# Combustion Optimization – Achieving Operational Flexibility & Improving Load Turndown

**by**

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## Introduction

*"It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us…"*

Charles Dickens, Tale of Two Cities

Such words of Charles Dickens can be applied to our times. Best of times – superb economic climate with excellent markers; worst of time for power generators – uncertainty in natural gas low pricing, the diminishing role of coal, the challenging market conditions etc. we hear many examples of wisdom and many more of foolishness; often it is difficult to distinguish between belief and incredulity such as "fake news" that shower on daily lives; the seasons of Light and Darkness overlap that like the weather so that the seasons are undiscernible; optimism suggests we are the strongest country in the world and there is talk of putting a man on Mars yet our daily news is filled with man's inhumanity to one another.

A few decades ago few would have predicted the advent of low cost natural gas and the effect that has had on the coal fired energy sector. Credit must be given to those leading the surge of renewable energy. Prudence suggests that we must keep coal in readiness even though the fleet is aging with few to no replacements slated for construction. While we bath in a good economic climate, we also know that in inactivity by the present US Environmental Protection Agency may lead to more restrictive emission levels in the future.

In recent years the coal-fired boiler fleet has diminished by over 20 percent as shown in Table 1.[1,2] Today many boilers range in age from 75 to 20 years. Only 35 new coal fired plants have been added in the last 15 years. The 30- to 50- year old boilers comprise only 93 GW and 34 per cent of the coal-fired fleet, a drop by 46 percent in only seven years. The demise was expected because of age and also because many would have required upgrades in equipment. While most of these units have high grade Air Quality Control Systems (AQCSs), they would have required upgrades to comply with Maximum Achievable Control Technology (MACT).

**Table 1 – Recent Changes to the Coal-Fired Boiler Fleet**

| Year | 2011 | 2018 | Change, % |
|---|---|---|---|
| No. of Coal-Fired Boilers | 1,105 | 686 | -38 |
| Capacity of same, GW | 342 | 275 | -21 |
| Capacity of Coal-Fired Boilers 30- to 50-years, GW | 216 | 93 | -23 |
| Portion of Coal-Fired Boilers, % | 63 | 34 | -46 |

These units will bear the burden of ensuring the usual high standards of performance, availability, and reliability. Add to this market demands for load swings, cycling, two shifting etc., all the while maintaining emissions compliance in check and boiler performance at high levels of availability and reliability to back up the intermittency of renewables. This all has to be managed within an ever-tightening budgetary environment.

Such units face many challenges; the need for life extension and life management, more stringent emissions regulation with associated compliance challenges, as well as operational flexibility & cost reduction in an ever-changing market environment. Key industry conferences such as this one hosted by EPRI illustrates the importance of such issues to the power industry.  Greenbank Energy Solutions Inc. (GESI) is proud to participate in such an event and be able to communicate some key value-adding solutions to the challenges faced. This paper and associated presentation focuses on two key areas of operational challenge:

- ✓ Operational flexibility
- ✓ Improved load turndown (how low can you go),

The paper and accompanying presentation will review and discuss various technologies and services (including predictive fuel distribution modelling) associated with delivering improved combustion performance in today's challenging operational environment and the associated value delivered. Reference will be made to several case studies illustrating performance improvement and return on investment in terms of improved combustion performance. Greenbank is a supplier of technology and engineering solutions.  Our preferred approach is to become a partner, working with the host user to ensure that our products and services achieve the agreed objectives.
(See Case Study 7.)

Fundamental to delivering satisfactory flexible operation, including load turndown and reducing minimum stable generation, is maintaining combustion stability throughout the load range.  Often, one of the limiting factors associated with load reduction is the onset of burner flame-out and the associated need for oil and or gas support. Addressing combustion and flame stability through improved fuel and air distribution, Pulverized coal fineness control, Primary Air/Pulverized Coal velocity control, reducing uncontrolled air-ingress and leakage, can deliver significant performance benefits. This includes emissions compliance, improved combustion efficiency and associated reduction in fuel cost as well as reduced levels of slagging, fouling, corrosion and erosion with associated commercial benefits. In terms of reduced load operation, improved flame stability can deliver lower load operation and reduced need for ignition oil support with commensurate commercial benefits.

## Background

As stated in EPRI's conference announcement, Flexible Operation impacts coal-fired boiler operation more than baseload operation. This puts significant pressure on these units ability to produce safe, reliable, affordable, and environmentally responsible electricity. These risks must be properly identified and managed to ensure the economic viability of the assets are maintained. Subcritical fossil, Supercritical fossil and Combined Cycle units are increasingly required to operate in flexible modes which may include; load following, weekend shutdowns, daily on/off shutdowns and extended shutdowns. In response to these new operating modes units have explored options to increase unit turndown and change fuels.

These new operating modes and changes in operating strategy alter damage mechanisms prevalent in the units necessitating new asset management strategies. The damage mechanisms in major components and evolving management strategies resulting from this shift in fossil generating operation are the primary focus of this conference. To ensure their continued operation in the long term, the remaining plants must take steps to improve the combustion performance conditions in their boilers and therefore maintain emissions compliance and improve operational efficiency. This can only be realistically achieved through a combination of appropriate fuel selection management (where possible) and improved fuel balancing, distribution, measurement and overall management and control.

## New Demanding Roles

A key part of the strategy is optimizing fuel delivery and enhancing boiler performance by delivering real and measurable improvements in emissions minimization and boiler efficiency, and allows higher performance levels under variable load conditions that the remaining coal-fired boilers must now operate. Some of these new roles in no particular order are as follows.

- **Ramping** - Boilers now need to react to rapidly changing grid load requirements as a result of increased reliance on renewables (with associated intermittency and load management challenges) requiring the need for rapid ramp rate response The current aging boiler technology was not originally designed to operate in this manner. So, owners and operators have to adapt their operational and maintenance strategies accordingly to accommodate the high degree of operational flexibility required.
- **Emissions** - Increasing emissions reduction requirements, especially carbon monoxide (CO) – bound to come sooner or later
- **Combustion Optimization** - Need good fundamental combustion optimization, i.e., good burner stoichiometry via improved coal distribution throughout the entire load range?
    - Improved Air / Fuel Ratio Control improves flame stability at low load
    - Reduced localized slagging
    - Higher Combustion Efficiency
    - Flame Stability - Stable Flame / Combustion

    - Reduction in erosion.
- **Improved NOx Reduction**
    - Achievable by controlling secondary air levels under stable operating conditions.
    - Maintaining consistent coal grind and equal coal flow to all burners
- **Improved Fuel Burnout** – Reduced Unburned Carbon in fly ash, e.g., LOI
    - Reduction of unburned coal in fly ash
    - Saleable ash
    - Reduction of land fill disposal cost
- **Reduced Carbon Monoxide (CO)**
    - Combining many combustion and precombustion activities
- **Combustion Air Control** - Improved, more stable, combustion air, e.g., Oxygen ($O_2$). Distribution

**Issues**

In dealing with boilers in the 30- to 50-year age, one might consider upgrades for more demanding service. Certainly such upgrades to the Fuel Delivery System can provide benefits[3]. Providing the capability of very low-load running will minimize the number of cold startup operations the combustion system needs to play its part. Conventional firing systems for hard coals have permitted typically 40 percent boiler load without the need for back-up firing. However, it is possible through changes to mill size and burner operating range to achieve 25 per cent load with two out of four mills operating.[4] As an example, four mills are in supplying tangential firing systems, the minimum load can be further reduced: in recent plants it has been shown that single-mill operation can be realized stably, with turndown to less than 20 percent, reducing the number of shut-down operations.[5]

A key stage in this process is the handling of fuel through the coal mills that feed the boilers at the heart of the power plant. There are currently many different types of coal mills in operation some with exhauster mills. There are varying forms of vertical spindle, (single or double) where each outlet splits off into multiple burners to multi-outlet mills where each outlet feeds its own coal burner and multi outlet designs and there are also horizontal tube mills with stand-alone classifiers. All of these coal mills should ideally deliver a balanced fuel supply to the boiler. In practice, however, this is easier said than done.[6]

Traditional methods of balancing have attempted to balance the air flow using orifice valves and measure the air flow in the lines using Pitot devices. However, the fuel rarely follows the air, due to its sizing and the effect of the pipework characteristics on the pulverized fuel (pf).

**GESI Products Overview**

Greenbank, an equipment, technology and engineering services supplier and provider is pleased to make this presentation joining other power plant experts representing utility organizations, other equipment manufacturers and consulting and research organizations. Together we can face and address these new challenges. GESI's expertise and experience is primarily with coal and thus coal-fired boilers in two areas that address:

1. Accurate measurement and control of air and coal flow distribution to the burners and combustion zone to control fuel lean and fuel rich conditions.
    a. Fuel lean conditions-
        i. During boiler load fluctuations and low pulverizer fuel loading the primary air/fuel ratio is usually very high leading to fuel lean burners and increased risk of flames instability (without the use of gas or oil igniters for support) which can limit the overall boiler turndown capability.
        ii. When there is low energy input into the burners they cannot maintain the air at combustion temperatures and the flame becomes unstable.
    b. Fuel rich conditions-
        i. Can result in increased carbon monoxide (CO) and increased unburned carbon in the fly ash which can increase fuel consumption.
        ii. Fuel rich burners demand that the boiler operate at higher levels of excess air which will also tend to result in local reducing zones that can compromise the integrity of the water walls (corrosion, slagging & fouling etc.).
        iii. Unburned fuel can possibly reignite in an uncontrolled manor downstream of the intended combustion zone.

