RESISTIVITY CONDITIONING OF AFBC GENERATED ASH

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Abstract

The downstream collection of sorbent and fly ash from dry, calcium-based SO_2 control processes is a critical issue for these processes. The electrical resistivity of the resulting particles can be high at typical cold-side electrostatic precipitator temperatures. High resistivity predictably reduces precipitator performance. Flue gas conditioning has traditionally been used to reduce the resistivity of fly ash from pulverized-coal-fired boilers, but there is little experience with its use in dry SO_2 control processes. The EPRI Conditioning Sidestream Pilot system was developed to evaluate the effect of conditioning agents on a small slipstream of flue gas so that the conditioning option could be evaluated without costly full-scale trials. This system was utilized at the Nucla AFBC to evaluate the effects of both SO_3 and water conditioning on the high resistivity dust generated by that device. Details of the CSSP and the results obtained at Nucla are presented in this paper.

Introduction

Dry, calcium-based, SO_2 control systems significantly affect the properties of the dust particles suspended in the process gas stream. These particle properties, in turn, affect the performance of downstream particulate control devices. When an electrostatic precipitator (ESP) is used as the particle control system, a major effect is the increased electrical resistivity of the ash/sorbent mixture. For SO_2 control systems which do not produce low outlet gas temperatures, the resistivity of the ash/sorbent particulate may be four orders of magnitude higher than a high-sulfur coal ash. The extremely high resistivity can result in very poor ESP performance, especially on small existing ESPs typical of retrofit situations.

Laboratory measurements made in simulated flue gas environments have indicated that the resistivity of all ash/sorbent dusts can be reduced to reasonable levels with either addition of SO_3 vapor or humidification/cooling of the gas stream. However, the accuracy of the laboratory simulation with these dusts has not been proven. Full-scale results at Edgewater indicated that resistivity could be reduced and ESP performance substantially improved by humidification of dusts generated by furnace sorbent injection [1]. However, pilot-scale combustor data suggested that furnace sorbent injection dusts might not condition well with reasonable levels of SO_3 addition [2]. No full-scale data are available on the effects of conditioning on AFBCs which use sorbent in the bed for SO_2 control. In the absence of adequate data, informed decisions about control device selection during design of combined SO_2-particle control systems are not possible.

To better understand the issues involved in resistivity conditioning of ash/sorbent mixtures and AFBC dusts in particular, a test program was conducted at the Nucla AFBC of Tri-State Electric Generation and Transmission Association. Previous measurements made at Nucla had indicated that the dust produced by that furnace had the highest resistivity of any observed on AFBCs [3]. The measurement program evaluated both SO_3 conditioning and humidification on a slipstream of gas taken from the main Nucla duct at the inlet of the baghouse. The results of the test program and the implications to ESP performance will be discussed in later sections of this paper.

The slipstream conditioning system used at Nucla was developed specifically for this project, although it has other applications. This system will be described in the following section. Also, a special system for sampling SO_3 in the presence of sorbent particles had to be used at Nucla. This system will be briefly described in a subsequent section.

Description of Conditioning Sidestream System

The Conditioning Sidestream Pilot System (CSSP) was developed for this project to allow evaluation of conditioning processes on a small scale, but in the actual flue gas environment produced by a full-scale combustor. The main components of the CSSP are illustrated in Figure 1. The system was designed to return the same results which would be obtained if the conditioning process was conducted in the main duct and the resistivity measured with a point-plane probe.

The CSSP extracts flue gas from the duct with a probe fixed with a right angle nozzle. The nozzle velocities are approximately isokinetic with the duct velocity to minimize basing the particle size distribution. The flue gas flow rate is measured and controlled to provide 1) a known volume for conditioning rate calculations, 2) sufficient gas velocity in the system to prevent particle dropout, and 3) reasonable residence times for the desired chemical reactions. Typical system gas flow is 140 acfm at 300°F. In addition to an inlet gas heater for temperature adjustment, essentially the entire gas handling system is heat-traced to maintain constant temperatures and avoid cold spots where condensation of conditioning agent could occur. Extensive monitoring facilities of both gas and wall temperatures are installed. System flow is produced by an induced draft fan close to the system outlet to minimize effects on the particulate stream. The treated flue gas is finally returned to the power plant duct. Returning the conditioned gas to the main duct will not affect the operation of the plant because of the very small volume involved. (The CSSP extracts less than 1/2000 of the flow of a 100 MWe generating unit).

The conditioning agents are added at the top of the piping system in Figure 1. The conditioned gas immediately enters the large vertical chamber which was designed to give residence times of 1-2 seconds without the 50-100 feet of ductwork that would be required at full duct velocity. The chamber is oriented vertically to prevent particle setting at the low gas velocities. The larger diameter of the chamber is also necessary to reduce wall-wetting during water addition. After exiting the vertical chamber, the conditioned gas enters the measurement section, where the dust electrical properties are determined with a shortened version of the standard point-plane resistivity probe. The resistivity port is designed so that typical gas velocities are maintained when the probe is inserted. Although not shown in the drawing, a port is installed just downstream of the resistivity port for measurement of flue gas chemistry.

