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SCALEUP TESTS AND SUPPORTING RESEARCH FOR THE DEVELOPMENT OF DUCT INJECTION TECHNOLOGY

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FINAL REPORT

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1.0 ABSTRACT

DOE'S Duct Injection Test Facility at Ohio Power Company's Muskingum River Plant was modified to enable performance of a comprehensive test program concerning duct injection of sorbents for SO_2 control. Injection of slaked lime slurries and injection of dry calcium hydroxide powder with humidification were carried out under a variety of process conditions. Slaked lime slurry injection was found to be superior in both operational reliability and SO_2 removal capability compared with dry hydrated lime injection with humidification. Calcium utilization of 50% was achieved with 50% SO_2 removal at the ESP outlet with recycle of unreacted sorbent collected in the precipitator hoppers. Electrostatic precipitator collection performance was found to be highly variable with sorbent injection, especially with close approach to saturation temperatures and high inlet mass loadings. Small-scale tests with a fabric filter in parallel with the precipitator indicated 5 to 10% more SO_2 removal could be obtained across the fabric filter than the ESP for all test conditions. Over 95% SO_2 removal was achieved with the fabric filter using a two stage cooling process in which the filter was cooled below the operating temperature of the duct spray dryer.

2.0 EXECUTIVE SUMMARY

2.1 Introduction

Duct Injection Technology is an SO_2 removal process that is intended to provide a simple, cost effective method for controlling SO_2 emissions. The technology is expected to be applicable at older power stations that are not subject to regulation under New Source Performance Standards. Performance goals for the process are to achieve a minimum of 50% SO_2 removal at a cost not to exceed $500/ton of SO_2 removed.

Gilbert/Commonwealth (G/C) and Southern Research Institute have completed a project under DOE sponsorship entitled "Scaleup Tests and Supporting Research for the Development of Duct Injection Technology". The project included extensive modifications to DOE's Duct Injection Test Facility (DITF) located at the Muskingum River Plant of Ohio Power Company. A comprehensive test program was performed at the facility to evaluate SO_2 removal and overall process operability with duct injection of slaked lime slurries and dry injection of calcium hydroxide powder with humidification. Detailed results from the project are presented in several topical reports.[1-3] This final report summarizes the work performed to modify the DITF and presents results from the experimental program.

After the system modifications were completed, the DITF was capable of testing duct injection technology over a range of process operating conditions. The essential elements of the system are:

- a 50,000 acfm slipstream which includes a duct reaction chamber and a downstream electrostatic precipitator,
- lime storage silos and a lime slaker,
- slurry and dry solids handling and injection equipment which permitted injection of slaked lime slurries or dry hydrated lime with humidification, either with or without ash/sorbent recycle, including a dedicated air compressor,
- a dilution burner system for control of slipstream inlet SO_2 and water vapor concentrations,
- comprehensive data acquisition and process control systems, and
- ash handling and storage equipment for collection and storage of waste ash/sorbent mixtures produced by the pilot plant.

2.2 Literature Review

A comprehensive compilation and analysis of thermodynamic data relative to duct injection processes was performed.[4] This analysis confirmed the generally accepted view that the limiting processes applicable to duct injection are more in the realm of mass transfer than chemical kinetics or chemical thermodynamics.

A review of previous work performed in DOE-sponsored proof-of-concept test programs was also conducted as a part of the literature review. Predictions of SO_2 removal as a function of Ca/S ratio were developed by General Electric (GE) and by Bechtel in separate projects involving duct slurry injection. A comparison of these predictions based on an approach temperature in the 35-40° F range indicated similar results, even though the inlet SO_2 concentrations were about 2000 ppm in the Bechtel study and nearly 4000 ppm in the GE project. Both projects indicated 50% SO_2 removal was achieved with a Ca/S ratio of approximately 1.1 without recycle. In contrast, a study of dry calcium hydroxide injection with humidification conducted by Dravo indicated that only 30-40% SO_2 removal was achieved at a Ca/S ratio of 1.8 at a 30° F approach.

The literature review included a brief examination of existing mathematical models dealing with (1) removal of SO_2 with sorbent, and (2) collection of particles in ESPs. Although a considerable amount of work has been done in the area of spray dryer modeling, major deficiencies remain in the treatments of fluid mechanics, droplet dispersion, and the role of the liquid phase resistance to mass transfer. Much less work has been done on modeling sorbent/droplet collision in the dry injection process. The one model reviewed for this process, while useful for illustrating certain trends, is deficient in its treatment of the two fluid jet dynamics and droplet trajectories. A comprehensive process model is currently under development as a part of a separate DOE-sponsored contract with other organizations.

At the time the literature review was conducted, none of the models simulating ESP performance had been adequately evaluated with duct injection of sorbent. During the course of this project, comparisons were made of predictions of two models with results obtained at the DITF. These comparisons indicated the models are not useful in predicting performance when low resistivity electrical reentrainment is occurring to a significant degree.

2.3 Experimental Results

For the purpose of this discussion, "conventional" duct injection means duct injection of dry calcium hydroxide with humidification, or injection of a slurry of slaked lime, followed by particulate collection in a downstream ESP. Within the constraints of this definition, the process mode providing the best performance in terms of operability and SO_2 removal consisted of injection of a slaked lime slurry using two fluid Lechler nozzles. The program goal of 50% SO_2 removal at the ESP outlet can be obtained with slurry injection at a 20-30° F approach to saturation with a Ca/S ratio of 1.0 without recycle. Slurry injection was found to be superior to dry hydrate injection in both ease of operation (control of deposits) and in calcium utilization.

Even though the project goal of 50% SO_2 removal could be achieved without recycle using slurry injection at a 20-30° F approach, higher operating temperatures are desirable to provide a margin of safety for avoidance of duct deposits. Higher calcium utilizations are also desirable, since sorbent cost represents the largest cost element of a duct injection process. Therefore, a significant effort was directed toward recycling ash/sorbent mixtures collected from the precipitator hoppers. Two test cases were evaluated: a low Ca/S ratio (1.05 reagent Ca/S ratio, recycle ratio = 2.05, 44° F approach) for 50% SO_2 removal, and a high Ca/S ratio (1.7 reagent Ca/S ratio, recycle ratio = 1.49, 24° F approach) for 88% SO_2 removal. Testing was continued for each of these test cases until the amount of calcium hydroxide in the recycle ash equaled that predicted for an equilibrium condition.

For the high Ca/S ratio case, due to limitations in the amount of ash that could be delivered by the recycle ash weighbelt feeder, it was difficult to maintain a recycle ratio above 1.5. If it had been possible to reach the desired recycle ratio, SO_2 removal at the ESP outlet would probably have exceeded 90%.

Although the equipment at the DITF was not designed to provide a continuous recycle operation, the feasibility of using recycle ash from the ESP hoppers to increase calcium utilization was successfully demonstrated. Of particular significance was the finding that the reactivity of unutilized calcium in the recycle ash was the same as that observed for the calcium in slurries of slaked lime with no recycle ash present.

The power requirement for compressed air used in two-fluid nozzles is another important economic consideration in the application of duct injection. The geometry of the horizontal test duct at the DITF (40 by 50 inches) placed constraints on nozzle arrangement and performance which are more severe than those which would be encountered in a full-scale duct. An array of six 2.88 gpm Lechler nozzles was used for most of the testing, and it was found to be necessary to operate these nozzles at an air to liquid ratio of 0.8 to 1.1 instead of the design value of 0.5 in order to avoid duct deposits. However, these high air requirements were an artifact of the necessity of operating the nozzles at less than the design value of liquid flow, and of the small duct used for a reaction zone.

A single 12 gpm Lechler nozzle was available for testing during the latter part of the experimental program. It was found that this large nozzle could be operated at an A/L ratio of 0.5 without duct deposits, and without any measurable change in SO_2 removal in comparison with the smaller nozzles. Since this large nozzle is capable of treating the equivalent of 15 MWe of flue gas, it has the potential for providing an economical means of slurry injection for full-scale applications of duct injection. More operating experience is needed with this nozzle in a larger duct to determine if the favorable results observed at the DITF with this nozzle can be obtained over an extended operating period.

Electrostatic precipitator performance is a critical consideration for a utility evaluating a duct injection process. The DITF ESP was first tested with flue gas from the host boiler at an inlet temperature of 315°F with a gas flow which resulted in a specific collection area (SCA) of 329 ft^2/1000 acfm. Under these conditions, collection efficiency was 99.9+%, as would be expected for an ESP of this size collecting fly ash with a resistivity in a favorable range.

A limited amount of precipitator testing was performed with dry sorbent injection because of the low calcium utilizations. With coplanar injection of calcium hydroxide powder and water, the best performance was a collection efficiency of 99.94% at an SCA of 336 ft^2/1000 acfm and a 37°F approach to saturation. Variability of performance was indicated, however, by the measurement of 99.61% at an SCA of 345 ft^2/1000 acfm and a 45°F approach to saturation. For both test series, severe corona current suppression was noted in the inlet field.

More extensive ESP testing was performed with slurry injection, but substantial performance variability was also encountered with this process mode. At approach temperatures ranging from 34°F to 43°F, collection efficiency ranged from 99.94% (at a 34°F approach) to a low of 99.23 (at a 41°F approach) with an SCA of ~390 ft^2/1000 acfm. Severe ESP performance degradation was observed at a 25°F approach with 1.7 Ca/S ratio with recycle. Under these conditions of high inlet mass loading and low ash resistivity, electrical reentrainment is believed to be the cause of the poor performance. Normal voltage-current relationships and electrical operating points were obtained during the period of performance degradation, which suggests reentrainment of dust due to low resistivity as the most likely cause of the excessive emissions. Unfortunately, the time available for testing precluded a study of additives which might have reduced or eliminated the reentrainment problem by changing the cohesive properties of the collected dust layers.

Comparisons were made between measured particle-size dependent performance of the ESP and predictions made by three different versions of an ESP mathematical model for an experiment with slurry injection. This comparison showed that none of the models performed an adequate prediction of fine particle (less than 2.0 microns diameter) collection efficiency. In addition, the models do not contain algorithms which provide a means of estimating the degree of electrical reentrainment which might be expected as a function of process operating conditions. Thus, although high values of collection efficiency with sorbent injection were sometimes measured, precipitator performance remains a source of concern, especially for potential application sites with ESP's having lower SCA values than the one installed on the DITF.

In view of the potential problems with ESP performance and the need to increase calcium utilization, a significant effort was directed toward evaluating the performance of a pulse-jet fabric filter installed downstream of duct slurry injection using a side-stream fabric filter device (SSFF). Although the SSFF is quite small (2.7 acfm), it has been successfully used to evaluate fabrics and dust filtration characteristics at a number of pulverized coal utility power boilers.[5,6]

Measurements of SO_2 removal at the outlet of the SSFF, which was installed at the DITF in parallel with the ESP, indicated that 5 to 10% more SO_2 removal (absolute basis) is obtained across the fabric filter than across the ESP for all test conditions. In addition, the filter cake was easily cleaned by the simulated pulse-jet action in the apparatus, and no handling difficulties were observed with the dust collected in the hopper. Further experiments were conducted with the SSFF using a unique two-stage cooling process. Results from this work indicated over 95% SO_2 removal could be achieved with the duct operating at a 25°F approach and the SSFF operating at a 10°F approach with a reagent Ca/S of 2.0 and 2000 ppm SO_2 at the system inlet.[2]

Figure 2-1 presents a graphical summary of SO_2 removal obtained with the various process operating conditions studied during the course of the project. This graph illustrates the improvement in SO_2 removal achieved by slurry injection compared with dry calcium hydroxide injection and humidification. Also illustrated are the increments in SO_2 removal measured across the precipitator, the SSFF, and the SSFF when it is cooled below the temperature of the duct spray dryer to within 10°F of saturation.