2. Maintaining coal fineness and flexible ramping rates
    a. Maintaining the required coal fineness throughout the mill load range is paramount to maintaining optimum combustion
    b. Improve and control the distribution and fineness of the pulverized coal to
        i. Reduce the oxides of nitrogen ($NO_X$) produced by the burners
        ii. Minimize slag production on the furnace walls and on pendant surface at the furnace exit.
    c. Maintain the currently acceptable levels of carbon content of the fly ash, bottom ash and pulverizer rejects.
    d. Reduce carbon monoxide (CO) production in conjunction with enhanced combustion controls

GESI guidelines for balancing and fineness are:

Combustion optimization targets for tuning to lowest possible excess air at the boiler outlet include:

- Coal pipe clean air balance — Pipe to pipe +/-3% or better
- Coal pipe dirty air balance — Pipe to pipe +/- 5% or better
- Coal pipe coal flow balance — Pipe to pipe +/- 10% or better

The effect of poor coal fineness on combustion and the benefit of good coal fineness:

- Coal line coal fineness - 75 percent passing 200 mesh or 75µm <0.01 percent passing 50 mesh or 200 µm
- Minimum coal flow velocity - 3,300fpm

**GESI Expertise & Experience**

The GESI products to address measurement and control of coal flow distribution Include:

- PfMaster an On - Line PF Metering System
- The Variable Area Rope Breaker VARB™ is a non-intrusive passive device designed to break a pulverized fuel rope. The VARB is used to break ropes ahead of 2 way, 3 way or 4 way splits and the resultant homogenized flow into a splitter results in equalized distribution to all burners.
- CoalFlo® PF Balancing Damper & New Insertable CoalFlo® PF Balancing Damper used in multi-outlet vertical spindle mill applications
- High Energy Pressurized (HEP) Dynamic classifier integral coal flow balancing dampers

The GESI products to address maintaining coal fineness and support flexible operation include;

- HEP Dynamic Classifier
- Greenbank UK products listed above including Advanced Combustion Modelling which utilizes Computational Fluid Dynamics (CFD) and gravimetric coal feeder

To illustrate Greenbank and GESI capability and the associated benefits delivered, a series of case studies are provided.

**Case Study 1- On-line flow monitor used to balance coal flow at a Mid-west power plant.**

- 830 MW
- 24 Mitsui Low $NO_x$ burners (LNBs)on front wall 24 on the back wall
- 8 Alstom Mills, each with 6 outlet pipes.
- Online coal flow monitor PfMaster installed on Mill D after it's been in service for approximately 3000 hours
- Campbell Plant's Unit 3 emissions are minimized or controlled through the use of LNBs, over-fire air (OFA) and selective catalytic reduction (SCR) for $NO_x$, activated carbon injection (ACJ) for mercury (Hg), spray dryer absorbers (SDAs) for acid gases, e.g., sulfur oxides ($SO_x$). HCl], and a low pressure/high volume pulse jet fabric filter (PJFF) system for particulate matter control.

Coal flow balance was measured in real time by PfMaster and achieved by:

- Making adjustments in the rotary classifier speed
- Making adjustments to the mill outlet assembly

Balance splits for the 6 outlet mill design would be 16.67 percent in each of the six outlet pipes.

For a boiler with an aggressive OFA a couple of burners out of each boiler row with the richer percentage of coal would be the main contributor to high unburned carbon levels when staging air to the upper furnace area. Distribution is the major influence on combustion efficiency and unburned carbon. Fineness does improve unburned carbon, but it is a second order effect to the actual coal to air ratio at each individual burner.

This large opposed wall boiler has 8 mills, with 4 mills arranged at the front and back of the boiler having Alstom high performance rotary classifiers. GESI participated in a joint project with OEM boiler manufacturers to improve the coal distribution from the multi-outlets to the burners of one mill. Following successful distribution results from the extensive testing GESI was awarded the contract to supply equipment to the complete boiler.

Multiple various paddle type arrangements were tested inside the classifier at a location below the coal pipe itself. This allowed adjustment to the amount of coal diverted away from any particular pipe without impacting the pressure drop down any particular pipe.

PfMaster, a triboelectric Coal Flow monitoring technology supplied from GESI, was used together with adjustable blades to optimize the coal distribution to the multiple outlets as shown in Photo 1.

**Photo 1 - PfMaster a triboelectric Coal Flow monitoring sensors**

Data from the graphs below show the complex tuning process where reducing coal flow to one pipe would see increases in adjacent pipes and required all pipes to be measured in real time to allow adjustment for coal flow balance. The optimum for the 6 pipes was a split of 16.7 percent flow each.

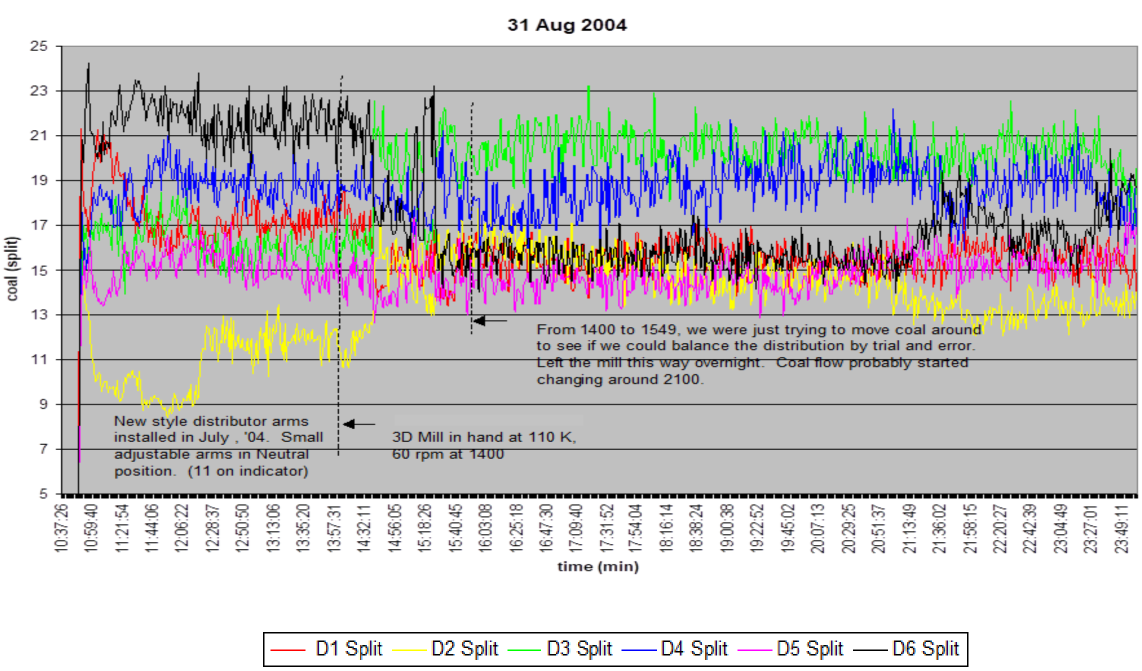



**Figure 1 - Day 1 Tuning Results**

The coal flow monitor indicated that initially there was gross maldistribution of fuel to the 6 burner lines off the mill outlet as high as 23 percent flow to a low of 9 percent flow (or +138 percent /-54 percent normalized flows).

- Mill loading was held constant at 110,000 lb/hr throughout most of the day.
- Adjustments were made to the individual coal dampers inside the mill to attempt to balance the coal flow distribution.
- The dynamic classifier was left at a constant 60 rpm on day one of the commissioning.

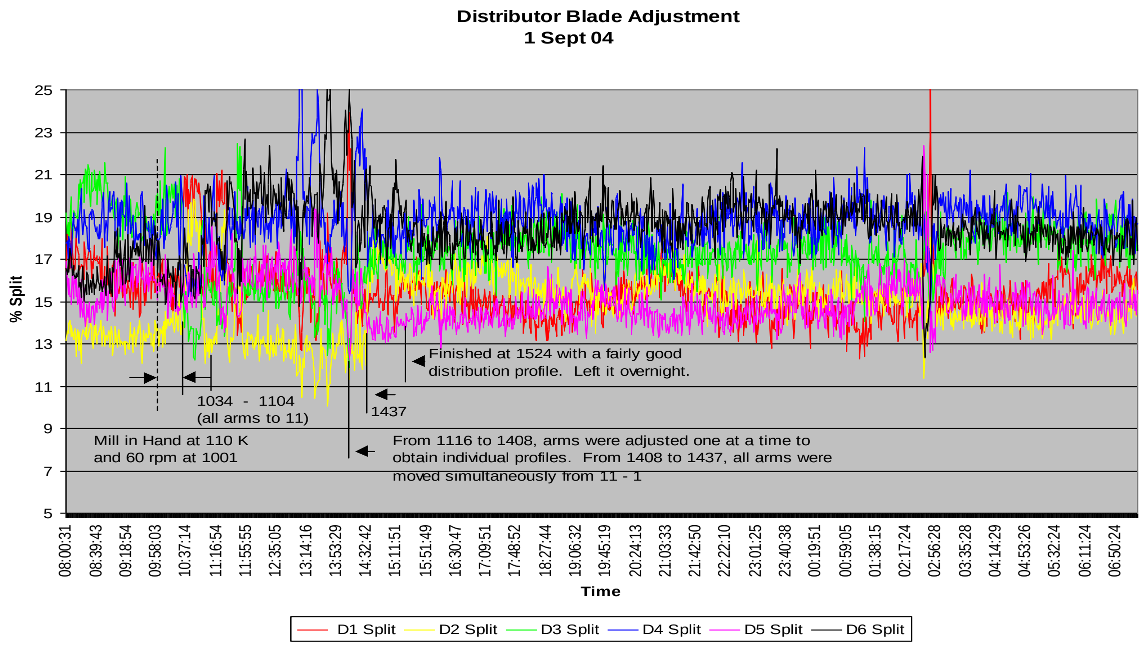



**Figure 2 - Day 2 Tuning Results**

On Day 2- additional individual adjustments were made one at a time via the coal dampers while mill load was left constant. The dynamic classifier was left at a constant 60 rpm.

