ULTRA HIGH EFFICIENCY ESP FOR FINE PARTICULATE AND AIR TOXICS CONTROL

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Introduction

Nearly ninety percent of U.S. coal-fired utility boilers are equipped with electrostatic precipitators[1] (ESP). Cost effective retrofittable ESP technologies are the only means to accomplish Department of Energy's (DOE) goal of a major reduction in fine particulate and air toxic emissions from coal-fired power plants.

Particles in the size range of 0.1 to 5 μm typically escape ESPs.[2] Metals, such as arsenic, cadmium, lead, molybdenum and antimony, concentrate on these particles.[2] This is the main driver for improved fine particulate control. Vapor phase emissions of mercury, selenium and arsenic are also of major concern. Current dry ESPs, which operate at temperatures greater than 280°F, provide little control for vapor phase toxics.

The need for inherent improvement to ESPs has to be considered keeping in perspective the current trend towards the use of low sulfur coals. Switching to low sulfur coals is the dominant approach for SO_2 emission reduction in the utility industry.[3] Low sulfur coals generate high resistivity ash, which can cause an undesirable phenomenon called "back corona." Higher particulate emissions occur if there is back corona in the ESP.[4]

Given this background, the primary technical areas that need to be addressed to improve collection of fine particulate and vapor phase metals (e.g., Hg) include the following:

High ash resistivity: ESP performance is strongly influenced by the properties of the collected dust cake (resistivity and cohesivity). High dust cake resistivity decreases particle migration velocities[4] and lowers collection efficiency. In most cases, an increased amount of sulfur trioxide (SO_3) and higher relative humidity in the flue gas decreases the resistivity of the fly ash and increases its cohesivity. Higher sulfur coals typically produce low resistivity ash and are easier to collect in an ESP compares to low-sulfur coals.

In the Unites States, the utilities are switching to low sulfur coals mainly from the sub-bituminous class mined in the Powder River Basin (PRB). These coals have lower heating values than the bituminous, higher sulfur coals that they are replacing. Switching to PRB fuels increases the flue gas flow in the boiler and lowers heat extraction in the boiler and convective sections compared to design specifications. The decreased heat removal increases the temperature of the flue gas entering the ESP and further exacerbates the problem of high resistivity ash. Additionally, the increased flue gas flow through the ESP exacerbates the original high design velocity, (increased reentrainment), and lowering collection efficiencies.

Particulate emissions can increase by a factor of ten when a utility burning a medium- or high-sulfur coal switches to a low-sulfur coal.[5] Flue gas conditioning with SO_3 is currently the most widely used technique for solving resistivity related problems caused by low-sulfur coals.

Power supply system: In an ESP, the precipitation of particles is enhanced by increasing the electrical field strength (i.e., high voltage) between the electrodes, while ensuring minimum back corona. The ESP is therefore operated with the maximum power input, but just below the sparking level or back corona limit. The back corona limit is usually reached first for high resistivity ashes.

Back corona can be controlled by regulating the production of ions (charges) at the discharge electrode by methods such as pulsing.[6] Flexibility in implementing various pulsing scenarios is important to control back corona and simultaneously maximizing the power input to the ESP.

Vapor phase control: Some of the metal hazardous air pollutants (HAPs) such as mercury and selenium are present in the vapor phase at ESP operation temperatures. Current dry ESPs have very low capture efficiencies for these vapor phase HAPs.[7] Vapor phase toxics control is a critical challenge for ESP advancements.

In summary, the control of fine particulate and air toxics by ESPs can be improved by:

- reducing fly ash resistivity
- agglomerating small particles and increasing cohesivity
- advanced pulsed energization when back corona is present
- reducing reentrainment

- increasing the condensation/adsorption of vapor phase species (for example, Hg) on the surfaces of ash or sorbent particles

Retrofitting existing ESPs to achieve ultra high particulate collection efficiencies is an extreme challenge for the technology developer. Ultra high efficiency is defined by ABB to mean an outlet particulate emission below 10 mg/Nm^3 (0.004 gr/dscf). Another challenge is to achieve the performance requirement with low-sulfur coals in cases where the original design is for mid-to-high sulfur coals. Finally, any retrofit technology must be cost effective and reliable in order to be accepted by the utility community. Each of the above challenges was addressed in the approach described below.

Approach

The approach focused on four retrofittable ESP elements that have high probabilities of contributing towards the achievement of the ultra high particulate collection efficiency goal as well as being likely to gain acceptance in the utility industry. The individual technical elements were investigated in an integrated pilot scale test facility in Phase I of the program.

