DOE/MC/27339--5310
(DE97002050)

Results of the PDF™ Test Burn at Clifty Creek Station

Topical Report

by
Stephen A. Johnson
Brent Knottnerus

October 1996

Work Performed Under Contract DOE-FC21 -90MC27339

for
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

by
ENCOAL Corp.
10 Miles N. of Gillette
Highway 14-16
Gillette, Wyoming 82716

Disclaimer

TABLE OF CONTENTS

1. INTRODUCTION

Process Derived Fuel (PDF™) from the ENCOAL® process is different from other coals used to generate steam for the power industry. Although PDF™ is currently produced from Powder River Basin (PRB) subbituminous coal, the coal structure changes during processing. Compared to the parent coal, PDF™ contains much less moisture and slightly lower volatile matter resulting in a higher heating value and higher ash per million Btu. Table 1 shows an analysis of the PDF™ shipped to Clifty Creek.

Table 1. PDF™ Analysis, as Received

Proximate, wt%	
Moisture	10.83
Ash	8.34
Volatile Matter	22.77
Fixed Carbon	58.06
Heating Value, Btu/lb	10,682
Sulfur, wt%	0.40

These coal properties can potentially benefit utility boiler performance. Combining the high combustion reactivity typical of PRB coals with significantly reduced moisure should produce higher flame zone temperatures and shorter flames. As a result, some boilers may experience increased steam production, better burnout, or lower excess air. Slag tapping, especially at low loads, should be more reliable when burning PDF™ as compared to raw PRB coal. The increased heat content of PDF™ also means additional pulverizer capacity compared to PRB coal. Where a boiler may be load limited or forced to run all mills to reach rated capacity with PRB coal, a switch to PDF™ will either help regain lost capacity or allow full load operation with a mill out of service. Spare mill capacity is important for base-loaded units because preventative pulverizer maintenance can be performed without losing generating capacity or waiting for mill internals to fail.

The major undetermined boiler performance concern when burning PDF™ relative to raw PRB coal is increased ash deposition on heat transfer surfaces. PRB coal itself can cause a thin calcium-rich ash coating on furnace waterwall tubes. This coating can solidify and reduce the rate of heat transfer to raise steam. Once the deposit hardens, it can be very difficult to remove by conventional sootblowers. Many units burning run-of-mine PRB coal must operate their sootblowers more frequently to control deposits and maintain boiler performance.

PDF™ could exacerbate the ash deposition problem due to higher furnace temperatures. Increasing upper furnace temperatures could sinter the deposit faster, requiring even more sootblowing. If furnace exit temperatures increase as a result of ash deposits, fouling of convective pass tubes could also increase. Reheater deposits could be troublesome in some units where tube spacing is narrow and sootblower coverage is inadequate, resulting in plugging the gas passages. Slight plugging may be tolerable, but eventually airflow limitations will require derating the boiler capacity or the unit must be taken offline for cleaning.

High furnace temperatures tend to propagate all the way to the stack. High cold-end temperatures (air heater outlet gas temperatures) represent a significant heat loss and boiler efficiency penalty. In addition, higher gas temperatures increase flyash resistivity in cold-side electrostatic precipitators and thus contribute to degraded electrostatic precipitator performance and higher stack opacity. With some burner types, higher furnace temperatures can also increase NO_x emissions, but lower NO_x is also possible with PDF™ in low-NO_x burners and other low-turbulence burner designs where improved ignition stability can reduce NO_x.

It should be evident from this discussion that temperature measurement is key to understanding and quantifying the impacts of PDF™ on boiler performance. The critical temperature to measure is the furnace exit gas temperature (FEGT) because it is a direct measure of the balance between steam production in the furnace and steam heating in the convective pass. Changes in FEGT result from changes in fireball location (heat release rate) or changes in slag coverage or thickness (heat absorption rate). In either case, FEGT serves as a direct comparison of two fuels fired in the same boiler.

At the Indiana-Kentucky Electric Corporation (IKEC) Clifty Creek plant, the ENCOAL® PDF™ was blended with Ohio bituminous coal and burned over a 1-week period. The amount of PDF™ in the blend was increased from 70% to 80% to 90% by weight as the test burn progressed. Blending PDF™ with high-sulfur Ohio coal was performed in order to maintain the same amount of SO_3 in the flue gas for efficient precipitator operation. The Clifty Creek environmental regulations require opacity levels below 40%. The initial 70% PDF™/30% Ohio coal blend contained roughly the same amount of sulfur on a lb/MBtu basis as the baseline coal blend.

The objective of the work contracted to Quinapoxet Engineering was to quantify the impacts of burning PDF™ on boiler performance at Clifty Creek Unit #3. A unique optical temperature monitor called SpectraTemp® was used to measure changes in FEGT with time and boiler operating parameters for both the PDF™ blends as well as a baseline coal blend consisting of 60% PRB coal, 20% Ohio coal, and 20% low-volatile eastern bituminous coal from Virginia. FEGT was then related to net plant heat rate, NO_x emissions, and electrostatic precipitator performance. The sections that follow explain the test scope in more detail, provide the Clifty Creek results, and draw conclusions concerning the viability of ENCOAL® PDF™ at Clifty Creek as well as other pulverized coal-fired wet-bottom boilers.

2. TECHNICAL APPROACH

2.1 Boiler Description

Clifty Creek Unit #3 is a Babcock & Wilcox Open Path boiler installed in 1954. The unit was designed to produce 1,340,000 lb/h of steam at 1050 F and 2075 psig, but is routinely pushed to over 1.45 million lb/h to produce 232 MW (gross). A sectional sideview of the unit is shown in Figure 1. Seven B&W EL-70 pulverizers supply pulverized coal to 14 B&W crosstube burners arranged in three elevations on the front wall of the primary furnace. The boiler is designed for slag-tap operation. Therefore the primary furnace is lined with studded refractory and the burners aimed downward toward the slag pool that drains from the back of the primary furnace.

Flue gas passes upward through the primary furnace and then downward through the open pass section. The open pass contains 10 waterwall sootblowers, five on each sidewall, arranged vertically about 9 ft apart. These sootblowers are hardly ever used because removing ash deposits can decrease superheated steam temperature by 50 to 100 F according to Mike Doherty at AEP Services Corp.

Flue gases then turn upward again to enter the convective pass. Flue gas recirculation to the open pass was originally used to control superheat and reheat steam temperatures by reducing FEGT, but the flue gas fans were removed long ago. To compensate for this change in heat balance, about half of the primary furnace refractory was removed. Long retractable sootblowers are located on the rearwall and both sidewalls to remove deposits from the screen tubes and convective sections.

Gases then pass upward through a Ljungstrom air heater and a new electrostatic precipitator to the stack. Flue gas from Units 1, 2, and 3 is vented to a single stack, so it is difficult to determine the impacts of Unit #3 operation on the NO_x emissions measured in the stack. Opacity, however, is monitored at the outlet of each precipitator. The designed cold end temperature (temperature of the flue gas exiting the air preheater) is 299 F at maximum continuous rated (MCR) load.

2.2 SpectraTemp Description

SpectraTemp is a non-intrusive electro-optical instrument that continuously and accurately monitors and reports temperatures of boiler gas streams. It is intended to help an operator or automatic control system maintain the optimum temperature distribution in the boiler, thereby optimizing the boiler's overall thermal efficiency by assuring a proper balance between heat absorption in the furnace and convective sections.

With its ability to measure temperatures from 675 to 2900 F, SpectraTemp can be used to continuously monitor furnace exit gas temperature (FEGT) during normal operations as well as during start-up or shutdown, plus it can monitor gas temperatures in superheater and economizer sections. Three different modes of installation and application are envisioned in the instrument design.