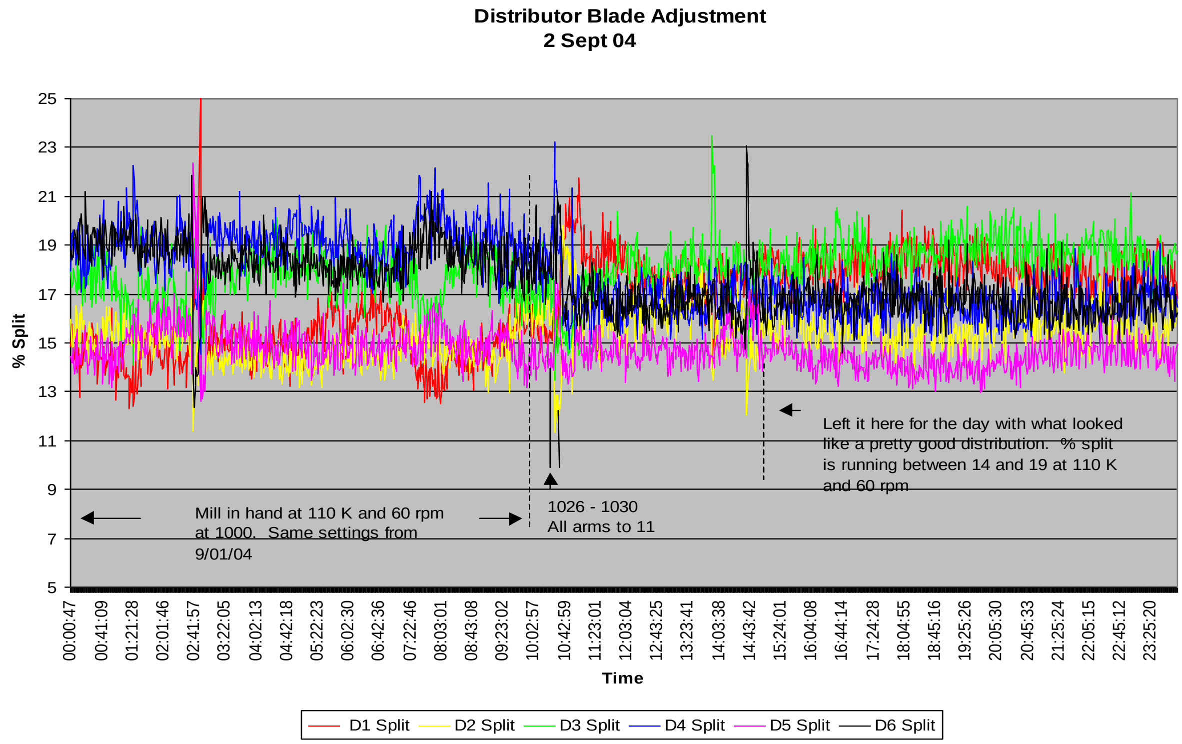



**Figure 3 - Day 3 Tuning Results**

Day 3 adjustments were made via the coal dampers while mill load was left constant.

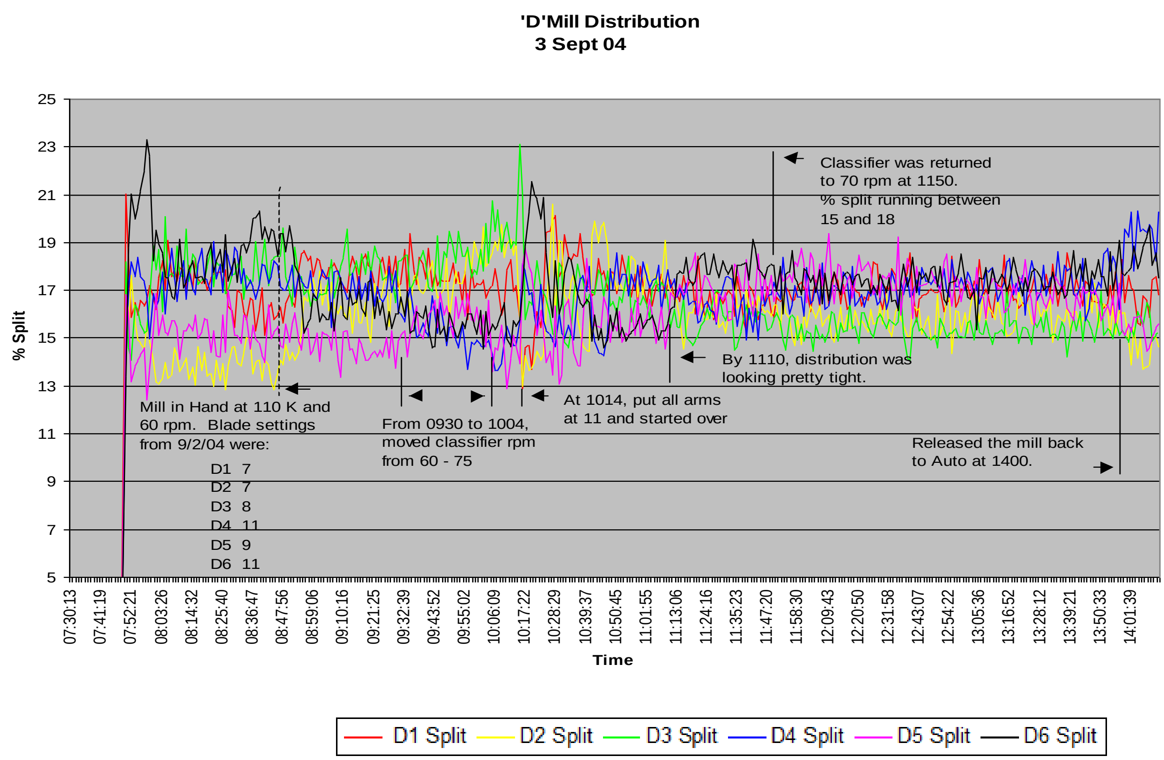
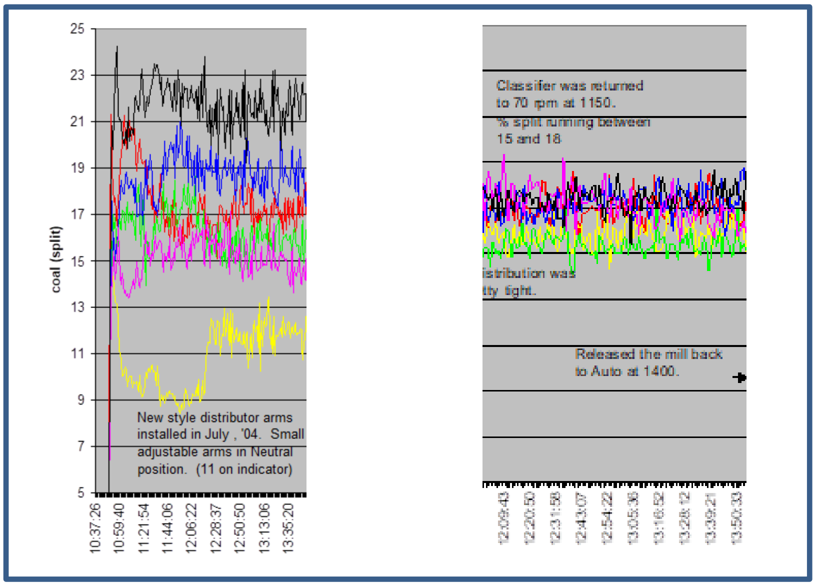



**Figure 4 – Final Day Tuning Results**

On Day 4 some adjustment in the rpm of the dynamic classifier were made to squeeze out some additional coal flow balance. Notice how at 1400 hours when the mill was released back to automatic mode there was a small decrease in the coal flow balance. This is to be expected.




**Initial Coal flow balance** **Coal flow balance after tuning**

**Figure 5 – Comparison Results**

Figure 5 clearly shows the results of good measurement and control of pulverized fuel for the mills to the burners. However, in this case only a single mill was tuned and as a result there were no combustion benefits noted.

Background VARB for in line splitting applications; The VARB family of devices is considered to be geometric fluidic mixers. They operate through a variety of modes and work by moving both fluid mass of air and momentum of the pulverized fuel phase. The VARB was developed by Greenbank Advanced Instrumentation and Measurement (GAIM), the research and development division of the Greenbank Group.

The H-VARB in essence operates like an aggressive non-uniform venturi. However, the design of the H-VARB overcomes many of the short comings of the non-uniform venturi. An aggressive venturi works by presenting the flow with an obstacle, which moves the pulverized fuel into the center of the stream. A non-uniform venturi has by its nature higher-pressure drop (and high wear) and does not deal with issues such as reattachment of solid phase in vertical lines or drop out in horizontal lines.

Reattachment occurs in most splitting devices due to the action of secondary flow patterns in the air and momentum of the pulverized fuel phase. This normally leads to certain devices moving a heavy rope away from the back of the pipe into the center for only a few pipe diameters.

The H-VARB device is able to overcome the pressure drop issue by its design that allows minimal constriction of the pipe. It is also able to prevent reattachment and drop out due to its unique shape that disrupts secondary flow patterns and alters the path of the pulverized fuel. In addition the unique cross section is designed to spread the pulverized fuel in the center of the pipe promoting mixing. The issue of accelerated pipe wear is handled by lining the internal surfaces of the device with ceramic tiling and abrasion resistant wear linings.

The fluidic mixing shape is unidirectional and precise placement and orientation of the device is necessary in order to optimize operating conditions. Predictive fuel distribution modelling is used to place the device in the appropriate location. Computer modeling is also used to optimize the shape of the VARB, which has given birth to several standard variants of the original VARB shape for special scenarios. The various shapes are tested in GAIM's scaled testing facilities to confirm and validate the computational data on the devices.