The four elements selected for evaluation and development for the advanced ESP were:

- A new transformer-rectifier set - Switched Integrated Rectifier (SIR)
- Gas cooling and humidification upstream of ESP
- ABB proprietary design Precharger, installed upstream of the ESP
- Wet ESP, with the potential for modifying the last field in an existing ESP

Each of the technical elements in the ESP are discussed further.

Switched Integrated Rectifier (SIR): SIR is a new transformer/rectifier (T/R) set developed by ABB which allows more flexible operation and higher voltage operation without sparkover. Instead of transforming and rectifying at normal frequency (50/60 Hz), the mains is first rectified, then chopped at 50 kHz and thereafter transformed to a high voltage. Thus a pure DC voltage is achieved, which allows ESP operation at a higher voltage level, and closer to the peak value, than with current T/R sets. The SIR unit also has an inbuilt microprocessor that is capable of intermittent energization with any desired charging frequency. For high resistivity fly ashes, the varying voltage, if correctly applied, can substantially reduce both power consumption and emission. The ability to implement pulsing scenarios is therefore important and the SIR provides that flexibility.

ABB Proprietary Design Precharger: The basic principle with a precharger is that the dust is efficiently charged in a specially designed section upstream of the main ESP. In the ABB precharger, an intense corona travels towards the gas flow, resulting in long treatment times and efficient gas mixing for ensuring fine particle charging. Significant particle collection also occurs in the precharger. With the precharger, there is potential for operating the main ESP with less corona current and higher electrical fields for more efficient dust precipitation.

Wet ESP : The wet ESP (WESP) is similar to a dry ESP except that water is added to the top of the collecting electrode assembly to bathe the entire collecting surface with flowing water. In comparison to dry ESPs, WESPs (i) have no rapping reentrainment losses, (ii) can operate at higher voltages and currents, (iii) operate at a higher velocity, (iv) have no resistivity problems, (v) require smaller specific collection area (50-100 ft^2/kacfm compared to 200-400 ft^2/kacfm for dry ESPs) and (vi) potentially condense and collect vapor phase species such as mercury and selenium. The main negative point with the WESP is that the further treatment of the ash-laden water stream is required.

Gas Cooling And Humidification: Current ESPs in the United States mainly are operating in the temperature range from 280 to 350^{o}F. Dust cake resistivity for most coal ashes peaks around 350^{o}F.[8] Significant benefits can, therefore, be derived from flue gas cooling. One of the advantages of gas cooling and humidification is the increased suface adsorption of SO_3 and moisture, which should decrease dust cake resistivity. Other positive impacts include the reduction in the volume of flue gas to be treated (increased specific collection area - SCA) and reduction in gas velocity which would reduce reentrainment. Gas cooling can also foster condensation and collection of vapor phase mercury, arsenic and selenium species. Thus, an ESP with a cooling and humidification system, could address the resistivity-related problems. It can also provide improved collection efficiency to effectively handle increased flue gas flows caused by switching from a high sulfur to a low sulfur coal.

Experimental

ABB Power Environmental Systems (ABB-PES) and ADA Technologies were subcontractors on this project. ABB-PES is responsible for the commercial ESP business within ABB. They constructed the pilot-ESP and provided guidance on the pilot ESP operation. ADA Technologies constructed the wet ESP section and assisted in its testing as well as with the mercury measurements.

Test Facility: Experimental testing was conducted on a pilot scale (3.5 MBtu/hr - 1 MW_{th}) facility. This facility consisted of a combustor, a cooling loop for the furnace gases and newly-designed and constructed mobile pilot ESP (Figure 1). Pulverized coal was fired up through a single burner into a refractory-lined furnace. The combustor, which has an extensive operational history, simulates the time-temperature-oxygen concentration profile of a field unit. This ensures that the fly ash-vapor phase species partitioning that will occur in the radiant zone of a field unit will be replicated in the pilot combustor. The ash-laden flue gases were cooled by a series of water-cooled heat exchangers and water-cooled ducts. The final temperature control was automatically performed by a air-cooled heat exchanger located just before an induced draft fan. Stable and accurate control of the flue gas temperature, to within +/- 3^{o}F, was achieved during the tests.

Typically, moisture is added via a water spray at the ESP inlet. Evaporation of the water at this location both cools the flue gas entering the ESP and increases its moisture content. It is important to quantify the the independent effects of flue gas temperature and humidity on the ESP performance. Controlled amounts of water was sprayed into the high temperature flue gas (about 2400^{o}F) to control its humidity (Figure 1). Gas temperature was independently controlled with downstream heat exchangers.