In view of the favorable results obtained with the SSFF, the use of a fabric filter should be given serious consideration if a utility boiler is installing a duct injection or spray dryer SO_2 control process upstream of a relatively small ESP. Additional operating experience with a pulse jet fabric filter using full-scale bags is needed to determine if the results obtained with the SSFF can be duplicated in full-scale applications.

2.4 Operation and Maintenance Experience

From start-up of the DITF on April 25, 1990, through shutdown on February 27, 1992, the DITF completed 471 hours of testing with dry hydrated lime injection, 1153 hours of testing with slurry

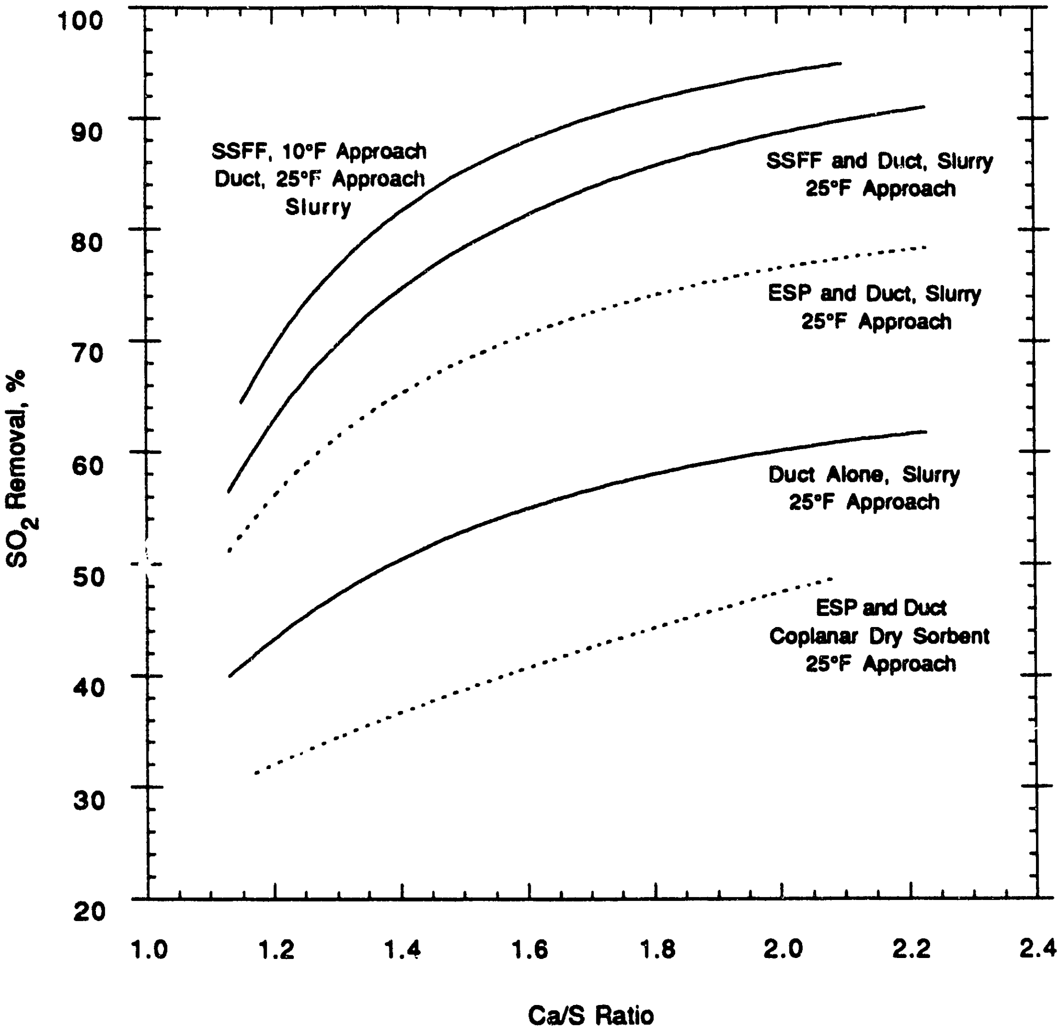

Figure 2-1. Summary of SO$_2$ removal obtained with various process operating conditions.

injection, and 240 hours of slurry/recycle ash injection. This period includes a three month outage by the Ohio Power Company in the fall of 1990 to rebuild part of the Unit 5 boiler. During this time, the DITF experienced a number of small problems typical of pilot plant operation. However, some operation and maintenance issues have emerged that are applicable to full-scale operation.

Lechler supersonic nozzles have been used for slurry injection since slurry testing began in August of 1990. The nozzles are designed with erosion-resistant silicon carbide inserts, and have required minimum maintenance. No visible wear has been detected on these inserts. The key to maintaining consistent nozzle performance has been adequate flushing when shutting down plus periodic inspection and acid cleaning.

A major problem occurs at the DITF when sorbent is injected as dilute slurry with less than 20% solids. With such dilute slurries, significant duct wall deposits can occur even at moderate approach temperatures. Duct deposits are minimized only when using concentrated slurries with 20% or more solids content. Extended tests of up to 120 hours and approaches as close as 25°F have been run with concentrated slurries without generating significant deposits. Duct deposits were less significant with slurry injection than with dry injection under similar test conditions.

It was found that deposits could be controlled by soot blowers and hoppers at conditions that minimize deposition. However, at conditions which promote deposit formation (dilute slurries, clogged nozzles, very close approach temperatures), these systems do not control solids buildup in the duct. On these occasions, the DITF eventually had to be shut down and the horizontal test duct cleaned out manually before testing could be resumed.

2.5 Conclusions and Recommendations

- Slurry injection is clearly superior to dry injection with humidification both in SO_2 removal and in operational reliability. With slurry injection, SO_2 removal efficiencies of 50% (44°F approach to saturation) with a reagent Ca/S of 1.0 and 88% (24°F approach) with a reagent Ca/S of 1.7 were achievable using recycle. These results exceed the DOE-stated goals for the Duct Injection Technology Program. Calcium utilizations and SO_2 removals at the ESP exit with slurry injection without recycle were similar to those obtained by DOE proof-of-concept contractors in previous projects. (Dry injection with additives was not within the scope of this project.)

- The feasibility of using recycle ash from the ESP hoppers to increase calcium utilization was successfully demonstrated. Of particular significance was the finding that the reactivity of unutilized calcium in the recycle ash was the same as that observed for the calcium in slurries of slaked lime.

- Commercial spray nozzles are available to support duct injection technology. Although most testing was performed with an array of six 2.88 gpm nozzles which required operation at relatively high A/L ratios, a single 12 gpm nozzle was available for testing during the latter part of the experimental program. It was found that this large nozzle could be operated at an A/L ratio of 0.5 without generating duct deposits, and without any measurable change in SO_2 removal in comparison with the smaller nozzles. Since this larger nozzle is capable of treating the equivalent of 15 MWe of flue gas, it has the potential for providing an economical means of slurry injection.

- Electrostatic precipitator performance was found to be highly variable with duct slurry injection. At approach temperatures ranging from 34 to 43°F, collection efficiency ranged from 99.94% (at a 34°F approach) to a low of 99.23% (at a 41°F approach) with a specific collection area of ~390 ft^2/1000 acfm. Severe ESP performance degradation was observed at a 24°F approach with a 1.7 Ca/S ratio with recycle. Electrical reentrainment of low resistivity dust is believed to be the cause of the variability in collection performance.

- Small-scale tests with a fabric filter system installed in parallel with the DITF ESP indicated that 5 to 10% more SO_2 removal could be obtained across the fabric filter than the ESP for all test conditions. Results from experiments using a unique two-stage cooling process upstream of the filter indicated that over 99% SO_2 removal across the duct and fabric filter could be achieved with a Ca/S ratio of 2.0 while good filtration performance and dust handling characteristics were maintained.

- Potential application sites for duct injection with small ESPs should consider the installation of a pulse-jet fabric filter. A follow-on proof of concept test program is needed to demonstrate this enhancement of the technology.

- Commercially available process control technology can be successfully used to control the duct injection process. The test facility control system was reconfigured using conventional techniques to successfully control the process outlet SO_2 concentration to demonstrate this capability.

- While duct deposits developed on occasion in the test facility, it is anticipated they can be avoided in a large-scale installation with a conservative approach to design and operation. The need for duct hoppers in a larger scale installation was not established based on the experience from the DITF. It was found that deposits could be controlled by soot-blowers at conditions that minimize deposits. However, at conditions which promote deposit formation (dilute slurries, clogged nozzles, very close approach temperatures), soot blowers were not effective, and the DITF eventually had to be shut down for manual cleaning.

- The waste product generated by the process is dry and readily handled using conventional materials handling technology for recycle and disposal. The waste was classified as non-hazardous by the State of Ohio and may be disposed of in a landfill. Ash/sorbent mixtures from the DITF ESP were subjected to the Toxic Characteristic Leaching Procedure (TCLP) to measure the leachability of these samples for heavy metals. The TCLP results suggest that neither the baseline ash nor the duct injection ash could be classified as hazardous by virtue of their content of leachable metals.

- The other topical reports produced on this project contain detailed presentations of data obtained during the project. Under a separate contract, United Engineers and Constructors, Inc. (UEC) and Babcock and Wilcox, Inc. (B&W) are using these and other data to develop a comprehensive process model. For this reason, the subject project does not include a correlating or modeling effort, and readers should refer to the forthcoming report on the UEC/B&W project for this information.

3.0 INTRODUCTION

3.1 Project and Task Descriptions

Duct injection has been investigated under the sponsorship of the U.S. Department of Energy with the objective of developing a low cost, retrofit technology for controlling SO_2 emissions from coal-fired electric power stations. This is a final summary report on a project entitled "Scaleup Tests and Supporting Research for the Development of Duct Injection Technology". The project was conducted by Gilbert/Commonwealth, Inc. and Southern Research Institute using the Duct Injection Test Facility (DITF) at Unit 5 of the Ohio Power Company's Muskingum River Station in Beverly, Ohio.

Descriptions of the four tasks comprising the project are provided in the following paragraphs.

Task 1--Project Definition

Subtask 1.1--Literature Review

A literature review and annotated bibliography were prepared which concentrated on previous duct injection process data and fundamental mechanistic issues. This work was published as "Topical Report No. 1--Literature Review".[4]

Subtask 1.2--Work Plan Preparation

A detailed work plan was submitted to and approved by DOE. The plan presented detailed descriptions of all activities required for successful completion of the project.

Subtask 1.3--Host Utility Agreement

G/C negotiated an agreement with American Electric Power (AEP) for use of the Beverly Test Site. The agreement covers interface points, purchase of all utilities and services, access to the test facility by contractor personnel, construction requirements, and demolition/restoration requirements.

Subtask 1.4--Waste Disposal Plan and Permits

G/C held discussions with AEP and local officials concerning the necessary permits to permit the project to proceed. All required permits were obtained.

Task 2--Modification of the Beverly Test Unit

This task consisted of all design, procurement, construction, and start-up activities required to modify the Beverly Test Unit so that the test program described in Tasks 3 and 4 could be accomplished. More detailed descriptions of this task are contained in Section 3.2, Facility Descriptions and Modifications.

Task 3--Enhanced Data Development

This task consisted of test plan preparation for each subtask, operation and maintenance of the test facility, performance of a measurement program designed to fully characterize duct injection technology, and preparation of topical reports documenting test results. Subdivisions of the effort are provided in the following subtask descriptions.

Subtask 3.1--Characterize System Performance

This task consisted of the initial phase of experimental work conducted at the DITF between April 30, 1990 and February 4, 1991. Work performed included the following topics:

Characterization of electrostatic precipitator (ESP) performance without sorbent injection.

Studies of procedures to avoid wall wetting with spray nozzles.

