ICESP X – Australia 2006
Paper 8A2

UPGRADE TECHNOLOGIES FOR ELECTROSTATIC PRECIPITATORS

LENA LILLIEBLAD[1*] AND CHRISTER MAURITZSON[1]
[1]ALSTOM Power Sweden AB
P.O. Box 1233
SE-35112, Växjö
Sweden
[*]Correspondence to: lena.lillieblad@power.alstom.com

ABSTRACT

Electrostatic precipitators (ESP's) are commonly used for collection of particles in power plants and industrial applications. There are many ESP's around the world not meeting today's requirements due to aging, process changes and more stringent regulations for emission limits. Before ESP performance improvements can be considered, measures must be taken to ensure that the equipment is mechanically sound. Once this is accomplished there are various upgrade technologies available to improve the ESP performance. In order to choose the most appropriate upgrading technology it is necessary to have a good knowledge about the site-specific conditions. Measures can be taken to:

- Avoid or reduce the effect of high resistivity dust
- Reduce re-entrainment of dust caused by rapping or high gas velocity
- Change the mechanical ESP design by replacing internals and/ or rapping system
- Upgrade the ESP energy supply and control systems
- Optimize gas distribution and reduce sneakage
- Increase the ESP size
- Change the particle size distribution with agglomeration technologies

In this paper different upgrading techniques are described and compared both from a technical and economical point of view. A modern ESP control system is often a cost-effective method with a significant potential to reduce both emissions and power consumption especially at high resistivity dust conditions.

Exchange of old transformer/ rectifiers (T/R's) to high-frequency power converters have been successful in reducing the effect of corona quenching and allowing a higher T/R power input when severe space charge conditions prevails at high dust loads. Significant reductions in emissions have been observed.

INTRODUCTION

Electrostatic precipitators (ESP's) have been used for a long period of time to control particle emissions. Many ESP's around the world have been in operation for several decades. More stringent emission requirements and more challenging conditions due to fuel switching and other process changes result in a need for improved collection efficiency and ESP upgrade. Often it is sufficient to improve the performance of the existing ESP system by utilizing appropriate upgrading techniques. Another reason to invest in new ESP technology is reduced operating cost. An example of working procedure for ESP upgrading projects is shown in fig.1.

The present electrical and mechanical status in the ESP is determined by a detailed inspection. The inspection should be documented in a structured and accessible way. Broken or worn out parts are then repaired or replaced. Corrosion holes in the casing and ductwork are repaired and other necessary measures taken. Acceptable gas distribution together with good mechanical and electrical conditions in the ESP is prerequisites for successful implementation of upgrading technologies.

In the overhaul periods the gas distribution should be checked. Improper gas distribution can be devastating for the emission level due to:

- Small fraction of flue gas is not treated, the so-called sneakage, due to missing or improper baffles
- Stratification within the ESP casing with respect to flue gas velocity, dust concentration and flue gas temperature
- Unbalanced flue gas flow distribution between parallel ESP casings

The effect of unbalanced gas flow distribution between two casings is shown in fig.2.

The applicability and the possibilities with different retrofit technologies can be investigated, once the ESP is restored to its original condition. A simplified summary is presented in table 1.

This paper will deal with some of the available upgrading techniques.

Table 1. ESP upgrading techniques for an ESP in mechanically and electrically sound condition

Operating condition	Measure	Available techniques
High resistivity with back-corona	Cope with high resistivity	• Controllers with intermittent charging and advanced rapping control including tuning • Discharge electrode design with more even current distribution
	Reduce resistivity	• Conditioning with e.g. SO_3, NH_3, moisture or other agent
High dust re-entrainment	Reduce rapping losses	• Optimized rapping procedures • Modified gas distribution • Improved dust cake agglomeration e.g. conditioning with ammonia alone or in combination with SO_3 • Increased ESP size e.g. increased height or increased number of fields
	Cope with high flue gas velocity	• Reduce effects of corona suppression e.g. install peak electrodes or high-frequency power converters • Improved dust cake agglomeration e.g. conditioning with ammonia alone or in combination with SO_3 • Increased ESP size to achieve lower flue gas velocity e.g. increased height
Insufficient collection efficiency for upgraded ESP		• Increased ESP size e.g. increased number of fields • Change the particle size distribution with agglomeration techniques • Change to more efficient ESP design e.g. combination of ESP and fabric filter (FF) technology

CONTROL SYSTEM FOR ELECTROSTATIC PRECIPITATORS

Modernization of the ESP control system is often an efficient and cost-effective measure to significantly improve the ESP performance. A well designed and properly tuned control system is crucial for high ESP performance, long equipment lifetime and optimized power consumption.

A modern control system should be able to take care of:

- Spark handling
- Rapping optimization
- Intermittent charging (charging ratio)
- Self-optimization algorithm for best performance
- Power optimization
- Alarm handling
- ESP operation overview

The experience with modern control systems is discussed with respect to rapping optimization, high resistivity conditions and cost.

Rapping optimization

Rapping efficiency is important for all ESP applications and especially for high resistivity applications. A high resistivity dust layer on collecting plates reduces the ESP performance.

Improved rapping efficiency can either be reached by increasing the rapping forces or by decreasing the holding forces on the dust cake. Tumati (1993) made laboratory investigations on rapping efficiency with fly ash from a coal fired pilot-scale combustor. The rapping efficiency was defined as the percent of dust dislodged during one rap. The rapping efficiency increased with increased rapping intensity and ash layer thickness and decreased with increased current density. The rapping intensity has to be a compromise between rapping efficiency and ESP component lifetime. Lillieblad et.al. (2001) discussed the importance of proper design of the rapping system to get the best benefit of the applied rapping forces.

The electrical holding forces can be reduced by decreasing the dust resistivity by conditioning measures. Another possibility is to decrease or turn off the T/R power during rapping.

A feature in new control systems is to reduce or turn off the power during rapping for improved rapping efficiency. Combinations of ordinary rapping methods and power controlled rapping (PCR) should be used to achieve the lowest possible emission. The loss in efficiency in connection with PCR is compensated with increased overall removal efficiency. PCR is typically used every third or fourth rapping cycle and allow an overall lower rapping frequency, which will increase the lifetime of the ESP internals and reduce the maintenance costs.

High resistivity

Intermittent charging and efficient cleaning of the collecting electrodes are important tools in coping with high resistivity ashes.

Jacobsson (1996) presented a method, where the delicate task to select the optimum charging ratio and pulse current is controlled automatically based on data from the actual transformer/rectifier (T/R) only. This self-tuning possibility has been successfully introduced on many installations.

Some examples of implementation of control systems and tuning are presented. In the first example an ESP after a 630 MW_e coal fired boiler was optimized by using recent principles. The ESP was equipped with old controllers without PCR capability. The strategy was to avoid too excessive rapping and high re-entrainment during rapping. Improved spark handling increased the power input in the first field. Fig. 3 and fig.4 show the results from the optimization of the ESP after this coal-fired boiler. This limited effort reduced the emission by almost 50%.

In the second example the results from installations of new controllers in ESP's after coal fired boilers in India are presented. Indian coals usually have low sulfur contents and high ash contents. The ash has high contents of silicon and aluminum. A high resistivity fly ash is generated. Indian power plants have been upgraded with modern controllers to handle the high resistivity conditions. Emissions before and after the upgrade are seen in figure 5.

The emission is, for most power plants, reduced by at least 50%.

Cost

Wu (2001) reported in his review about costs for environmental control in coal fired power plants. The capital cost for ESP control upgrade was in comparison with most other upgrading technologies very low.

In addition the operating cost is decreasing for plants with high resistivity dusts, where the power can be substantially reduced and used much more efficiently with intermittent charging. If the PCR is used with less frequent rapping, it can in addition to an increased efficiency save the maintenance cost for replacement of wear parts.

The capital cost for ESP control upgrade could typically be around 0.20 Euro/ kW_e boiler capacity for a coal-fired boiler. The T/R power consumption could be around 1 MW without intermittent charging for a 500 MW coal fired boiler. Intermittent charging will for high resistivity fly ashes result in significantly decreased emissions. At the same time the T/R power consumption could often be reduced to approximately 20%.

Assuming a power cost of 0.035 Euro/kWh and 80% reduction in T/R power consumption, the investment will be paid in about half a year operation under these conditions.

CONDITIONING SYSTEMS

An alternative to cope with high resistivity dust is to reduce the resistivity. Different conditioning agents are successfully used. SO_3 is the most common conditioning agent and is mostly used for upgrading of existing ESP's and sometimes to help reduce the total installed cost of new ESP's. The ESP size can sometimes be halved for a plant with conditioning compared to a non-conditioned plant collecting high resistivity fly ash (Porle et.al., 1996). Ammonia is sometimes used alone or in combination with SO_3 (dual conditioning). Dual conditioning is especially used to avoid high dust re-entrainment during rapping in ESP’s with high flue gas velocities.

Conditioning for resistivity reduction is usually a more powerful upgrading measure for high resistivity fly ashes than T/R control upgrade with respect to emission levels, i.e.for the same ESP size lower emissions are reached for the conditioned ash than for high resistivity ash with intermittent charging and PCR.

The capital cost for the addition of a conditioning system could typically be ten times higher than for control upgrade. The operating cost will increase, since the T/R power consumption will be much higher in addition to cost for conditioning agents and power consumption for the conditioning plant.

POWER SUPPLIES

Efficient charging of the particles is essential to achieve high removal efficiency. It is important to achieve a sufficient power input. At high concentrations of fine particles the power can be significantly reduced due to corona suppression. This situation is applicable for example in the first ESP field, overloaded ESP’s in general and ESP applications with high concentration of fine particles. Increased power input is in these cases beneficial for the ESP performance.

Conventional power supplies generate a rectified voltage with the double mains frequency, usually 100 or 120 Hz. The voltage varies throughout each cycle. High-frequency power converters generate a voltage with negligible ripple, which will result in higher currents and improved charging. Modern high-frequency power converters have similar control possibilities as other modern control systems with respect to intermittent charging and PCR. Ranstad et.al. (2004) reported the results from upgrading projects with replacement of conventional power supplies in part of ESP's or in complete ESP's. Substantially reduced emissions were found for applications handling low to medium resistivity dust. Also applications producing high concentrations of fine dust (corona suppression) experienced significant improvements. The high-frequency power converters are now available at power capacities up to 120 kW, which will significantly increase the applicability of these power supplies for upgrading projects.

The cost for high-frequency power converters is generally higher than for upgrading of the control system only, but is still small compared to other alternatives, e.g. ESP extension and conditioning. It is a very cost-effective measure for the appropriate projects. The high-frequency power converters are usually easy to install, typically not requiring the ESP to be taken out of operation. The operation cost will increase slightly due to the increased power input.

ESP MECHANICAL DESIGN

The ESP mechanical design has to be suitable for the actual task. As previously discussed it is essential to have an efficient rapping system, where the applied forces are used in an optimal way.

Discharge electrodes like spirals and ribbons are superior to peak discharge electrodes with respect to current distributions along the collecting electrodes. It is desirable to have an as even current distribution as possible especially for high resistivity applications, where back corona condition needs to be minimized. In other cases, e.g. high corona suppression in front fields, low power input might limit the performance. In such cases peak discharge electrodes with their high emitting capabilities could be favorable. Adjustment of the discharge electrode design to the prevailing conditions could be very beneficial for the ESP performance.

A more compact ESP design is currently under investigation. ALSTOM has a license agreement with ERDEC Company Ltd in Japan. The expectations are a more compact design implying lower emissions for a given ESP casing volume. Back (2006) describes the status of this work in more detail.

REMOTE OPERATION

In many plants there are frequent changes in operating conditions like load and fuel, which influence the conditions in the ESP. A supervisory control system allows remote ESP support and troubleshooting. Stored ESP data and actual ESP conditions could be made accessible by means of Intranet or modem. Specialists within the company or from the ESP manufacturer can remotely analyze the ESP conditions and suggest or introduce changes in the control system. Opacity data is registered and stored together with the ESP data and used for the optimization. Fig.6. shows examples of data displays from remote support.

Remote service agreements are often signed due to these possibilities, where specified emission levels and/ or power consumptions are guaranteed.

COST

The cost for four different upgrading technologies is estimated for a typical ESP after a 500 MW_e coal fired boiler. Both first cost and total cost including the effect of operating cost are considered. The relative costs are presented in figure 7.

The upgrading technologies are not fully comparable. The potential improvement for each technology has to be evaluated for the actual plant. In appropriate cases the emission can typically be reduced by 50% with the upgrading technologies except for conditioning, where further emission reduction is expected.

Upgrades of control systems and power supplies including tuning with modern strategies are inexpensive compared to competing technologies.

CONCLUSIONS

The most appropriate ESP upgrading action should be selected based on a careful evaluation of the conditions at the actual plant. Initially the ESP needs to be inspected and restored to original conditions.

Upgrading of the control system is often an inexpensive and effective measure to reduce the emission and operating cost at high resistivity conditions. High-frequency power converters is a cost-effective alternative, when the performance is limited by a low power input, e.g. due to overloaded ESP's or obsolete power supplies.

Conditioning could be an alternative for high resistivity cases, where further reductions in emission are needed in addition to what can be gained with improved control systems.

REFERENCES

Back A, Porle K, Tomiyama H and Nolin K; Investigation of the ERDEC-type ESP after an oil fired boiler; Planned for presentation at 10th International Conference on Electrostatic precipitator, Cairns, Australia, June 26-30, 2006

Jacobsson H, Thimanson M, Porle K and Kirsten M; Back-corona control with help of advanced microprocessor enhances performances; 6th International Conference on Electrostatic Precipitation, Budapest, Hungary, 1996

Lillieblad L, Thimanson M, Porle K and Jacobsson H; On dust cake removal in Electrostatic precipitator; 8th International Conference on Electrostatic precipitator, Birmingham USA, May 14-17 2001.

Porle, K., Bradburn, K. Bader, P; FGC as a Means for Cost-Effective ESPs for Low Sulfur Coals, 6th International Conference on Electrostatic Precipitation, Budapest, Hungary, 1996

Ranstad R, Mauritzson C, Kirsten M, Ridgeway R; On experience of the application of high-frequency power converters for ESP energisation; 9th International Conference on Electrostatic precipitator, Kruger Park, South Africa, May 17-21 2004

Tumati P.R.; Evaluation of ESP rapper performance and optimum rapping force; 10th Particulate Control Symposium, Washington D.C., The United States, April 5-8, 1993

Wu Z; Air pollution control costs for coal-fired power stations; IEA Coal Research. ISBN 92-9029-366-7, 2001

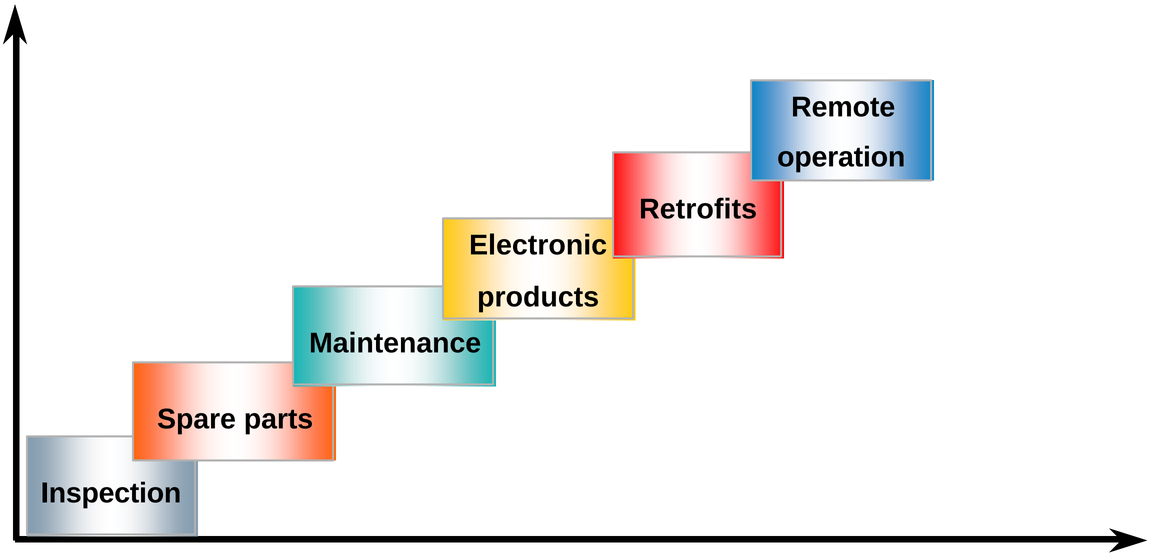


Figure 1. Working procedure for ESP upgrading projects

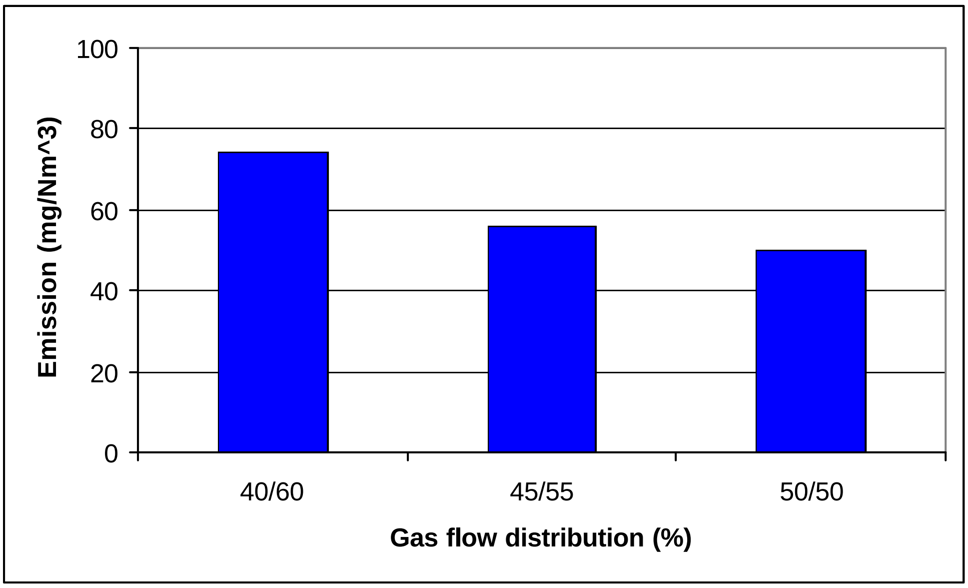


Figure 2. Estimated average emissions (mg/Nm^3) showing the effect of unbalanced gas flow distribution between casings after a coal fired boiler

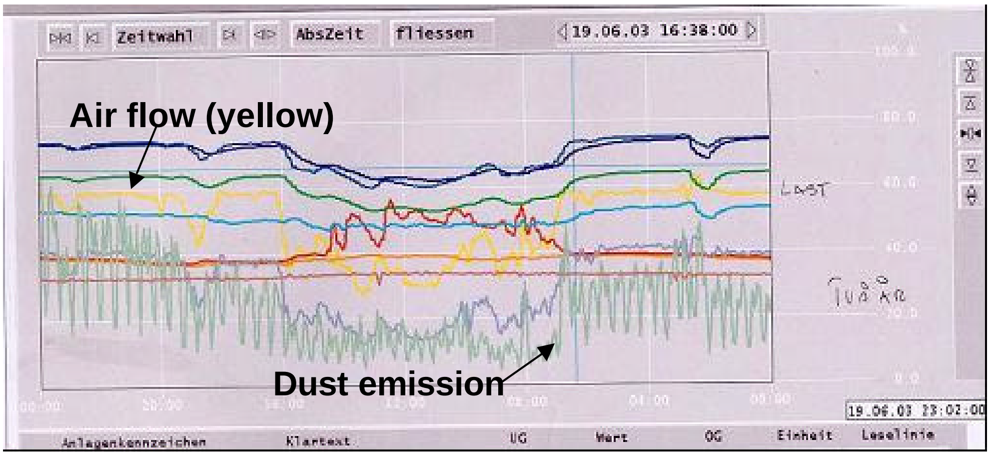


Figure 3. Dust emission before the tuning

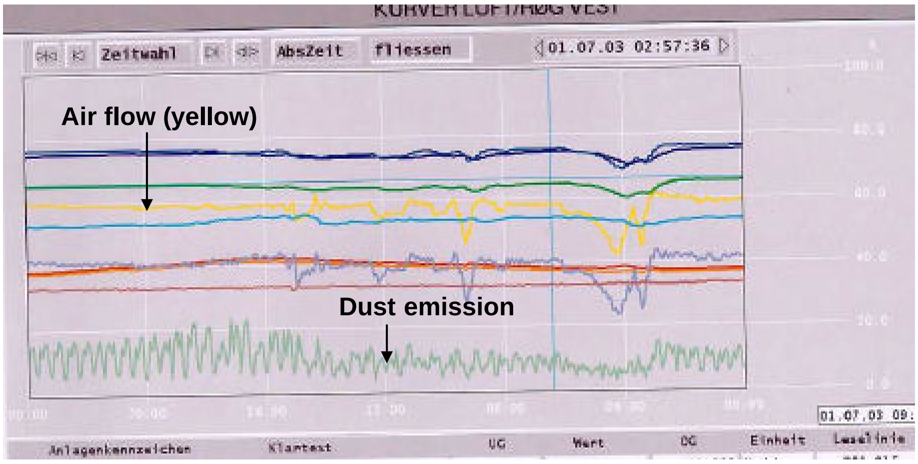


Figure 4. Dust emission after tuning

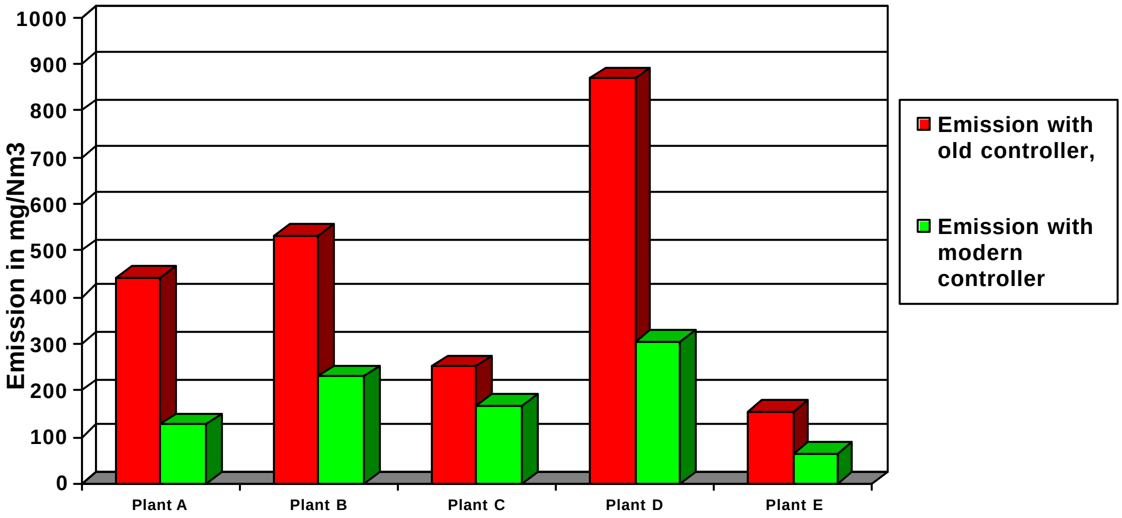


Figure 5. Emissions before and after upgrade with new controllers after coal fired boilers in India

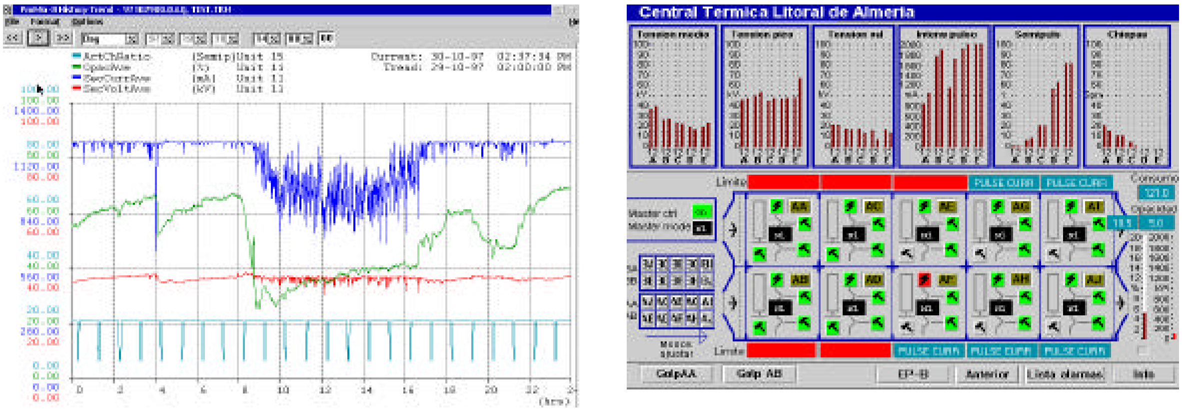


Figure 6. Example from remote support

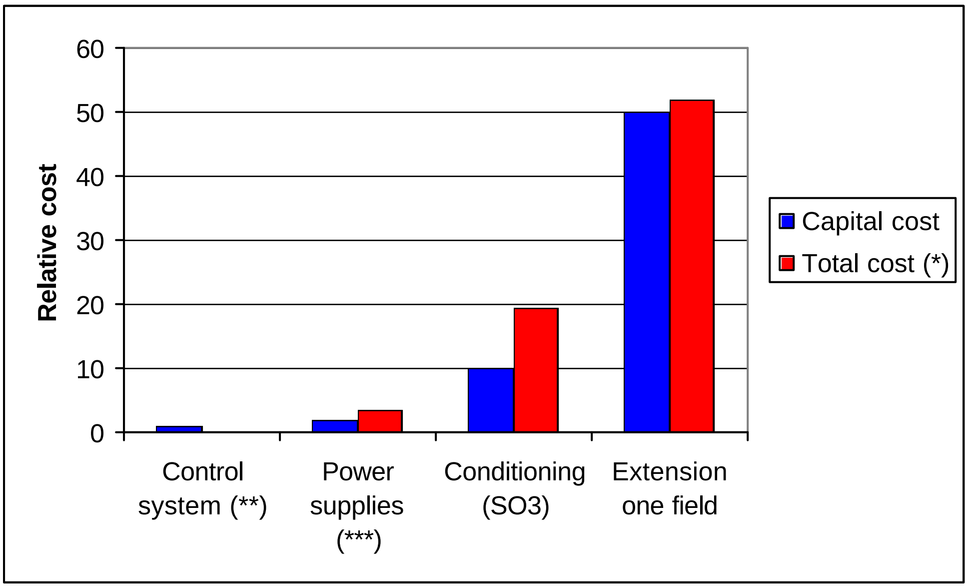


Figure 7. Relative cost for four different upgrading technologies using the capital cost for control system as basis (relative cost =1)
(*) Total cost includes evaluated cost for power consumption and consumables
(**) The capital cost for the control system is paid off due to reduced power consumption
(***) Power supplies = High-frequency power converters in the first ESP field

ELECTRIC POWER
RESEARCH INSTITUTE

Guidelines for Upgrading Electrostatic Precipitator Performance

Volume 2: Electrostatic Precipitator Upgrade Options

Guidelines for Upgrading Electrostatic Precipitator Performance

Volume 2: Electrostatic Precipitator Upgrade Options

TR-113582-V2

Final Report, December 1999

EPRI Project Manager
R. Altman

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Grady Nichols Enterprises, Inc.

ORDERING INFORMATION

Requests for copies of this report should be directed to the EPRI Distribution Center, 207 Coggins Drive, P.O. Box 23205, Pleasant Hill, CA 94523, (800) 313-3774.

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. POWERING PROGRESS is a service mark of the Electric Power Research Institute, Inc.

Copyright © 1999 Electric Power Research Institute, Inc. All rights reserved.

CITATIONS

This report was prepared by

Grady Nichols Enterprises, Inc.
400 Kiowa Street
Montevallo, AL 35115

Principal Investigator
G. B. Nichols

Consultant
A. Ferguson

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Guidelines for Upgrading Electrostatic Precipitator Performance: Volume 2, Electrostatic Precipitator Upgrade Options, EPRI, Palo Alto, CA: 1999. TR-113582-V2.

REPORT SUMMARY

This guide, the second volume of a two-volume set, presents an analytical procedure to evaluate cost-effective options for enhancing the performance of an existing electrostatic precipitator (ESP) when the performance of the ESP, even after optimization, is not satisfactory. The guide focuses on ESPs that require significant improvements (more than $20/kW) to achieve their emissions goals. The first volume of this report, published in September 1999, treated low-cost options that could be used to optimize ESP performance. It is intended that the two volumes be used together to perform a complete ESP analysis.

Background

Various factors are spurring power producers to improve the performance of their electrostatic precipitators. Equipment aging causes ESP performance to drop off from original levels, even as emissions limits become more stringent. New $PM_{2.5}$ standards under consideration could require increased capture of fine particles, which are hardest for ESPs to collect. Measures for SO_2 compliance are another driver: low-sulfur coals generally produce fly ash particles with higher electrical resistivity, which are more difficult for an ESP to collect and cause ESP performance to drop as a result of the coal switch. Another compliance option, dry SO_2 control systems, dramatically increases the mass loading into the precipitator and can also alter the resistivity of fly ash such that particle reentrainment becomes a serious problem—again, reducing ESP collection efficiency. Power plant engineers need tools for determining the most strategic repair/replace/redesign option to meet their particulate emission targets.

Objectives

To provide plant operators and engineers with information and a systematic method for determining the most cost-effective upgrade option for their ESP.

Approach

The project team, comprising experts on ESP design and operation, summarized published EPRI research and drew on their own expertise to identify and characterize the most cost-effective upgrade options currently available. Performance and cost data were gathered for all of the options, and the options were sorted into performance-limiting categories. Illustrative examples for estimating the impact of each option on collection efficiencies were developed. Information on the strengths and weaknesses of each upgrade option was also gathered and is included in the report.

Results

This guide leads the user through a systematic process to: (1) identify the principal factors that limit ESP performance, (2) identify suitable upgrade options for overcoming each of these factors, (3) estimate the performance impacts for each option under site-specific conditions, and

(4) estimate the cost of the most attractive upgrade option. Most of the site-specific analyses rely on the use of a calibrated ESP model, either ESPM or ESPert, to calculate the expected performance enhancement. This approach makes accurate performance projections possible, and thus enables a more reliable evaluation than an approach based on generalized charts or rules-of thumb. While there are many site-specific factors that affect the cost of plant modifications, the cost estimates in this volume are accurate enough to allow the choice of options to be narrowed to a minimum number, one or two in most cases, for final consideration and bidding.

EPRI Perspective

Power producers face the difficult task of meeting increasingly stringent pollution abatement regulations while simultaneously reducing costs to compete in a deregulated market. Adding to the challenge, various measures to meet acid rain regulations have had a negative impact on ESP performance. This performance drop, combined with the new compliance assurance monitoring (CAM) regulation for particulate emissions, requires many utilities to restore, or even improve, precipitator performance to stay in compliance. EPRI has developed a large body of information to help its members meet this challenge cost-effectively. Much of that information has been synthesized in the two volumes of TR-113582. Volume 1 helps plant operators get the most out of their existing ESPs. If further improvement is needed, power producers can consider the newest upgrade options, analyzed and presented in Volume 2, to identify the least-expensive option for their situation. Together, these two volumes help the user streamline the evaluation process and identify the optimum solution to any ESP performance problem.

TR-113582-V2

Keywords

Air pollution equipment upgrades
Electrostatic precipitator optimization
ESP upgrade
ESP troubleshooting
ESP performance improvement
Particulate control

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

1.1. Purpose of This Guide

This guide is the second volume of a two-volume set of *Guidelines for Upgrading Electrostatic Precipitator Performance.* The first volume, *Optimizing an Existing Electrostatic Precipitator,* discusses how to determine:

1. The current performance of your existing ESP
2. Whether your existing design, when repaired, can meet your desired level of particulate control
3. How to diagnose the cause(s) of your ESP's under-performance
4. How to fix your existing ESP to restore its collection efficiency

Volume 1 is limited to optimizing the existing precipitator—which entails relatively inexpensive corrections in the range of $10 to $20 per kilowatt of generating capacity. If the process in Volume 1 reveals that your existing precipitator, even when optimized, will still not achieve the needed emissions reductions, then you will need to take more extensive measures, such as rebuilding the ESP (perhaps with additional plate area), adding a polishing device, or adding a new ESP or fabric filter, either in lieu of the original ESP, in parallel, or in series. These more extensive approaches are the focus of this second volume. Costs may run as high as $40–$70/kW if the ESP must be replaced or a fabric filter retrofit is required. In addition to these major upgrade options, Volume 2 also discusses three simpler measures that were touched upon in Volume 1—gas flow optimization, flue gas conditioning, and replacing the power supply controls.

This second volume assumes you have followed the procedures described in Volume 1—in particular, that you have (1) calibrated a computer ESP model, such as EPRI's ESPM, to describe your existing ESP, and (2) have conducted diagnostic tests to identify the factors limiting the collecting efficiency of the existing unit. Even if it is obvious from the outset that the existing precipitator is inadequate to meet performance goals, it is important to model and diagnose the existing unit, as the information obtained will be indispensable in selecting and designing the best upgrade option. This volume does not assume you have made the corrective repairs suggested in Volume 1; only that you have fully diagnosed your ESP's shortcomings so you are in an informed position to find the best workable solution. It is possible that optimizing the performance of the existing equipment and adding a polishing device is the most cost-effective way of meeting your goal, but a complete analysis of available options is needed to make this determination.

1.2 Drivers for an ESP Upgrade

Unlike Volume 1, which addresses installations where ESP collection efficiency is only marginally less than required, this volume addresses situations calling for a significant increase in collection efficiency. The reasons for needing a substantial performance increase are varied and include the following:

1.2.1 More Restrictive Emission Limits

In some areas, regulated limits have tightened, such that an ESP that easily met former limits is now under-designed for the stricter limits. The amount of emissions reduction required will dictate the appropriate corrective measures to consider for the reduction program. If the reduction level required is small—say, a 15% reduction—then gas flow optimization and power supply control upgrades should be investigated. Note that these measures are also discussed in Volume 1 (Sections 6.8 and 6.6). However, if the required reduction is on the order of 50% or higher, more aggressive measures are called for. Options include installing a flue gas conditioning system (if high ash resistivity is limiting performance), rebuilding the ESP with design improvements, installing a polishing device, substituting a new ESP or adding one in series or parallel with the old precipitator, or using a new pulse-jet or reverse-gas fabric filter.

1.2.2 Coal Switching

When a power plant changes the type of coal being burned—whether due to spot market purchases, mine closure, or SO_2 regulations—the new coal may diminish ESP performance. Typically, this occurs due to increased ash loading, increased fly ash resistivity, or an increased proportion of fine particles, which are harder to collect.

For example, lower-sulfur coals reduce the amount of SO_3 naturally occurring in the flue gas, which increases the resistivity of the ash, making it harder for an ESP to collect. If the coal change is from a medium-sulfur eastern coal to a low-sulfur eastern coal, the only significant parameter changed will be the ash resistivity. However, if the change is from an eastern bituminous to a western subbituminous coal, both the ash resistivity and particle size distribution will likely change to more-difficult-to-collect values.

If the new coal source can be identified with sufficient advance notice, the anticipated increases in emissions can be estimated prior to a permanent change using either a test burn of the new coal in the particular boiler, a test conducted at a similar power station burning the candidate coal, or from test burns of both the current and the proposed coals in a combustion test facility. Measurements of the critical parameters of ash loading, ash resistivity, and particle size distribution will provide data to use in the ESP computer model to estimate the influence of the coal change.

If the coal switch will result in a significant increase in emissions, an ESP upgrade may be in order.

1.2.3 Installation of SO_2 Controls

Just as switching to a lower-sulfur coal can impair ESP performance, so can SO_2 control equipment, wet or dry.

The most commonly installed control, a wet scrubber, is usually installed downstream from the ESP, and therefore does not influence ESP performance directly. However, scrubbers lower the flue gas temperature to well below the acid dew point for SO_3, allowing the sulfuric acid to condense into a fine fume that can create a visible bluish plume out the stack. This plume can be eliminated by injecting ammonia gas into the flue gas before it passes through the ESP. The reaction products of ammonium sulfate and bi-sulfate form a acid fume, which has a particle size distribution (mass mean diameter of about 0.5 micron) that is difficult to collect. The fume can be successfully collected by an ESP with an appropriate SCA; however, the existing ESP may require upgrading to effectively collect this fume.

Dry SO_2 control processes—such as spray dryers, sorbent injection, and fluidized-bed combustion processes—affect the ESP directly by increasing the particulate loading. Spray dryers can also lower the resistivity of the fly ash to the point where particle reentrainment becomes a serious problem. These and other dry SO_2 control processes are discussed in EPRI report TR-104594, *Guidelines for Particulate Control for Advanced* SO_2 *Control Processes* (December 1994). This document describes the changes in fly ash characteristics and how they influence ESP and fabric filter performance.

1.2.4 Aging Equipment

The ESP installed in a typical coal-fired power station is expected to remain functional for several decades. Over the years, it is common to replace internal components such as discharge electrodes many times over. However, there comes a point when many collecting plates need replacement—an expensive proposition—and even the casing itself becomes worn and requires repair. At this point, a wholesale rebuild or replacement makes sense, given the many advances in ESP technology since the old installation was designed. The new designs should result in more reliable operation.

1.2.5 CAM Compliance

To satisfy compliance assurance monitoring (CAM) requirements, power producers will typically be conducting more frequent mass emissions tests than in the past. In rare situations, an installation can meet the opacity limits yet fail to meet the mass emission limits. Thus, an ESP upgrade may be required to ensure the station passes all mass emission tests.

Note that there is some question as to what type of monitor is available for measuring the emissions, short of mass train measurements. An ESP model, calibrated to the specific plant and ESP conditions, may be appropriate for this function.

1.3 Organization of This Guide

The flow chart in Figure 1-1 indicates the procedures to follow in conducting an ESP upgrade exercise. As stated, begin the upgrade study by characterizing current ESP performance, calibrating an ESP model, and diagnosing performance problems as described in Volume 1. Should an extensive upgrade be needed, proceed through the remaining chapters in Volume 2 in sequence. Namely, identify the factors that are limiting ESP performance; identify appropriate technologies to address these issues; and project the expected performance improvement from each appropriate option. For those options that show promise of meeting performance goals, develop comparative cost estimates to select the final candidate options. Formal quotes can then be requested to make the final technology selection.

Chapter 2 of this volume discusses the types of problems that limit ESP performance and provides a matrix to match these problems to potential solutions.

Chapter 3 very briefly describes the available upgrade options. A more detailed discussion of the options is presented in the appendices.

Chapter 4 provides example upgrade evaluations for a representative power plant to illustrate the decision process for selecting among upgrade options. The purpose is to provide guidance on the level of performance improvement that can be expected for the different solutions.

Chapter 5 presents cost estimates for the different upgrade options for a typical 300-MW power station. Clearly, site-specific variations will influence the final cost for any upgrade; the intent here is to provide comparative costs for the various options that can be evaluated against the expected improvement in performance to select the appropriate technology. The costs are expected to be accurate to approximately +/- 25%.

Appendices describe each of the upgrade options in enough detail to enable evaluation of their applicability to the power station in question.

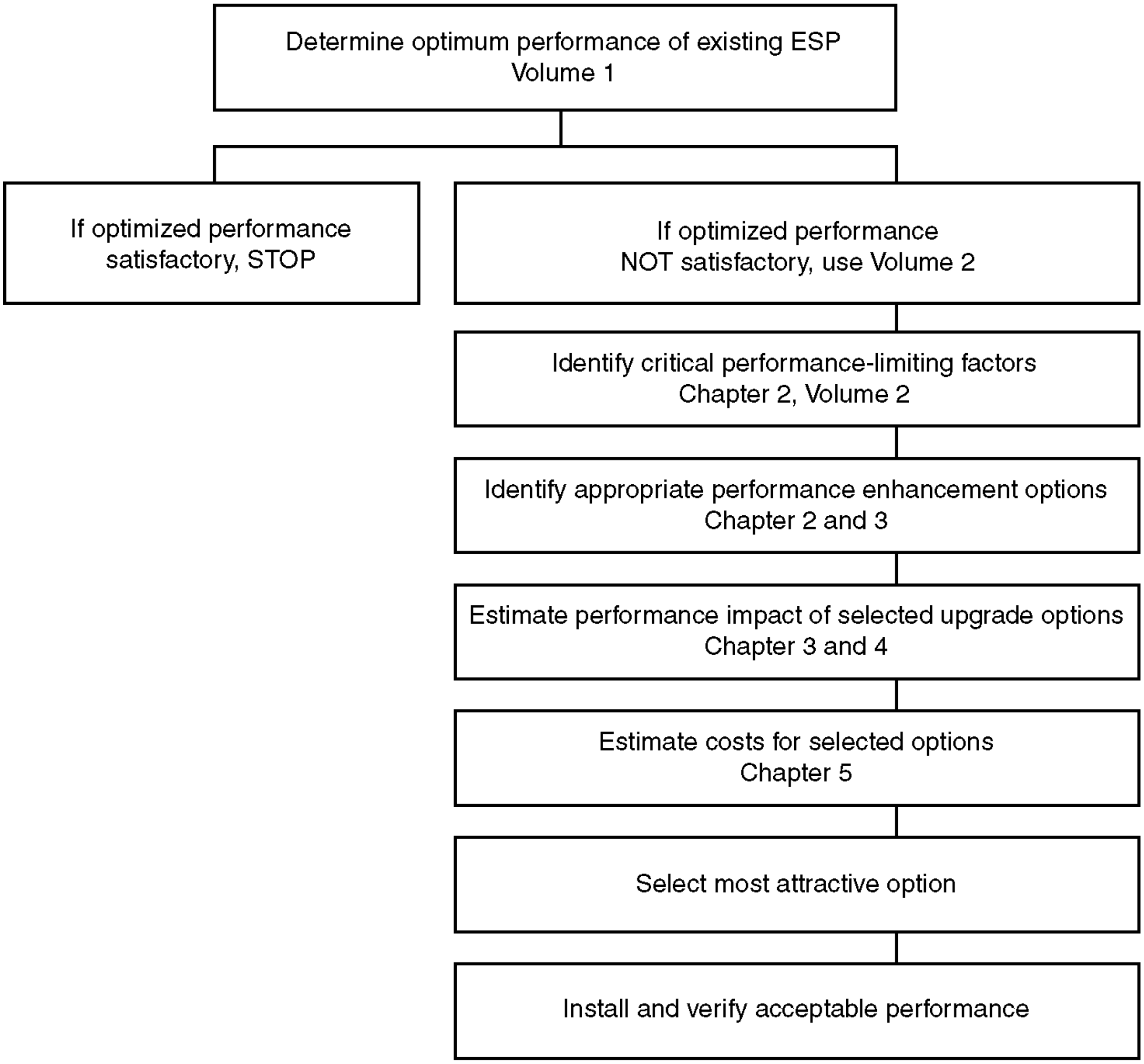


Figure 1-1
Flow Chart of Procedure for ESP Upgrade Study

2

DIFFERENT UPGRADES FOR DIFFERENT PERFORMANCE LIMITATIONS

Upgrade options range from the relatively simple—adopting flue gas conditioning, for example—to the complex, such as conversion of a hot-side ESP to cold-side operation, with the addition of flue gas conditioning. Determining the best upgrade strategy for your situation depends on why your current ESP is not adequate to meet your emissions target.