Operation of the pilot ESP at collection efficiencies similar to the field unit is critical for correct scaling of the performance data. The pilot ESP had 3 electrical and mechanical sections. At a nominal gas flow of about 1200 acfm, the maximum specific collection area was about 400 ft^2/kacfm. The high SCA allowed operation at very high collection efficiencies even with the most difficult (high resistivity) ash. This was important, given the focus of achieving ultra-high efficiency. The pilot ESP was also equipped with rappers for dust cleaning, as well as an ash transport and collection system

The precharger was located in front of the dry ESP unit (Figure 1) and all the ash-laden flue gas flowed through it. About 70 percent of the ash entering the ESP was collected in the precharger. A controlled portion of the flue gas leaving the dry ESP was routed to the wet ESP test section (Figure 1). The wet ESP test section consisted of 10 inch diameter, 6 feet long tube (collecting electrode) with a smooth wire discharge electrode. A sheath of water flowed down the length of the tube when the unit was operated wet. Tests were performed both with and without the water flow to measure the improvement from "wet" operation.

Measurement Methods: On-line opacity monitoring was the principal method used for measuring ESP performance. The opacity meter (Sick Optik-Electronik, OMD-41, Optical Density Monitor) was located at dry ESP outlet, straddled across a 6 feet length of the flue gas duct. The advanced self-correcting feature, which compensated for any fouling of the optical elements, allowed accurate long-term opacity measurements.

Particulate loading was measured at the dry ESP inlet and outlet and at the wet ESP outlet. EPA Method 5/29 was used for gravimetric measurements. Mass size distributions of the ash leaving the ESP were obtained with a Berner-type low pressure impactor (BLPI).[9,10] The BLPI resolves the ash sample into 11 size classes between 0.01 and 25 μm. The sampling system for the BLPI measurements is shown in Figure 2.

Vapor phase mercury measurements were made using a modification of the Mercury Speciation Adsorption (MESA) method (Figure 3).[11] The modified MESA system employs two iodated carbon traps assembled in series, with a quartz wool plug installed within a quartz probe upstream of the traps. Particulate in the sampled flue gas is trapped in the quartz wool. The iodated carbon traps are analyzed for the mercury by Cold Vapor Atomic Fluorescence spectroscopy and data converted to a vapor phase mercury concentration in the flue gas.

Results

Two low sulfur coals were evaluated in two separate test campaigns: an Eastern Kentucky bituminous coal (0.6% sulfur) and a Powder River Basin (PRB) sub-bituminous coal (Cordero - 0.3% sulfur). They are typical of the two classes of low-sulfur coals available in the United States. An abbreviated analysis for the two coals is provided in Table 1.

Table 1. Coal Selection - Selected Composition Data

	E. Kentucky- Bituminous	Cordero (sub-bituminous, PRB)
Ash Content (weight%)	8	5.5
Weight% Sulfur	0.6	0.3
Weight% Na_2O	0.9	1.6
Weight% K_2O	2.5	0.2
Weight % Fe_2O_3	5.5	5.4
Weight % (CaO + MgO)	1.6	30.3

As indicated earlier, the focus was on low-sulfur coals with moderately high resistivity and difficult-to-collect fly ash. Tests on the precharger and wet ESP were limited to the PRB coal. The results of the ESP performance as a function of the the operating parameters is discussed next.

Effect of Flue Gas Temperature: Flue gas temperature is one of the most critical parameters affecting ESP performance. For the test discussed here with the PRB coal, the ESP configuration included only the precharger and the C-field. A and B-fields of the dry ESP were turned off. The initial ESP inlet temperature was 340^{o}F. It was decreased in two steps: first to 270^{o}F and then to 215^{o}F (Figure 4).

The opacity plot (Figure 4) shows that there is a dramatic reduction in emissions as a result of decreasing flue gas temperature. Opacity decreased from 33 percent at 340^{o}F to 18 percent at 270^{o}F and to 11 percent at 215^{o}F. Clear stack opacity was 10 percent (optical element fouling) during these tests, indicating a very low outlet particulate loading when the ESP was operated at 215^{o}F.

The voltage-current (V-I) data from the ESP indicated back corona during operation at the high temperature. Ash resistivity was measured to be $8x10^{11}$ Ω.cm at 340^{o}F and $6x10^{10}$ Ω.cm at 215^{o}F. No back corona was observed at 215^{o}F. The operating voltage in both the precharger and the C-field increased significantly as the flue gas temperature was lowered from 340 to 215^{o}F. Both the decrease in back corona and the increase in the operating voltage are responsible for the reduced emissions at low flue gas temperatures.

ESP performance improved dramatically for the East Kentucky bituminous coal as well, when flue gas temperature was lowered. With three fields (A, B and C) in operation in the continuous charge mode, the outlet emission was between 90 and 100 mg/Nm^3 at 300^{o}F (150^{o}C) and between 5 and 10 mg/Nm^3 at 215^{o}F (102^{o}C).