In-situ measurement of droplet size distributions produced by the spray nozzles.

Studies of SO_2 removal with dry hydrated lime injection and humidification.

Studies of SO_2 removal with injection of a slurry of slaked lime.

System operation and maintenance tasks as required for the performance of the test program.

Subtask 3.2--Scale-up Testing

This task consisted of extensive testing of both dry and slurry mode injection of calcium hydroxide. Effects of sorbent injection on ESP performance were studied in detail with dry calcium hydroxide injection plus humidification, and with slurry injection using slurries made from slaked lime, and from mixtures of slaked lime and recycle ash. For most experiments, slurry injection was evaluated using six two fluid Lechler nozzles at a flow rate of 2.88 gpm. Limited testing was performed using a single 12 gpm Lechler nozzle to evaluate operation at a design air to liquid ratio of 0.5.

Subtask 3.3--Advanced Configurations

Most of the experimental work with this task was concerned with testing a small side stream fabric filter operating in the pulse jet mode in parallel with the DITF ESP. The purposes of this work were to evaluate the additional SO_2 capture obtained with a fabric filter downstream from a duct injection process, and to evaluate the filtration characteristics of the filter cake collected at low approach temperatures. In addition, a limited amount of testing was performed with calcium chloride addition to slurry/recycle ash mixes to investigate the effect of this additive on SO_2 removal.

Subtask 3.4--Process Controls

An Allen Bradley 5/25 programmable logic control system was used to operate the DITF. This same system was used to control the outlet SO_2 emissions to a predetermined level while key process variables were allowed to change within prescribed limits. The objective of this exercise was to demonstrate that the basic philosophy of control of outlet SO_2 values is an acceptable method of control for a full-scale application of duct injection technology.

Subtask 3.5--Failure Modes

Various process upsets and equipment failures occurred during the course of the project. The causes of these events were analyzed, and recommendations were made for changes in future system designs to minimize unscheduled shutdowns.

Subtask 3.5--Waste Characterization

Samples of ash from the Unit 5 ESP and from the DITF ESP were subjected to the Toxic Characteristic Leaching Procedure to measure the leachability of these samples for heavy metals. The purpose of this task was to evaluate the effect of the duct injection process on the waste properties relevant to landfill disposal.

Task 4--Mathematical Model Validation

This task contained two subtasks, 4.1 and 4.2, which were originally conceived as validating first and second generation process models. However, the models were not available during the time performance of this task was required, and the effort was therefore directed toward supplying data which could be used by UEC/B&W in their DOE-sponsored model development project. A topical report was prepared which compared selected results from the DITF project with those predicted by an existing process models.

Other subtasks contained within Task 4 include preparation of this final report (Task 4.5), and the dismantling and site restoration (Task 4.4) of the DITF per the host utility's requirements. This task has been delayed pending a decision on the ultimate disposition of the facility.

Appendix A contains a table giving a weekly description of work performed at the DITF.

3.2 Facility Description and Modifications

3.2.1 Description of the Duct Injection Test Facility (DITF)

The Duct Injection Test Facility of the Department of Energy (DOE), located in Beverly, Ohio, at the Muskingum River power plant of Ohio Power Company, has been used for this contract to test alternative duct injection technologies. The technologies tested include slurry sorbent injection of slaked pebble lime with dual fluid nozzles and pneumatic injection of dry hydrated lime with flue gas humidification before or after sorbent injection. The test facility was modified to test a range of flue gas SO_2 concentrations and a range of flue gas temperatures in vertical and horizontal duct test sections. This test program is part of a larger DOE program to fully characterize low cost, retrofittable dry SO_2 removal technologies for application to existing power plants.

In a two year test program, two types of duct injection technologies were tested: (1) slurry sorbent injection of slaked pebble lime, using dual fluid nozzles; and (2) pneumatic injection of dry hydrated lime, with flue gas humidification before and after sorbent injection. A wide range of flue gas SO_2 concentrations and temperatures was utilized for testing.

3.2.1.1 System Description

The DITF operates as a 12 MWe, 50,000 ACFM "slipstream" system on Ohio Power Company, Muskingum River Unit No. 5, in Beverly, Ohio. The boiler is a B & W dry-bottom pulverized coal, front and rear wall-fired unit, rated at 585 MW (net).

The unit is base-loaded but it can drop to half load during summer months, usually between midnight and morning. The plant burns local coal with an as-received sulfur content of about 4.2%. The nominal flue gas conditions at the exit of the air preheater (feeding the test facility) are as follows:

N_2	75.6%
CO_2	11.9%
H_2O	7.5%
O_2	4.6% (30% excess air)
SO_2	3200 ppm
Ash	3.4 gr/acf
Molecular Weight	29.46
Temperature	325°F

The slipstream is taken from the existing air preheater discharge, through ductwork with three test stations to the DITF precipitator, then to an induced draft fan, and back to the existing precipitator inlet. A provision also exists to bypass the pilot precipitator and allow gas to flow through a high-efficiency cyclone. Figure 3-1 is a schematic drawing of the DITF.

The DITF precipitator is a weighted-wire design, consistent with the majority of older units for which the sorbent duct injection technology is intended. The precipitator has four independent electrical fields and is designed for an SCA of 360 ft^2/1000 acfm at a system inlet flow rate of 40,000 acfm at 190°F. Although this design is somewhat larger than most units that are candidates for duct injection technology, it provided additional flexibility for the test program.

The test facility was originally designed to deliver slaked pebble lime slurry to a rotary atomizer in one of three duct locations--one location in a vertical duct and two locations in a horizontal duct. Under this contract new equipment was designed and installed to test two different types of duct injection technologies: (1) slurry sorbent injection of slaked pebble lime, using dual fluid nozzles; and (2) pneumatic injection of hydrated lime, with flue gas humidification before or after sorbent injection. The new equipment consisted of:

- Flue gas dilution air heater to vary SO_2 content and temperature of the incoming gas.
- Flue gas steam humidifier.
- Slurry sorbent injection pumps and nozzles.
- Hydrated lime silo and blowers.
- Flue gas humidification nozzles and water pump.
- Ash recycle system.

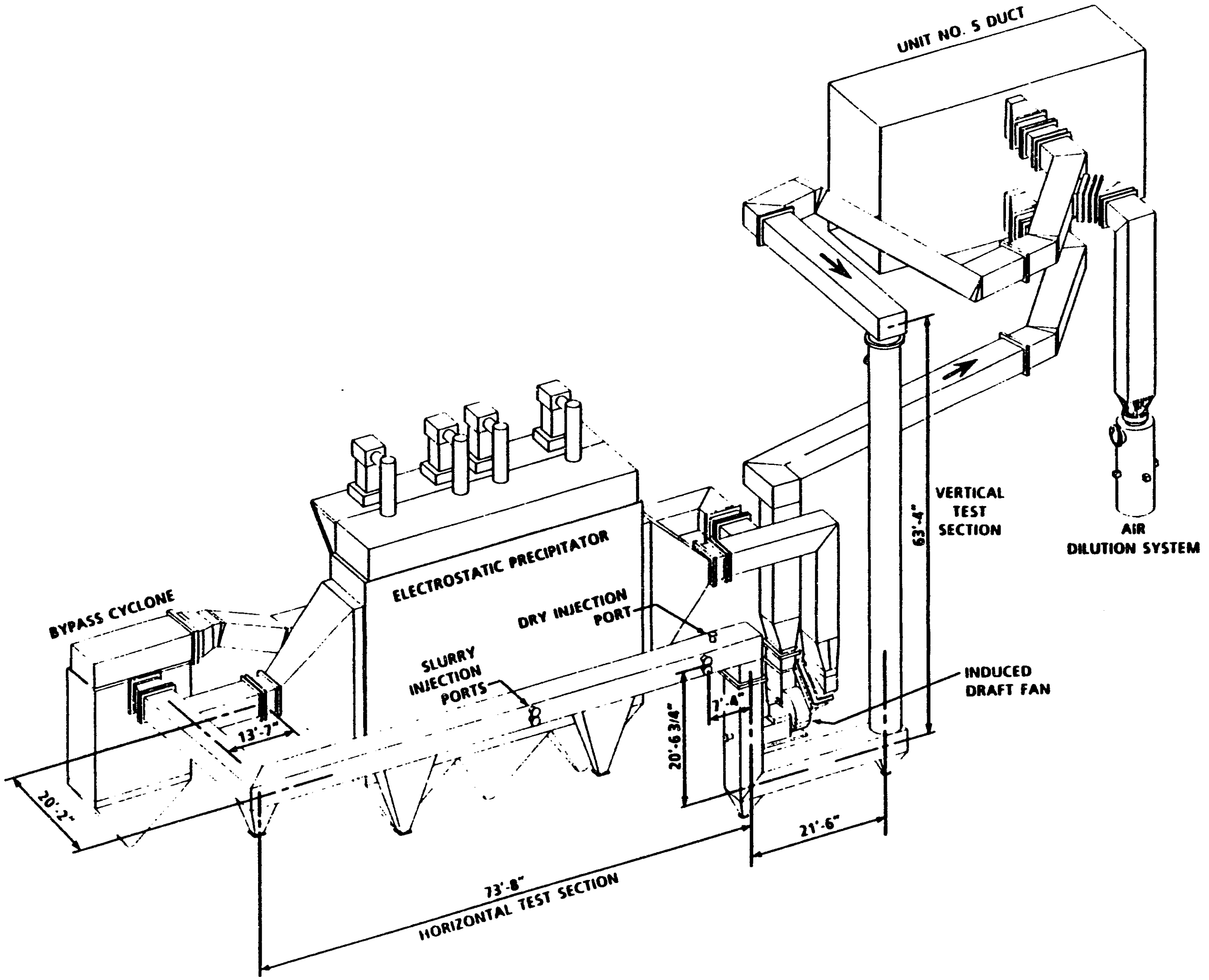

Figure 3-1. Schematic of Duct Injection Test Facility.

- Compressed air system.
- Duct hoppers and cleaning systems.
- Waste ash silo.
- State-of-the-art programmable logic controller and data acquisition system.

Considerable flexibility was designed into the facility to provide the capability of testing over a wide range of process conditions. These capabilities include the following:

- Flue gas velocity of 20-60 ft/s which corresponds to a gas flow of 16,700-50,000 acfm at the inlet conditions.
- Inlet gas temperature 275-320° F.
- Inlet gas SO_2 concentration of 1100-3200 ppmv.
- Sorbent addition at a Ca/S ratio of 1.0-2.0 (nominal limits).
- Duct residence time of 0.5-3.0 s.
- Approach to adiabatic saturation temperature of 20-80° F.
- Recycle of spent sorbent for either slurry or dry sorbent injection.

Figure 3-2 shows a simplified process flow diagram of the facility. Table 3-1 lists the major equipment capacities by system. The reader is referred to the Project Work Plan, Gilbert/Commonwealth Report 2787, for a more detailed description of equipment and systems. Construction was completed in May 1990. Testing began in April 1990 and was completed at the end of February 1992. The site is currently mothballed.

3.2.1.2 Flue Gas Dilution System

The SO_2 concentration of about 3200 ppm in the flue gas received from Unit 5 is set by the coal burned and the operating excess air level. The only practical method of reducing the SO_2 concentration to 1100 ppm is by flue gas dilution, since burning lower sulfur coal was not an option. Various methods of diluting the flue gas were evaluated and an approach was developed based on combustion of No. 2 fuel oil to heat ambient air for flue gas dilution. Natural gas is not available on site.

The system consists of a dilution air fan, combustion air fan, an air heater firing No. 2 fuel oil and control equipment. The heated air leaving the air heater is humidified to match the Unit 5 flue gas moisture concentration by adding steam at the outlet of the air heater. The overall air flow rate is controlled by the dilution air requirements to achieve a desired SO_2 concentration at the inlet to the test facility. The dilution air temperature is controlled by the firing rate of the air heater to maintain the desired flue gas temperature at the test facility inlet.