The control gate device, which is fitted after the VARB but before the splitter, is designed to fine tune the dispersed material to provide a better split and in some stations allow biasing of the pipe legs

**Case Study 2 – VARB used to balance coal flow at a North Western Generating Station, Unit 1**

- 220 MW (Online in 1966)
- B&W Opposed Wall Fired Boiler
- 10 B&W EL-76 Mills w/ Two 20" Pipe Outlets each feeding a single LNB
- 20 LNBSs – the configuration is 12 Front Wall and 8 Rear Wall
- Fuel - North Dakota Lignite

The plant had numerous issues with fuel preparation, delivery, and combustion resulting in poor efficiency and combustion byproduct problems. Fuel balance is major one factor. In 2007 GESI was asked to look at two of the worst performing mills with regard to pipe-to-pipe fuel balance by supplying two VARB assemblies for installation on mills.

The Plant had already had installed a Microwave Coal Flow Measuring System to report real-time flow. Mill B uses a two-probe system; Mill H uses a three-probe system. This Coal Flow Measuring System was used to set the position of the Control Gate blades to fine-tune the coal flow balance.

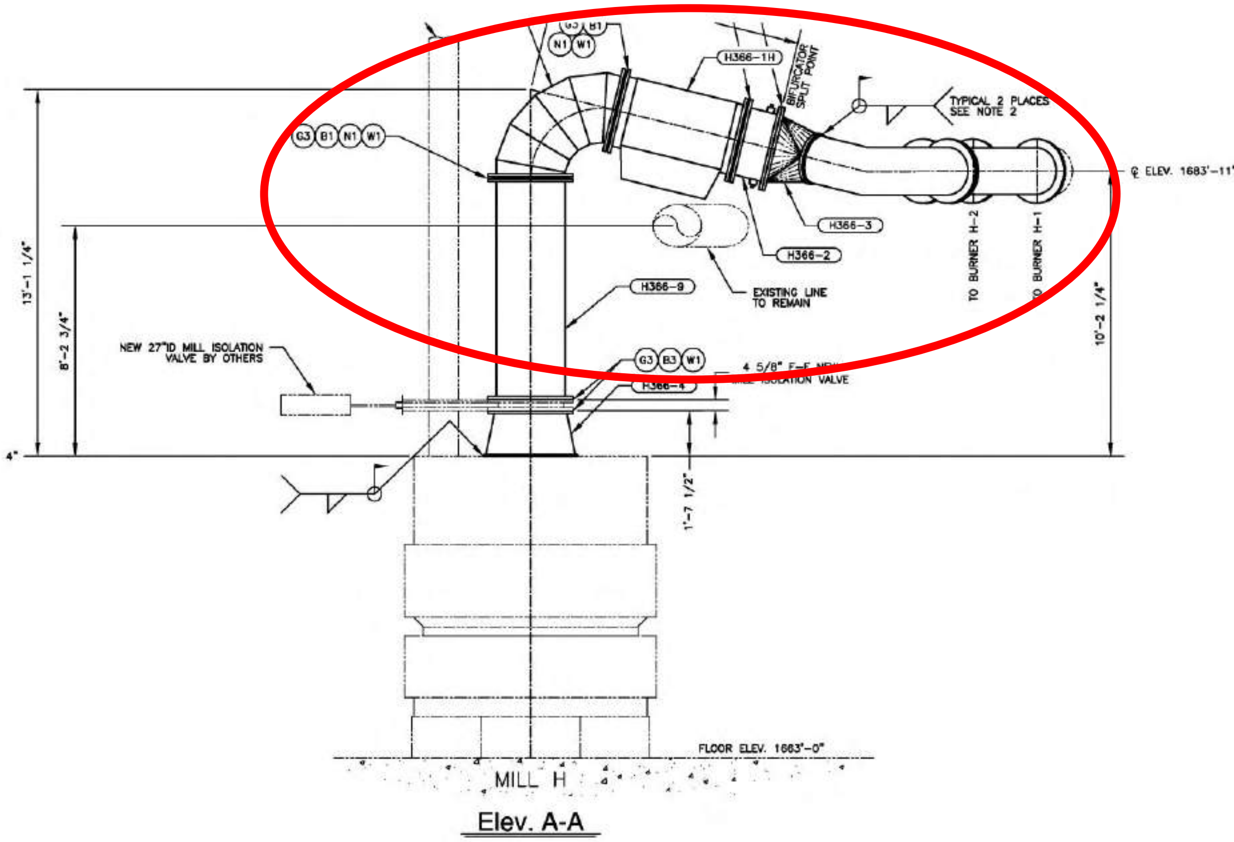



**Figure 6 – Mill H VARB layout**

During commissioning of the GESI supplied VARB coal flow balancing system the commissioning team encountered a problem with the balancing for Mill H, the coal flow balance on this 2 way bifurcation could not be trimmed to a perfect 50-50 balance which marked the first time this has ever happened. See below the burner line H1 in red and burner line H2 in blue. In the past the VARB technology was able to be manually adjusted for a 3 way splitting application to a 33.3-33.3-33.3 balance and a 4 way split application to a 25-25-25-25 balance for a single mill load condition which are considered more difficult.

The following DCS Screen Shots shown below in Figure 7 document the balancing results achieved during the first day of commissioning for the VARB coal flow balancing system. As can be seen only a 48 percent – 52 percent split was achieved at a steady mill operating load.

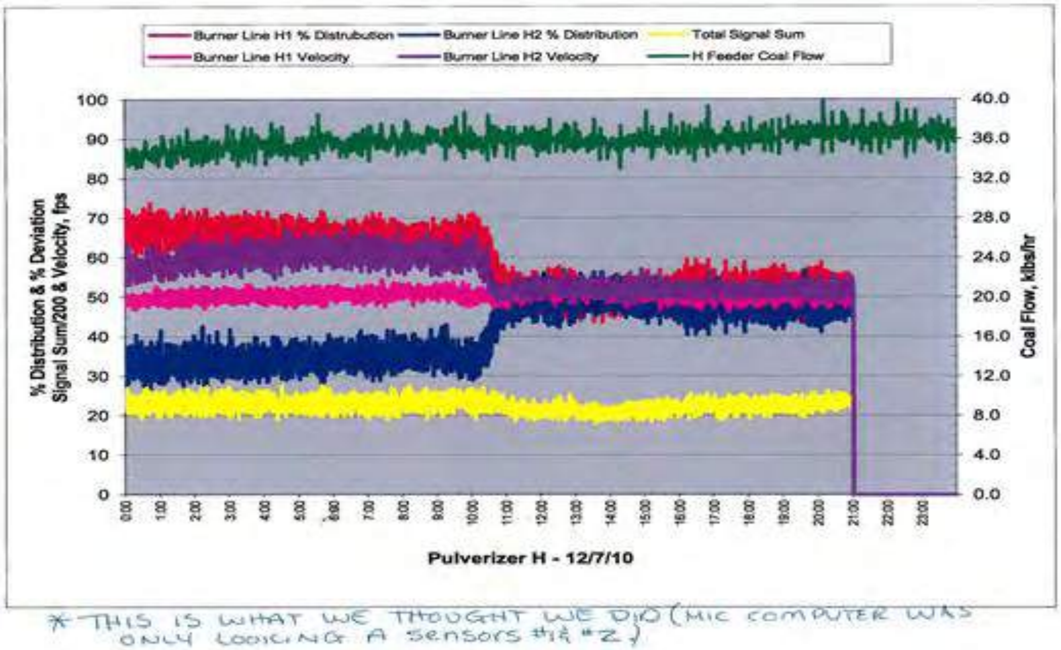
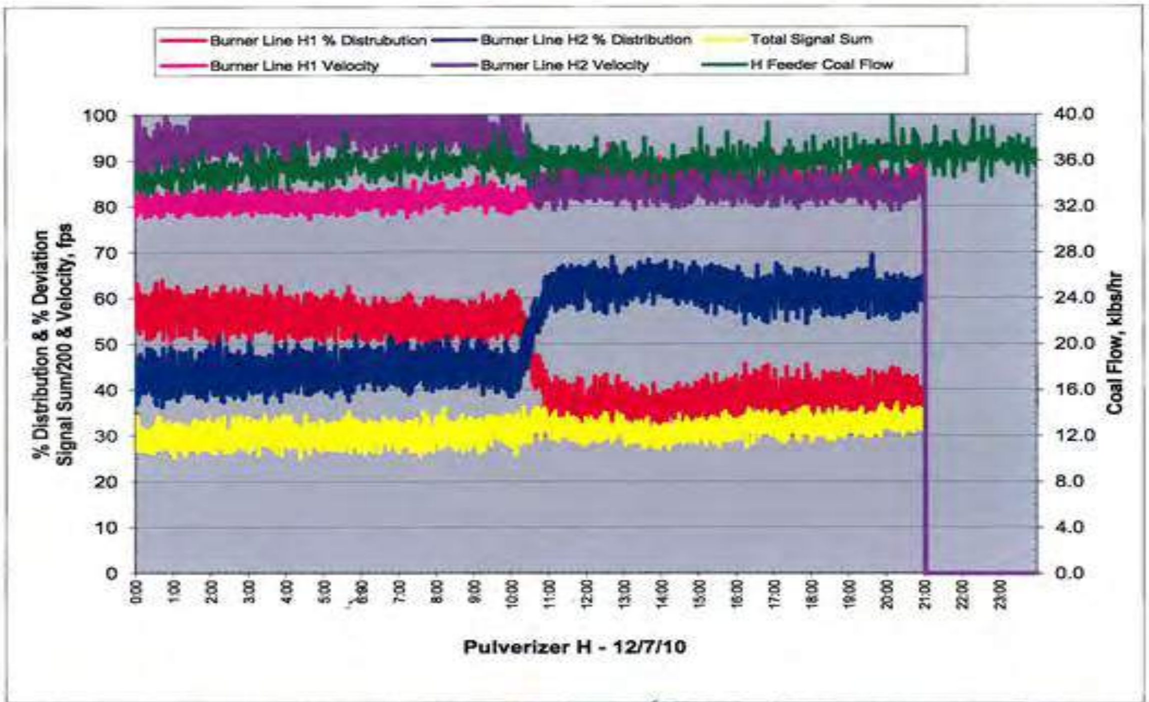



**Figure 7 – Tuning Results Based on a Single Axis Measurement**

This plant had a microwave absorption technology coal flow measurement system installed on Unit 1 before the project was started utilizing VARB technology balance the coal flow.
The microwave absorption technology installed at Leland Olds is axially sensitive due to the polarization of the microwave signal from a transmitter and the receiver and has a blind spot 90º to the orientation to the axis pair. Therefore this technology must always be installed in two axis X&Y of the coal pipe so second receiver located 90º will allow the measurement of the entire pipe cross section vertical and horizontal.