This chapter discusses different types of performance limitations. At the end of the chapter is a "cause"/"solution" matrix to help you decide which upgrade options are most appropriate for your situation. If you prefer, you can then jump directly to the technical description of those options in Chapter 3 and the appendices.

2.1 Ash-Related Performance Limitations

2.1.1 High or Low Ash Resistivity

The electrical resistivity of the fly ash entering the ESP is a very significant factor in establishing the precipitator's attainable performance. Ash resistivity was discussed in Volume 1 (Sections 4.5.3, 5.2, 6.9.1, and Appendix D); a brief summary follows.

2.1.1.1 High Ash Resistivity

High ash resistivity restricts ESP collection efficiency by limiting the electrical energization attainable in each electrical section of the ESP. Ash resistivity limits the maximum allowable average local current density, which in turn limits the permissible operating voltages, both peak and average, in each ESP section. A decrease in operating voltage doubly reduces ESP collection capability, by (1) reducing the electrical charge that resides on the particles to be collected and (2) reducing the value of the electric field adjacent to the collecting electrode that serves to remove the particles.

To correct high ash resistivity, the treatment of choice is flue gas conditioning with an agent such as sulfur trioxide. Power controls can also be modified to cope with high-resistivity ash: intermittent or pulse energization schemes are helpful in this situation. Naturally, other design factors that generally improve performance—such as higher specific collecting area (SCA) or improved gas flow—will also contribute to an ESP's ability to deal with high-resistivity ash.

2.1.1.2 High Resistivity Due to Sodium Depletion

In hot-side ESPs (and possibly some cold-side units as well), sodium depletion can cause high fly ash resistivity to develop in the residual ash layer retained on collecting plates. Volume conduction of electricity in the ash layer occurs via the actual migration of alkali metal ions. The direction of flow in the ash is from the positive collecting plate towards the negative discharge electrode. This electrical current flow in negative-corona ESPs depletes the carriers adjacent to the collecting plates (see Volume 1, Appendix D). The continued flow of electrical charge carriers through the residual ash deposit creates high resistivity in the remnant layer adjacent to the collecting electrode.

In such situations, the original collection efficiency can be completely restored by entirely clearing the ash deposit off the collecting plates, either by water washing or grit blasting. However, to reduce shutdown frequency, units with sodium depletion problems should investigate the same measures that help with high resistivity in general, including fly ash conditioning with chemical compounds suitable for hot-side ESPs, new controls with IE, and pulsed power supplies. In addition, a “positive polarity” power supply should also be considered.

2.1.1.3 Low Ash Resistivity

Very low ash resistivity contributes to the reentrainment of previously collected ash (see Sections 3.2.7 and 6.9.2 of Volume 1). When the electric field in the ash layer is less than in the gas space adjacent to the layer, the electrical force in the ash layer is in the direction to assist reentrainment. This problem is generally not a common concern in conventional utility ESPs, and is usually associated only with high-sulfur coals, lower operating temperatures, or large amounts of unburned carbon. (The mechanism of low-resistivity reentrainment applies in a general way to the reentrainment of carbon particles if there are high levels of unburned carbon in the fly ash.) Flue gas conditioning can sometimes be used to reduce this reentrainment.

2.1.2 Particle Size Distribution (Excessive Fines)

Fine particles smaller than a few microns in diameter are much more difficult to collect and usually dictate the design of the ESP (SCA) required to meet a given emission limit (see Volume 1, Appendix C).

Switching to a low-sulfur coal such as Powder River Basin coal can result in a fly ash with a greater amount of particles in the smaller size range. These low-sulfur western coals often also have higher ash resistivity, compounding the collection problem.

Because the proportion of fine particles has such a huge impact on ESP performance, typically no single remedy is relied upon to solve the problem with excessive fines. Enhancing an ESP’s overall performance will generally improve fine particle collection, and hence, adopting any of the technologies described in this report will improve the collection of fines. If excessive fines are your main problem, you may be interested in a new device entering commercialization called a Laminar Flow Fine Particle Agglomerator™, which uses reentrainment principles to agglomerate fines into larger particles that can be more easily captured.

2.1.3 Increased Mass Loading

In the United States, air pollution emission limits are stated in terms of the amount of material emitted from the stack per unit of heat input to the system (lb/MBtu). (Other countries state limits in terms of the particulate concentration in the flue gas, or mg/Nm^3). Electrostatic precipitators are typically designed to provide a given collection efficiency, and are, at least to a first approximation, constant-efficiency devices when operating conditions are constant. Thus, if an ESP was designed to meet a given emission limit based on a coal with a given ash content, a change to a coal with an increased ash content can cause an increase in emissions. For significant coal ash increases, the ESP will likely require some modification to maintain the specified emissions level. Fortunately, the percentage increase in emissions is often less than the incremental increase in ash content in the coal because higher-ash coals in the United States may not cause a proportionate increase in the fine particle fraction of the ash. It is this fine particle fraction that actually dictates the requirements for the ESP design. Again, any of the performance enhancing technologies that result in an increase in the overall collection efficiency will help return emission levels to the pre–coal switching level.

2.2 Size-Related Performance Limitations

In some cases, no matter how “well-tuned” your ESP, it may simply be undersized to achieve your emissions goal. Perhaps regulated emission targets have been ratcheted down, or the coal being burned has changed. In such cases, the original ESP will not provide the collection efficiency necessary to meet the permissible emission limit, with the possible exception that the original design was intended for collecting low-resistivity ash. If the cause limiting the collection efficiency is higher fly ash resistivity, flue gas conditioning may provide the required improvement. Otherwise, a complete rebuild or replacement may be necessary.

In other cases, the original design was inadequate to begin with. A marginal original design may be the result of an overly optimistic evaluation of the fly ash characteristics, a highly competitive bidding environment, or an outright error by the supplier. In some older plants, the original design may have been intended to protect plant equipment (e.g., protect the induced draft fans from erosion) rather than meet air pollution emission requirements—although by and large, such plants have already had their ESPs upgraded for proper emissions control.

If an overall increase in design capacity is needed, options are numerous, ranging from minor improvements to adding a larger new ESP or even a fabric filter, in series, in parallel, or in lieu of the original unit. Chapter 3 summarizes the available options, which are described in greater detail in the appendices.

Note that even though the existing ESP is not capable of attaining the required collection efficiency, tests on this ESP can be extremely useful for obtaining data to establish the design of the new equipment. If you expect your plant to continue using the same coal and do not anticipate a major boiler redesign, the fly ash into and out of the existing ESP will define the characteristics of the ash for the new equipment. The electrical readings from the existing power supplies can be interpreted to determine the expected conditions for the new ESP as well.

2.3 Choosing an Appropriate Upgrade Solution

The following matrix indicates which upgrade options (vertical axis) are appropriate for different performance limitations (horizontal axis).

Notice that replacing the existing ESP with a new, larger ESP or a fabric filter is not included in Table 2-1. This omission is deliberate because these options would solve any of the problems identified in the top row of the table.

Table 2-1
Matrix of Candidate Solutions for Specific Performance Limitations

Corrective Measure	**Item Needing Correction**					
	High Resistivity	Sodium Depletion	Low Resistivity	Particle Loading & Size Distribution	ESP Too Small	Reduced Emission Limits
Power Supply						
PC-based	Perhaps	Perhaps		Perhaps	Perhaps	Perhaps
Hi Freq. Supply	Perhaps	Perhaps		Perhaps	Perhaps	Perhaps
Pulse & IE	Yes	Yes		Yes	Perhaps	Perhaps
Positive Polarity		Yes				
Arc Snubber™	Perhaps	Perhaps		Perhaps	Perhaps	
Flue Gas Conditioning						
SO_3	Yes				Only If Resistivity Is High	Only If Resistivity Is High
H_2O	Yes				Only If Resistivity Is High	Only If Resistivity Is High
NH_3	Hot-Side		Perhaps			To Correct Reentrain-ment in Cold-Side
SO_3 and NH_3	Yes		Yes			For Difficult Ash
Sodium	Probably	Yes				Some Hot-Side
Proprietary	Yes	Yes	Perhaps			Perhaps
Gas Flow Optimization			Perhaps	Yes	Perhaps	Perhaps
ESP Rebuild						
As-Is				Perhaps		
Wide Plate Spacing	Perhaps			Perhaps	Perhaps	
Increased SCA	Yes	Yes	Perhaps	Yes	Yes	Yes
Polishing Devices						
COHPAC	Yes	Yes	Yes	Yes	Yes	Yes
Wet ESP	Yes	Yes	Yes	Yes	Yes	Yes
ElectroCore™	Probably	Perhaps	Yes	Yes	Yes	Yes
Laminar Flow Agglomerator™	Perhaps	Perhaps		Yes	Yes	Yes
Hot-Side to Cold-Side Conversion		Yes				

3

OVERVIEW OF UPGRADE OPTIONS

This chapter briefly summarizes the various upgrade options. The appendices provide a more detailed discussion for a better understanding of the technologies.

Note that SO_2 control—whether through coal switching or addition of control equipment such as scrubbers, spray dryers, or sorbent injection systems—affects the performance of particulate collection devices. The effects of SO_2 control options are summarized in Appendix G and should be considered in tandem with particulate upgrade decisions.

3.1 Upgrades for Power Supply Controls

If the ESP has not previously been converted to digital, PC-based controls, this modification should be made during the upgrade. Modern power supply controls are available from a number of suppliers, including original equipment manufacturers and power supply specialty companies.

3.1.1 PC-based Controls

There has been a significant amount of progress in the development of power supplies and controls for ESP use. The analog controls originally installed in U.S. utility applications have largely been replaced, but a few are still in service. The modern replacement controls are based on a personal computer (PC), which is connected to various feedback signals that indicate ESP condition and is programmed to respond accordingly, using silicon-controlled rectifiers to modulate the energization to the ESP.

These digital controls are superior to their analog predecessors in detecting the effects of changes in the combustion process that will affect ESP performance (e.g., ash resistivity, ash loading, particle size distribution, and unburned carbon in ash) and adjusting power levels to compensate for these fluctuations. Digital controls respond much more quickly to arcing and sparking, thereby minimizing these effects. Unlike analog controls, they can detect back corona to minimize back corona operation.

PC-based controls are available from a number of suppliers, with some variation in capabilities depending upon the interests, understanding, and capability of the suppliers.

3.1.2 High-Frequency Power Supplies

One of the newer approaches to power supplies and controls uses a source power with a much higher frequency than line frequency. These supplies rectify the 50 or 60 Hz line voltage, filter it to DC, then convert the DC power to a much higher frequency (in the 20-kHz range) before it passing through the high-voltage step-up transformer. This conversion to a higher frequency allows for a smaller transformer and core, saving weight and size—which could avoid the need to increase the capability of the foundation during a rebuild.

High-frequency power supplies are presented here for information; whether they improve ESP performance is yet to be determined. Preliminary tests indicate that in low- to medium-resistivity applications, they may produce superior performance because the average voltage approaches the peak voltage; and hence, these supplies may increase the effective power level in the precipitator.

3.1.3 Pulse and Intermittent Energization

Pulse and intermittent energization (IE) are two related energization methods intended to improve collection of high-resistivity ash particles. The collection efficiency of an ESP is related to the product of the peak and average values of the electric field in the interelectrode space. Pulse and intermittent energization are intended to provide the highest value for the product of the peak and average value of electric field at the permissible current density allowed by the ash resistivity when the resistivity is relatively high.

Pulse energization provides for a very uniform current density distribution along the corona (discharge) electrode. This modification requires an extra power supply for each electrical field to be pulsed and is thus expensive, but very effective: pulse energization on an ESP operating with heavy back corona should reduce the outlet emissions by a factor of two or more.

Unlike pulse energization, IE does not provide a more uniform current density distribution; rather, IE applies one cycle of the input waveform, then skips several cycles on a repetitive basis to yield a product of peak and average voltages that is greater than for conventional full wave or double half-wave energization. IE provides only about half the emissions reduction that could be obtained with pulse energization. However, IE does not require any extra equipment, since any PC-based control can be programmed to operate in IE mode.

3.1.4 Positive Polarity for Hot-Side ESPs

Back corona in a hot-side ESP is often caused by sodium depletion, which results in formation of a high-resistivity ash layer on the collecting electrodes (see discussion in Volume 1, Section 6 and Appendix D). Experiments have shown that reversing the direction of current flow will reverse the sodium depletion and bring the ash resistivity back down to its initial value.

EPRI pilot studies have shown that reversing ESP operation from the usual negative polarity to positive polarity can avoid sodium depletion problems. The unit can either be permanently converted to positive polarity, or can undergo periodic switches between positive and negative operation. Either way, positive-polarity operation will probably require a rebuild of the high-voltage distribution system.

3.1.5 Arc Snubber™

Marketed by Zero Emissions Technologies, the Arc Snubber™ is a filter system designed to compensate for and control the high-frequency electrical components in the electrode system of an ESP field. The Arc Snubber is custom-designed for each installation based on site-specific waveform measurements. The filter is installed between the ESP power supply and the collecting field to become part of the high-voltage distribution system.

These filter devices have been used in a number of power plant ESP systems with mixed results. In instances where opacity was reduced, the mechanism for improvement was not clear—possibly a better impedance match between the high-voltage power supply and the ESP collecting field in those cases where a significant mismatch existed. The success of this device appears highly site specific and must be established by trial and error. As of this writing, ZET was providing a risk-sharing guarantee for evaluating the filters.

3.2 Flue Gas or Fly Ash Conditioning

The primary use of conditioning agents in ESP installations is to reduce the electrical resistivity of the fly ash to be collected. There are a few instances where conditioning has been used to minimize reentrainment or eliminate an acid mist plume, but the great majority of instances are for resistivity reduction. A variety of conditioning agents have been employed for power plant ESP installations during the past several decades. These include sulfur trioxide, ammonia, sodium, triethylamine and several proprietary compounds. Of these agents, sulfur trioxide has become the established agent for cold-side installations and sodium for the hot-side units.

3.2.1 Sulfuric Acid (SO_3) Conditioning

The naturally occurring SO_3 in flue gas reacts with the water vapor to form sulfuric acid vapor that reduces fly ash resistivity. For those stations burning low-sulfur coals, there may be insufficient sulfur trioxide produced to effectively reduce the ash resistivity, and the higher-resistivity ash can impair ESP collection efficiency. In such cases, sulfur trioxide gas can be injected into the flue gas stream near the ESP to “condition” the ash. A proven technology, these SO_3 conditioning systems are available from a number of suppliers. They provide adequate resistivity reduction in cold-side ESPs for most fly ash compositions in the United States. SO_3 conditioning is not appropriate for ESPs with operating temperatures much greater than 300–325°F (150–163°C).

3.2.2 Moisture Conditioning and Humidification

Moisture conditioning and flue gas humidification are related means to improve the performance of ESPs collecting high-resistivity fly ash. These technologies only differ in the amount of water added to the flue gas. Humidification is based on adding enough moisture to increase the flue gas moisture content by about 0.5%, while moisture conditioning—which requires significantly more water—necessitates sufficient water addition to reduce the flue gas temperature by several degrees Fahrenheit.

Both types of conditioning reduce the electrical resistivity of the ash by increasing the moisture interaction with the fly ash. They also increase the sparkover voltage within the ESP. Moisture conditioning also reduces ash resistivity by cooling the flue gas.

Installation costs are low, and the approach is effective for all known fly ashes. The primary disadvantages are the amount of water required for full moisture conditioning—typically over 1500 gallons of water per hour for a 100-MW power station—and the difficulty of keeping metal surfaces in the vicinity of the moisture conditioning system clean and dry.

3.2.3 Ammonia Conditioning

Ammonia conditioning is used in the United States for three different purposes: to reduce ash reentrainment, to avoid sulfuric acid opacity plumes, and to improve performance of hot-side ESPs with sodium depletion. In cold-side applications, ammonia reacts with the SO_3 to form a composite ammonium sulfate–ammonium bisulfate material in the flue gas; this sticky composite chemical is co-precipitated with the fly ash in the ESP. Because ammonia reacts with SO_3 and forms a particulate that can be collected in an ESP, it can also be used to reduce a sulfuric acid plume. In hot-side applications, ammonia appears to influence the electrical mobility of the charge carriers, which may be the mechanism for improvement in ESPs suffering from sodium depletion.

3.2.4 Combined Sulfuric Acid and Ammonia Conditioning

A few fly ashes—typically those high silica and alumina—do not readily respond to ammonia or sulfur trioxide as conditioning agents when applied singly. Combined ammonia and sulfuric acid conditioning is appropriate for these ashes. The SO_3 can be injected on either the high-temperature side or the cold-temperature side of the air heater, while the ammonia must be injected on the cold side, to form an ammonium sulfate–ammonium bisulfate composite. Both materials must not be injected on the high-temperature side of the heater, else the sticky composite will be liable to plug the gas flow passages. The composite particles are co-precipitated with the fly ash particles and serve to bind the ash layer together, as well as to reduce the resistivity of the resultant fly ash layer.

3.2.5 Sodium Conditioning

Sodium conditioning involves the addition of a compound containing sodium, such as sodium sulfate or sodium carbonate, to the coal prior to combustion. The sodium becomes a part of the "glassy" fly ash material, providing a reduction in the ash resistivity by supplying sufficient electrical carriers to prevent sodium depletion.

Sodium conditioning is typically used in hot-side ESPs that have developed high resistivity due to sodium depletion. The technology may also be useful for cold-side ESPs for stations burning coal with very low sulfur coupled with a reasonably high concentration of lime. The lime effectively removes most of the SO_3 produced in the combustion process, preventing the development of any sulfuric acid to serve as a conditioning agent. The addition of sodium compounds can also reduce the resistivity of an ash that has a high enough bulk resistivity to interfere with precipitation. The principal drawback of this technology is that sodium addition tends to increase boiler fouling.

3.2.6 Proprietary Conditioning Agents

A number of suppliers have offered a variety of conditioning agents intended to improve the collecting efficiency of power plant ESPs. Most proprietary agents have been designed for cold-side ESPs, but none has proven significantly superior to SO_3 conditioning. These systems do, however, have the advantage of relatively low capital cost.

In addition, some proprietary agents are now available to treat the high resistivity that develops in hot-side ESPs. The advantage of such an agent over sodium conditioning is that it is added just prior to the hot-side ESP rather than on the coal, which means the injection rate can be modulated to meet the needs for conditioning on a near real-time basis, and there is no risk of slagging or fouling due to increased sodium levels in the coal.

3.3 Optimal Flow Distribution: Uniform vs. Skewed Flow

Gas flow has such a significant effect on ESP collection efficiency that any ESP upgrade should consider optimizing the gas velocity distribution. At a minimum, the gas flow distribution should meet the standards set by the Institute of Clean Air Companies for uniformity. However, experience indicates that many ESPs do not meet these standards and there is plenty of room for improvement.

Traditionally, it has been believed that a uniform gas velocity distribution provides the highest collection efficiency (see Volume 1, Appendix C). However, there may be ESPs that could benefit from a non-uniform gas flow distribution termed “skewed flow.” The skewed flow distribution aims to minimize reentrainment by adjusting gas flow at the bottom of the plates close to the hoppers. To date, skewed flow is considered an experimental concept that would require site-specific evaluation, but in ESPs where reentrainment is significant (as indicated by rapping puffs and a noisy opacity trace), it could improve performance significantly.

3.4 ESP Rebuild

Most ESPs require rebuilding during the life of the power station. Normal wear and tear in the somewhat hostile flue gas environment will cause a need to replace various components; once the collecting plates have reached the end of their useful life, it is time to consider a full-scale rebuild. Note that gas flow modeling and correction should routinely be included as a part of any ESP rebuild, as should replacement of antiquated analog power controls with new digital controls.

3.4.1 Rebuild As-Is

In rare instances, it can make sense for an ESP to be rebuilt according to the original design. If the precipitator, when new, was able to attain the currently required collection efficiency with some degree of safety margin, then a rebuild as-is can be considered. Usually, however, a rebuild is used as an opportunity to incorporate design upgrades that will improve the unit's operation and reliability.

3.4.2 Rebuild With Wide Plate Spacing

An ESP that requires rebuilding will typically have its collecting plates spaced 9 or 10 inches (about 250 mm) apart. The current norm is to use wider plate spacing, from 12 to 16 inches (about 300–400 mm). Any rebuild planned for an existing ESP should probably include upgrading the internals to these new standards. Advantages include reduced weight of the ESP internals; improved plate alignment because allowable tolerances are greater; more uniform current density distribution; and possible improvement in collecting high-resistivity particles.

Rebuilding with wider plate spacing does not require replacing the foundation. A design with 12-inch plate spacing built into the same casing originally designed for 10-inch spacing should attain the same collection efficiency, even though specific collection area (SCA) will be less than that of the original unit. The high-voltage distribution system must be redesigned and installed.

3.4.3 Rebuild With Increased Collecting Electrode Area

When a rebuild is necessary to improve collection efficiency, it generally requires an increase in SCA—through installing taller collecting plates and/or adding an extra collecting field. Even though some original designs included space to install an extra field in the original casing and accounted for the extra weight this would entail, a rebuild for increased collection efficiency will usually require a major overhaul—perhaps including a new foundation for the new portion of the ESP and auxiliary equipment as needed.

3.5 Polishing Devices in Series

It is not always necessary to rebuild the entire ESP to achieve significant performance improvement. Various new technologies are available as "polishing" devices, to be added downstream of the last field of an ESP or, if there is not room, to replace the last field. The technologies discussed below have been tested at either pilot or full scale, and have achieved emission reductions exceeding 50%.

3.5.1 Compact Hybrid Particulate Collector (COHPAC)

This EPRI-developed technology uses a small pulse-jet baghouse as a polishing unit downstream of the ESP. The low ash loading to the baghouse allows it to use a higher gas velocity than is needed for a baghouse operating alone. The lower ash loading should also increase the life of the fabric filter material.

There are two ways to apply the concept. COHPAC I retains the existing ESP and adds the baghouse downstream on its own foundation, whereas COHPAC II replaces the outlet field of the ESP with the baghouse. The outlet emissions from either version should be comparable to those from a conventional pulse-jet fabric filter. Both approaches can achieve collection efficiencies well over 99%, usually at less cost than building a replacement ESP.

3.5.2 Wet Electrostatic Precipitator

Wet ESP (WESP) uses a flowing sheet of water to entirely cover the collecting plates in the ESP. Since the film of water serves as the collecting electrode, there is no significant reentrainment and the detrimental effects of high resistivity are eliminated. The collected material flows down the plate with the water film to be collected in the drain system. Collection efficiency for a modestly sized WESP with an SCA on the order of 50 ft^2/kcfm (9.8 m^2 per m^3/s) is expected to be greater than 90% (typically more like 95%).

The wet system can be installed either as a conversion of the outlet field of the existing ESP or as a separate housing downstream from the primary ESP collector. If the wet unit is installed in the existing housing, the existing dry field will have to be removed and replaced with a field made of corrosion-resistant materials.

A proven technology in industrial applications, WESP holds promise as a polishing unit for utility installations with either high resistivity or excessive reentrainment; it is also particularly applicable to plants with wet scrubbers that are emitting “blue plume” sulfuric acid mists.

3.5.3 ElectroCore™ Separator

The ElectroCore™ separator is a new EPRI-sponsored technology designed to enhance particle collection in power plant applications. It consists of an ensemble of electrically enhanced cyclonic collectors. The inertial force of the cyclone is augmented by an electrical force that enhances the separation of fine particles about 5 microns and smaller. The device separates the flue gas into two streams: the outer stream with the heavy concentration of particles (about 10% of the total gas stream) is extracted and re-injected into the ESP inlet, while the cleaner gas stream (about 90% of the flow) is sent to the stack. Separation efficiencies of well over 90% have been measured in large pilot-scale tests.

3.5.4 Laminar Flow Fine Particle Agglomerator™

This nearly commercial device uses the principle of laminar flow in a special ESP section to achieve 100% collection of fine particles. The device replaces an inner field of the ESP. Relying on residual electrical charge from the previous field, it collects the remaining particles in a static field with no corona flow (i.e., under near–laminar flow conditions). The particles are then reentrained, but as larger, easier-to-collect clumps larger than 5 microns. These “agglomerated” particles can then be better collected by the outlet field of the ESP.

The device must be built to close tolerances to maintain near–laminar flow conditions, but should significantly increase ESP performance.

3.6 New Primary Collecting System

When the existing ESP requires replacement, the available options expand to include other technologies. If the existing ESP can be made to function properly, it may remain as part of the final particle collecting package. Either an additional particle control device can be added in series or parallel or the old unit can be completely removed, depending on site-specific conditions.

3.6.1 Replace With Larger ESP or Add Additional ESP

Measurements of the characteristics of the existing ESP will provide valuable information about the desirability of replacing the existing ESP with an entirely new one or keeping the existing unit and adding an additional ESP in series or parallel. Space availability and economics generally dictate one approach over another. The resistivity of the fly ash and the electrical readings from the power supplies provide the data necessary to determine if a new ESP is the appropriate upgrade technology. If these readings indicate that the ash is difficult to collect in an ESP (low power levels), then an alternate technology that is less sensitive to fly ash properties (such as a fabric filter) should be considered.

3.6.2 Convert Hot-Side ESP to Cold-Side

A hot-side ESP experiencing high resistivity from sodium depletion can be converted to cold-side operation. The modification requires re-routing the gas flow ductwork so that the input flue gas comes from the air heater outlet rather from the economizer outlet. This change in effect “increases” the size of the ESP because of the volumetric change due to temperature reduction. A reduction in flue gas temperature from 700°F to 300°F (370°C to 150°C) reduces the gas volume flow rate to about 65% of the previous value—thereby increasing the specific collecting area by more than 50%. In many instances, conversion to cold side alone is adequate to achieve performance goals, but in others, resistivity conditioning may also be required.

3.6.3 Replace ESP With Fabric Filter

The ESP is usually the lower-cost option for collecting fly ash when the ash resistivity is less than 5×10^{11} Ω-cm. For higher resistivities, a fabric filter generally becomes the lower-cost option. Fabric filter collection efficiencies are excellent; the main challenge is fitting them into the existing space.

When adding a fabric filter (baghouse), there is the question of whether or not to retain the ESP in service, either in series or parallel. If there is room, the ESP should generally be retained unless it would require an extensive rebuild to operate properly; economics should guide this decision. If retained in series, the installation becomes similar to COHPAC I. If the fabric filter is added in parallel, the effective SCA of the ESP will be increased, as a significant portion of the flue gas will bypass the ESP to the new fabric filter.

4

EVALUATION OF EXPECTED PERFORMANCE IMPROVEMENT FROM TECHNOLOGY OPTIONS

To evaluate which upgrade technology—or combination of technologies—is the best solution for your power station, you will need an ESP model calibrated to your site-specific conditions. (See Volume 1, Section 3 for instructions on calibrating the model.)

This chapter illustrates how to estimate the expected performance improvement offered by each of the various upgrade options, using ESP model projections and other means. The next chapter, Chapter 5, presents an example of how to determine costs for the various options. Both chapters illustrate the proper estimation procedures using an example 310-MW power station, which is described in Table 4-1.

As shown in Table 4-1, the primary example ESP is an older unit with four fields with an SCA of 138 square feet per thousand cubic feet per minute of gas (27.2 m^2 per m^3/s); the inlet field is 3.5 feet long (1 m) and the other fields are 6 feet (1.8 m) long. A second ESP with an extra field is also evaluated to provide guidance for somewhat larger ESPs with an SCA in the range of 177 $ft^2/kacfm$ (34.8 m^2 per m^3/s). Except for the increased length, the larger ESP has the same design features of the smaller ESP.

The examples in this chapter are intended to provide an estimate of the range of performance improvements to expect for the different upgrades. If you need to reduce the outlet emissions by a factor of two, scan the improvement expected for each option and select those appropriate for your installation for detailed evaluation. This prescreening will reduce the number of alternatives that you must evaluate.

Note that two upgrade technologies discussed in Chapter 3 are not treated in this chapter: the Arc Snubber™ filter and skewed flow gas distribution. As discussed in Chapter 3, performance improvements with the Arc Snubber™ filter are not yet understood, so there is no way to predict the estimated change in performance with the addition of this device. Rather, performance improvements must be measured directly through a trial installation. There is similar uncertainty regarding the use of skewed flow. Much of the test data available were recorded during improvement programs where several variables changed simultaneously. While there is a logical basis for the skewed flow design concept, the data supporting such a claim are not yet sufficient to allow an accurate estimate of the effects of this technology on collection efficiency.

Throughout this chapter, performance improvements are shown primarily in terms of secondary current density levels and emission levels, which are given in English units of measure (current density in microamperes per square foot and emissions in pounds per million Btu). However, the metric equivalents for current densities in nanoamperes per square centimeter (nA/cm^2) and emissions in grams per normal cubic meter (g/Nm^3) are approximately the same as the English values, because 1 $\mu A/ft^2 = 1.076\ nA/cm^2$ and 0.1 lb/MBtu is about 0.1 g/Nm^3. (Note that the relationship between lb/MBtu and g/Nm^3 is not actually constant, but varies with the actual coal being burned.) Because of this close relationship, the metric equivalents for these two items are not included at every appearance in the text and tables.

Table 4-1
Characteristics of Example ESP

Plant Size	310 MW
Boiler Type	Front and Rear Wall Fired, Pulverized Coal
Stack Exit Diameter	17.4 ft (5.3 m)
Cold-Side ESP	
Total Collecting Area	142,416 ft^2 (13,231 m^2)
SCA	138 ft^2/1000 acfm (27.16 m^2 per m^3/s)
Number of Fields	1 x 3.5 ft, 3 x 6 ft (1 x 1.07 m, 3 x 1.83 m)
Number of Bus Sections	4 bus sections across flow
Number of TRs	8—each serves 2 bus sections, 4 deep
	Vibrator Rappers—Wires
	MIGI Rappers—Plates
Collecting Plate Spacing	9 inches plate to plate (229 mm)
Flow Area	2484 ft^2 (230 m^2)
Velocity	6.90 ft/s (2.1 m/s)
Height	27 ft (8.23 m)
Width	92 ft (28 m)
Depth	21.5 ft (6.55 m)
Number of Gas Passages	123
Aspect Ratio	0.80
Hot-Side ESP	
Total Collecting Area	456,720 ft^2 (42,430 m^2)
SCA	313 ft^2/1000 acfm (61.6 m^2 per m^3/s)
Number of Fields	4 x 10 ft (4 x 3.05 m)
Number of Bus Sections	4 bus sections across flow
Number of TRs	8—each serves 2 bus sections, 4 deep
	Vibrator Rappers—Wires
	MIGI Rappers—Plates
Collecting Plates Spacing	9 inches plate to plate (229 mm)
Flow Area	4282 ft^2 (397.8 m^2)
Velocity	6 ft/s (1.82 m/s)
Height	33 ft (10 m)
Width	130 ft (39.6 m)
Depth	40 ft (12.2 m)
Number of Gas Passages	173
Aspect Ratio	1.2

4.1 Upgrades to Power Supply Controls

The installation of an upgraded power supply control may make a small difference in performance for an ESP collecting intermediate resistivity (10^{10} to 10^{11} Ω-cm) ash particles. There may be some improvement in energization as well as some power conservation. A more significant improvement will occur when the upgrade is applied to an installation collecting higher-resistivity (>10^{11} Ω-cm) ash.

The following discussion is based on the example ESPs described in Table 4-1—namely, a small, cold-side ESP with four fields and an SCA of 138 ft^2/kacfm (27.16 m^2 per m^3/s); a similar five-field ESP with an SCA of 177 ft^2/kacfm (34.8 m^2 per m^3/s), which is not shown in Table 4-1; and a hot-side ESP with an SCA of 313 ft^2/kacfm (61.6 m^2 per m^3/s). For the cold-side units, the plate area is 23,247 ft^2 (2160 m^2) for the inlet field and 39,852 ft^2 (3702 m^2) for the remaining fields. The plate spacing is 9 inches (~230 mm) and the weighted-wire discharge electrode has a diameter of 0.109 inch (~2.8 mm). The fly ash has a resistivity of about 10^{12} Ω-cm.

The existing ESPs have older analog controls that allow operation in back corona. In our example, these existing power supplies are assumed to be currently operating with the electrical readings given below in Table 4-2. (Note that the actual currents could be significantly higher than reported below, but the useful current where the V-I curve changes shape into a backslant is used for modeling.) Actual expected secondary voltages and estimated currents are used in the example for older analog controls since the actual currents would be expected to be much higher with severe back corona. In fact, the values used in this example are typical values noted during several field tests. In your own study, use actual measured values for your ESP, taking care not to use excessive back corona current in the calculation. See Volume 1, Appendix A for more information.

Table 4-2
Electrical Readings for Original Analog Power Supply Controls

Electrical Field	Secondary Voltage, kV	Secondary Current, mA	Current Density*, μA/ft^2
Inlet	27.5	85	3.2
Second	25.5	190	4.5
Third	24.0	250	7.5
Fourth	23.0	350	8.0
Outlet	22.5	450	9.5

* Current density values expressed in •A/ft^2 are almost identical to current density values expressed in nA/cm^2, because 1 •A/ft^2 = 1.076 nA/cm^2.

The preceding electrical data were used as input data to the ESP model, which was then run to project the performance for these four- and five-field ESPs. Model projections are summarized in Table 4-3.

Table 4-3
Predicted Efficiency for ESPs With Older Analog Controls

ESP	Efficiency, %	Opacity, %	Emissions, lb/MBtu*
4 Fields, SCA = 138	89.6–90.5	76–78	0.502–0.548
5 Fields, SCA = 177	93.2–93.8	65–67	0.326–0.361

* Emissions in grams per normal cubic meter are numerically very close to the emissions as stated above in lb/MBtu. The actual ratio varies somewhat, but for our example plant, the ratio is about 1.07.

Without further changes, neither of these installations comes close to meeting an emission limit of 0.1 lb/MBtu (~100 mg/Nm^3). Thus, it makes sense to model control upgrades, starting with the simplest options and proceeding to the more complex.

4.1.1 Basic Upgrade to Digital Control

The first improvement to consider is the conversion to new PC-based controls. These controls can be programmed to operate either at the onset of back corona or with intermittent energization. The first evaluation is at back corona onset (IE will be discussed later along with pulse energization). When the new controls are set to avoid back corona, the electrical readings will improve from those in Table 4-2 to those in Table 4-4. These electrical readings were selected from Volume 1. The current densities were selected from Figures A-1 through A-3, and the voltages were translated from the 10-inch (~250 mm) spacing data in Figure A-4 by multiplying the voltage by the ratio of the plate spacing (9/10). Plant number 11 in Table A-2 has electrical readings similar to these data. Note that as the actual operating current is reduced, the operating voltage increases as the operating point moves to the beginning of back corona. If the analog controls were allowed to operate with heavy back corona, the currents would be higher and the voltages lower.

Table 4-4
Digital Controls Operated at Back Corona Onset

Electrical Field	Secondary Voltage, kV	Secondary Current, mA	Current Density, µA/ft^2
Inlet	34.2	75	3.2
Second	33.2	175	4.4
Third	33.0	300	7.5
Fourth	30.3	350	8.8
Outlet	29.6	375	9.4

With this upgrade, the example ESPs are now predicted to have the collection efficiencies shown in Table 4-5.

Table 4-5
Predicted Efficiency for Digital Controls Operated at Back Corona Onset

ESP	**Efficiency, %**	**Opacity, %**	**Emissions, lb/MBtu**
4 Fields, SCA = 138	92.9–93.6	67–69	0.340–0.374
5 Fields, SCA = 177	95.3–95.9	55–57	0.153–0.175

Although modernization of the power supplies successfully reduces emissions by about a factor of two, neither ESP meets the emissions target with this upgrade alone.

4.1.2 High-Frequency Controls

The newer high-frequency power supplies should provide about the same degree of performance improvement as the other PC-based systems. However, the reduction in weight and size from the higher-frequency supplies may be a significant consideration if their use can preclude the need to replace the ESP foundation in a contemplated rebuild.

4.1.3 Intermittent and Pulse Energization

The next evaluation is for operating the digital controls with intermittent energization (IE) to further reduce the influence of the high-resistivity ash. The power supplies will continue to operate at approximately the same average secondary voltage and current densities. The significant difference is that the peak-to-average secondary voltage will increase. Typically, IE tests have shown that the peak-to-average voltage increases from a nominal value of 1.2 for conventional energization to about 1.6 for IE. When the peak-to-average voltage setting is changed to 1.6 in the ESP model, the predicted outlet information now changes to that shown in Table 4-6.

Table 4-6
Predicted Efficiency for Digital Controls Operated With IE

ESP	Efficiency, %	Opacity, %	Emissions, lb/MBtu
4 Fields, SCA = 138	95.0–95.6	57–60	0.232–0.262
5 Fields, SCA = 177	97.0–97.4	43–46	0.137–0.158

The next power supply upgrade to be evaluated is pulse energization, which currently requires adding a pulse power supply to each field. The added power supply provides a fast-rise-time pulse of voltage to a background level of energization from the original power supply. Again, the average secondary voltage remains about the same, but the peak voltage and the secondary current density increase. To simulate the effect of pulsing, it is recommended that the peak-to-average voltage be increased to about 2.0 and the current increased by about 20%. This increase in average current density is possible because of the greater uniformity of current flow from pulsing.

The results, as predicted from the ESP model projection using the higher peak-to-average voltage and the small increase in secondary current, are shown in Table 4-7.

Table 4-7
Predicted Efficiency for Digital Controls With True Pulse Energization

ESP	Efficiency %	Opacity %	Emissions, lb/MBtu
4 Fields, SCA = 138	96.4–96.9	48–51	0.163–0.188
5 Fields, SCA = 177	98.0–98.3	34–37	0.091–0.106

Pulsing alone would not bring the four-field ESP into compliance with a 0.1 lb/MBtu emission limit, but it does bring the five-field ESP within range. However, neither of these small units will meet the NSPS limit of 0.03 lb/MBtu (30 mg/Nm^3) with pulse energization alone.

Another means of estimating the improvement in performance due to pulsing is known as the ω_k enhancement factor method. The enhancement factor is the number by which the old ω_k value must be multiplied to get an ω_k value that is appropriate for a specific modification. The Matts-Ohnfeldt equation forms the basis for this method. The Deutsch-Anderson (DA) equation is modified from a simple exponential relationship to the following:

$$\eta = 1 - e^{-(\omega kA/V)^k}$$

The Matts-Ohnfeldt modification to the D-A equation provides a single-value relationship between collecting efficiency and SCA, taking into account that the ESP is collecting a wide range of particle sizes. The exponent k for fly ash ESPs usually has a value of about 0.5. The value of ω_k for the ESP with digital controls is about 52 ft/min (26.4 cm/s). For pulse energization, the enhancement factor is about 1.6. The value of 1.6 for an enhancement factor is in line with the full-scale results of a pulse energization study reported in EPRI report CS 4717, *An Investigation of Precipitator Pulse Energization*, September 1986. However, this is a conservative estimate, and the actual ω_k improvement for full scale with fast-rise-time pulses may exceed this value.

Using this method for the example ESPs, with an exponent in the Matts-Ohnfeldt equation of 0.5 (appropriate for fly ash), ω_k is calculated to be 52 ft/min (26.4 cm/s). The ω_k value is multiplied by the factor of 1.6 for pulsing to yield an ω_k of 83 ft/min (~42 cm/s). The efficiencies calculated with pulsing are 96.6% for the four-field ESP and 98% for the five-field unit. These numbers are consistent with the model projections, and either method can be used to evaluate the effect of pulsing.

The results of the changes to the electrical energization controls are shown in Figures 4-1 and 4-2 for the four- and five-field ESPs, respectively.

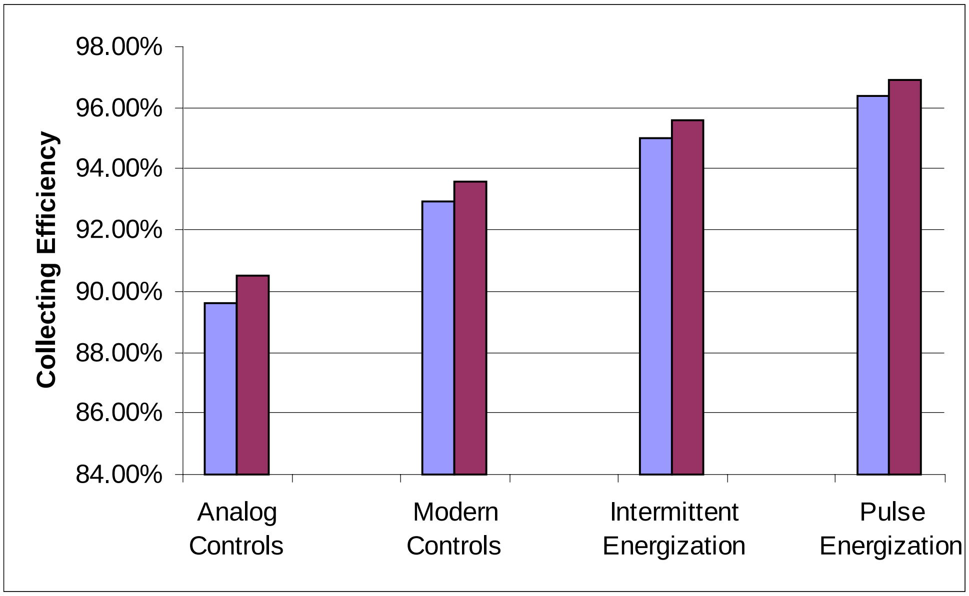


Figure 4-1
Performance of Different Modes of Energization (Example Four-Field ESP)

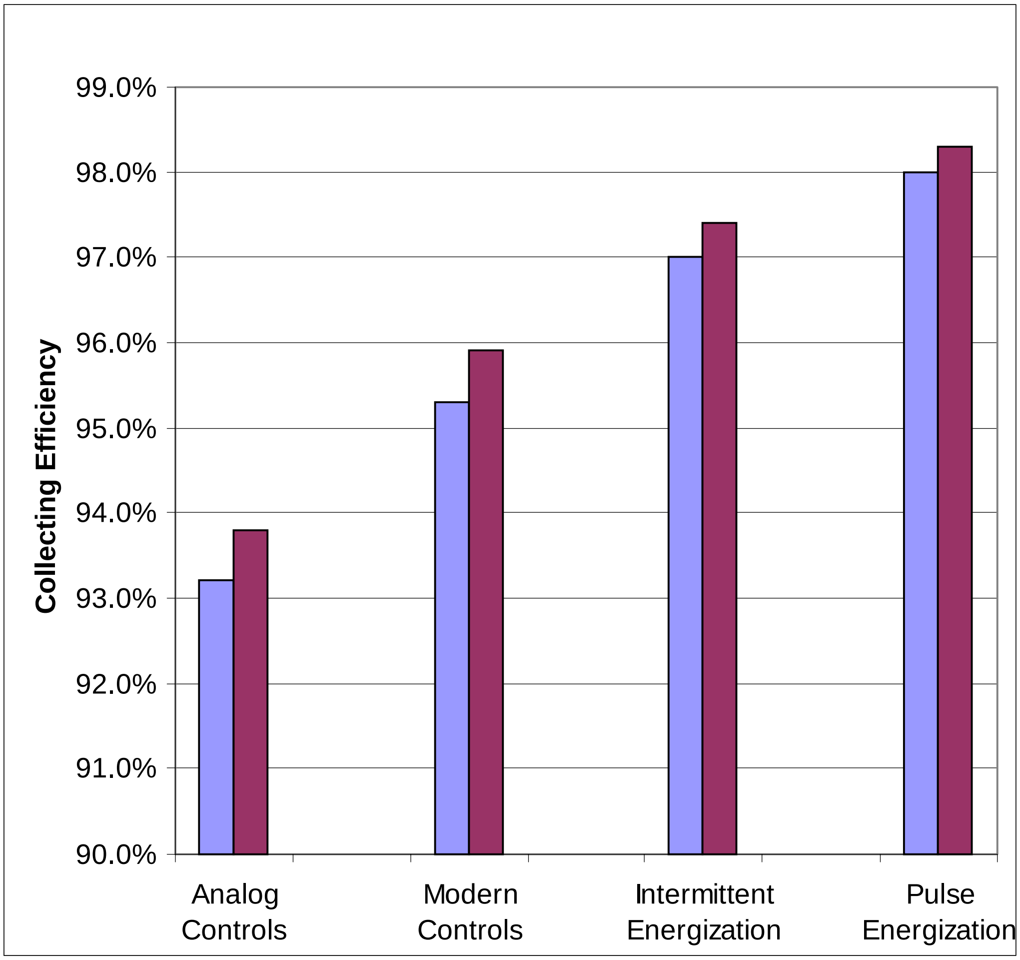


Figure 4-2
Performance of Different Modes of Energization (Example Five-Field ESP)

4.1.4 Positive Polarity for Hot-Side ESPs

In this subsection, we estimate the effect of converting the energization of a hot-side ESP from negative to positive polarity. This conversion is less costly than the conversion from hot-side to cold-side operation and may produce satisfactory performance.