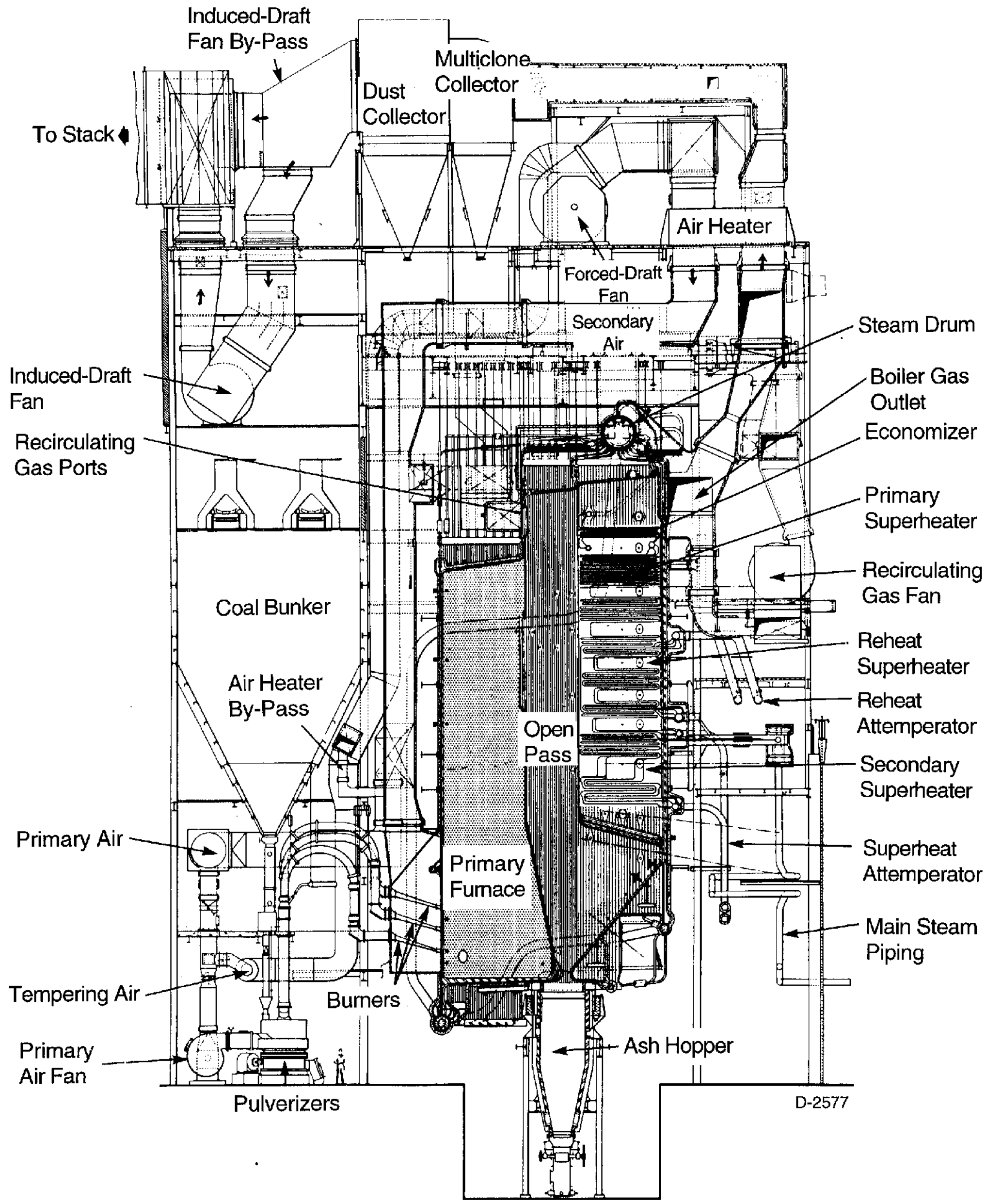


Figure 1. Sectional Sideview of Clifty Creek Unit #3

1) It can be used as a field test diagnostic tool, either as a stand-alone instrument or in conjunction with a personal computer that serves as a local data logger.

2) It can serve as an on-line boiler performance monitor, functioning as an integral part of a larger monitoring and control system.

3) It can serve as an on-line boiler performance monitor, functioning as a stand-alone diagnostic providing read-outs and alarms to existing control room indication and annunciation equipment.

SpectraTemp is based on an innovative application of optical pyrometry. Unlike infrared pyrometers, SpectraTemp detects radiation primarily at visible wavelengths where its accuracy is maximized while minimizing errors resulting from the relatively cool walls that surround the gas. This visible radiation is emitted by the ash particles transported by the exhaust gases, and not by the gases themselves. Since the ash particles are typically smaller than 30 μm in diameter and thermally equilibrate with the surrounding gas in a few tens of microseconds, their temperature accurately reflects the local gas temperature.

The SpectraTemp instrument is illustrated schematically in Figure 2. An optics tube collects radiation emitted by the hot particles contained within a narrow field of view. That radiation is projected onto a fiber optic bundle which carries the radiation to a group of photodetectors. An optical filter is placed in front of each photodetector to limit the detected radiation to a specific narrow band of wavelengths. The photodetectors convert the incident radiation into measurable voltages, which, after amplification, are digitized and supplied to an internal microprocessor. The microprocessor has been pre-programmed to utilize the information to calculate the temperature of the ash cloud.

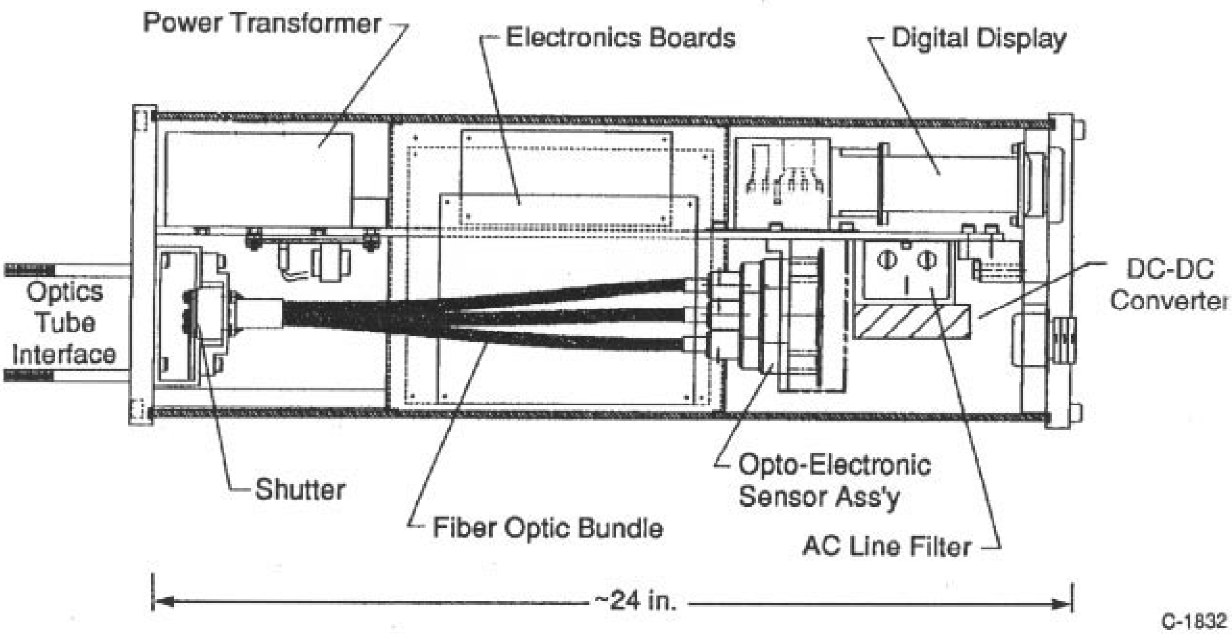
Temperature updates are provided approximately once every 4 s. The SpectraTemp algorithm incorporates a unique proprietary feature that disregards rapid fluctuations in the particle emissivity, yet accurately and rapidly responds to gas temperature changes that affect boiler operation. Special algorithms can be supplied to suit specific customer needs.

The instrument measures 24 in. in length and weighs about 27 lb. An air-cooled lens tube is mounted in any standard furnace viewport having a diameter of 2 in. or larger. For permanent installations, the lens tube is inserted several inches into the furnace so that the instrument doesn't require periodic port cleanout to function. Installations have operated unattended for over two years. For short term boiler performance testing, the lens tube can be recessed inside the viewport and still provide accurate and reliable readings.

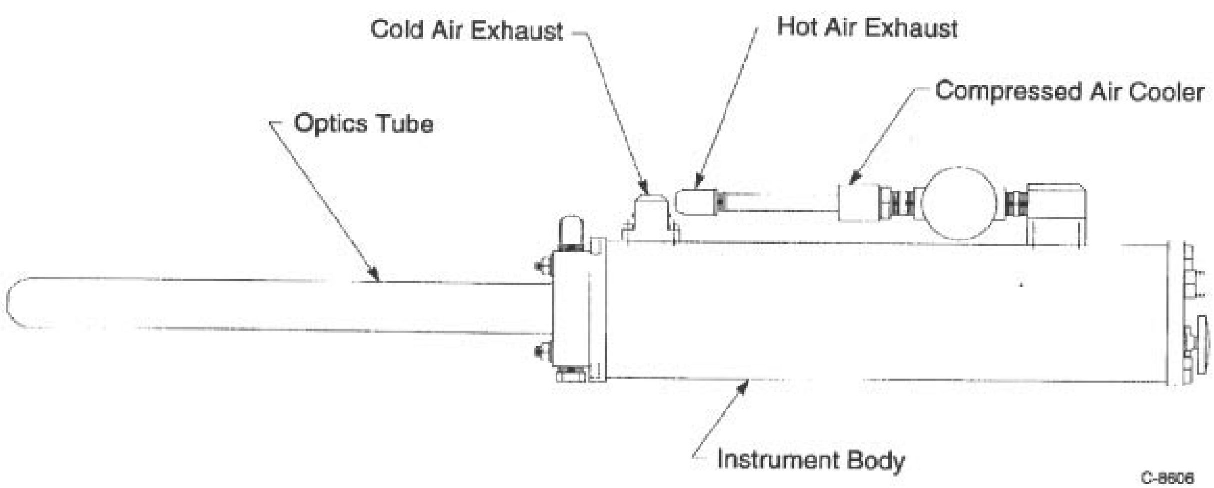
The SpectraTemp was shipped to Clifty Creek with the following components:

- 1 SpectraTemp optical temperature monitor
- 1 optics tube assembly
- 1 18-pin interface cable (10 ft)
- 1 operators manual
- 1 installation kit.