Effect of Flue Gas Humidity: Flue gas humidity is determined by the hydrogen content in the coal as well as the coal moisture content. Combustion of sub-bituminous coal generates a higher flue gas moisture content compared to a bituminous coal. Flue gas humidity cannot be independently varied in full-scale operation easily. In our testing, moisture was introduced at high temperature, in the flue gases leaving the main furnace.

Flue gas moisture could therefore be independently controlled from flue gas temperature.

The as-received Cordero coal had about 30 percent moisture. In the field, all of this moisture is introduced into the pulverizer and then to the boiler. As the fuel-feed system in the pilot first dries the coal and then transports only the coal to the pulverizer, the final moisture content of the as-fired coal was about 10 percent. To make up the moisture deficit, standard operation of the pilot furnace included continuous injection of water in the top of the furnace to achieve the same flue gas humidity as would be expected in the field. This was considered as the baseline condition. The effect of altered humidity levels was studied by changing the water injection rate from this baseline operation.

Figure 5 shows opacity data for different humidity levels at a constant flue gas temperature (340^{o}F). The precharger and C-fields were in operation during this test. Opacity dropped from 25 percent at the baseline humidity level to 15 percent when the humidity was increased by 60 percent above the baseline value. Clear stack opacity was 6 percent during these tests. Improved ESP performance with increasing humidity results from decreased dust cake resistivity and increased operating voltage. This effect is similar to that observed with decreasing flue gas temperature.

Effect of Pulsing with SIR: In the pilot-scale unit, the impacts of various modes of electrical operation were evaluated by varying current settings, types of charging (pulsed versus continuous charge), and, in the case of pulsed operation, the pulse characteristics.

The effect of pulsing on the outlet emissions and particle size distribution is shown in Figure 6 for the E. Kentucky coal. Flue gas temperature was maintaned at 300^{o}F during these tests and all the 3 fields were in operation. Emissions decreased from 35 mg/Nm^3 in the continuous charge mode to 15 mg/Nm^3 in the pulsed mode.

For an optimally operating ESP, there needs to be a balance between the ions generated at the discharge electrode and arriving at the dust cake surface and their transport through the dust cake to the collecting electrode. If the resistivity of the dust cake is too high, there is an excessive buildup of negative charges in the dust cake, leading to a discharge in the cake (back corona). The negative impacts of back corona include (i) dispersal of collected ash into the flue gas stream and (ii) generation of positive ions, which discharge the negatively charged particles in the flue gas. Pulsing regulates the production of ions at the discharge electrode and hence can minimize back corona.

The positive effects of pulsing were noted throughout the size spectrum (Figure 6). Detailed outlet size distributions were measured using the low pressure impactor (BLPI). Measurement of such size distribution data is necessary for identifying retrofit solutions that can address potential fine particulate ($PM_{2.5}$) emission regulations.

Precharger Operation: A constant collecting area was used as the basis for comparing the precharger performance with that of a standard ESP. One of the potential advantages of the precharger is the smaller volume for a given collecting area compared to a standard ESP. The first configuration consisted of the precharger and C-fields in operation. This was contrasted to the case with half the A-field (same collecting area as the precharger) and the C-field in service. Figure 7 shows the outlet size distribution for the two cases.

The precharger configuration gave higher emissions overall. However, in the particle size range below 1 µm, the performance was similar for the two configurations (Figure 7). Overall, the potential savings in space requirements with the precharger may provide an advantage is some commercial applications. Further development is necessary before the precharger can be considered for commercialization.

Wet ESP Operation: Results of the particulate emission measurements with the wet ESP are shown in Table 2. The original design of the wet ESP included stabilizers in the hopper which held the discharge electrode centered in the WESP tube. During operation, the water tracked the stabilizers, creating a path to ground. High voltages needed for a corona could therefore not be created. The problem was solved by using a free-hanging weighted discharge electrode.

Table 2: Particulate Test Results For Wet ESP

	Particulate Results					Field	Current	WESP	Test #/
	Dry ESP Outlet	Wet ESP Outlet	Date	WESP mA	WESP kV	Strength kV/cm	Density nA/cm^2	SCA ft^2/kacfm	Water
gr/dscf	0.017	0.0074	19-Nov	0.7	32	2.61	47.87	82	1/On
% removal		56.5							
gr/dscf	0.018	0.0078	20-Nov	0.7	32	2.61	47.87	78	2/Off
% removal		56.7							
gr/dscf	0.0144	0.0138	20-Nov	0	0	0.00	0.00	NA	3/On
% removal		4.2							

Comparing Tests 1 and 2 in Table 2, we see that the water had no effect on particulate removal efficiency under the pilot-test conditions. The flue gas temperature at the WESP inlet was 270^{o}F. At the WESP outlet, the flue gas temperature was 180^{o}F with the water on and 240^{o}F without flowing water. There are two reasons for the little difference seen between the wet and dry cases. Since a significant amount of ash was not present in the flue gas stream, there was only a small amount of ash buildup on the collecting electrode. This combined with the low temperature in the wet ESP, even when operated dry, meant that the ash resistivity was not high enough to cause back corona problems.