The chemical conditioners used at Nucla were SO_3 and water. The SO_3 was generated by passing known quantities of SO_2 gas over vanadium pentoxide at elevated temperature (1000°F). Validation measurements indicated that the system could produce concentrations of 100 ppm in the CSSP gas stream with SO_2 to SO_3 conversion efficiencies of 94-98%. The humidification system utilized a Spraying Systems two-fluid spray nozzle to produce a fine mist of water droplets. This system proved capable of producing a 110°F temperature drop of the gas stream without serious wall-wetting or deposit accumulation.

Vapor-Phase SO_3 Measurement System

Determining SO_3 vapor concentrations in the presence of active calcium-based sorbent is notoriously difficult. Reaction of the free sorbent in the fly ash and the SO_3 vapor will occur readily if given the opportunity, resulting in much lower than true concentrations. Measurement of the residual SO_3 in the gas stream requires that the dust particles be removed from the sample stream prior to collection of the SO_3 by condensation as H_2SO_4. Removing the particulate by the standard method of simple filtering, provides, in effect, a packed-bed reactor for the reaction of the calcium and flue gas acids. To obtain the most accurate measurements possible, it is

necessary to remove the particulate as quickly as possible with as little interaction between the particles and gas.

The system utilized for SO_x sampling during this project was developed by Burdett and Hotchkiss of the CEGB [5] and is shown in Figure 2. Two stages of inertial separation are employed to rapidly remove the majority of the sorbent from the sample gas. The residence time in the system of the sampled gas is less than 0.5 seconds. The final filtering of the remaining particulate occurs at high temperature (550°F) to prevent reaction on the filter cake. The theoretical size cut of the second-stage cyclone collector was less than 0.5 μm, and this was supported during the Nucla tests by the very small mass collected on the final filter. The remainder of the system (not shown in Figure 2) consisted of a standard Cheney-Homolya controlled-condensation SO_x measurement system. Analyses of sulfate concentrations on the filter catch indicated that the system performed as expected during the tests and that significant losses of SO_3 vapor did not occur in the sample system. Total sulfate content of the filter catch accounted for less than 2 ppm SO_3 during all tests.

Nucla Plant Description

The Nucla Station of Tri-State Electric Generation and Transmission Association is a 110 MWe circulating-bed, atmospheric-pressure, fluidized-bed combustor (AFBC) designed by Pyropower. A hot cyclone is installed between the radiant furnace and the convective heat-transfer sections for recovery of large particulate for recycle to the bed. Pulverized calcitic limestone is continuously added to the lower combustion chambers for SO_2 control. During the test program, the Ca/S ratio ranged from 1.76 to 2.72 with an SO_2 removal efficiency calculated from the coal analysis and measured SO_2 concentrations of approximately 80%.

The fuel burned during the test program was a subbituminous coal from western Colorado with an average sulfur content of 0.89% The coal had a low moisture content for a subbituminous coal (7.1%), but a high ash content (25%). The relatively low sulfur combined with low inherent calcium in the coal ash resulted in a fairly low calcium content of the ash-sorbent dust mixture of around 11%. The chemical composition and other physical parameters for samples of the ash/sorbent dust removed from the baghouse hoppers are provided in Table 1. The B.E.T. surface area values of approximately 10 m^2/g shown in the table are fairly typical of AFBCs which range from 4-25 m^2/g [6]. These surface areas are considerably higher than ash/sorbent mixtures generated by other SO_2 control processes, which are typically 7 m^2/g or less. The high surface area has the potential to produce a particle which is highly reactive and difficult to condition.

Test Results

SO_3 Conditioning

Measurements of the resistivity and vapor phase SO_3 concentrations were made in situ with five levels of SO_3 addition to the CSSP gas stream. Table 2 shows the results obtained with SO_3 addition rates of 0, 25, 60, 80, and 100 ppm. During baseline operation (0 ppm added), the resistivity averaged 4.5×10^{12} ohm-cm at 294°F with the seven measured values ranging from 1.8×10^{12} to 1.4×10^{13} ohm-cm. These resistivity values are as high as any we have successfully measured with a point-plane probe and would result in very poor ESP performance. The baseline data measured in the CSSP are indistinguishable from those measured in the main Nucla duct. There was no measurable SO_3 vapor in the gas stream down to the lower limit of resolution of the measurement technique (0.3 ppm).

The addition of 25 ppm of SO_3 to the gas stream had no effect on the measured values of resistivity, and consistently, no free SO_3 vapor was measured in the gas stream. Apparently, all of the added SO_3 reacted with the alkaline components of the particulate and was not useful for reducing resistivity. At 60, 80, and 100 ppm both residual SO_3 was detected and resistivity was reduced, although only a small fraction of the added SO_3 was found in the vapor state. Even with the highest addition rate of 100 ppm, the resistivity was reduced to only the low 10^{11} ohm-cm range. Figure 3 illustrates the effect of residual SO_3 concentration on the measured resistivity values. The solid line on the graph is a linear regression to the logarithms of the data values with an r^2 of 0.91. For the cases where no SO_3 was detected, the SO_3 concentration was arbitrarily assigned a value of 0.1 ppm, just below the detection limit. The slope of the fitted line in log-log space is -0.8, which is considerably lower than the slopes of -2 and -5 typical of fly ashes [4].

