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Comparison of gaseous and particulate emissions from a pilot-scale combustor using three varieties of coal

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Abstract

Gaseous and particulate emissions generated from the combustion of coal have been associated with adverse effects on human health and the environment, and have therefore been the subject of regulation by federal and state government agencies. Detailed emission characterizations are needed to better understand the impacts of pre- and post-combustion controls on a variety of coals found in the United States (U.S.). While the U.S. Environmental Protection Agency (EPA) requires industry reporting of emissions for criteria and several hazardous air pollutants (HAPs), many of the methods for monitoring and measuring these gaseous and particulate emissions rely on time-integrated sampling techniques. Though these emissions reports provide an overall representation of day-to-day operations, they represent well-controlled operations and do not encompass real combustion events that occur sporadically.

The current study not only characterizes emissions from three coals (bituminous, sub-bituminous, and lignite), but also investigates the use of instrumentation for improved measurement and monitoring techniques that provide real-time, continuous emissions data. Testing was completed using the U.S. EPA's Multi-Pollutant Control Research Facility, a pilot-scale coal-fired combustor using industry-standard emission control technologies, in Research Triangle Park, North Carolina. Emissions were calculated based on measurements from the flue gas (pre- and post-electrostatic precipitator), to characterize gaseous species (CO, CO₂, O₂, NO_x, SO₂, other acid gases, and several organic HAPs) as well as fine and ultrafine particulate (mass, size distribution, number count, elemental carbon, organic carbon, and black carbon). Comparisons of traditional EPA

Disclaimers

The research described in this article has been reviewed by the U.S. EPA National Risk Management Research Laboratory and approved for publication. The contents of this article should not be construed to represent Agency policy nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

methods to those made via Fourier Transfer Infrared (FTIR) Spectroscopy for CO, NO_x, and SO₂ are also reported.

Keywords

Coal combustion; Emissions characterization; Methods comparison

1. Introduction and background

In the past several decades, coal combustion emissions – both particulate and gaseous – have been a focus of research and regulation by the U. S. Environmental Protection Agency (EPA) and other regulatory authorities. Increasingly stringent regulations have forced industry to find ways to mitigate many pollutants present in their pulverized coal combustor facility emissions. As a result, industry has deployed many pre- and post-combustion controls in order to reduce emissions of these pollutants (an overview of many current control technologies utilized for coal combustion is provided by [1], [2]). Pre-combustion controls include, but are not limited to, the use of low NO_x burners, burning lower-sulfur and/or lower-chlorine coals, and firing or co-firing on natural gas. Post-combustion controls include, but are not limited to, selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), flue gas desulfurization (FGD), electrostatic precipitators (ESP), fabric filters (baghouses), and sorbent injection. In order to continue to make strides toward cleaner coal combustion, it is imperative that a better understanding of emissions (how and why they vary), newer technologies, combinations of existing technologies, and alternative fuels is gained through research. For this reason, the current study was designed to investigate these emissions, and the emissions measurement techniques available, from a variety of three coals using combustion conditions and characteristics (time–temperature profile) similar to those of a full-scale coal-fired electric generating unit (EGU). An overview of previous work on full-scale facilities and on a smaller-scale drop tube facility with three similar coals is discussed in Linak et al. [3], and a detailed description of the coal combustion facility used for the current study is available in Yelverton et al. [4].

1.1. Gaseous emissions

In general, combustion of fossil-fuels leads to emissions of many gaseous species. Coal-fired combustion, in particular, emits gases that have been shown to have impacts on human and environmental health as well as climate, leading to numerous regulations in the US over the past several decades (a brief overview of such regulations with references is available in [5]). Due in part to regulation, instrumentation and methods to measure and monitor these gaseous emissions have been developed over the years. As technologies to mitigate many species of gaseous emissions have been developed and utilized by industry, the instrumentation and methodology to measure and monitor these emissions has also improved – often to lower detection limits and/or for the addition of new species and compounds.