The operating voltages and currents for positive- and negative-polarity hot-side units will be different. For example, a pilot ESP with 12-inch (~300 mm) plate spacing tested at Alabama Power Company's Plant Gaston operated at 50 kV and 62 $\mu A/ft^2$ at 755°F (402°C) with negative polarity and 45 kV and 37 $\mu A/ft^2$ for positive polarity. These values are for clean plate conditions immediately after reaching operating temperature. After several days of operation, the voltages and current densities decreased to 43 kV and 50 $\mu A/ft^2$ for negative polarity, and 40 kV and 35 $\mu A/ft^2$ for positive polarity. These numbers illustrate the types of changes to expect between positive- and negative-polarity hot-side ESPs.

The operation with positive polarity can entail either a permanent conversion to positive or switching between polarities as needed. The permanent conversion will probably be less costly, but other factors may dictate switching. An ESP operates with a higher collecting efficiency with negative polarity than positive, when other factors do not limit performance. Both conditions are discussed.

Three conditions are modeled for the positive polarity evaluation:

1. Negative polarity before degradation
2. Negative polarity seriously degraded
3. Positive polarity

For the purposes of this example, we model a hot-side ESP operating at 750°F (400° C) with an SCA of just over 300 ft^2/kcfm (59 m^2 per m^3/s) burning a Powder River Basin coal. The same power station is considered for this hot-side example as was used above in the cold-side examples. The volume flow rate from the 310-MW station will increase from 1 million to 1.6 million at the hot-side gas temperature.

The ESP is modeled with 12-inch spacing, since the pilot-scale ESP used to establish the electrical readings for the inlet section has 12-inch (~300 mm) spacing. It is recognized that the hot-side ESPs in service are in actuality units with 9- or 10-inch (~250 mm) plate spacing, but the differentials in performance will be expected to be the same, regardless of plate size. (In fact, the current densities are expected to be approximately the same for both plate spacings. The voltages at different plate spacings would be approximately proportional to the plate spacing.)

The electrical readings for the next three fields are estimated from the inlet readings from the pilot ESP, and given below in Table 4-8. Again, these estimates are "typical" values based on experience. In your own study, use actual readings from the ESP in question for the negative-polarity simulation and use the ratio of positive to negative factors in Tables 4-8 and 4-10 to obtain positive-polarity voltages and current densities to use in the positive-polarity simulation.

Table 4-8
Electrical Readings for Negative-Polarity Hot-Side ESP Before Degradation

Electrical Field	Secondary Voltage, kV	Secondary Current, mA	Current Density, $\mu A/ft^2$
Inlet	43.0	5000	42.5
Second	41.0	5600	47.6
Third	39.0	6200	52.7
Outlet	37.0	7000	60.0

Table 4-9 presents electrical readings after heavy sodium depletion has occurred and performance has seriously degraded. In reality, the ESP would be washed or some other action would be initiated before performance would be allowed to degrade this much. The numbers in Table 4-9 are typical for a hot-side unit operating with sodium depletion; naturally, however, you should use your actual degraded voltage and current readings in the model for comparison to the positive-polarity performance calculation.

Table 4-9
Electrical Readings for Negative-Polarity Hot-Side ESP After Degradation

Electrical Field	**Secondary Voltage, kV**	**Secondary Current, mA**	**Current Density, μA/ft^2**
Inlet	32.0	1750	14.9
Second	30.5	2300	19.6
Third	28.5	2900	24.7
Outlet	27.5	3500	29.8

When the polarity is reversed, the positive-polarity electrical readings would be degraded as well. However, as the charge carriers are replaced through the ionic migration, the electrical readings would recover more quickly than the depletion formed. With positive polarity, a combination of diffusion and conduction forces work together to replenish the thin depleted layer that remains on the collecting electrodes. Laboratory data confirm the recovery of electrical conditions when the polarity is reversed. The polarity reversal recovery has been demonstrated in the EPRI pilot-scale program currently active. There is a distinct recovery in electrical conditions in the currently operating pilot ESP with reversible polarity, but the specific sequence of weekly polarity reversals has not been verified at this time. The polarity reversal is expected to be needed on perhaps a weekly basis for stations that would develop back corona in a four- to six-week period.

The expected power supply values are reported in Table 4-10.

Table 4-10
Electrical Readings for Positive-Polarity Hot-Side ESP After Conversion

Electrical Field	**Secondary Voltage, kV**	**Secondary Current, mA**	**Current Density, μA/ft^2**
Inlet	40.0	3750	31.9
Second	38.5	4000	34.0
Third	36.5	4750	40.4
Outlet	33.0	5000	42.5

The electrical readings before degradation are significantly better for the negative-polarity operation than for positive polarity. However, the electrical readings for the positive-polarity condition are much better than that for the degraded negative-polarity case. If the SCA of the ESP is large enough, it may be possible to operate continuously in the positive-polarity mode. On the other hand, if the station operates on load dispatch rather than baseload, the ESP polarity can be reversed to positive during the low-load periods at night and during weekends to reverse the electrical degradation, and can then operate with negative polarity during full-load periods. The results of the ESP model projections are shown in Table 4-11.

Table 4-11
Performance Predicted for Each Condition From the Polarity Reversal Example

Operating Mode	Collection Efficiency, %	Outlet Opacity, %	Emissions, lb/MBtu
Good Negative	99.50–99.35	8–10	0.026–0.033
Degraded Negative	97.50–97.10	33–37	0.129–0.149
Positive Polarity	99.13–98.90	13–16	0.045–0.055

The preferred mode of operation for a small, non-baseloaded station may be to have reversible-polarity power supplies and controls installed. The ESP can be normally operated with negative polarity. The system can be switched to positive polarity at intervals appropriate for the rate of degradation from sodium depletion. Preliminary data suggest that polarity reversals on each weekend could be adequate to prevent the development of high-resistivity-limited performance. The ESP should maintain electrical readings and collecting efficiencies near those for fresh-start conditions except for extreme cases.

The results of the model simulation for polarity reversal are shown below in Figure 4-3

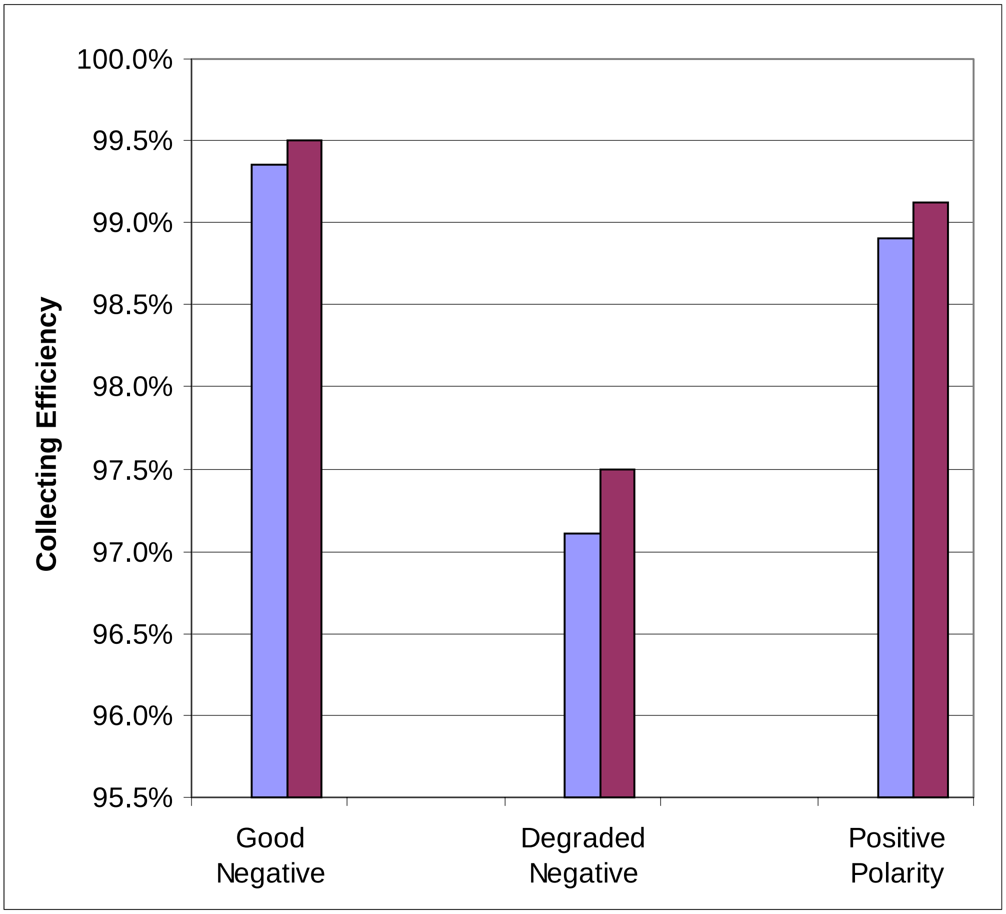


Figure 4-3
Collection Efficiency With Polarity Reversal (Model Projections)

4.2 Flue Gas/Fly Ash Conditioning

This section illustrates the effect of modifying ash resistivity using flue gas conditioning. Conditioning can be achieved by a number of agents, including SO_3, ammonia, and proprietary agents, among others.

4.2.1 General Resistivity Reduction

The performance impacts of flue gas conditioning are illustrated for the same two cold-side ESPs used throughout this chapter: an installation with an inlet field 3.5 feet (1 m) long followed by three fields 6 feet (1.8 m) long and an SCA of 138 ft^2/kacfm (27.2 m^2 per m^3/s); and a larger installation with an extra 6-foot field and an SCA of 177 ft^2/kacfm (34.8 m^2 per m^3/s).

The various approaches to resistivity modification will have to be evaluated from a cost standpoint in addition to a performance standpoint since they should all succeed in lowering ash resistivity to the levels shown in this section. The following tables compare the net result of conditioning to a resistivity of either 1 x 10^{11} Ω-cm or 2 x 10^{10} Ω-cm. The difference, of course, is the allowable secondary voltages and current densities that can be applied to the ESP.

The electrical readings for the five-field ESP are given in Tables 4-12 through 4-14 for each resistivity condition. The four-field ESP unit should have the same readings as the first four fields of the five-field unit. These voltage and current readings are typical for small ESPs with 9-inch (~230 mm) plate spacing. For a given resistivity, the current densities would be the same; but for wider plate spacing, the voltages should be multiplied by the ratio of the plate spacing divided by 9.

Table 4-12
Electrical Readings for Resistivity = 1 x 10^{12} Ω-cm

Electrical Field	Secondary Voltage, kV	Secondary Current, mA	Current Density, µA/ft^2
Inlet	34.5	75	3.2
Second	33.2	175	4.4
Third	33.0	300	7.5
Fourth	30.3	350	8.8
Outlet	29.6	375	9.4

Table 4-13
Electrical Readings for Resistivity = 1 x 10^{11} Ω-cm

Electrical Field	Secondary Voltage, kV	Secondary Current, mA	Current Density, µA/ft^2
Inlet	39.5	140	6.2
Second	38.2	400	10.0
Third	38.0	600	15.1
Fourth	35.0	700	17.6
Outlet	34.0	800	20.0

Table 4-14
Electrical Readings for Resistivity = 2 x 10^{10} Ω-cm

Electrical Field	Secondary Voltage, kV	Secondary Current, mA	Current Density, µA/ft^2
Inlet	46.0	500	21.5
Second	44.0	1100	27.6
Third	43.0	1500	37.6
Fourth	41.5	1900	47.7
Outlet	39.0	2000	50.0

The model projections are reported in Table 4-15 for the four-field example. Similar improvements result from conditioning a five-field ESP, as indicated in Table 4-16. The model results for the four- and five-field examples are also shown in Figures 4-4 and 4-5.

Table 4-15
Improving Performance by Reducing Resistivity in Four-Field ESP (SCA = 138)

Resistivity, Ω-cm	Collecting Efficiency, %	Outlet Opacity, %	Emissions, lb/MBtu
1 x 10^{12}	92.90–93.60	67–69	0.340–0.374
1 x 10^{11}	96.90–97.30	43–46	0.143–0.164
2 x 10^{10}	98.80–99.06	20–23	0.050–0.062

Table 4-16
Improving Performance by Reducing Resistivity in Five-Field ESP (SCA = 177)

Resistivity, Ω-cm	Collecting Efficiency, %	Outlet Opacity, %	Emissions, lb/MBtu
1 x 10^{12}	95.30–95.90	55–57	0.218–0.246
1 x 10^{11}	98.20–98.50	30–32	0.079–0.093
2 x 10^{10}	99.61–99.50	10–12	0.020–0.027

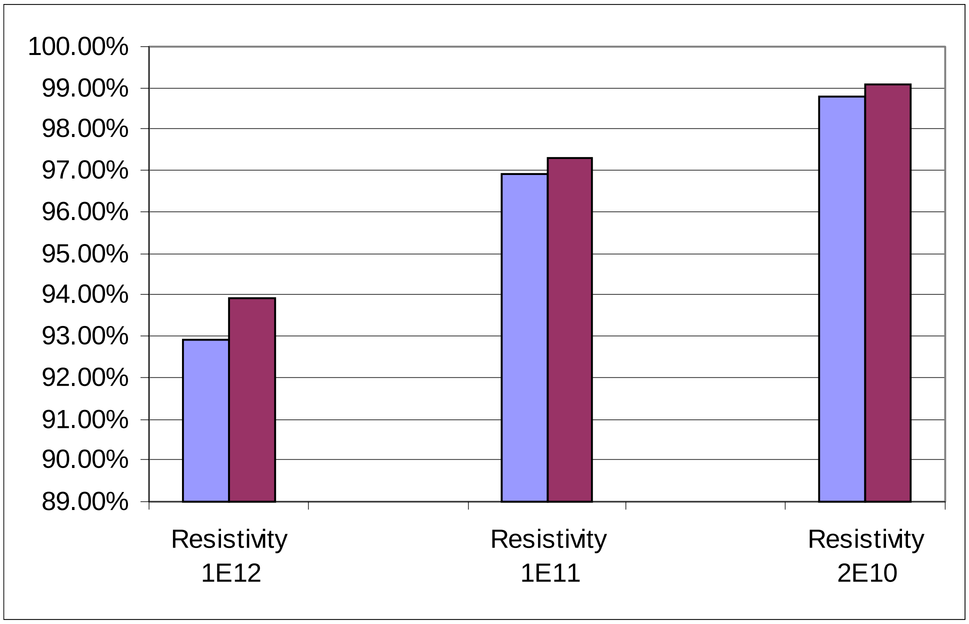


Figure 4-4
Collection Efficiency for Resistivity Changes in Four-Field Unit

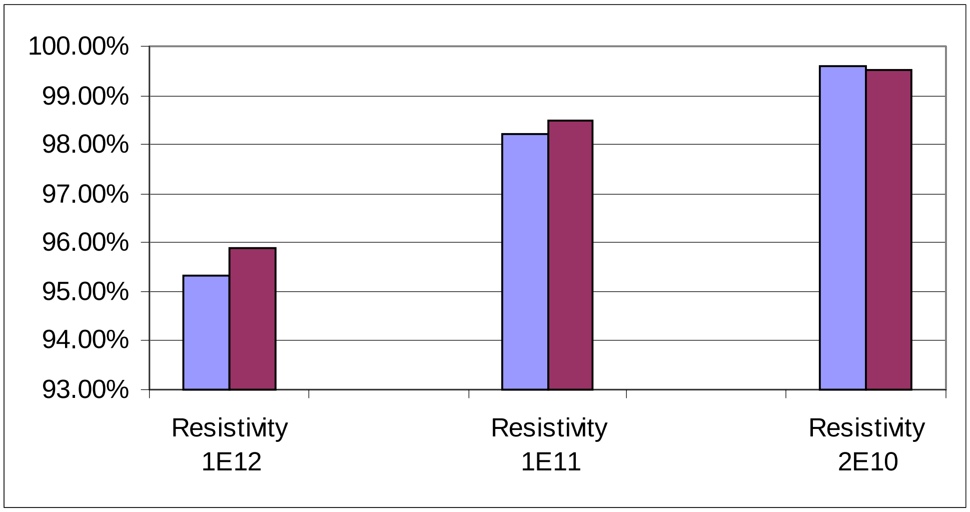


Figure 4-5
Collection Efficiency for Resistivity Changes in Five-Field Unit

4.2.2 Ammonia Conditioning

Ammonia conditioning warrants additional discussion, as it is difficult to accurately estimate the performance effects of ammonia conditioning for some situations. In applications where ammonia is added to SO_3 conditioning to make SO_3 conditioning effective, the estimates for resistivity reduction just illustrated should provide a good estimate for combined SO_3 and ammonia conditioning. For example, a fly ash with very high silica plus alumina content (over

80%) can be difficult to condition with SO_3 alone, but if SO_3 is combined with ammonia conditioning, the resistivity can be lowered to the 1×10^{11} Ω-cm range or even the 2×10^{10} Ω-cm range.

It is more difficult to quantify the effect of ammonia conditioning for the case where the fly ash resistivity is already low and ammonia is added to reduce reentrainment. Reentrainment is sensitive to fly ash properties, the gas velocity distribution, the aspect ratio of the ESP, and rapping system design. Nevertheless, field test data indicate that rapping losses account for roughly half of the total emissions from a small ESP and that ammonia addition will eliminate about half of the rapping emissions. These numbers suggest that ammonia addition will reduce emissions from a typical small precipitator by around 25%. A test with a temporary ammonia conditioning system is the best way to accurately determine the effect of ammonia addition for this application.

There is one additional situation where ammonia conditioning can be used to good advantage. If a boiler produces an ash with high carbon content (high LOI), it is possible that carbon makes a significant contribution to ESP outlet emissions because ESPs collect carbon with low efficiency. A combined ammonia- SO_3 conditioning system should significantly reduce carbon emissions. For example, if conversion to low-NO_x burners increases ash LOI to over 10%, there will likely be an increase in outlet emissions. For this case, a combined ammonia-SO_3 conditioning system should return emissions to their pre-low-NO_x burner level.

4.3 Rebuild Options

An ESP can be rebuilt with the original plate spacing (rebuilt as-is) or with wider plate spacing. In either case, the expected performance improvement is the same.

4.3.1 Rebuild As-Is

The first rebuild option considered is to rebuild as-is, with the same plate and discharge electrode designs. If the existing unit originally met the required emission limits and the rebuild is triggered by only the condition of the equipment, rebuilding as-is may be the appropriate choice. Even rebuilding as-is may improve performance for the following reasons. First, there is likely to be an improved gas velocity distribution. Next, there will be improved power supply controls, and finally, there is an opportunity to reduce rapping reentrainment. (Changes from rapping and power supply controls are too site-specific to evaluate in a general example.) Naturally, the rebuild would also be expected to correct any plate warping or other misalignment within the ESP that had developed over time. Correcting misalignment will improve the electrical operating conditions. An ESP that requires rebuilding because of age will likely be 20 or more years old. The gas velocity distribution and sneakage factors can be in the range of $\sigma_g = 0.2$ to 0.25 and S = 0.10 to 0.13. These factors should decrease to $\sigma_g = 0.12$ and S = 0.08 after a careful rebuild, since a gas flow model study should be an integral part of any rebuild project.

The four- and five-field ESPs with SCAs of 138 ft^2/kacfm (27.2 m^2 per m^3/s) and 177 ft^2/kacfm (34.8 m^2 per m^3/s), respectively, are evaluated for the improved flow conditions, when high resistivity is not limiting the performance. It is assumed that the baseline ESP is equipped with modern electrical controls for the following sets of model comparisons. Two examples of poor gas flow distribution and sneakage are illustrated.

Table 4-17
Increasing Performance by Improving Gas Velocity Distribution During Rebuild

Four Fields, SCA = 138	Collecting Efficiency, %	Outlet Opacity, %	Emissions, lb/MBtu
1. $\sigma_g = 0.25$, S = 0.13	98.60	25	0.072
2. $\sigma_g = 0.2$, S = 0.1	99.00	21	0.054
3. $\sigma_g = 0.12$, S = 0.08	99.27	17	0.038
Five Fields, SCA = 177			
4. $\sigma_g = 0.25$, S = 0.13	99.40	13	0.032
5. $\sigma_g = 0.2$, S = 0.1	99.57	11	0.023
6. $\sigma_g = 0.12$, S = 0.08	99.71	8	0.015

The improvement from very bad to very good gas flow reduces the emissions by about a factor of 2, with a significant reduction in opacity as well. The conditions modeled were for a resistivity of 2 x 10^{10} Ω-cm, but similar improvements are expected for higher-resistivity ash as well.

Figure 4-6 shows the ESP model projections for the improvement in gas flow distribution.

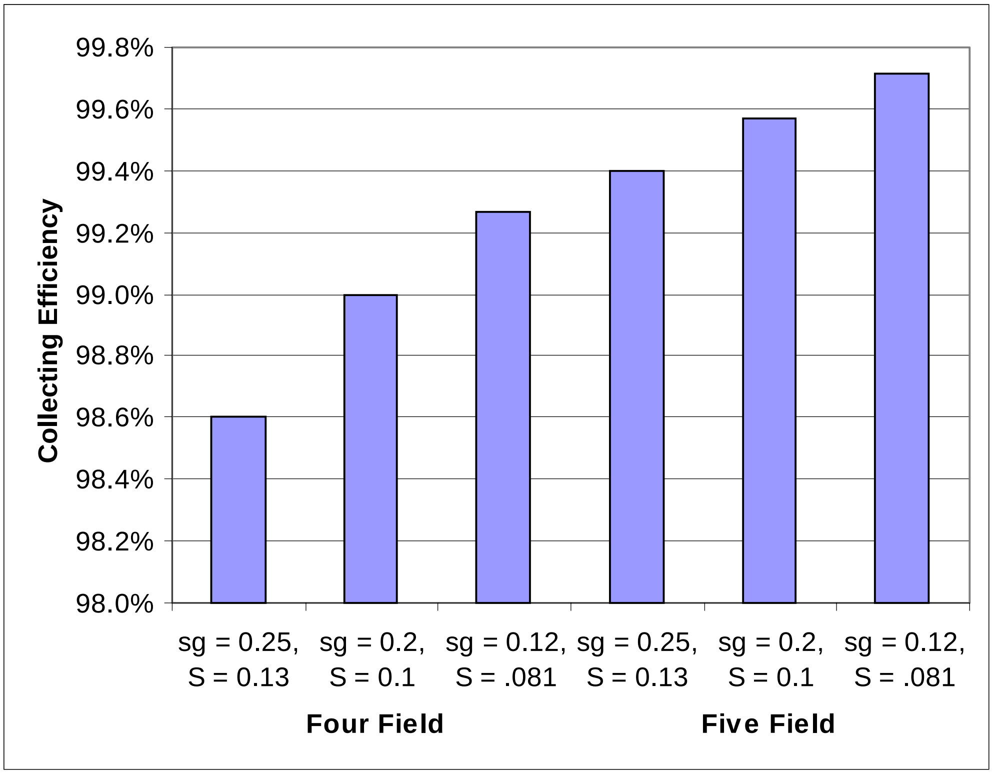


Figure 4-6
Increasing Efficiency by Improving Gas Flow and Sneakage

4.3.2 Rebuild With Wide Plate Spacing

Rebuilding with wider spacing will provide about the same outlet emissions and opacity as rebuilding as-is. The principal benefit offered by wide plate spacing is the weight reduction from the reduced number of collecting plates and associated equipment.

4.3.3 Rebuild With Increased Collecting Area

Rebuilding with increased collecting plate area can be accomplished by either increasing the plate height, adding a collecting field in series, or both. The older installations with plate heights on the order of 27 to 36 feet (8.2 to 11 m) can be rebuilt with 42 to 45 foot (12.8 to 13.7 m) plates. It is not advisable to rebuild three-field ESPs with plate heights too great as the aspect ratio (L/H) becomes too small, tending to increase the percentage of material reentrained during rapping.

The example used to illustrate collecting area increase is a four-field ESP with an SCA of 138 collecting intermediate-resistivity ash ($\rho = 1 \times 10^{11}$ Ω-cm). Table 4-18 reports the range of collecting efficiencies for several example configurations. In the first example modification, a single field is added in series; in the next, plate height is increased from 27 to 42 feet (8.2 to 12.8 m). The final example shows the combination of taller plates and the extra field. In each case, the plate spacing is increased from 9 inches to 12 inches (228 to 300 mm) for the rebuild. The new aspect ratio is considered to be too great when only the plate height is increased. However, there may be cases where this is the only option.

Table 4-18
Improving Performance by Rebuild With Taller Plates and Added Field

Configuration	Collection Efficiency, %	Opacity, %	Emissions, lb/MBtu
Original Four Fields, SCA = 138	96.90–97.3	43–46	0.143–0.164
Add Fifth Field, SCA = 177	98.20–98.50	29–32	0.079–0.093
Add Plate Height, SCA = 215	99.01–9.18	18–21	0.043–0.052
Field & High Plates, SCA = 275	99.59–99.68	9–10	0.017–0.022

The addition of the extra field increases the SCA by about 28.5% and the increased plate height boosts the SCA by 55%. The combination of adding a field and increasing height essentially doubles the original SCA. The addition of an extra field also provides an additional stage of mixing and reduces the amount of material collected on the outlet field, thereby decreasing the rapping reentrainment.

All modifications bring the station into compliance with a 0.1 lb/MBtu (~100 mg/Nm^3) emission limit. The combination of an added field and increased plate height is required to meet the NSPS limit of 0.03 lb/MBtu (~30 mg/Nm^3). There is a question about the absolute opacity, as the projections must also be calibrated, but the relative changes should be accurate. The results of the model projections are shown in Figure 4-7.

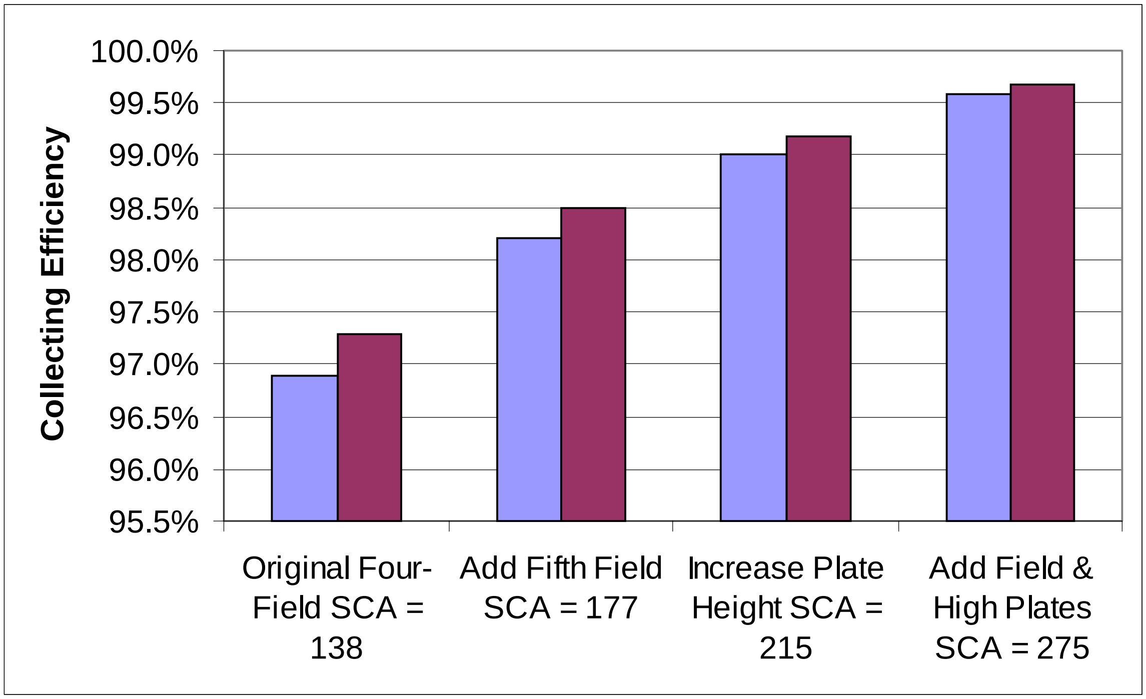


Figure 4-7
Model Results for Increasing Collecting Plate Area

4.4 Polishing Devices

4.4.1 COHPAC

The installation of a small pulse-jet fabric filter in series with the original ESP will meet a 0.03 lb/MBtu emissions limit with less than 20% opacity. The small fabric filter addition is expected to provide the same outlet loading as when a fabric filter is used as the only particle collecting device. However, the size and cost of the COHPAC installation should be considerably less, because this approach takes advantage of the collection that has already occurred in the ESP.

The pulse-jet fabric filter installed for COHPAC will operate with a gas-to-cloth ratio of about 8 to 1 ft/min (2.44 to 1 m/min), while a pulse-jet fabric filter operating alone would have a design gas-to cloth ratio of perhaps 4 to 1 ft/min (1.22 to 1 m/min). The expected inlet ash loading to the COHPAC unit would be less than 0.2 grains per actual cubic foot of gas or about 0.6 lb/MBtu (0.6 g/Nm^3), depending upon the collection efficiency of the ESP that COHPAC is being added to. The ESP efficiency will decrease significantly if COHPAC is installed in place of the last field in an existing ESP. If the mass loading is significantly greater than 0.2 grains/acf (0.6 g/Nm^3), a more conservative COHPAC design (lower gas-to-cloth ratio) may be necessary.

4.4.2 Wet ESP

There are two options for adding a wet collecting electrode ESP to an existing installation. An entirely new structure can be added downstream from the existing ESP or an outlet field can be converted from a dry to a wet system. As with COHPAC, the advantage of adding a new structure is again that the total collecting efficiency of the original ESP is retained, while the advantage of converting an existing electrical section from wet to dry operation means that no new external structural foundation or building is required.

The rebuild to convert from a dry to a wet system requires removal of an existing dry field; consequently, the new wet field may be rebuilt with different plate spacing and perhaps extended in length. The weight of a wide-spaced ESP is less than that for a narrow-spaced unit in the same structure; therefore, additional foundation can be avoided.

The decision of whether to build within the existing ESP housing, extending the existing structure to accommodate longer or taller collecting electrodes, or whether to add a new structure, depends on both technical and economic issues. If the existing ESP can be converted without the additional structure and meet the emission limits with adequate margin, this will be the low-cost option.

Again, the example ESP evaluated for the addition of a wet collecting section is the same four-field unit with an inlet field 3.5 feet long, followed by three 6-foot-long fields with collecting plates 27 feet high (SCA of 138 ft^2/kacfm). The comparisons include meeting either 0.1 or 0.03 lb/MBtu for ash resistivities of 10^{10} and 10^{11} Ω-cm. The only difference in the examples for high and low resistivity is the inlet loading to the wet field, as the electrical readings in the wet section will be independent of ash resistivity. The higher-resistivity ash will present a greater ash loading to the wet section than the lower-resistivity ash.

The electrical readings for the baseline ESP are the same as shown previously in Tables 4-12 through 4-14. The electrical readings for the wet section modifications represent an ESP with good mechanical alignment and no resistivity limitation. The readings for this field are given in Table 4-19.

Table 4-19
Electrical Readings for Wet ESP Section With 12-Inch Plate Spacing

Electrical Field	Secondary Voltage	Secondary Current	Current Density
Wet Section	60 kV	2000 mA	67 μa/ft^2

The wet section was modeled singly, with the outlet loading and particle size distribution from the inlet three fields used as input data to that section. To simulate the very low (virtually zero) reentrainment from the wet field, the reentrainment factor in ESPM can be set equal to zero, or a very large reentrainment particle size can be selected in ESPert. The gas sneakage values selected for the wet ESP were 1% and 3%, while the gas velocity distribution standard deviation ranged from 8% to 10%. The sneakage values were set very low because the wet collector can be built with a shallow pan under the collecting plates rather than a deep hopper.

The results from the example for higher-resistivity comparisons are given in the Table 4-20. Table 4-21 provides the comparisons for the lower-resistivity case.

Table 4-20
Improving Performance With a Wet ESP Field, Resistivity = 10^{11} Ω-cm

ESP Description	Collection Efficiency, %	Opacity, %	Emissions, lb/MBtu
Original SCA = 138	96.90	43	0.143
Convert Outlet to Wet	98.54	33	0.074
Convert to Wet 10-ft, SCA = 157	99.25	20	0.037

Table 4-21
Improving Performance With a Wet ESP Field, Resistivity = 10^{10} Ω-cm

ESP Description	Collection Efficiency, %	Opacity, %	Emissions, lb/MBtu
Original SCA = 138	98.80	20–23	0.050
Convert Outlet to Wet	99.36	16	0.0326
Convert to Wet 10-ft, SCA = 157	99.66	9	0.0166

The conversion of the outlet field to a wet collecting system will bring the small ESP into compliance with an emission limit of 0.1 lb/MBtu for either ash resistivity. If the emission goal is 0.03 lb/MBtu, it will be necessary to extend the outlet field from the existing 6 feet to 10 feet for the low-resistivity ash and even more for the higher-resistivity ash.

The ESP model predicts a collection efficiency of 85–95% for a stand-alone wet ESP added downstream from a dry ESP that has a collection efficiency of around 95%. These projections are for SCAs ranging from 30 to 50 ft^2/kacfm (5.9 to 9.8 m^2 per m^3/s) in the stand-alone WESP. Experiments with a pilot-scale wet ESP operating downstream from a dry pilot ESP actually achieved collecting efficiencies in the mid-90% range for similar specific collecting areas. The pilot-scale WESP also collected condensed sulfuric acid mist with an efficiency greater than 50%. The measured performance for the WESP was somewhat greater than that predicted by the ESP model. Figure 4-8 shows the projected efficiencies for converting to a wet collector.

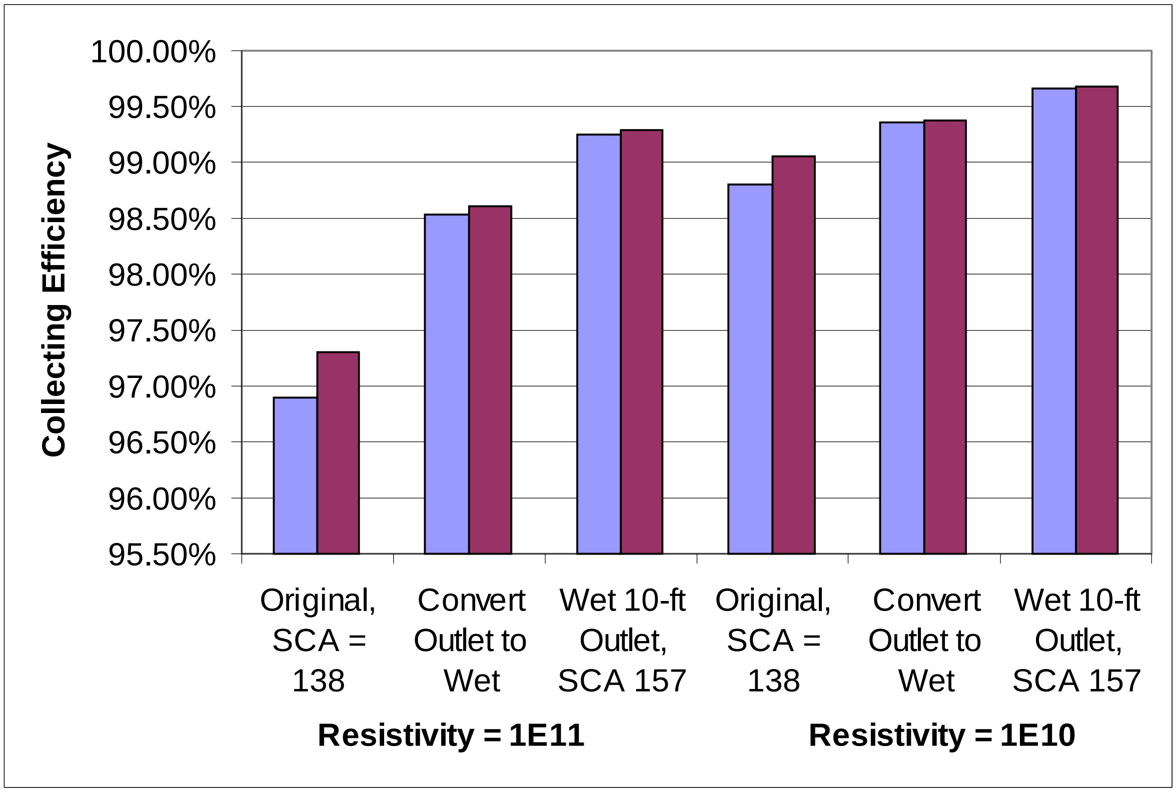


Figure 4-8
Efficiency Increase With Wet Field

4.4.3 ElectroCore™ Separator

The ElectroCore™ separator is an electrically augmented mechanical separator based on an entirely mechanical design from the same supplier, termed a core separator. The addition of an electric field in the core separating zone and the charging of the particles prior to their introduction into the separator increases the separation of the smaller particles. The individual devices are installed in an array much like a multiclone collector.

The ElectroCore device does not actually collect particles. They are concentrated into a gas stream comprising about 10% of the total flow and either reintroduced into the ESP or routed to an independent collector, either an ESP or fabric filter.

The experiments to date indicate that the addition of an ElectroCore separator to the example 138 SCA ESP would allow the station to meet the NSPS limit of 0.03 lb/MBtu. The projected separation efficiency of the ElectroCore is in the high 90% range. Since this technology is very new, the operating characteristics and influence on collection efficiency for the overall particle control system should be carefully evaluated. Note that the gas flow in the original ESP will increase by about 10% with the addition of the ElectroCore separator, unless an auxiliary collector is added. The collecting efficiency of the original ESP will decrease somewhat with the reintroduction of 10% of the flow from the ElectroCore separator.

It is possible to determine the ElectroCore separation efficiency needed to achieve a given outlet emission level if the collection efficiency of the ESP is known. The following equation can be used for this purpose:

$$E_t = E_{esp}/[1-S_E(1-E_{esp})]$$

where E_t equals overall collection efficiency needed to achieve the required outlet emission limit, E_{esp} equals the collection efficiency of the ESP, and S_E equals the required separation efficiency of the ElectroCore.

Table 4-22 contains typical numbers that could apply to the example plant in this chapter. Notice that the required separation efficiencies for all cases are within the measured efficiency (high 90%) from large pilot-scale tests of the technology. For a given plant, it is necessary to estimate the collection efficiency for the existing ESP with 10% additional gas flow. This calculation is needed because the bleed flow from the ElectroCore will be recirculated back to the inlet of the ESP for final collection of the ash in the bleed flow. The estimate can be made by increasing the gas flow in a calibrated ESP model (either ESPM or ESPert) to 110% of the unit’s full-load gas flow rate.

4.4.4 Laminar Flow Fine Particle Agglomerator™

The Laminar Flow Fine Particle Agglomerator™ is intended to improve the performance of an ESP by increasing the effective particle size distribution of the particles collected in the latter fields of the ESP. Experimental results from studies conducted and reported by the supplier on a salt cake ESP indicated an increase in the modified Deutsch migration velocity (ω_k) by about 50%. This is equivalent to increasing the ESP SCA by about the same amount. The example ESP with an SCA of 138 is expected to behave as if the SCA is 207. If this improvement is indeed realized, the collecting efficiency for low and moderate ash resistivities would increase as indicated in Table 4-23.

Table 4-22
ElectroCore Separation Efficiency Requirements

Inlet Concentration, lb/MBtu	Target Outlet Concentration, lb/MBtu	Required Net Efficiency, %	Calculated ESP Efficiency, %	Required ElectroCore Efficiency, %
5.00	0.10	98.00	80.00	91.84
5.00	0.10	98.00	85.00	88.44
5.00	0.10	98.00	90.00	81.63
5.00	0.10	98.00	92.00	76.53
5.00	0.10	98.00	94.00	68.03
5.00	0.10	98.00	95.00	61.22
5.00	0.10	98.00	96.00	51.02
5.00	0.10	98.00	97.00	34.01
5.00	0.10	98.00	98.00	0.00
5.00	0.03	99.40	80.00	97.59
5.00	0.03	99.40	85.00	96.58
5.00	0.03	99.40	90.00	94.57
5.00	0.03	99.40	92.00	93.06
5.00	0.03	99.40	94.00	90.54
5.00	0.03	99.40	95.00	88.53
5.00	0.03	99.40	96.00	85.51
5.00	0.03	99.40	97.00	80.48
5.00	0.03	99.40	98.00	70.42

Table 4-23
Improving Performance With a Laminar Flow Fine Particle Agglomerator

ESP with $\rho = 10^{10}$ Ω-cm	Collection Efficiency, %	Opacity, %	Emissions, lb/MBtu
Original SCA = 138	98.80–99.06	20–23	0.050–0.062
Add Fine Particle Agglomerator	99.61–99.72	7–8	0.0148–0.021
ESP with $\rho = 10^{11}$ Ω-cm	96.90–97.3	43–46	0.143–0.164
Add Agglomerator	98.80–99.02	21–24	0.052–0.063

The Laminar Flow Agglomerator is expected to bring the low-resistivity ESP up to meet NSPS standards, while the higher resistivity will be below the 0.1 lb/MBtu limit. Figure 4-9 shows the performance changes for two values of resistivity.