The test unit also included a filter set to remove moisture and oil from the compressed air needed to cool the instrument optics. Airflow to the SpectraTemp was regulated by a pressure gauge, and two 6-ft long fire-resistant hoses (one 3/8 in. and the other 5/8 in.) connect the

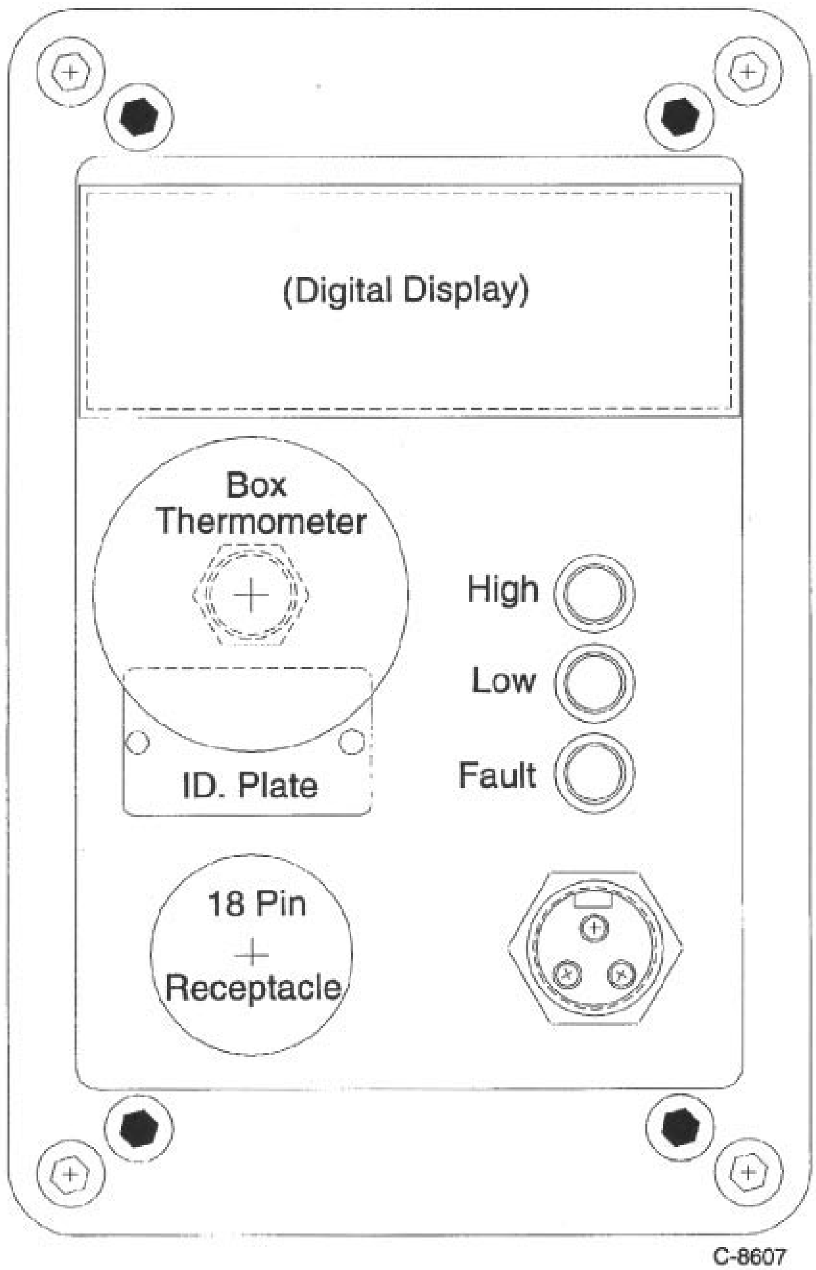


(a) Internal Assembly



(b) External Assembly

Figure 2. Schematic Illustrations of SpectraTemp



(c) Back Panel

Figure 2. Schematic Illustrations of SpectraTemp (continued)

SpectraTemp flair fittings to the filter. All the above equipment was delivered to the test site by Quinapoxet Engineering. Clifty Creek personnel supplied the hoses, fittings and labor to connect SpectraTemp to the plant air system.

SpectraTemp was mounted in an existing viewport located on the north sidewall about 6 ft below the screen tubes at the control room elevation. The SpectraTemp sight tube was angled slightly upward and outward away from the adjacent hopper slope. Both the instrument and its air filter set were secured to a railing. The plant provided a chart recorder to convert the SpectraTemp 4 to 20 mA signal to a plot of temperature versus time. Thus FEGT could be related to boiler operating variables such as load, mills in service, excess air, or sootblowing sequences.

2.3 Test Scope

The aim of the tests was to compare the baseline coal blend and the PDF™ coal blend under identical boiler conditions. Weather conditions and equipment problems during the baseline tests prevented such a direct comparison.

Baseline tests took place from May 1 at 1600 hours to May 4 at 1200 hours. During this time, mill 3-2 was down for repairs and load was further curtailed by coal feeder problems caused by wet coal. Just prior to the test, the plant had experienced 5 in. of rain over 36 h and the coal yard was flooded. Cloudbursts were prevalent throughout the 10 days of baseline and PDF™ testing.

The PDF™ shipment was also subjected to the same heavy rains as the baseline coal. The PDF™ was shipped to Clifty Creek by barge. The heavy rains occurred both during shipment and while the barges were docked for several days before the test burn started. The PDF™ in the barge was checked several days into the test. Within an inch or so of the pile surface the PDF™ was dry, indicating little water permeability under drenching conditions. The PDF™ stayed dry because the rain was unable to penetrate the top layer of coal.

By the time PDF™ testing began on May 6, mill 3-2 was back in service, although the same mill was purposely removed from service on May 8 to test load capacity of the Unit with only six mills in service. The SpectraTemp was removed at 1500 hours on May 8, but PDF™ was burned through the morning of May 11, 1996.

The test was designated a “go/no-go” test by Clifty Creek personnel. That is, the unit was operated under normal load dispatch while the operators logged any changes in unit operation observed during the test period. No formal boiler performance testing was conducted. However, the following parameters were varied during the test:

- load (190 to 230 MW at steady state)
- excess air (1.7 to 2.6% O_2)
- mills in service (all seven mills versus one mill out of service).

Sootblowing of the open pass waterwalls and convective sections was performed as needed to control steam temperatures and pressure drop across the convective section.

The primary measure of boiler performance was FEGT. Other measures of boiler performance were obtained from control room instrumentation:

- superheater outlet steam temperature (average)
- reheater outlet steam temperature (average)
- reheater attemperator spray flows
- air heater outlet gas temperature
- pressure drop across the convective sections.

Quinapoxet Engineering also recorded observations of the following:

- flame length and ignition distance
- slag tapping
- ash deposit thickness and description at the entrance to the convective pass.

Results and conclusions derived from the data collected are discussed below.

3. TEST RESULTS

3.1 Overview

The boiler performance was different when burning the PDF™ blend compared to the baseline coal burned prior to the PDF™ tests. Table 2 contains a summary of the differences measured or observed during these tests. It should be reemphasized that boiler output was limited during the days when baseline data were taken. Thus we are comparing baseline data at 190 MW to PDF™ data at 230 MW.

Table 2. Summary of Test Results

Plant Section	Baseline Coal	PDF™ Blend
Pulverizers	Coal was wet from heavy rains. Frequent feeder pluggage. Load limited to 190 MW due to wet coal and mill out of service.	Coal was wet from heavy rains. Infrequent feeder pluggage. Max load 232 MW with all seven mills and 228 MW with mill out of service.
Burners	Ignition 1 to 2 ft off the burner deflector blocks. NO_x = 600 ppm @ 190 MW and 630 ppm @ 225 MW. (1.20 to 1.25 lb/MBtu)	Ignition 0 to 1 ft off the burner deflector blocks. NO_x = 490-520 ppm @ 220-230 MW for 6 or 7 mill operation.
Primary Furnace	Slag tapping okay @ 190 MW.	Slag tapping okay @ 220-230 MW. Flame visible at slag tap.
Open Pass	Sootblowing required 1-3 times per week. Boiler exit O_2 = 2.4-3.0%. FEGT = 2120-2180 F @ 190 MW.	More frequent sootblowing required. Reduced excess air to increase heat transfer; O_2 = 1.4-3.0%. FEGT = 2250-2350 F @ 220-230 MW.
Convective Pass	Sootblowing required 1-2 times per shift. Deposits are granular and removable. Reheater pressure drop 5-5.4 in. W.G. Air heater outlet T = 385-390 F @ 190 MW.	Sootblowing required 3-4 times per shift. Deposits appear wet on screen tubes and division wall. Reheater pressure drop 5.2-6.3 in. W.G. Deposits are removable; more ash falls during sootblowing. Air heater outlet T = 400-430 F @ 220-230 MW.
Electrostatic Precipitator	Opacity = 14% @ 190 MW. Opacity = 9-16% @ 200-230 MW.	Opacity = 12-25% @ 200-230 MW.

Plant personnel were especially impressed with the ability to achieve full generating capacity on PDF™ with one mill out of service. The tests afforded the plant time to perform mill calibrations without losing capacity or revenues. At the same time Unit #3 was burning the PDF™ blend with one mill out, Unit #5 (a nearly identical sister unit) was burning the baseline coal with one mill down for repairs. Unit 5 could only reach 208 MW, a difference of 20 MW or 9.6%. The increase in mill output was greater than expected based on the estimated heating value difference between the PDF™ and baseline coal blends. Because this was not a performance test, no pulverized coal samples were obtained to check for differences in coal fineness between baseline and PDF™ operation.