Recent health studies have linked many gaseous emissions – among them carcinogenic and mutagenic compounds – from coal-fired combustion to negative human health impacts [6],

[7], [8]. Given these results, the current study focused on emissions of four of the six US EPA criteria pollutants (CO, SO₂, NO_x and PM) as well as a suite of other gaseous pollutants (i.e. Hazardous Air Pollutants, or HAPs). Further, the current study compares traditional US EPA Reference Methods 6C, 7E, and 10 (40 CFR Part 60, Appendix A) for measuring stack emissions to Fourier-Transform Infrared (FTIR) Spectroscopy measurements. This comparison is of particular interest because, while various FTIR spectroscopy configurations have been used to study gas phase combustion emissions [9], [10], there are very few publications reporting combustion stack emissions via FTIR implementing an approach such as US EPA Method 320 (40 CFR Part 63, Appendix A) or ASTM Method D6348. Further, there are no known studies available in the literature where FTIR measurements are compared to more traditional EPA Reference methods for stack emissions.

1.2. Particulate emissions

Exposure to particulate matter (PM), specifically fine PM (PM_{2.5}), emissions has been linked to adverse health effects through numerous epidemiological studies over the past several decades [11], [12], [13], [14], [15], and as such PM has been deemed one of US EPA's six criteria pollutants. A study by Pope and co-workers [16] shows that over a ten-year span (1980s–1990s) there was a reduction of PM_{2.5} exposure that on average increased life expectancy by 4.9 months in the US alone. The majority of fine PM in the United States is attributed to source emissions, with a recent study by Thurston and co-workers [15] showing that PM_{2.5}, specifically from coal and on-road emissions, are directly linked to ischemic heart disease mortality and other health impacts.

Advances in measurement technologies since the 1990s have led to the classification of even smaller particles, known as ultrafine particles (particle diameter < 1.0 μm), being identified and measured/monitored. These particles have further been associated with health effects – as this particle size range is highly inhalable – and in more recent years have been associated with climate impacts [17], [18], [19], [20], [21], [22].

Fine and ultrafine PM measured directly from coal-fired stationary sources are, for the most part, comprised of elemental carbon (EC), organic carbon (OC), black carbon (BC), and/or metal oxides and inorganic compounds [19], [23]. In addition, a recent study by Zhou et al. [24] showed that greater than 65% of total PM (coarse+fine) emitted from coal-fired power plants can be classified as fine (inclusive of ultrafine) PM. EGUs and industrial sector facilities are required by US EPA to report PM emissions under a host of rules and regulations. However, research studies on bench, pilot, and full-scale facilities have often only classified PM mass – PM_{2.5} and/or PM₁₀ – but have overlooked or been unable to measure the ultrafine PM to gain a better understanding of EC, OC, and BC emissions. For this reason, the current study uses time-integrated filter sampling (for EC and OC) or real-time transmission sampling (for BC) to characterize each of these from the effluent generated from the combustion of three varieties of coal. Further, the PM from this investigation is classified not only by mass, but is also characterized by particle size distribution (PSD).

2. Experimental approach

The focus of this investigation was on characterizing particulate and gaseous emissions from a variety of coals on a pilot-scale facility that mimics the time–temperature profile of a large-scale EGU. Further, emphasis was placed on using improved online measurement techniques to better understand the potential surrogacy relationships between difficult to measure HAPs and the more routinely measured/monitored emissions where the technology is more mature.

