desired fineness. Fuel line orifice sizing was calculated and changes recommended to further improve line-to-line balance.

Airflow
Over fire air was accurately measured and controlled by the use of venturis to within ±2%. To insure the DCS was indicating the correct flow to within ±2%, the venturi was calibrated by performing a Cold "K" factor Test and Hot "K" factor tests over the load range.

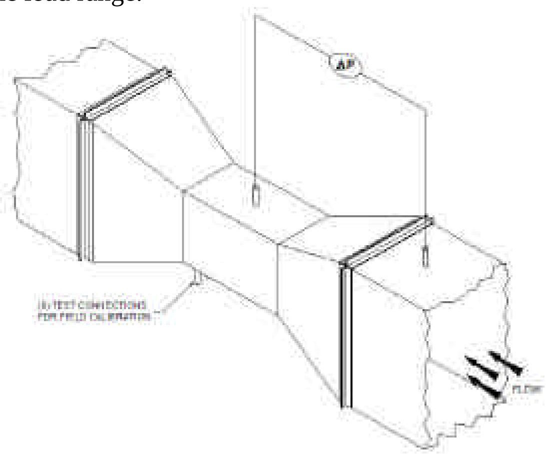


Figure 41

Staging of Fuel and Air
The fuel and air were staged within the furnace both vertically and horizontally to utilize the entire furnace area. Staging vertically was performed by progressively setting the burner tilts downward, as shown below in Figure 42 showing a typical burner tilt arrangement.

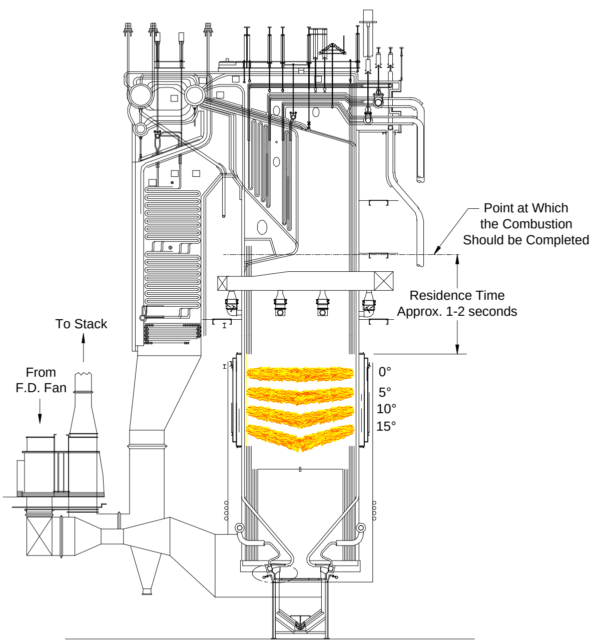


Figure 42

In order to achieve horizontal staging within the furnace, STORM Air Diverters were installed on the auxiliary air buckets. It is essential to maintain an oxidizing environment on the waterwalls to prevent waterwall wastage from occurring. By diverting a percentage of the secondary air toward the furnace walls both farther staging of the fuel and air and wastage prevention was achieved. The figure below shows the separation of the fuel and air required for staging for NOx reduction.

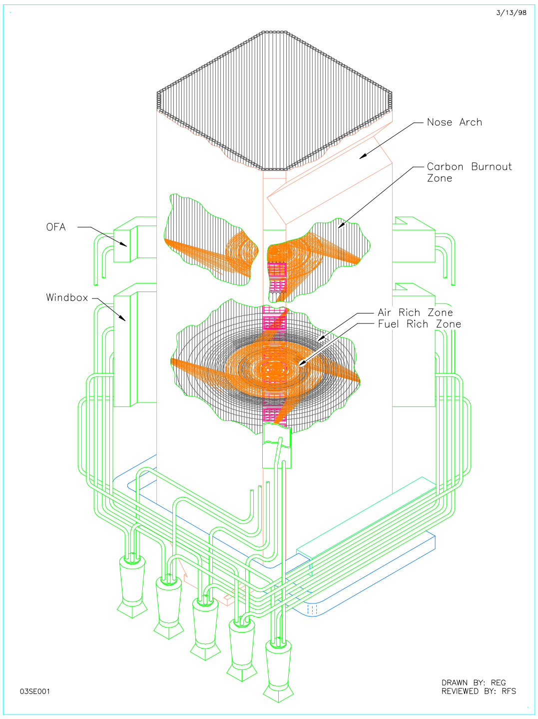


Figure 43

OFA and Combustion Optimization Project Results

The table below shows previous full load data showing the correlation between Excess air, LOI, and NOx.

Date	Gross Load (MW)	Excess O_2 (%)	LOI (%)	NOx (Lb/MMBtu)
Pre NOx Limitations	80	3-3.5	1.86	0.85
	80	1.5-2.5	5.43	0.68
	78	2-2.5	4.53-4.77	.6143-.8077
	80	3-3.5	-	.6237-.8907
	78	4-4.5	1.08-2.68	.8455-.9229
NOx Limitations Enforced	88	1.3-1.6	+20	.400-.491

Figure 44

The table below shows previous data at 60 MW. The points taken for the “Pre NOx Limitations” were at normal operation and the “NOx Limitations Enforced” data was with lower excess air and staging of the fuel and air to lower NOx.