In this case the microwave absorption technology was supplied with biaxial (X&Y) measurement however the equipment output was set to display only a single axis (X) of measurement but this information was not available at the time of the commissioning.




* THIS IS WHAT WE ACTUALL DID. (FROM MIC DATA USING ALL THREE (3) SENSORS.

**Figure 8 – Tuning Results Based on a Single Axis Measurement**

The error was corrected and the data for both X&Y was used in the above Figure 8 chart which shows the results. It became very obvious the commissioning team over corrected the coal flow balance for this mill H due to this poor coal flow measurement. The lesson learned in this case was make sure that any on-line coal flow measurement technology that is being used in accordance with the manufactures' specifications for installation and operation. Obviously, if the coal distribution was left not corrected there would be no combustion optimization benefit to the boiler.

## Case Study 3 – A Canadian Power plant , Units 2 & 4

- Plant capacity 8 x 500 MW
- VARB installation 2006 Unit 2 Mill A
- VARB installation 2007 Unit 4 full boiler set
- 5 B&W UK 10E10 pulverizer mills, 40 LNBs per unit opposed-fired
- Two 28-inch outlets exit the mill each quadrifurcating to four 14.25 in.
- Furnace coal blend
  - 80% Power River Basin
  - 20% Central Appalachian

The typical plant piping configuration is shown in Figure 9. A venturi was placed in front of the 4-way splitter aid to distribution. However, predictive fuel distribution modelling suggested this venturi design was not aggressive enough to disperse the rope. Physical and computational models as well as field measurements confirm that the rope quickly reforms on the outer wall[8].

The Normalized Distribution of the Pre-VARB results in two of the four outlet pipes being heavily loaded with pf. Table 2 shows the results of physical modeling for Unit 2 mill A. Pipes 3 and 4 and graphically in Figures 10 & 11 in this example are located above the outer radius of the inlet pipe elbow. [7]

**Table 2 Typical Baseline Pulverized Fuel Distribution**

| PF Distribution | Pipe 1 | Pipe 2 | Pipe 3 | Pipe 4 |
|---|---|---|---|---|
| **Normalized Distribution Pre-VARB,%** | 49 | 62 | 138 | 152 |
| **Normalized Distribution Post-VARB, %** | 98 | 96 | 97 | 109 |

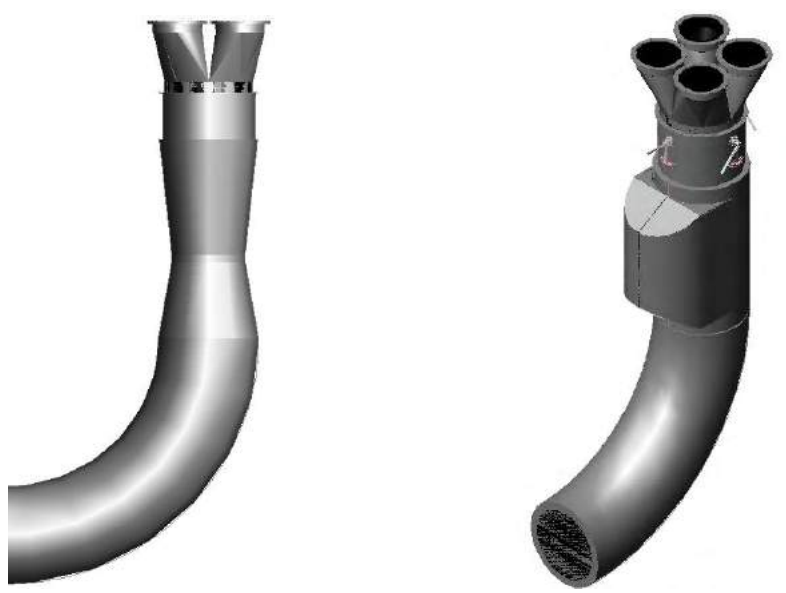
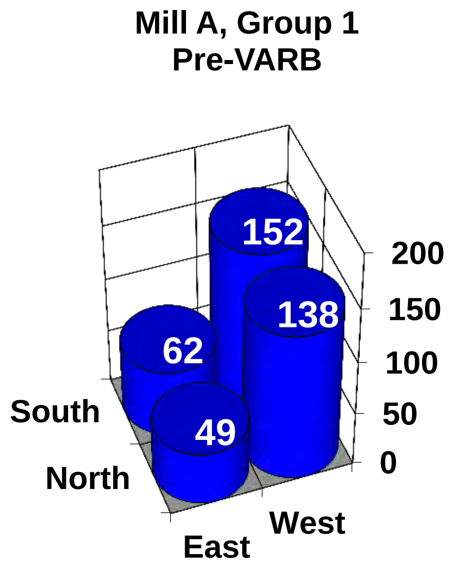


**Figure 9: Original Arrangement and VARB of the plant's PF Distributor**



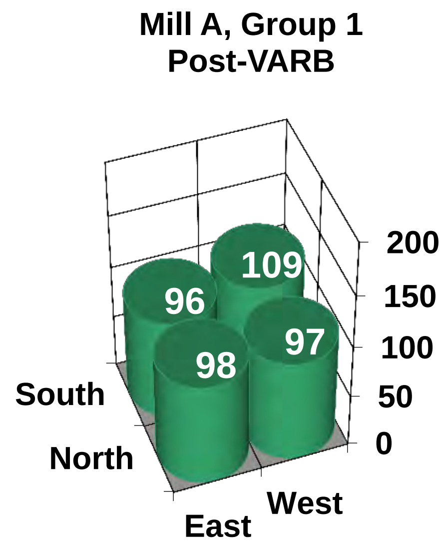




**Figure 10-Typical pre-VARB Balance**

**Figure 11 Typical post-VARB Balance**

These B&W boilers have 3 rows of 8 burners on the front wall and 2 rows of 8 on the rear wall as shown in Figure 12 below.

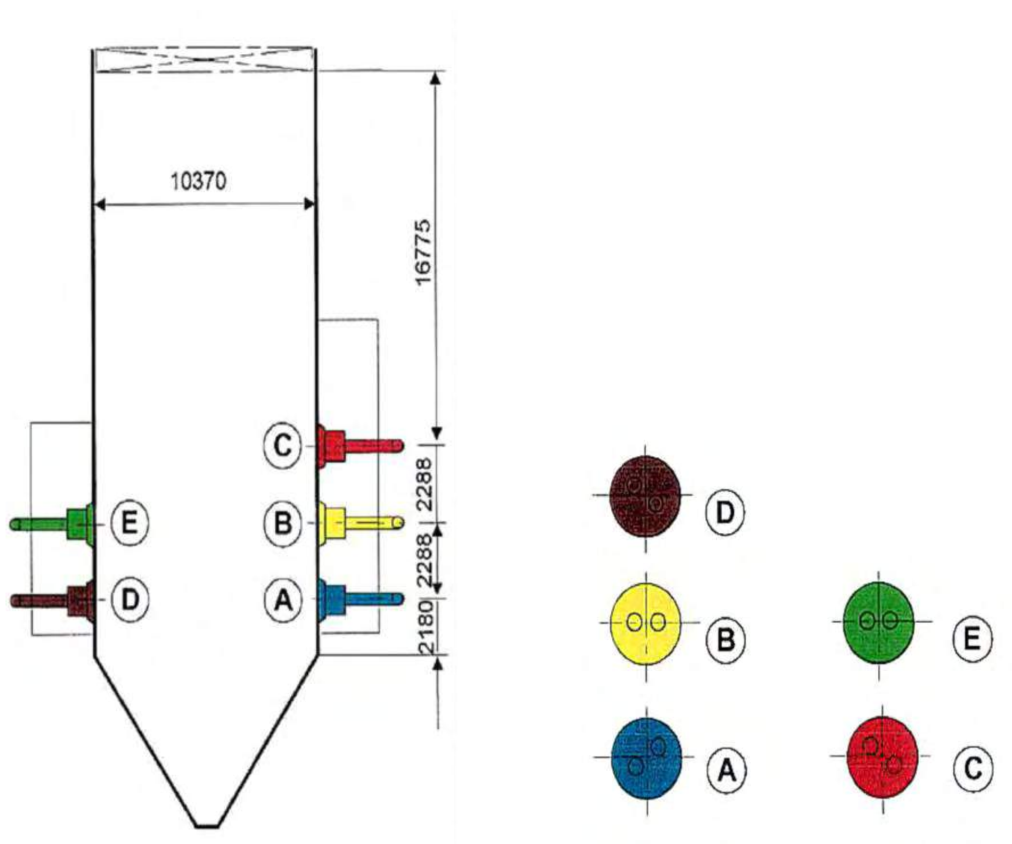



**Figure 12 The Burner Configuration**

There were two different projects a year apart at the plant and the first project was on a single mill in 2006 to prove the technologies worked as advertised. The coal flow measurement system (PfMaster) and the coal flow control system VARB were selected. The goal was that the control system had to be set and then the mill loading was incrementally varied between 50, 60, 70, 80, 90, and 100 percents loading with the coal flow balance must be maintained an RMS deviation of less than 10 percent without making any adjustments to the VARB's control gate during the change in mill loading. It is important to note that the PfMaster system in addition to being used to verify the coal flow balance for the test it was also utilized to monitor the pulverized coal's velocity to ensure the velocity did not drop below 3000 fpm during low mill loading.

