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**FUNDAMENTAL MECHANISMS
IN FLUE GAS CONDITIONING**

QUARTERLY REPORT

April 1995 - June 1995

Prepared for

U.S. DEPARTMENT OF ENERGY
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INTRODUCTION

This project is divided into four tasks. We developed our Management Plan in Task 1. Task 2, Evaluation of Mechanisms in FGD Sorbent and Ash Interactions, focused on characteristics of binary mixtures of these distinct powders. Task 3, Evaluation of Mechanisms in Conditioning Agents and Ash, was designed to examine effects of various conditioning agents on fine ash particles to determine mechanisms by which these agents alter physical properties of ash. We began Tasks 2 and 3 with an extensive literature search and assembly of existing theories. We completed this phase of the project with publication of two special Topical Reports. In our literature reviews reported in Topical Reports 1 and 2, we emphasized the roles adsorbed water can have in controlling bulk properties of powders. During the next phase of the project we analyzed a variety of fly ashes and fine powders in the laboratory. The experiments we performed were primarily designed to define the extent to which water affects key properties of ashes, powders, and mixtures of sorbents and ashes. We have recently completed a series of pilot-scale tests designed to determine the effects that adsorbed water has on fabric filtration and electrostatic precipitation of entrained fly ash particles in actual flue gas environments. Under Task 4 we will issue our Final Report that will summarize the results of our laboratory and pilot-scale work and will also include a model of flue gas conditioning.

Our efforts during this reporting quarter have been directed toward production of the Draft Final Report and the Flue Gas Conditioning Model. In addition to these efforts, we have prepared a paper for presentation at the Eleventh Annual Coal Preparation, Utilization, and Environmental Control Contractor's Conference to be held in Pittsburgh in July, 1995.

MODELING THE EFFECTS OF FLUE GAS CONDITIONING

We took a pragmatic and phenomenological approach to the development of a model of flue gas conditioning that could be used in conjunction with existing models of particulate control devices. The nature and scope of this project precluded the derivation of anything but a generalized, empirical model. We, nevertheless, studied the fundamental interactions between particles and their environment in order to make sure that our empirical findings were consistent with the basic mechanisms that govern interparticle interactions. Our study entailed the literature survey and the laboratory analyses completed earlier in the project.

We found in our study that conditioning agents affect fine particle collection in control devices by one of two mechanisms that alter particulate properties: adsorption of the agent onto particle surfaces, or addition of sufficient numbers of particles of different surface chemistry and morphology to change the bulk properties. The latter mechanism applies largely to processes whereby solid sorbents are added to a gas stream to capture vapors (e.g., lime for SO₂ capture, or carbon for Hg capture), although the use of additives to improve filtration performance is another application of this mechanism. In general, this mechanism by which bulk properties are changed does not require a distinct model; rather, existing models of particulate control processes apply when the new bulk chemistry of the particulate matter is used as input to the models.

The mechanism of adsorption of conditioning agents onto particle surfaces does entail more subtle effects on particulate control systems. There are, in fact, distinct effects on electrostatic precipitation

and fabric filtration that can be predicted. Therefore, these effects can be incorporated into the models of these particulate control processes. The following discussion describes separately the enhancements to the models of fabric filtration and electrostatic precipitation.

FABRIC FILTRATION

The existing model of fabric filter performance was developed at Southern Research Institute for the Electric Power Research Institute (Pontius and Marchant, 1991). The model describes the pressure drop across a fabric filter as sum of resistances to flow, some of which are in series and some are in parallel. The relationships of the parameters included in the model are shown in Figure 1.

Flue gas conditioning affects, primarily, the filtering resistance of the dust cake. This is affected by altering ash properties in some way. Our research in this project has demonstrated that the adsorption of agent onto the surface of particles tends to increase the cohesivity of the bulk powder. The formation of liquid bridges between particles increases the interparticle bonds. Since the particles adhere to one another more firmly, they build a more porous agglomerate. Porosity is a major variable in determining the resistance to flow through an agglomerate. The following equation expressed the dependence of flow resistance on porosity:

$$R = \Delta p / (WU) = (\mu / D^2) \cdot [1 / (\rho(1-\epsilon))] \cdot [(1-\epsilon)^2 / \epsilon] \cdot [30 + 36.2(1-\epsilon) - 143(1-\epsilon)^2 + 2240(1-\epsilon)^3]$$

in which:

R = specific gas flow resistance of the porous bed, $\mu\text{bar}/[(\text{g}/\text{cm}^2) \cdot (\text{cm}/\text{s})]$

Δp = pressure drop across the porous bed, μbar

W = areal mass loading of the porous bed, g/cm^2

U = face velocity of the gas, cm/s

μ = gas viscosity, poise

D = drag-equivalent diameter of the ash, cm

ρ = average true density of the ash particles, g/cm^3

ϵ = porosity of the porous bed, dimensionless ($0 < \epsilon < 1$).

Anything that increases porosity without altering other ash properties (in particular, particle morphology) will decrease the flow resistance. We have shown in this project that flue gas conditioning, in the form of elevated water vapor content, decreases the flow resistance through filter cakes. Our conclusion is that increasing relative humidity forms liquid bridges among the particles so that the filter cake that is built up as the ash is deposited has an increased porosity.

Increased porosity, or decreased flow resistance, is expressed as a component of fabric filter models in the parameter known as K_2 , the specific drag coefficient of the filtered material. K_2 is equivalent to the relative gas flow resistance, R. The definition of K_2 is as follows.

$$K_2 \propto (\Delta P_t - \Delta P_e) / tV^2c$$

in which:

BAGHOUSE DESIGN DATA

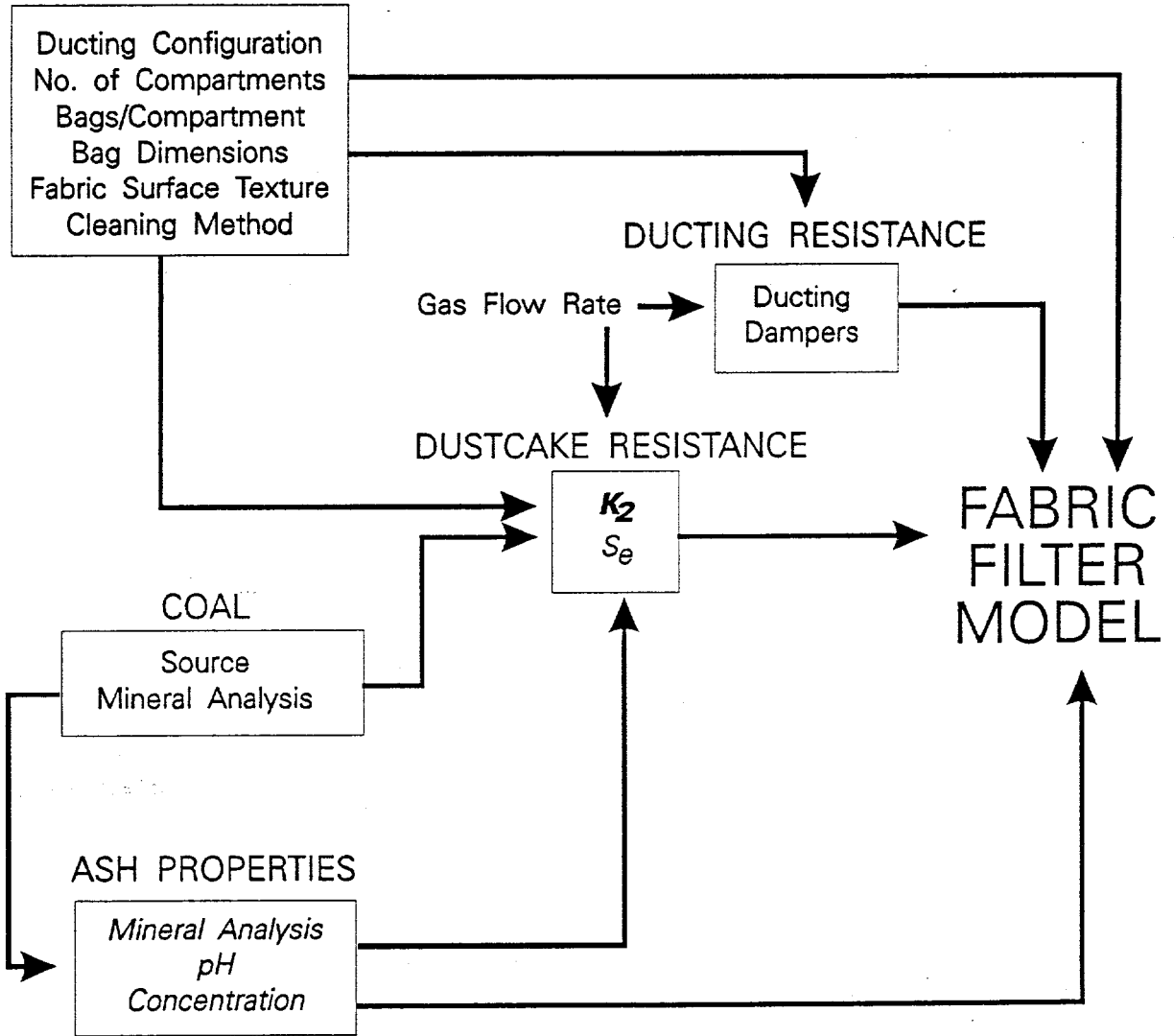


Figure 1. Fabric Filter Model Components.

ΔP = pressure drop
 t = filtration time
 ΔP_e = effective pressure drop after cleaning
 V = air-to-cloth ratio
 c = grain loading.

K_2 is implemented in the fabric filter model, as shown in Figure 1, through empirical relationships that we developed between filtering drag and ash properties. Our approach for including the effects of conditioning agents on fabric filter performance is to add an adjustment to K_2 as a module on the existing fabric filter model. With the empirical results from our pilot-scale tests, and previous data, we can estimate the nature and scale of the adjustment factor required to predict the effects of a conditioning agent on K_2 .