The Nucla in-situ resistivity data agree with some of the results obtained with furnace injection of hydrated lime [2]. The furnace injection study found that resistivity of ash/sorbent mixtures could only be reduced to the low 10^{11} ohm-cm range with addition of 125 ppm SO_3 when the lime was injected at relatively low temperature (<2200°F). Lime which was injected at higher temperature (>2400°F) could be conditioned more effectively, suggesting that particle surface area may be important. Unfortunately, the surface areas of the two sets of samples in the furnace injection study were apparently not measured. Typical surface areas during hydrated lime addition in the furnace injection study were <5 m^2/g [12].

Figure 4 compares the in-situ data with the results of measurements of resistivity made in the laboratory on samples of dust from the Nucla baghouse hoppers. The lab measurements were made in a simulated flue gas environment of air containing the water content of the Nucla flue gas. Measurements were obtained with 0 and 4.9 ppm SO_3 vapor in equilibrium with the ash. With no added SO_3, the lab measurements agreed almost perfectly with the average of the in-situ results. With acid addition, the lab data are all lower than the in-situ values for the same SO_3 concentration. The lowest lab value is from 9/17 when the ash calcium content was the lowest and the sodium the highest observed for the program. Unfortunately, 9/17 was a baseline test

day and no in-situ data with SO_3 are available for comparison. It is not surprising that the lab values with SO_3 would be somewhat lower than the in-situ data considering the difference in equilibrium times of the measurements. The in-situ sample is exposed to acid vapor for only one hour while the lab sample may take up to a week of exposure to reach the equilibrium value defined by the standard technique. If the sample from 9/17 is excluded, a factor of 3 difference was obtained between the in-situ and lab measurements. This is usually considered fair agreement for these measurements, but since the lab measurements have the lower resistivity, projections of ESP performance made on that basis would be overly optimistic.

Figure 5 shows the same data as the previous two graphs with the addition of the resistivity values predicted from the dust compositions by the resistivity models developed by Bickelhaupt [4, 7]. Resistivity model version 2 is generally considered to be the current standard and is shown as the shaded region on the graph. The upper and lower bounds of the region represent the highest and lowest values predicted by the model for the various sample compositions. The model did correctly predict that the sample from 9/17 would have the lowest resistivity. Also, with no SO_3 present, the model did an excellent job of predicting the baseline resistivity values. However, the slope of resistivity as a function of SO_3 assumed by the model for this ash was -2, considerably greater than the slope of -0.8 calculated for the in-situ data. This difference in slope caused errors in resistivity of more than one order of magnitude at 5 ppm SO_3 and over two orders of magnitude at 15 ppm. The effect that this size of an error would have on predicted ESP performance would be considerable, making this model of questionable value with this dust.

The predicted relationship between resistivity and SO_3 from resistivity model 1A is shown in Figure 5 by the dashed line. The 9/17 sample was not used in this model. Although model 1A has a much more elementary resistivity vs SO_3 algorithm than model 2, it is still preferred by some users because it often provides more conservative estimates with low values of SO_3. On the Nucla dust, model 1A gives essentially the same result as model 2 up to about 4 ppm, and then drops precipitously to a value five orders of magnitude below the in-situ data at 15 ppm. Model 1A does not appear to be a useful or even conservative tool for predicting ESP performance during SO_3 conditioning with this dust.

Humidification

Measurements of resistivity were made over a wide range of gas temperatures using a water spray for flue gas cooling. Although some benefit is derived from the higher flue gas moisture content, the primary benefit to resistivity from humidification is from the temperature decrease. Gas temperature was dropped in six increments up to a maximum ΔT of 110°F. The highest level of humidification required increasing the flue gas moisture content by about 4.5% and resulted in actual gas temperature of 180°F. Some wall wetting was indicated at the higher addition rates by wall temperature readings in the main conditioning chamber which were lower than the final gas temperature. However, apparently the water droplets which struck the walls subsequently evaporated, since no serious wet deposits were found, and the actual gas temperature change agreed well with the addition rate. Figure 6 plots the measured gas temperature drop as a function of the measured flue gas moisture increase. The theoretical relationship is shown on the

figure by the solid line. This theoretical relationship takes into account not only the heating and evaporation of the added water, but also the cold air added by the injection nozzle. The agreement between theory and measurement indicates that water loss was not a problem during the Nucla tests.

As expected, humidification reduced the resistivity of the dust, with increasing effect at higher addition levels. The solid triangle symbols on Figure 7 represent the in-situ resistivity data during humidification. The data show approximately a straight line relationship between temperature and resistivity over the range tested with resistivity dropping to below $2x10^{10}$ ohm-cm at 180°F. This lowest temperature is approximately 50°F above the adiabatic saturation temperature. At this resistivity level, good performance should result even from a moderately sized ESP. To provide acceptable performance for somewhat larger ESPs, a target resistivity of $2x10^{11}$ ohm-cm would be appropriate. The Nucla data indicate that a temperature of 220°F is necessary to achieve this higher level of resistivity. This is a considerably lower temperature than was required to condition the sorbent/ash mixture during furnace sorbent injection at Edgewater [1]. During those tests, resistivity values of $2x10^{11}$ ohm-cm were obtained at temperatures of 275°F.