Test 3 shows that the test methods used at the WESP inlet and outlet compare well. These tests confirm that the water, without power on, did not remove any particulate. The water's effects were on the electrical conditions and flue gas temperature.

It is worth noting that similar ESP performance was achieved in the wet and dry modes when the cylindrical ESP section was operated at low flue gas temperatures.

Mercury Testing: Mercury data for various tests with the Cordero coal are summarized in the adjoining table (Table 3). Both Method 29 and iodated carbon traps (modified Frontier Geosciences Method) were used for determining mercury concentrations in the flue gas.[11]

The data show the importance of flue gas temperature on mercury removal from the flue gas. The inlet concentration of about 14 mg/Nm^3 at 310^{o}F(155^{o}C) corresponds to the value of 0.17 ppm Hg measured in the coal. Very little Hg removal occurred across the main ESP (Test 1) or across the "wet" ESP section when operated in a dry mode (Test 5) at the high temperature.

When the flue gas temperature was lowered (Test 7) the inlet mercury loading decreased by a factor of two to 7.2 mg/Nm^3 at 275^{o}F(135^{o}C). The concentrations at the main ESP outlet at this operating condition (Tests 8-10) were in the range of 6-8.8 mg/Nm^3 at 265^{o}F(130^{o}C), indicating again minimal removal across the ESP. Most of the reduction due to lowering of the flue gas temperature seems to be in the duct leading up to the main ESP.

When the wet ESP is operated in a "wet" mode, the flue gas is cooled significantly because of water evaporation. This is evident in the temperature differential between the inlet and the outlet of the wet ESP. A portion of the mercury in the flue gas is removed in the wet ESP due to this large temperature drop (Test 6,11).

The preferential removal of mercury as the flue gas is cooled identifies the importance of maintaining low flue gas temperatures in particulate removal devices. A lower flue gas temperature is also synergistic with sorbent injection schemes and may lead to lower sorbent consumption and increased mercury capture.

Table 3 : Mercury Measurement Results

Test #	Location	Method	Temperatures (^{o}C)	Hg Concentration Total (µg/Nm3)	Hg Concentration Vapor (µg/Nm3)
1	Main ESP Inlet	Iodated Carbon Trap	(155)	13.51	1.89
2	Main ESP Outlet	Method 29	155	14.1	--
3	Wet ESP Out (wet/on)	Iodated Carbon Trap	152/132/75**	9.63	9.35
4	Main ESP Outlet	Iodated Carbon Trap	155	6.41 (!!)	6.41
5	Wet ESP Out (dry/on)	Iodated Carbon Trap	152/134 /120**	13.76	13.66
6	Wet ESP Out (wet/off)	Iodated Carbon Trap	152/132/75**	5.89	5.58
7	Main ESP Inlet	Method 29	135	7.2	---
8	Main ESP Outlet	Method 29	130	8.8	
9	Main ESP Outlet	Iodated Carbon Trap	130	6.04	6.04
10	Main ESP Outlet	Iodated Carbon Trap	130	6.14	6.14
11	Wet ESP (wet/on)	Iodated Carbon Trap	130/117/--**	4.19	4.02

** Temperature at Main ESP Outlet / Wet ESP Inlet / Wet ESP outlet
!! Data Point does not fit trend

Summary

Results of the pilot-scale testing identified the "low temperature ESP" concept to have the biggest impact for the two low sulfur coals investigated. Lowering the flue gas temperature to 220^{o}F provided the maximum impact in terms of decreased emissions. Intermediate operating temperatures (reduction from 340 to 270^{o}F) also gave significant ESP performance improvement. A significant reduction in particulate emissions was also noted when the flue gas humidity was increased (temperature held constant) from the baseline condition for these moderately high resistivity ash coals. Independent control of flue gas humidity and temperature was an important and a notable element in this project.

Mercury emissions were also measured as a function of flue gas temperature. Mercury emissions decreased as the flue gas temperature was lowered, indicating the native ability of ash to capture the mercury.

Pulsed operation of the ESP with the SIR module provided a 2 to 3-fold reduction in emissions at the higher operating temperatures.