Data that we have collected suggest that the degree to which a conditioning agent alters K_2 is mainly dependent on the concentration of the additive. In our study, we evaluated water vapor as the additive, and there were noticeable effects of particle surface chemistry and morphology on the relationship between K_2 and water vapor concentration. In the case of a generic additive, added as a liquid or vapor to the particle-laden flue gas, we can not assume exactly the same moderating effects of surface chemistry or morphology (though morphology is likely to have similar effects). So, we propose a model of flue gas conditioning that expresses a simple relationship between K_2 and the concentration of the additive.

We have taken the data from laboratory and pilot-scale filtration tests to determine the empirical dependence of K_2 on the concentration of conditioning agent (in this case, water vapor). Relative humidity is the expression of water vapor concentration that normalizes all of our data; this choice is necessary because of the usually non-isothermal effect of the addition of water vapor, or the purposeful variation of temperature to change the relative partial pressure of water in the flue gases. The values of K_2 assigned to the data were derived from the rates of change of pressure drop, normalized by the filtering face velocities and the particulate loadings of the filtered gases. Filtration data plotted in Figure 2 show a consistent, monotonic relationship between K_2 and water vapor concentration.

A logarithmic relationship, also shown in Figure 2, provides an acceptable model with which to predict K_2 as additive concentration changes. We can use this relationship as the basis of a model for the effects of conditioning agents on filtration properties. A primary justification for this approach is the finding from this project that the mechanism by which any agent alters particulate properties is at least analogous to, if not equivalent to, the adsorption of water vapor onto the particle surfaces. Furthermore, we have shown that the effects of coal and ash properties on filtration performance also follows a logarithmic relationship (Bush *et al*, 1989). This is additional support for our interpretation of the mechanism involved in conditioning particles.

Therefore, we propose that the following adjustment be incorporated into filtration models whenever flue gas conditioning is used for the purpose of altering ash cohesivity:

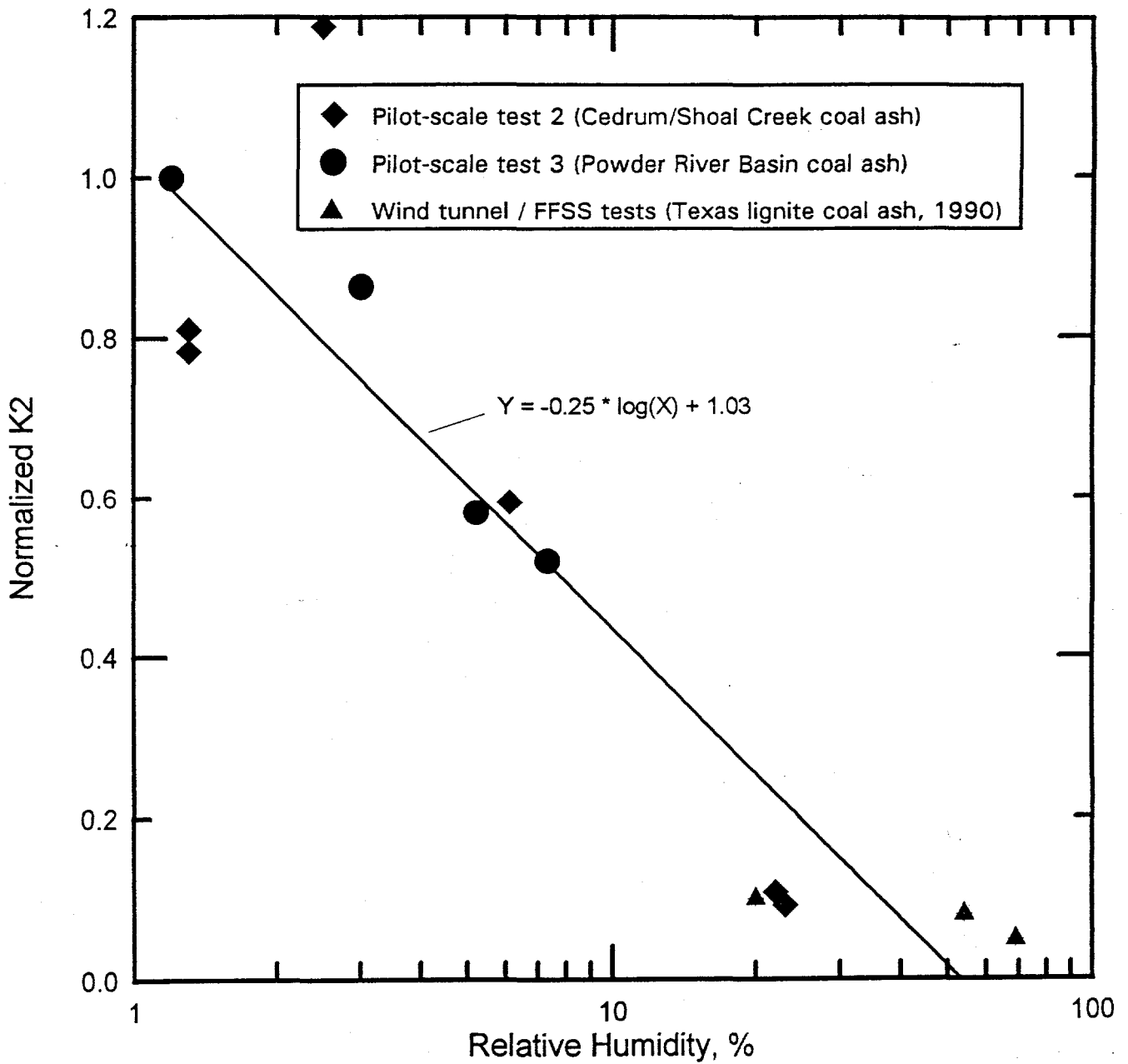


Figure 2. Relationship showing the dependence of normalized K_2 on the relative humidity of the gas being filtered. The logarithmic relationship shown provides an acceptable model with which to predict K_2 as additive concentration changes.

$$K'_2 = K_2 \cdot (-\alpha \cdot \text{LOG}(\eta) - 1)$$

in which α is the scale factor defined for each additive, and η is the concentration of additive in the flue gas. In the case of water vapor, as shown in Figure 2, the value of α is approximately 0.25, with the concentration, η , expressed in terms of relative humidity.