Figure 7 also compares the results of descending-temperature laboratory resistivity measurements to the in-situ data. The upper temperature of the measurement was limited to 488°F to prevent affecting the sorbent chemistry. Two sets of lab data are shown which represent the extremes in resistivity values obtained. The two lab sets include the lowest and highest moisture contents, combined with the highest and lowest inherent resistivity values to provide a range of expected values. These data show good agreement with the in-situ data with almost all in-situ values bracketed by the lab measurements. In sum, the lab measurements did a good job of estimating the effect of humidification on resistivity.

The model 2 estimates of the effects of temperature and moisture on resistivity are compared to the in-situ data in Figure 8. When no acid is present, the results of the two versions of the model would be similar. The agreement here is much better than was obtained with the model during SO_3 conditioning. However, the model did tend to underpredict the effect of humidification somewhat, which would result in a more conservative ESP design.

The reasonably good agreement between the model predictions and the lab and field measurements should be taken with a grain of salt. Because of the low sulfur coal and low inherent calcium content of the Nucla ash, there is much less calcium in these samples than would be present with another coal. The resistivity models have shown a tendency to dramatically underpredict resistivity with ash/sorbent mixtures which have high calcium contents [3].

ESP Performance Projections

As an illustration of the effects of the various conditioning methods on ESP performance, a series of hypothetical ESPs of varying sizes were modeled using the SRI mathematical model of ESP performance [8]. The particle size distribution, mass loading, etc., from the previous comprehensive Nucla AFBC evaluation [3] were used as input to the model. The physical hardware configuration used was a typical modern design with 12 inch collecting plate spacing. Two sets of non-ideal model conditions that have been established as representing typical full-scale ESPs [9] were used to provide a range of expected performance. Under humidification conditions, the effect of the change in gas volume was taken into account in addition to the effect on resistivity. The electrical operating conditions used in the model were estimated from the resistivity by a correlation developed from the EPRI ESP database [9].

Excessive levels of particle reentrainment have been observed in ESPs collecting ash/sorbent mixtures downstream of spray dryers [10, 11]. This reentrainment can reduce overall ESP collection performance dramatically under certain circumstances. However, this effect has only been associated with gas temperatures within 40°F of adiabatic saturation. We do not expect excessive reentrainment at the temperatures encountered with humidification at Nucla and no such effect was included in the model.

Theoretical ESP performance was computed for baseline (no conditioning), with 80-100 ppm of SO_3 addition, and two levels of moisture conditioning. The particle emission results are plotted as a function of ESP specific collection area (SCA) in Figure 9. The upper limit of each bounded area represents the poorer set of the model's non-ideal conditions and should be typical of older ESPs, while the lower limit should be more representative of modern ESPs in good condition. The model data indicate that, under baseline conditions, an ESP with an SCA over 800 ft^2/1000 acfm would be required to meet an emissions limit of 0.03 lb/10^6 Btu. However, with some of the higher resistivity values measured at Nucla ($1x10^{13}$ ohm-cm), even this estimate of performance may be optimistic.

With SO_3 conditioning to lower resistivity to $2x10^{11}$ ohm-cm, ESP performance would be improved substantially. In this case, an ESP with an SCA of 450 ft^2/1000 acfm or larger could meet 0.03 lb/10^6 Btu. Humidification to 220°F results in the same level of resistivity as with SO_3 conditioning, but slightly better performance results from the lower gas viscosity at the lower temperature. The reduced gas volume with humidification also increases SCA for the same physical size of ESP. This means that an ESP with an unhumidified SCA of 400 ft^2/1000 acfm should be able to meet emissions requirements. In addition to shrinking the gas volume and decreasing viscosity, humidification to 180°F produces nearly ideal dust resistivity and good ESP performance should result. With high levels of humidification, an ESP with a humidified SCA of 350 ft^2/1000 acfm (SCA without humidification of 300 ft^2/1000 acfm) should provide acceptable performance.

Summary and Conclusions

The dust produced by the Nucla AFBC has very high resistivity in the absence of flue gas conditioning. The average resistivity was $4.5x10^{12}$ ohm-cm at 300°F with values as high as $1x10^{13}$ measured. Electrical power input to an ESP collecting this dust would be very limited by the resistivity and performance would be very poor. An ESP of at least 800 ft^2/1000 acfm would be required to meet a particle emission rate of 0.03 lb/10^6 Btu.

Conditioning the dust with SO_3 vapor was successful in lowering the resistivity. However, much higher addition rates were required than are typical of fly ash installations, and the resistivity was not lowered as much as desired. All of the added SO_3 was consumed by the ash with 25 ppm of addition. At 60 ppm addition and higher, free SO_3 vapor was found in the gas stream with an increasing fraction remaining as vapor with higher addition rates. With 80 and 100 ppm addition, the resistivity was reduced to only $1x10^{11}$ ohm-cm despite 10-15 ppm of SO_3 vapor in the gas. While this would dramatically improve ESP performance compared to the baseline resistivity values, many small retrofit ESPs would not provide acceptable performance at this level. An ESP with an SCA of 450 ft^2/1000 acfm would be advisable for collection of this dust.