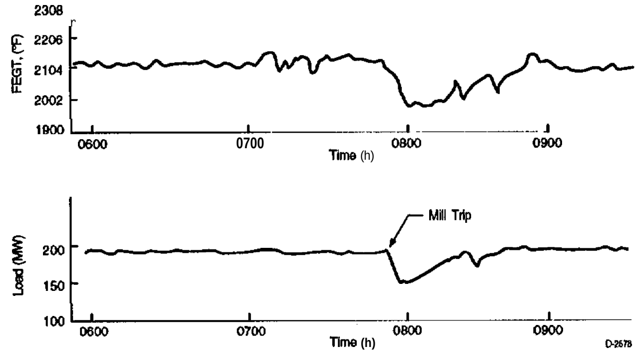
Also noteworthy was a measurable decrease in NO_x emissions when burning PDF™. The NO_x concentrations measured in the stack represent the combined emissions from boilers #2 and #3. Assuming that emissions stay constant for Unit #2, a 0.125 lb/MBtu total NO_x reduction represents a 0.25 lb/MBtu NO_x reduction for Unit #3 on PDF™, indicating a 20% decrease from baseline conditions.

The one concern voiced by the plant operators was an increase in open pass slagging and convective pass fouling when burning the PDF™ blend. Both the amount of deposits and the frequency of sootblowing increased. One reason for the increase in ash deposition is the increase of powder river basin (PRB) coal ash from the baseline blend (60%) to the PDF™ blends (70 to 90%). More PRB ash means more low-melting calcium compounds in the flyash. Since furnace temperatures increased only slightly (10 to 20 F) when burning the PDF™ blends, the change in ash deposition is probably due primarily to changes in ash composition. Deposits were controlled using normal operating procedures during the 6-day test. As with all candidate fuels for Clifty Creek, a much longer test (about six weeks) is required to assess the impacts of ash deposition on unit operability, availability and capacity factor.

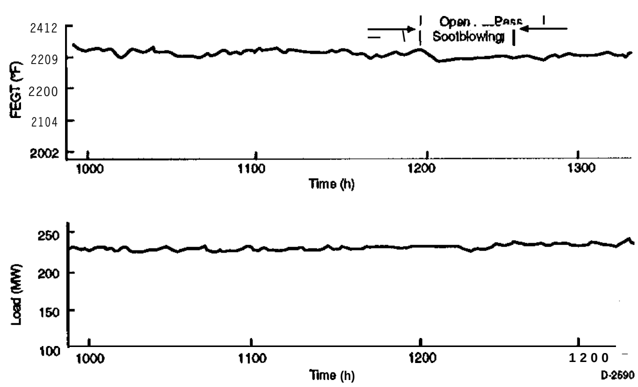
Detailed test results are provided below.

3.2 Boiler Performance

Furnace exit gas temperature (FEGT) is a direct, real-time measure of boiler performance. FEGT measurements were recorded during baseline coal and ENCOAL® PDF™ operation. Figure 3a shows typical FEGT and load versus time traces for the baseline coal blend. Figure 3b shows how FEGT and load varied with time during the PDF™ test period. Both the load and FEGT changes can be correlated to interruptions to the fuel delivery system that caused one or more mills to trip offline. Note that even under steady load conditions, the average FEGT fluctuates by ± 20 F on this boiler. These temperature fluctuations are likely to be caused by fluctuations in the gas flow patterns as the flue gas turns 180 deg to enter the upflow convective pass. FEGT fluctuations are usually no more than ± 5 F in conventional wall-fired or tangentially fired units.



(a) Baseline Coal



(b) PDF™ Blend

Figure 3. Typical FEGT and Load Traces

FEGT at constant load also trended up and down by as much as ± 40 F during these tests. A gradual increase in FEGT usually results from an increase in ash deposit coverage or thickness. Sootblower usage usually drops FEGT immediately as deposits are removed and heat transfer increases.

As discussed later in Section 3.4, deposits on the wall between the convective pass and the open pass became more fluid during PDF™ tests. The fluid deposits were accompanied by a 10 to 20 F increase in FEGT. Since molten deposits at the furnace exit can be an early indicator of reheater ash deposition, plant personnel increased open pass sootblowing frequency.

For Clifty Creek #3, the deposits in the open pass section should most influence FEGT. Only the open pass sidewalls can be cleaned using 10 IR sootblowers. The open pass sidewalls are only 9-ft wide (as compared against the furnace width of about 55 ft). Therefore, the cleanable heat transfer surface in the open pass (assuming 9-ft diameter cleaning circles) is only about 6% of the total surface area. Blowing one sootblower at a time during the PDF™ tests cleaned less than 1% of the waterwall surface. Therefore, it is not surprising that average FEGT did not change much during sootblowing. Therefore, much of the gradual increase in FEGT can be attributed to increased deposit thickness or coverage.

However, sootblowing the open pass had a measurable affect on steam temperature, especially superheat steam temperature. On 7 May all five wall blowers on the south sidewall were actuated between 1200 and 1240 hours. Superheat temperature decreased from about 1025 F to 1000 F after the first blower was used, and further decreased to 990 F after all five blowers had been used. Reheat attemperator sprays decreased from about 40,000 lb/h to less than 10,000 lb/h, partially offsetting the heat rate loss due to lower steam temperature. FEGT decreased by about 15 F after the first sootblower was used as indicated in Figure 3b, but no further change occurred with additional sootblowing. The FEGT data are consistent with the steam temperature observations, given the small amount of surface area exposed during sootblowing.

The operating change with the largest effect on FEGT was boiler load. Figure 4 shows FEGT versus load data obtained during both baseline blend and PDF™ operation. A linear decrease in FEGT as load (heat input) decreases is typical for all boilers. Steady-state data were obtained at 220 to 232 MW with PDF™ and 172 to 192 MW with the baseline blend because these loads represented maximum capacity during the tests. Transient FEGT readings were also obtained at lower loads during baseline tests due to frequent mill trips, but these values are probably lower than steady state values since burner airflows were maintained during the trip.

While it was not possible to compare FEGT at the same load for each fuel, the operators reported that the furnace exit looked hotter during PDF™ combustion. That is, ash deposits were brighter and more molten/glassy at full load with PDF™ than were usually observed with the baseline coal blend. The test crew looked at Unit #5 when both Units #3 and #5 were operating at 230 MW and confirmed the differences in ash deposit appearance on the screen tubes and walls at the entrance to the convective section. (A plan to bring the

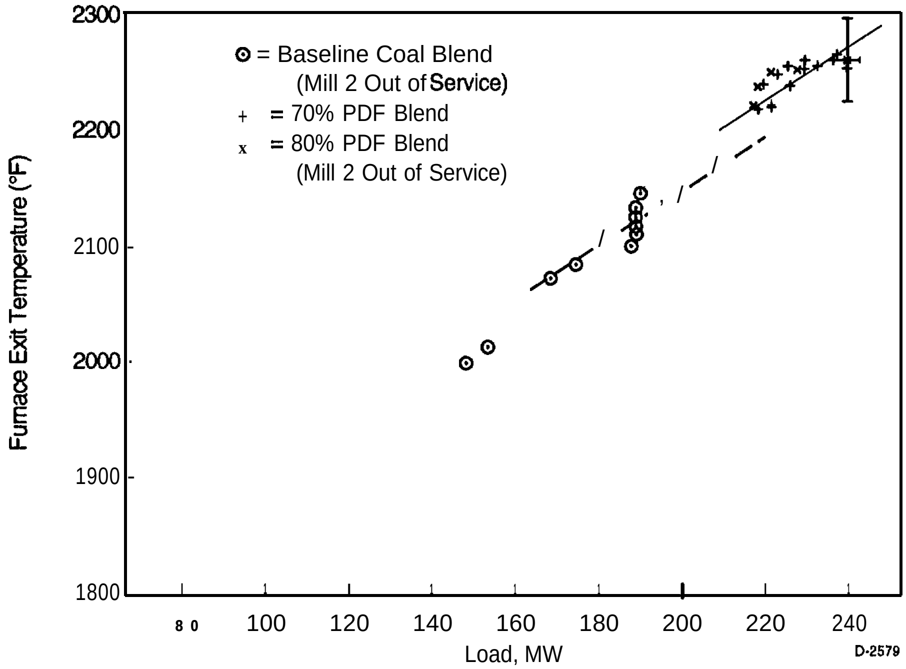


Figure 4. FEGT vs. Load at Clifty Creek #3

SpectraTemp instrument to Unit #5 to measure full load FEGT on the baseline blend was aborted when Unit #5 lost a pulverizer and was limited to 209 MW capacity.)

It is likely that the FEGT is slightly higher with the PDF™ blend (by 20 to 30 F) due to higher flame temperatures and lower fuel moisture. Future tests may better quantify this observation.

Another indicator of boiler performance changes is the gas temperature at the air preheater outlet, sometimes called the cold end temperature (CET). The CET should be as low as possible to maximize the total amount of fuel energy transferred to the steam, but should remain above the acid dewpoint of the flue gas to prevent cold-end corrosion. The design CET for the Clifty Creek units was 299 F. Due to a variety of fuel, equipment, and operational changes over the unit's lifetime, cold end temperature at 230 MW is now normally around 400 F (boiler capacity has been more important to the utility than efficiency over the years).

During PDF™ testing, the cold end temperature was slightly higher than it was during baseline tests. This temperature (average of the three ducts) ranged from 400 to 430 Fat full load when burning PDF™. In general, the cold end temperature was lowest in the morning and highest in the afternoon, reflecting the impact of ambient air temperature. As a rule of thumb, boiler efficiency decreases by 0.25% for each 10 F rise in cold end temperature. Therefore, the increase in cold end temperature when burning PDF™ had a O to 1 % impact on boiler efficiency.