This expression for modifying K_2 is the only modeling extension that we feel is reasonable to formulate based on our data. The mechanism by which conditioning agents alter dust cake porosity is also the mechanism governing the tendency of particles to penetrate through the dust cake. Certainly it is true that increasing ash cohesivity through the use of additives affects emissions (Felix *et al.*, 1986, Miller and Laudal, 1987). In the exceptional cases where ashes are very non-cohesive, the use of additives can have dramatic effects on emissions. Nevertheless, we have not addressed any effects of additives on fine particle collection efficiency in the context of predictive modeling. There are no existing models of industrial filtration processes that can predict emissions. Generally, emissions in industrial filters are dominated by leaks not directly associated with dust cake properties. (This is the main reason fabric filters tend to have constant efficiency performance for all particle sizes.)

ELECTROSTATIC PRECIPITATION

Parameters that are involved in the modeling of electrostatic precipitation are shown in Figure 3. The two inputs that are modified by conditioning agents are electrical resistivity and emissions from so-called 'non-ideal effects', such as rapping. Electrical resistivity modifications are extremely important to the performance of ESPs, evidenced by the fact that almost all flue gas conditioning for ESPs has focused on this parameter. And flue gas conditioning for resistivity modification is a mature technology, with roots as far back as 1912 (White, 1963). Because of its importance and the wealth of experience in practice, the effects of flue gas conditioning on electrical resistivity are well known. Predictive models of the electrical resistivity of fly ash were developed in the 1970s at Southern Research Institute (Bickelhaupt, 1975, Bickelhaupt, 1979). These resistivity predictions have become accepted components of ESP models, and the work described in this report does not add to these capabilities.

We can bring some new understanding of the effects of flue gas conditioning on emissions associated with reentrainment. Reentrainment in an ESP is the process by which a fraction of emissions are attributable to particles that have been, at one or more times in their passage through the ESP, precipitated onto the collection plates. These particles are either scoured off of the collecting surfaces, are electrostatically repelled from the collecting surfaces, or reenter the gas stream when the electrodes are rapped because they do not form agglomerates of sufficient size to settle into the ESP hoppers. In any case, reentrainment can be considered a phenomenon dependent on the combined effects of electrical and cohesive forces.

By decreasing electrical resistivity of ash, the electrical force that holds ash to the collecting plate (called the electrical clamping force) is reduced. For ashes with very high resistivity, conditioning and the resulting lower resistivity would lessen the clamping force enough to improve rapping