2.1. Facility

This investigation was completed using the U.S. EPA's Multi-Pollutant Control Research Facility (MPCRF), a 4MMBtu/h (roughly 1.2megawatt thermal – MW_t) down-fired combustor. The facility is capable of operating on natural gas, distillate fuel oil, pulverized coal (or biomass), or combination of these fuels. The facility utilizes a low- NO_x burner, a refractory-lined furnace, and has multiple heat-exchangers downstream of the furnace to closely mimic the time–temperature profiles of full-scale EGUs. As the name suggests, MPCRF research focuses on the “control” aspect of the facility, as the flue gas can be directed in various flow paths through emissions control equipment, with sampling locations upstream and downstream of each. The facility is equipped with a low- NO_x burner and SCR for NO_x control, ESP and fabric filter/baghouse (BH) for PM control, and a wet-lime scrubber for control of acid gases. The MPCRF's ability to redirect and bypass flue gas flow provides a great deal of flexibility for varying test conditions. Further detail and full description of the facility, as well as a plan-view drawing, can be found in Yelverton et al. [4]. For this study, the facility was configured to use the low- NO_x burner as the primary means of NO_x control while bypassing the SCR; the SCR was bypassed due to the costs associated with operation of the unit and catalysts. The MPCRF utilized an ESP for PM control, a BETH model KEF 4 standard dry ESP (with mechanical rappers) that was designed for the facility to capture fly ash from the flue gas generated by the combustion of lignite, subbituminous and bituminous coals. This ESP has a 775 square foot collection area and is designed for a flow of 1000 standard cubic feet per minute at 300 degrees Fahrenheit, with an overall capture efficiency of 99%.

As mentioned previously, three coal varieties were tested independently – a Pennsylvania bituminous, a Powder River Basin (PRB) sub-bituminous, and a Texas lignite. Proximate/Ultimate analyses of these coals for each test day are provided in Supplemental Information (Table S1). While most full-scale utilities are designed for a specific (often regionally available) type of coal, the MPCRF is capable of operation on a variety of coals with slight adjustments to combustion conditions.

For the current study, the facility was operated at 20% excess air which, depending on the coal being used, resulted in a firing rate (FR) ranging from nominally 2.5 to 2.8MMBtu/hr. In addition to slight variations in FR, in order to maintain the target stoichiometric ratio (nominally 1.2) without overheating the combustor, water-cooled slag tubes were inserted into the furnace lid to provide cooling. Specifically, a set of two slag tubes was used for all of the testing, but the depth at which the tubes were inserted (providing more cooling surface area) was variable from test to test. These slag tube depths varied from 6 to 33inches, but

remained constant during a given test. A table with stoichiometry, FR, and slag tube depth is available in the Supplemental Information (Table S1).

2.2. Gaseous and particulate measurements

The current investigation utilizes a suite of instrumentation to characterize gaseous and particulate emissions from the flue gas through several ports in the ductwork. More specifically, emissions were sampled and reported both upstream and downstream of the ESP (referred to as inlet and outlet, respectively). The ESP inlet is downstream of the heat exchangers simulating an air heater (at a coal-fired EGU) and the ESP outlet is downstream of the ESP but upstream of the wet-lime scrubber. The instrumentation and methodology used for all sampling are detailed in the Supplemental Information (Table S2).

Continuous emissions monitors (CEMs) were used to measure many of the gaseous emissions using standard EPA Reference methods including: CO, O₂, CO₂, NO_x, and SO₂. In addition to the traditional CEMs used to measure gaseous compounds, extractive, high resolution (nominally 0.5cm⁻¹) Fourier Transform Infrared (FTIR) spectroscopy – using a slightly modified ASTM Method D6348 – was also used to measure real-time gaseous emissions of additional pollutants from the flue gas at the outlet location. Specifically, the FTIR was used to measure select organic and HAP emissions, as well as some of the same gaseous species listed above for comparison purposes. These comparisons are discussed in detail in subsequent sections. The complete list of pollutants quantified in this study by FTIR can be found in the Supplemental Information (Table S3) along with a more detailed discussion of the FTIR measurement approach.

Measurement of particulate emissions for the current study included fine PM mass, EC, OC, BC, and ultrafine PM PSD. All PM samples were collected through an eductor-based system with a cyclone to remove large fly ash and particles with a diameter greater than 2.5µm. In order to correct for dilution, CO₂ was monitored after PM sample extraction. As stated previously, PM samples were collected at both the ESP inlet and the ESP outlet locations and the instrument, manufacturer, model, and associated EPA method (where applicable) are given in Table S2.