3.3 Emissions

The transition period when PDF™ blend began reaching the pulverizers showed changes in NO_x, SO_2, and opacity emissions as measured by the plant continuous emission monitoring system. The plant reports hourly average emissions, so sharp changes are difficult to find. Also recall that Units 1, 2, and 3 send flue gas to a common stack. The CEM system measures emissions in the stack so that changes in emissions from Unit #3 are damped out by emissions from the other two boilers.

Because Unit #1 was out of service during the test period, measured emissions originated from only Units 2 and 3. Any changes to emissions on Unit #3 thus were more noticeable than they would have been if all three units were operating, and data interpretation was a tractable problem.

Figure 5 shows NO_x and SO_2 emissions along with FEGT and load trends for 6 May 1996, the first day of PDF™ combustion. The PDF™ blend had been loaded into the coal bunkers the previous evening. Plant operators estimated that Unit #3 would be on PDF™ blend by sometime between 1000 a.m. and noon on the 6th.

The SO_2 emissions changed significantly during the day. Since the amount of SO_2 is proportional to the amount of sulfur in the blend, SO_2 is a good indicator of the amount of high-sulfur Ohio coal in the blend. The baseline coal contained about 20% Ohio coal while the PDF™ blend included 30% Ohio coal. Therefore, the conversion to PDF™ should be marked by a 25% increase in SO_2 (half of the 50% increase in coal sulfur). Figure 5 shows a 20% increase in SO_2 from 9:00 a.m. to 6:00 p.m. on May 6th.

NO_x emissions also increased initially from 620 ppm to 680 ppm (1.24 to 1.29 lb/MBtu) over the same time period. Since load was relatively constant during this transition, the initial increase in NO_x can be attributed to higher flame temperature with PDF™ as well as the amount of Ohio coal in the blend. Fuel nitrogen conversion to NO_x is inherently higher for eastern bituminous coals than for western subbituminous coals. Thus NO_x would be expected to decrease as the amount of PRB coal in the blend increases.

Starting in the evening of 6 May and continuing throughout the morning of 7 May, SO_2 emissions fell gradually to below 700 ppm (below baseline values). It is probable that the amount of PDF™ in the blend was increasing as the test went on. Figure 6A shows hourly average emissions for 7 May 1996. Note that SO_2 and NO_x emissions track each other; that is, NO_x decreases as the SO_2 decreases. At the end of the day, NO_x had decreased by about 100 ppm to 510 ppm. The 40 ppm drop in NO_x between 0600 and 0700 was accompanied by a large increase in stack gas air inleakage evidenced by a change in stack CO_2 from 10.5% (about 80% excess air) to 9.5% (about 120% excess air). NO_x in lb/MBtu did not change! However, the NO_x reduction from 0800 to the end of the day on 7 May 1996 is real since stack excess air remained constant. NO_x decreased from 1.25 to 1.12 lb/MBtu. Average daily NO_x remained below 1.1 lb/MBtu for the remaining four days of the PDF™ tests as shown in Figure 6B. The

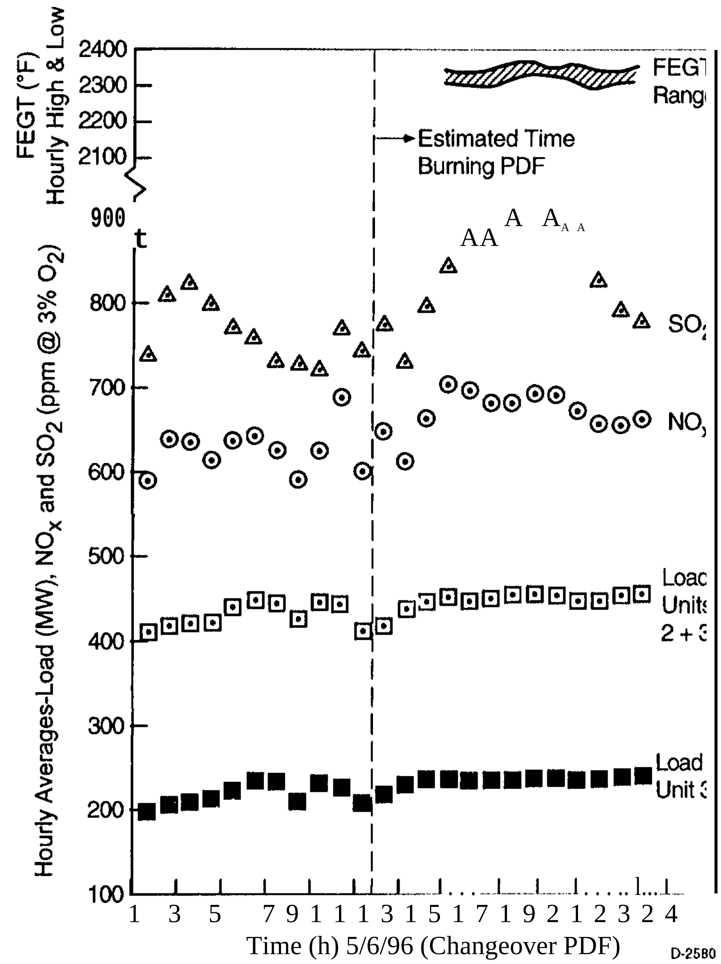


Figure 5. Emission Data During the Changeover to PDF™

total NO_x reduction attributable to PDF™ is about 0,15 lb/MBtu or about 12%. Assuming emissions were constant from Unit #2, the decrease in NO_x from Unit #3 alone was about 24%.

Any discussion of NO, emissions must be accompanied by an understanding of the burner system. The Clifty Creek boilers are fired by Babcock & Wilcox (B&W) Cross-tube type burners. A schematic of the Cross-tube type burner is given in Figure 7,

Cross-tube burners are used on large, water-cooled boilers whose design requires horizontal firing, low in the furnace. Although the cross-tube burner has been employed successfully in dry-ash removal furnaces, it was designed primarily for slag-tap units. It is especially applicable to slag-tap installations where the ash-fluid temperature is relatively high. The proximity of the burners to the slag pool and the ability to regulate flame elevation permit slag tapping when it would not be possible with other burner types.

B&W Cross-tube pulverized coal burners discharge the primary fuel-air mixture to the furnace in a thin, wide, horizontal layer. As fuel enters the furnace, it is dispersed upward and downward by deflector blocks that act as an impeller. Secondary air is admitted to the burner above and below the fuel port through adjustable dampers. Both the quantity of air and its direction can be closely regulated, The furnace end of the fuel port is shielded from radiation by water-cooled tubes. Fuel is prevented from impinging on pressure parts by protectors fastened to the tubes.

NO_x formation in this type of flame is very sensitive to the distance into the furnace at which the fuel mixture ignites. The reasons for this NO_x formation behavior are well understood (and are the basis for recent improvements to the tangential firing system):

- Fuel nitrogen conversion to NO, depends on the local oxygen concentration in the regions where the coal releases its volatiles. To minimize NO, , volatile nitrogen should be released where 0_2 is limited.

- The rate of volatile release is maximized just upstream of the ignition region due to the inherent sharp increase in temperature as the coal nears the flame.