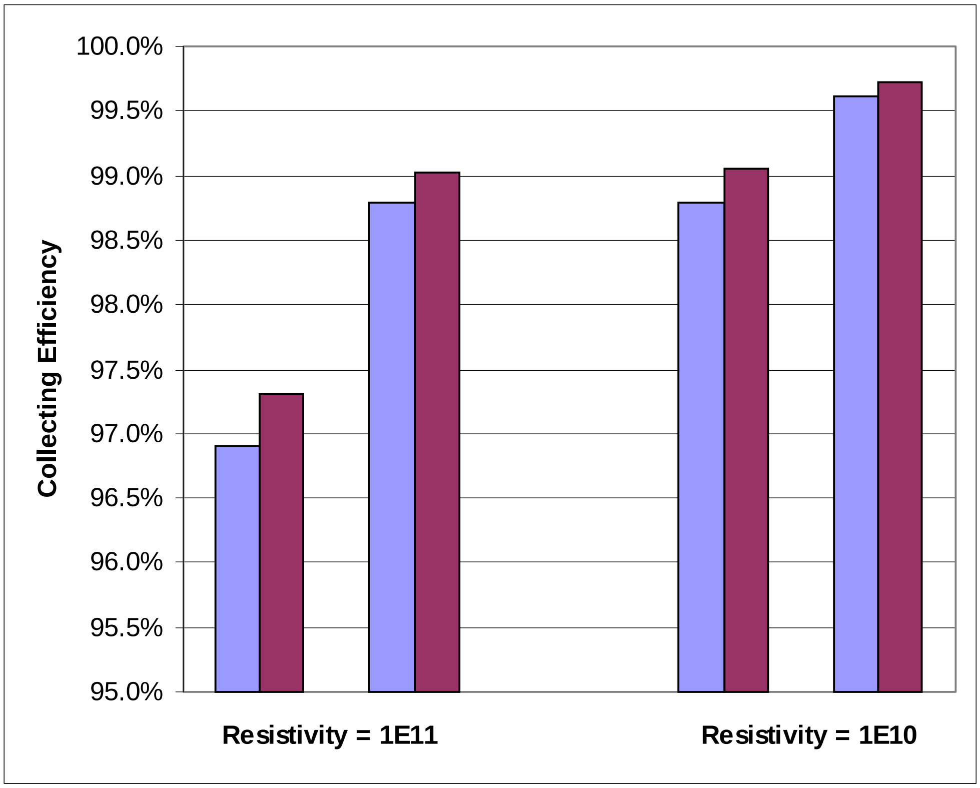


Figure 4-9
Performance Increases From Adding a Laminar Flow Agglomerator

4.5 Add New Primary Control Device

4.5.1 Replace With Larger ESP or Add New ESP Downstream

When adding a new ESP, it must be decided whether to refurbish and retain the existing ESP or completely remove it. The decision depends only on economics and whether there is adequate real estate to retain the old and build a new one. Both options must be evaluated in consideration of plant outage time required for the rebuild. This decision of whether to retain does not influence the final collecting efficiency for the replacement, as any rebuild can be brought to meet either the 0.1 lb/MBtu limit or NSPS limit of 0.03 lb/MBtu. However, there is a concern for opacity limits when the 0.1 lb/MBtu emission limit applies.

If the old ESP is retained, there is also the decision of whether to install the new control device in series or in parallel. The decision depends on site-specific factors. If the gas velocity is high and rapping reentrainment is a significant contributor to the emissions, a parallel arrangement may be better. If rapping is not a major contributor, in series may be appropriate.

The performance of the new ESP will, of course, depend on its SCA. Tables 4-15 and 4-16 show performance for representative four- and five-field ESPs. More comprehensive estimates are given in Volume 1, Figures 2-3 through 2-8, which show expected performance for a given SCA. Finally, the procedures outlined in EPRI report CS-5040, *Precipitator Performance Estimation Procedure*, can be used to make site-specific ESP size selections.

4.5.2 Convert Hot-Side to Cold-Side

The conversion of a hot-side unit to cold-side operation will provide an increase in the specific collecting area because of the decrease in flue gas volume flow rate as the flue gas cools in the air heater. When converted to cold-side operation, the example hot-side unit described in Table 4-1 will experience a reduction in gas volume flow rate from 1,458 kacfm (688 m^3/s) at 650°F (343°C)to 1,029 kacfm (486 m^3/s) at 300°F (150°C)**.** This reduction in gas volume increases the SCA by about 40%.

The example ESP used in the model projection is for a unit with 9-inch plate spacing and an original SCA of 313 under hot-side conditions. This station represents one that should meet an NSPS limit of 0.03 lb/MBtu under hot-side conditions in the absence of high resistivity caused by sodium depletion in the residual dust cake layer. A unit with this design SCA represents one of the more conservatively designed hot-side units installed in the 1970s. The ESP for this example is similar to the one used for the negative to positive polarity conversion described earlier, except the plate spacing in that example was 12 inches to match the pilot plant data used. The gas temperature before the air heater is 650°F (°C), and following the air heater the gas temperature drops to 300°F. The resistivity under cold-side conditions is expected to be 10^{11} Ω-cm for the first case and 10^{12} for the second case. The model results follow.

Table 4-24
Performance Predicted for a Hot-Side to Cold-Side Conversion

Operating Mode	**Collecting Efficiency, %**	**Opacity, %**	**Emissions, lb/MBtu**
Good Negative Polarity	99.35–99.50	8–10	0.026–0.033
Degraded Negative	97.10–97.50	33–37	0.129–0.149
Cold Side, $\rho = 10^{11}$ Ω-cm	99.94–99.96	1–2	0.002–0.003
Cold Side, $\rho = 10^{12}$ Ω-cm	99.73–99.79	7–9	0.011–0.015

For either resistivity level, the conversion to cold-side operation will bring the station into compliance with NSPS with a significant safety margin. There may be instances where the ash resistivity is so high that a hot to cold conversion will not meet NSPS. In such situations, either resistivity conditioning or other measures may be required. The costs for each option should be combined to determine the actual cost if multiple modifications are to be implemented. Figure 4-10 shows the results of the ESP model projections for the hot to cold conversion.

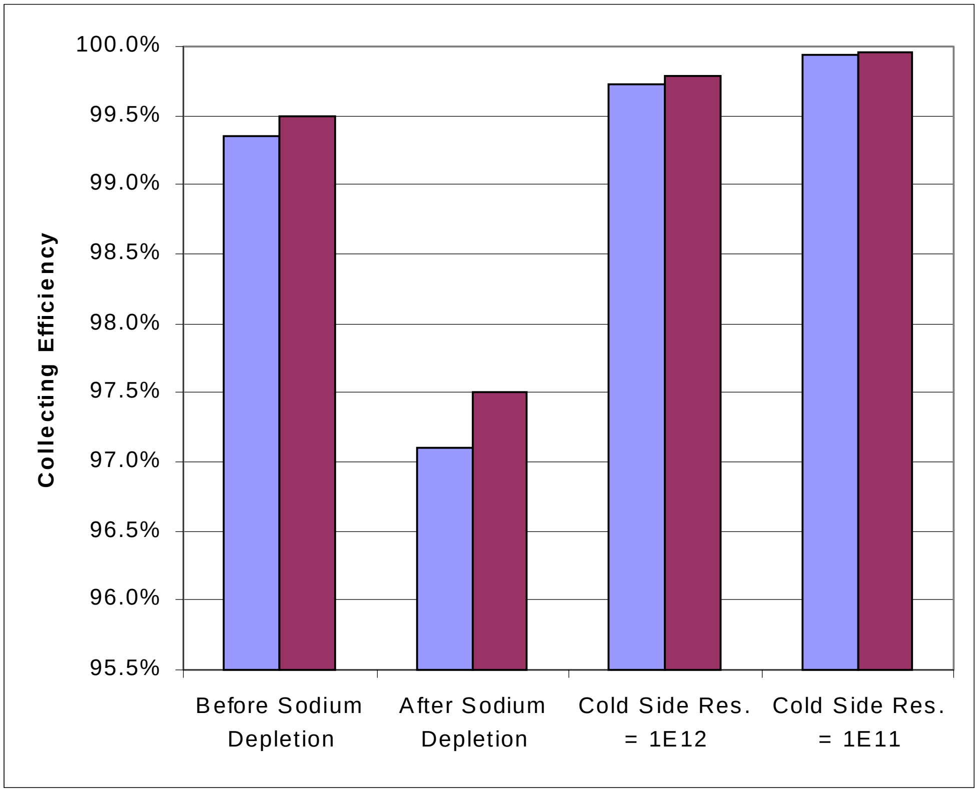


Figure 4-10
ESP Collection Efficiency for Hot-Side to Cold-Side Conversion

4.5.3 Replace With Fabric Filter

When the ash resistivity is greater than 10^{12} Ω-cm, it may be appropriate to replace the ESP with a fabric filter system. The fabric filter is expected to provide sufficient particle removal to meet NSPS with almost any fly ash. There are a few fly ashes that are extremely fine and with such a smooth surface that they “bleed” through a conventional fabric. The ash should be adequately characterized to ensure that the fabric filter is appropriate for the new installation.

4.6 Modeling SO_2 Control Impacts

Flue gas desulfurization as such is not an upgrade option for particle collection. However, sulfur oxide control technologies do influence the particulate control equipment through modifications that they introduce to the particle characteristics, and thus the impacts of SO_2 control systems—those already installed or being contemplated for future installation—should be taken into account when determining the particulate control upgrade strategy.

The addition of a wet scrubber, either upstream or downstream, with a pressure drop in the range of a few inches of water will not appreciably reduce the particle emissions. The low-pressure-drop scrubber is expected to have a D-50 (particle size with 50% removal) in the 5 to 10 micron range. A scrubber would not likely be installed in a high-resistivity situation, since most high-sulfur coals produce low-resistivity ash. A wet scrubber installed before the ESP would reduce the gas volume flow rate because of the temperature reduction. This reduction in gas volume would increase the ESP SCA and improve collection.

However, a wet scrubber is typically installed downstream from the ESP. Given that the station is probably burning high-sulfur coal, the scrubber will usually condense enough sulfuric acid mist to create an opacity violation. In this case, it may be necessary to install a wet ESP downstream from the wet scrubber to control these emissions. Alternatively, ammonia conditioning can be used to reduce the SO_3 concentrations reaching the scrubber.

Other SO_2 control options—such as a spray dryer—may be installed upstream from the ESP. In this case, there may be increased ash loading to the ESP, but the ash resistivity will also likely be reduced. Corrective measures may be required, depending upon what changes the SO_2 control equipment makes to the particles required to be collected in the ESP. Refer to EPRI's *Guidelines for Particulate Control for Advanced SO_2 Control Processes* (TR-104594).

5

COST ESTIMATES FOR UPGRADE OPTIONS

This chapter provides comparative cost estimates for the various upgrade alternatives. Making a general cost estimate is a difficult task, especially in a retrofit situation, because these costs are by nature highly site specific. But although the cost estimates in this chapter may not be accurate for your particular site, they are valuable for comparative purposes to demonstrate the relative expense of the alternative upgrade options.

These analyses cover capital costs only; they do not consider operating costs for any of the options. However, most alternatives will share operating costs on the same order of magnitude. A lifetime cost estimate for the options is beyond the scope of this work, as the site-specific staffing, salary, benefits, and overhead costs would have a significant effect and these values would be different for nearly every power plant.

The particular size and arrangement of the installed equipment may make some alternatives infeasible, while other schemes that might appear higher cost on first look could actually be the most advantageous when all of the problems are considered. Schemes with very similar costs should be considered equivalent; the site-specific nature of a retrofit could easily compensate for the perceived small cost difference. In general, the cost estimates presented in this chapter should be within the +/- 25% range.

There is a distinct possibility that the cost and performance estimates will indicate that a combination of alternatives is the best option. For example, there are a number of plants that have converted from hot-side to cold-side operation and have added fly ash conditioning equipment as well. If multiple options are used in the upgrade, add the costs for independent options. For example, if the ESP internals are to be rebuilt and sulfur trioxide conditioning is to be added, simply add the costs for both. For other combinations, there may be some redundancy in the costs; simply eliminate the redundant cost element.

5.1 Example Plant

The plant used as the basis for these cost estimates is the same fictitious 310-MW unit used in the Chapter 4 performance estimates; additional design parameters are listed in Table 5-1. Because plants with larger ESPs are not likely to suffer the severe performance problems and therefore would not need the replacement alternatives described in this report, the example plant has a very small ESP. For information purposes, design data are provided for both hot-side and cold-side ESPs, even though a real plant would not have both installed as original equipment. Note that a possible upgrade option would be to add a cold-side ESP after the hot-side ESP originally installed on the unit. The hot-side ESP would help keep the air heater from fouling and protect the ID fans from a high particulate concentration, while the new cold-side ESP would act as a polishing device and ensure particulate emission compliance.

In our example, the existing ESP was designed for a high particulate emission rate of 0.10 lb/MBtu (about 100 mg/Nm^3) and 20% opacity. The unit had been operating in compliance with emission limits, but there has been a fuel switch and the particulate emissions are now higher than allowed without derating the boiler. Lowering the electrical output from the unit is not acceptable, so the utility finds that a significant upgrade of the particulate removal equipment is required.

5.2 Cost Elements

The costs for each upgrade option are provided as separate entries in the multi-page Table 5-2 at the end of this chapter. For each upgrade, costs are provided for four basic categories:

1. **Price of new equipment/components.** This is the first line item in Table 5-2.

2. **Installation costs for new equipment/components.** Costs assume the work will be performed by union labor with a good productivity rate. Labor unions and “Right to Work” rules will affect the construction costs. Different productivity rates for labor in different areas will also have a large effect on the construction costs. Many utilities have agreements with selected contractors at pre-arranged pricing based on preferred use of the contractor’s services for maintenance work. These agreements could have a significant effect on the construction costs for any alternative. The installation costs are provided for relative positioning of the alternatives and not for absolute value accuracy.

3. Installation costs include incidental demolition and relocation of existing equipment (i.e., ESP internals, fan housings, ash pipes, ash system blowers, and ductwork). However, none of the estimates include costs for demolition of large equipment. The assumption was made that all new equipment would be located in areas where there was no existing equipment in the way.

4. **Costs to satisfy balance-of-plant impacts.** These costs account for most of the line items in Table 5-2 and will be discussed in greater detail in the next section. Costs have been tabulated separately so that a line item can be easily omitted if it will not be needed.

5. **Contingency.** The contingency was based on the level of uncertainty in one or more elements in the cost estimate. Fifteen percent (15%) was used for cases where the uncertainties were minimal. Twenty percent (20%) was used if the technology was very new or if it required extensive new construction.

Table 5-1
Plant Definition for Cost Estimates

Plant Size	310 MW	
Boiler Type	Front and Rear Wall Fired, Pulverized-Coal Fuel, Oil Startup	
Stack Exit Diameter	17.4 ft	
	Original Design	New Projected
Coal Analysis (wt%)		
Moisture	14	27.6
Carbon	63.4	50.9
Hydrogen	3.1	3.6
Nitrogen	0.5	0.6
Chlorine	0	0
Sulfur	2.5	0.3
Ash	7	5
Oxygen (diff)	9.5	12
	100	100
Heat Value, Btu/lb	10,500	8,802
Ash Analysis (wt%)		
Silica		30.4
Alumina		15.8
Titania		1.3
Ferric Oxide		5.4
Lime		22.9
Magnesia		4.9
Sodium Oxide		1.2
Potassium Oxide		0.3
Sulfur Trioxide		14.6
Phosphorus Pentoxide		1
Unknown		2.2
Boiler Heat Input, MBtu/hr	2,947	3,206
Emission Rate, lb/MBtu	0.10	0.02
Opacity Limit, %	20	10
Flue Gas Flow, acfm@300F	974,000	1,029,000
Flue Gas Flow, acfm@650F	1,397,000	1,458,000
Flue Gas Temperature, Economizer Outlet, F	650	650
Flue Gas Temperature, Air Heater Outlet, F	300	300

	Original Design	New Projected	
ESP, Cold Side			
Total Collecting Area, ft^2	194,304	194,304	
SCA, ft^2/1000 acfm	199	189	
Number of Fields	4 x 6 ft	4 x 6 ft	
Number of Bus Sections	8	8	bus sections across flow - 2
Number of TRs	8	8	Each serves 1 bus section, 4 deep
	Vibrator Rappers - Wires MIGI Rappers - Plates		
Collecting Plate Spacing, inches	9	9	
Flow Area, ft^2	3036	3036	
Velocity, ft/s	5.3	5.6	
Height, ft	33	33	
Width, ft	92	92	
Depth, ft	24	24	
Number of Gas Passages	123	123	
Aspect Ratio	0.73	0.73	
ESP, Hot Side			
Total Collecting Area, ft^2	456,720	456,720	
SCA, ft^2/1000 acfm	327	313	
Number of Fields	4 x 10 ft	4 x 10 ft	
Number of Bus Sections	8	8	bus sections across flow - 2
Number of TRs	8	8	Each serves 1 bus section, 4 deep
	Vibrator Rappers - Wires MIGI Rappers - Plates		
Collecting Plates Spacing, inches	9	9	
Flow Area, ft^2	4290	4290	
Velocity, ft/s	5.4	5.7	
Height, ft	33	33	
Width, ft	130	130	
Depth, ft	40	40	
Number of Gas Passages	173	173	
Aspect Ratio	1.21	1.21	

Table 5-2
Equipment Cost Estimates

	Upgrades for Power Supply Controls				
	Install PC Based Controls (with Intermittent Energization)	High-Frequency Power Supplies	Pulse Energization	Positive Polarity for Hot-Side ESPs	Arc Snubber™
Basic Equipment	$ 40,000	$ 240,000	$ 280,000	$ 1,240,000	$ 80,000
Installation	$ 16,000	$ 80,000	$ 80,000	$ 930,000	$ 40,000
ID Fans					
Rotor	$ -	$ -	$ -	$ -	$ -
Motor	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Ash Removal System	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Auxiliary Power					
Wiring	$ -	$ -	$ -	$ -	$ -
Switchgear	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Compressed Air Equipment	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Water Supply Equipment	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Waste Disposal Equipment	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Ductwork	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Instrumentation	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Boiler Implosion and Ductwork Stiffening	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Contingency	$ 8,400	$ 48,000	$ 54,000	$ 325,500	$ 18,000
TOTAL	$ 64,400	$ 368,000	$ 414,000	$ 2,495,500	$ 138,000

Flue Gas or Fly Ash Conditioning

	Sulfuric Acid (SO_3) Conditioning	Moisture Conditioning and Humidification	Ammonia Conditioning	Combined SO_3 and Ammonia Conditioning	Sodium Conditioning (Hot-Side ESP Only)	Proprietary Conditioning Agents
Basic Equipment	$ 436,000	$ 261,000	$ 85,000	$ 544,000	$ 290,000	$ 300,000
Installation	$ 356,000	$ 356,000	$ 35,000	$ 445,000	$ 65,000	$ 240,000
ID Fans						
Rotor	$ -	$ -	$ -	$ -	$ -	$ -
Motor	$ -	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -	$ -
Ash Removal System	$ -	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -	$ -
Auxiliary Power						
Wiring	$ 50,000	$ 50,000	$ 50,000	$ 50,000	$ 50,000	$ 50,000
Switchgear	Incl Above	Incl Above	Incl Above	Incl Above	Incl Above	Incl Above
Installation	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000	$ 20,000
Compressed Air Equipment	$ -	$ -	$ -	$ -	$ -	Incl Basic Equip
Installation	$ -	$ -	$ -	$ -	$ -	Incl Basic Equip
Water Supply Equipment	$ -	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -	$ -
Waste Disposal Equipment	$ -	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -	$ -
Ductwork	$ -	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -	$ -
Instrumentation	$ -	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -	$ -
Boiler Implosion and Ductwork Stiffening	$ -	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -	$ -
Contingency	$ 129,000	$ 103,000	$ 29,000	$ 159,000	$ 64,000	$ 92,000
TOTAL	$ 991,000	$ 790,000	$ 219,000	$ 1,218,000	$ 489,000	$ 702,000

ESP Rebuild

	Rebuild As-Is	Rebuild With Wide Plate Spacing	Rebuild Taller and With Additional Field	Modify Flow Distribution to Skewed Flow	Add Extra Field, Separate Casing
Basic Equipment	$ 2,526,000	$ 2,186,000	$ 2,893,000	$ 200,000	$ 2,600,000
Installation	$ 3,497,000	$ 2,915,000	$ 2,600,000	$ 150,000	$ 2,600,000
ID Fans					
Rotor	$ -	$ -	$ -	$ -	$ 295,000
Motor	$ -	$ -	$ -	$ -	$ 195,000
Installation	$ -	$ -	$ -	$ -	$ 350,000
Ash Removal System	$ -	$ -	$ 66,000	$ -	$ 99,000
Installation	$ -	$ -	$ 48,000	$ -	$ 72,000
Auxiliary Power					
Wiring	$ -	$ -	$ 60,000	$ -	$ 90,000
Switchgear	$ -	$ -	Incl Above	$ -	Incl Above
Installation	$ -	$ -	$ 24,000	$ -	$ 36,000
Compressed Air Equipment	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Water Supply Equipment	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Waste Disposal Equipment	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Ductwork	$ -	$ -	$ -	$ -	$ 186,000
Installation	$ -	$ -	$ -	$ -	$ 242,000
Instrumentation	$ -	$ -	$ -	$ -	$ -
Installation	$ -	$ -	$ -	$ -	$ -
Boiler Implosion and Ductwork Stiffening	$ -	$ -	$ -	$ -	$ 256,000
Installation	$ -	$ -	$ -	$ -	$ 244,000
Contingency	$ 904,000	$ 765,000	$ 854,000	$ 53,000	$ 1,090,000
TOTAL	$ 6,927,000	$ 5,866,000	$ 6,545,000	$ 403,000	$ 8,355,000

Polishing Devices in Series

	Compact Hybrid Particulate Collector (COHPAC I)	Compact Hybrid Particulate Collector Within the Casing (COHPAC II)	Wet Electrostatic Precipitator (WESP)	Wet Electrostatic Precipitator Within Casing (last field)	ElectroCore^{TM} Separator	Laminar Flow Fine Particle Agglomerator^{TM}
Basic Equipment	$ 3,400,000	$ 2,224,000	$ 4,600,000	$ 2,717,000	$ 964,000	$ 2,592,000
Installation	$ 2,640,000	$ 1,716,000	$ 1,300,000	$ 3,321,000	$ 793,000	$ 3,133,000
ID Fans						
Rotor	$ 432,000	$ 432,000	$ 295,000	$ -	$ 33,000	$ -
Motor	$ 286,000	$ 286,000	$ 195,000	$ -	Incl Above	$ -
Installation	$ 350,000	$ 350,000	$ 350,000	$ -	$ 43,000	$ -
Ash Removal System	$ 33,000	$ 16,500	$ -	$ 143,000	$ -	$ -
Installation	$ 24,000	$ 12,000	$ -	$ 114,000	$ -	$ -
Auxiliary Power						
Wiring and Switchgear	$ 25,000	$ 25,000	$ 25,000	$ 20,000	$ 44,000	$ 44,000
Installation	$ 25,000	$ 25,000	$ 25,000	$ 8,000	$ 83,000	$ 83,000
Compressed Air Equipment	Incl Basic Equip	Incl Basic Equip	$ -	$ -	$ -	$ -
Installation	Incl Basic Equip	Incl Basic Equip	$ -	$ -	$ -	$ -
Water Supply Equipment	$ -		$ 100,000	$ 40,000	$ -	$ -
Installation	$ -		$ 50,000	$ 20,000	$ -	$ -
Waste Disposal Equipment	$ -		$ 200,000	$ 80,000	$ -	$ -
Installation	$ -		$ 75,000	$ 40,000	$ -	$ -
Ductwork	Incl Basic Equip	Incl Basic Equip	$ 372,000	$ -	$ 1,493,000	$ 186,000
Installation	Incl Basic Equip	Incl Basic Equip	$ 483,000	$ -	$ 792,000	$ 242,000
Instrumentation	$ 25,000	$ 25,000	$ 25,000	$ 25,000	$ 25,000	$ -
Installation	$ 25,000	$ 25,000	$ 25,000	$ 25,000	$ 25,000	$ -
Boiler Implosion and Ductwork Stiffening	$ 458,000	$ 458,000	$ 458,000	$ -	$ -	$ -
Installation	$ 435,000	$ 435,000	$ 435,000	$ -	$ -	$ -
Contingency	$ 1,632,000	$ 1,206,000	1,803,000	$ 1,311,000	$ 859,000	$ 1,256,000
TOTAL	$ 9,790,000	$ 7,235,500	$ 10,816,000	$ 7,864,000	$ 5,154,000	$ 7,536,000

Note: ElectroCore^{TM} does not require ID fan changes but does require a bleed fan installation

New Collecting Systems

	Add New ESP in Series	Convert Hot-Side ESP to Cold-Side	Replace ESP With Fabric Filter (within casing)	Replace ESP With Fabric Filter (new casing)	Add Sulfur Dioxide Removal System
Basic Equipment	$ 3,100,000	$ 3,328,000	$ 1,791,000	$ 5,140,000	$ 26,925,000
Installation	$ 2,700,000	$ 2,956,000	$ 1,612,000	$ 2,410,000	$ 23,460,000
ID Fans					
Rotor	$ 295,000	$ 295,000	$ 432,000	$ 432,000	$ 432,000
Motor	$ 195,000	$ 195,000	$ 286,000	$ 286,000	$ 286,000
Installation	$ 350,000	$ 350,000	$ 350,000	$ 350,000	$ 350,000
Ash Removal System	$ 176,000	$ 66,000	$ -	$ 66,000	$ -
Installation	$ 128,000	$ 48,000	$ -	$ 48,000	$ -
Auxiliary Power					
Wiring and Switchgear	$ 160,000	$ 60,000	$ 25,000	$ 25,000	$ 25,000
Installation	$ 64,000	$ 24,000	$ 25,000	$ 25,000	$ 25,000
Compressed Air Equipment	$ -	$ -	$ 40,000	$ -	$ -
Installation	$ -	$ -	$ 20,000	$ -	$ -
Water Supply Equipment	$ -	$ -	$ -	$ -	$ 100,000
Installation	$ -	$ -	$ -	$ -	$ 50,000
Waste Disposal Equipment	$ -	$ -	$ -	$ -	$ 200,000
Installation	$ -	$ -	$ -	$ -	$ 75,000
Ductwork	$ 279,000	$ 743,000	$ -	$ 279,000	$ 372,000
Installation	$ 362,000	$ 966,000	$ -	$ 362,000	$ 483,000
Instrumentation	$ 25,000	$ 25,000	$ 25,000	$ 25,000	$ -
Installation	$ 25,000	$ 25,000	$ 25,000	$ 25,000	$ -
Boiler Implosion and Ductwork Stiffening	$ 256,000	$ 256,000	$ 458,000	$ 458,000	$ 458,000
Installation	$ 244,000	$ 244,000	$ 435,000	$ 435,000	$ 435,000
Contingency	$ 1,672,000	$ 1,917,000	$ 1,105,000	$ 2,073,000	$ 10,735,000
TOTAL	$ 10,031,000	$ 11,498,000	$ 6,629,000	$ 12,439,000	$ 64,411,000

5.3 Balance-of-Plant Considerations

The balance-of-plant (BOP) cost items are components of the plant auxiliary equipment that will be affected by the change in particulate removal equipment.

5.3.1 Induced Draft Fans

One obvious change will be to the draft system. Depending on the upgrade scheme selected, the ID fans may need to be upgraded for additional pressure capability and possibly additional gas flow capability. Unless the motor wiring and switchgear were oversized when originally installed, particulate control modifications could require a new fan rotor, motor, power supply wiring, and even switchgear for electrical power supply to the ID fan motors.

The upgrades to the ID fans may be possible without replacing the fans. The speed and/or the wheel size may be increased to achieve both an increase in mass flow capability and an increase in pressure rise capacity. For certain wheel designs, when the fan speed is increased the wheel may actually decrease in diameter while the capability increases for flow and pressure rise. This should allow the reuse of the ID fan housings and foundations. The foundations can be saved if the new vibration levels expected are the same or less and the weight of the fan has not increased. The bearings will probably require replacement for any scheme because the fan wheel shaft will be changed. If the fan housings can be reused, the inlet and outlet ductwork and possibly instrument locations may remain satisfactory. The alternative is replacement of the entire fan, which would require new foundations, bearings, inlet and outlet ductwork, and consideration of location since it may not be possible to add the new fans without removing the old ones first.

The ID fan cost includes the cost for changing the ID fan wheels and motors. The assumption is made that this will allow the draft capability to be increased to 1,050,000 acfm (496 m^3/s) and 30 inches (762 mm) of pressure rise (additional 10 inches Wg) in the ID fans. Not all fans can accommodate this capability increase and this estimate may be about 2/3 of the cost of new fans.

Another cost was calculated when the pressure rise increase would be above the negligible level but not more than 10 inches Wg, since there are some options that will cause modest increases in the capacity requirements for the ID fans. These options will not require the higher pressure capability and the cost for these schemes is less because the rotor and motor would be less costly.

For most upgrade options, the ID fan cost estimates assume the existing foundation is re-used. This cost element has been added to those schemes where the pressure loss in the new equipment significantly exceeds the pressure loss in the existing equipment. These options include a fabric filter, hot-side to cold-side conversion, and wet FGD (scrubber).

Installation costs run about the same for any ID fan modification. The flue gas flow rate with the new coal is slightly different (5% increase) over that from the old fuel. This value was not considered significant enough to warrant fan changes for all the alternatives if the pressure requirement did not change.

5.3.2 Fly Ash Handling System

The fly ash removal system requires review. A system designed with extra capacity (removing ash at twice the rate of collection) to allow maintenance will probably not require a capacity upgrade but could require a different piping and valve scheme. Even with new hoppers, the total amount of fly ash collected (lb/hr) will not be much different, if at all, than is presently collected. If the ash content of the coal selected is greatly different, a change in capacity may be required, but that change should be rare. New piping and valve layouts with consideration of the number of hoppers will be needed. It is possible that relocation of the ash silos could be required but that would occur only if the new particulate removal equipment is placed where the silos already sit.

The cost for modifying the ash removal system is for the re-design of the piping and valves for the ash system. The capacity will not be increased and the only change required is the increase in the number of pickup points for those options with new collectors and a change in piping arrangement for those options that keep the existing precipitator. The COHPAC I option maintains the existing ESP and adds additional ash hoppers for the COHPAC unit. The capacity of the system does not change and so the modification is for extensive pipe and valve changes and additions. Relocation of the ash silo and replacement of the blowers or vacuum source will not be required for implementation of these options.

5.3.3 Auxiliary Power

The auxiliary power changes will include new wiring to the components of each option that adds additional power consumption devices. The switchgear changes include the new equipment for the new ID fan motors as well as for other new devices. For upgrade options that re-use the ESP, all additional capacity and wiring is included. For options that eliminate the existing ESP, the power is available since it will no longer be needed for the ESP, but wiring and switchgear changes will be required because of the different users. Many of the ESP options will include use of the existing TRs and add new TRs. This cost for additional power supply wiring and switchgear is included here.

5.3.4 Compressed Air Equipment

Upgrades using pulse-jet fabric filters will require additional air compressors (although the potential for the existing air system to supply compressed air for short times should also be investigated). The schemes use both a primary and a secondary compressor. The necessary controls for a lead/lag situation will be included with the secondary compressor coming on for failure of the primary or low cleaning header pressure. These compressors will be located within 100 feet (pipe length) of the pulse-jet fabric filter.

5.3.5 Water Supply

The wet ESP and humidification alternatives will need water addition. A wet scrubber would require added water supply as well.

5.3.6 Waste Disposal

Only the wet ESP and wet scrubber options require new waste disposal equipment. The other schemes do not create a new waste stream (i.e., slurry form rather than dry solids). The existing disposal system is assumed to be adequate. Cost estimates give no credit for fly ash sales. The use of some of the flue gas conditioning schemes may change the chemical make-up of the ash and make it unusable by certain ash purchasers depending on their needs. This does not mean that ash sales are not possible with flue gas conditioning, but another purchaser who can use the conditioned ash may have to be identified.

5.3.7 Flue Gas Ductwork

A change in the flue gas duct routing may be required depending on the alternative selected, the amount of room for new equipment, the ease with which existing equipment can be relocated (if necessary), and the capability of the draft system components. A model study of the flow in the revised duct should be performed to minimize pressure loss and optimize flow distribution. Flue gas distribution to the new equipment may be critical to satisfactory performance. Some of the schemes may require multiple components: correct gas distribution to each of these components is important. Another consideration is turndown capability. Multiple, parallel operating components may require shutoff to achieve satisfactory turndown operation. These costs are included in the basic equipment cost if they are required.

5.3.8 Instrumentation

It may be necessary to relocate existing instrumentation in order to correctly measure the flue gas temperature and pressure as well as other parameters. In many cases the rearranged ductwork will render some of the instrumentation inappropriately placed. The new locations should consider the control scheme for the new equipment as well as the needs of the operators to have reliable information from the instrumentation. Additional instrumentation may be required depending on the scheme selected for particulate removal. New instruments for pressure, temperature, power use, control, vibration sensing, and component status will be needed for new equipment.

5.3.9 Boiler Implosion and Ductwork Stiffening

A change in the draft capacity of the ID fans will affect the boiler implosion potential and could lead to the need for additional stiffening of the boiler, flue gas duct, and possibly the air supply ducts or pressure relief panels. The air heaters could also require changes or stiffening. A careful review of the boiler implosion potential with the increased fan capability is important to maintaining the safety of the plant and the insurability of the components. A study to determine the capability of the existing equipment based on design is important, but equally important is a review of the current condition of the components.

Determination, even by observation, of the condition of the components compared to an “as installed” condition will verify the design strength values. It may be necessary to reduce the capacity of the steel due to corrosion or weld problems and to review the implosion analysis with these reduced values. Stiffening the boiler will require removing the insulation and adding reinforcement steel to the structure. This is not as daunting an undertaking as might be perceived. However, problems with the existing components may discount or eliminate the use of certain upgrade options that would require added draft capability.

5.4 Cost Estimates

As stated, Table 5-2 at the end of this chapter presents the cost estimates for the different upgrade options, following the same categorization scheme and sequence used throughout the rest of this report.

5.4.1 Power Supply Upgrades

Upgrade of the power supplies and ESP controls requires installation of the particular equipment for enhancing the controls. This includes new TR sets, wiring, and control cabinets. Other BOP items and auxiliary system upgrades are not required with these options and the cost is therefore shown as zero.

5.4.2 Flue Gas/Fly Ash Conditioning

Flue gas/fly ash conditioning options do not have significant BOP costs. The cost to provide electrical power to the auxiliaries such as the burner, heater, and injection skid has been included. This is a general cost and does not account for slight differences between schemes. All will require some power at various times during operation and this will provide that power. The particular type of conditioning selected should be determined based upon the conditions of the coal and plant. Compressor costs are included in the cost estimates for the proprietary systems.

5.4.3 ESP Rebuild

The ESP rebuild options each incur different BOP costs. Both options to make the system larger—either by adding height and additional collecting area (one or two additional fields) or by adding an additional field (with extra height) downstream in its own casing—will require more ash pick-up points. System capacity will not require expansion, but the pipe and hopper valves will require modification for the additional hoppers. A new field in a separate casing will require additional ID fan capacity. The costs will be less than for a fabric filter retrofit but the additional duct will cause additional flow losses. New ductwork will be needed for this separate-casing option, and since the ID fan capability will be increased, boiler stiffening will probably be required. Whenever an extra field is added, additional wiring will be required since new TRs will be added. Still, adding an extra field, within the existing casing or in its own new housing, may cost less than the construction of a completely new ESP.

5.4.4 Polishing Devices

5.4.4.1 COHPAC

The COHPAC options are fairly involved. COHPAC I, which adds an additional fabric filter collector in series behind the existing ESP, requires that the ESP remain operational. Rebuilding to minimize the potential for equipment failure and to maximize the performance may be required. The cost presented does not include this requirement. If rebuilding is needed, the cost for rebuilding as-is or with wide plate spacing should be added.

The COHPAC II alternative uses the existing ESP casing to hold the polishing pulse-jet fabric filter. The ESP (especially in the example case) may have to be changed in size to accommodate sufficient bags and equipment to allow the scheme to provide the emission rate required. Thus there could be a very economic solution by increasing the existing ESP casing size prior to installing the COHPAC II. This would require modifying the ID fans, adding extra ash hoppers, and adding more power supply wiring for the new equipment.

5.4.4.2 Wet ESP

A very good method for additional particulate removal, wet ESPs are available from most of the OEM ESP suppliers. The addition of a wet ESP may require extensive BOP modifications. Since SO_3 and possibly heavy metal emissions will be reduced with this equipment, the extra investment may result in the ability to meet some of the more restrictive proposed emission standards.

5.4.4.3 ElectroCore™ Separator

The ElectroCore™ separator requires that the existing ESP remain functional. Since no particulate removal occurs in the ElectroCore, the particulate removal must take place either in the existing ESP or in a special collector (fabric filter or ESP) sized for high-efficiency removal from the bleed stream. This bleed stream is about 10% of the inlet flue gas flow. It is very possible that retrofit of the ElectroCore on an existing ESP will also include a rebuild of the ESP for proper functioning. The cost presented does not include the rebuilding of the ESP. If that is needed the “Rebuild As-Is” or “Rebuild with Wide Plate Spacing” cost should be added.

5.4.4.4 Laminar Flow Fine Particle Agglomerator™

A proprietary technology offered by a single supplier, the Laminar Flow Fine Particle Agglomerator™ replaces some of the existing ESP internals with a near–laminar flow section. This alternative requires that the existing ESP be completely functional. The cost for the rebuild is included in the basic equipment cost since part of the new internals is the laminar flow section. The ESP will require modification and perhaps an increase in size so the cost for ductwork modification is provided for this option. Depending on the size of the ESP casing where the Agglomerator is to be installed, the ductwork modification may not be required.

5.4.5 New Particulate Control System

5.4.5.1 New ESP

The cost estimate for a new precipitator assumes it will be installed in series with the existing precipitator, which will be retained. (The decision to build in series or parallel depends on site-specific considerations.) The existing hopper connections would remain functional and the new ESP would have new ash pipe and valves connected to the existing system.

5.4.5.2 Hot-Side to Cold-Side Conversion

Conversion to cold-side operation will be a choice for some plants when the fuel changes. The conversion amounts to a change in the duct routing. The basic equipment cost estimate includes these items. After conversion, an SO_3 fly ash conditioning system may have to be added in some instances to provide an acceptable emission rate.

5.4.5.3 Replace ESP With Fabric Filter

Replacement of the ESP with a fabric filter would not require the existing ESP to remain in service. The casing could be left and the gas could just pass through. In this case, the ash removal system for the existing ESP should still remain in service. The revised ash system would have the same capacity but with additional pick-up points for the new fabric filter. This estimate assumes the new fabric filter would be added in an area where no other equipment was located. This would allow the fabric filter to be constructed while the ESP remained on-line. The outage required would then be only for changing the ductwork, minimizing the outage time.

5.4.6 SO_2 Control

It may be that flue gas desulfurization (FGD) is being considered at the same time as a particulate control upgrade. If so, its collecting characteristics and influence upon particulate control should be considered when determining the best particulate control upgrade strategy. Table 5-2 also shows the most commonly installed FGD system, a wet scrubber, to give an idea of its relative cost.

A
POWER SUPPLY CONTROLS

There has been a significant amount of progress in the development of power supplies and controls for ESP use. The modern energization era has its roots in the development of the synchronous mechanical rectifier in the early 1900s, selenium rectifiers in the mid-1940s, silicon diodes in the 1950s, and thyristor controls in the 1960s. Modern microprocessor-based controls use a personal computer (PC), which is connected to various feedback signals that indicate ESP condition and is programmed to respond accordingly, using silicon-controlled rectifiers to modulate the energization to the ESP.

Today's PC-based controls are superior to their analog predecessors. Digital controls can monitor changes in the combustion process that will affect ESP performance (e.g., ash resistivity, ash loading, and particle size distribution) and adjust power levels to compensate for these fluctuations. Digital controls respond much more quickly to arcing and sparking, thereby minimizing these effects. Unlike analog controls, they can detect back corona to minimize back corona operation.

Digital controls are available from a number of suppliers, with some variation in operational modes depending upon the interests, understanding, and capability of the suppliers.

A.1 PC-based Controls

Modern power supply controls use digital circuits to control the gating signals to the silicon control rectifiers. The gating is modulated to provide the appropriate energization to the operating characteristics of the ESP, depending upon the ash loading, particle size distribution, and resistivity. In addition, the new control systems use a computer to provide overall supervision of the controls. These computers also make possible much more sophisticated control algorithms. The computer is programmed to recognize various characteristics of the ESP and to adjust the energization algorithm to match the current needs of the ESP. For example, if the ash resistivity is in the mid-10^{10} Ω-cm range, the control will select the ESP spark rate as the appropriate control algorithm. However, if the resistivity is in the high 10^{11} Ω-cm range, the computer will detect a change in the shape of the voltage waveform or V-I curve and change to an appropriate new algorithm to avoid back corona.

Some of the microprocessor controls are programmable to coordinate the operation of all the power supplies to provide the best overall collection efficiency for the ESP. Such input parameters as opacity meter signals, flue gas volume flow rates, and flue gas temperature are the primary factors considered. Some of the controls can centrally control the rapping program to avoid rapping two fields concurrently, thus avoiding generating multiple rapping puffs that may exceed allowable opacity limits. Combined rapping and ESP controls make it possible to use power off or reduced power rapping to improve plate cleaning.

For more information on controls, see *Precipitator Control System Upgrade Specifications,* EPRI report RP-2819.

Advantages: Advantages exist only if the controls have not been previously upgraded; there is little, if any, benefit to be gained by upgrading one type of digital control to another. Converting from analog controls to the PC-based controls will usually increase ESP collection efficiency. The degree of improvement depends on the ash characteristics.

Disadvantages: Some new controls are sensitive to electronic noise, and careful grounding is required. It is sometimes necessary to replace transformer/rectifier (TR) sets with ones with higher voltage and current ratings to take full advantage of the new controls.

A.2 High-Frequency Power Supplies

Another development in power supply operation and control is the use of higher-frequency input power to the power supply. Conventional energization uses the standard line frequency as the input to the high-voltage step-up transformer: 60 Hz in the United States and 50 Hz in most of the rest of the world. Some suppliers are now providing power supplies with the step-up transformer operating at several kilohertz or higher. The input line voltage is rectified, filtered to DC, and then converted to a much higher frequency by one of several types of switching circuits. This allows for a smaller transformer and core, saving weight and size.

There is also a claim that the high-frequency control can respond more quickly to changes in internal ESP conditions. Typically, one expects a few cycles of input waveform to be required for a control system to respond to changing conditions. This means several intervals of 16 2/3 to 20 milliseconds are needed for the conventional system to respond, compared with fractions of a millisecond for the high-frequency system to respond. This time difference may or may not be significant.

High-frequency supplies originated in Europe, and although they are now widely available throughout the world, they are not yet used extensively in the United States, so there is not yet a U.S. field history for evaluating advantages and disadvantages.

Advantages: One clear advantage is that conversion to a higher frequency allows the use of a much smaller, lighter-weight high-voltage step-up transformer. Lighter-weight components may allow a rebuild and upgrade without rebuilding the ESP foundation. The higher frequency also allows quicker response to changes in operation. These controls may provide higher power levels than conventional digital controls in medium-to-low resistivity applications.

Disadvantages: This type of control generally is more complex than a control operating at line frequency because of the additional rectification and switching circuitry. Other disadvantages may surface with experience in the U. S.

A.3 Pulse and Intermittent Energization

Pulse and intermittent energization (IE) are two related energization methods intended to improve collection of high-resistivity ash particles. These methods are based on the fact that the collection efficiency of an ESP is related to the product of the peak and average values of the electric field in the interelectrode space.