3. Results and discussion

A pilot-scale, coal-fired combustor was used to evaluate emissions from the combustion of three varieties of coal: Pennsylvania bituminous, PRB sub-bituminous, and Texas lignite. Particulate and gaseous emissions measurements were taken using a suite of both online (real-time) and time-integrated measurement techniques in order to better characterize the emissions as well as to evaluate the capabilities of FTIR as compared to existing EPA Reference methods using CEMs.

As discussed previously, many of the samples for both gaseous and particulate emissions measurements were taken both upstream and downstream of an ESP, representing the inlet and outlet of the ESP. This was done mainly in order to monitor the functionality of the facility and for comparison of instrumentation. In addition, removal efficiencies were determined from emissions calculated. Integrated PM samples were collected coincidentally at

the ESP inlet and ESP outlet locations, with at least three replicates during steady state combustor operation. CEM concentrations were averaged over the time period associated with each integrated PM sample. Table 1, Table 2, Table 3 provide the average gaseous and particulate emissions with associated standard deviation for each of the test days. It should be noted that repeated test days with each fuel are averaged per test day rather than overall for a specific fuel.

Average emissions data [lb/MMBtu], are provided at both the inlet and outlet locations for CO, NO_x, and SO₂ in Table 1. CO₂ data at the inlet and outlet locations are also provided but as an average percentage rather than emissions, as CO₂ was used to calculate all other emission factors. With few exceptions, the data show good repeatability and consistency for NO_x and SO₂ within coal types. CO shows a lot more scatter and unpredictability, which is normal for emissions that are characterized by momentary combustion events among otherwise low measurements. Also, as expected, there is no systematic bias between the inlet and outlet measurements for NO_x and SO₂, but CO drops significantly through the ESP.

In addition to reporting emission factors for several gaseous pollutants of interest using traditional CEM test methods (see Table S2), FTIR was used at the outlet location to measure for comparison of CO, NO_x, SO₂, as well as acid gases, aldehydes, volatile organic carbon (VOCs), and methane (see Table S3). As with CEM data, FTIR concentrations were averaged over integrated sample times. Table S3 provides a list of all compounds analyzed via FTIR using the EGU recipe, of which only seven compounds were present at or above detection limits. These average emissions and standard deviations are provided in Table 2, noting that FTIR measures NO and NO₂ separately to determine NO_x emissions. Like the traditional CEM system measurements, the data show good repeatability for NO_x and SO₂, while CO shows characteristically higher amounts of scatter.

Further, three of these FTIR measured emissions (CO, NO_x, and SO₂) are plotted in relation to emissions measured using traditional EPA methods in Fig. 1a–c, respectively representing emissions for concurrent sampling intervals for all three coals. Regardless of the coal type used for testing, it is apparent that correlation between measurements made by FTIR and emissions calculated using EPA Methods 10 (CO), 7E (NO_x), and 6C (SO₂) is strong ($r^2=0.993$, 0.996 , and 0.998 , respectively). For NO_x and SO₂, the trend lines appear to pass through the origin, as would be expected for equivalent measurements; inclusion of an intercept in the trend line calculations would improve the relative standard error by less than 1%. Emissions of CO, however, show a slight bias creating a non-zero y-intercept. This bias is likely the result of an observed negative CO₂ interference response in the traditional CEM system measurements (with simple NDIR detection), and demonstrates one of the advantages of FTIR measurement technology; its ability to separately measure and compensate for interfering species. Regardless, with such a significant correlation in emissions between measurements from the FTIR and EPA methods for these three compounds, there is support that the other compounds (e.g. HCl and HF) detected are accurate using the FTIR's EGU recipe. Conversely, compounds that were observed as non-detects are likely not present at or above the instrument detection limits.