Date	Gross Load (MW)	Excess O_2 (%)	LOI (%)	NOx (Lb/MMBtu)
Pre NOx Limitations	56	3.06-3.58	0.67-1.54	0.6237-.8852
	60	2.35	2.54	0.8077
	60	4.23	1.57	0.9229
NOx Limitations Enforced	65	2.1	-	.277-.309

Figure 45

Post OFA Testing & Tuning results are shown below for both Full Load and at 60 MW.

Date	Gross Load (MW)	Net Load (MW)	Excess O_2 (%)	NOx (Lb/MMBtu)
Post OFA	90	83	1.5-2.1%	0.288-0.330

Figure 46: Post OFA Full Load Test Data

Date	Load (MW)	Excess O_2 (%)	NOx (Lb/MMBtu)
Post OFA	60	2.0-2.2	0.249-0.335

Figure 47: Post OFA Mid-Load Test Data

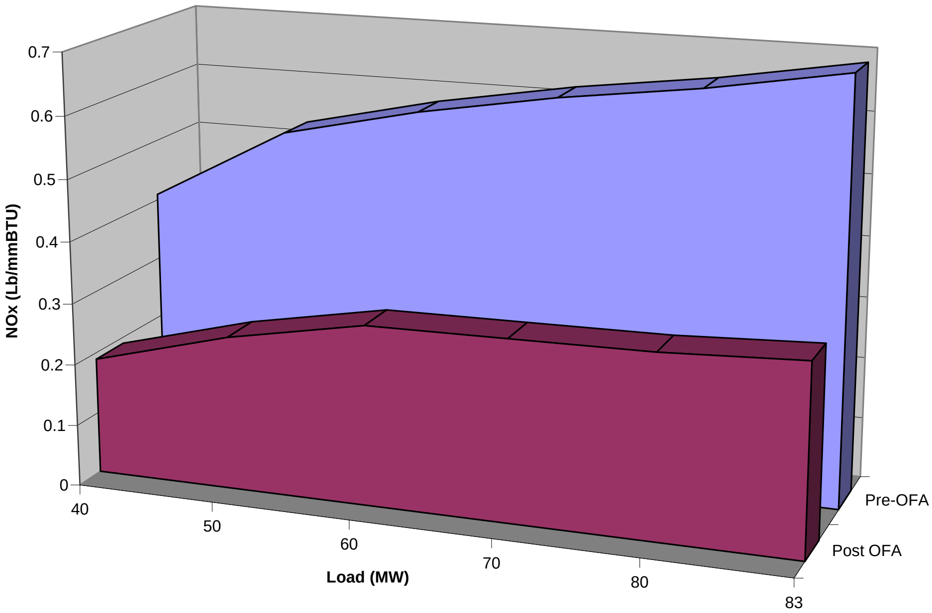


Figure 48

The following data shown below are average data points collected following installation of the OFA and tuning period. Currently, the boiler has been operating at much lower NOx levels from operators tuning the system across the entire load range (0.18 - 0.20 Lb/MMBTU at 36 MW and 0.28 - 0.32 Lb/MMBTU at 83 MW).

Net Load	Gross Load	OFA		Pre-OFA (Ozone Season)		% Reduction	
MW	MW	lb/hr	lb/mmBtu	lb/hr	lb/mmBtu	lb/hr	lb/mmBtu
40	43.0	124.8	0.304	159.7	0.409	21.8%	25.6%
50	53.5	155.5	0.309	226.8	0.441	31.4%	30.0%
60	64.0	186.2	0.313	293.8	0.474	36.6%	33.9%
70	74.5	216.9	0.318	360.9	0.506	39.9%	37.3%
80	85.0	247.6	0.322	428.0	0.539	42.1%	40.2%
83	88.0	256.4	0.323	447.1	0.548	42.7%	41.0%

Figure 49

Prior to NOx limitations Unit 13 had an LOI in the single digits around 3%, once running for NOx the LOI climbed to >20% due to staging of the fuel and much lower excess oxygen levels. With the injection of OFA above the burners, proper air and fuel staging, pulverizer optimization, lower excess oxygen levels, etc…the carbon char is capable of being burnt out at the OFA level. The following table indicates the LOI levels for each condition (pre-low NOx firing, low NOx firing, and low NOx firing with FBOFA).

	Average LOI	NOx (Lb/mmBtu)
Pre-low NOx Firing	3%	0.61-0.92
Low NOx Firing	>20%	0.27-0.49
Low NOx Firing with FBOFA	5-7%	0.19-0.33

Note: The NOx levels shown above are for the entire load range

Figure 50

SUMMARY:

Periodic testing and tuning of the furnace inputs can improve heat-rate, capacity, reliability, and the capacity to use fuels with more difficult ash characteristics. The intent of the authors is to review the practical application of the fundamentals to achieve the best possible operation efficiency. The authors wish to express our sincere appreciation for this opportunity to share our experiences and techniques for combustion optimization with you.

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