As a result of the successful 2006 demonstration of the VARB technology on Unit 2 mill A. the station's team installed a full boiler set of H-VARB on Unit 4 in Fall 2007 and commissioned in July 2008.

Due to budget restraints no coal flow measurement system was installed on this 2007 installation of this full boiler set VARBs on Unit 4, and as a result fine tuning was not done. However the below Combustion results were achieved in spite of the coal flow not being fine-tuned:

- 10% reduction in $NO_x$ (20 ppm @ CO 50ppm).
- More importantly low load flame stability without gas flame support was achieved on the unit 4 installation[8].
- Both project objectives were deemed a success by the client.

**Case Study 4 – A Northern Midwest Generating Plant, Unit 3**

- The Plant's staff commissioned GSEI in 2010 to balance the coal distribution out of the four mill exhausters
- Before this coal flow balancing project Unit 3 had to be shut down every two weeks to clean of heavy slag clinker which formed on the superheater.
- Plant engineers felt that gross mal-distribution of air and fuel to the burners was in part the cause of the slag formations.
- The utility I started to re-power the plant's two remaining coal-powered units (Units 3 and 4) to natural gas in 2016
- Unit 3 - 108 MW was put on line in 1955
- Unit 3 consists of 2 mills feeding 2 exhausters with 2 levels of 4 burners for 8 in total.

Before and after coal flow analyses was not available. Data from several years earlier was used to make the determination of the coal maldistribution being one of the root causes for the extreme slagging coupled with the coal the plant was burning at that time.

After the installation of the VARBs the forced outage due to slag formation was extended to 3 months. Interestingly this was achieved without optimizing the coal flow balancing by fine tuning with the control gate which needs a coal measurement for adjustment. Therefore, the control gates were left the neutral position and not optimized. Figure 13 and Photo 2 show the VARB, Control Gate and splitter configuration.

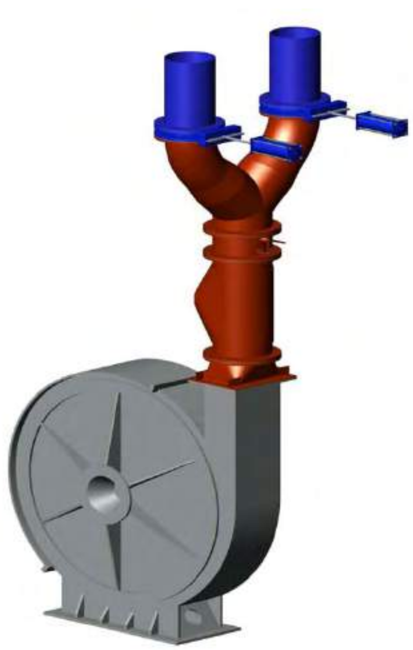


**Figure 13 - VARB Configuration** **Photo 2 - VARB, Control Ggate, and Splitter**

**Background CoalFlo® Dampers for Multi Outlet Mill Applications -** Balancing the flow of pf in this case coal from multi-outlet mill classifiers is generally hindered by differing pressure drops across the multiple pipelines which convey pf to the burners. As each pipeline takes a different route to the boiler and connects to a different burner, it is inevitable that some pipelines will be longer than others and some will have more complex changes in direction.

Assuming the mill classifiers are performing well and the piping system is well maintained, the air and finer pf will take the easiest route out of the classifier, this being the pipeline with the least resistance (pressure drop). It can also be deduced from this that adding further flow resistance can be used to redirect or redistribute finer pf. Changes in the load, fuel type and particle size, plus deterioration (wear and tear) of the piping system, valves, milling and classification plant, can each affect the pressure drop in any particular pipeline.

Orifice plates work on Bernoulli's principle, i.e., an increase in the speed of a fluid occurs simultaneously with a decrease in dynamic pressure. Predetermining the pressure drop between mill outlets and burner inlets for each pipe route allows for deficits in terms of pressure drops to be identified. These deficits can then be corrected by using Bernoulli's equation to determine the area and hence diameter of an orifice that would create the needed added on pressure drop in the pipe route. Predictive fuel distribution or CFD modelling can be utilized to simulate the flow through the pipe, and determine pressure drops more accurately as it takes into account turbulence and also fuel flow through the pipe. The CFD model can be validated against the plant existing performance data.

CoalFlo® dampers work on the same principle as an orifice plate but the pressure drop for balancing can be dynamically adjusted. The ability to dynamically adjust pressure drop using a CoalFlo® damper gives it a significant improvement compared to standard orifice plates if the flow dynamics are in flux.

**Figure 14 -Typical CoalFlo® PF Balancing Dampers**

**Figure 15 CoalFlo® PF Balancing Dampers Details**

**Case Study 6 – A Chinese Power Station, Unit 7**

- 600-MW subcritical, opposed-fired boiler
- Bituminous coal
- Six vertical spindle mills each with five outlets, each of which was fitted with a CoalFlo® balancing damper

In 2012, following design and engineering, GESI supplied new CoalFlo® balancing dampers on Unit 7 mills. These were used as part of an integrated control system using advanced monitoring equipment and technology. Upon evaluation, the CoalFlo® dampers used in conjunction with a PfMaster measurement system contributed to an improvement in boiler efficiency of 0.3 – 0.8 percent and reduced $NO_x$ emissions by 16 to 25 percent.

The CoalFlo® damper blade design was unique and CFD and was used to ensure pressure drops in the pf lines could be adjusted and to allow the fuel flow to be balanced. A damper was installed on all of the 30 outlets from each mill and each mill was trimmed to balance the pulverized fuel flow.

The damper specification was:

- Improved PF distribution from multi outlet mill +/-7.5%
- Ability to bias coal between legs by up to 25% if required (+/-12.5%)

Therefore, the damper tests were divided into three tests:

- Ability to bias coal between legs by -12.5%
- Ability to bias coal between legs by +12.5%
- Improve pf distribution from multi outlet mill +/-7.5% from the mean.

**Test 1: CoalFlo® PF Balancing Dampers Ability to Bias Coal between Legs by -12.5% -**
The test was carried out initially on Mill E because the station had only 3 mills available. Mill E was selected at random.

Test Procedure:

- The E Mill coal feeder was set to manual mode, 46 tph (Station operation engineer put the feeder into 46 tph according to the boiler load at that time.) at 10:22. On Mar 19, 2014
- Recorded time and action; waited for one hour to let the E mill settle down.
- E5 had the highest mass split percent which was around 25%, so closed the E5 damper down to 0° at 11:24.
- Recorded time and action; waited for E mill to settle down.
- Return E5 dampers to 42°.

From the below Table 3, the mass split percentages in the rest of four legs were increased and the mass balance among the five legs was improved.

**Table 3 - E Mill Average Mass Split Percentage Comparison Before and During Test**

| Damper | E1 | E2 | E3 | E4 | E5 |
|---|---|---|---|---|---|
| Before Test, % | 20.62 | 18.32 | 18.24 | 17.25 | 25.58 |
| During Test, % | 21.36 | 20.36 | 18.50 | 19.59 | 20.19 |

**Test 2: CoalFlo® PF Balancing Dampers Ability to Bias Coal between Legs by +12.5% -** The test was carried out initially on Mill D because the station had only 3 mills available. Mill D was selected at random.

Test Procedure:

- The D Mill coal feeder was set to manual mode 50.5 tph since this was the availability at 09:45, Mar 18, 2014. Fully opened all five dampers.
- Recorded time and action; waited for one hour to let the D mill settle down.
- D4 had the lowest mass split percent, so closed the D1, D2, D3 and D5 damper down to 30° at 13:45 and then fully closed D5.
- Recorded time and action; waited for D mill to settle down.

**Table 4 - D4 Mass Split Percent Increasing**

| | D4 Mass split % | D4 Mass bias % (movement from the mean) |
|---|---|---|
| D1, D2, D3 and D5 fully open, % | 17.53 | 18.31 |
| D1, D2, D3 and D5 fully closed, % | 20.74 | |

As shown in Table 4 above, before closing D1, D2, D3 and D5, the average mass split percent in D4 was 17.53 percent. After closing D1, D2 and D3 down to 30° and D5 to 0°, the mass split percent in D4 gradually went up to 20.74 percent. That means the mass split percent in D4 leg was increased by 18.31 percent. It was noticed that on test 2 the mill balancing was nearly possible in making these changes.

GSEI undertook the same procedure to obtain the results.

**Test 3 - CoalFlo® PF Balancing Dampers Improved PF Distribution from Multi Outlet Mill +/-7.5%**

Test Procedure:

- The D Mill coal feeder was set to manual mode 50.5 tph at 09:45. Last damper position change on D mill was at 15:00. All five leg's dampers were fully open.
- Closed the D1 and D2 dampers down to 40° at 14:18 and then fully closed D5.
- Recorded time and action; waited for D mill to settle down.

**Table 5 - CoalFlo® Dampers Balanced D Mill**

| Damper | D1 | D2 | D3 | D4 | D5 |
|---|---|---|---|---|---|
| Before test, % | 20.97 | 20.01 | 19.07 | 17.86 | 22.09 |
| After test,% | 20.21 | 20.74 | 20.00 | 18.92 | 20.14 |

It can be seen from the Table 5. Dampers Balanced D Mill, by closing down D1, D2 and D5 dampers, the mass split percent in the five legs were improved and they were all within the +/-7.5 percent balancing aim for 35 minutes. Boiler load changed at 16:56 which affected the Primary Air and feeder's load. The boiler load created out of balance in the pf on D Mill.

From the Test 1 and Test 2, by closing/open dampers on Mill E and D, the mass split percent in E5 and D4 were biased -17.70 and +18.31 percent, respectively. These results proved the dampers have the ability to bias coal between legs by up to 25 percent (+/-12.5%).