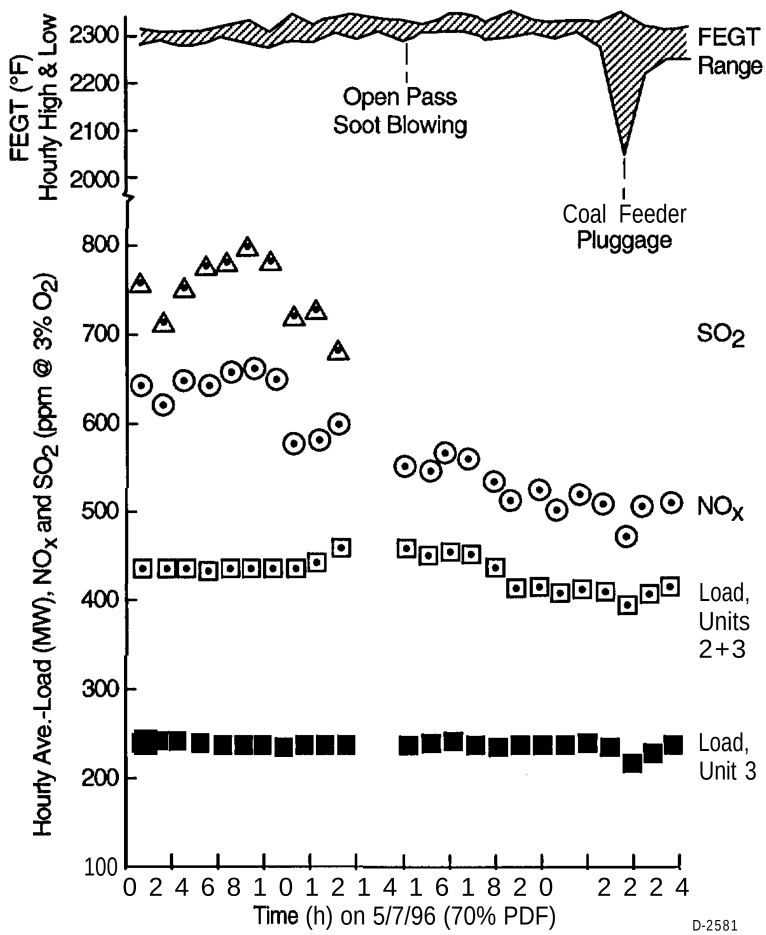


Figure 6A. Hourly Average Emissions for 7 May 1996

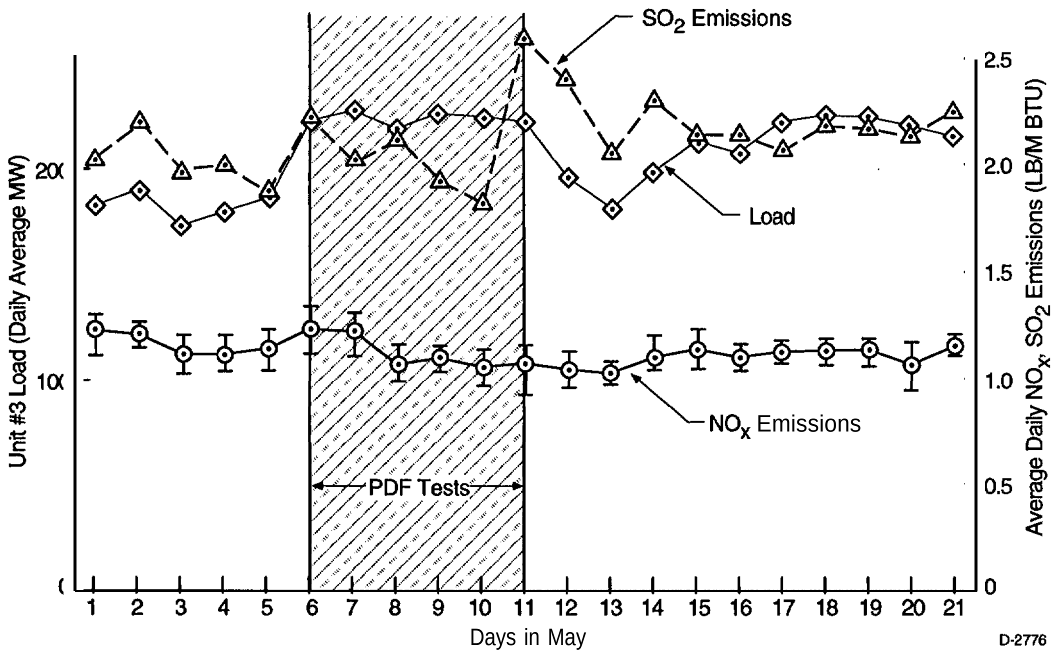


Figure 6B. Average Daily NO_x Emissions in lb/MBtu

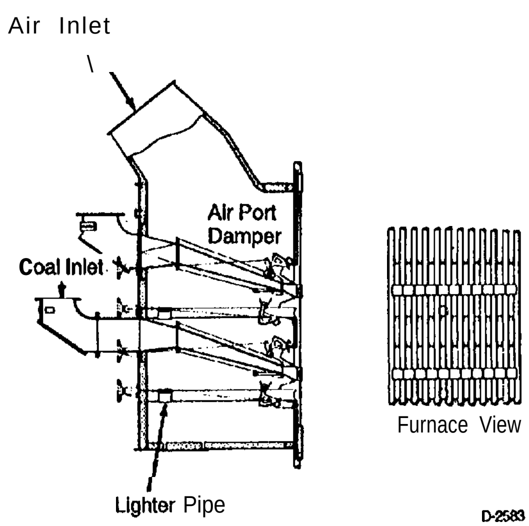


Figure 7. Cross-Tube Type Burner

- The ignition point is determined by the ignition temperature of the coal, the temperature of the flame (which determines coal heatup rate), and the burner aerodynamics (recirculation of hot combustion products as a source of ignition energy).

- Therefore, any change to the burner or the fuel that results in ignition close to the burner will also reduce the NO, emissions.

The ignition distances were observed for both baseline and PDF™ blends on Unit #3 at different loads. Additional flame observations were recorded on Unit #5 at full load with the baseline coal blend. In all cases with the baseline coal, ignition occurred 1 to 2 ft away from the coal nozzles. When PDF™ was burned, however, ignition was right at the coal nozzle. In fact, on one burner the coal was igniting behind the deflector block and ash deposits were visible on the deflector block. Therefore, the high reactivity of the PDF™ also contributed to the low NO_x measured during the tests of the PDF™ blend.

NO_x remained low on 8 May 1996 when the PDF™ content of the blend was increased to 80% as shown in Figure 8. Later the PDF™ content was further increased to 90%. NO_x emissions remained below 500 ppm.

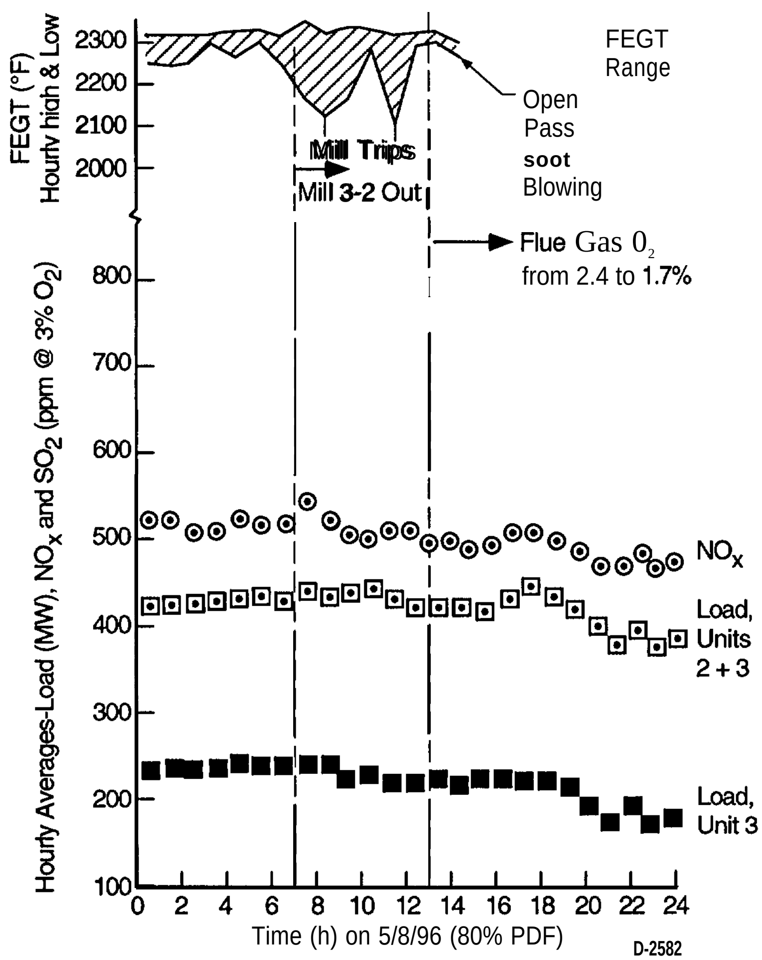


Figure 8. Hourly Emission Trends for 8 May 1996

If it is assumed that NO_x remained constant on Unit #2 at 600 to 650 ppm (1.2 to 1.3 lb/MBtu) during the PDF™ tests, the NO_x emissions from Unit #3 must have been around 400 ppm (1.0 lb/MBtu) for the combined NO_x to measure 490 to 520 ppm (1. 1 lb/MBtu). If the Indiana State Implementation Plan for Phase 11 of the Clean Air Act Amendments Acid Rain Title follows the recommended NO_x limit of 0.86 lb/MBtu for wet-bottomed units, addition of PDF™

to the fuel blend may get the station half way toward achieving NO_x compliance with a conservative margin of safety.

3.4 Load Capacity with One Mill Out

Due to mill maintenance requirements, this short PDF™ test afforded an opportunity to compare maximum load on Unit #3 for each coal when mill 3-2 was down for maintenance (baseline tests) and airflow calibration (PDF™ tests). As mentioned previously, the Clifty Creek units were designed to reach full load with six out of seven pulverizers in operation on Ohio bituminous coal (Hardgrove grindability index of 50). Several years ago when the pulverizers were upgraded to the B&W EL design, even more spare mill capacity was gained. However, when the station converted to low-sulfur PRB coal, with its low Btu and grindability, all spare mill capacity was lost.

Extra mill capacity is advantageous for base-loaded units like Clifty Creek. Mill internals suffer lots of wear. This wear results in degraded combustion efficiency as well as unscheduled downtime to repair mills that fail. Most utilities have found that mill failures are best managed by an ongoing inspection and maintenance program rather than relying on an annual boiler outage to service the mills. Thus both availability and capacity factors can be increased by having spare mill capacity, while maintenance costs can be decreased.

Clifty Creek was able to operate close to full load on Unit #3 with six mills in service while burning PDF™. The unit was operated at 232 MW for 2 h during which the active pulverizers were pushed to their limits. Occasional pulverizer trips resulted. The load was then backed off to 225 to 228 MW and pulverizer operation stabilized for the remainder of the test day (see Figure 8).

For comparison, Unit #3 was limited to about 190 MW during the baseline coal tests with mill 3-2 out of service. Higher loads should have been possible, but the coal was wet and difficult to feed. A fairer comparison was made against Unit #5 on 8 May 1996. On this test day, Unit #3 was operating without mill 3-2 and Unit #5 had mill 5-4 down for repairs. Unit #3 maintained a stable load of 225 to 228 MW while Unit #5 could only achieve a steady 208 MW. Thus operators could pick up an additional 9% capacity when burning the 80% PDF™, 20% Ohio coal blend.