The difficulty in conditioning this dust is probably related to the remaining calcium sorbent and the high particle surface areas. Although the sidestream test indicated that 100 ppm of SO_3 addition was able to lower resistivity to $1x10^{11}$ ohm-cm, we have some concerns about whether the resistivity of the collected dust would remain low. Reaction of the alkaline particle interior with the surface acid film will consume the adsorbed acid, which must be continuously replenished to maintain low resistivity and unimpeded current through the dust layer. The 15 ppm which remained in the gas phase after 1.5 seconds of residence time may not be sufficient to keep all the collected dust in an ESP conditioned. Higher addition rates than those tested may be required to provide this replenishing acid vapor all the way to the outlet fields of the ESP. It would seem likely that sufficient SO_3 must be added to provide free acid vapor at the outlet of the ESP, not just at the inlet.

Humidification was more successful at reducing resistivity than was SO_3 conditioning and provides an additional benefit to ESP performance in shrinking the flue gas volume and increasing SCA. (However, water addition without creating wet duct deposits may be technically more difficult than SO_3 conditioning.) Humidification to 220°F reduced resistivity to approximately the same value as 100 ppm of SO_3 addition. As for SO_3 conditioning, an ESP with an SCA of 450 ft^2/1000 acfm should be able to meet 0.03 lb/10^6 Btu. However, because of the reduced gas volume, a humidified ESP with an SCA of 450 ft^2/1000 acfm corresponds to only 400 ft^2/1000 acfm prior to humidification (300°F). When additional water was added to reduce temperature to 180°F, the resistivity was reduced to the range considered ideal ($2x10^{10}$ ohm-cm). In this case, an ESP with an unhumidified SCA of 300 ft^2/1000 acfm should be able to meet 0.03 lb/10^6 Btu. These temperatures are sufficiently high that the low resistivity reentrainment problems observed in ESPs downstream of scrubbers should not be a problem.

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Table 1
ASH/SORBENT DUST PROPERTIES

	9/17/92	9/19/92	9/21/92	9/22/92
Li_2O	0.02	0.03	0.03	0.02
Na_2O	0.32	0.15	0.15	0.14
K_2O	1.2	1.0	0.9	0.9
MgO	0.85	0.75	0.77	0.73
CaO	7.4	10.1	11.9	10.9
Fe_2O_3	3.1	3.1	3.4	3.3
Al_2O_3	27.3	28.5	28.7	27.9
SiO_2	54.3	50.2	48.1	49.2
TiO_2	0.8	0.9	1.2	1.0
P_2O_5	0.07	0.03	0.04	0.03
SO_3	3.5	3.9	3.5	3.6
LOI	2.2	4.5	4.9	4.3
B.E.T, m^2/g		10.1	9.6	

Table 2
RESISTIVITY AND SO_3 RESULTS DURING ACID CONDITIONING

SO_3 Concentration, ppm		Gas Temperature, °F	Dust Resistivity, ohm-cm
Injected	Measured		
0	<0.3	294	4.5×10^{12}
25	<0.3	292	4.5×10^{12}
60	4.6	299	2.2×10^{11}
80	9.9	307	1.5×10^{11}
100	14.1	299	1.1×10^{11}