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Particulate emissions were characterized by a number of instruments at two locations in the facility in order to better understand the variation in emissions as well as the removal efficiency of the ESP for fine and ultrafine particles. Table 3 shows for each test day, the average total fine PM, EC, OC, and BC emissions, as well as the total ultrafine PM number concentration at both the ESP inlet and outlet locations. It should be noted that the average OC emissions were tabulated without post-processing to correct for any artifact, but were corrected for background that was present in the system.

A study by Wang et al. [25] completed on a similar pilot facility (approximately one third the size), took fine PM measurements to characterize particle size, EC, and OC at a variety of stoichiometric ratios. Test #2 from their study has a stoichiometric ratio of 1.25 burning a low-sulfur western bituminous coal, and is used for comparison to the current tests where stoichiometric ratio was nominally 1.2 for all coals tested. It should be noted that Wang and co-workers [25] were collecting and analyzing samples pre-control device and are therefore compared to the current study's measurements at the ESP inlet location.

Fig. 2a–f illustrates by test day the average ultrafine PM size distribution, both pre- and post-ESP, for each of the three coals used. In all instances, the particle size distributions shown represent the average from a minimum of three, 200s scans covering size bins from approximately 14nm up to 700nm. Tables S4 and S5 (available in the Supplemental Materials) also provide size fractionated particle count averages as well as tabulated minimum and maximum standard deviations. Veranth and co-workers [26] showed that soot and char from a pulverized coal test facility had bi-modal size distribution across submicron up to coarse particles. However, their results were based on Transmissions Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM) grid analysis rather than Scanning Mobility Particle Sizer (SMPS) instrumentation classifying particles into numerous size bins. The current study resulted in averaged values with bi-modal size distributions across all three coals tested, with a peak number concentration (#/cm³) between 30 and 70nm for all three coals at the inlet to the ESP. At the outlet of the ESP, peak number concentrations ranged between 15 and 40nm for bituminous and lignite and between 70 and 80nm for sub-bituminous. It should be noted that the size distributions at the ESP outlet location for test days using lignite were unexpected in the larger ultrafine size range, as the average particle number concentration spiked around 600nm. Furthermore, a number of size bins for these scans contain zero particles and are not represented on the figures due to the logarithmic scale. At this time there is no explanation for this behavior but it is included here as these patterns were present on multiple test days and were the average results from several particle size scans with the SMPS instrument. The present bituminous ultrafine PM size distributions at the ESP inlet location agree well in comparison to Wang et al. [25], where they report a bi-modal size distribution with peak number concentration between 60 and 70nm and a total particle concentration of $4.1 \times 10^6 \text{ #/cm}^3$. The current study's average of ultrafine PM total particle concentration for bituminous coal is $3.6 \times 10^7 \text{ #/cm}^3$, but this order of magnitude greater total PM concentration is attributed to the higher sulfur content in the eastern versus western bituminous coals. With the additional sulfur in the Pennsylvania bituminous coal, particles with a diameter of less than 150nm in the nuclei (<50nm) and accumulation (>50nm) modes could be substantially more abundant [3].

Understanding the EC, OC, and BC subsets of fine PM emissions are of great interest, and for that reason all were measured and emissions reported for the current study. Again comparing to Wang et al. [25], that study's authors chose to define EC equal to BC and therefore report OC and BC values. Those OC and BC values were, however, obtained through thermal-optical techniques – a method protocol defined to measure OC and EC – so, their results are compared to the current study's OC and EC values in ratio, as their values are given in concentration rather than emission factors. Tests #1 (SR=1.09) and #2 (SR=1.25) from Wang et al. [25] reported OC/BC ratio of 0.244 and 21.3, respectively.