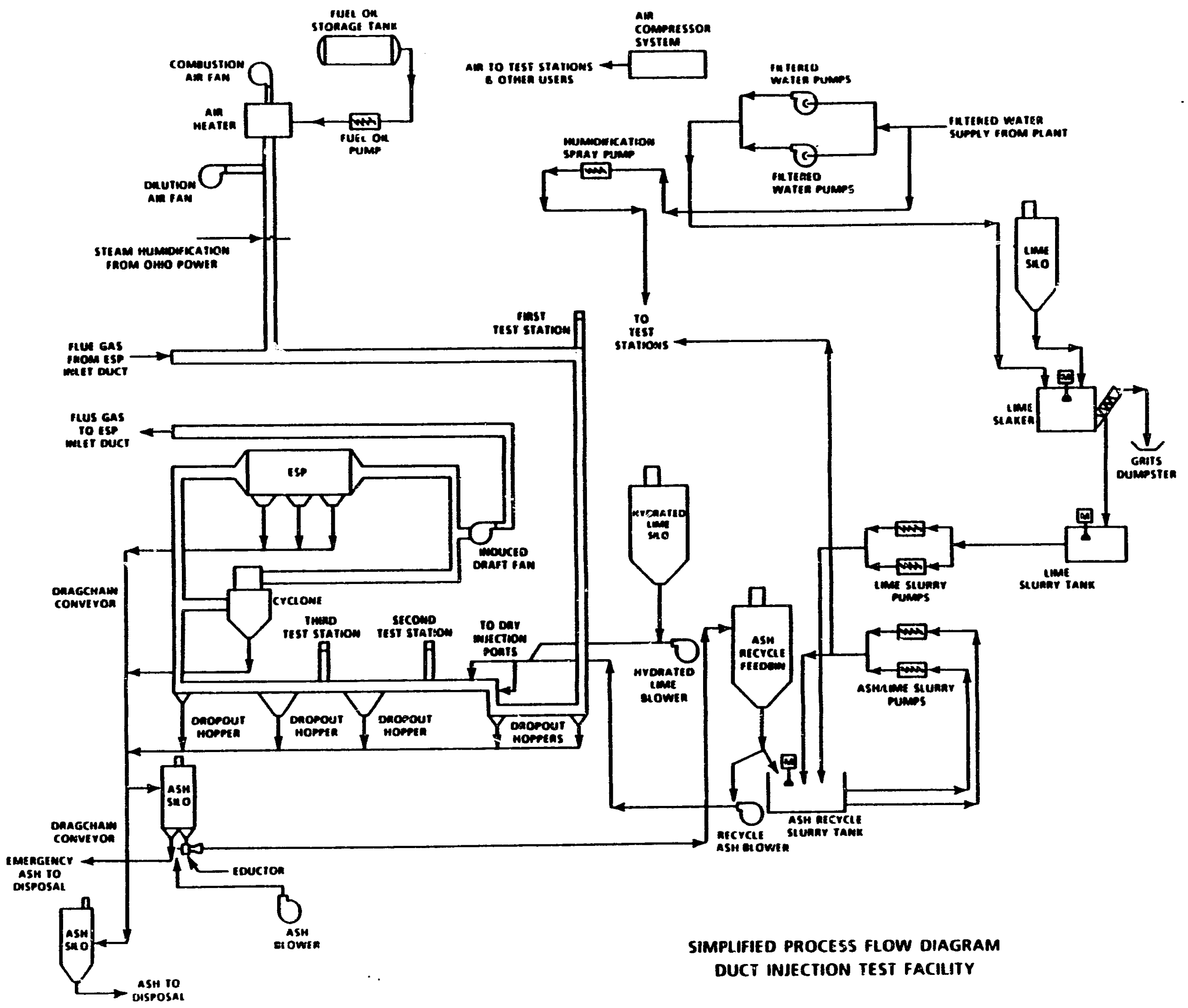

Figure 3-2. Simplified process flow diagram.

TABLE 3-1

Major Equipment Capacities

Description	Max. Capacity
Air Compressor System	
Air Compressor	2200 SCFM
Air Receiver	450 cu. ft.
Duct Cleaning Receiver	100 cu. ft.
Ash Collection System	
Drag Chain Conveyors	5 tons/hr.
Rotary Airlocks (old)	2 cu. ft/min.
Rotary Airlocks (new)	26 cu. ft/min.
Duct Hopper A	13 cu. ft.
Duct Hopper B	13 cu. ft.
Duct Hopper 1	117 cu. ft.
Duct Hopper 2	117 cu. ft.
Duct Hopper 3	19 cu. ft.
ESP Hopper 1, 2, & 3	300 cu. ft.
Waste Ash Silo	4500 cu. ft.
Recycle Ash Silo	5000 cu. ft.
Dilution Air System	
Dilution Air Fan	26000 ACFM
Combustion Air Fan	1400 ACFM
Fuel Oil Tank	3000 Gals.
Steam Humidification	4400 lbs/hr.
Air Heater	8,500,000 BTU/hr.
Fuel Oil Pump	1.7 GPM
Dry & Slurry Injection Systems	
Ash Recycle Feed Bin	290 cu. ft.
Hydrated Lime/Silo	2000 cu. ft.
Recycle Feed Belt	4000 lbs/hr.
Lime Feed Belt	2600 lbs/hr.
Ash REcycle/Slurry Tank	1000 gals.
Moyno Pump	34 GPM
Lechler/P-H Nozzles	2.8 GPM
Slaker	2080 lbs/hr.
Existing Slurry Holding Tank	2800 gals.
Pebble Lime Silo	2500 cu. ft.
Slurry Flow Meter	18 GPM
Humidification Water Flow Meter	15 GPM

TABLE 3-1 (continued)

Description	Max. Capacity
<u>Electrostatic Precipitator (Weighted Wire)</u>	
Transformer Rectifiers (inlet)	15 KVA, 225 MA(DC)
Transformer Rectifiers (outlet)	22 KVA, 330 MA(DC)
Number of Chambers	1
Number of Bus Sections:	
wide	1
deep	12
Number of Gas Passages	10
Space of Gas Passages	9 in.
Collecting Surface Height	24 ft.
Collecting Surface Depth	36 ft.
Total Area of Collecting Plate	17280 sq. ft.
Specific Collecting Area	
Per 1000 CFM	345.6
Total Number of Electrodes	480
Total Number of Rappers	36
Voltage Rating of T-R, Avg.	45 KV(DC)
<u>Miscellaneous</u>	
System I.D. Fan	60000 ACFM @ 325°F
Dampers Seal Air Fan	2000 ACFM
Process Water Pumps	40 GPM
Humidification Water Pump	30 GPM

The use of dilution air has some limitations for the test conditions of high incoming flue gas temperatures and high SO_2 concentrations. At high SO_2 concentration test conditions with little requirement for the dilution air, there is limited cooling capability available from the dilution air. The majority of tests were conducted at SO_2 concentrations of approximately 1900 ppm. At incoming SO_2 concentration of 3200 ppm and test SO_2 concentration at or below 1900 ppm, the dilution air is adequate for temperature control.

Figure 3-3 shows the limits for controlling temperature using dilution air with steam humidification. The flue gas test temperature control range with dilution air temperature control is dependent upon the entering flue gas temperature, ambient temperature, and amount of SO_2 dilution required. The graph indicates the maximum inlet flue gas temperature and SO_2 concentrations at which test section entrance temperatures are obtainable with dilution air cooling.

The use of dilution air for SO_2 control will change the flue gas moisture, oxygen, and CO_2 content and also affect the saturation temperature. By matching the flue gas moisture content with steam humidification and controlling the flue gas temperature, the effect on saturation temperature is minimized.

Changes in the oxygen concentration are not of major importance since the low-temperature reaction of SO_2 with sorbent leads to the formation of calcium sulfite. This is formed without the participation of oxygen, unlike the calcium sulfate produced in high temperature sorbent processes.

Changes in the CO_2 concentration over the range caused by the dilution burner system are considered unimportant. This conclusion is based on the fact that reaction rates of sorbent with CO_2 are almost negligible compared with the rates of reaction with SO_2 under conditions of interest for this project.

3.2.2 Description of the Process Control System

The DITF instrument and control system was developed from a mixture of existing equipment hardware and software and a new Allen-Bradley Programmable Logic Controller (PLC) 5/25 control system. All of the process and equipment control is assigned to the new PLC system while the existing Data Acquisition System (DAS) was strictly limited to data acquisition. Figure 3-4 shows a schematic of the PLC and DAS systems.

All new equipment start and stop functions are performed via a work station in the control room. The work station consists of a keyboard and CRT and has the capability of displaying the various process loops in real-time. The control scheme for slurry injection is based on setting the slurry feed rate to maintain a desired Ca/S ratio, while slurry concentration is adjusted by dilution water to maintain exit gas approach temperature. For dry sorbent injection, both lime addition and exit gas temperature can be controlled independently. In addition, the capability is present to test the use of SO_2 removal efficiency as the control point by automatically adjusting the lime or slurry feed rate. The PLC system is able to respond to fluctuations in inlet SO_2 concentration, gas temperature, gas flow rate, and allow process or equipment upset conditions to be detected and corrected without process shutdown.

Process control relative to flue gas dilution and temperature is designed to produce a flue gas stream with a specified or test SO_2 concentration, inlet gas temperature, and inlet gas volumetric flow rate.

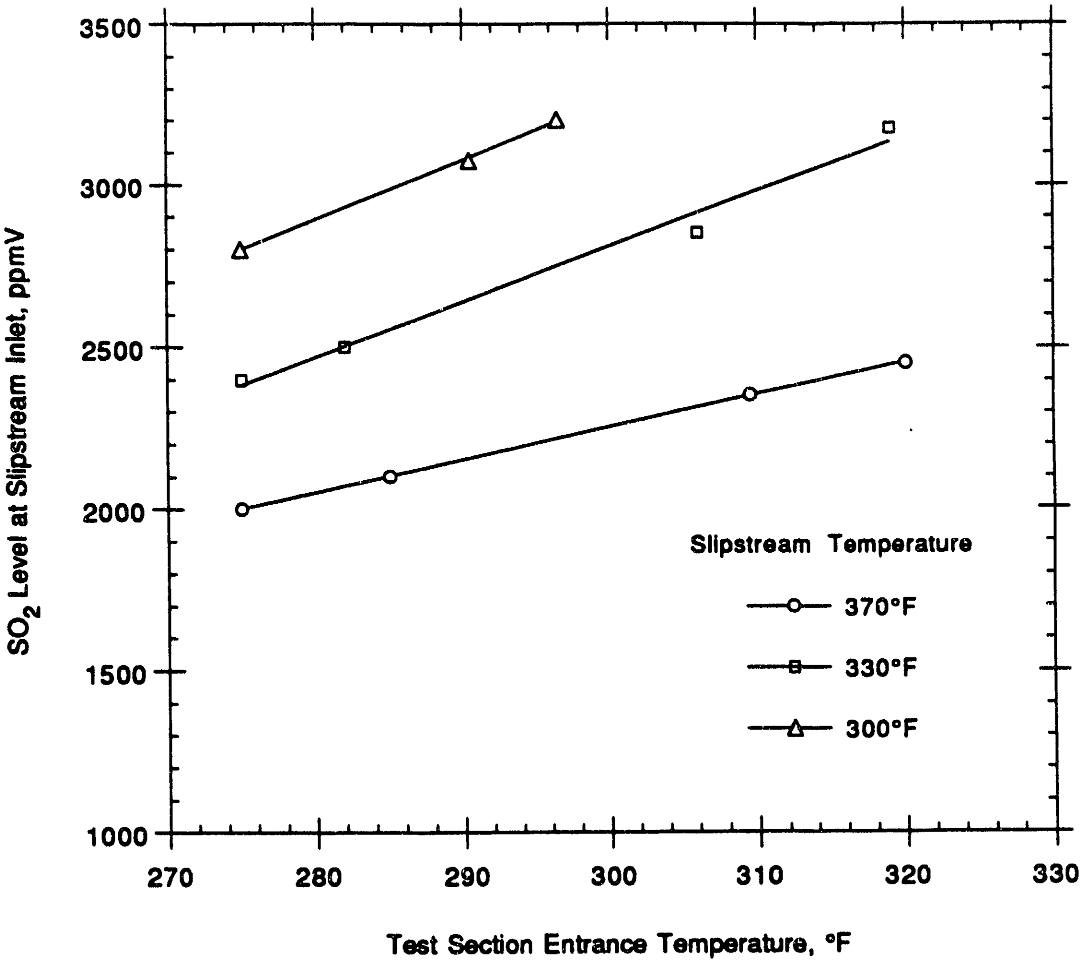

Figure 3-3. Duct injection operating map, 750° F humidification steam 3260 ppmv incoming SO_2 in slipstream.