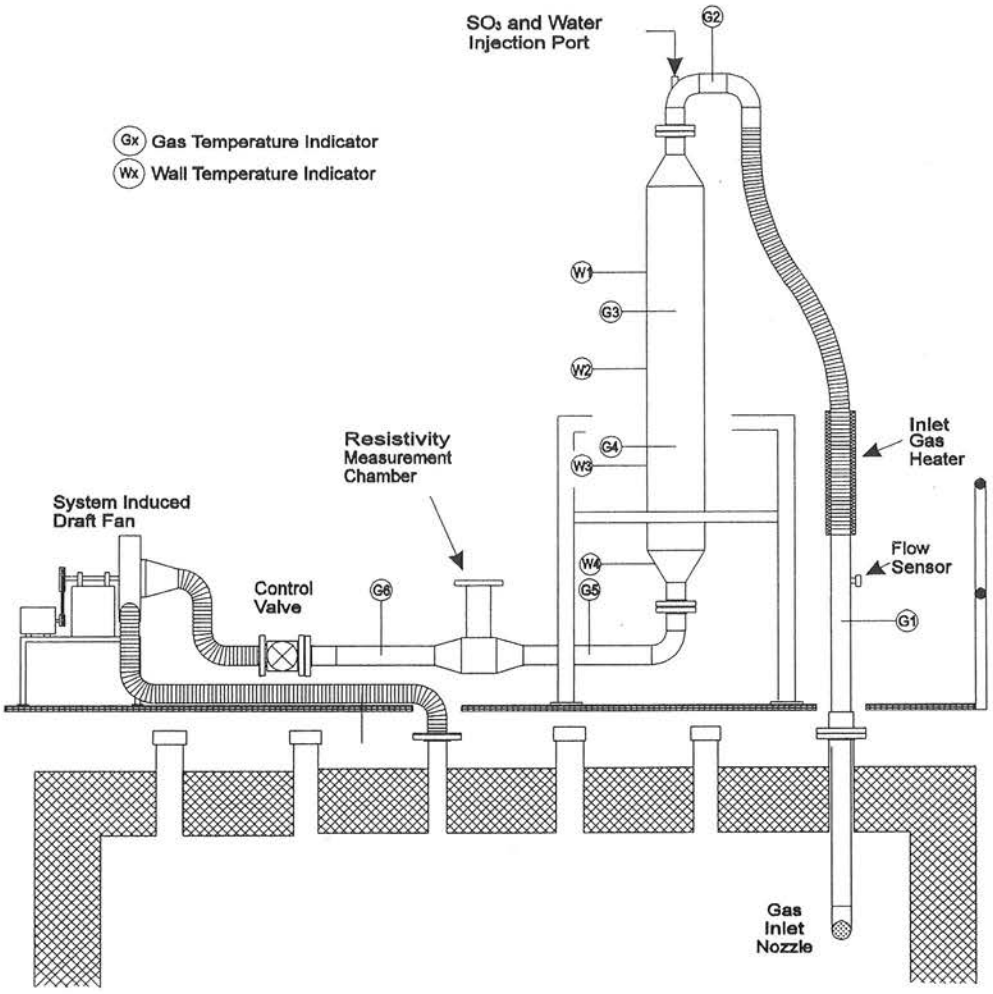

Figure 1. Conditioning sidestream system.

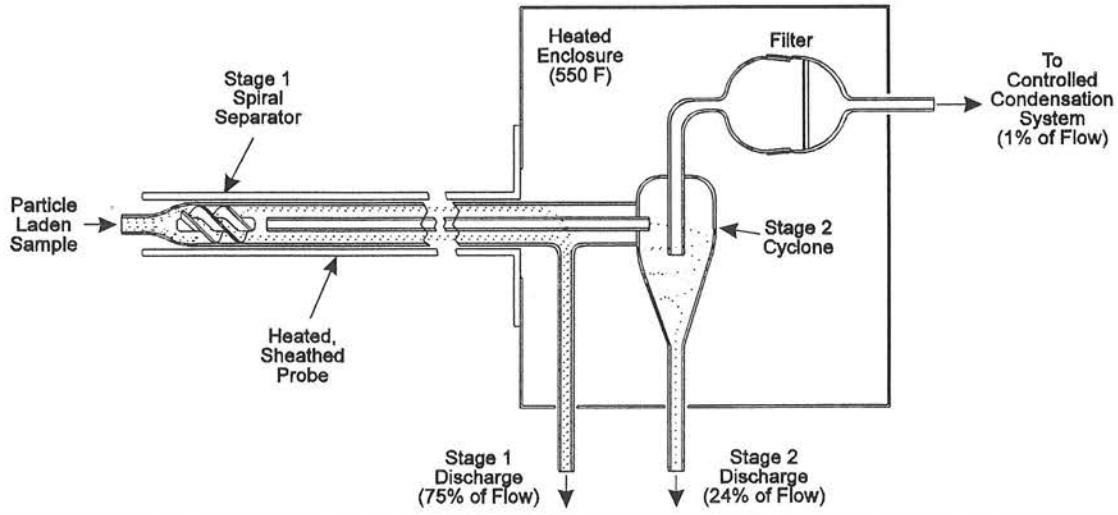

Figure 2. Inertial separation SOx sample probe.

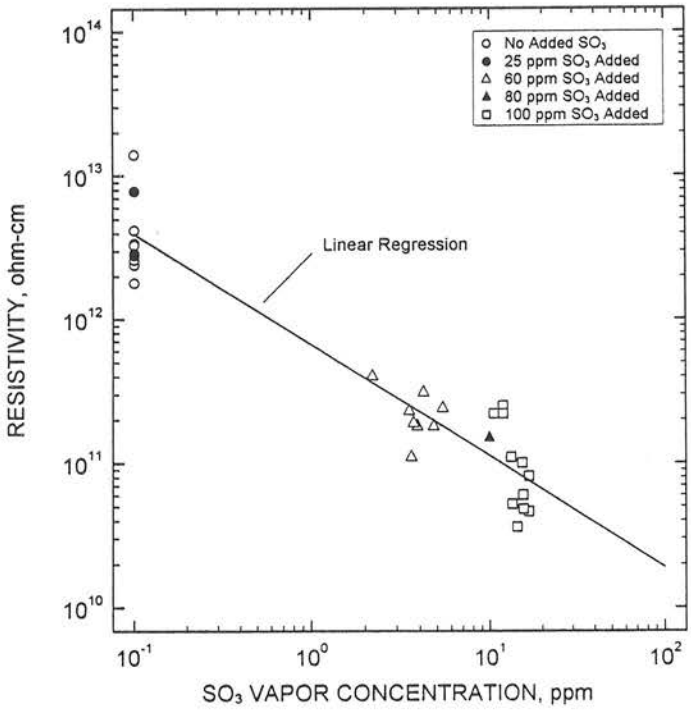

Figure 3. Nucla afbc in-situ resistivity as a function of SO_3 concentration.