The electrical charge that resides on the particles due to field charging (the dominant charging mechanism for particles with a size greater than about 2 μm in diameter) is proportional to the peak value of the electric field where the particles are charged: the greater the electric field, the greater the charge on the particles.

The electrical force that actually removes a particle from the gas stream is proportional to the average value of the electric field adjacent to the collecting plate where the particle is to be collected. The actual collecting force is the product of the electrical charge on the particle times the electric field where collection occurs. Thus, the peak and average electric fields are the primary factors governing collection. On the other hand, the current flow through the collected ash layer establishes an electric field in the layer proportional to the current density and resistivity of the ash. Therefore, the ash resistivity establishes the maximum allowable value of average current density that can flow through the ash layer without forming back corona (see Volume 1, Appendix C). However, the electric field in an ESP is determined by the voltage in the precipitator. Since the maximum voltage level is controlled by the maximum allowable current level, this level ultimately controls the maximum sustainable electric fields in the precipitator.

Pulse energization is the superposition of a fast-rise-time voltage pulse on top of the voltage provided by a conventional power supply. This technology was originally investigated by Dr. Harry J. White while Director of Research at Research Cottrell. This investigation made use of the electrical pulse technology developed for radar use at the MIT Research Laboratory of Electronics during World War II. Investigations of pulse energization in full-scale ESP installations were conducted in the 1970s. These studies showed that the primary improvement in collection efficiency was the ability to operate with a much more nearly uniform current density distribution on the collecting electrodes. There was also some increase in the level to which the larger particles could be charged with pulse energization, but the primary improvement was associated with the more uniform current density distribution. (Even though the larger particles are charging toward the peak value of the pulse-established electric field, the pulse duration is so short that the actual incremental difference in field charging is small.) The more nearly the current density approaches uniformity, the greater the applied voltage can be, without forming back corona. Thus, pulse energization allows the ESP to operate at higher peak and, to some degree, higher average voltages than conventional energization.

Pulse energization currently requires the installation of a separate power supply on each electrical section. This new power supply provides the fast-rise-time pulses of voltage needed to cause the current density distribution to be much more uniform. The conventional power supply is retained and operated with a background voltage at or near corona start, to maintain a collecting electric field on the ESP between pulses. The new power supply provides pulses of voltage to the ESP with rise times on the order of a few microseconds, with pulse duration ranging up to several tens of microseconds.

The pulse power supply requires a significantly higher peak current capability than the conventional one. The higher current capability is required to charge the distributed capacitance of the ESP field to a peak voltage on the order of 70 kilovolts in a few microseconds, in order to provide the very short rise times on the pulses. The average value of current needed is approximately the same as for a conventional power supply.

Using pulse energization for collecting particles that produced back corona reduces outlet emissions by about a factor of two or more. Since the formation of back corona is related to the average local value of the current flowing through the ash layer, reducing areas of high current density while distributing current to the previous "dead" spots allows operation at a higher overall current density, with a concurrent increase in voltage. The increase in voltage improves the collection efficiency.

For more information on pulse energization, see *An Investigation of Pulse Energization*, EPRI report CS-4717.

Intermittent energization (IE) was developed as a lower-cost option to pulse energization for collecting high-resistivity particles. The concept, as introduced by Mitsubishi in Japan, is to increase the product of the peak and average values of operating voltage on the ESP, at the allowable current density established by the ash resistivity. This increase in voltage is achieved by passing one cycle of the input waveform and blocking the next several cycles, producing a higher peak value of voltage during the energization cycle and allowing the voltage to decay over several cycles before the next energization period. The optimum number of cycles on versus cycles off is established by trial and error. After Mitsubishi introduced the concept, it was recognized that any modern PC-based power supply control could be programmed to operate with IE.

IE provides some improvement in collecting high-resistivity particles. The degree of improvement is approximately half that provided by true pulse energization, but the cost is significantly less. The actual cost is essentially zero if the ESP is already equipped with PC-based controls. The only change required is to program the controller to recognize the back corona voltage waveform and initiate IE when back corona is present. The reason that IE provides less improvement than pulsing is the limited degree to which the average current density can approach uniformity. Pulse energization causes the corona pattern from the corona electrode to approach that for positive polarity operation, while IE retains the tufted appearance of negative corona.

Generally, IE works best (produces the most improvement) when it is used in the inner fields of an ESP. Reducing the average current in the front field of an ESP can slow particle charging, and hence, IE is only beneficial in this field if there is severe sparking or back corona. Reducing the average current density in the outlet field can increase reentrainment and rapping losses, and hence, IE is only useful in an outlet field if there is severe sparking or back corona.

Advantages: Both pulse energization and IE improve the performance of an ESP collecting high-resistivity particles where conventional energization would produce back corona. (Neither method improves the performance of an ESP collecting low-resistivity particles. Conventional controls provide optimum collection efficiencies for ESPs when the performance is not limited by high resistivity.) IE also provides the opportunity to reduce the power consumption in an ESP collecting lower-resistivity particles while retaining the collection efficiency; the power savings are on the order of 10–20%.

Disadvantages: The disadvantage of the IE system is that the improvement in collecting efficiency is considerably less than would be provided by true pulse energization. The disadvantage of the true pulse system is the added cost and complexity, as the current designs for pulse energization require the addition of a pulse power supply with interconnections to the existing energization equipment; in some instances the high-voltage distribution system may also require redesign.

A.4 Positive Polarity for Hot-Side ESPs

The formation of back corona in a hot-side ESP is caused by the depletion of electrical charge carriers in the ash deposit that resides on the collecting electrodes. The sodium-depleted, high-resistivity layer develops because the electrical conduction mechanism in the ash layer for hot-side ESPs is the physical migration of alkali metal ions—principally sodium and lithium—through the fly ash material. The conventional utility ESP operates with negative polarity on the corona electrode. This negative energization produces negative ions that flow across the interelectrode space and deposit on the surface of the ash layer. The conduction in a high-temperature ash layer, however, is provided by the migration of positive sodium ions. These ions move in a direction opposite to the negative ions from the corona electrode. Electrical charge transfer occurs at the surface of the ash layer. It is conjectured that the negative oxygen ions associated with the sodium ions in the fly ash glassy structure migrate to the collecting electrode and combine to be liberated as oxygen gas. (For more discussion, see Volume 1, Appendix D.)

Converting the electrical energization to the ESP from negative to positive polarity can prevent the formation of the sodium-depleted, high-resistivity layer. When the ESP is operated with positive polarity, the corona system produces positive ions that flow across the interelectrode space. This reversal of polarity changes the direction of migration of the sodium ions in the ash deposit. The sodium ions now migrate from the surface of the ash deposit towards the collecting electrode.

Under these positive-polarity conditions, the ash layer does not develop a sodium-depleted zone. The newly deposited ash provides an adequate amount of charge carriers to effectively conduct the electrical current through the ash layer. The ash layer builds up to an appropriate thickness, the plate rappers are activated to remove the deposit, and the collecting process continues. Through this process, the newly collected ash provides the necessary charge carriers and a high-resistivity region is never formed.

Conversion to positive polarity will probably require a rebuild of the high-voltage distribution system. The operating voltage in an ESP is typically set to a value that produces some amount of electrical sparking. Sparks always develop through the formation of small flares that originate on a region of the positive-polarity portion of the ESP and grow progressively until a sparkover occurs. The initial flare develops when the local value of the electric field (in the positive region) reaches a value on the order of 5 to 10 kilovolts per centimeter. Conventional negative-corona ESPs have the positive polarity of the supply on the ground side of the electrical circuit. This region is in the low electric field region of the system.

If an attempt is made to convert the existing ESP to positive polarity, the small pipes and other structural shapes in the high-voltage distribution system now operate with positive polarity. The electric field near these members exceeds the initiating value, which is in the range from 5 to 10 kV/cm, before the ESP has sufficient voltage on the discharge (corona) electrodes to operate effectively. An entirely redesigned high-voltage distribution system is required to allow operation at reasonable positive-polarity voltage levels.

The power supplies can be either permanently converted to positive polarity or provided with the ability to be polarity-reversed at intervals of time. The reason to allow polarity switching is that the negative-polarity operation provides greater collection efficiency than positive polarity before sodium-depleted high resistivity limits the operating voltage. The station can be programmed to operate with negative polarity until back corona develops and then switched to operate with positive polarity until the back corona is eliminated. Since reversing the polarity of a TR set requires that the TR set be de-energized during the switching process, power stations that operate at low load during nights and weekends should have the polarity switching coordinated with the load variations to maximize collecting efficiency and to avoid possible opacity and emissions violations. Baseloaded plants may require some modification to the ESP to be able to operate with a permanent polarity reversal.

EPRI is conducting a pilot-scale evaluation of the conversion of a hot-side ESP to positive polarity. This pilot ESP was installed at an operating power station burning low-sodium Powder River Basin coal. Operation with negative polarity for extended periods of time developed the characteristics of high resistivity, indicating the development of a sodium-depleted ash layer.

The pilot ESP was then converted to positive-polarity operation. The system operated for several weeks without any indication of the formation of high resistivity, confirming the earlier laboratory work. The ESP was next converted back to negative polarity, allowing high resistivity to develop, after which a polarity reversal to positive immediately indicated a reduction in resistivity and continued until the resistivity was reduced to approximately the original conditions. This ongoing pilot study will provide a conceptual design for the high-voltage distribution system appropriate for positive polarity operation.

For more information on positive polarity, see *Positive Polarity for Hot-Side Electrostatic Precipitators,* EPRI report GC-111877.

Advantages: The primary advantage of polarity reversal for hot-side ESPs with sodium depletion is that no conditioning equipment or material must be purchased. There is a one-time cost of modification, which should permanently eliminate the problem. If the ESP meets the required collection efficiency when operating without back corona, conversion to positive polarity should eliminate the problem.

Disadvantages: The primary disadvantages are the need to completely redesign the high-voltage distribution system and to provide for the capability to reverse polarities as needed. The power supplies must be equipped with a dual diode rectification stack and dual polarity controls. These power supplies are more complicated and may require more attention than conventional power supplies.

A.5 Arc Snubber™

A patented device marketed by Zero Emissions Technologies (ZET), the Arc Snubber™ is described as a filter system designed to compensate for high-frequency electrical components present in the electrode system of an ESP field. Each filter is custom-designed based on measurements of the secondary voltage waveforms. The filter is then installed in the high-voltage distribution system, replacing a section of the center pipe electrode connecting the power supply to the ESP collecting field.

The filter system has produced mixed results in utility field trials. In some instances the supplier and user have agreed that there was a significant reduction in opacity, while in others, there was no significant change in performance as indicated by an opacity meter. When improvement did occur, it was not obvious what actually changed after installation, i.e., what was the mechanism for improvement. It is possible that the filter provided a much better impedance match between the high-voltage power supply and the ESP collecting field in those cases where a significant mismatch existed.

The filters should provide an increase in the isolation between the power supply and the ESP. They may also improve the impedance match between the ESP collecting fields and the power supply while the thyristors are in the conduction mode. Their installation may or may not provide an improvement in opacity for any given ESP system. As of this writing, ZET is providing a risk-sharing guarantee for evaluating the filters.

Advantages: The Arc Snubber™ can be designed from measurements conducted while the power plant is operating and can be installed during a very short shutdown. The expected costs are low and there is little financial risk associated with its evaluation.

Disadvantages: The success or failure of the device seems to be very site-specific, and it is not clear what condition the filter will correct. Determination of its usefulness can only be established on a “trial and error” basis. Installation of the Arc Snubber™ is not expected to provide a sufficient reduction in emissions to avoid a complete rebuild. If installed, the filter system would only be used as a part of an upgrade program.

B

FLUE GAS OR FLY ASH CONDITIONING

High electrical resistivity is recognized as a fundamental factor limiting the collection efficiency of ESPs. Indeed, one of the first attempts to use an ESP to control particulate emissions resulted in failure due to high electrical resistivity. The installation was a lead smelter in North Wales, which produced a lead oxide fume with particles that were very small in diameter and very high in resistivity. Not surprisingly, test results were disappointing.

Early fly ash resistivity conditioning experiments were conducted in Kincardine, Scotland, by Lodge-Cottrell of England (now owned by FLS miljo of Denmark). Sulfur trioxide was used effectively to reduce the ash resistivity. Fly ash conditioning studies continued through much of the latter part of the twentieth century, and were brought to maturity in the 1970s and 1980s. A variety of conditioning agents, proprietary as well as generic, were used in this period of experimentation and development.

B.1 Sulfuric Acid (SO_3) Conditioning

The burning of coal containing sulfur produces sulfur dioxide in the combustion process. As the flue gas progresses through the ductwork and heat exchange surfaces to the inlet of the ESP, a small fraction of the SO_2 is further oxidized to SO_3. At the lower temperatures encountered in the air heater, SO_3 reacts with the water vapor in the flue gas to form a sulfuric acid vapor that reduces the resistivity of the ash for ESPs operating in the 300°F (150°C) temperature range.

For those stations burning low-sulfur coals, there may be insufficient sulfur trioxide produced to effectively reduce the ash resistivity. In such situations, SO_3 can be injected into the flue gas stream near the ESP to provide additional “conditioning.”

These SO_3 conditioning systems are considered a proven technology and are available from a number of suppliers. They provide adequate resistivity reduction in cold-side ESPs for most fly ash compositions in the United States. SO_3 conditioning is not appropriate for ESPs with nominal operating temperatures much greater than 300–325°F (150–160°C) .

William Archer of WAHLCO was one of the pioneers that worked to establish the technology in the United States. Drs. Roy E. Bickelhaupt and Edward B. Dismukes of Southern Research Institute also contributed significantly to the understanding of this technology.

Bickelhaupt identified the electrical conduction mechanisms in fly ash materials for both bulk and surface conduction (see Volume 1, Appendix D). Surface conduction, which is the dominant mechanism for cold-side ESP installations, depends on the interaction of moisture and/or sulfuric acid with the fly ash material. The combustion of medium- to high-sulfur (1.5–3%) coal produces sulfur dioxide in the combustion process of approximately 1000 to 3000 ppm (by volume). Some portion of this SO_2 (typically 0.1–0.4%) is further oxidized to SO_3 as the flue gas traverses the ductwork through the air heater to the cold-side ESP. This $SO_{3,}$ together with the water vapor in the flue gas, interacts with the fly ash material to effectively reduce the ash resistivity to somewhere in the range of 10^{10} Ω-cm at the normal cold-side ESP operating temperature. This resistivity value is in the optimum range for collection in a conventional ESP.

The trend toward using lower-sulfur coals in the U.S. power industry has led to an increase in the electrical resistivity of the fly ash. ESP systems designed to operate with ash and flue gas from high-sulfur coals no longer provide the degree of particle control desired or required. The need to correct this particulate collection problem provided the impetus to develop commercial SO_3 conditioning systems. Injecting quantities of SO_3 in a range of a few ppm to as high as 20 ppm usually restores ESP collection efficiency to that when collecting ash from a similar high-sulfur coal. An extensive manual for SO_3 conditioning is found in EPRI report CS-4145, *A Manual for the Use of Flue Gas Conditioning*, published in August 1985.

The SO_3 conditioning systems for utility boilers usually operate with a source of SO_2 which is oxidized to SO_3 in a catalytic converter system. The source of the SO_2 is generally from burning sulfur on site, but systems based on liquid SO_2 and stabilized SO_3 (Sulfan) have been used. The catalytic converter is usually a single-pass system with an to SO_3 conversion efficiency in the low 90% range. The process is exothermic with the gas stream flowing from the converter with a temperature in the 700°F (370°C) range. The acid dew point for very high concentrations of sulfuric acid vapor is such that the injection manifolds and distribution system must be maintained in the above temperature range to avoid condensing sulfuric acid droplets in the injection manifold system.

Advantages: For most fly ashes, SO_3 conditioning restores the collection efficiency of an ESP to the level expected when collecting ash from high-sulfur coals. The systems have been developed to the point that they operate almost automatically with the capability to load-follow and to adjust injection rates to maintain acceptable opacity. Their costs have been reduced considerably, thanks to competitive pressures and improvements in equipment.

Disadvantages: Disadvantages include installation costs and the cost of raw materials. SO_3 conditioning systems require maintenance and some degree of monitoring. The distribution manifolds are quite complex and require heating to maintain the injected gas stream temperature well above the acid dew point until injection. There is also concern about sulfuric acid emissions in some localities, even though the SO_3 slip can be kept quite low.

B.2 Moisture Conditioning and Humidification

Both flue gas temperature and moisture content influence fly ash resistivity. Figure B-1 illustrates an example of fly ash resistivity as a function of temperature for flue gas streams containing different amounts of moisture and SO_3. Adding a sufficient quantity of water to reduce the temperature in a cold-side ESP will reduce ash resistivity. Adding water also reduces resistivity by encouraging the chemical intersection between the fly ash surface constituents and the water vapor in the flue gas. This interaction produces an increase in the number of charge carriers for surface conduction, thereby reducing the ash resistivity. (For more detail, see Volume 1, Appendix D.)

In addition, increased moisture content improves ESP collection efficiency by increasing the electrical sparkover voltage. The water molecule is a somewhat lower-mobility electrical carrier than oxygen and other electronegative components of the flue gas. An increase in the number of moisture molecules causes an increase in the water vapor ions participating in the conduction process. This has been reported to increase the voltage for a given current density and to increase sparkover voltage.

Moisture conditioning and flue gas humidification are related conditioning mechanisms that boost flue gas water content to improve the performance of ESPs collecting high-resistivity fly ash. These technologies differ only in the amount of water added to the flue gas. Humidification is based on adding enough water to increase the flue gas moisture content by about 0.5%, while moisture conditioning—which requires significantly more water—is defined as adding sufficient water to reduce the flue gas temperature by several degrees Fahrenheit.

Moisture conditioning reduces the electrical resistivity of the ash in three ways: (1) by cooling the gas, (2) by increasing the moisture interaction with the fly ash, and (3) by increasing the sparkover voltage within the ESP. Humidification provides only two out of three benefits, namely, increased interaction between the flue gas moisture and the fly ash surface, and increased sparkover voltage.

Both methods use the same injection equipment: dual fluid nozzles with steam or high-pressure air to atomize the water into a fine spray of droplets with a mass mean diameter in the 10 to 50 micron range. Frequently, the injection nozzles are placed in the duct leading to the ESP, but a better (though more costly) approach would be to add an evaporation chamber similar to that used in a spray dryer to ensure complete evaporation of the droplets, so as to avoid any deposition of droplets on ductwork surfaces. Newer nozzles under development may eliminate the requirement for high-pressure atomization gas.

Advantages: Compared with SO_3 conditioning, moisture conditioning and humidification avoid the need for a high-temperature distribution manifold as well as the need to handle somewhat hazardous chemicals. The mechanism for moisture conditioning/humidification operation is understood and applies to all known fly ashes. Installation costs are quite low.

Disadvantages: The primary disadvantages are (1) the quantity of water required to effectively reduce the resistivity and (2) either the high-pressure air or steam to provide the atomization force. The moisture content of flue gas is typically about 8–12%. Moisture conditioning usually requires increasing this moisture content by at least 2–3%, which requires a significant amount of water. For example, a 100-MW power station requires over 1500 gallons of water per hour to raise the flue gas moisture content by 2%.

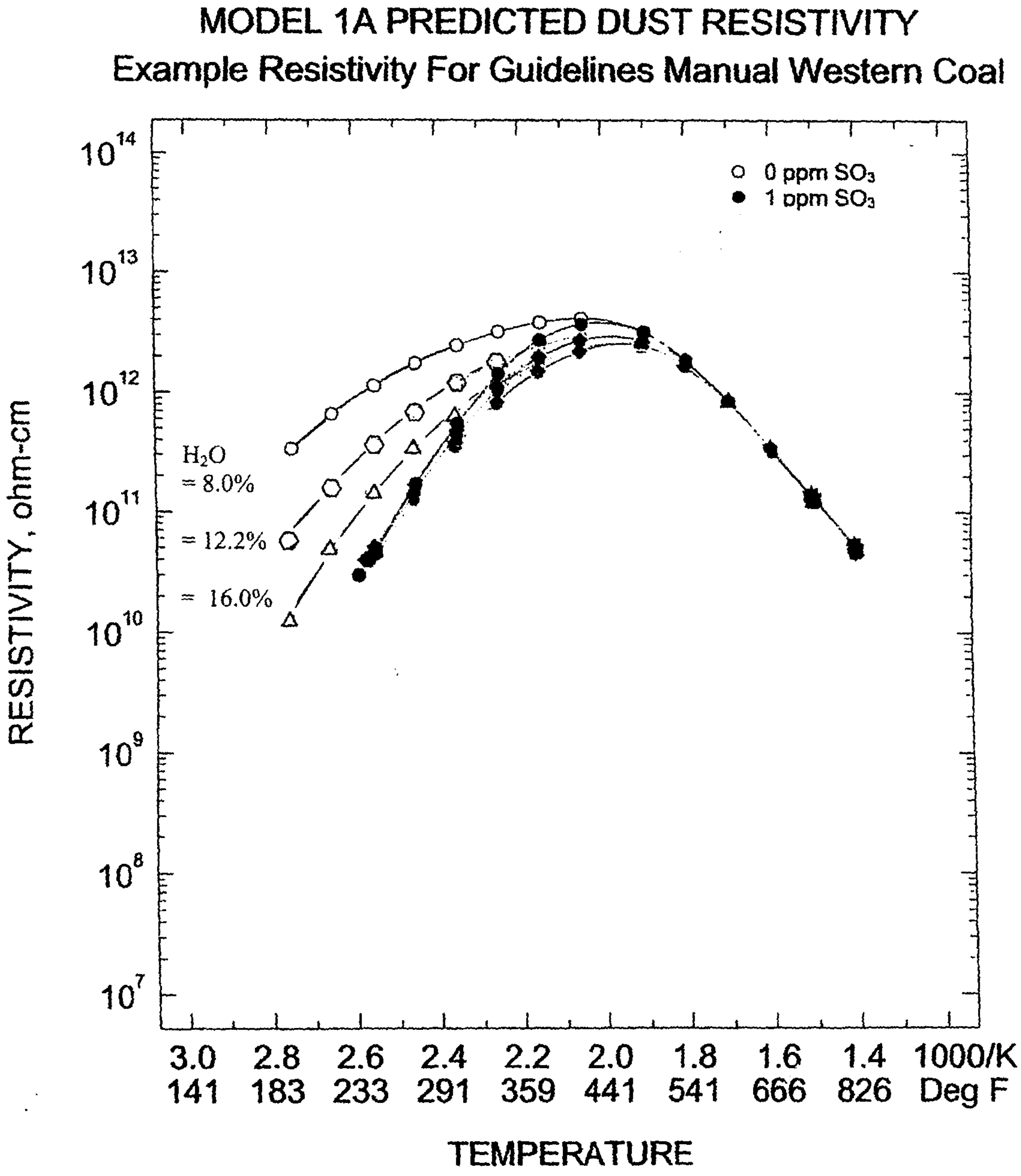


Figure B-1
Resistivity Change With Moisture Conditioning

B.3 Ammonia Conditioning

Ammonia conditioning is used on fly ash for three purposes: to reduce ash reentrainment, to avoid sulfuric acid opacity plumes, and to improve performance of hot-side ESPs experiencing back corona.

Ammonia serves to reduce the rapping reentrainment from ESPs collecting ash from high-sulfur coals. If the ash resistivity is less than about 1 x 10^{10} Ω-cm, the applied electric field and current flow conditions in the ESP cause an electrical force on the fly ash layer that is in the direction to cause particle reentrainment. If the adhesive and cohesive forces holding the fly ash together are quite small, this electrical force can cause reentrainment of the fly ash. Stations operating under these conditions typically exhibit severe opacity spikes when the rappers are activated. Figure B-2 illustrates an example of such an opacity monitor output record.

To reduce this excessive ash reentrainment, ammonia is injected into the flue gas downstream of the air heater. Flue gas from the combustion of high-sulfur coal usually contains sulfuric acid vapor in the 10 ppm range. Injecting ammonia into this flue gas stream will cause the formation of ammonium sulfate and ammonium bisulfate in a ratio established by the relative concentrations of ammonia and sulfuric acid. The ammonia and sulfuric acid gas-phase reaction produces a particle composite that is quite sticky; the product can be either solid particles or liquid droplets, depending on the temperature of the carrier gas. Ammonium bisulfate remains as a liquid in the 300°F temperature range in which cold-side ESPs operate. This material serves to increase the cohesivity of the ash deposit on the collecting electrodes so that the ash rapped from the plates tends to fall into the hoppers as clumps with a minimum of reentrainment. In this way, ammonia modifies the opacity trace in Figure B-2 to appear more like that in Figure B-3. Generally, it is desirable to inject ammonia at a rate that produces a one-to-one stoichiometric ratio with the SO_3 in flue gas. This level encourages the formation of ammonium bisulfate, the "sticky compound."

Figure B-2
Opacity Trace With Large Rapping Reentrainment

Figure B-3
Example Opacity Trace After Ammonia Injection

A station burning high-sulfur coal that also has a wet scrubber for SO_2 control can sometimes produce a sulfuric acid opacity plume. The acid vapor in the flue gas condenses in the scrubber to form the acid mist. The scrubber will not collect the acid mist because of its extremely small particle size. Ammonia injection upstream of the ESP converts the sulfuric acid vapor to an ammonium sulfate–bisulfate composite similar to the situation described above to reduce low-resistivity reentrainment. The newly formed compounds are collected in the ESP before the flue gas is introduced into the scrubber, avoiding the condensation of the acid in the scrubber.

In this application, it may be desirable to inject ammonia at a higher rate to encourage the formation of ammonium sulfate. The higher proportion of ammonium sulfate will keep the ash from becoming too sticky, making the ash hard to remove from the plates. In general, the rate of ammonia addition that provides optimum performance is determined by trial and error. There is no analytical procedure that can be used to calculate the rate of addition that will produce the optimum level of “stickiness.”

Ammonia conditioning is also used to improve the performance of hot-side ESPs suffering from high resistivity, whether the resistivity problem is inherent in the ash or a result of sodium depletion. For ammonia conditioning to make a measurable improvement, the ESP must have developed back corona; if back corona is not present, ammonia will not improve collection efficiency.

The mechanism by which ammonia assists these hot-side ESPs is not yet understood, but the ammonia causes an immediate increase in the secondary voltage of the ESP, with a concurrent increase in collection efficiency. Since the response to ammonia conditioning is almost instantaneous, the mechanism is not likely because of resistivity modification. It is more likely influencing the electrical mobility of the charge carriers. There is some conjecture that the ammonia gas molecule, which is electropositive, tends to attach to the positive ions formed in the back corona to reduce their electrical mobility in the flue gas stream. Reducing the mobility of these charge carriers causes a decrease in the electrical current at a given voltage, allowing the operating voltage for the system to increase, thereby improving the collection efficiency of the unit. The operating voltage of a hot-side ESP with back corona immediately increases by about five kilovolts when ammonia is injected.

Advantages: The advantages of ammonia conditioning include the quick response of the ash and flue gas to the injected material and the ability to adjust injection rates as needed.

Disadvantages: Ammonia does not directly modify resistivity but works secondarily in the hot-side ESP application. If the fly ash is used to make cement, the ammonia may be detrimental to the curing process; it can also lend an objectionable odor to cement and concrete.

B.4 Combined SO_3 and Ammonia Conditioning

Some fly ashes do not readily respond to either SO_3 or NH_3 conditioning applied singly. These ashes are usually high in silica and alumina content; under reasonably high magnification, their surfaces appear very smooth, in contrast to typical fly ashes, which have a very rough appearance. A combination of both ammonia and sulfuric acid is sometimes necessary to effectively condition these ashes.

As discussed above, ammonia and sulfuric acid gases react to form ammonium sulfate and ammonium bisulfate. Since these gases readily react at temperatures up to about 550–600°F, it is important that they not be injected together before the flue gas passes through the air heater. If so injected, the material will be deposited on the heat exchanger surfaces and plug the air heater (which requires a plant shutdown to repair). The preferred arrangement is to inject the SO_3 before the air heater and the ammonia downstream from the air heater; this injection sequence avoids the tendency to plug the air heater. However, in some installations, both SO_3 and ammonia are injected downstream of the air heater.

The conditioning mechanism for combined ammonia andSO_3 is the co-precipitation of the reaction products and fly ash, with perhaps some resistivity reduction by the SO_3. The ammonium sulfate–ammonium bisulfate particles are small and dispersed in the flue gas. Even though there may be some deposition on the ash surface while suspended in the flue gas, the co-precipitation is considered to be the means for bringing the fly ash and chemical reaction products together. This co-precipitation provides for the intimate mixing of the two materials as they are collected.

The ammonium sulfate compounds provide two mechanisms for improving ESP collection efficiency: (1) the fly ash rapping reentrainment is reduced because of the stickiness of the sulfate material and (2) the electrical resistivity of the ash layer including the co-precipitated materials is lower than that of the fly ash alone.

Advantages: Combined conditioning can improve capture of very-difficult-to-collect fly ashes that do not respond to single conditioning agents.

Disadvantages: Use of two chemicals increases storage and handling issues. The operation of both injection systems must be coordinated, and two systems must be maintained instead of just one.

B.5 Sodium Conditioning

Sodium conditioning is typically used in hot-side ESPs that have developed high resistivity due to sodium depletion. In some hot-side ESPs collecting fly ash from low-sodium coal, sodium depletion in the ash layer remaining on the collecting electrode produces a high-resistivity layer where back corona develops (see Volume 1, Appendix D).

Sodium depletion is readily recognizable in a hot-side ESP. The collection efficiency of the ESP is very good after a clean electrode startup, with good electrical conditions and very low emissions. However, as the plant operates over a several week period, the secondary operating voltage begins to be reduced by the power supply controls, as sparking begins to develop at lower voltages. The performance degradation continues when the development of back corona further decreases the collection efficiency, until the plant is forced to shut down for cleaning the collecting electrodes.

The relationship between sodium and ash resistivity results from the fact that electrical conduction in the bulk of the fly ash material consists of the physical migration of alkali metal ions, principally sodium. Thus, the amount of sodium contained in the fly ash material establishes the bulk resistivity of the material, if all other chemical constituents remain constant. Figure B-4 shows the bulk resistivity of a given ash with two levels of sodium, 0.24% and 1.74%, reported as Na_2O. The bulk resistivity is the linear portion of the resistivity vs. temperature plot that decreases with increasing temperature. Note that the higher sodium concentration reduces the bulk resistivity.

Adding sodium changes only the bulk resistivity of fly ash. Figure B-5 shows the decrease in ash resistivity from changing the surface conduction characteristics, by adding moisture alone and by adding SO_3, for the two different ash sodium concentrations illustrated above. Modifying the surface conduction yields a lower composite resistivity. The surface and bulk conduction modes are thought of as parallel resistors. This suggests that sodium can be useful for conditioning fly ash in either hot-side or cold-side installations.

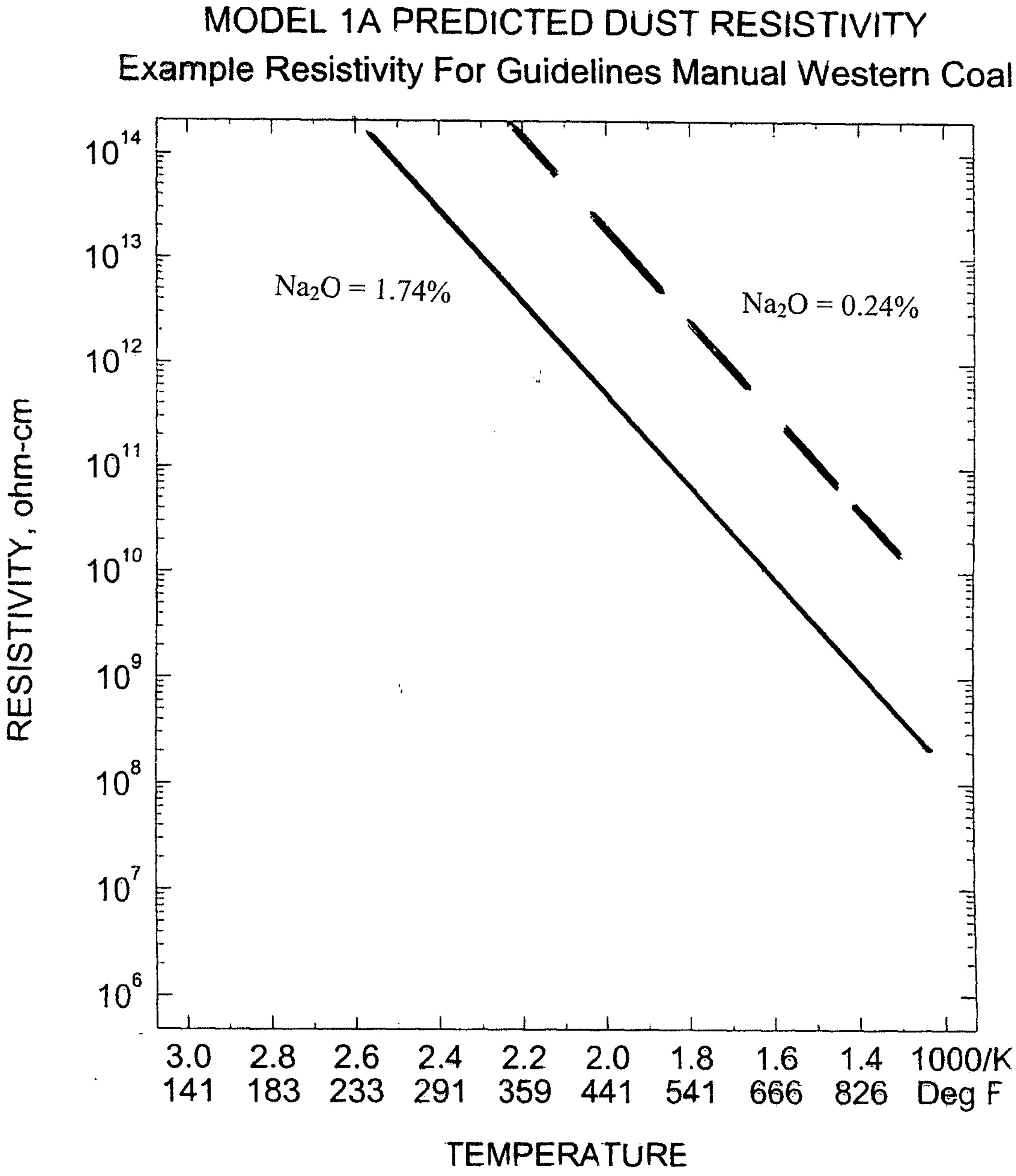


Figure B-4
Bulk Resistivity vs. Temperature for Two Sodium Contents

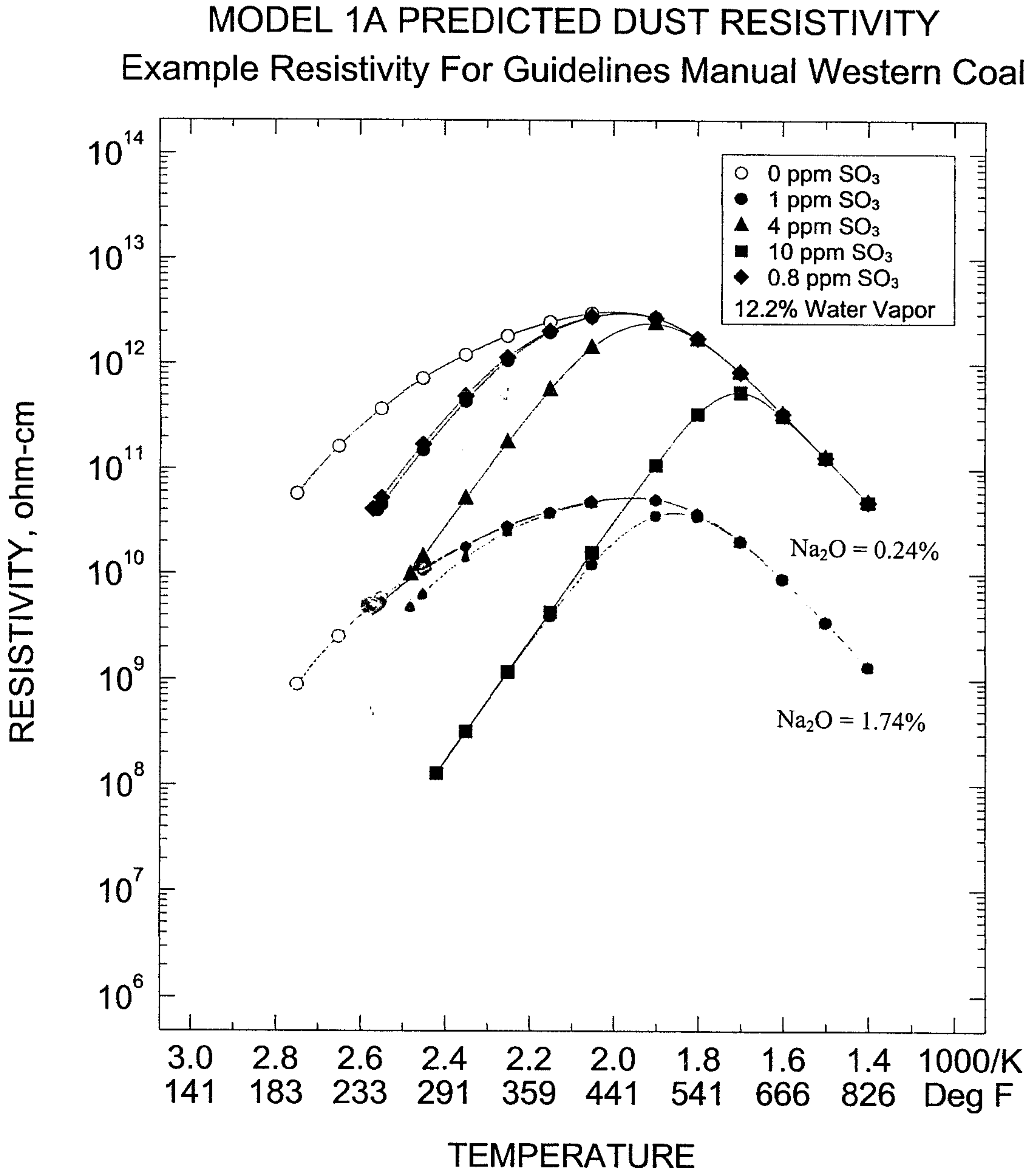


Figure B-5
Resistivity vs. Temperature for Sodium Conditioning

Sodium conditioning was first commercially verified at Gulf Power's Lansing Smith Station, which burned a South African coal and employed a Buell hot-side ESP. The station routinely shut down to water-wash the ESP internals at about six week intervals to remove the sodium-depleted ash layer. This washing was necessary to restore ESP collection efficiency.

Although sodium conditioning is generally used for correcting hot-side sodium depletion problems, it also has applications for cold-side units. As shown in Figure B-5, increasing the sodium concentration in the fly ash reduces the resistivity of the ash even for cold-side units. In fact, the first experiment with sodium conditioning was at the Wabamun Station near Edmonton, Canada (of what is now Transalta Utilities), using a pilot ESP operating at about 325°F. In situ resistivity measurements confirmed the success of sodium conditioning.

Additional sodium conditioning tests have been completed (1999) at the Balco Power Station of the National Thermal Power Corporation in India. The coal burned in this station is very high in ash and very low in sulfur. Early results show that sodium conditioning is reducing ash resistivity and improving collection efficiency of a cold-side ESP operating in the 325°F temperature range. The addition of sodium sulfate to increase the ash sodium oxide concentration by about 0.5% resulted in a completely clear stack.

Another cold-side application of sodium conditioning is at power plants burning coals that are very low in sulfur and high in lime. The lime removes most of the SO_3 produced in the combustion process, preventing the usual formation of sulfuric acid, which serves as a naturally occurring flue gas conditioning agent.

Sodium conditioning requires that the sodium-containing compound, either sodium carbonate or sodium sulfate, be added to the coal prior to combustion. Both laboratory and full-scale tests have verified that it is necessary for the sodium to actually become a part of the fly ash material, rather than a material to be co-precipitated with the original ash, to be most effective. Tests with sodium-containing material dispersed into the ductwork prior to the ESP show only a small improvement in collection efficiency. Laboratory measurements of resistivity also confirm the failure of mixed ash and conditioning materials to effectively reduce the resistivity of the composite material.

Consequently, the sodium-containing compound should be metered onto the coal before it is loaded into the station coal bunkers. A subsequent water spray ensures that the sodium adheres to the coal. The conditioning material and the coal pass through the coal mills where they are intimately mixed. Once in the combustion zone of the furnace, the sodium is vaporized to recondense and become a constituent of the fly ash. Note that the combustion temperature must be sufficiently high to allow the added material and fly ash to become somewhat homogeneous. The combustion temperatures in U.S. pulverized coal and cyclone boilers are typically high enough to melt the ash; however, in some units firing high-moisture lignites, the combustion temperatures may be borderline.

The amount of additive required is the amount needed to bring the total sodium content of the fly ash up to the range of 1–1.5% when reported as sodium oxide. The amount usually is in the range of 5–8 pounds of additive per ton of coal (2.5–4 kg/tonne) for most coals burned in the United States. Of course, higher-ash coals would require more conditioning material. For more information on the technology, see *Sodium Conditioning for Improved Hot-side Precipitator Performance,* EPRI report CS-3711, Volumes 1 and 2.

Advantages: Sodium conditioning is an effective technique for restoring the collection efficiency of a hot-side ESP to its original level. The injection system is quite simple, requiring only a metering system for dry powder and a small amount of water spray to retain the powder on the coal. It has also been shown to work on cold-side units with very high-ash, low-sulfur coal, and may well be an attractive alternative to the combined SO_3-NH_3 injection system for those cases where the difficult-to-condition ash is low in sodium.

Disadvantages: Sodium conditioning presents a potential problem for some power stations. The addition of alkali metal compounds to fly ash usually reduces the temperature that causes the ash to begin to melt; thus, sodium can exacerbate slagging or fouling problems. The furnace system should be closely monitored during the experimental stages of sodium conditioning evaluation tests.

B.6 Proprietary Conditioning Agents

A number of proprietary conditioning agents have been marketed to the electric power industry over the years. The majority of these agents were intended for use on cold-side ESPs for resistivity modification. Some compounds were stated to promote particle agglomeration while particles were suspended in the flue gas stream, but this mechanism was never experimentally verified. Solutions of ammonium sulfate were used briefly but are no longer used. At this point, proprietary agents for cold-side ESPs have been fundamentally supplanted by the widespread acceptance of the more effective sulfur trioxide as the appropriate agent for conditioning cold-side ESPs collecting high-resistivity ash. For more information on proprietary conditioning agents, see *Flue Gas Conditioning at Rochester Gas and Electric's Russell Station,* EPRI report TR-109011.

In contrast, hot-side ESPs experiencing high resistivity due to sodium depletion are important candidates for proprietary conditioning agents. Sodium conditioning may not be appropriate for stations with a tendency to develop slagging and fouling or for stations burning coal from a wide variety of sources (to establish the correct injection rate, it would be necessary to determine the chemical composition of the particular coal in use). Proprietary conditioning agents can be employed on an as-needed basis for these specific installations.