In light of the positive results from Phase I, we propose proof of concept testing in the field in Phase II. The main objective of the Phase II testing would be to determine the ESP performance improvement as a function of flue gas temperature and humidity for a range of low-sulfur coals being fired by utilities. Equally important will be the long-term evaluation of the risk of corrosion and plugging (due to acid condensation) associated with low temperature operation. The impact of higher flue gas velocities (lower SCA-specific collection area), compared to the laboratory pilot program, would also need to be evaluated. A secondary objective would be to examine mercury capture by the ESP at the different temperatures and with sorbent injection.

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Advanced ESP Modules Testing

- **Flue Gas Cooler**
- **Precharger**
- **Switched Integrated Rectifier**
- **Wet ESP**

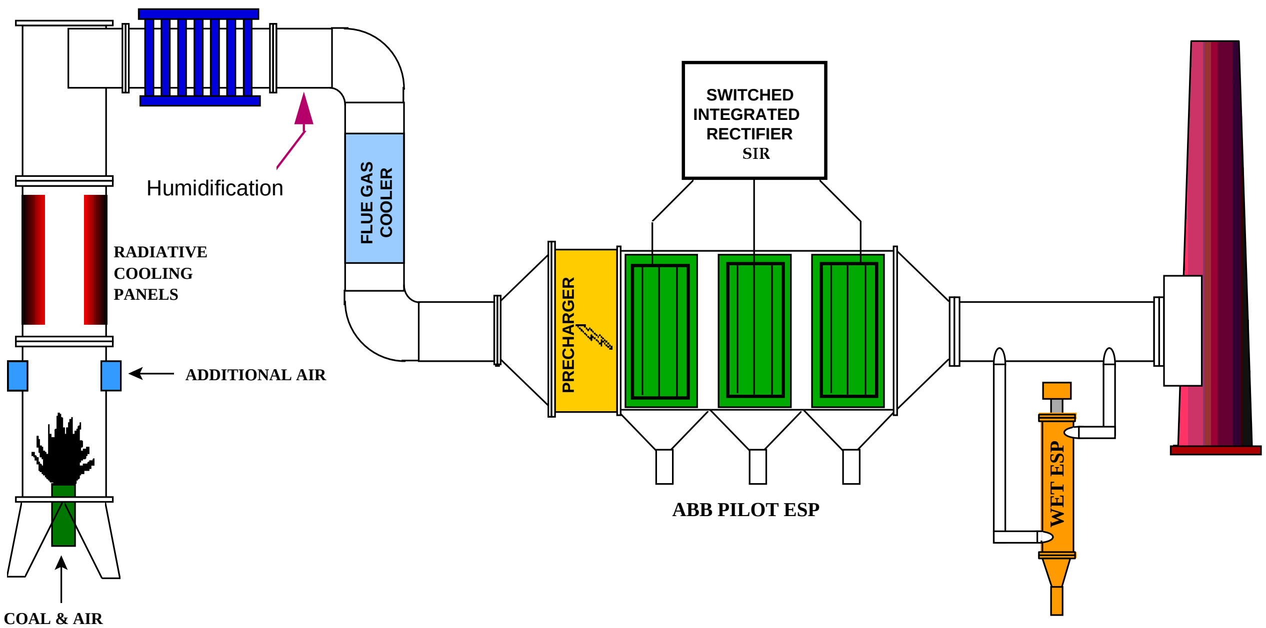
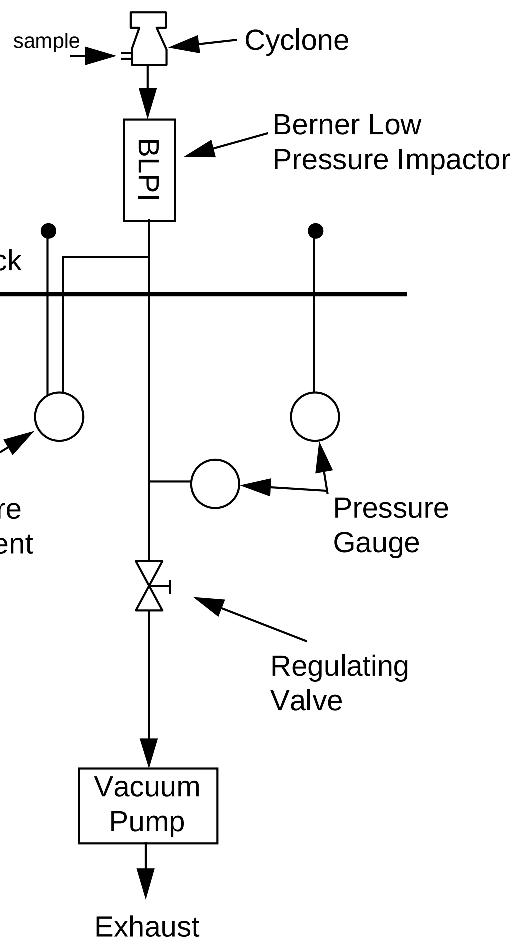