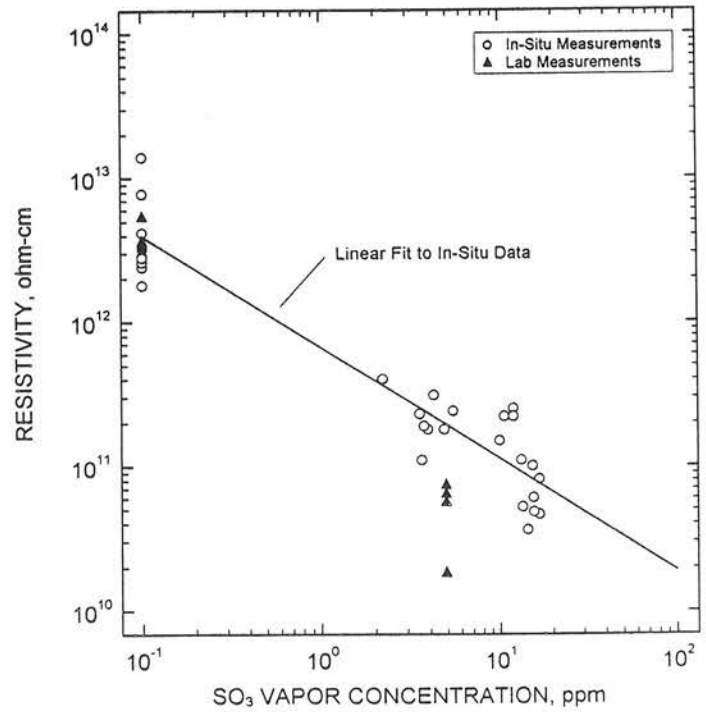

Figure 4. Comparison of in-situ and lab resistivity as a function of SO_3 concentration.

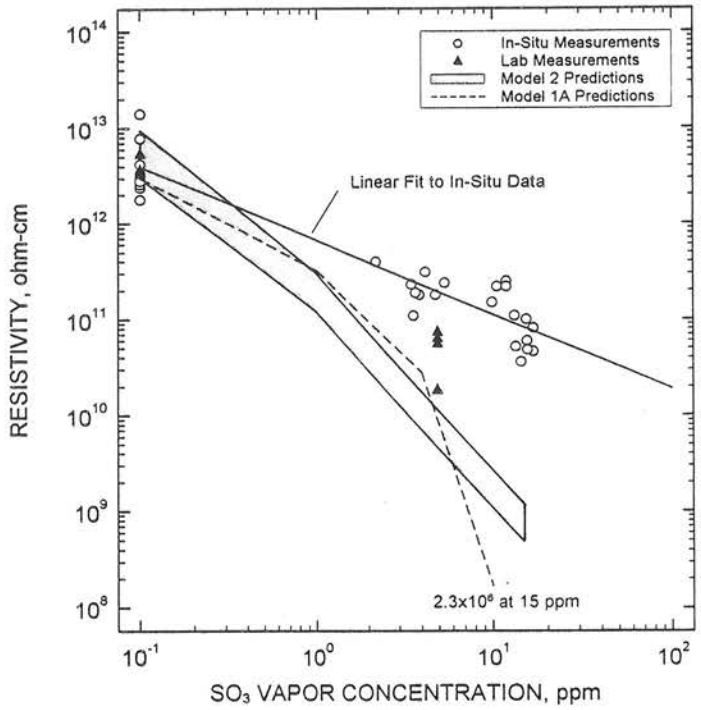

Figure 5. Nucla resistivity as a function of SO_3 vapor concentration.

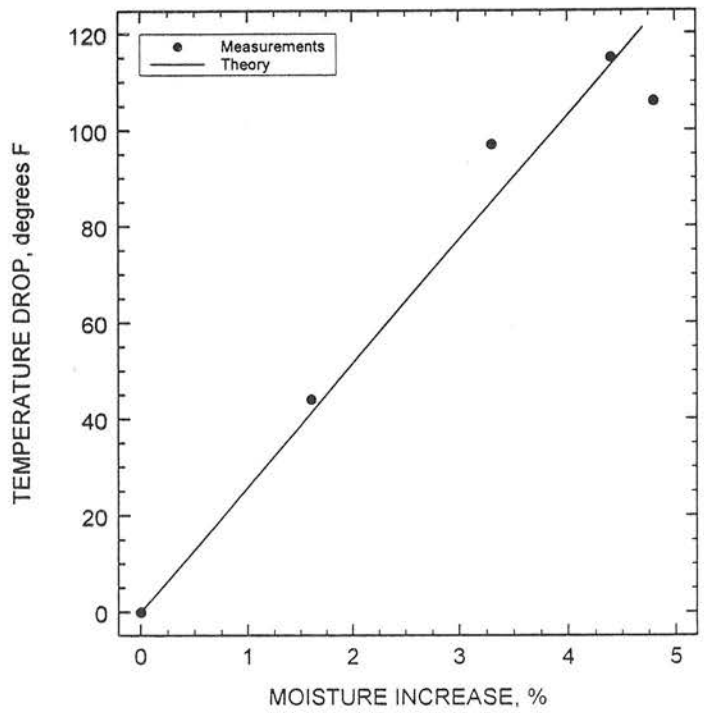

Figure 6. Nucla flue gas moisture increase as a function of flue gas temperature drop.