While the current study was conducted at a stoichiometric ratio of 1.2, and therefore should most closely relate to their Test #2, OC/EC ratio reported here averaged 0.169 across four days of testing at the ESP inlet with bituminous coal, which compares best with Wang et al. [25] Test #1 combustion conditions OC/EC results. It should be noted that the average values of OC/EC ratio varied greatly from one test day to another, and these ratios per day can be tabulated from data shown in Table 3 for inlet and/or outlet sampling locations. Ratios tabulated for OC/EC at the ESP inlet were lower for bituminous and sub-bituminous, 0.169 and 0.171 respectively, which is roughly one third that of lignite. For the current study, there was very little variation in stoichiometric ratio for testing (regardless of coal type) with all testing completed at steady state, in order to closely mimic combustion for full-scale PC combustors in industry. Average OC/EC ratio from the current study is observed to vary less from the rank of coal than Wang et al. [25] observed by changing the SR. Therefore, the results from these two studies suggest that changes in SR present a much more dominant effect on OC/EC ratio than the rank of the coal used.

Across all test days and conditions, the relationship between the BC (real-time) and EC (time integrated) measurements at the ESP inlet is better correlated than expected ($r^2=0.831$), as shown in Fig. S1 in Supplemental Material. This correlation is somewhat inconsistent with other source-level measurements of BC and EC available in the literature [20], [21], [27], [28], [29], where BC concentration at times is reported to be nearly twice that of EC concentration. Both BC and EC show good removal efficiencies across the ESP, often better than the overall PM removal efficiency, which was not anticipated as ESPs typically have lower removal efficiency as the PM gets smaller. With one exception, when the OC concentration was unusually high, the OC removal efficiencies were uniformly poor. This could suggest that the OC measured was not associated with fine PM and is largely the result of an artifact potentially caused by quartz filter adsorption of gaseous semi-volatile organic carbon or condensation during the eductor sampling process.

Comparisons of the average particle number concentrations of the inlet and outlet locations do show a substantial overall particle removal (~95–99%) measured across all size fractions, with an ESP having 99% or greater removal efficiency [4]. The ultrafine PM removal efficiencies for various size fractions of particles can help gain a better understanding of the particles escaping control and being emitted to environment. Detailed removal efficiencies across the ESP, over several size fractions, are available in Supplemental Material (Tables S4 and S5) along with overall percent removal of particles. Of particular interest are the smallest size fraction of the ultrafine PM (diameters<150nm) removal efficiencies. For the current study, the average ultrafine PM removal efficiency across all coals tested was 94.9% for particles less than 50nm and 99.7% for particles between 51 and 150nm; which is much greater than expected. This removal efficiency is likely due to agglomeration of the smallest ultrafine particles while passing through the ESP, where they are subsequently removed or escaping the ESP as agglomerated larger particles [19], [30], [31], [32].

4. Conclusions

The results presented within describe the gaseous and particulate emissions from a pilot-scale coal-fired combustor operating on three varieties of coal. The facility incorporated a

low- NO_x burner, ESP, and wet-lime scrubber for control of emissions. Many emissions were measured both pre- and post-ESP in order to better characterize the operation of the facility, investigate removal efficiencies of several pollutants, and enable comparison of traditional EPA Methods with FTIR measurements.

From this investigation a better understanding of the particulate emissions from coal combustion is gained. Coal rank was found to have little effect on OC/EC ratio of the fine PM compared to variations between replicate tests. Further, particle size distributions are bimodal and result in peak number concentrations for all three coals between 50 and 70nm when measured upstream of the ESP. Exceptional overall fine PM removal was provided by the ESP, however, particles of the smallest size fractions (<50nm) have the lowest average percent removal across nearly all test conditions. Removal of particles with diameters between 51 and 150nm were much greater than expected, likely due to the smallest particles passing through the ESP and escaping (or being removed) as larger agglomerated particles. Nonetheless, it is the smaller size fraction ultrafine particles that are of primary concern, as this is where freshly emitted BC would exist, and have greatest potential for impact if escaping control. However, the current results suggest an average 98% control of BC.