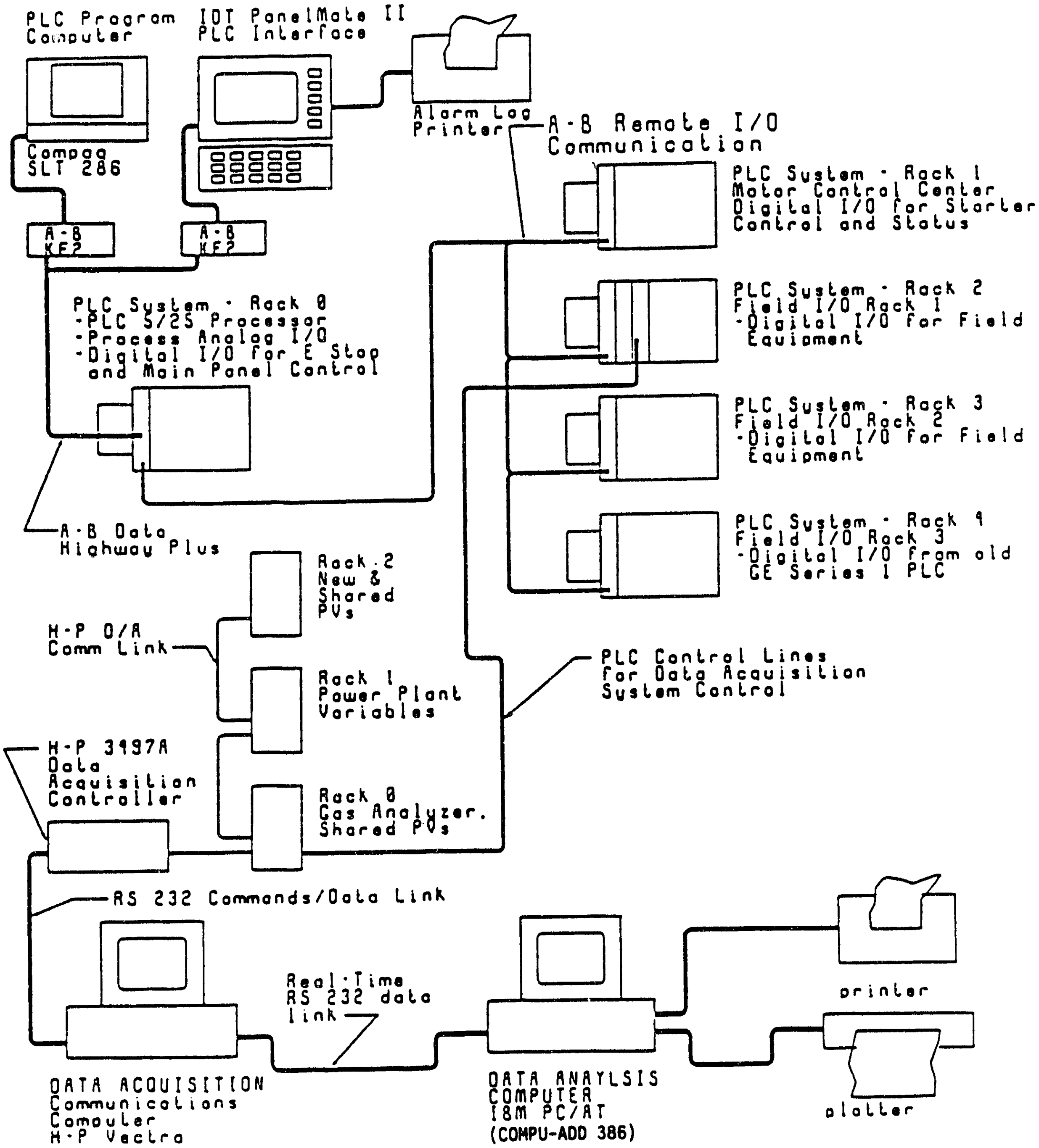

Figure 3-4. Process Control System Configuration.

In order to minimize changes to other flue gas parameters, particularly the adiabatic saturation temperature, when diluting the extracted flue gas from Unit 5, the water concentration of the diluting gas must match those of the extracted flue gas from Unit 5. The dilution air is controlled by the desired SO_2 concentration, the duct burner firing by the desired test temperature, and the moisture addition by an algorithm which calculates the required humidity from the coal analysis and the measured excess air and ambient humidity. Moisture is added by a controlled steam flow based on dilution air flow rate.

3.2.2.1 Hardware/Equipment

Allen-Bradley PLC 5/25 System

5 Rack Configuration

2 - Main Control Panel (CP003 and CP004)
2 - Motor Control Center (MCC)
1 - Existing Control Panel (CP-001)
1 - Dilution Air Variable Frequency Drive (VFD)

20 K Word Processor RAM Memory (approximately 16 K used)

A-B 1770-KF2 Data Highway Plus Communications Interfaces for (1) Programming, and (2) PanelMate

COMPAQ SLT 286 with ICOM PLC 5 Programming and Documentation software (purchased as part of the PCSV Particle Measurement system)

IDT PanelMate II Operator Interface - 16 Screen Capacity

3.2.2.2 Operation/Controls

With the exception of the Air Compressor system, the two Lime Slurry Pumps, the Lime Slurry Agitator, the Air Heater Burner Ignition which are controlled from the Main Control Panel, and the existing motors controlled at the existing motor control center (MCC), all of the equipment in the Test Facility is controlled using the PanelMate which is located on the Main Control Panel. Nearly all of the equipment is set up to have a "Hand" and an "Auto" mode of operation. In the "Hand" mode, the selected device will operate on command, taking into account any safety interlocks. In the "Auto" mode, the device is "enabled" and will operate when called upon by the logic of the operation.

- PanelMate Control Screens

  All of the "Hand-Off-Auto" controls for a specific area are located on one or two screens of "Legend Displays". These PanelMate displays show the status of each device. In addition, any equipment fault is shown on this display. Selecting one of these "Legend Displays" from the 15-key panel displays the associated control function, such as "Start - Auto", "Start - Hand" or "Stop".

Any alarm condition detected by the PanelMate/PLC system causes the central alarm system light and horn to be activated. The alarm condition is displayed on the PanelMate and logged on the alarm printer. The alarm system may be "Acknowledged" with the pushbutton on the Main Control Panel or the "Silence Alarm" key pad on the PanelMate. The "Acknowledge" is also logged.

- PanelMate System Status Screens

  For each process loop there is a graphic screen showing the process flow and equipment status for the process. There is normally no operator control on this screen. However, the state of the devices shown on the control screens is indicated by the color of the device.

  Also shown on this screen are process alarm conditions such as high or low hopper or silo levels.

- PanelMate Process Control Screens

  To set the process parameters, there are several Process Control Screens. These screens contain two types of displays: a controller on which the Process Variable, Setpoint, and Alarm Limits are shown in a format very similar to the classic stand-alone controller and a variable display format which simply indicates the current value of the Process Variable and Setpoint.

For either of these displays, the numbers in the white legend block can be modified by the operator to alter the setpoint as needed.

3.2.2.3 COMPAQ System Support Computer

In addition to being used for gas particle size measurements, the INSITEC computer provides the PLC/DAS System Support. For this purpose, it was configured to perform the support operations listed below.

- PLC 5/25 Programming and Documentation
- Equipment Data Base
- Reports - IDT PanelMate Support

3.2.3 Description of the Gas Sampling System (GSS)

3.2.3.1 System Requirements

In order to measure the effectiveness of duct injection for the removal of SO_2 and NO_x and to control the level of SO_2 at the inlet to the DITF, it is necessary to know the constituency of the flue gas at a number of points. Before the DITF was configured to study the duct injection process, it was operated by General Electric Environmental Services, Inc., (GEESI) for a previous DOE project. As part of that earlier project GEESI contracted with Pace Environmental to design and install a "multiple point" flue gas sampling system (GSS) that could measure flue gas concentrations of SO_2, O_2, CO_2, and NO_x at up to five locations throughout the facility. This existing system was been modified and updated by SRI. In addition to this multiple point GSS, a "single point" GSS was been installed to provide continuous SO_2 and O_2 information at the system inlet (after dilution). Data from the single point GSS is used by the Allen-Bradley Programmable Logic Controller (PLC) that controls DITF operation to set the amount of dilution required to maintain a constant SO_2 level at the system inlet.

3.2.3.2 Evolution of GSS to the Present Form

As installed, the GEESI/Pace GSS took a gas sample from one of five probes inserted into the DITF ductwork, transported the gas sample through heated sample hoses to a heated switching network that, in turn, routed the gas sample to a dilution system (with a dilution ratio of 10:1) and a gas permeation dryer, and finally sent the diluted gas sample to a bank of gas analyzers. Motor-driven mechanical relays in the GSS control circuitry then activated a bank of motorized ball valves to sample through the next port in the gas sampling sequence. After all ports were sampled, each sample line was purged with unheated high pressure air to clean the sample probes. The sample probes were made of a fritted stainless steel filter that was inserted midway into the duct, enclosed in a semi-circular protective shell. The advantage of this system was that no sample conditioning was required to remove water vapor. Major disadvantages of this system were (1) because of low sample flow rates about 3 minutes could elapse from the time a sample was withdrawn from a sample probe to the time that a measurement of flue gas concentration was made, and (2) the sample lines were operated below the SO_3 dewpoint. The 3-minute sample time was usually doubled because measurements were made with wet diluted flue gas (by bypassing the permeation dryer) and with dry diluted flue gas to obtain an estimate of water vapor concentration at a given sample port. Indeed, a considerable time could elapse from the time a gas sample from the DITF inlet (port 1) was analyzed to the time a gas sample from the outlet of the ESP (port 5) was analyzed. Thus, changes in system operation that occurred between the time the inlet and outlet samples were analyzed could affect the results of a particular test in an unpredictable manner.

Before the DITF was brought on line the GEESI/Pace GSS was inspected and cleaned. It was found that the permeation dryer was inoperable; most of the stainless steel sampling lines, valves, and solenoids were internally corroded; and many of the flue gas analyzers required maintenance or repair. It was decided to rebuild the GSS completely. As part of this rebuild, a "double bypass" design was adopted with an integral refrigerated sample conditioning system for water removal. Heated sampling probes were also designed and installed at each sample port. The purge airline was also heated. The GSS was also integrated into the PLC control system for the DITF so that control of the GSS is no longer governed by a set of motor-driven mechanical relays. Currently, sample ports are located at the inlet to the system, at the inlet to the horizontal test duct (before sorbent injection or humidification), at the end of the horizontal duct (1.0 s residence time), at the ESP inlet (1.5 s residence time), and at the ESP outlet (ESP residence time is approximately 10 s).