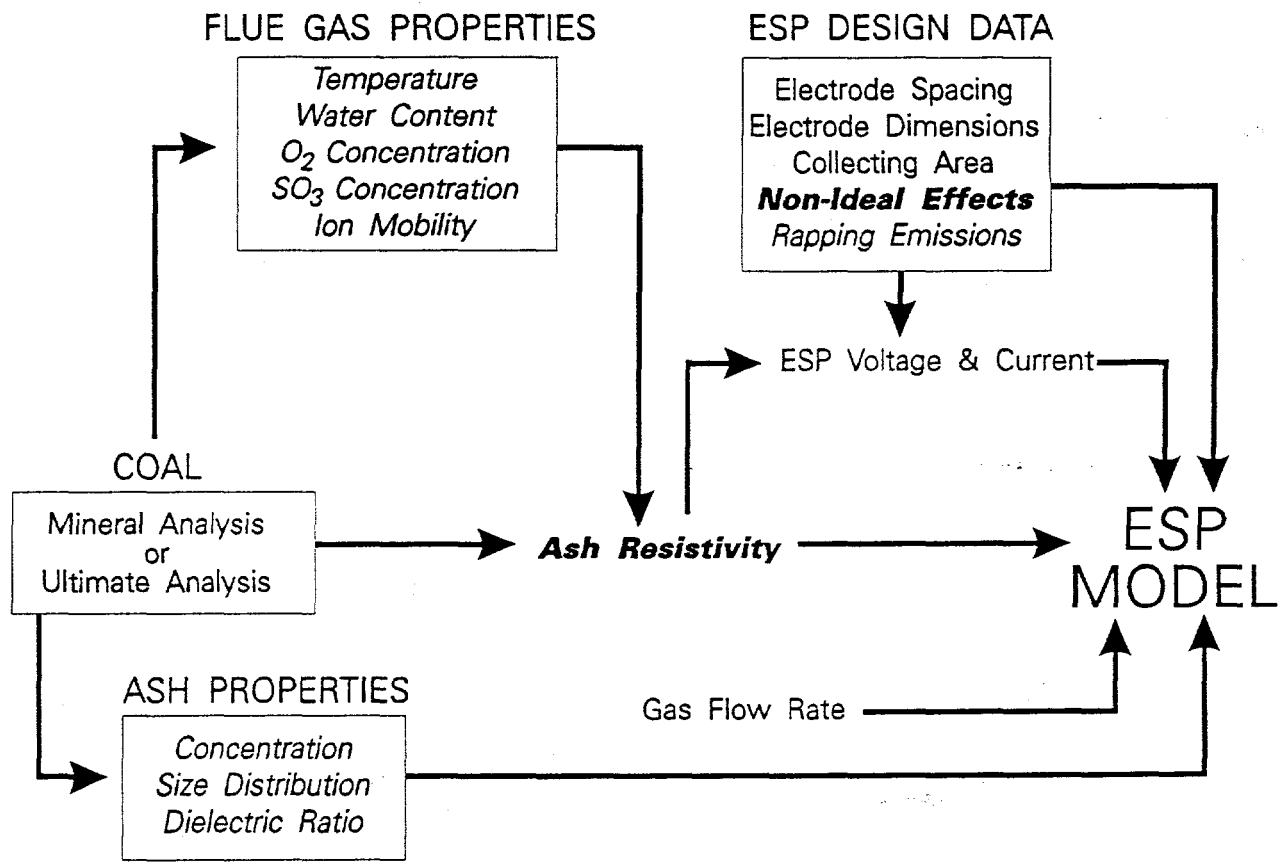


Figure 3. ESP Model Components.

efficiency and reduce the dust layer thickness on collecting electrodes. The resistivity of ash would have to be below 5×10^8 ohm-cm before any appreciable non-rapping reentrainment would be expected. The amount of conditioning agent injected to accrue the benefits of lower resistivity should be limited to the amount that results in ash resistivity in the range of 5×10^8 to 2×10^{10} ohm-cm.

Flue gas conditioning, while reducing the electrical clamping force, can alter the tensile forces holding the collected particles together. Depending on the conditioning agent and the ash, it is possible to increase the tensile strength enough to suppress reentrainment. There is a body of empirical data that shows that water and calcium chloride have both acted in this manner (Brindle *et al*, 1995, Durham, Holstein *et al*, 1991).

Reentrainment is incorporated into existing ESP models through the selection of the non-ideal parameters s , representing sneakage and reentrainment, and σ_g , representing the non-uniformity of gas flow. In the absence of mechanical problems, the performance of ESPs collecting fly ash is typically bracketed by values for (s, σ_g) of 0.05, 0.15 and 0.10, 0.25 (Dubard and Dahlin, 1987).

Data on ESP performance for cases in which particulate properties were altered by processes for flue gas desulfurization show that the existing models of ESP performance provide acceptable predictions if appropriate values of the non-ideal parameters, (s, σ_g) , are used (Landham and Cushing, 1994). Based on field tests for a variety of FGD processes, the conclusion was made that there was the potential for increased reentrainment from those processes in which water spray is used to enhance the reaction between a sorbent and SO_2 . The explanation for these observed increases in emissions was the combination of a reduction in electrical resistivity of the particulate matter (caused by low temperature and high water vapor content) and an inherently low tensile strength of the mixture of sorbent and ash (Landham and Cushing, 1994).

We propose adopting the following modeling approach for ESPs with flue gas conditioning:

1. Use the existing model to predict electrical resistivity of the particulate matter in the presence of the flue gas conditioning agent, incorporating the chemistry and temperature effects of the conditioning process.
2. If the resultant electrical resistivity of the particulate matter is greater than 10^9 ohm-cm with the flue gas conditioning process, use the standard range of ESP model non-ideal parameters (for s a range of 0.05 to 0.10, and for σ_g a range of 0.15 to 0.25) to model the ESP performance.
3. If the resultant electrical resistivity of the particulate matter is less than 10^9 ohm-cm with the flue gas conditioning process, use for s a range of 0.25 to 0.40, and for σ_g a value of 0.25.

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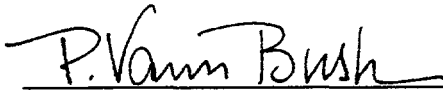
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