The reason for additional capacity is probably the increased heating value of the PDF™ blend. However, based on expected coal analyses, heating value should have increased by only 5% — half the observed capacity gain. Without actual coal samples from the test day, we are left to speculate whether baseline coal surface moisture was higher than expected due to the rains, or whether PDF™ grindability or combustibility is higher than the baseline coal resulting in acceptable pulverizer operation at higher coal throughputs.

3.5 PDF™ Handling Characteristics

Other operational improvements noted with PDF™ include fewer coal feeder trips due to wet coal and lower excess air. Figure 9 shows FEGT data from 3 May 1996 when wet coal problems plagued Unit #3 operation. The FEGT data have been plotted as the hourly high and low in order to compare against plant records of load and other operations. By comparison, FEGT data from 6-8 March 1996 show only one coal feeder trip due to wet coal. Past experience with PDF™ shows that it flows well. Based on the results of this test, which included drenching rains, PDF™ has been demonstrated to handle much better than conventional coal under wet conditions.

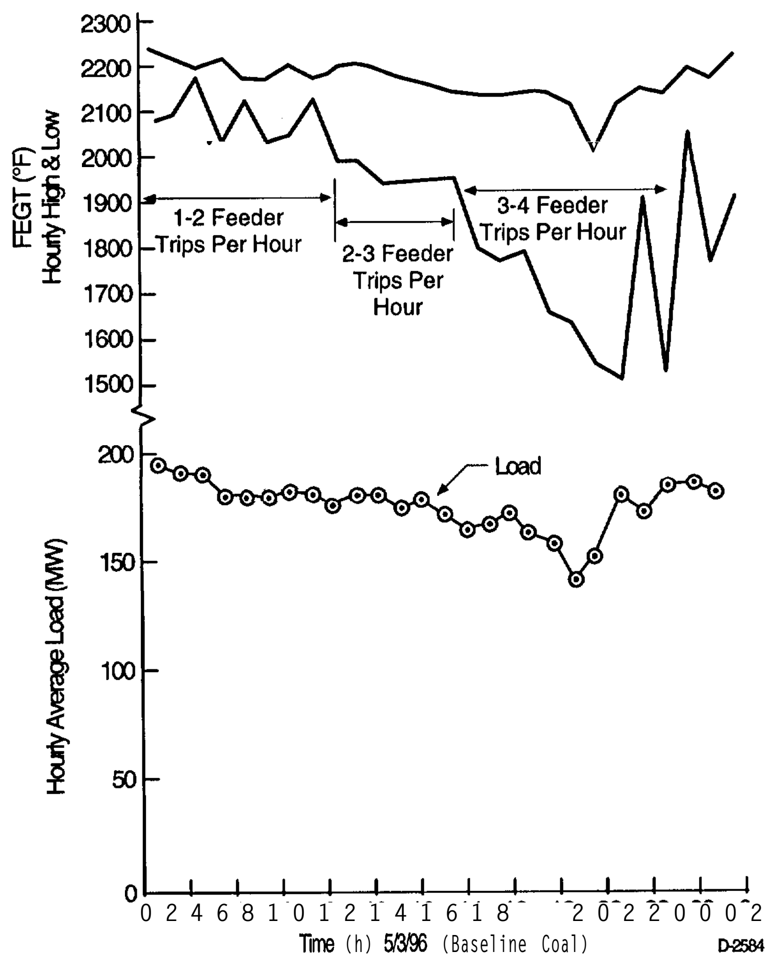


Figure 9. Unsteady Operation with Baseline Coal

3.6 Operation at Reduced Excess Air

The plant operators reduced excess air on Unit #3 during the afternoon of 8 March 1996. The Purpose of this action was to dry molten ash deposits noticed on the waterwalls at the entrance to the convective pass. Reducing excess air is a standard plant response to wet ash deposits.

Figure 8 shows that FEGT trended lower by about 20 F in response to a reduction in flue gas O_2 from 2.4 to 1.7% (stoichiometric air/fuel ratio of 1.1). Mill 3-2 was out of service at this time, with minimal airflow to the two burners supplied coal by mill 3-2. Therefore, the stoichiometric air/fuel ratio at the 12 active burners was probably lower still, in the range of 1.02 to 1.05.

The excess air level is exceptionally low, even for wet-bottomed units where high combustion temperatures can partially offset low burnout rates caused by limited contact between fuel and air. Flyash samples were obtained during the low O_2 tests to quantify any increases of unburned carbon at these low excess air levels. This flyash sample showed 5.2% loss on ignition which is only slightly higher than normal for this unit. Ignition stability was excellent at all burners under reduced excess air operation. This observation supports previous laboratory data that PDF™ is easier to ignite than the baseline coal blend.

3.7 Slagging and Fouling

It has already been stated that ash deposits at the open pass exit and convective pass entrance changed during PDF™ tests. Visual access to the boiler is limited to these two general areas just above and just below the screen tubes. No change in slagging and fouling was expected since the PDF™ contains the same ash minerals as the baseline PRB coal. However, other factors point toward increased ash deposition for the PDF™ blend:

- Higher furnace temperatures due to lower fuel moisture could increase deposition or make deposits more difficult to remove.

- PDF™ blends (70, 80, 90% PRB) contain more PRB coal than the baseline coal blend (60% PRB). PRB coal flyash is dominated by calcium-rich particles. Depending on deposit compositions, an increase in calcium can decrease (or increase) deposit melting temperature as well as increase deposit sintering rate. In either case, the end results is deposits that may be more difficult to remove using conventional sootblowers.

As discussed, Clifty Creek Unit #3 experienced a slight increase in FEGT. Deposits were observed to be somewhat wetter at the furnace exit for at least a part of the 6-day test period.

In the convective section, operators noted periodic increases in pressure drop indicative of deposit build-up. Steam temperatures were measured in three bundles referred to as north middle, and south. Higher temperatures in the north and south bundles indicate some gas-side flow impedance in the middle lanes caused by ash deposits. Table 3 shows convective pass pressure drop and other plant operating data taken at representative times during the tests.

These convective pass deposits, however, were controllable using the long retractable sootblowers. Sootblowing frequency was increased from 1 to 2 times per shift with the baseline coal to 3 to 4 times per shift with the PDF™ blend. Blowing each sootblower four times per shift is the plant operator's definition of continuous sootblowing because at least one sootblower will be operating at all times.

Table 3. Plant Data Indicative of Convective Pass Fouling

Date	5/6/95	5/7/96	5/8/96	5/9/96	5/10/96	5/11/96	5/12/96
Time, hrs	1900	1500	1445	1530	1500	1500	1500
Coal blend, PDF™/Ohio	70/30	70/30	80/20	80/20	90/10	90/10	base
Load, MW (gross)	229	230	223	233	224	228	209
Steam flow, M lb/hr	1.426	1.420	1.410	1.470	1.430	1.460	1.320
SH spray flow, lb/h							
A	0	0	1,000	1,000	0	1,000	0
B	5,000	5,000	5,000	2,000	2,000	1,000	1,000
RH spray flow, lb/h							
A	27,000	0	38,500	20,000	13,000	3,000	4,000
B	33,000	30,000	23,100	1,000	2,000	2,000	1,000
Convective Pass ΔP, in. wg							
Sec. SH	0.63	0.66	0.49	0.48	0.48	0.49	0.34
Reheater	5.2	5.5	5.2	6.3	5.2	5.4	4.5
Pri. SH	3.6	3.68	2.98	3.77	3.4	3.6	3.0
Economizer	0.75	0.74	0.60	0.67	0.66	0.75	0.5
Total	10.2	10.6	9.3	11.2	9.8	10.2	8.3
Gas temperature to AH °F							
North	765	776	741	741	735	715	725
Middle	755	757	737	741	740	715	735
South	760	755	740	760	774	740	760
Cold end temperature °F	395	399	389	401	405	375	405
Superheated steam T, °F	1006	1008	967	986	957	969	982
Reheated steam T, °F	1041	1038	1005	1017	1015	1007	1014

Operators also reported more ash removal during sootblowing for the PDF™ blend as compared to the baseline coal. Chunks of ash could be heard raining down to the ash pit when the lower portion of the secondary superheaters or reheaters were blown. The falling slag appeared granular and caused no ash removal problems, whereas a few large chunks are common when burning the baseline coal. The operators also noted that the noise from the ash pit was louder than normal when the PDF™ deposits were removed.

Slag tapping was similar for both the baseline and PDF™ coal blends. In both cases, the proximity of the flame to the furnace floor kept the bottom hot at 190 to 230 MW. At the higher load with PDF™, more flame was visible passing through the slag tap opening into the bottom of the open pass. Slag did not run continuously, but would build up then flow out of the slag tap.

These slagging and fouling measurements and observations were initially a concern to the boiler operators. However, during the 6-day test, ash deposits did not get any worse. Operators were able to control deposits and stabilize boiler performance using sootblowers and excess air according to normal procedures. Deposit strength can change over time due to changes in the deposit residue after sootblowing. Therefore an extended test burn would be required to demonstrate that ash deposits can be controlled in the long term.

3.8 ESP Operation

The effectiveness of ESP operation was judged by flue gas opacity measured downstream of the precipitator. Figure 10 shows how opacity increased from 10% to 24% during the transition from the baseline coal blend to the PDF™ blend, However, after the initial increase, opacity decreased each day throughout the test period as shown in Figure 11. After the PDF™ tests were completed, opacity averaged 7% and remained in the 5 to 12% range for the rest of the month.

Opacity is affected most by the amount of subrnicron-sized flyash that escapes the precipitator. Fine particle capture is influenced by both gas temperature and the amount of fine particles contained in the flyash. Although precipitator entrance temperatures were generally lower for the baseline coal, Figure 12 shows no correlation between gas temperature and opacity.