Test 3 results proves that by adjusting the dampers positions, pf distribution from multi outlet mill provides mass splits percentages within +/-7.5 percent.

**Table 6 – Test 3 Results**

| Test | Name | Results | Within Criteria |
|---|---|---|---|
| 1 | PF Balancing Dampers Ability to Bias Coal between Legs by -12.5% | E5 Mass decreased from 25.58% to 21.06%, biased by -17.70%. | Yes |
| 2 | CoalFlo® PF Balancing Dampers Ability to Bias Coal between Legs by +12.5% | D4 mass increased from 17.53% to 20.74%, biased by +18.31%. | Yes |
| 3 | CoalFlo® PF Balancing Dampers Improved PF Distribution from Multi Outlet Mill +/- 7.5% | Mill D mass split % were within+/-7.5% balancing aim for 35 minutes. | Yes |

The results from Test 1, Test 2 and Test 3 prove the CoalFlo® PF Balancing Dampers met the balancing scope in the technical contract and therefore can be utilized to optimize coal flow distribution for a multi outlet pulverizer mill at different loading conditions.

As a result of this test work on this Power Station Unit 7 Mills E & D have the same low load flame stability and a reduction in slagging that has been documented in the previous case studies on coal flow balancing in in-line splitting applications.

**Case Study 7 Northern Mid-Western , Units 1 and 2** – Dynamic classifier (DC) project to improve coal fineness

- Two 750-MW CE tangentially-fired controlled circulation subcritical boiler commissioned in 1976 and 1977, units
- Each unit has seven RP-1003 mills, with 4 outlets each splitting to 8 burners
- Eight pulverized coal pipes from each mill feed one elevation of tilting tangential burners located in the corners of twin side by side furnaces on each unit.
- Each unit can make full load with six pulverizers
- Burning a mix of 8300 Btu Powder River Basin coal (30% Absaloka and 70% Black Thunder ) w/Hargrove grindability index of 52
- In 2014 a retrofit project started consisting of 14 Dynamic Classifier retrofitted for Units 1 and 2
- Both units were kept online during the project while 1 classifier per unit was replaced at a time on a one DC/month schedule.

The State agreed on a settlement in 2015 of 0.15lb/$10^6$ Btu $NO_x$ from the EPA/DER with a 30 day rolling average, starting Jan 1, 2015. The plant's focus was on the mill performance and new optimizer. Before the DC project the previous 6 month average $NO_x$ was at 0.173 lb/$10^6$ Btu just outside of the allowable limit[9]. The plant engineering staff conducted an analysis of mill parameters, verify current operating conditions, analyze variances from design basis, and document changes from original construction in preparation for the DC project. Space available for the installation of the new DCs was very tight (See Photos 3 and 4 below). The engineers hired a contractor to perform combustion study of coal flow pre and post retrofit so they could document the improvement (See results in below in Figure 16).

The post installation Mill $NO_x$ optimization goals were:

- Balance in-line resistance
- Monitor coal flow to each burner
- Improve coal fineness from mills
    - >75% thru 200 mesh
    - >99.9 % thru 50 mesh

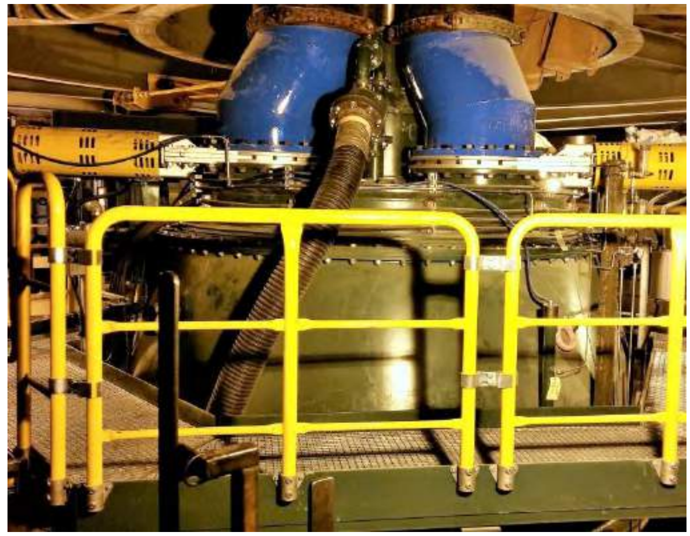
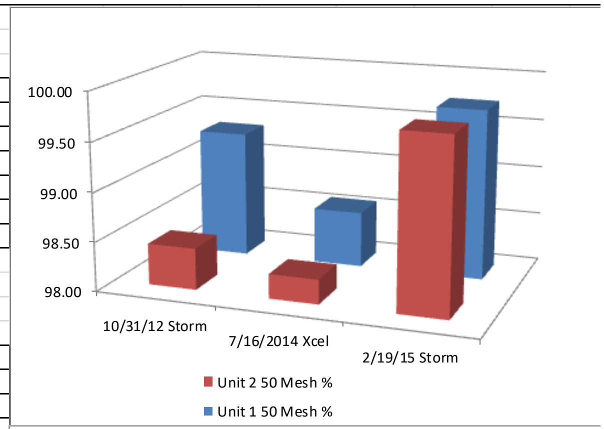


**Photo 4 - Before Retrofit**

**Photo 5 - After Retrofit**

| Unit 1 Fineness Analysis (%) | | | | Unit 2 Fineness Analysis (%) | | | |
|---|---|---|---|---|---|---|---|
| 10/31/12 Storm | | | | 10/31/12 Storm | | | |
| Mill | 50 Mesh | 200 Mesh | Feed Rate | Mill | 50 Mesh | 200 Mesh | Feed Rate |
| 11 | 98.79 | 67.61 | 131 | 21 | 99.5 | 71.35 | 131 |
| 12 | 99.21 | 70.05 | 130 | 22 | 97.65 | 60.27 | 132 |
| 13 | 99.73 | 74.03 | 129 | 23 | 96.93 | 65.33 | 129 |
| 14 | 98.69 | 72.35 | 129 | 24 | 96.89 | 62.31 | 133 |
| 15 | 99.53 | 70.87 | 129 | 25 | 99.5 | 69.22 | 130 |
| 16 | 99.71 | 75.08 | 129 | 26 | 99.4 | 74.92 | 131 |
| 17 | 99.47 | 71.93 | 129 | 27 | 99.09 | 69.92 | 132 |
| **AVG** | **99.30** | **71.70** | | **AVG** | **98.42** | **67.62** | |
| 7/16/2014 Xcel | | | | 7/16/2014 Xcel | | | |
| Mill | 50 Mesh | 200 Mesh | Feed Rate | Mill | 50 Mesh | 200 Mesh | Feed Rate |
| 11 | 97.5 | 67.9 | 130 | 21 | 98.7 | 67.2 | 130 |
| 12 | 99 | 71.1 | 130 | 22 | 97 | 62.1 | 130 |
| 13 | 99.1 | 72.6 | 130 | 23 | 98.7 | 65.3 | 130 |
| 14 | 97.8 | 65.3 | 130 | 24 | 97.5 | 65.8 | 130 |
| 15 | 98.9 | 68.8 | 130 | 25 | 98.9 | 68.4 | 130 |
| 16 | 99.1 | 73.9 | 130 | 26 | 98.7 | 68.1 | 130 |
| 17 | 98.6 | 68.8 | 130 | 27 | OUT | OUT | OUT |
| **AVG** | **98.57** | **69.77** | | **AVG** | **98.25** | **66.15** | |
| 2/19/15 Storm | | | | 2/19/15 Storm | | | |
| Mill | 50 Mesh | 200 Mesh | Feed Rate | Mill | 50 Mesh | 200 Mesh | Feed Rate |
| 11 | OUT | OUT | OUT | 21 | OUT | OUT | OUT |
| 12 | 99.8 | 81.2 | 131 | 22 | 99.8 | 80.3 | 130 |
| 13 | OUT | OUT | OUT | 23 | 99.6 | 71.8 | 128 |
| 14 | 99.7 | 83.4 | 131 | 24 | 99.8 | 80.2 | 131 |
| 15 | 99.8 | 79.5 | 131 | 25 | 99.8 | 80.7 | 130 |
| 16 | 99.7 | 78.9 | 131 | 26 | 99.8 | 78.4 | 130 |
| 17 | 99.7 | 73.1 | 130 | 27 | 99.8 | 73 | 129 |
| **AVG** | **99.74** | **79.22** | | **AVG** | **99.77** | **77.40** | |
| **GOAL:** | **99.9%** | **75%** | | **GOAL:** | **99.9%** | **75%** | |



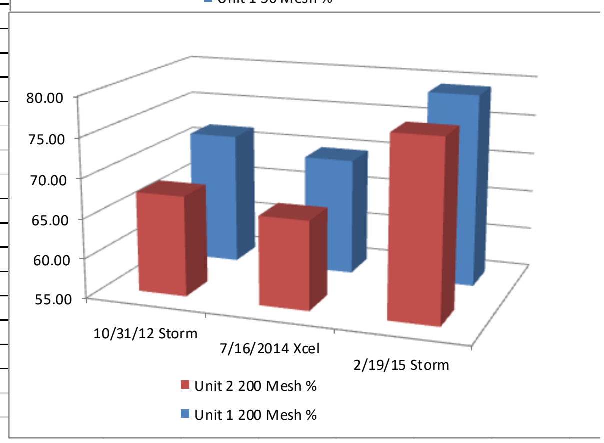




**Figure 16 - Before and After Fineness Results[8]**

The retrofitted DC on average met or exceeded project goals (the exceptions were mills 17, 23 & 27) but absolutely exceeded the manufactures performance guarantees and was an improvement overall when compared to the pre-retrofit performance. The post retrofit resulting fuel flow balance was somewhat less conclusive as the piping configuration four-mill outlet each bifurcating to 2 burners totaling eight pipes was outside the control of this project.