In addition to particulate emissions, simultaneous flue gas sampling with EPA Reference Methods (M10, M7E, and M6C) and FTIR for several gaseous compounds showed high correlation. With this high correlation between measurements of CO, NO_x , and SO_2 , it can be assumed that other gaseous emissions measured via FTIR are also reasonable. Therefore, it is plausible that FTIR could be used to provide viable, real-time measurements of criteria pollutants as well as other gaseous compounds including HAPs, with a single method that could otherwise leave those compounds of interest undetectable by multiple existing EPA methods.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.
Comparison of gaseous emissions as measured by CEMs and FTIR for (a) CO, (b) NO_x, and (c) SO₂

Fig. 2.

Average particle size distributions for three coals at the inlet and outlet of the ESP.

Table 1.

Gaseous emissions for three coals at the inlet and outlet of the ESP as measured by CEMs using EPA Methods 10, 7E, and 6C.

Test Date	Coal Type	CO inlet		CO outlet		NO _x inlet		NO _x outlet		SO ₂ inlet		SO ₂ outlet		CO ₂ inlet		CO ₂ outlet	
		average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (lb/MMBtu)	Std Dev	average (%)	Std Dev	average (%)	Std Dev
06/04/13	Bituminous	0.063	0.011	0.044	0.011	0.766	0.027	0.755	0.024	2.413	0.003	2.444	0.005	10.87	0.654	9.73	0.686
06/07/13	Bituminous	0.031	0.013	0.012	0.010	0.722	0.020	0.717	0.021	2.239	0.039	2.244	0.040	10.71	0.275	9.65	0.194
08/15/13	Bituminous	0.054	0.005	0.033	0.005	0.601	0.100	0.605	0.102	2.478	0.044	2.451	0.048	10.89	0.096	10.16	0.094
11/19/13	Bituminous	0.097	0.066	0.080	0.065	0.605	0.048	0.611	0.048	2.481	0.022	2.421	0.026	10.44	0.171	9.71	0.161
08/01/13	Lignite	0.100	0.106	0.108	0.161	0.381	0.023	0.387	0.019	1.784	0.128	1.906	0.068	11.34	0.304	10.47	0.230
08/02/13	Lignite	0.075	0.018	0.057	0.018	0.327	0.009	0.327	0.009	1.471	0.057	1.538	0.039	11.40	0.032	10.56	0.255
06/27/13	Sub-bituminous	0.041	0.035	0.027	0.044	0.375	0.018	0.377	0.018	0.500	0.081	0.524	0.090	11.20	0.067	10.23	0.235
07/19/13	Sub-bituminous	0.030	0.008	0.008	0.008	0.388	0.013	0.410	0.009	N/A	N/A	0.677	0.011	11.04	0.192	11.08	0.053

Table 2.

Gaseous emissions for three coals at the outlet of the ESP as measured by MKS FTIR using a modified ASTM D6348.

Date	Coal Type	CO average (lb/ MMBtu)	Std Dev	HCl average (lb/ MMBtu)	Std Dev	HF average (lb/ MMBtu)	Std Dev	NO average (lb/ MMBtu)	Std Dev	NO ₂ average (lb/ MMBtu)	Std Dev	SO ₂ average (lb/ MMBtu)	Std Dev	SO ₃ average (lb/ MMBtu)	Std Dev
06/04/13	Bituminous	0.066	0.011	0.042	0.001	0.001	0.001	0.771	0.025	0.010	0.000	2.482	0.010	<MDC	<MDC
06/07/13	Bituminous	0.038	0.013	0.044	0.001	0.001	0.001	0.745	0.028	0.012	0.001	2.378	0.009	<MDC	<MDC
08/15/13	Bituminous	0.058	0.005	0.047	0.001	0.002	0.001	0.614	0.105	0.004	0.001	2.577	0.047	<MDC	<MDC
11/19/13	Bituminous	0.105	0.066	0.049	0.001	0.001	0.001	0.611	0.050	0.006	0.001	2.527	0.026	<MDC	<MDC
08/01/13	Lignite	0.139	0.174	0.004	0.000	<MDC	<MDC	0.382	0.020	0.008	0.002	2.028	0.055	<MDC	<MDC
08/02/13	Lignite	0.081	0.014	0.004	0.000	<MDC	<MDC	0.314	0.010	0.013	0.000	1.594	0.043	<MDC	<MDC
06/27/13	Sub-bituminous	0.044	0.033	0.007	0.001	0.001	0.001	0.363	0.020	0.012	0.002	0.552	0.089	0.007	0.001
07/19/13	Sub-bituminous	0.033	0.006	0.010	0.000	0.001	0.001	0.399	0.008	0.010	0.001	0.708	0.009	0.007	0.000