One such agent for these hot-side units has been tested extensively at pilot scale and verified by full-scale operation. Selection of this proprietary agent vs. sodium injection should be based on economic and feasibility considerations. The proprietary agent has the advantage of being easily brought into service when needed, rather than requiring addition to the coal as the bunkers are loaded. The agent is injected downstream from the furnace just before the ESP, thus avoiding slagging and fouling problems in the boiler. For more information on proprietary agents for hot-side ESPs, see *Full-Scale Demonstration of a New Flue Gas Conditioning Technology for Hot-Side ESPs,* EPRI report TR-109012.

Advantages: Unlike sodium, the proprietary agent for hot-side units can be injected after the boiler, and therefore avoid potential slagging and fouling problems. Moreover, its injection rate can be adjusted in real time, whereas the sodium must be added to the coal as the bunkers are loaded. It may be possible to have an automatic injection system that uses a signal proportional to opacity to adjust the usage rate.

Disadvantages: Proprietary conditioning agents are usually more expensive than off-the-shelf chemicals. Also, the use of an unknown chemical compound leaves some uncertainty about potential detrimental effects on the system. Careful monitoring of the system during trials is strongly recommended.

C

OPTIMAL GAS FLOW DISTRIBUTION: UNIFORM VS. SKEWED FLOW

Gas flow distribution has a significant impact on ESP collection efficiency. Over time, the flow distribution in an ESP often deteriorates due to degradation of the flow control devices, ash deposits in ducts and on turning vanes, and others factors, thereby compromising unit performance. Indeed, many older ESPs were never optimized for gas velocity distribution in the original design. Gas flow model studies and flow corrective measures have improved significantly in recent years, and gas flow optimization should be considered as part of any significant rebuild or upgrade project.

The first step in a gas flow study is to measure the actual gas flow distribution using thermal or vaned anemometers (see Volume 1, Section 5.7). Compare these measurements to the standards set by the Institute of Clean Air Companies (formerly IGCI): 85% of the measurement points should have velocities less than 1.15 times the average velocity, and 99% of the measured velocities should not be more than 1.4 times the average velocity. If the gas velocity distribution in an ESP meets these criteria, further improvement in the uniformity of the gas flow distribution will provide very little incremental performance improvement, if any at all. It is, however, likely that the gas flow does not meet these criteria, and the next step will be to contract for a good gas modeling study (see Volume 1, Section 6.8.3). This study should determine, among other things, whether flow patterns should be modified to be uniform or skewed.

When considered from first principles, ESP collection efficiency is best when the gas velocity distribution within the collecting zone is uniform. This is because the collecting characteristics of the device are exponential in nature. If the collection efficiency for any part of the ESP is 90%, then adding an equal amount of collecting surface will increase the collection efficiency to approximately 99%, removing only 9% more particles than the initial unit. Therefore, if there is an uneven gas velocity distribution in the collecting zone, the regions with the high velocity flow will have an SCA smaller than the average while the low velocity regions have a higher SCA, analogous to the example given above. Thus, following the above example, there will be a greater amount of particles lost in the high-velocity regions than will be collected in the regions with lower velocity. (A more detailed discussion is provided in Volume 1, Appendix C.)

Thus, one expects ESP performance to be better with a uniform gas velocity distribution. This is clearly true until the factor for rapping reentrainment is added to the equation.

When the collecting plates are rapped, the ash collected near the top of the collecting plates must fall the entire plate height before reaching the hoppers. The greater the fall distance, the greater the velocity attained during the fall. Higher falling velocities tend to cause a greater break-up of ash agglomerates, both during the free fall and when the ash hits the hoppers and discharge wire and plate support structure. Therefore, it is advantageous to have a greater percentage of the ash collected near the bottom of the plates close to the hoppers, in order to minimize reentrainment.

This consideration favors having a higher gas velocity (which means a higher gas volume carrying a greater portion of the total ash particles) near the bottom of the plates. However, ash reentrainment is expected to be greater in regions of higher gas velocity—a particular concern for particles reentrained near the exit of the ESP, which would be immediately carried to the outlet ductwork, since there are no more downstream collecting sections to recollect the particles. This second consideration favors a lower gas velocity near the bottom of the collecting electrodes near the outlet of the ESP.

Combining these two considerations leads to a conjecture that the overall collecting efficiency may actually be better, because of reduced reentrainment, if the gas velocity is skewed to provide higher gas velocities in the lower part of the inlet fields, transforming to a flow with higher gas velocities near the top of the outlet fields. There is a second school of thought that recommends keeping the gas velocity at the bottom of the plate low throughout the ESP. This approach is defended by arguing that hopper reentrainment, even in the inlet fields, overwhelms the collection effect.

Some data have been presented to support both concepts, but questions remain, and several successful full-scale installations will be required to establish either approach. At this point, adopting the skewed flow approach would necessitate installation-specific evaluation. Fortunately, the concept can be evaluated inexpensively, as only changes to the gas flow control devices are required.

Advantages: The cost for flow modification is quite nominal in comparison to a rebuild, and requires only a short outage. If flow correction provides the needed performance improvement needed, it is an elegant solution.

Disadvantages: The skewed flow approach remains to be definitively field-proven, and except in unusual situations, is likely to provide only a minor incremental improvement in collection efficiency over uniform flow.

D
ESP REBUILD

Through normal aging or perhaps for other reasons such as fire or corrosion, an ESP may require rebuilding at intervals during its lifetime. Several alternatives should be considered: rebuild as is, rebuild with the same footprint but with wider plate spacing, rebuild with taller collecting electrodes, add a field in series, or a combination of these.

Whatever course you choose, gas flow should be optimized, and power controls should be replaced with digital systems (unless you have already made the upgrade to digital controls). If the auxiliary equipment has not been recently upgraded, it is almost always best to replace it.

D.1 Rebuild As-Is

Most rebuild situations involve an older ESP with collecting plates spaced 9 or 10 inches (about 250 mm) apart and with a weighted-wire discharge electrode system. Rebuilding to such an original design is an unusual situation that will only occur if the original equipment was over-designed or the coal characteristics have changed drastically from high to intermediate resistivity. Under some circumstances, however, this approach to rebuilding can be a good option. If the required collecting efficiency is easily attained by the existing design, if a large quantity of spare parts is available, or if economics dictate low investment, rebuilding to the current design may be appropriate.

Advantages: If the original design can achieve emissions goals with a sufficient safety margin, rebuilding to this design is probably the least-expensive long-term option. In addition, any spare parts can be retained or used in the project. Note that cost estimates in Chapter 5 (Table 5-2) indicate that rebuilding with wider plate spacing may be a lower-cost option. Site-specific conditions will dictate the selection. If some of the internals or power supplies can be reused, the rebuild as-is may be the correct choice.

Disadvantages: There will be no significant reductions in outlet emissions. The expense of the rebuild as-is should be carefully weighed against the cost of a rebuild that includes some decrease in emissions.

D.2 Rebuild With Wide Plate Spacing

If the internals are to be refurbished, you will probably want to upgrade to wider plate spacing, i.e., 12–16 inch (~300–400 mm) spacing rather than 9–10 inch (~230–250 mm) spacing. This upgrade calls for new power supplies and controls, because the wide plate design operates at higher secondary voltages.

Rebuilding with wide plate spacing provides about the same collection efficiency as the original design, even though the specific collecting area is reduced (by about 17% in going from a 9-inch to a 12-inch design, for example). This is because the operating voltages are higher and the space charge contribution to the collecting electric field is proportional to the wire-to-plate spacing (at a given mass loading and current density). This increase in the electric field near the collecting plate improves the collection efficiency to compensate for the reduction in SCA. Rebuilding to wider plate spacing is almost always an appropriate decision due to the advantages listed below.

Rebuilding with wider plate spacing does not require replacing the foundation. A design with 12-inch plate spacing built into the same casing originally designed for 10-inch spacing should attain the same collection efficiency. However, wider plate spacing does require rebuilding the high-voltage distribution system and purchasing new power supplies and controls, as the wider-spaced units operate at higher voltages.

In this rebuild, it also makes sense to upgrade weighted-wire discharge electrodes to a design with support frames, or to use rigid discharge electrodes (RDE), which do not need frames.

For more information on the effect of plate spacing on ESP performance, see *An Investigation of Precipitator Wide Plate Spacing*, EPRI report GS-6711, and the paper, “Performance of the Dale Station Precipitators With Increased Plate Spacing, published in *Proceedings: 7th Particulate Control Symposium*, Vol. 1, EPRI report GS-6280.

Advantages: Rebuilding with wider plate spacing offers several advantages. The weight of the internals will be reduced because the total plate area is reduced (naturally, the amount of weight reduction depends on plate thickness). Relative plate alignment is expected to be better because the allowable tolerances are greater for the wide-spaced rebuild. The wider plate spacing makes it easier to use the newer discharge electrode designs, which are more reliable than weighted wires. Current density distribution tends to be more uniform for the wide spacing situation. Moreover, there is the possibility for some improvement in collecting high-resistivity particles, as the electric field adjacent to the collecting electrode is increased from the added space charge.

Disadvantages: New power supplies will be required, and frequently the high-voltage distribution system must be rebuilt to avoid sparking.

D.3 Rebuild With Increased Collecting Plate Area

If the rebuilt ESP must attain a higher collection efficiency, then it is appropriate to increase the specific collection area (SCA). This is accomplished by increasing the plate height, adding a field in series, or both.

Rebuilding with wider plate spacing and with taller plates can increase the collecting efficiency even though the actual plate area may not be increased over the original design. The rebuild with wide plate spacing and taller plates allows the use of the original foundation, since there is a weight reduction with the wide plate design . Of course, the original plate thickness or weight per unit area must be preserved for the weight reduction to occur. The allowable amount of plate height increase is limited to approximately the proportional increase in plate spacing. Increases above this ratio may require a rebuild of the foundation.

Adding a collecting field in series will also increase the collecting plate area. Some original designs included space within the existing ESP casing for adding an extra field. These units were also built with the foundation to withstand the added weight from an additional field. The added field should be built with 12-inch or wider spacing, even if the original collecting fields are not rebuilt. If the casing doesn't have room for an extra field, then it may be possible to enlarge the casing to make room for one or more extra fields. This option is only practical if there is space for the additional casing length. It is possible to make estimates of the increased collection the added fields will produce using the computer models ESPM or ESPert. This improvement in performance can be used with the cost data in Chapter 5 of this report to determine if this option is more cost-effective than others (like COHPAC). Of course, rebuilds with taller plates and added fields can be considered together, if both are needed.

Advantages: A rebuild with increased collecting plate area improves the collection efficiency and allows the electrode structures to be modernized. If the increase involves adding a field, the sectionalization will increase and the rapping reentrainment can be reduced.

Disadvantages: Compared to less extensive rebuilds, increasing the SCA costs more and usually requires a longer outage for the rebuild.

E

POLISHING DEVICES

If the installation of taller collecting electrodes or another field in series is not an economical approach to increasing ESP collection efficiency, or if it is insufficient to achieve performance goals, then it may be appropriate to add a polishing device in series with the ESP. It may also be necessary to rebuild the existing ESP in addition to adding the polishing device, depending upon the amount of collection efficiency increase required.

The following technologies have been tested at either pilot or full scale, and have achieved emissions reductions exceeding 50%.

E.1 Compact Hybrid Particulate Collector (COHPAC)

COHPAC is an EPRI-developed technology that will provide emission levels of less than 0.03 lb/MBtu (about 30 mg/Nm^3, depending on the coal) when added downstream from an ESP that is either under-performing or designed to meet much lower emission standards. The concept is to add a pulse-jet fabric filter (baghouse) in series with an ESP currently operating with a collection efficiency in the range of 95% or higher.

Because the mass loading into the baghouse is very low, it can be operated at twice the gas-to-cloth ratio, gas-to-cloth ratio of 8 to 1 (2.4 m/min) instead of 4 to 1 (1.2 m/min) of the pulse-jet baghouse that would be needed if there were no ESP upstream; the reduced mass loading also allows less frequent cleanings. This ESP/baghouse combination produces very low outlet emissions at the cost of a relatively small increase in pressure drop through the baghouse (the typical pressure drop is about 4 to 6 inches of H_2O (1.0–1.5 kPa). All existing COHPAC units use bags made of a needled felt, Ryton, although they could easily use other filtering media such as pleated filter cartridges or ceramic filters.

There are two approaches to applying COHPAC technology. COHPAC I is based on the installation of an entirely separate pulse-jet baghouse downstream from the existing ESP, while COHPAC II replaces the outlet field of the ESP with the baghouse. COHPAC I thus has a larger footprint and requires a new foundation, but it takes advantage of the full collection efficiency of the original ESP. For COHPAC II, no new structures are required, but the collection in the outlet ESP field is lost, increasing the ash loading into the pulse-jet baghouse; the pressure drop is also greater than for COHPAC I. Given the new foundation, COHPAC I usually costs more to install than COHPAC II. Performance of both COHPAC units should be comparable to that of a conventional pulse-jet baghouse. The appropriate selection depends on site-specific factors, such as space, economics, and emissions limits.

There are two full-scale utility COHPAC installations in the United States. Both employ the first approach, a fabric filter in a separate casing. COHPAC II has only been tested at pilot scale, but results have been promising. For more information on pulse-jet fabric filters and COHPAC, see *Pulse-Jet Fabric Filters for Utility Applications*, EPRI report TR-102978, Vols. 1 and 2, and the paper "COHPAC: The Next Generation in Particulate Control Technology, Alabama Power, E.C. Gaston Units 2 and 3," in *EPRI-DOE-EPA Combined Utility Air Pollution Control Symposium: The Mega-Symposium,* TR-113187, Vol. 3.

Advantages: COHPAC can achieve higher performance standards at lower cost (usually) than an ESP rebuild. COHPAC I is expected to operate with a lower pressure drop across the collector, and COHPAC II requires no additional real estate.

Disadvantages: For both COHPAC I and II, the added pressure drop across the baghouse may require replacement of the induced draft fan to maintain full-load gas flow. An extended shutdown may be required for installation of either approach, with COHPAC II likely requiring a longer shutdown.

E.2 Wet Electrostatic Precipitator

Wet ESP (WESP) uses a flowing sheet of water to entirely cover the collecting plates in the ESP. Since the film of water serves as the collecting electrode, there is no significant reentrainment and the detrimental effects of high resistivity are eliminated. The collected material flows down the plate with the water film to be collected in the drain system.

The wet system can either be installed as a conversion of the outlet field of the existing ESP or in a separate housing downstream from the primary ESP collector. If the wet unit is installed in the existing housing, the last field of the ESP will have to be removed and replaced with equipment suitable for wet operation. This, of course, is not the case if the WESP is installed as a separate unit downstream of the dry ESP. Note that installation after the ESP rather than in lieu of the last field retains the collection capability of the last dry section and thus reduces the particulate loading into the WESP—and hence, reduces the amount of wet ash material.

WESP technology has been used for many decades in industrial applications and has been tested for power plants at pilot scale. It holds promise as a polishing unit for installations with either high resistivity or excessive reentrainment; it is also particularly applicable to plants with wet scrubbers that are emitting "blue plume" sulfuric acid mists.

Blue plume results from the condensation of sulfuric acid in a wet SO_2 scrubber system. Coal combustion produces about 700 ppm of SO_2 in the flue gas for each percentage of sulfur contained in the coal. Approximately 0.4% of the SO_2 is converted to SO_3 as the flue gas progresses from the furnace to the stack. The SO_3 converts to sulfuric acid vapor in the presence of the moisture in the flue gas, remaining as a vapor until the flue gas temperature is reduced to the acid dew point.

The flue gas temperature drops below the acid dew point either in the ESP following the air heater or more probably in the wet scrubber. When the acid condenses, it forms a very fine liquid aerosol of sulfuric acid droplets with a mass mean diameter probably less than 0.5

microns. Droplets of this diameter are not collected in the wet scrubber, but pass through to be emitted to the atmosphere.

WESP will effectively collect this fine acid fume. Experiments with a modestly sized wet ESP with an SCA of about 50 ft^2/kcfm (9.8 m^2 per m^3/s)—operating downstream from a dry ESP with a collection efficiency in the high 90% range—attained a collection efficiency of 90 to 95%. In addition to removing over 90% of the remaining ash, the ESP field removed approximately 20% of the SO_2 and over 50% of the SO_3.

The installation of a WESP adds to the complexity of the ESP system, as the water from the plate irrigation system requires disposal. If the ESP uses a sluice system for ash disposal, the WESP could probably be connected to the existing ash disposal system. If not, a new disposal system would be required. More details about this technology can be found in *Water Treatment for Wet Electrostatic Precipitators,* EPRI report TR-108926.

Advantages: A wet ESP system downstream from a dry ESP will significantly reduce emissions, eliminate rapping reentrainment, and effectively remove any condensed acid fume formed in the duct system. Acid plumes are more prevalent in plants with wet scrubbers.

Disadvantages: Although this option is relatively cost-effective, it is new to the utility industry and hence there is not a large body of data on which to base reliability projections. Water source and water disposal issues have to be carefully addressed. If there is a wet scrubber currently in use, WESP effluent can probably be added to the sludge.

E.3 ElectroCore™ Separator

This EPRI-sponsored technology from LSR Technologies is an electrical augmentation to a special cyclonic separator device known as a Core Separator. The Core Separator is a non-collecting cyclone intended to enrich the particle concentration in a recirculated gas stream from the portion of the exhaust gas passing to the atmosphere. Separation is achieved by inertial forces on the particles, the same as in conventional cyclonic collectors.

Cyclonic collectors typically provide high removal efficiencies for particles larger than 5 to 10 microns, but very poor collection for submicron particles. The ElectroCore™ separator adds an electrical force to the inertial force to increase separation efficiency for submicron particles.

An ElectroCore installation operates by passing flue gas from the existing ESP through a precharger to electrically charge the particles in the gas stream. The gas then passes into the ElectroCore separation chamber where an electrode system placed in the center of the Core Separator is energized with a high voltage to establish an electric field to drive the charged particles towards the outer portion of the ElectroCore Separator. The outer portion of the gas stream becomes enriched with particles, while the central portion has the majority of the particles removed. The flow through the separator is divided into a high dust loading stream (about 10% of the flow) and a low dust loading stream that is exhausted to the plant's existing stack. The high-load stream is recycled into the inlet of the primary particulate collector, where the particles are again collected for removal.

Pilot-scale tests suggest collection efficiencies in the high 90% range for particles from a power station ESP. Full-scale tests are planned. For more information on this technology, see the paper, “Electrostatically Enhanced Core Separator System,” in *EPRI-DOE-EPA Combined Utility Air Pollution Control Symposium: The Mega-Symposium*, TR-108683, Vol. 3.

Advantages: The ElectroCore device shows promise to be a competitively priced device to install downstream from an ESP that is not providing the removal efficiency required. The device operates with a pressure drop of less than 1 inch (2.5 cm) of water column. The electrical power consumption is expected to also be low.

Disadvantages: A portion of the exhaust gas from the separator is re-introduced into the inlet of the ESP. This recirculation of gas reduces the effective specific collecting electrode area of the ESP, typically by about 10%.

E.4 Laminar Flow Fine Particle Agglomerator™

As a result of fundamental differences in operation, a laminar flow ESP could attain a collection efficiency of 100% where a turbulent flow ESP of the same size would only attain a collection efficiency of about 63%. Therefore, it would be highly desirable to construct industrial ESPs with laminar flow, if practical. A laminar flow ESP requires a gas flow Reynolds Number in the low thousands, which demands very uniform gas flow inside very narrow gas passages. These conditions essentially preclude the flow of corona current and the irregularities in the boundary caused by particle collection. Thus, a truly laminar flow ESP big enough to use to collect fly ash from a power plant is probably not practical.

The Laminar Flow Fine Particle Agglomerator™ was developed from attempts to develop a laminar flow ESP. The limitations discussed above prevented this development, but the experimental results suggested that a similar device could be used to agglomerate particles, making them much more easy to collect. Even fine particles—the limiting factor for ESP collection efficiency—can be collected in a near laminar flow device with close to 100% efficiency. Once collected, the particles are reentrained, but upon reentrainment, they do not break up into their original particle size distribution. Rather, the reentrained particles stick together in clumps with mass mean diameters in the 5 to 10 micron range, which are a size range that is collected with a much higher efficiency than the original fine particles.

The installation requires the use of a particle charger ahead of the laminar flow collecting device. Hence, the device is installed in place of an inner field of the ESP, e.g., the second of a three-field ESP or the third of a four-field ESP. The previously charged particles (i.e., bearing residual electrical charge from the upstream field) are collected in a static electric field, with no corona flow (i.e., under near laminar flow conditions). The collected particles are reentrained and flow into the outlet field, where they are captured and fall into the ash hopper.

This new technology has undergone significant testing and is approaching commercial maturity.

Advantages: A successful installation of the Laminar Flow Fine Particle Agglomerator should significantly increase the collection efficiency of a marginally designed ESP.

Disadvantages: The disadvantages are that the device must be built to close tolerances, which must be maintained to preserve laminar flow conditions. The experimental database is also quite limited.

F
NEW PRIMARY COLLECTING SYSTEMS

The expected useful life of the plant will guide selection of the best upgrade option for particle control. If the expected life of the generating system is sufficiently long, replacement of the existing ESP may be necessary. This approach is correct when the required collection efficiency is much greater than the existing equipment is capable of providing.

If the collection efficiency of the existing ESP is much lower than desired or if the mechanical condition is very poor, a complete replacement of the existing ESP with another particle-collecting device should be considered. Alternatively, if the existing ESP is a hot-side unit, the choice may be to convert it to cold-side operation. A broad range of options is available if a complete replacement is planned.

Naturally, the general condition of the existing ESP plays a part in the selection of options. If the ESP is merely too small to provide the level of control required but is in good mechanical and electrical condition, the original ESP may be retained in service with an additional collector added, either in series or parallel. The design selection study should provide the information needed to make this determination.

F.1 Install a New ESP

A prime option for improved collection efficiency is to install a new ESP. This could be a larger ESP replacing the old one, or an additional unit installed with the existing precipitator, either in parallel or downstream. Whatever the desired configuration, the existing ESP can provide valuable data to guide the design for the new unit. The electrical operating conditions, rapping characteristics, and fly ash parameters are readily determined from measurements conducted on the existing unit. These data, along with the use of an ESP computer model, will provide design data that can be used with confidence in establishing the design characteristics for the new ESP.

If the electrical conditions in the existing ESP were good and the performance of the existing unit was near to the expected performance when this ESP was in good operating condition, then a new ESP may be a good upgrade choice. This set of circumstances makes it possible to design the new ESP with confidence and minimizes the risk associated with this option.

Retaining the existing ESP in service with the new unit added in series (or parallel) is also a possible approach. The new unit can be essentially completed while the power station remains in service. The new control device can then be put into service during a relatively short shutdown period, avoiding the costs of an extensive outage. Taking advantage of the collection efficiency of the existing ESP, assuming the existing ESP is still in good physical condition, makes it possible to reduce the size of the added ESP. The location for the new ESP will depend upon the available real estate and the conditions within the existing ESP that are limiting performance and cost. If the existing ESP was built with gas velocity exceeding about 6 ft/min (1.8 m/s), there is a reasonable probability of excessive reentrainment. This condition would suggest a parallel configuration. If there is little evidence of reentrainment, the series unit will probably attain a somewhat greater collection efficiency because of sectionalization considerations.

For more information on new ESPs, see *Electrostatic Precipitator Guidelines, Vol. 1: Design Specifications,* EPRI report CS-5198; see also *Precipitator Performance Estimation Procedure,* EPRI report CS-5040.

Advantages: The new system can be assured of proper design thanks to directly relevant data from the existing ESP. The measured performance from the operating unit together with an ESP computer model will yield a new design that will have a very high probability of meeting the performance requirements.

Disadvantages: A complete replacement may require an extended outage for construction and tie in. If the fly ash from the station has very high resistivity, an extremely large ESP will be required, unless the replacement also incorporates flue gas conditioning.

F.2 Convert Hot-Side ESP to Cold-Side

Conversion of a hot-side ESP to cold-side operation is an option for units experiencing high resistivity caused by sodium depletion. A hot-side ESP typically operates with a flue gas temperature in the range of 700°F (370°C). The fly ash is removed from the flue gas stream before passing through the air heater. Hot-side ESPs were usually built with an SCA of about 300 ft^2/kcfm (60 m^2 per m^3/s) at the normal operating temperature.

If the flue gas ductwork is modified to have the flue gas pass through the air heater before passing through the ESP, the gas temperature will be reduced to about 300°F (150°C). The reduction in gas temperature decreases the gas volume by the ratio of the absolute temperature of the flue gas. A reduction in flue gas temperature from 700° to 300°F (370° to 150°C) decreases the gas volume to about 65% of the original volume. Since the original collecting electrode area is retained in the conversion, the SCA increases from the original 300 (~60 m^2 per m^3/s) to about 460 (~90 m^2 per m^3/s). The actual flue gas volume will be somewhat greater than expected because of some air in leakage across the seals in the air heater, and perhaps others.

In some instances, the simple conversion from hot to cold-side operation will not provide the required increase in collecting efficiency. If the ash resistivity is very high at the cold-side temperature, flue gas conditioning may also be required. Laboratory measurements of resistivity during the study phase of the project can provide the information to evaluate this need, prior to conversion.

Advantages: The advantage of converting from hot side to cold side is that the ESP can be retained essentially as-is with only the gas flow redirected. Conversion costs should be significantly less than for constructing a new ESP.

Disadvantages: If the ash resistivity is very high, the converted ESP may still require resistivity conditioning. The original design likely had 9-inch (~230 mm) plate spacing and weighted wires, so an internal rebuild may also be needed.

F.3 Replace ESP With Fabric Filter

When the ash resistivity is in the range from 10^9 Ω-cm to something less than 10^{12} Ω-cm, the ESP will usually be the less expensive option. However, as the ash resistivity increases beyond these values, the fabric filter (baghouse) will likely become the more economical option.

Reverse-gas or shake-deflate fabric filter designs (sometimes referred to as low-ratio baghouses) are proven technologies for coal-fired power stations. These baghouses were installed in the United States starting in the 1970s for power stations anticipating high-resistivity fly ash. These fabric filters require a significant amount of area for construction, as the gas-to-cloth ratio is typically about 2 ft/min (0.6 m/min) to minimize the pressure drop across the filter.

Pulse-jet fabric filters are now considered an appropriate technology for U.S. utility installations. They have been in use in Australia and perhaps other locations for several years prior to their introduction in the U.S. The pulse-jet filter is typically built with a gas-to-cloth ratio of 4 ft/min (1.2 m/min) or greater.

Selection of fabric filter technology should be based on cost considerations, as both designs should provide very good collection efficiencies.

When adding a fabric filter (baghouse), there is the question of whether or not to retain the ESP in service, either in series or parallel. Generally, the ESP should be retained unless it would require an extensive rebuild to operate properly; economics should guide this decision. If retained in series, the installation becomes similar to COHPAC I, with either a pulse-jet or reverse-gas type of fabric filter. If the fabric filter is added in parallel, the effective SCA of the ESP will be increased, as a significant portion of the flue gas will bypass the ESP to the new fabric filter.

Another option is to gut the existing ESP internals and use the existing casing to house a pulse-jet fabric filter. A pulse-jet fabric filter usually has somewhat higher operating costs than either an ESP or reverse-gas fabric filter system, because of the greater pressure drop across the filter. The savings in construction costs, from using the ESP foundation and casing to house the pulse-jet baghouse, may more than compensate for the increased operating costs. For more information on pulse-jet fabric filters, see *Pulse-Jet Fabric Filters for Utility Applications*, EPRI report TR-102978, Volumes 1 and 2, and *Fabric Filters for the Electric Utility Industry*, EPRI report CS-5161, Volumes 1 through 5.

Advantages: Fabric filters achieve extremely high collection efficiencies regardless of ash resistivity. The outlet loading and opacity will almost always be lower than legal limits. Since the system is usually insensitive to ash properties, a variety of coals can be burned without emissions problems.

Disadvantages: The increased pressure drop across the fabric filter sometimes requires upgrading the induced draft fan. The fabric filter will also cost more than an ESP for most installations where the ash resistivity is less than about 5×10^{11} Ω-cm. Fabric filters have not provided reliable operation in applications where operation below the acid dew point is experienced on a regular basis.

G

EFFECTS OF SO_2 CONTROL TECHNOLOGY

The adoption of a new sulfur oxide removal technology can modify the ash loading and ash characteristics into an ESP. EPRI has conducted extensive studies of the use of SO_2 removal equipment and the influence each technology had on the operation of either an ESP or fabric filter. The results of this study are reported in *Guidelines for Particulate Control for Advanced SO_2 Control Processes*, TR-104594, December 1994. This report discusses the effects of converting a conventional boiler to fluidized-bed combustion (AFBC or CFBC) operation, sorbent injection in the furnace or in the ducts ahead of an ESP, and the addition of a spray dryer ahead of the ESP. If SO_2 control equipment is installed at the power plant, it is strongly recommended that these guidelines be consulted for the expected influence on the fly ash mixture that will be collected in the upgraded particulate collector.

Either a wet or dry scrubber will collect some portion of the fly ash particles, but the collecting efficiency for particles passing through the ESP will be very small, except possibly for the reentrained agglomerates. This low collection efficiency results from the small size of the particles that escape an ESP and the relatively low collection efficiencies that a mechanical collector, in this case a scrubber, has for fine particles.

When a wet scrubber is installed on a station burning intermediate to high sulfur coals (S = 1.5% or more), an SO_3 or H_2SO_4 plume will probably be formed. The scrubber will likely condense any sulfuric acid vapor present in the gas stream as the flue gas temperature falls below the acid dew point while passing through the scrubber. The particle size distribution of the acid mist has a mass mean diameter of less than 1 micron. Particles or droplets of this small size are not collected with any significant percentage in a scrubber.

If the scrubber is installed before the ESP, some flue gas reheating is required to avoid ash deposit formation in the ESP. Reheat can be accomplished by either bypassing a portion of the flue gas around the scrubber to remix or by actual heating the flue gas. Bypassing and remixing is probably the low-cost choice.

However, the wet scrubber is typically installed downstream of the ESP. The sulfuric acid vapor passes through the ESP without collection (since it is still a vapor at the ESP operating temperature). As the ESP is a particle collecting device, it is ineffective for collecting vapors. One solution to the acid mist problem is to inject ammonia into the gas stream ahead of the ESP to react with the acid vapor to form ammonium sulfate and ammonium bisulfate. These particles can usually be collected reasonably well in the ESP. However, the fairly high concentration of fine particles poses a challenge to the ESP. The ammonium sulfate–bisulfate fume becomes electrically charged upon entry into the ESP. These charged particles represent a space charge that tends to quench the current in the inlet section of the ESP.

An ESP upgrade may be necessary to maintain particle emissions below allowable values if a wet scrubber is added to an existing ESP system. Sometimes installing a very aggressive discharge electrode with high-current, low-voltage characteristics makes it possible to "push through" the space charge (i.e., operate at reasonable voltage and current levels in spite of the space charge).

With the exception of furnace sorbent injection, installation of SO_2 controls upstream of the ESP will reduce the fly ash resistivity. A wet scrubber may reduce the ash resistivity to the point that electrical reentrainment will occur in the ESP, reducing the ESP collecting efficiency. A dry scrubber will also add to the mass loading into the ESP, because of the carry-over of sorbent particles from the spray dryer evaporation tower. The ESP will be required to collect these particles in addition to the original fly ash.

Sorbent injection into the furnace—though not a likely choice for SO_2 control—has an extreme adverse effect on the ESP, unless water activation is used in conjunction. Injection of hydrated lime or limestone into the furnace produces a very high-resistivity ash, which is difficult to collect in an ESP.

Coal switching and blending will also present a challenge to the ESP. Plants switching or blending coals typically will have an ESP designed for high-sulfur, low-resistivity fly ash. Changing to burning a much lower-sulfur coal, either a blend or an entirely new coal, will almost certainly produce an ash that is much higher in resistivity than that from the original high-sulfur coal. If the ESP was performing well enough to maintain emissions below the allowable limits, gas conditioning is probably an appropriate solution to this emissions problem. Other upgrade technologies may also apply, but if the only change was in the ash resistivity, conditioning is a probable solution. All of these effects are discussed in detail in EPRI report TR-104594.

Advantages of Wet Scrubber: The advantages of adding wet scrubbers are that the existing coal can continue to be burned, the plant personnel are familiar with the fuel characteristics and the supply is established. The plant ESP people are familiar with the collecting characteristics and have a historical record of the ESP behavior.

Disadvantages of Wet Scrubber: The primary disadvantage is the probability of generating a sulfuric acid plume when the scrubber is commissioned. Even though the same amount of sulfuric acid vapor was present in the gas stream before the addition of the scrubber, the flue gas exited the stack at a temperature above the acid dew point. The sulfuric acid vapor had some time to disperse before condensation, likely avoiding the formation of the "blue plume" formed in the scrubber.

Advantages of Coal Switching: The advantage of switching or blending coal is that no SO_2 control equipment must be purchased. The trade-off is the cost of the expected ESP upgrade in comparison with the cost of SO_2 control equipment. Another advantage is the opportunity to upgrade the ESP, if there were some problems before.

Disadvantages of Coal Switching: The disadvantages include the requirement to upgrade the ESP to handle the higher resistivity ash and to lose the historical data pertinent to the ESP behavior. The ESP staff will have to start over in developing the background information on the ESP.

ICESP X – Australia 2006
Paper 6A2

ENHANCED FINE PARTICLE COLLECTION USING THE INDIGO AGGLOMERATOR

**RODNEY TRUCE[1], JOHN WILKINS[1], ROBERT CRYNACK[2]
AND WALLIS HARRISON[3]**
[1]Indigo Technologies (Australia)
[2]Indigo Technologies (US)
[3]Particulate Control Technologies

ABSTRACT

Fine particles are a major health issue as they remain suspended in the atmosphere for extended periods, are able to penetrate deep into the human lung and contain significant concentrations of heavy metals, such as Arsenic. They are also a significant component of the smog that limits the visibility in many cities and even in some national parks plus scientists believe they have an effect on global weather patterns. The Indigo Agglomerator enhances fine particle collection by attaching the fine particles to the larger particles. These large agglomerated particles are easily collected in existing control devices, such as electrostatic precipitator, fabric filters, scrubbers and cyclones. This paper concentrated on PM2.5 particles, that is particles less than 2.5um in diameter, including data that was collected on particles down to 50nm in diameter. It was found that the reduction in fine particle emission from an electrostatic precipitator provided by installing an Indigo Agglomerator increases with reducing particle size from a factor of 5 at 2um to a factor of 10 at 100nm. Reductions of this magnitude will have a significant effect on the impact of fine particles on both visibility and health. It will also result in a reduction in heavy metal emissions.

THE FINE PARTICLE PROBLEM.

Extensive research has been carried out on the health effects of Particulate Matter and it is universally accepted that the main cause of health problems are the PM2.5 particles with a diameter less than 2.5um, by current convention known as fine particles. The EU Working Group on Particulate Matter in its Second Position Paper on Particulate Matter recommended that PM2.5 should be used "as the principal metric for assessing exposure to particulate matter". This was based on a report by the World Health Organization identifying PM2.5 as the key component of particulate that impacts on health issues.

Although small in terms of mass, the sub-micron fraction contains a very high proportion of the heavy metals, which are initially volatilized in the furnace area and then condense in the cooler region of the plant. This condensation will coat the surface of existing particles and form some fine particles. Because most of the surface area is in the fine particles, this is where most of the heavy metals condense. Also the surface area to volume is high in fine particles, so the concentration of the condensed heavy metals will be higher in the fine particles. The sub-micron particles are respirable and in passing into the lungs can be retained in the alveoli, which are small sacks through which oxygen is extracted by the blood stream and carbon dioxide released. Any heavy metals particles reaching the alveoli can eventually become absorbed by the blood stream and being accumulative can lead to various health problems.

The US EPA has carried out a number of studies that identify the following health issues, (see www.epa.gov/ttn/oarpg/naaqsfin/pmhealth.html):

- Premature death;
- Respiratory related hospital admissions and emergency room visits;
- Aggravated asthma;
- Acute respiratory symptoms, including aggravated coughing and difficult or painful breathing;
- Chronic bronchitis;
- Decreased lung function that can be experienced as shortness of breath;
- Work and school absences.

The EPA believes that reducing fine particle ambient air quality levels can:

- Save 15 000 lives per year;
- Reduce hospital admissions by thousands each year due to reduced heart and lung diseases;
- Improved visibility.

There are two factors that cause the greatly increased contribution of fine particles to the plume visibility, which is what is measured by Opacity:

- The first factor is the increase in obscuration of a given mass of particles as the particle size reduces. This is because the mass is dependent upon volume, which is proportional to the cube of the particle diameter, while the obscuration is proportional to the cross sectional area, which is proportional to the square of the particle diameter. For given mass of particles, as size reduces from say 10 microns to 1 micron, the amount of obscuration will increase by a factor of 10.
- The second factor contributing to the increased obscuration of fine particles is the fact that white light has a wave length of about 0.8 microns. Thus particles about this size

will have a significantly increased obscuration due to refraction of the light. This results in these particles being over three times as visible.

Thus the emission of 0.8 micron particles will be over thirty times as visible as the emission of the same mass of eight micron particles. This effect is shown in Figure 1, a graphic from a simulation of the Watson Precipitator using the EPRI ESPM performance modeling program. It can be seen that although the majority of the particulate mass is in the 5um to 10 um size range the main contributor to the plume visibility or Opacity are the 0.5um to 1 um size particles. It is these fine particles that also contribute most to the reduced visibility in our cities and nature reserves.

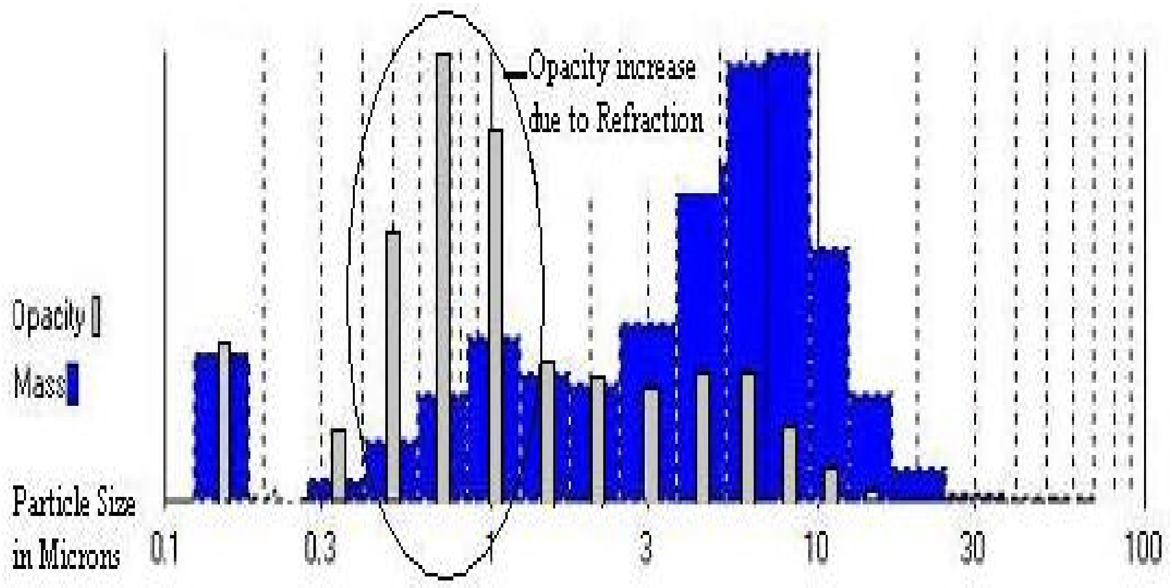


Figure 1. - EPSM Model estimates of Opacity and Mass Emissions

Finally there is increasing evidence that fine particles are a major contributor to global warming, generally referred to as the Greenhouse Effect. Scientists carrying out research in this area suggest that up to 30% of global warming may be due to fine black particles carried into the upper atmosphere.

THE ELECTROSTATIC PRECIPITATOR PROBLEM.

The electrostatic precipitator is very efficient (>99.9%) at collecting large particles, those greater than 10um, but as the particle size falls below 2um the electrostatic precipitator efficiency falls off dramatically. In extreme cases the collection efficiency can drop below 50% but will generally be less than 90% for particles between 0.5um and 2um. This is greater than two orders of magnitude (that is over 100 times) increase in the emission of this particle size range.

A typical electrostatic precipitator dust emission for particle sizes from 0.05um to 10um is given in Figure 2. This data was collected using two particle size measurement instruments, namely:

- The Process Metrix, Model PCSV-P, dual beam forward scatter laser particle size analyzer was used to measure particle size distribution from 0.5um to 50um. This analyzer has a water cooled probe that is inserted into the gas flow to measure the particles suspended in the gas. The particle size was adjusted slightly, a factor of 0.7 was applied, on the data collected by the PCSV analyzer so that the data coincided with the SMPS analyzer data, see Figure 2.

- Sub-micron particle tests were carried out at Plant Watson by the Southern Research Institute using a TSI Model 371A SMPS Analyzer, which uses electrostatic mobility to measure particle distribution from 0.03um to 0.85um. The TSI Model 371A SMPS Analyzer uses an extraction system that removes the larger particles followed by an electrostatic mobility based particle size selector that is used to scan and count the sub-micron particles.

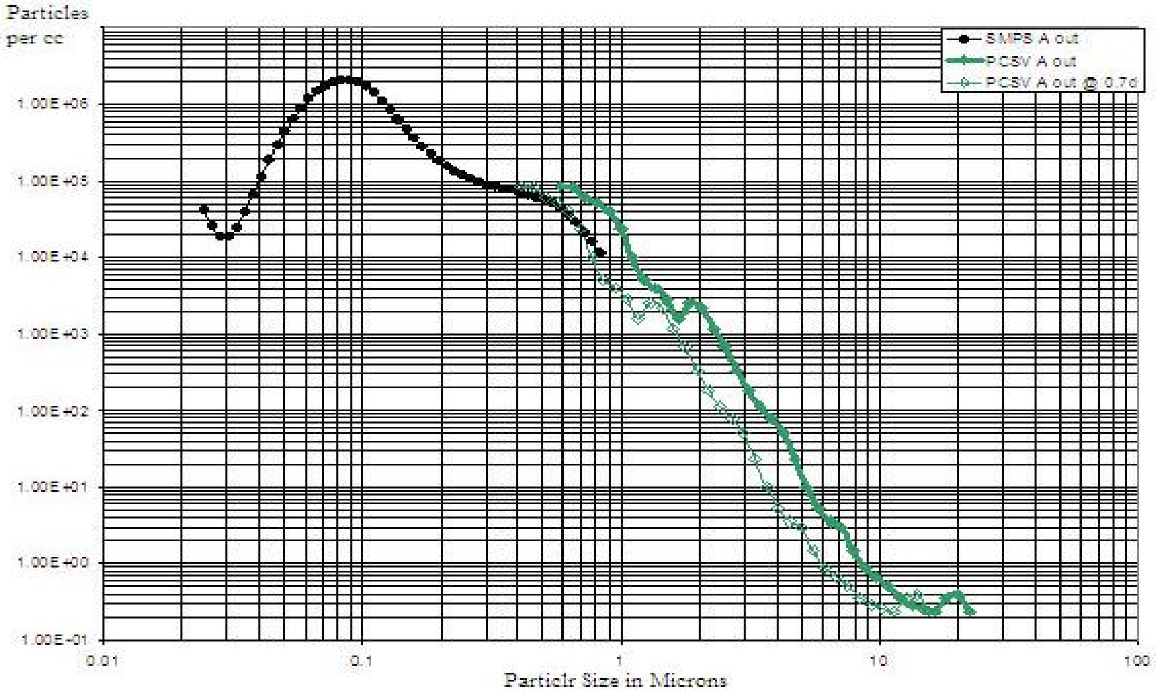


Figure 2. - Electrostatic Precipitator Emissions.