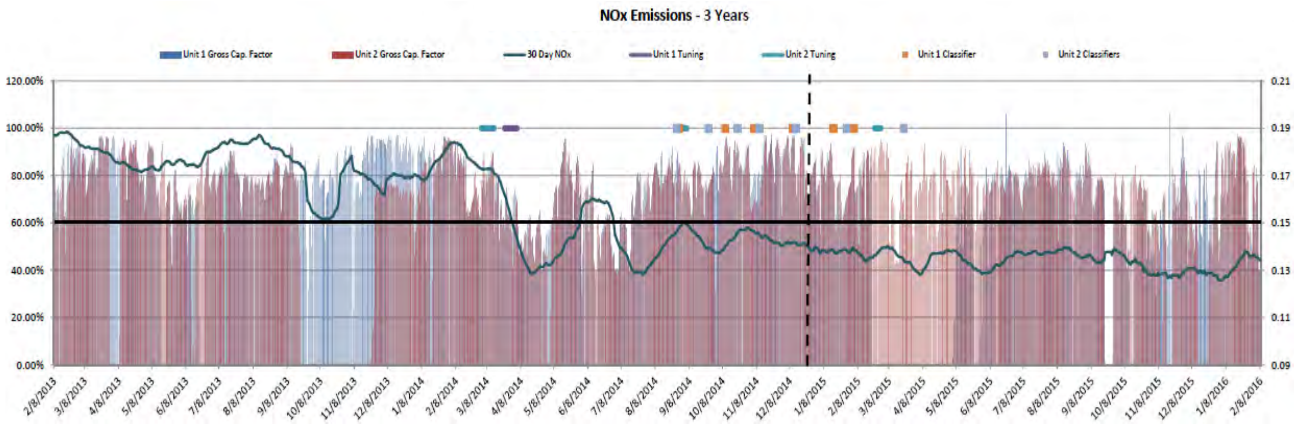



**Figure 17 - $NO_x$ Emissions vs. Unit Load from February 2013 through February 2016**[8]

Final results were U1 NUHR improved 1.93 percent and reduced slagging at burner tips on both boilers along with improved fineness. This allowed stable burn at much lower excess air level and ability to operate in a low mill loading scenario. Overall the project was deemed a success by the client. $NO_x$ emission limit was met before the deadline of Dec 31, 2014[8].

As an example of GESI's and the DC manufacturer's ability of becoming a partner with its customer, This utility joined with GESI during a retrofit of 14 DCs in moving each retrofit DC assembly from the delivery area to the respective mill. Every possible access was blocked by other operating equipment. The best access route was blocked only by a few pumps and piping. Excel staff suggested turning the DC 135 degrees on a jig which cleared the pumps and piping negated removal which would have resulted in a boiler shutdown.

**HEP Dynamic Classifier**

The HEP Dynamic Classifier shown below in Figure 18 has the ability to balance the air/coal ratio in each coal pipe served by a classifier, with externally adjustable guide vanes at the outlet to each coal pipe. The HEP Classifier provides burners with a finer, more evenly ground coal. More precise distribution of the coal particles avoids oversized particles that would otherwise pass, unburned, through the boiler furnace.

Better particle distribution also allows the unit to operate at lower excess air levels and allows greater turndown without auxiliary fuel for stabilization. For proper NOx and combustion control, even distribution of the primary air and coal is essential and it is necessary to control the air/coal ratio to each burner.

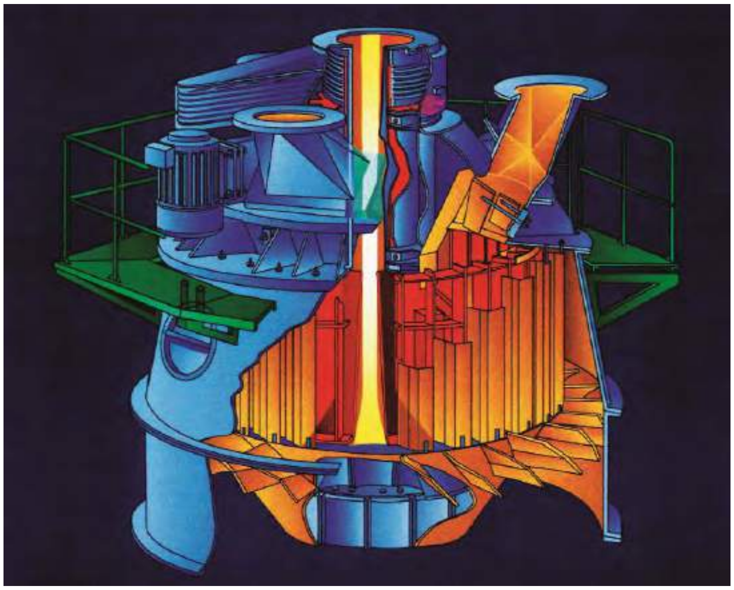


**Figure 18 – General Arrangement of the HEP Dynamic Classifier**

These guide vanes shown below in Figure 19 are designed and positioned to either capture or divert the pulverized coal from entering the outlet.

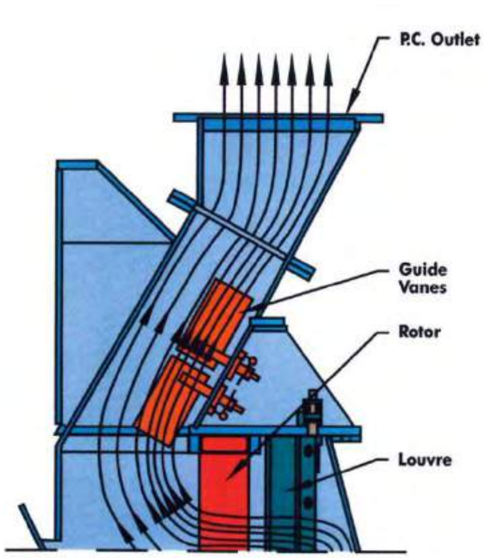



**Figure 19 - HEP coal flow balancing guide vanes**

Field experience has demonstrated that individual coal pipes can be balanced with +-2-5% variation see data from an North Eastern Power Station below Figure 20. Improved particle size distribution, together with more even coal distribution to the burners, produces a more stable flame, reducing the boiler load level where the support fuel must be started. Actual operating experience has shown this to be 10% or more below previous minimum operating levels.

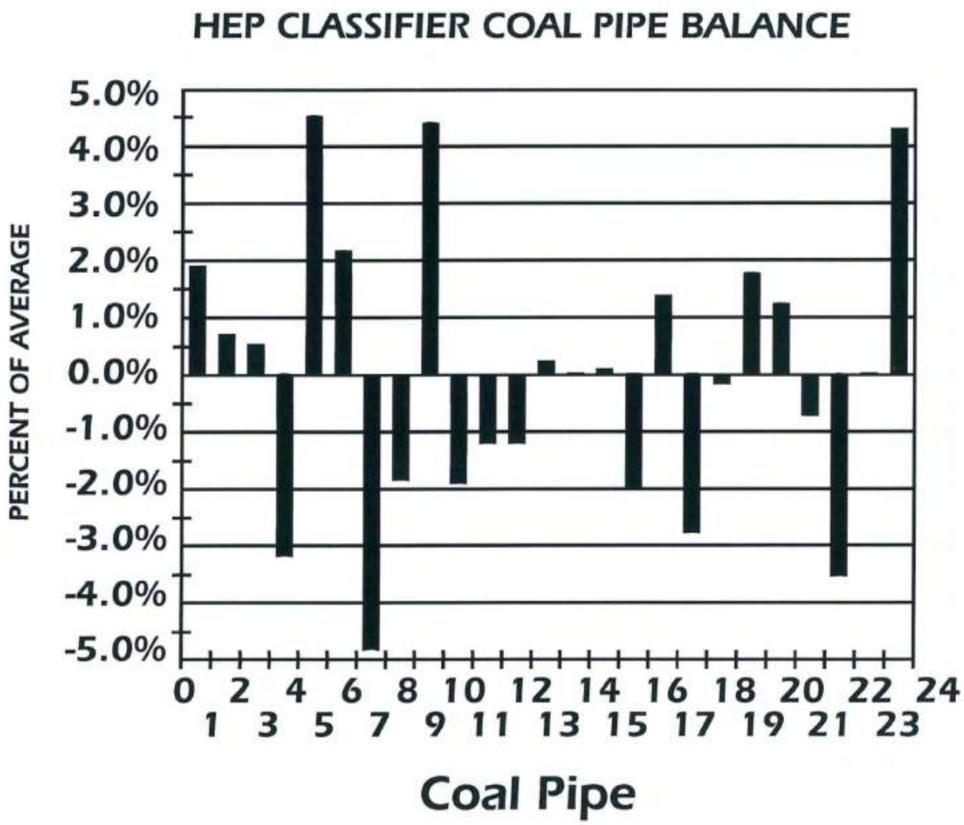



**Figure 20 – Pipe to Pipe Coal flow balance data**

Rotor speed control is provided with a ramp time function that adjusts both the acceleration and de-acceleration of the rotor. This feature creates a temporary difference between the actual rotor speed and the speed demanded by the control system, allowing fast response to boiler load demands.

## Conclusions

Although the challenges for optimizing fuel delivery and enhancing boiler performance can be significant, solutions are available to meet these challenges equipment suppliers including GSEI, and consulting and research organizations, and architect/engineers are ready to assist. The issues covered in this paper clearly show that the challenges are among the greatest ever experienced by the power generating community in these new demanding roles but the community is better equipped with solutions to meet these demands more than ever, and GESI is one equipment supplier that is prepared to assist the coal-fired power generating community with its expertise and experience and determination in these challenging times. GESI is a "can do" supplier and this paper is merely an overview of its capabilities. GESI can do!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