Figure 1

Figure 2: Flue Gas Particulate Sampling System



Note: ESP Outlet Measurement is Without Cyclone

Figure 3: Sketch of Modified Mercury Specification Absorption (MESA) Sampling Train for Total Mercury Measurements

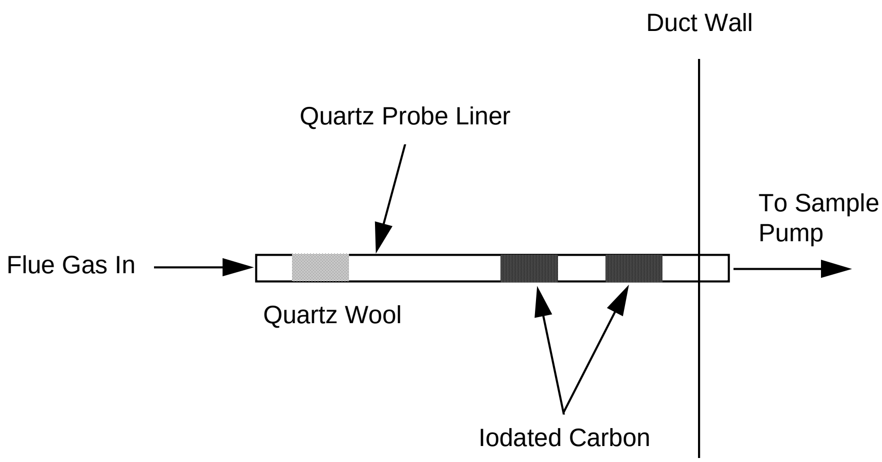


Figure 4 - Effect Of Flue Gas Temperature On Opacity (Cordero Coal)