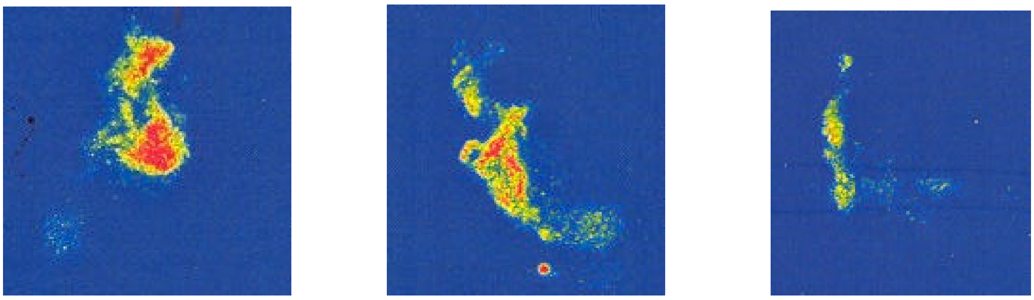
The above graph shows the number of particles per cubic centimeter that the electrostatic precipitator emissions are worst in the particle size range where the particles are most visible and most dangerous for human health, namely from 0.2um to 2um. Because of their small size, these particles will have a very low mass but a very high visibility. Electrostatic precipitator mass emissions of less than 10mg have been measured using the US Method 17 at Hammond Power Station while still measuring Opacity levels approaching 20%. Opacity levels below about 8% are normally invisible to the human eye. This shows that very visible plumes can result from high fine particle emissions even with extremely low mass emissions.

THE INDIGO AGGLOMERATOR SOLUTION

The Indigo Agglomerator is a new technology initially developed five years ago in Australia. It has been tested on a range of Australian, U.S. and South American coals with significant success in reducing fine particles emissions. The Indigo Agglomerator is installed in the inlet duct immediately prior to the electrostatic precipitator. Fine particles entering the Indigo Agglomerator are attached to the larger particles by a combination of electrostatic and fluidic processes. These large agglomerates are then easily collected in the electrostatic precipitator that follows the Indigo Agglomerator.

The Indigo Agglomerator utilizes two patented processes that cause the fine particles to attach to the large particles, which are easily captured by the electrostatic precipitator. The first process is the Fluidic Agglomeration Process (FAP), a physical process that occurs without the need for electrical energisation. The Bipolar Electrostatic Agglomeration Process (BEAP) requires electrical energisation to charge the particles. It is the combination of these two processes that result in the massive reduction in fine particles shown in the test data.

The Fluidic Agglomeration Process (FAP), which uses enhanced fluidic based particle size selective mixing to increase the physical interaction between the fine particles and the large particles. This increased interaction vastly increases collisions between the fine and large particles resulting in the formation of agglomerates, which significantly reduces the number of fine particles. Extensive testing at the University of Adelaide using Laser Induced Fluorescence (LIF) has confirmed that FAP greatly reduces the number of fine particles. One micron water droplets, doped with a chemical that fluoresces when it passes through a laser sheet, were introduced into the gas flow in a wind tunnel. The intensity of the fluorescence, which is proportional to the total volume of fine particles passing through the laser sheet, was measured using a digital video camera with a filter set at the wavelength of the fluorescence. A computer was used to analyze this video data by averaging over time then scaling and color coding the fine particle spatial distribution from blue, indicating no fine particles, through the spectrum to red, as the number of fine particles increases. Larger un-doped droplets, of about ten microns, could be injected as required but appear blue in the LIF analysis due to the filter. When the fine droplets collide with the large droplets they are absorbed and cease to fluoresce, due to the high dilution of the un-doped large droplets.



(a) Fine Particles Only

(b) Fine and Large Particles

(c) Fine and Large Particles with FAP

Figure 3. - Color Coded LIF Analysis of Fine Particle Mass Density
Color Code - Blue - no 1um droplets
Red – maximum concentration of 1um droplets

Figure 3a, the color coded distribution (Blue - no 1um droplets through to Red - maximum concentration of 1um droplets) of fine droplets without any large droplets or FAP, is the base condition for fine droplet mass comparison. Figure 3b, the distribution of fine droplets with large droplets injected but no FAP, shows increased fine droplet dispersion but little change in total fine droplet mass. Figure 3c, the distribution of fine droplets with large droplets injected and FAP operating shows a greatly reduced fine droplet mass. This data proves FAP greatly increases the collisions between fine and large droplets thereby significantly reducing the number of fine droplets. The percentage of collisions that result in agglomeration is, as yet unknown, but site test have shown FAP reduces fine particle count by more than half on the full size installation.

The Bipolar Electrostatic Agglomeration Process (BEAP) uses two key processes to reduce fine particle emissions. A Bi-polar Charger is used to charge half of the dust with a positive charge and half negatively. The Bipolar Charger has a series of alternating positive and negative parallel passages that the gas and dust pass through to acquire a positive or negative charge. The second key process is a specially designed size selective mixing system that causes the fine positive particles to be carried by the gas and mixed with the large negative particles emitting from the adjacent negative passage. The mixing system also causes the fine negatively charged particles to mix with the large positive particles, as shown in Figure 4. Because electrostatic force decreases rapidly with distance, the mixing system is essential as it brings the fine particles close to the oppositely charged large particles so that the electrostatic force is sufficient to cause them to attach forming agglomerates. Plant tests have shown that BEAP also reduces fine particles by more than half on the full size installation.

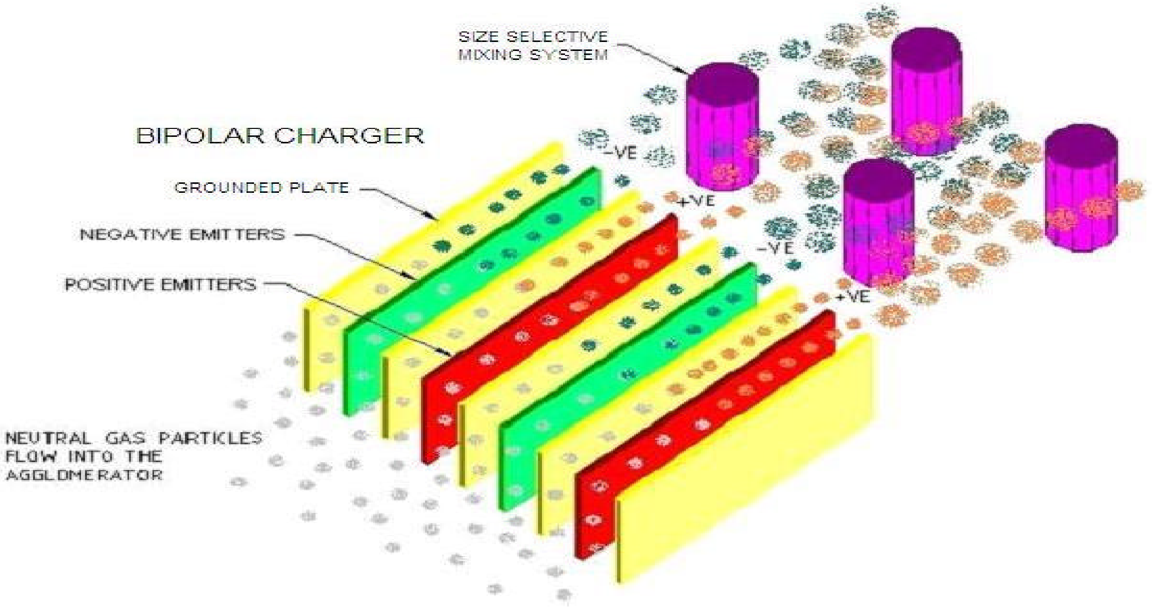


Figure 4. - The Bipolar Electrostatic Agglomeration Process (BEAP)

Test results from Watson Power Station

Tests performed at the Indigo Agglomerator trial installation at Watson Power Station show a huge reduction in fine particle emissions when an Indigo Agglomerator was installed in front of an existing electrostatic precipitator. Watson Power Station is a 250MW wall fired pulverized coal boiler with two air-heaters connected to two separate electrostatic precipitators. An Indigo Agglomerator was installed in front of the “B” electrostatic precipitators and particle size tests were performed on both “A” and “B” electrostatic precipitators. Figure 5 shows a comparison of the Slip, the percentage of the dust entering the electrostatic precipitator that is emitted to the atmosphere, from both “A” and “B” electrostatic precipitators, for particle sizes from 0.05um to 10um. These tests were performed using the two probes described above.

The collection efficiency of “A” electrostatic precipitator decreases rapidly below 2um particle size, as indicated by the increasing slip (Slip%=100-Efficency%). Over 50% of the particles in the key 0.6um to 1um size range are not captured by "A" electrostatic precipitator. The "B" electrostatic precipitator captures 90% of those particles, resulting in a greatly reduced visible emission as measured by Opacity.

It can be seen that the reduction in fine particle emissions provided by the Indigo Agglomerator increases with reducing particle size, as indicated by the improvement trend line in Figure 5. This shows a 60% improvement at 10um increasing to 75% at 1um and 90% at 0.1um. Thus, the fine particle emission reduction provided by the Indigo Agglomerator increases from a factor of 2 at 10um to a factor of 10 at 0.1um. The average reduction in PM2.5 emissions is about a factor of 5 or 80%.

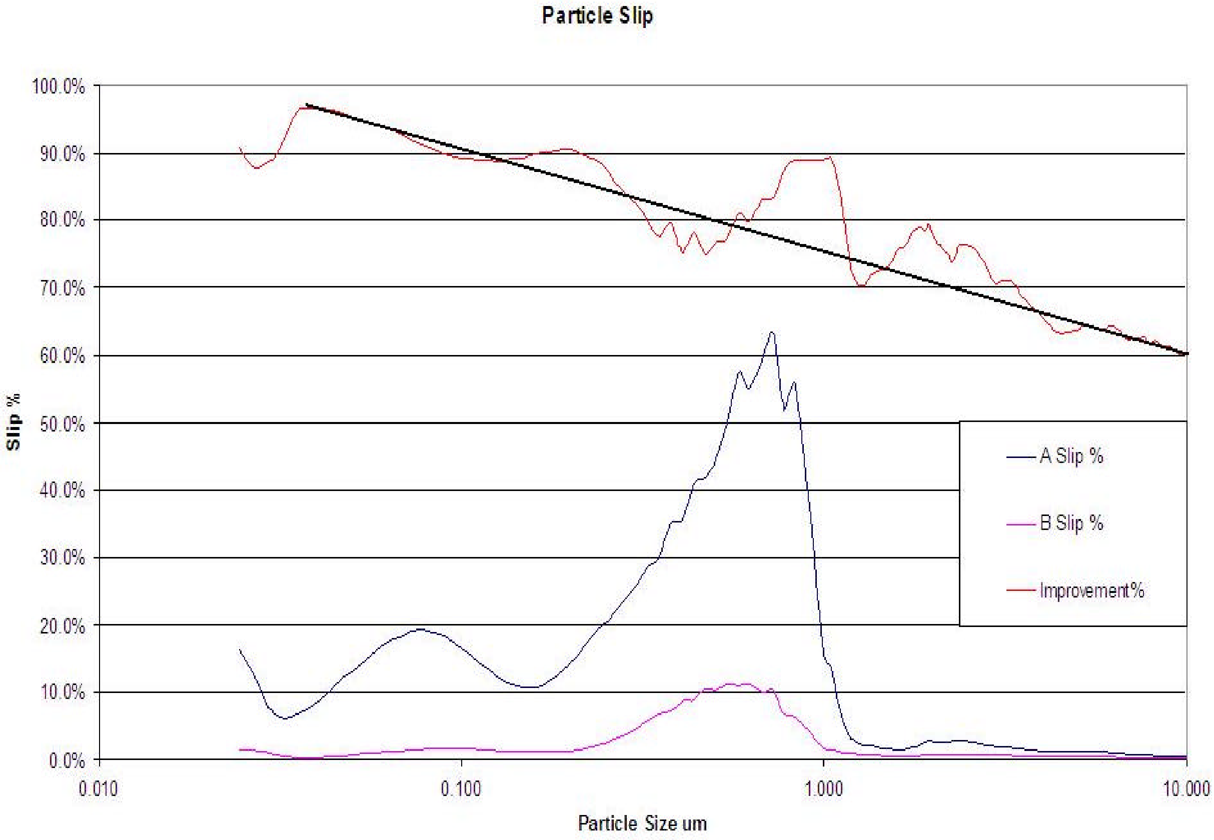


Figure 5 - Comparison of dust emitted to the atmosphere with and without the Indigo Agglomerator

Test results from Tarong Power Station

Tests performed at Tarong Power Station show an increase in fine particles collected in the electrostatic precipitator hoppers and an increase in Arsenic concentration in the collected dust on Pass 1, with an Indigo Agglomerator installed before the electrostatic precipitator, compared to Pass 2, without an Indigo Agglomerator. Both Pass 1 and Pass 2 treat gas from Air-heater A while Pass 3 and Pass 4 treat gas from Air-heater B. Each electrostatic precipitator pass at Tarong Power Station has six Zones or Sections with a separate hopper for each. Ash was taken from hoppers 1, 2, 4 and 6 for particle size and/or Arsenic concentration measurement are representative of the dust collected in the 1, 2, 4 and 6 electrostatic precipitator zones.

Figure 6 shows the particle size distributions for Hoppers 1, 4 and 6. The larger particles are mainly captured in the in the front of the electrostatic precipitator. Most of the larger particles are found in the front hopper, Hopper1, however there are more fine particles captured in this hopper on Pass 1. The fine particles are captured in the in the rear of the electrostatic precipitator, as is evident from the rear hopper particle size distribution. There are less large particles in the rear hoppers of Pass 1 but there are more fine particles. The agglomeration of the fine particles to the larger particles will result in the larger agglomerates being captured in the front of the Pass 1 electrostatic precipitator with the Indigo Agglomerator, hence the reduced number of larger particles in the rear hoppers. The agglomeration of fine particles to slightly larger particles will increase the number of fine particles collected in the rear of the electrostatic precipitator, hence the increased number of fine PM2.5 particles in the rear hoppers.

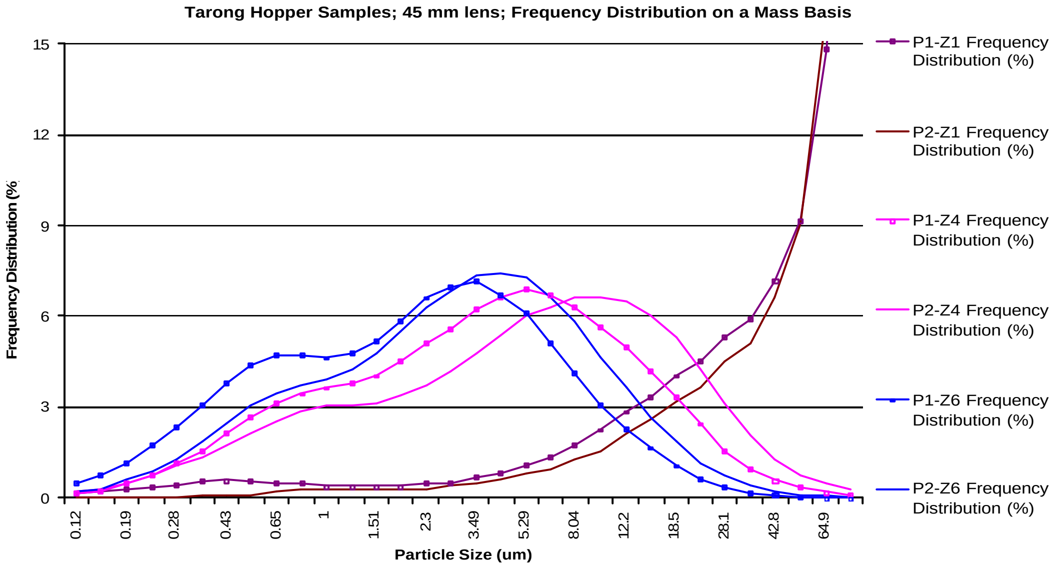


Figure 6 – Hopper Particle Size Distribution

Arsenic vaporizes in the combustion process but condenses in the colder rear section of the boiler. The condensation will preferentially form on the surface of existing particles on the basis of surface area. Some may also condense to form ultra-fine particles. Because the vast majority of the surface area is in the fine particles, most of the condensed Arsenic ends up in the fine particles. The concentration of Arsenic will also be higher in the fine particles because the ratio of surface area to volume is inversely proportional to particle size.

Table 1 shows the Arsenic concentration in the ash samples from Hoppers 1, 2, 3 and 4. The Arsenic concentration is consistently higher on the Pass 1 electrostatic precipitator, with the Indigo Agglomerator, as this electrostatic precipitator consistently collects more fine particles, as shown in Figure 6. As the fine particles are preferentially collected in the rear of the electrostatic precipitator, the concentration of Arsenic is largest in the rear hoppers. The increase in the fine particle collection on Pass 1 provided by the Indigo Agglomerator has less of an impact on the Arsenic concentration because there is already a high concentration of fine particles and Arsenic. The electrostatic precipitator preferentially collects large particles in the front section, where most of the dust is collected (up to 90%), hence the concentration of Arsenic is lower, due to the dilution of the large particles, and the improvement is lower, due to the large mass of dust collected.

The improvement is greatest in Hopper 2, which represents the dust collected in Zone 2 of the electrostatic precipitator. The amount of dust collected in electrostatic precipitator Zone 2 is a lot less, up to an order of magnitude, than that collected in Zone 1 and therefore there is a lot less dust in Hopper 2 than Hopper 1. The increase in fine particles and, hence Arsenic concentration, is therefore more significant.

	Hopper 1	**Hopper 2**	**Hopper 4**	**Hopper 6**
ESP Pass 1	**2.98 mg/kg**	**7.94 mg/kg**	**20.3 mg/kg**	**24.7 mg/kg**
ESP Pass 2	**1.7 mg/kg**	**2.78 mg/kg**	**14.1 mg/kg**	**20.2 mg/kg**
Pass 1 Increase	**75%**	**186%**	**45%**	**22%**

Table 1 – Arsenic Concentration in the Ash

CONCLUSION

Fine particles, in particular PM2.5, are an acknowledged health hazard and government environmental protection organizations around the world are now focusing on controlling the emission of these fine particles. Electrostatic precipitators are poor collectors of fine particles, particularly between 0.5um and 2um. The electrostatic precipitator collection efficiency, normally around 99.9% for larger particles, is generally less than 90% in this particle size range and can fall below 50% in worst case conditions. This results in the emission of large numbers of very fine but very visible particles. Although these emissions may have a very low mass emission, in some cases less than 10mg/m3, the Opacity, the measurement of visibility will be very high.

The Indigo Agglomerator provides a significant reduction in fine particle emissions by attaching the fine particles to the large particles, which are easily collected in the electrostatic precipitator. The reduction in fine particles provided by the Indigo Agglomerator technology increases from 60%, about a factor of 2, at 10um to 90%, about a factor of 10, at 0.1um. PM2.5 emissions may be reduced by up to 80% with the installation of an Indigo Agglomerator in front of an electrostatic precipitator. This will provide a significant reduction in visible emissions, as measured by Opacity.

The hopper ash tests carried out at Tarong Power Station show increased fine particle collection and a significantly increased Arsenic concentration in the ash. This supports both the relationship between fine particles and heavy metal concentration plus the enhanced fine particle removal provided by the Indigo Agglomerator. Thus the Indigo Agglomerator also will significantly reduce heavy metal emissions by reducing fine particle emissions.

Long-Term COHPAC Baghouse Performance at Alabama Power Company’s E. C. Gaston Units 2 & 3

Kenneth M. Cushing[1], W. Theron Grubb[2], Byron V. Corina[3], Ramsay L. Chang[4]
(1 Southern Research Institute, P. O. Box 55305, Birmingham, AL 35255-5305 USA
E-mail: cushing@southernresearch.org
2 Grubb Filtration Testing Services, Inc., P. O. Box 1156, Delran, NJ 08075 USA
E-mail: theron@gfts.com
3 Alabama Power Company, Plant Gaston, P. O. Box 1127, Wilsonville, AL 35186 USA
E-mail: corina@southernco.com
4 Electric Power Research Institute, 3420 Hillview Avenue, Palo Alto, CA 94304-1395 USA
E-mail: chang@epri.com)

Abstract: Following a successful pilot-scale baghouse testing program and after reviewing the performance of Luminant’s COHPAC (EPRI’s patented Compact Hybrid Particulate Collector technology) baghouse installation at its Big Brown Station, Alabama Power Company (APCO) decided to install a COHPAC baghouse on Unit 3 at its E. C. Gaston Steam Plant located near Wilsonville, Alabama in late 1996. A second COHPAC baghouse was installed at Gaston Unit 2 in 1999. These baghouse systems were designed with the low pressure/high volume pulse-jet cleaning technology (Hamon Research-Cottrell) that orients the bags in concentric rings and uses rotating pulse manifold arms. Performance of these systems at Plant Gaston Unit 3 and Unit 2 has been excellent during the past eleven and a half and nine years, respectively. Original 3.0 and 2.7 denier Ryton felted fabrics have given way to higher permeability 7.0 denier PPS felt bags in both units. Overall flange-to-flange and tubesheet pressure drop performance has improved without compromising particulate collection efficiency. Recent filter drag values of 0.5 in. H_2O/ft/min on Unit 3 and 0.3 in. H_2O/ft/min on Unit 2 have been experienced at air-to-cloth values of 8.0 ft/min. Average pulsing frequencies have ranged from 0.2 pulses per bag per hour for recently installed 7.0 denier PPS felted bags up to 0.7 pulses per bag per hour for older 2.7 denier Ryton felt bags. COHPAC baghouse installation has successfully reduced stack opacity. Comparing the average of the last eleven years of operation (1997 – 2007) to the average of the two years prior to COHPAC baghouse installation on Unit 3 (1995 – 1996), the average opacity has been reduced 50% and the number of hours per month that the average opacity has exceeded 20% has been reduced 95%. Similar results have been experienced on Unit 2. Except for early bag failure episodes on each unit caused by bag-to-bag abrasion, bag life has been very good. The original 3.0 denier Ryton felted bags in the rear modules of the Unit 3 baghouse remained in service for five years accumulating over 39,500 hours of exposure to flue gas with few bag failures. Front module bags in Unit 3, however, had much shorter bag lives because of a higher incidence of bag failures. Average service lives for the 3.0 and 2.7 denier filter bags were similar to those of the follow-on 7.0 denier PPS felted fabrics, typically two to three years, 19,000 to 27,000 hours of exposure to flue gas. Evaluation of the performance of various test bags has been ongoing for several years. Early tests compared the performance of 6.0 denier and 7.0 denier PPS felts with traditional 2.7 denier felts. 7.0 denier felted fabrics performed very well. More recently, various dual-density felts have been tested. Results after 20,000 hours of flue gas exposure indicate that the Dual Density Torcon – 9058 felt is the best of the four test fabrics. The test program is continuing. COHPAC baghouse performance for Alabama Power Company has exceeded expectations and continues to provide an excellent air pollution control benefit.

Keywords: Fabric filter, baghouse, COHPAC

1 INTRODUCTION

1.1 COHPAC Technology

COHPAC technology was developed by the Electric Power Research Institute in the early 1990s. COHPAC is an acronym for Compact Hybrid Particulate Collector. COHPAC incorporates a small, pulse-jet baghouse installed downstream of a poorly performing electrostatic precipitator (for example) to act as a particulate polishing unit to allow the combined ESP/baghouse system to successfully meet federal or state mandated particulate emission limits. This eliminates the need for costly ESP retrofits or rebuilds. The small pulse-jet baghouse, able to operate at higher than normal filtering velocities (4.0-6.0 cm/s (8-12 ft/min) versus 0.75-2.5 cm/s (1.5-5.0 ft/min) for a conventional baghouse) because of the relatively low inlet mass concentration, requires a significantly smaller footprint compared to a low-ratio fabric filter. The use of a baghouse also overcomes the sensitivity of electrostatic precipitator particulate collection efficiency to variations in particulate and flue gas properties. A United States Patent, Number 5,024,681, was issued on June 18, 1991. [1,2].

1.2 E. C. Gaston Electric Generating Plant

Alabama Power Company (APCO), a Southern Company subsidiary, owns and operates the E. C. Gaston Electric Generating Plant located near Wilsonville, Alabama, approximately 40 miles southeast of Birmingham, Alabama. This plant consist of four (4) 270 MW balanced draft and one (1) 900 MW forced draft, coal-fired boilers. Each boiler is outfitted with hot-side electrostatic precipitators for control of particulate emissions. All five boilers burn low sulfur, eastern bituminous coals. At Plant Gaston a single stack services Units 1 through 4. Units 1 and 2 share a common stack liner; Units 3 and 4 share a second common stack liner. Although the coals used at Plant Gaston were originally treated with sodium sulfate to enhance performance of the hot-side ESPs, load reductions and frequent ESP washings were required to maintain acceptable opacity levels. Alabama Power in the mid-1990s began to investigate ways to remedy this problem. After studying the experience of the first full-scale COHPAC installation at Luminant's (formerly TXU) Big Brown station [3], EPRI and Southern Company Services (SCS) in September 1995 installed a 1-MW scale COHPAC pilot plant at APCO's J. H. Miller Steam Electric Generating facility in anticipation of using this technology at their E. C. Gaston plant.

1.3 Pilot Plant Testing

Prior to the application of the COHPAC technology to the Plant Gaston full-scale utility, coal-fired boiler, there was a period of pilot plant testing that took place at a separate Alabama Power Company plant, the James H. Miller Steam Electric Generating Plant. This site was chosen because the coal-fired boiler incorporated a hot-side electrostatic precipitator followed by an air heater similar to the E. C. Gaston units and the coal supply was similar to that used at Plant Gaston. The Miller Station pilot plant was installed downstream of the existing Unit 2 hot-side ESP and air preheater and utilized a low pressure/high volume pulse-jet cleaning technology, similar to the Hamon Research-Cottrell design that was ultimately used at Plant Gaston. The pilot plant was modified to operate with interstitial can velocities of less than 1,000 feet per minute while filtering at nominal air-to-cloth ratios of 8.5 to 10.0 feet per minute, and utilizing, exclusively, an on-line cleaning mode of operation. This was done to ensure that this method of operation was viable and reliable prior to implementing it on a full-scale basis.

Ryton felt filter bags (18 oz.yd^2) were installed in the pilot baghouse. To achieve the desired filtration velocities the bags were 23-feet long. Testing with both timed- and pressure-drop-initiated cleaning took place to maintain desired pressure drop levels across the pilot unit. The COHPAC pilot facility operated very well during its two-year test program, with no significant problems [4]. The low pressure/high volume pulse cleaning technology with on-line cleaning successfully maintained tubesheet pressure drops of 4 inches w.c. with 8.5 to 10.0 foot per minute air-to-cloth ratios. Pulse frequencies were easily kept at or below one pulse per bag per hour on average.

2 COHPAC BAGHOUSE INSTALLATION

Because of the success of the COHPAC pilot testing at Alabama Power Company's Miller Station and the experiences at Luminant's Big Brown Station (two 575 MW COHPAC units), Alabama Power decided to install a full-scale COHPAC baghouse to filter the flue gases on their E. C. Gaston Unit 3 coal-fired boiler. Alabama Power contracted with Hamon Research-Cottrell in early 1996 to install a COHPAC, pulse-jet-cleaned, fabric filter system downstream of Unit 3's existing hot-side electrostatic precipitator and air heater. Following the installation, startup, and successful operation of the COHPAC system on Unit 3, Alabama Power again selected Hamon Research-Cottrell in early 1998 to install a similar system on Unit 2. Both systems were nearly identical in scope, design, and complexity[5].

Due to site and space restrictions each COHPAC system was installed in two (per unit) abandoned cold-side ESP casings located on the cold-side of the existing Ljungstrom air pre-heaters. These units were located directly under the existing hot-side precipitators, and between Units 1 and 4, which were in full operation during the construction phase of the program. These unusual site conditions made the installation of these two systems extremely difficult, especially because of the relatively short outage windows available.

2.1 Description of the COHPAC Baghouse Installation

Each of the COHPAC baghouses was designed to treat flue gas volumes of 1,070,000 acfm at 290 F, producing a design gross filtration velocity of 8.5 feet per minute with all compartments in service. Each baghouse casing (two casings per unit using the old cold-side ESP boxes) consisted of four (4) isolatable compartments, two compartments per air-preheater identified as Side A or B. Each compartment consisted of two bag bundles (modules) oriented in the direction of gas flow, each having a total of 544, 23-foot long, filter bags. The original equipment bag was a 3.0 denier Ryton felt having a nominal weight of 18 oz./yd^2. There were 1,088 bags per compartment, or 2,176 bags per casing. Fig. 1 shows an elevation view of the COHPAC baghouse/bag module arrangement.

Due to the limited size of the abandoned cold-side ESP casings, and to be able to accommodate the design flue gas volumes and provide the specified air-to-cloth ratios, each original ESP casing was extended by approximately 12 feet in length. The two isolatable compartments in each casing are separated by a central flue gas bypass section. The bypass system can be 100% opened to handle the full flow of the casing or can be regulated to maintain the proper air-to-cloth ratio in the single compartment that is not isolated. To allow inspection and /or maintenance of any given compartment, a bypass condition is mandated on the side being entered. Each compartment is equipped with a multi-louver inlet damper and a guillotine outlet damper to allow isolation during periods of inspection and/or maintenance.

Each compartment is outfitted with individual, low leakage, purge/ventilation poppet dampers designed to allow the introduction of ambient air into the compartment to purge the compartment of flue gases. The poppets are mounted below the tubesheet. These dampers also serve as a vacuum breaker to aid in opening the roof hatches. The dampers open automatically when a single compartment is isolated or when the entire baghouse is either bypassed or shut down. Purge air is then drawn through the purge poppets using the system's induced draft fans.

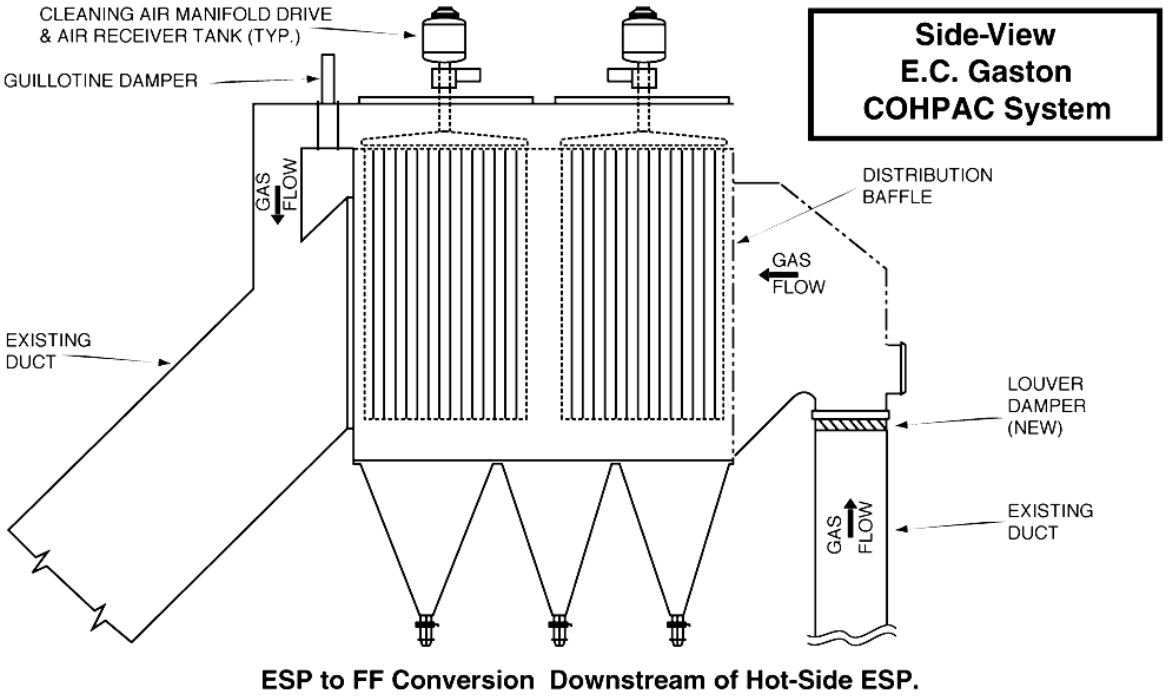


Fig. 1 E. C. Gaston COHPAC Baghouse System Elevation View

Access to the individual compartments is provided through roof mounted hatches which are located over each individual bag bundle. Each hatch is separated into two (2) hinged halves. A short ladder allows access to the top of the tubesheet. The tubesheet is about five (5) feet below the compartment roof. The low pressure/high volume pulse-jet cleaning system, with its rotating pulse manifold, simplifies access to each filter bag since individual blowpipes do not have to be removed. Unit 3's blowers are located at grade behind the unit's induced draft fans and abandoned stacks, while Unit #2's blowers (now at grade) were originally located directly above the Unit #3 COHPAC system on a platform located under the hot-side ESP's return ductwork.

Prior to the completion of the final design of each baghouse system, a model study was performed to confirm flow profiles from the inlet and outlet ductwork configurations. There was limited headroom between the top of the casing and the bottom of the hot-side ESP directly above the baghouse. This necessitated the use of split filter-bag cages. In addition, baghouse construction was quite challenging because crane access to the area was highly restricted. [6]

2.2 Remote Monitoring System

Southern Research Institute installed individual remote baghouse monitoring systems on both Unit 2 and Unit 3. These systems can be accessed via modem to allow real-time monitoring of the system operation, along with current and long-term trend analysis. [7] These monitoring systems were functional at the startup of each baghouse system and remain in service to this day. These systems were developed by Mr. Ray Wilson of Ray Wilson Consulting. The proprietary software packages retrieve, display and store the COHPAC baghouse performance data. Besides performance, date, time, boiler load, and stack opacity are also logged and displayed. The datalogging system's software also stores the data for later retrieval, archiving, and preparation of historical trend graphs.

3 LONG-TERM UNIT 3 BAGHOUSE PERFORMANCE

The first E. C. Gaston COHPAC baghouse was installed on Unit 3 and began operation on December 26, 1996. Through the end of 2007 the Unit 3 COHPAC baghouse had accumulated 94,428 "clock hours" (total number of hours the filter bags could have been exposed to flue gas, equivalent to the number of hours between bag installation and removal) of operational time.

3.1 Pressure Drop and Air-to-Cloth Ratio

The baghouses were designed to operate at a nominal air-to-cloth ratio of 8 to 8.5 ft/min. Typical flange-to-flange pressure drop and air-to-cloth ratio performance data collected during the first half of 2007 are shown in Fig. 2.

Pressure transducers to track tubesheet pressure drop were not installed on the Unit 3 baghouse compartments.

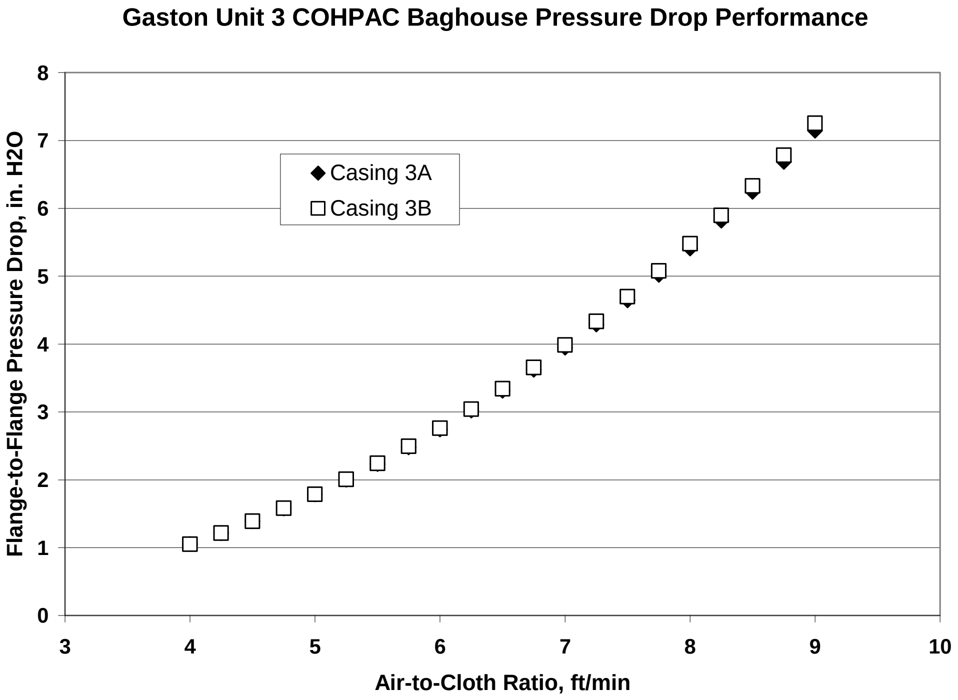


Fig. 2 Gaston Unit 3 COHPAC baghouse pressure drop performance. The relationships are based on over 2,700 data points (hourly averages) from the first half of 2007. Points on polynomial curve fits to the data for each casing are shown

The relationships shown in Fig. 2 were developed as polynomial equations fitted to over 2,700 data points (hourly averages) from operating data collected during the first half of 2007. Air-to-cloth values ranged from 4 to 9 ft/min as the boiler load varied from about 70 to 270 megawatts. The flange-to-flange pressure drop performance for Casing A and Casing B was almost identical.

At an air-to-cloth value of 8 ft/min the average flange-to-flange pressure drop is about 5.45 in. H_2O. The baghouse supplier estimated that the difference in pressure drop between the flange-to-flange and tubesheet pressure drop values at an air-to-cloth value of about 8 ft/min would be 1.25 in. H_2O. The estimated value of the tubesheet pressure drop then would be about 4.2 in. H_2O for the data shown in Fig. 2. The tubesheet drag value then would be about 0.5 in. H_2O/ft/min, a desirable value for COHPAC baghouse operation.

3.2 Pulsing Frequency

As described earlier, each baghouse casing has two compartments separated by a bypass duct. Each compartment contains two bag bundles (modules) oriented in the direction of gas flow. Each bundle contains 544 filter bags, except module 3B11 which contains 18 additional filter bags. The bags are arranged in 14 concentric circles or rows. A rotating dual arm pulse manifold delivers pulse air to the tops of the filter bags. One arm has rectangular nozzles oriented over the even rows, while the other manifold arm cleans the odd rows. The pulse manifolds rotate at approximately 1 rpm. Pulse pressure is maintained at 10 psig. When cleaning is initiated the pulsing alternates between the four pulse manifolds in each casing. This allows time for the air reservoir mounted above each pulse manifold to recharge before the next pulse. Bags are cleaned randomly depending on the location of the pulse arm when pulsing occurs. The baghouse control system was programmed to count the number of pulses in each five minute period continuously. These data are fed to the baghouse monitoring system and are used to calculate a pulse frequency, pulses per bag per hour (p/b/h). If continuous cleaning is in progress, approximately 57 pulses per five minutes are counted, a rate of about 4.2 p/b/h.

The baghouse was designed for bag cleaning to be initiated in one of three ways. These were pressure drop initiation/termination, drag initiation/termination, or time. When the baghouse was first started up the system used drag initiation and termination set points to control cleaning. Eventually, because test programs on Unit 3 in 2000 and 2001 required pressure drop initiation and termination set point cleaning, this became the normal mode to control cleaning of the bags. Timed cleaning has always been the third method. The timed cleaning set point has always been five hours between cleaning events.

During the first half of 2007 typical average cleaning frequencies for Casing A and Casing B were 0.21 and 0.17 pulses per bag per hour, respectively. These rates are typical for the 7.0 denier PPS felt bags currently installed. During operation with 3.0 and 2.7 denier Ryton felt bags, pulsing frequencies would range from 0.4 to 0.7 p/b/h, with occasional excursions over 1.0 p/b/h depending on how long the bags had been in service and the performance of the upstream hot-side

ESP. A cleaning frequency of 0.5 p/b/h or less is a desirable value for COHPAC baghouse operation.

3.3 Baghouse Emissions and Unit 3&4 Opacity

Since startup of the baghouse Alabama Power Company has had outlet particulate concentrations (gr/dscf) from the Unit 3 baghouse measured on a yearly basis. They provided these data for this report. Testing was performed separately on the outlet of Casing A and Casing B. These data are shown in Fig. 3 as a bar chart. It is likely that the higher particulate emissions measured in March 1997 were caused by bag failures or improperly installed bags that had not yet been located and corrected after startup. Outlet emissions degraded each year until the filter bags in the four front bag modules were replaced in October 2000. Outlet emissions have remained relatively low since that time. The trend toward higher outlet emissions in 2006 and 2007 reflect the aging of the 7.0 denier PPS bags installed in Casing 3B in 2003 and Casing 3A in 2005. These bags were scheduled to be replaced in December 2007 and March 2008, respectively. While the preceding data reflect the outlet emissions of the Unit 3 COHPAC baghouse alone, data have also been collected over the years regarding the opacity of the stack containing the flue gases from both Unit 3 and Unit 4. While the baghouse installed on Unit 3 greatly improved the overall opacity for the Unit 3 and 4 stack, the values, of course, have also been dependent on the performance of the hot-side ESP on Unit 4 since it is that unit's sole particulate control device.

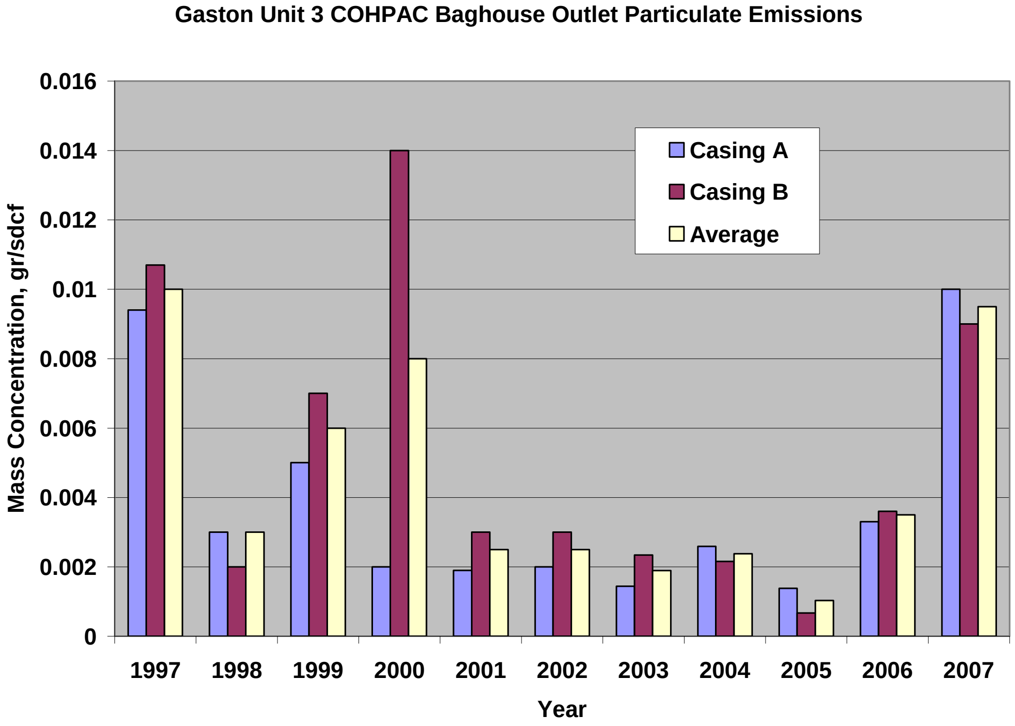


Fig. 3 Gaston Unit 3 COHPAC baghouse outlet average particulate mass concentrations by year since startup

Fig. 4 shows the monthly averages for stack opacity and the number of hours each month that the average opacity exceeded 20%. These data represent only those times when both units were in operation simultaneously and no baghouse compartments were bypassed. As can be seen in the figure, after the installation of the baghouse there was a significant reduction in stack opacity values. The effect of baghouse installation on the hours per month when opacity exceeded 20% was dramatic. Notice the improvement in opacity near the end of 2000 (68 months) when the filter bags in the four front modules of the baghouse were replaced. Comparing the average of the last eleven years of operation to the average of the two years prior to baghouse installation, the average opacity has been reduced 50% (12.7% to 6.3%) and the number of hours per month that the average opacity has exceeded 20% has been reduced 95% (140 to 7).