NOTE: "<MDC" indicates value is below minimum detection limit as determined by ASTM D6348 MDC#3.

Table 3.

Particulate emissions for three coals at the inlet and outlet of the ESP.

Test Date	Coal Type	Fine PM inlet		Fine PM outlet		Fine PM Removal	Total Number Concentration PM inlet		Total Number Concentration PM outlet		EC inlet		EC outlet		EC Removal	OC inlet		OC outlet		OC Removal	BC inlet	BC outlet	BC Removal
		average (lb/ton)	Std Dev	average (lb/ton)	Std Dev		average (#/cm3)	Std Dev	average (#/cm3)	Std Dev	average (lb/ton)	Std Dev	average (lb/ton)	Std Dev		average (lb/ton)	Std Dev	average (lb/ton)	Std Dev				
06/04/13	Bituminous	1.989	1.489	0.139	0.174	93	3.88E+07	2.52E+06	1.04E+06	4.43E+04	0.081	0.026	0.002	0.001	97	0.012	0.012	0.010	0.012	17	0.112	0.001	99
06/07/13	Bituminous	1.748	1.319	0.100	0.049	94	4.27E+07	1.54E+06	1.82E+06	6.24E+05	0.029	0.007	0.003	0.001	91	0.003	0.008	0.002	0.001	16	0.030	0.001	98
08/15/13	Bituminous	1.033	0.122	0.040	0.029	96	3.52E+07	8.14E+05	9.53E+05	4.68E+04	0.068	0.041	0.006	0.003	92	0.029	0.010	0.006	0.004	79	0.147	0.002	99
11/19/13	Bituminous	1.479	0.611	0.133	0.195	91	2.66E+07	2.77E+06	2.29E+05	2.73E+04	0.256	0.124	0.002	0.000	99	0.005	0.005	0.005	0.002	4	0.216	0.001	99
08/01/13	Lignite	0.853	0.116	0.039	0.034	95	3.31E+07	5.00E+05	7.99E+04	1.18E+05	0.007	0.004	0.001	0.001	89	0.009	0.007	0.003	0.002	64	0.009	0.000	95
08/02/13	Lignite	0.342	0.041	0.042	0.019	88	3.02E+07	1.41E+06	5.30E+05	2.89E+05	0.027	0.009	0.000	0.000	99	0.001	0.003	0.001	0.001	N/A	0.038	0.000	99
06/27/13	Sub-bituminous	0.630	0.124	0.150	0.127	76	3.09E+07	8.76E+05	6.00E+04	4.74E+03	0.010	0.007	0.001	0.001	91	0.002	0.005	0.001	0.002	68	0.010	0.000	96
07/19/13	Sub-bituminous	0.629	0.103	0.148	0.036	77	3.24E+07	1.88E+05	5.37E+04	5.33E+03	0.025	0.016	0.001	0.001	94	0.003	0.001	0.004	0.001	N/A	0.045	0.000	>99

NOTE: All data displayed in this table was collected or corrected to a temperature of 20 degrees C with the exception of Total Number Concentration which was collected via SMPS at a temperature of 23 degrees C. Corrections for this 3 degree temperature variation would have resulted in less than 2% change in total concentration; N/A indicates a value for removal could not be calculated.