The heated probes were designed and installed because no provision was made in the GEESI/Pace system to prevent the reaction of sorbent caught on the surface of the in-stack filter with flue gas as it passed through the layer of sorbent. Figure 3-5 shows how these probes are designed. The probes are made of 316 stainless steel. The reaction of flue gas with sorbent caught on the fritted stainless steel filter in the probe is quenched by heat. The interior of the probe is maintained at 350°F or above so that the surface of the in-stack filter is heated to a point where no reaction can take place

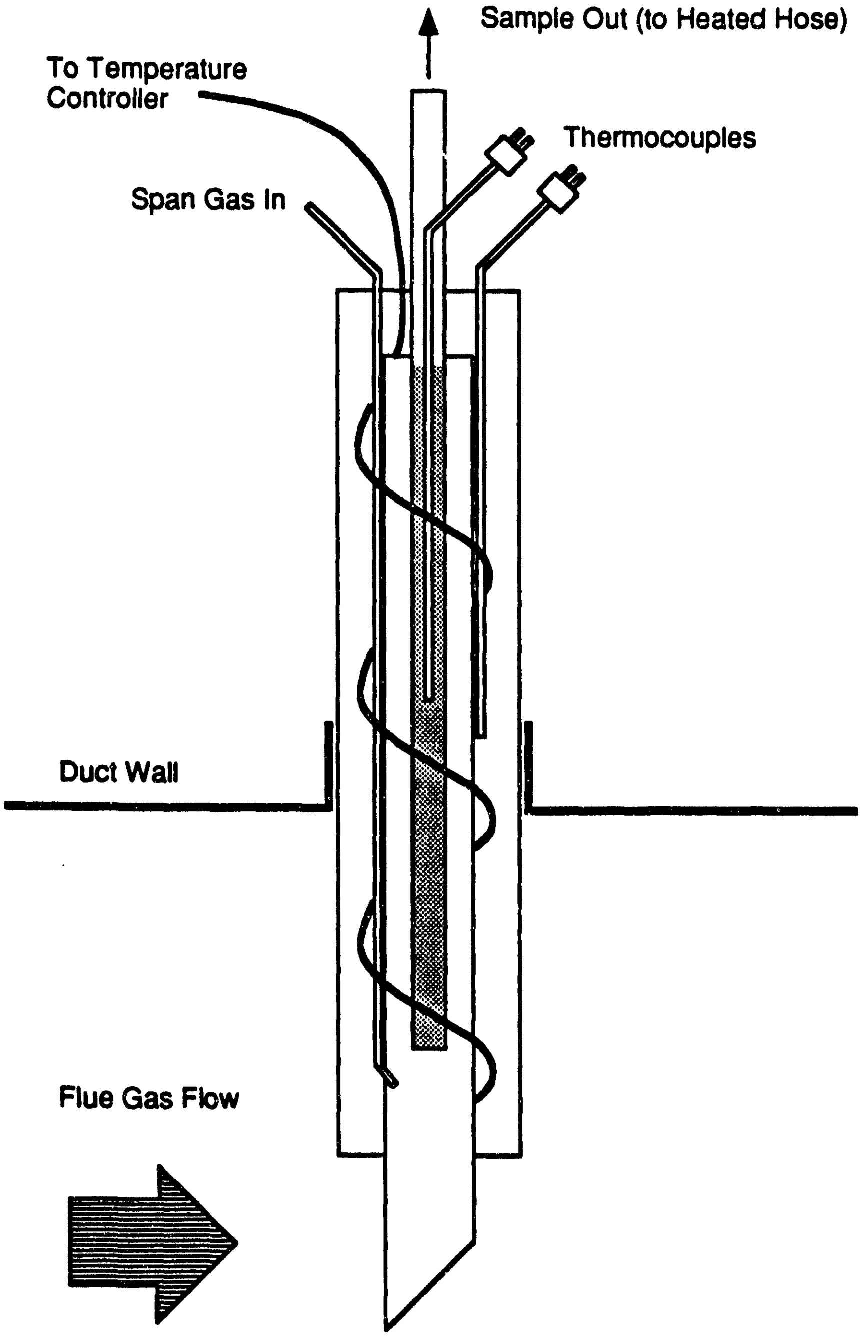

Figure 3-5. Probe for extracting solids-free stream for gas analysis.

with fresh sorbent caught on the surface of the filter. Each probe is also fitted with a stainless steel line through which span or zero gas can be bled into the probe. This probe design has been tested by introducing SO_2 span gas to the interior of the filter which was coated with a thick layer of unreacted $Ca(OH)_2$ sorbent. In each test, 98% or more of the span gas was recovered downstream of the probe.

As Figure 3-6 shows, flue gas is drawn through each heated probe and is conveyed through a heated sampling line to a heated oven where the stream passes through a motorized ball valve, filter, and solenoid valve that either routes all of the sample flow to the main bypass pump through a sampling manifold that is shared by all of the sample lines or diverts the sample flow to two sets of condenser coils in a refrigerated bath maintained at 33°F. Condensed water is removed with a double-headed peristaltic pump. A second sample pump is located between the two sets of condenser coils, providing sample flow to an array of gas analyzers located downstream of the refrigerated cooler. The gas analyzers are each equipped with an appropriate sample pump. The second sample pump is sized so that it delivers more sample flow than is required for the gas analyzers. Extra sample flow is vented. This sample conditioning system serves a Western Research Model 721-AT SO_2 analyzer, a Servomex Model 540A oxygen analyzer, an Automated Custom Systems Model 3300 CO_2 analyzer, and a Thermoelectron Model 10 NOx analyzer.

A separate heated line is connected to the gas sample coming from port 1 at a point after the filter but before the solenoid valve. This line supplies a gas sample from the inlet of the DITF to the single point GSS. This system is constructed in much the same manner as the multi-point GSS. The gas sample passes through a refrigerated cooler and passes to a Fuji Model ZRC/760 SO_2 analyzer and a Servomex Model 540A oxygen analyzer. Water is removed from the refrigerated cooler with a single-headed peristaltic pump. As with the multi-point GSS, the single point GSS is controlled by the PLC that is used to run the DITF.

A Servomex PSA 402C water analyzer was added to the multi-point GSS. This analyzer takes a sample from the heated line that passes a gas sample to the refrigerated cooler, passes it through a heated head pump and filter, and conveys the gas sample to the water analyzer through a heated sample hose. The measurement cell of the water analyzer is maintained at 150°C. The water analyzer measures absorption of light energy by water vapor at a wavelength of 6.01 μm. This wavelength was chosen by the manufacturer because none of the components of the flue gas exhibit significant absorption at this wavelength. The water analyzer is calibrated with a "mimic" gas, propylene, that strongly absorbs light energy at 6.01 μm. This device was found to work very reliably.

As indicated above, the multi-point GSS and the single point GSS are controlled by the Allen-Bradley PLC system that is used to control the DITF. Each gas sampling line is purged with heated compressed air immediately after the PLC switches the GSS to the next sample line. When a line is selected for sampling by the PLC, approximately 90 s elapses before any measurements are accepted from the gas analyzers. This is to ensure that the previous gas sample is completely flushed from the refrigerated cooler and analyzers before any measurement is made. The PLC can select any number of ports or combination of ports to sample. If only one port is selected for sampling, that port is not purged until the port is deselected.

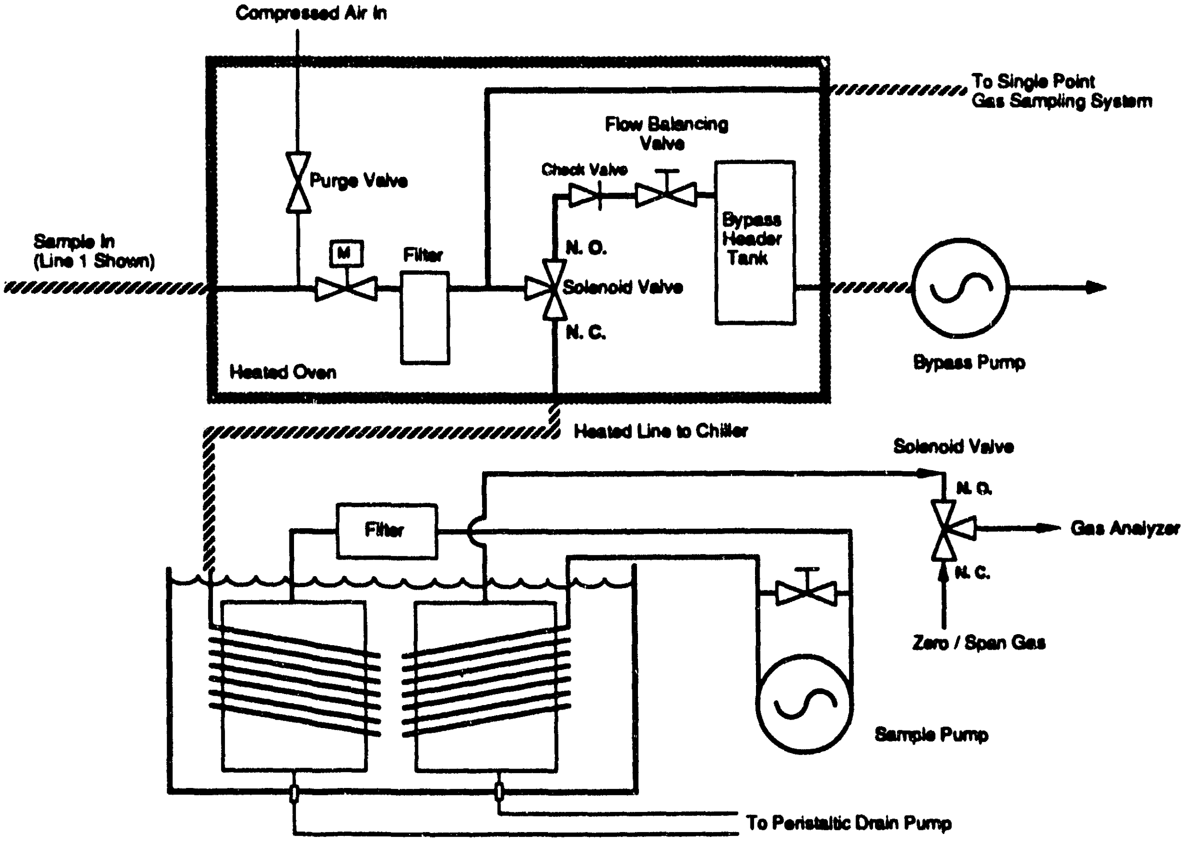

Figure 3-6. System for conveying filtered gas sample to analyzers.

3.2.3.3 QA/QC Concerns

To make sure that the GSS functioned properly, frequent checks were made of system integrity. Each gas analyzer was calibrated on a daily basis, and a log kept of zero and span adjustments as well as any maintenance that had been performed on components of either GSS. Calibrations were not based on meter response but were based on instrument output to the DITF data acquisition system (DAS). Filters in the GSS were changed on a regular basis, and the single point and multi-point GSS systems were monitored to assure that both systems agreed. On a weekly basis, each heated sample probe was checked to be sure it was operating properly, and span gas was introduced into each probe in the duct. Slight losses in sample recovery caused by small leaks were corrected before proceeding to the next probe. Although this process was time-consuming, it assured the integrity of the GSS. Results of these checks were kept in the GSS maintenance and calibration log.

3.2.4 Description of the Data Acquisition System (DAS)

3.2.4.1 System Requirements

The DAS was required fulfil several major requirements. First, it had to produce a permanent record of test activity carried out at the DITF to permit subsequent analysis of process data. Second, the DOE requires that all data must be logged in Lotus 123™ format files on floppy disks that are transmitted to the DOE on a regular basis. This second requirement generates a back-up of all data and provides process data to other individuals interested in results obtained at the DITF. Third, in addition to producing permanent records of process data, the DAS had to provide real-time information for ongoing experiments at the DITF. Ideally, this real-time information should be available for any process parameter over the duration of the most recent test.