3.4 A Discussion of Bag Life

The filter bags are the major O&M cost of baghouse operation. The goal is to maximize the performance and life of the bag, thereby minimizing the frequency of bag replacement. Bag life at Gaston Unit 3 has in general been very good. The baghouse started up with 3.0 denier Ryton felt bags (provided by the OEM) installed in all compartments. Grubb Filtration Testing Services (Delran, NJ) has provided advice on bag replacement and conducted special testing of used bags removed from the baghouse throughout its life.

Since startup all filter bags have been replaced twice. The baghouse is currently on its fourth set of filter bags. The filter bags in Casing B were replaced during a fall 2007 outage. The filter bags in Casing A werereplaced during a March 2008 outage. Filter bags in the front modules (A10, A20, B10, B20) have been replaced more frequently than those in the rear modules.

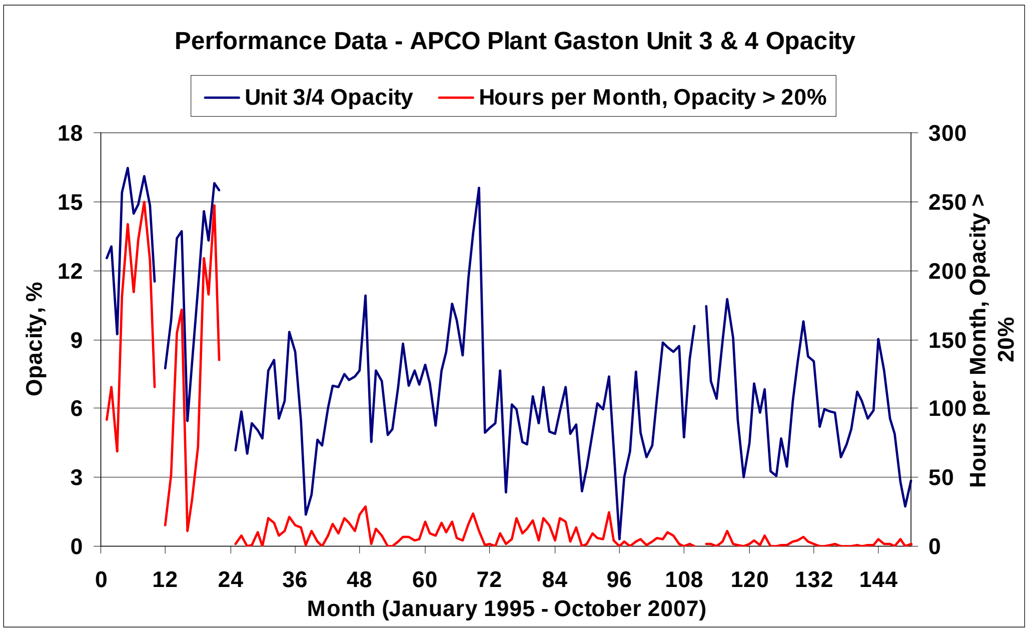


Fig. 4 Monthly average opacity and 20% opacity exceedence from January 1995 though October 2007 for Gaston Units 3 and 4

There were early bag failures in the front modules of both casings (A10, A20, B10, B20) caused by bag-to-bag abrasion. This occurred mainly on the bags located near the sides of the modules closest to the compartment walls. Even though there were perforated plates at the inlet to the compartments to even the flow across the face of the bag bundles, flue gas tended to sweep around the bundle and attempt to pass between the bundle and the compartment walls. This resulted in excessive bag swinging and rubbing against other bags. Bag inspection confirmed more failed bags on the sides of the bag bundles adjacent to the compartment walls. Inspection of the perforated plates installed downstream of the compartment inlet dampers also showed areas of ash buildup that resulted in uneven flow across the face of the plate and sneakage under the plate. Compartment particulate emissions continued to climb until a full replacement of the filter bags in the four front bag modules in October 2000. Opacity values were significantly lower following the replacement of these bags, as can be seen in Fig. 4 (October 2000, 68 months).

During that outage a novel solution to the bag swinging/abrasion problem was implemented. Two concentric rings were installed on each of the four front bag bundles. These tubular rings were mounted inside and outside the outer row of bags about six inches above the bottom of the bags. This minimized bag movement and reduced bag-to-bag abrasion. Fig. 5 shows a photograph of these rings installed on one of the bag bundles.

In addition to these retaining rings, vibrators were attached to the perforated plates to prevent buildup of ash that could block the holes and cause flow stratification.

Baghouse emissions remained low through 2004. In December 2003 in the B casing and in May 2005 in the A casing 7.0 denier PPS felt filter bags were installed. These bags were designed for higher permeability (lower pressure drop at similar flow rates), but they are not as good a barrier for ash penetration. While pressure drop performance of these bags has been excellent, there has been a steady increase in outlet emissions since these bags were replaced. This has not been noticeable in the opacity data because of lower average load values over the last couple of years.

3.5 Summary

The COHPAC I baghouse on E.C. Gaston Station Unit #3 has operated exceptionally well. Other than a few initial mechanical problems, the unit has operated better than anticipated. The COHPAC I technology has provided Alabama Power with a high degree of system flexibility; it has moderated ESP opacity spikes and reduced average stack outlet opacity levels by almost 50%. This has increased the choice of acceptable fuels that can be used on this unit, and has reduced overall operating costs. Alabama Power has also been able to eliminate the use of sodium sulfate (an ash resistivity modifier) on Units #3 and #4 and reduce the frequency of ESP washings. [8,9,10]

4 LONG-TERM UNIT 2 BAGHOUSE PERFORMANCE

The second COHPAC baghouse installed at Alabama Power Company's E. C. Gaston plant was on Unit 2. The design of this fabric filter was almost identical to the Unit 3 baghouse. The only significant change was a different bag arrangement pattern for the eight tubesheets even though there was the same number of filter bags per bag module.

The Unit 2 COHPAC baghouse started up on June 14, 1999. Through December 2007 the baghouse had accumulated 74,938 "clock hours" (total number of hours the filter bags could have been exposed to flue gas, equivalent to the number of hours between bag installation and removal) of operating time.

Performance of the Unit 2 baghouse has been very similar to that experienced by the Unit 3 baghouse and a detailed discussion will not be presented. Highlights have been included in the abstract. Additional information may be obtained from the authors.

Fig. 5 Photograph of concentric tubular stainless-steel rings installed on Gaston Unit 3 COHPAC baghouse bag bundle 3A10. There were installed to reduce bag movement and bag-to-bag abrasion

5 SPECIAL FILTER BAG TEST PROGRAMS

Various test bags have been evaluated at the Gaston COHPAC baghouses since 2000. These include filter bags that have become the current replacement filter bags, plus special non-standard bags especially manufactured for testing. Filter bag performance has been measured by the use of a special drag measurement device designed for low pressure/high volume oval (Carter-Day/Howden) filter bags. This device allows the drag of individual bags to be measured. It consists of a fan, venturi, flexible hose, and a gasketed adaptor that fits over and around the cage's top flange to seal with the tubesheet. This insures that the induced flow is pulled only through the bag being tested. Pressure taps are located to measure the pressure drop across both the venturi and the filter bag. Knowledge of the venturi flow rate and pressure drop across the filter bag allows calculation of the bag's drag (in. H_2O/ft/min).

Test programs have taken place with both the Unit 2 and Unit 3 COHPAC baghouses. Prior to the rebagging of the entire Unit 2 baghouse with 7.0 denier PPS felt bags in November 2003, a small number of these bags were installed in the 2A11 bag module in June 2001. In addition the entire B casing on Unit 2 was rebagged with 6.0 denier Ryton felt bags in December 2001. Drag testing of these bags took place in May 2002 and March 2003. Comparative drag measurements were conducted on selected 2.7 denier Ryton felt bags from Unit 2 and Unit 3 at the same time. The test results for the 7.0 denier PPS felt bags are presented in Table 1.

The average drag for the eighteen 7.0 denier PPS felt bags was 0.18 in. H_2O/ft/min. The average drag for 10 adjacent 2.7 denier PPS felt bags was 0.31 in. H_2O/ft/min. An additional 27 randomly located 2.7 denier PPS felt bags were tested.

Table 1 Drag Measurements Conducted on May 6, 2002 in Bag Module 2A11

Bag Type	Average Drag	Stn. Dev.	# of Bags	Service Hours	Comments
	(in. H_2O/ft/min)				
7.0 denier PPS	0.18	0.03	18	7,500	Average of all bags
2.7 denier PPS	0.31	0.09	10	7,500	Average of all bags

2.7 denier PPS	0.35	0.14	27	7,500	Average of all bags
2.7 denier PPS	0.31	0.06	24	7,500	Average excludes three Row 15 bags

Their average drag was 0.35 in. H_2O/ft/min. Three of the bags had exceptionally high drag. If they are excluded from the average, the remaining 24 2.7 denier PPS felt bags also had an average drag of 0.31 in. H_2O/ft/min., identical to the average drag of the ten 2.7 denier bags adjacent to the 7.0 denier bags. After 7,500 hours of operation the 7.0 denier PPS felt bags had 42% lower drag on average than the 2.7 denier PPS felt bags.

Drag measurements on the 6.0 denier PPS felt bags installed in December 2001 were conducted in May 2002 and March 2003. Additional comparative measurements on 2.7 denier PPS felt bags from Unit 3 also took place in March 2003. Bags from modules 3B10, 3B11, 3B20, and 3B21 were tested. The test results are presented in Table 2 below.

Table 2 Drag Measurements on 6.0 denier PPS and 2.7 denier PPS Felt Bags

Bag Module	Bag Type	Average Drag	Stn. Dev.	# of Bags	Service Hours	Comments
		(in. H_2O/ft/min)				
2B10	6.0 den. PPS	0.24	0.10	37	3,650	Average of all bags
2B10	6.0 den. PPS	0.41	0.07	42	10,870	Average of all bags
3B10	2.7 den. PPS	038	0.04	28	20,370	Average of all bags
3B11	2.7 den. PPS	0.32	0.08	32	11,000	Average of all bags
3B20	2.7 den. PPS	0.39	0.05	28	20,370	Average of all bags
3B21	2.7 den. PPS	0.29	0.10	25	11,000	Excludes 6 bags with high drag

The average drag values for the 6.0 denier PPS felt bags after both 3,650 hours and 10,870 hours (0.24 and 0.41 in H_2O/ft/min) were higher than the average drag value for the 7.0 denier bags at 7,500 hours (0.18 in. H_2O/ft/min). Drag values for the 2.7 denier PPS felt bags at 11,000 and 20,000 hours were slightly higher than the values measured after 7,500 hours (Table 2). The average drag values for the bags in the front modules (3B10, 3B20) were higher than the drag values for the bags from the rear modules (3B11, 3B21) because of their longer service life.

The latest test program with the Unit 3 baghouse is an ongoing program that is evaluating the performance of special dual-density PPS felt filter bags. These bags were installed in May 2005. The test bags are installed in baghouse module 3A11. Subsequent measurements of filter drag took place in February 2006 and November 2007. There are four fabrics being evaluated, including the current "standard bag," a 7.0 denier Torcon PPS felt. The fabrics are described in below. Additional information is provided in Table 3.

1) High Permeability Dual-Density Torcon PPS Felt (Blended/Lined Face Out)-Midwesco Filter Resources Product Number FWA429-9058 (12 bags).
2) 7-Denier Procon PPS Felt (BHA Group Product Number 02985898) (24 bags).
3) High Permeability Dual-Density Torcon PPS Felt (7-Denier/Unlined Face Out)-Midwesco Filter Resources Product Number FWA429-9059 (11 bags).
4) "Standard" 7.0 denier Torcon PPS felt (9 bags).

Table 3 Test Fabric Properties – QA Test Results

Test Fabric (QA Test Results)	Weight (oz/yd^2)	Thickness (inches)	Permeability (cfm @ 0.5 in. H_2O)	Mullen (psi, gross)
7-denier Procon	16.69	0.105	128	505
Dual-Density (9058)*	15.36	0.097	86	444
Dual Density (9059)*	14.67	0.098	109	399

*Note from Grubb Filtration – These fabrics from the same master roll were just singed on opposite faces. We suspect that the samples submitted for QA testing exhibited normal variations in weight and permeability throughout the master roll. It is not conclusive, based on testing only one sample from the roll ends, whether there was any real difference in the average fabric properties for the 9058 and 9059 test bag sets.

The high permeability, dual-density fabrics are essentially dual-density versions of the standard 7-denier Torcon PPS felt bags that are used at Plant Gaston. The only differences were that the batt on one face would be a 50/50 blend of 2.7-denier and 7-denier Torcon (rather than all 7-denier) and that the permeability would be 85 ± 15 cfm (rather than 125 ± 20 cfm).

Half of the bags were to be made from fabric singed on the blended-denier (lined) face (9058) and the rest of the bags were to be made from fabric singed on the 7-denier (unlined) face (9059).

Table 4 presents the test results. The table includes the number of filter bags originally installed of each type. The bags were alternately installed in the 14th row, the next to outer row.

Table 4 Test Bag Drag Measurements for Special Dual-Density Felts

Bag Description	# of Bags	Installation Date	Test Date	Clock Hours	Exposure Hours	Drag (in. H_2O/ft/min)	Stnd. Dev.
7-denier Torcon PPS	9	5/23/2005	2/23/2006	6,527	6,399	0.20	0.06
7-denier Torcon PPS	9	5/23/2005	11/26/2007	20,631	19,661	0.48	0.13
7-denier Torcon PPS	11	2/23/2006	11/26/2007	13,713	13,262	0.56	0.14
Dual-Density .Torcon – 9058	10	5/23/2005	2/23/2006	6,527	6,399	0.25	0.04
Dual-Density Torcon – 9058	10	5/23/2005	11/26/2007	20,631	19,661	0.45	0.05
Dual-Density Torcon – 9059	9	5/23/2005	2/23/2006	6,527	6,399	0.22	0.06
Dual-Density Torcon – 9059	9	5/23/2005	11/26/2007	20,631	19,661	0.52	0.09
7.0 denier Procon	17	5/23/2005	2/23/2006	6,527	6,399	0.25	0.05
7.0 denier Procon	17	5/23/2005	11/26/2007	20,631	19,661	0.54	0.10

Note-Eleven Standard bags installed 2/23/2006 replaced failed or missing test bags. All bags were in the front two quadrants. No failed or missing bags were observed on 11/26/2007.

Note that the drag values on average approximately doubled during the 14,000 hours between the first measurements in February 2006 and the most recent measurements in November 2007. The eleven "standard bags" installed in February 2006 to replace the failed or missing bags had the highest drag values in November 2007, even with only about 13,500 hours of exposure. This is likely attributable to the fact that they were front quadrant bags that would have been exposed to the highest dust loading.

The apparent best performer after 20,000 hours of exposure appears to be the Dual-Density Torcon – 9058. This can be seen visually in Fig. 6 that shows the average drag value plus standard deviation for each of the four bag types. The Dual-Density Torcon -9058 clearly has the lowest average drag and smallest standard deviation of the four fabric types. Testing of these filter bags will continue with additional measurements planned for the fall of 2008.

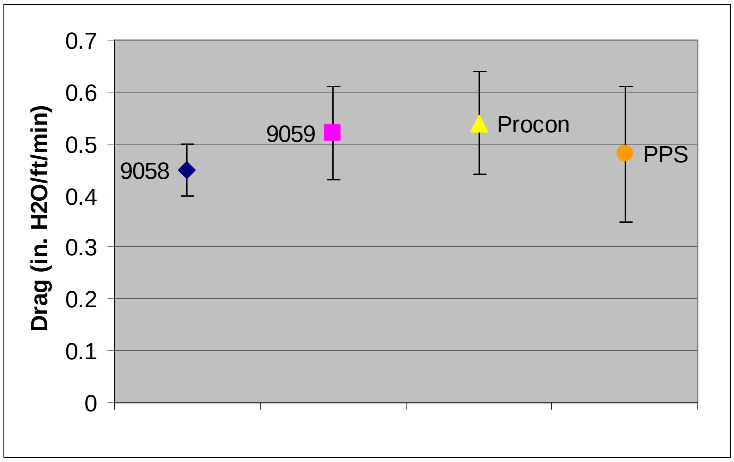


Fig. 6 Drag values and standard deviation ranges for November 2007 measurements

6 CONCLUSION AND RECOMMENDATIONS

Following a successful pilot-scale baghouse testing program and after reviewing the performance of Luminant's COHPAC (EPRI's patented Compact Hybrid Particulate Collector technology) baghouse installation at its Big Brown Station, Alabama Power Company (APCO) decided to install a

COHPAC baghouse on Unit 3 at its Gaston Steam Plant in late 1996. A second COHPAC baghouse was installed at Gaston Unit 2 in 1999. These baghouse systems were designed with the low pressure/high volume pulse-jet cleaning technology that orients the bags in concentric rings and uses rotating pulse manifold arms.

Original 3.0 and 2.7 denier Ryton felted fabrics have given way to higher permeability 7.0 denier PPS felt bags in both units. Overall flange-to-flange and tubesheet pressure drop performance has improved without compromising particulate collection efficiency. Early bag failures caused by bag-to-bag abrasion in the four front bag modules on both units were minimized by the installation of two concentric tubular stainless steel rings to restrain movement of the outer ring of filter bags. Recent filter drag values of 0.5 in. H_2O/ft/min on Unit 3 and 0.3 in. H_2O/ft/min on Unit 2 have been experienced at air-to-cloth values of 8.0 ft/min. The lower drag values for Unit 2 reflect the younger age of its filter bags. Average pulsing frequencies have ranged from 0.2 pulses per bag per hour for recently installed 7.0 denier PPS felted bags up to 0.7 pulses per bag per hour for older 2.7 denier Ryton felt bags. Continuous cleaning resulting from heavy ash accumulation has not been a problem unless the performance of the upstream hot-side electrostatic precipitators degrades.

Special felted bag fabrics have been tested in the Gaston baghouses since 2000. Early tests compared the performance of 6.0 denier and 7.0 denier PPS felts with traditional 2.7 denier felts. 7.0 denier felted fabrics performed very well. This led to full rebagging with this filter material in both baghouses. More recently, various dual-density felts have been tested. Results after 20,000 hours of flue gas exposure indicate that the Dual Density Torcon – 9058 felt is the best of the four test fabrics. The test program is continuing.

COHPAC baghouse installation has successfully reduced stack opacity and eliminated the need for load reduction. Unit 3 outlet mass concentrations have averaged 0.0046 gr/dscf. Comparing the average of the last eleven years of operation to the average of the two years prior to COHPAC baghouse installation, the average opacity for Units 3 and 4 has been reduced 50% and the number of hours per month that the average opacity has exceeded 20% has been reduced 95%. For Unit 2's eight years of operation, the comparable values for the Unit 1 and 2 stack have been 38% and 89%, respectively. Unit 2 outlet mass concentrations have also averaged 0.0046 gr/dscf.

Except for early bag failure episodes on each unit caused by bag-to-bag abrasion, bag life has been very good. The original 3.0 denier Ryton felted bags in the rear modules of the Unit 3 baghouse remained in service for five years accumulating over 39,500 hours of exposure to flue gas with few bag failures. Front module bags in Unit 3, however, had much shorter bag lives because of a higher incidence of bag failures. Average service lives for the 3.0 and 2.7 denier filter bags were similar to those of the follow-on 7.0 denier PPS felted fabrics, typically two to three years, 19,000 to 27,000 hours of exposure to flue gas.

COHPAC baghouse performance for Alabama Power Company has exceeded expectations and continues to provide an excellent air pollution control benefit. Monitoring of the performance of these baghouse should continue to insure the future success of this technology for Plant Gaston.

ACKNOWLEDGEMENTS

We would like to gratefully acknowledge the contributions of Mr. Ray Wilson of Ray Wilson Consulting. He did an excellent job developing the software and screen graphics that have made it easy and simple to monitor and log the performance of the Gaston Unit 2 and Unit 3 baghouses since 1996. Most of the information presented here would have been unavailable without his contributions. A special note of thanks goes out to the many staff members at Alabama Power's E. C Gaston Steam Plant that have assisted in the operation and testing of the baghouses over the years. These individuals include David Prater, Steve Howe, Richard Reaves, Ben Haynes, Shane McCray, Lee Coxwell, Joel McCray, and Danny Cobb.

REFERENCES

1. R. L. Chang, U. S. Patent No. 5,024,681. Compact Hybrid Particulate Collector. Issued on June 18, 1991.
2. R. L. Chang. COHPAC compacts emission equipment into smaller, denser unit. Power Engineering, July 1996, pp. 22-25.
3. R. L. Miller. Advanced Technology Development Dry Filtration Systems. Council of Industrial Boiler Owners – ADVANCED TECHNOLOGIES II ROUNDTABLE, July 1996, Washington, DC.
4. W. A. Harrison, K. M. Cushing, R. L. Miller, R. L. Chang. Recent COHPAC Data for Fine Particulate Matter & Air Toxics Removal from Coal-Fired Power Plants. In Proceedings: Power-Gen International 96, Orlando, FL, December 4-6, 1996.
5. R. Miller, W. Harriosn, B. Corina, K. Cushing, R. Chang. COHPAC (Compact Hybrid Particulate **C**ollector) The Next Generation in Particulate Control Technology Alabama Power Company's E. C. Gaston Units #2 and #3 'A Success Story'. in Proceedings: EPRI-DOE-EPA Combined Utility Air Pollutant Control Symposium, Atlanta, Georgia, August 16-20, 1999, Electric Power research Institute, Palo Alto, CA.
6. R. Jones. Gaston Rebuild Project Tops Site Difficulty. Clear Stacks, Reinhold Environmental Ltd., December, 1996.
7. K.M. Cushing. SRI Remote Baghouse Monitoring System for Plant Gaston. Clear Stacks, Reinhold Environmental Ltd., December, 1996.
8. R. Miller, W. Harrison, D. Prater, R. Chang. Alabama Power Company E. C. Gaston 272 MW Electric Steam Plant – Unit No. 3 Enhanced COHPAC I Installation. In Proceedings: EPRI-DOE-EPA Combined Utility Air Pollutant Control Symposium, Washington, DC, August 25-29, 1997; Electric Power Research Institute Report No. TR-108683-V3, August 1997.

9. K.M. Cushing, R. R. Wilson, W.A. Harrison, D. B. Prater, R.L. Chang. Performance Monitoring of a COHPAC I Baghouse System on Unit 3 (270 MWe) at Alabama Power Company’s E.C. Gaston Electric Generating Plant. In Proceedings: EPRI-DOE-EPA Combined Utility Air Pollutant Control Symposium, Washington, DC, August 25-29, 1997; Electric Power Research Institute Report No. TR-108683-V3, August 1997.
10. R. Miller. COHPAC: Full-Scale Demonstrations of an Advanced Particulate Collector. ICAC Clean Air Technology News, Winter 1999.

March 1, 2010

Big Stone Remodels ESP into Pulse Jet Fabric Filter

Thomas W. Lugar, Buell Division, Fisher-Klosterman and Jeff Endrizzi, Stu Schreurs, and DJ Haggerty, Big Stone Plant, Otter Tail Power Co.

Short of replacement, what are your options when your original electrostatic precipitator fails to meet your current emissions and opacity requirements? The management of Big Stone Plant chose the unconventional, yet economic approach of building a pulse jet fabric filter inside the casing of the old electrostatic precipitator. The upgrades restored plant availability and prepare the plant to meet the next regulated reductions in particulate matter emissions.

Otter Tail Power Co.'s Big Stone Plant Unit 1, located in Milbank, South Dakota, is a 475-MW plant that burns Powder River Basin (PRB) coal (Figure 1). This unit was originally outfitted with an electrostatic precipitator (ESP) when it was constructed in 1975. During the mid-1970s the number of ESPs installed on coal-fired boilers across the U.S. spiked in response to the Clean Air Act of 1970. The long-established technology of the ESP was at the time considered the best choice to meet the particulate emission requirements of the Clean Air Act.

1. ESP upgrade needed. Big Stone Unit 1 elected to use the casings of its electrostatic precipitator (ESP) to house a pulse jet fabric filter. The upgrade not only ended unit derates for opacity excursions and induced draft fan pressure drop limitations, but the new equipment also performs well enough to meet anticipated future fine particulate matter legislation. Courtesy: Buell APC

Many of those original ESPs are now candidates for an upgrade or replacement to meet the latest emissions and opacity requirements. The precipitator's collection efficiency can be maintained within the normal variations in boiler operation, but its performance is sensitive to the electrical characteristics of the fly ash as defined by the type and source of the coal burned. Many of these "first-generation" ESPs have been rebuilt with new and improved plate and emitting electrode systems, power supplies, and control systems to extend their life. Others cannot meet current outlet emissions and stack opacity rules, so plant owners face eventually replacing their aged ESPs with a pulse jet fabric filter (PJFF).

At Big Stone Unit 1, a different and more cost-effective alternative was selected: Buell APC was retained to replace the existing ESP with a PJFF configured to fit within the ESP casing. After overcoming the inevitable challenges that occur when putting a square peg in a round hole, the conversion was completed in late December 2007. These challenges were plant-specific, but many, as you will see, also apply to other utilities that might be considering similar projects.

Many Conversion Considerations

There are many reasons, beyond a poorly performing ESP, that would push a utility to consider an ESP replacement. Some plants have completed a fuel switch that has adversely affected ESP performance. Others may have added a flue gas desulfurization (FGD) system or scrubber upstream or downstream of the ESP for SO_2 reduction, thereby reducing the effectiveness of the ESP. Others are looking ahead to the advantages of a modern fabric filter system to help meet mercury emission limits or future fine particulate control (PM2.5) legislation. When considering future emission requirements, replacing an ESP with a PJFF is probably on many plants' short list of large-dollar projects.

Another issue: If the ESP is not consistently meeting outlet emission or opacity requirements due to aged internals and close electrical clearances between electrodes, then a rebuild may solve these problems. However, performance problems may be compounded if the ESP is treating a higher-than-original design gas volume that often results from a fuel switch.

Switching to a low-sulfur coal, especially a subbituminous PRB, will also result in higher-resistivity ash and degradation in ESP performance. Derating of the entire unit has been required in many cases to maintain emission and/or opacity requirements. Depending on the severity of the performance deterioration, upgrade requirements may include the addition of sections to the ESP, gas conditioning, or replacement/conversion to a PJFF system.

Some plants have selected a spray dryer FGD system for SO_2 reduction. In such cases, a pulse jet baghouse downstream is a logical addition given the additional adsorption of SO_2 in the baghouse filter cake that reduces lime consumption. If a wet limestone forced oxidation FGD system producing commercial grade gypsum is selected, the amount of ash exiting the ESP and its chemical composition can cause potential problems with the quality of the byproduct and the chemistry of limestone dissolution that affects overall SO_2 removal efficiency. The role of the existing ESP, when adding a wet FGD system, thus extends beyond achieving stack opacity requirements. The mechanical condition of the ESP and its ability to consistently meet the required fly ash loading limitations to the scrubber have pushed many to add a PJFF.

Mercury removal efficiency with sorbent injection is also highly dependent on coal type, loss on ignition, flue gas temperature, chlorine content in the coal, and SO_3 content of the flue gas. A number of test programs with injection upstream of an ESP of various sorbents and enhanced sorbents, conducted by a number of sorbent suppliers with funding from the Department of Energy, show that mercury removal rates of 30% to 90% are achievable. For many coal-fired plants, the best option that gives consistent, high mercury removal efficiencies (frequently >90%) is sorbent injection followed by a PJFF. The PJFF is an integral part of this mercury removal system.

In the future, standards will likely be enacted for stationary sources, limiting their release of particulate matter that is 2.5 micron diameter and less (PM2.5). These solid particulates will likely be limited to between 0.01 lb/million Btu and 0.015 lb/million Btu of fuel burned. Utilities may also need to control air toxics, with particulate matter becoming the surrogate for a group of hazardous air pollutants in the form of heavy metals, a large percentage of which are emitted from coal-fired boilers as fine particulates. For many older, relatively smaller specific collection area ESPs (collecting plate area/1,000 acfm of flue gas treated), performance upgrades will be required to achieve PM2.5 emission limits.

In sum, there are many site-specific requirements that must be carefully studied when considering a PJFF upgrade or conversion. Some utilities will conclude, after weighing their options, that removing the ESP and replacing it with a PJFF is the right decision. Others, such as Otter Tail, will conclude that the conversion of an existing ESP casing to a PJFF is the most flexible and economic path forward.

Candidates for Conversion

We determined that there are two basic criteria that must be met for an ESP to be a good candidate for conversion to a PJFF. First, the casing must be large enough in volume to accommodate the required cloth area for the filters. Second, the casing of the ESP must be structurally sound and show minimal corrosion.

Other existing equipment modifications or replacements are often required, so a careful evaluation of the "as-built" plant condition is obligatory. For example, know that there will be additional pressure drop in the exit gas ductwork with a PJFF — often up to 8 inches wg. The additional pressure drop may require rebuilding or replacement of the plant’s induced draft (ID) or combustion air fans, depending on the plant configuration. Structural reinforcement of the ESP casing and ductwork may also be required if the original design pressure is exceeded.

Once the decision is made to convert an ESP to a PJFF, there are a number of advantages that the plant owner may enjoy.

The obvious first advantage is economics — the conversion route is usually much cheaper than replacing an old ESP with a new one or with a new PJFF. Those economics are often driven by the ability to install the PJFF in the existing ESP footprint with minimal ductwork modifications required and the reuse of the existing hoppers and ash-conveying systems.

For plants that have significant variability in their fuel supply specification, a PJFF also is much more forgiving in operation than an ESP and stands ready for future sorbent injection addition for mercury control.

A third advantage: The PJFF can be designed with the capability (filter bag selection) to meet future PM2.5 emission regulations during the design stage.

Big Stone Project Case Study

The Big Stone Plant entered commercial service in 1975 with a Wheelabrator-designed ESP for particulate emissions control. The cyclone-fired boiler originally burned North Dakota lignite coal; however, in 1995 the unit was converted to burn subbituminous PRB coal.

The precipitator consists of four chambers in parallel, each with four electrical fields. Each field measured 40 ft high x 45 ft wide x 14 ft deep. The plate spacing is 12 inches with 45 gas passages across each field. Guillotine-type inlet and outlet dampers can close off a chamber if necessary. The discharge electrodes are "star" wires mounted on pipe frame supports. Collecting plates are rapped with tumbling hammer rappers while the discharge electrodes use a falling hammer/cam-drop style of rapper.

The process of realizing a well-functioning particulate collection system took a number of unexpected twists and turns over the years. Following are a few of the challenges encountered by the staff of Big Stone.

Fuel Conversion Problems

ESP performance problems immediately began with the conversion from lignite to PRB coal. The problems were principally due to the higher-resistivity ash and subsequent back corona formation, resulting in problems with meeting the 20% stack opacity limit. A humidification system was added to condition the ash but did not prevent back corona formation, and performance problems persisted.

In 1997 the plant considered a potential ESP retrofit technology, the Advanced Hybrid Particulate Collector (AHPC) then under development by the University of North Dakota’s Energy and Environmental Research Center. AHPC technology development was supported by the Innovations for Existing Plants component of the DOE Fossil Energy R&D Program and then demonstrated under the Power Plant Improvement Initiative. The concept, which combines filter bags and electrostatic precipitation zones in alternate gas passages in the same casing, was successfully pilot tested on a 9,000-scfm slipstream at the Big Stone Plant in 2001, and Big Stone pulled the trigger for a full-scale

AHPC retrofit of three outlet ESP fields in each of the four ESP chambers with the inlet field in each chamber left in place but not energized. The retrofit was completed in October 2002.

Long story short, the upgraded ESP failed to meet its expected performance and operational goals. Frequent boiler derates of between 30 MW and 50 MW were caused by ID fan limitations with high bag pressure drops and stack opacity exceeding the 20% limit due to bag failures. By the spring of 2005, the AHPC technology was abandoned. It did not eliminate the high-resistivity ash condition and back corona formation, which severely limited the effectiveness of the electrostatic zone of the AHPC. The search for another ESP replacement technology began again.

PJFF Conversion Selected

Otter Tail Power Co. decided to replace the AHPC with a new conventional design PJFF that would be built alongside the existing collector. The plan was to demolish the existing ESP after tie-in of ductwork to the new baghouse.

Buell Division of Fisher-Klosterman also proposed to Big Stone Plant management and engineering staff the cost-saving alternative of converting the existing ESP casings to an intermediate-pressure, long bag PJFF. The ESP met the criteria for conversion to a fabric filter. The casing volume was large enough to accommodate the required air-to-cloth ratio, and the casing mechanical integrity was good (the go/no go criteria described earlier). ESP conversion to fabric filter would be less than half the turnkey cost of a total replacement with a new baghouse.

Because the ESP configuration has four independent chambers, an added benefit of the conversion was that each chamber could be blanked off during a short outage, allowing each of the four chambers to be converted while online, albeit at reduced boiler load.

After competitive bidding, Buell APC was awarded a contract for engineering and material supply for the ESP to fabric filter conversion (see sidebar for the design specifications). Otter Tail Power Co. directly contracted the construction work (Figure 2).

2. One at a time. The ESP has four independent chambers that could be blanked off during an outage, allowing each of the four chambers to be converted while online, albeit at reduced boiler load. Courtesy: Buell APC

PJFF Design Specifications

Pulse jet fabric filter (PJFF) conversion project design parameters are as unique as the fuel that a plant burns. For Big Stone Plant Unit 1, the basic PJFF specifications follow.

The guaranteed performance of the PJFF was:

- Opacity: 10%
- Outlet loading: 0.01 lb/million Btu
- Bag life: Three years
- Maximum ∆p: 8 inches wg
- Other key specifications included:
- Air-to-cloth (A/C) ratio, gross: 1:3.4
- A/C, net (with off-line cleaning): 1:3.6
- Interstitial/can velocity: 178 ft/min

Filter bags are made from 21-ounce woven fiberglass with PTFE membrane, acid-resistant coating. Each bag is 6 inches in diameter and 25 feet long. Split cage, carbon steel, 24-wire cages are used with 4,028 bags per chamber. There are 16 compartments total, four compartments in each electrostatic precipitator chamber, yielding a total of 16,112 bags for the project. Also, each blowpipe pulses 27 bags with two blowpipes per bag row.

PJFF Conversion Design and Construction

The ESP chambers had been partially converted to a pulse jet with the prior retrofit of the AHPC equipment. The walk-in outlet plenums, vaned outlet dampers, and outlet ductwork installed with the AHPC retrofit were retained (Figure 3). The precipitator plates and emitters, support channels, rappers, bags, cages, and tubesheets from the hybrid design were removed from each ESP chamber. Also, the gas-flow baffle plates were removed from the inlet pyramidal nozzles.

3. Keep the best, out with the rest. The AHPC retrofit technology walk-in plenums, dampers, and outlet ductwork were retained. The ESP and AHPC internal hardware and ESP external electric hardware was removed as part of the PJFF upgrade. The four separate chambers are shown with roof walk-in plenums and the long outlet ducts. Courtesy: Buell APC

After all internals were removed, new tube sheets were installed and supported by a shelf angle around the perimeter of each chamber. Three partition walls were installed in each chamber to compartmentalize each chamber into four pulse jet compartments. Each compartment uses off-line cleaning by closing off the existing dampers located on the roof of the outlet walk-in plenum.

No damper was added to the inlets of the compartments. An inlet transition duct with turning vanes was added to each inlet pyramidal nozzle that fed the gas flow to a pulse jet compartment inlet plenum that extended down the lower center of the chamber its full length (Figure 4). Gas flow entered each of the four compartments via a vaned opening on either side of the inlet plenum. The top of the rectangular inlet plenum has a peaked "roof" at the top to prevent buildup of ash from bag cleaning.

4. New entry created. Each ESP inlet pyramidal nozzle duct was modified with turning vanes and transition duct to connect to a PJFF inlet plenum that extends the length of the chamber’s centerline. Courtesy: Buell APC

For bag cleaning, 32 completely shop-assembled air header assemblies were installed using a 4-inch solenoid valve for each blowpipe. Each row of 54 bags on each tube sheet has two blowpipe assemblies with 27 bags per blowpipe and 19 rows per compartment (Figure 5). The blowpipe pulse discharge hole size varies along the length of the blowpipe to ensure equalized pulse air cleaning volume to each bag. For access to the header assemblies and solenoid valves, three new platforms were installed: two outboard of the end precipitator chambers (with weather cover) and one under the existing control room located between the two pairs of ESP casings. A walkway was added with a new side access door for bottom access to each pulse jet compartment

5. Ready for installation. These are three of the 608 required blowpipes in the fabrication prior to shipment to the Big Stone plant. A 4-inch solenoid controls the compressed air used by each blowpipe to clean the filter bags. A total of 608 pulse valves were used on the project. Courtesy: Buell APC

An Allen Bradley PLC with a Control Logix 5561 Controller was selected to manage the sequencing of the 608 pulse valves and 16 compartment outlet dampers. A cleaning cycle for the 16 compartments is initiated when the integrated average of the four chambers' pressure drop reaches a setpoint or by a timer control with a pressure drop setpoint override. The preferred pulse cleaning mode, with pulse pressures of 45 psi to 55 psi, is off-line cleaning, but the system has the capability of online cleaning to accommodate outlet damper maintenance, if required. Each pair of blowpipes on either side of a row of 54 bags is pulsed simultaneously in sequence from row 1 through row 19. In online cleaning mode, a staggered blowpipe pulsing sequence is used. The individual compartment tube sheet differential pressures are monitored and compared to the before cleaning values to display the bag cleaning effectiveness.

During the design phase, both a numerical model study and physical model study were performed on the PJFF flow configuration. To ensure optimum pulse cleaning of the 27, 25-foot-long bags on a blowpipe, blowpipe design and optimization laboratory tests were conducted by the pulse valve supplier.

Buell APC contracted Airflow Sciences Corp. to perform a flow model study to ensure that the new baghouse conversion configuration met the Institute of Clean Air Companies (ICAC) standards for flow uniformity. The flow study used both numerical and physical modeling techniques. The computational model of the Big Stone conversion scope was from the guillotine damper just upstream of the inlet nozzle to the ID fan inlets.

Numerical Model Study. The goals of the numerical modeling were to ensure that the flow split between compartments in a chamber met ICAC F-7 criteria (within ±10%) and to optimize gas flow distribution and minimize losses in the inlet transition to the fabric filter inlet manifold. The computational model found that the flow split between the four compartments in a chamber met the ICAC criteria, although several changes were made to the inlet transition vanes to further improve the flow distribution and reduce the flow losses below that of the baseline design.

Scale Model Testing. The goals of the physical modeling were to confirm the numerical modeling results, ensure that no significant ash buildup occurred in the ductwork and inlet manifold floor through dust deposition tests, and quantify the system pressure losses. The physical model testing was based on a 1/12 scale model (Figure 6). As the four chambers of the baghouse are identical, only a single chamber was modeled. The physical model scope extended from the inlet transition nozzle of the baghouse through the outlet ducts to the common duct that leads to the ID fan inlets.

6. Computer-designed and model-tested. A numerical flow study confirmed that the flow split and distribution met ICAC standards and that the inlet design kept flow losses to a minimum. A 1/12 scale model of one of the four identical chambers of the PJFF was tested to confirm the computational modeling results. Courtesy: Buell APC

The results of the physical modeling showed that there was good agreement between the numerical and physical model results. Dust deposition tests confirmed that the majority of dust was swept clean from the inlet manifold floor at 75% of full load flow velocity and no significant buildup of dust was observed at 100% flow. The flow split between the four compartments was 23.1%, 22.8%, 26.6%, and 27.5% — well within predictions.

Blowpipe Design and Optimization Tests

Goyen Controls Co. Pty Ltd., Sydney, Australia, conducted blowpipe design optimization laboratory tests. A 27-outlet blowpipe was fabricated per Buell's specification with additional pressure tap locations. Four-inch blowpipes and valves were selected to meet the pulse cleaning airflow requirements for 27 bags per blowpipe.

The goals of the blowpipe optimization tests were to determine the staggered pipe orifice sizes along the pipe that would provide equal pulse air volume to each bag (within ±10%); determine the optimum blowpipe air straightening nozzle diameter, length, and height above the tube sheet; and determine the air consumption required per blowpipe.

A clean filter bag is usually not very indicative of the cleaning performance with dust-laden filter bags when testing a blowpipe system. Rather than using clean filter bags, Goyan accurately simulated a dust-laden filter bag using a jet pump duct. A significant advantage of the jet pump duct is that it is possible to simulate a range of dust loadings by altering the position of the blast gate (altering the resistance to the pulse), thereby mimicking the varying dust loads on the filter bags. The jet pump duct is 3 meters long with a diameter of 150 mm. A blast gate is located 1 meter from the entry of the duct. A flow meter arrangement using an orifice plate is located at the exit of the duct. Pressure taps are located halfway between the duct entry and the blast gate. Test runs along the blowpipe outlets were conducted at 45 and 60 psi pulse pressure. A good distribution of cleaning flow along the blowpipe was achieved with cleaning flows within ±10% of the average, as designed.

Pulse Jet Conversion Installation

The outboard two ESP chambers were converted during the spring of 2007, one at a time, starting in early March. The first chamber was removed from service with a short outage for blanking plates to be installed in the chamber’s inlet and outlet rectangular ducts. The first chamber was converted during a six-week period, with the unit at reduced load, and started up in April 2007. Conversion of the second outboard chamber followed during another six-week period. Start-up of the second converted chamber occurred in June 2007. During the summer and early fall, the unit operated with the two converted pulse jet chambers and the two chambers with the AHPC design. The remaining two ESP chambers were converted to pulse jet operation during a scheduled late fall outage. The completed conversion was fully operational in December 2007.

All performance guarantees were met, including stack opacity and pressure drop. The stack opacity was close to zero, prompting Big Stone Plant to forego the outlet emission tests. In 2008, Big Stone Plant Unit 1 set a new annual generation record. Operating restrictions caused by opacity problems or ID fan pressure drop limits are just a memory.

——Thomas W. Lugar (twl@fkinc.com) is vice president of the Buell Division of Fisher Klosterman, A CECO Environmental Company. Jeff Endrizzi is plant manager, Stu Schreurs is principal engineer, and DJ Haggerty is plant engineer at Otter Tail Power Company’s Big Stone Plant.

Close Window