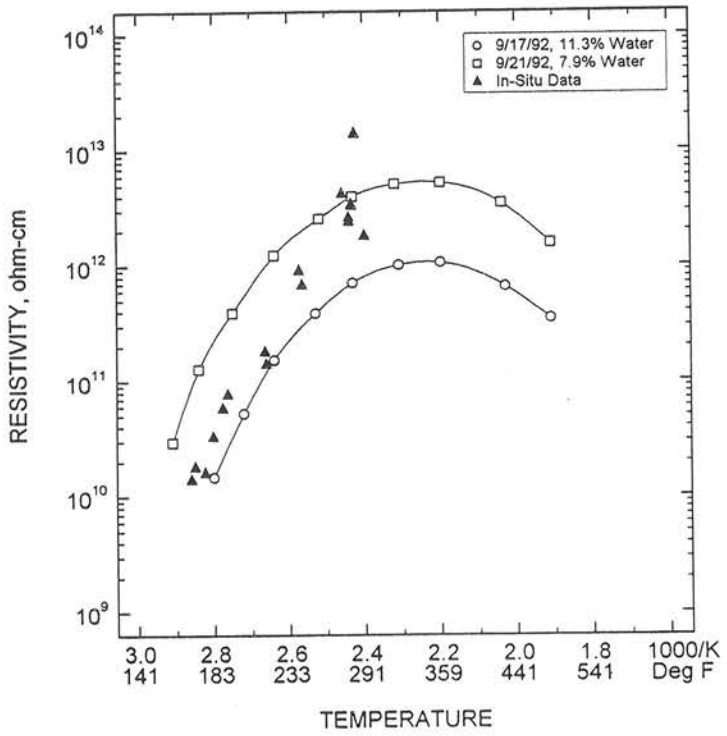

Figure 7. Comparison of low-temperature lab descending and in-situ resistivity data.

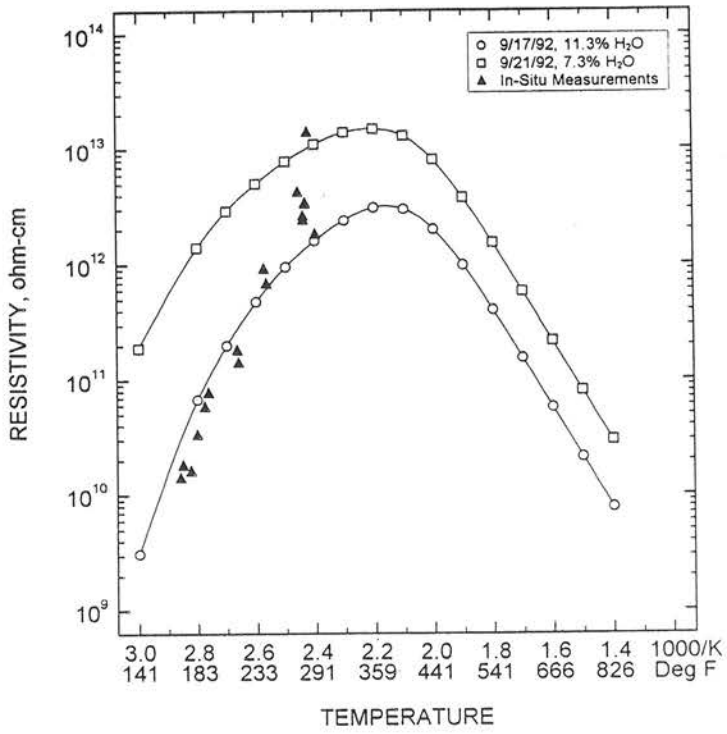

Figure 8. Comparison of predicted and measured dust resistivity during humidification.

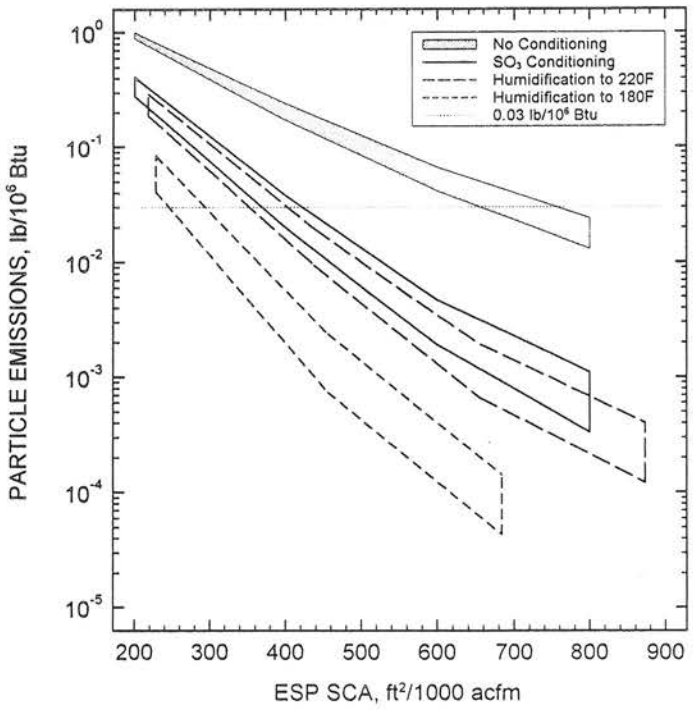

Figure 9. Effects of various conditioning strategies on ESP performance.