3.2.4.2 Evolution of the DAS

When the DITF was first brought on line, DAS hardware consisted of a Hewlett Packard (HP) Model 3497A data logger connected to an HP Vectra PC/AT computer, which was also connected to an AST 286 PC/AT computer. Custom software was written in Microsoft QuickBasic™ to interface the HP Vectra computer with the HP datalogger, to allow on-line analysis of process data from the DITF, and store each data scan in an archival file. The AST computer was primarily intended for data analysis although it could be used to monitor raw data as it was echoed from the HP Vectra computer.

Before a decision was made to write site specific software to automate data collection and retrieval, commercial software packages were investigated. However, with the amount of information to be stored (in excess of 300 channels of data and calculations per scan) any commercial package that could handle the stream of data (approximately one scan every 90 s) was either very expensive, required a considerable investment in training to configure, or both.

Initially, data scans were stored on the HP Vectra in an ASCII format and these files were transformed into a Lotus-compatible file format on the AST computer. This process was time consuming and inefficient. In addition, while process data were displayed for each scan, it was difficult to view earlier data acquired during a test without stopping data collection to copy a data file or by performing frequent screen dumps to a printer attached to the HP Vectra. Because it was very desirable to be able to view recent process data and compare it with current system behavior, it was decided to modify the DAS. A major requirement was that this modification could not disrupt the ongoing program of experimentation during its development, testing, and installation.

As indicated above, the QuickBasic program that polls the HP datalogger also echoes process data and calculations to the AST computer. This ability to echo data to a second computer was the key to the new data analysis system. In order to provide on-line analysis of recent as well as current process data, it was decided to replace the AST 286 PC with the 386-based PC and utilize the multi-processing capabilities of this type of microprocessor to log the data received from the HP Vectra and provide a display of any process parameter or parameters desired within the last 1200 data scans (approximately the last 30 hours of data). This display could be up-dated as required.

The expanded data analysis system consisted of a 386-based PC, a serial data communications buffer, a multi-tasking operating system (Deskview^{TM}), custom software written in Borland's Turbo Pascal^{TM}, and an Iomega Bernoulli^{TM} removable cartridge drive. The 386 platform and Deskview are necessary to allow the computer to perform two simultaneous tasks. The serial buffer is used to allow the 386 computer to go off line for up to several hours and not lose process data relayed from the HP Vectra. Hourly and daily process data were logged on removable 44MB Bernoulli cartridges. Data continued to be logged on the HP Vectra as it was in the past. After bringing the expanded data analysis system on line, data files from the HP Vectra were archived on the Bernoulli cartridges.

The custom software performed several tasks: it accepted data from the HP Vectra, checked for communication errors, wrote the process data to compact binary files, printed historical data to a line printer or to a file, plotted process data to the screen or to an HP plotter file, and converted hourly data files to Lotus 123 compatible spreadsheets for subsequent data manipulation. The software written to produce Lotus 123 compatible spreadsheets from the process data files can convert a day's worth of process data into worksheets in 10 to 15 min.

One important addition to the expanded data analysis system was the ability to view graphical images of process data in essentially real time while data logging continued. A file containing all of the data from the last 1200 scans was maintained on the fixed disk in the 386 computer and echoed to a 2.8 MB ramdrive. Through a series of menus, predefined sets of data or operator selected data could be viewed to monitor a test in progress or view the results of recent testing. Data were stored in a ramdrive to minimize access time.

The ability to write typed files of binary numbers yielded a large saving in disk space: one hour's data in ASCII format required 420 KB of disk space, while the same file in a typed binary file format required only 60 KB of disk space. One disadvantage of such binary files is that the data cannot be viewed directly from DOS.

3.2.5 Methods to Measure Sorbent Utilization

Central to the evaluation of a SO_2 removal technology is measurement of sorbent utilization. Sorbent reacts with SO_2 in the flue gas and if $Ca(OH)_2$ is the sorbent material $CaSO_3$ is formed by the reaction. The sorbent never reacts completely, however, and thus is never fully "utilized". Utilization can be determined from gas-phase measurements or from analyses of solids.

3.2.5.1 Gas Sampling

Sorbent utilization is calculated from gas phase measurements by dividing the percent of SO_2 removal by the Ca/S ratio. Because the Ca/S ratio is a molar ratio, this calculation really determines the ratio of the number of moles of sulfur to the number of moles of calcium present (as sorbent). Sources of error that can affect this method of determining sorbent utilization are an inaccurate determination of the Ca/S ratio--through an incorrect measurement of slurry flow, inlet SO_2 concentration, or the physical parameters of the slurry (% $Ca(OH)_2$, density, or % solids) and an inaccurate measurement of SO_2 concentration downstream of the point where sorbent is introduced into the system. This measurement can also be affected by accumulations of moist sorbent in the duct (for example, as duct wall deposits) that tend to remove SO_2. In this case sorbent utilization as determined from gas-phase measurements will be higher than utilizations determined from solids analyses.

3.2.5.2 Solids Samples

Sorbent utilization can also be determined from chemical analysis of ash/sorbent samples obtained downstream from the point where sorbent was introduced into the system. In the case of the DITF, these samples were almost immediately available from the ESP hoppers but were also available from mass train catches. However, samples of solids obtained with particle sampling devices can also become over utilized (compared to suspended solids in the flue gas) because they remain in contact with flue gas for the duration of sampling.

3.2.5.2.1 ESP Hopper Samples

The ESP of the DITF has three hoppers, and the ash conveying system was modified to permit samples of ash to be obtained from each ESP hopper. However, most of the ESP hopper samples analyzed were obtained from the inlet hopper only. Sorbent utilization determined from chemical analyses of ESP inlet hopper samples was always somewhat higher than utilization determined from gas phase measurements.

3.2.5.2.2 Quench Probe Samples

To obtain samples of solids that were not over-utilized either by extended contact with flue gas on the collection plates of an ESP or in a particle collection device, a specialized sampling probe was designed and built. This "quench probe" is designed to capture an isokinetic sample of a flue gas aerosol, immediately dilute the aerosol sample with hot filtered air, and convey the sample to a heated filter where it is retained for subsequent analysis. Figures 3-7 and 3-8 show the basic elements of the design of this device. In contrast to the gas sampling probes where the sorbent-SO_2 reaction is quenched by heating, this device quenches the sorbent-SO_2 reaction by dilution with heated air. At the tip of the probe heated air is injected into the sample stream through a section of porous sample line. Thus, contact between sorbent and a solid surface is prevented until the sample stream has been heated by mixing with heated dilution air.

This probe was first tested with unreacted sorbent on the filter. The probe was spiked with SO_2 span gas that was diluted by a known amount of fresh air that passed through the porous section at the end of the probe. Little (<2%) uptake of SO_2 by the sorbent was observed. Subsequently, in comparisons of sorbent utilization determined from gas phase measurements and from chemical

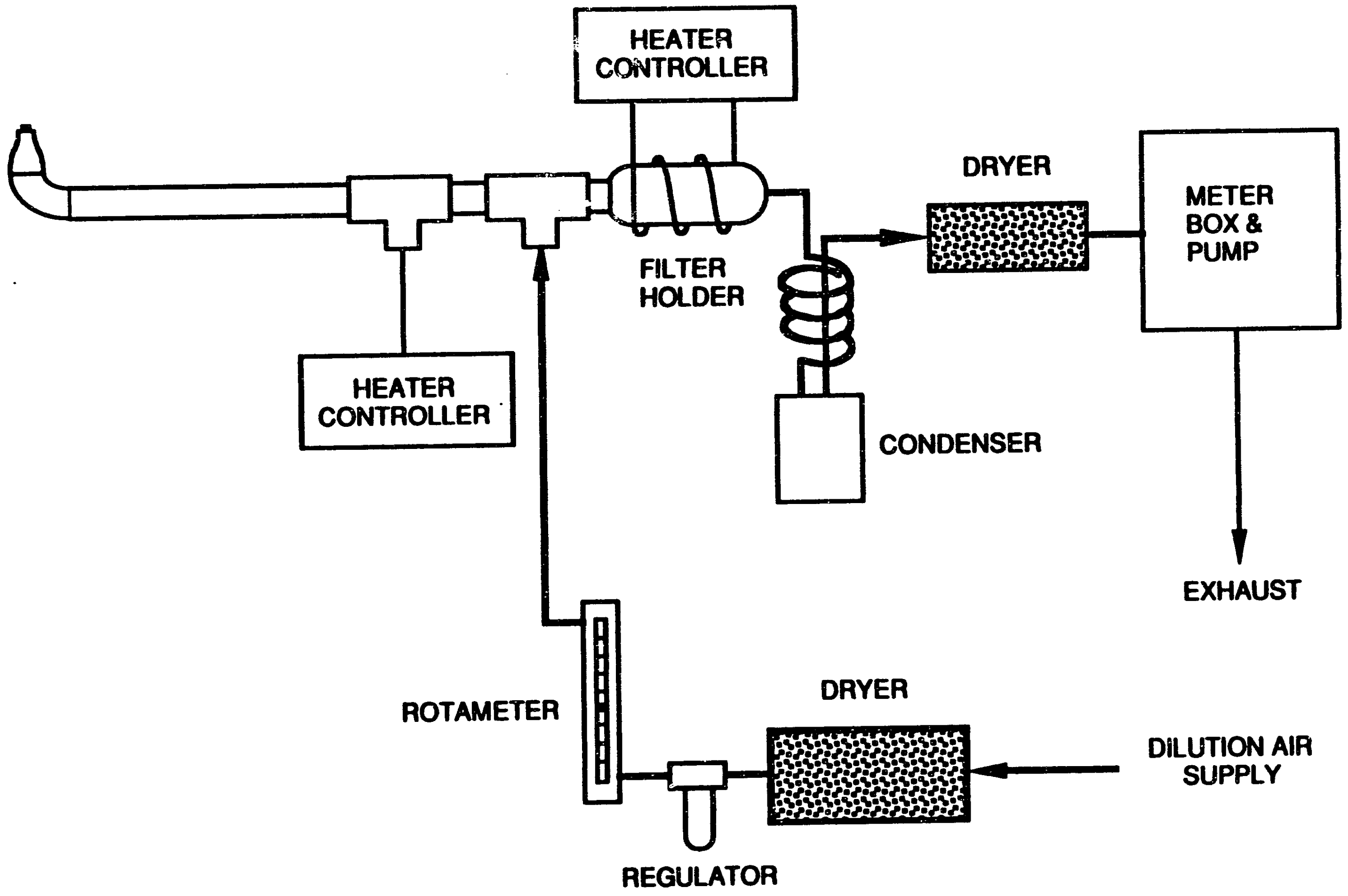

Figure 3-7. System for withdrawing a gas sample through a quench probe and recovering the entrained solids on a filter.