One might also expect the fraction of submicron flyash to increase as the amount of PRB in the coal increases, since PRB coal contains a higher fraction of organically bound minerals that are released from the coal as a submicron aerosol during combustion. Figure 11, however, shows that opacity decreases as the PRB coal percentage increases.

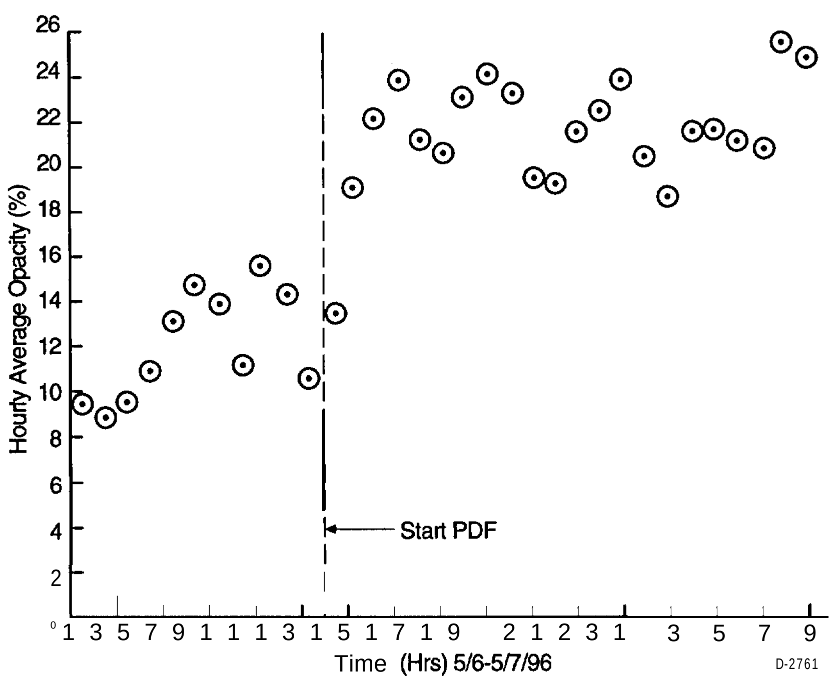


Figure 10. Opacity Increased with Onset of PDF™

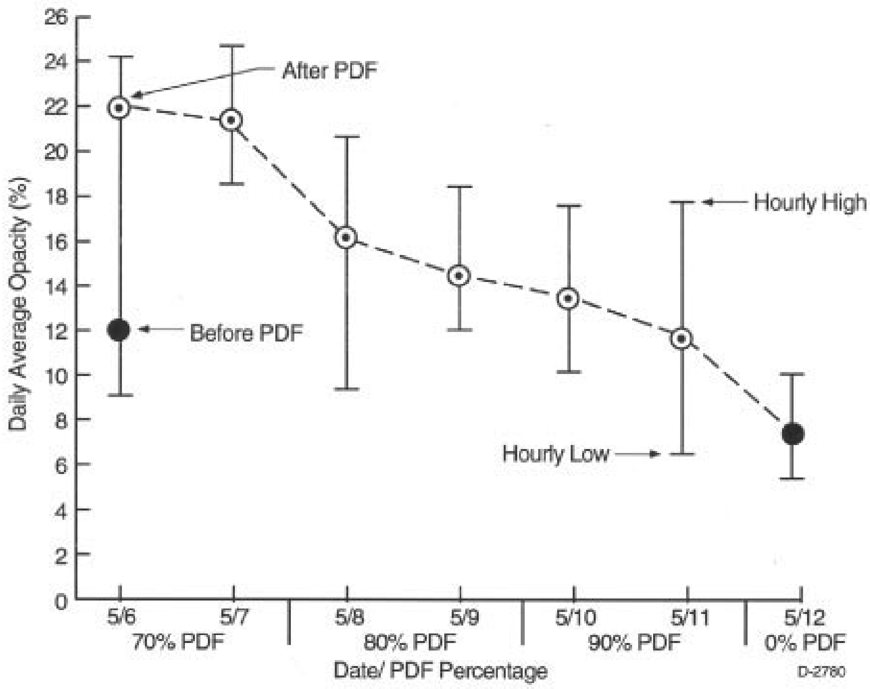


Figure 11. Opacity Decreased throughtout the PDF™ Test Peirod

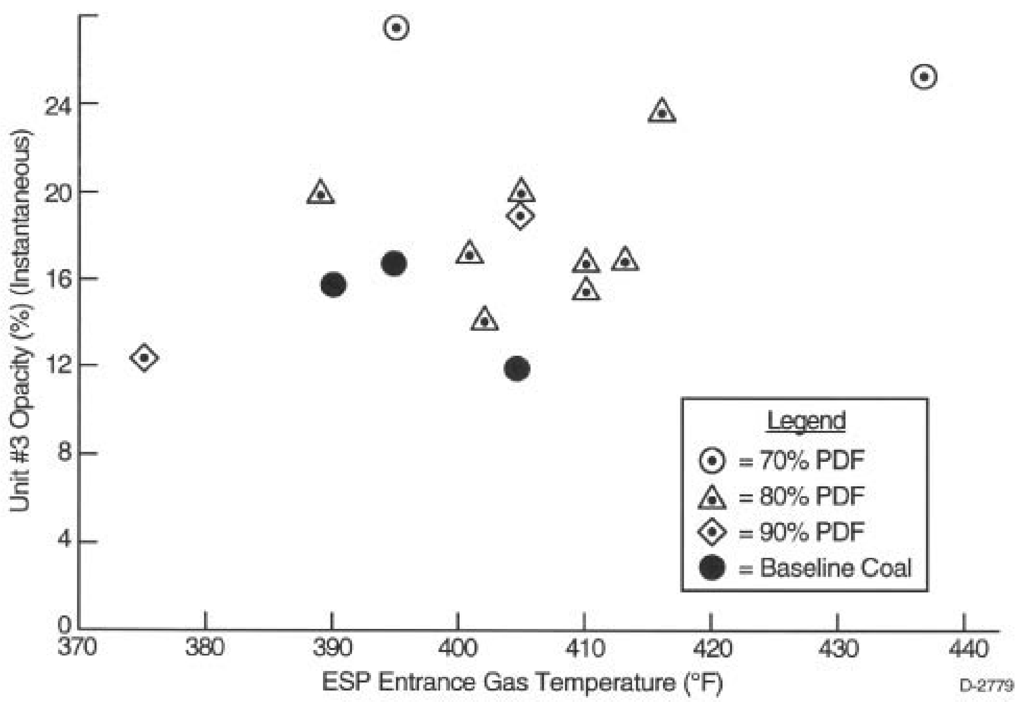


Figure 12. Gas Temperature has No Correlation to Unit #3 Opacity

Therefore, all we can report is an 80% increase in opacity when the PDF™ blend was introduced and a 36% decrease in opacity after the baseline coal was re-established. ESP performance tests will be required in future tests so that ENCOAL® can understand the impacts of PDF™ on opacity. Clifty Creek has an opacity limit of 40%, so the observed increase was not critical. Many boilers, however, are in violation of environmental regulations if they operate above 20% opacity.

4. CONCLUSIONS AND RECOMMENDATIONS

Overall, the PDF™ blend was an acceptable fuel for Clifty Creek Unit #3. Significant benefits were quantified:

1. PDF™ handling was not affected by drenching rains that caused significant feeding problems for the baseline coals. The unit could achieve an extra 20 MW over the course of each operating hour by avoiding feeder trips.

2. PDF™ allowed boiler capacity with one mill out of service to be increased from 208 to 228 MW, with attending benefits of increased capacity factor and availability, and decreased O&M costs.

3. Unit #3 experienced a 20% decrease in NOx down to an estimated value of 1.0 lb/MBtu. A switch to PDF™ may allow compliance with Phase II NOx regulations with minimal changes in combustion or boiler performance.

The remaining issue from this abbreviated PDF™ test burn is the long term impact of the PDF™ blend on slagging and fouling at Clifty Creek. Wetter deposits were observed at the entrance to the convective pass, especially on the common wall between the convective pass and the open pass. Open pass deposits may have increased as well, but the unit operates more effectively when deposits cover open pass waterwall surfaces. A problem could arise if more open pass sootblowing is required to reduce convective pass entrance temperatures: superheated steam temperature decreases of 25 to 50 F were measured when open pass deposits were removed (reheated steam attemperation is no longer needed, so the efficiency penalty associated with low superheat temperatures is partially offset).

The other problem that ash deposits could cause is pluggage of the reheater tube sections. Pressure drops fluctuated between 5.4 and 6.2 in. w.g. during PDF™ tests, indicating that the gas passes were partially blocked. If this pressure drop had increased further, the unit induced draft fan capacity would have decreased and the boiler would be forced to reduce load. During the tests, reheater deposits could be easily removed by the sootblowers thus keeping the pressure drop within the normal range. Further testing or long-term operating experience is required to assure that deposit strength doesn't increase over time and cause a boiler derate.

Given the benefits shown by the subject test program, ENCOAL® should be in a strong position to recommend test burns to other utility customers who need extra pulverizer capacity, lower emissions, or higher reliability. In the case of Clifty Creek, there may be justification for a longer test burn during which performance tests can quantify heat rate improvements. The longer test burn will also provide an opportunity to evaluate ash deposit accumulation and removal on a more appropriate long-term basis.