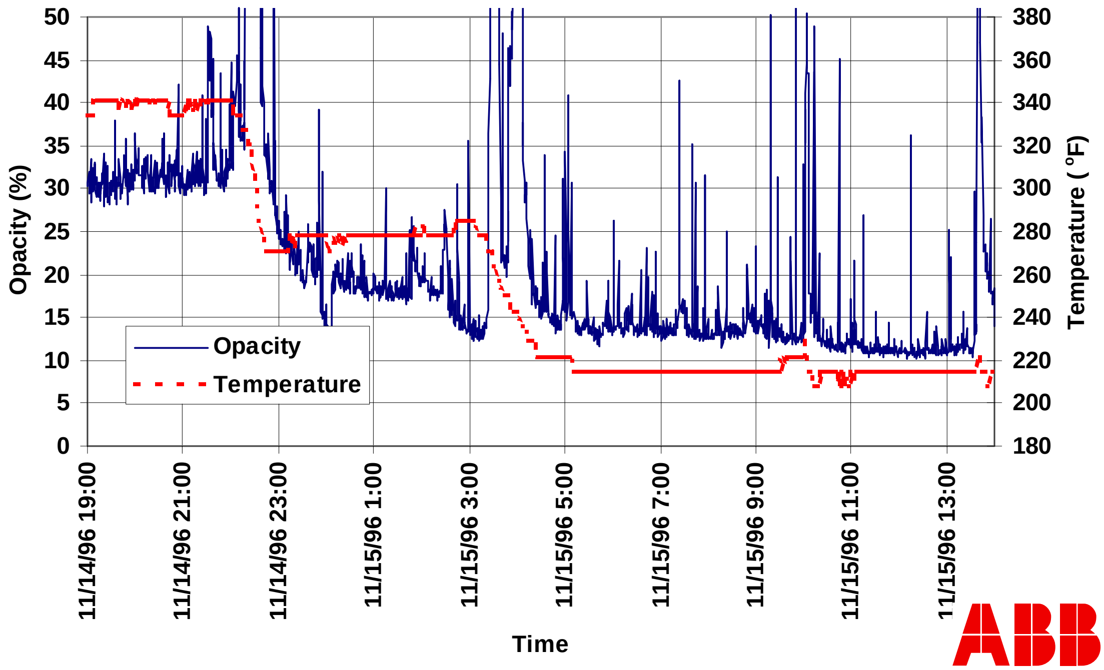


Figure 5 - Effect Of Humidity On Opacity

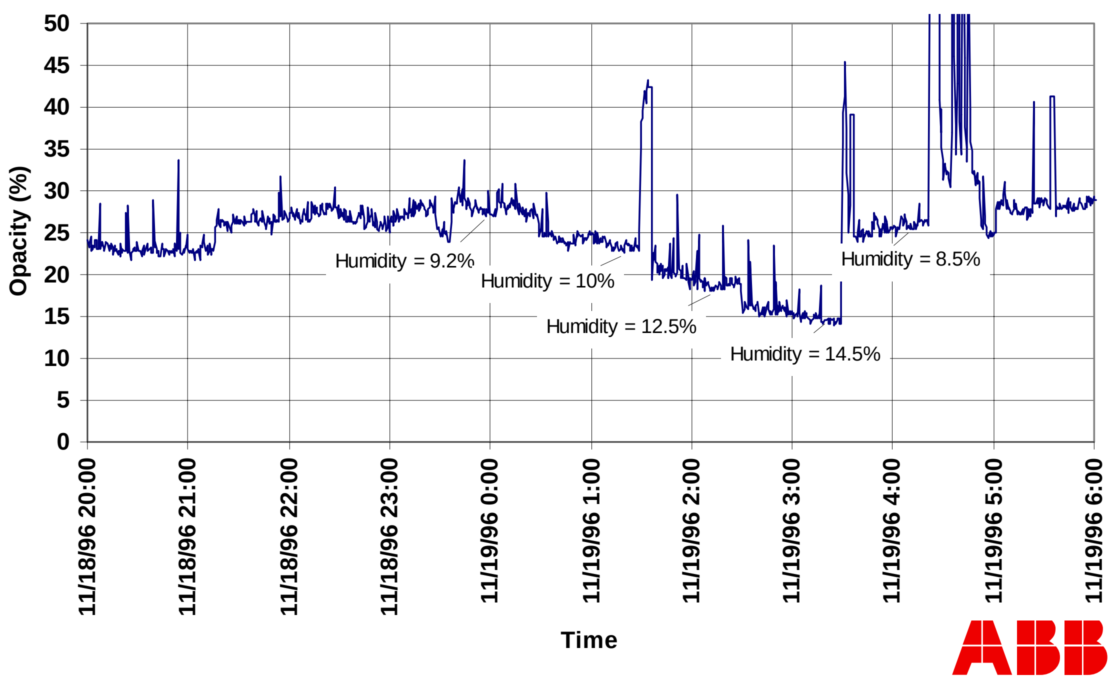


Figure 6 - Effect of Pulsing With the SIR on Outlet Emissions and Size Distribution (E. Kentucky Coal)

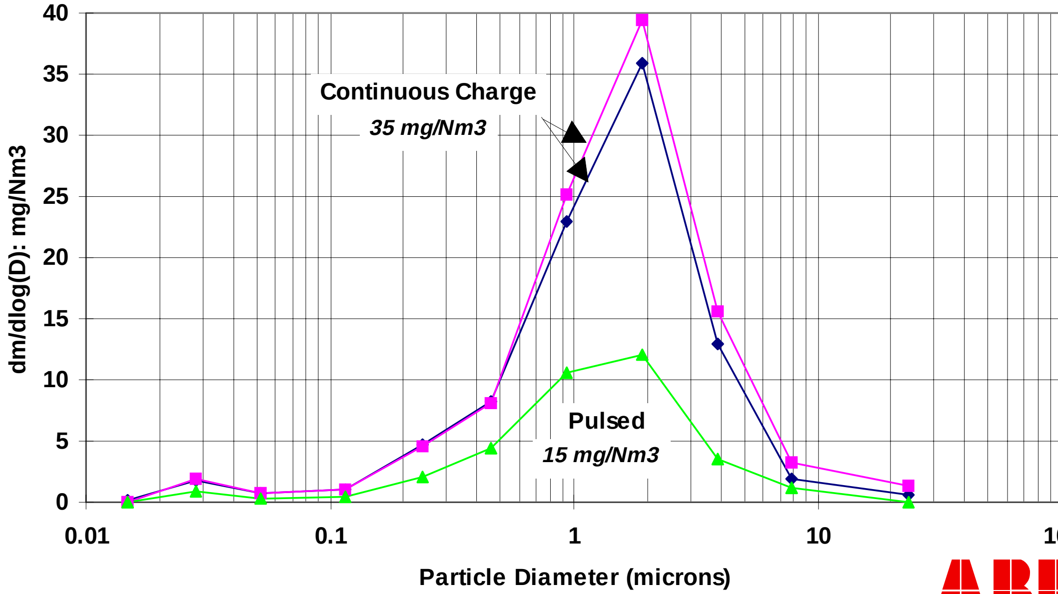


Figure 7 - Comparison of Outlet Emissions: Precharger versus Standard Configuration