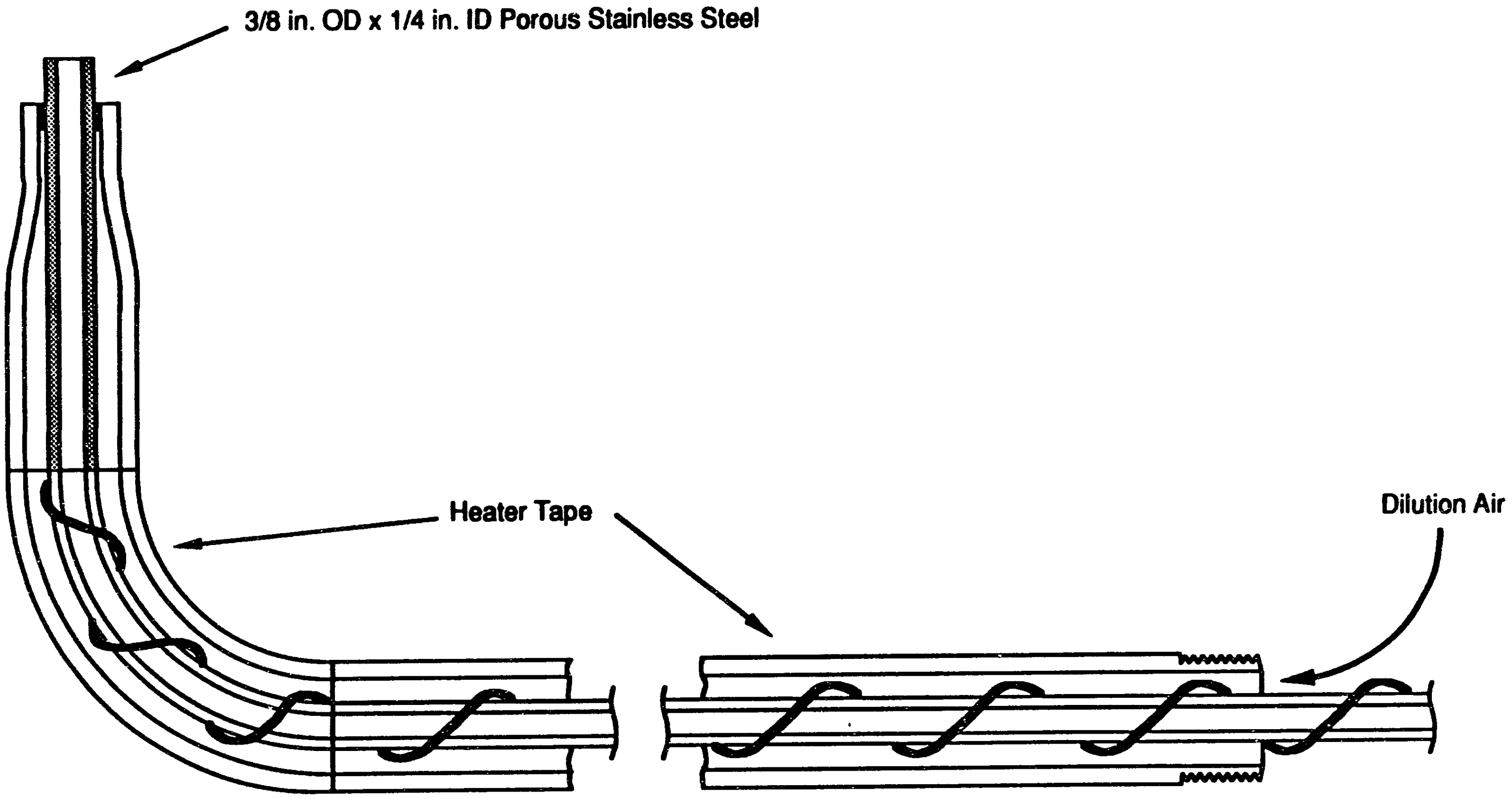

Figure 3-8. Quench probe for extracting a solids sample.

analyses of solids samples obtained with the quench probe, utilizations measured with the quench probe were usually less than utilizations determined from gas phase measurements. This is in the direction that should be expected if the quench probe operates properly because gas-phase utilization determinations can be increased by deposits of active sorbent inside the duct reacting with SO_2 in the flue gas.

4.0 NOZZLE SELECTION AND TESTING

4.1 Nozzle Selection Process

The two-fluid spray nozzles are the key element of the lime slurry injection and dry sorbent humidification processes. Good performance of the nozzles is essential for the sorbent-SO_2 reaction to proceed to completion in a short residence time typical of duct injection without the occurrence of wall wetting and concomitant wall deposits. Unlike previous in-duct injection projects, the DITF design required long-term operation and scale-up provisions. Key design requirements for these nozzles are described herein.

4.1.1 Nozzle Design Criteria

The design criteria used in specifying the nozzles and lances for procurement are listed below:

	Humidification Nozzles	Slurry Nozzles
Fluids:	1. air 2. water	1. air 2. lime slurry or lime/ash slurry
Max. Liquid Flow:	13.0 gpm	15.2 gpm lime slurry 17.3 gpm lime/ash slurry
Min. Liquid Flow:	1.7 gpm	1.9 gpm
Max. Solids Content: in liquid	-	28% lime slurry 50% lime/ash slurry
Liquid S.G.:	1.0	1.34
Liquid Design Viscosity:	-	1000 cP (min)
Max. Liquid Pressure:	100 psig	100 psig
Max. Air Pressure:	100 psig	100 psig
Max. Allowable Air/Liquid Ratio (by weight):	0.5	-
Droplet Size: Max. SMD	70 μm 30 μm	70 μm 30 μm
Duty:	Continuous 24 hour/day for 1 year.	

4.1.2 Droplet Size and Distribution

For the evaporation to be completed within the design residence time (approximately one second at full load) and the sorbent reaction to be maximized, the droplet sizes should be within a certain range. Too small a droplet will dry out too fast and too large a droplet will not completely evaporate resulting in wall wetting and deposits. Ideally, a droplet range between 20 and 50 microns is believed to be suitable for in-duct injection. For conditions existing in the DITF estimations were that 70-80 μm droplets will have a life of approximately one second. The droplet size requirement for the nozzles was set at 30 μm Sauter mean diameter (SMD) and 70 μm maximum. The spray cone angle was specified to be kept small to avoid wall wetting but still provide thorough mixing of the spray with the flue gas to promote rapid evaporation.

4.1.3 Number of Nozzles

The nozzle specification allowed for an array of up to 12 nozzles but expressed a desire for 6 or less. This resulted in a 6 nozzle (2.88 gpm each) array divided into two lances that was used for the majority of the testing for both humidification and slurry injection. A single 12 gpm nozzle was used for testing late in the program with equally good results. Success of this approach in a 40 x 50 inch duct indicated that scale-up to larger commercial size ducts can be accomplished with a reasonable number of nozzles for maintenance and reliability while avoiding wall wetting and subsequent deposits.

4.1.4 Nozzle Life

The nozzles were ordered with hardened or ceramic materials where necessary to withstand erosion from the abrasive nature of the slurry and fly ash mixture. This resulted in the use of ceramic inserts in the mixing zone of the nozzles. Nozzles were fabricated from type 316 stainless steel and Hastelloy for longevity in the corrosive flue gas environment.

4.1.5 Lance Design

The lances were specified to provide the means of mounting the nozzles in the duct and transporting liquid and air to the nozzles. The lance design allowed for testing of different manufacturers' nozzles. The lances were made of Hastelloy to allow long term operation in a flue gas environment. They were designed to provide a certain amount of flexibility in that nozzle positions or directions could be altered. The lances were to be suitable for use at any of the three test stations in the duct. The resulting design provided two lances mounted horizontally in the duct, each with five mounting positions. The lances could be rotated on their mounting flanges to allow for tilting of the nozzles relative to the upper and lower duct walls. Subsequent modifications in the field allowed for rotation of the outer nozzles relative to the side walls.

4.1.6 Auxiliary Power Consumption

The high pressure air used by the nozzles for atomization was the biggest source of power consumption. In a full scale installation this could translate to between 1-2% of the station power. To minimize auxiliary power, the specification limited the air/liquid ratio to 0.5 and the air pressure to 100 psig. The preferred value was 0.4 at 80 psig.

4.1.7 Nozzle Selection

After an extensive technical and commercial evaluation of proposals offering commercially available nozzles, twelve (12) Parker-Hannifin VIP External mix nozzles and four (4) lances were purchased. (6 nozzles, 2 lances for slurry injection and 6 nozzles, 2 lances for humidification). These nozzles along with a sample Lechler Supersonic internal mix nozzle and a B&W I-Jet nozzle were characterized at the B&W Alliance Research Laboratory.

As a result of that testing, the Parker-Hannifin nozzles were modified to reduce their spray cone angle. In addition, based on their good performance in characterization tests, twelve (12) Lechler nozzle with wear resistant carbide inserts were purchased for mounting on the Parker- Hannifin lances.

During the actual test program at the DITF, the Lechler Supersonic internal mix nozzles were used for both slurry injection and humidification service while the Parker-Hannifin VIP external mix nozzles were used solely for humidification service.

4.2 Particle Size Distribution Tests

Prior to the test program at the DITF the Lechler Supersonic internal mix nozzle and the Parker-Hannifin VIP external mix nozzle were characterized in tests at the B&W Alliance Research Center's Atomization Facility. For comparison, a B&W Mark 7, I-Jet nozzle was tested at the same time. All nozzles were 2.88 gpm capacity.

4.2.1 Test Facility and Conditions

The B&W facility is an 8 ft. x 8 ft. test chamber in a duct having glass walls on two sides for viewing and projection of a laser beam from a Malvern ST2600 Droplet Size Analyzer with a 600 mm lens. This provides a droplet size range capability of approximately 11 to 1100 μm.

A shield was used to reduce obscuration of the laser beam measurements on some tests. The shield is specially designed so that it can deflect away part of the spray without affecting the remaining spray. This avoids the use of the empirical correction factor for dense spray characterization. B&W uses the Model Independent technique for the Malvern data analysis.

Tests were run at 1440, 1080, and 720 lbs/hr nominal water flow rate representing 100%, 75% and 50% of slurry design flow rate for the DITF. The tests were conducted at three nominal air pressure levels - 80, 100 and 120 psig. All tests were taken by the Malvern Instrument near the center of the spray cone at 5 ft. downstream of the atomizer. The ambient air was at room temperature and the air velocity in the test duct was approximately 10 ft./sec.

4.2.2 Test Results

Droplet Size

The data are summarized on Tables 4-1, 4-2 and 4-3. Review of the test results indicates that the Lechler nozzle has the lowest droplet size and it has a higher air/liquid ratio than either the Parker-Hannifin or B&W nozzle. However, the Lechler nozzle requires much lower air pressure for the atomization. Since compressor power consumption is a function of air quantity as well as the pressure, for proper comparison both variables should be taken into account.

Figures 4-1 and 4-2 compare the characteristics of the droplets of the three types of atomizer by taking into account both air quantity and pressure.

TABLE 4-1

B&W MK-& I-JET Atomizer Test Data
(Measurements at 5 ft from Atomizer without shield)
October 17, 1989

Water Flow lb/hr	Air Pressure psig	Water Pressure psig	Air to Liquid Ratio	Measured SMD μm	% Above 130 μm	Obscuration
1439	80.5	71.6	0.22	39.35	5.6	0.95
1077	80.4	67.2	0.32	34.59	2.7	0.90
730	80.4	61.3	0.53	27.92	1.5	0.87
1442	100.4	87.0	0.27	35.26	2.6	0.90
1075	100.2	81.3	0.41	29.99	1.0	0.87
725	100.1	75.0	0.66	23.93	0.6	0.85
1454	120.5	102.4	0.34	32.95	0.8	0.90
1070	120.8	96.0	0.50	28.09	0.4	0.88
713	120.6	88.5	0.82	22.36	0.1	0.85

TABLE 4-2

Lechler Supersonic Atomizer Test Data
(Measurements at 5 ft from Atomizer without shield)
October 17, 1989

Water Flow lb/hr	Air Pressure psig	Water Pressure psig	Air to Liquid Ratio	Measured SMD μm	% Above 130 μm	Obscuration
1436	80.5	68.3	0.66	26.15	0.0	0.93
1076	80.5	65.5	0.90	24.05	0.0	0.90
708	80.4	62.6	1.42	20.93	0.0	0.84
1441	60.5	52.2	0.50	31.21	0.1	0.90
1086	60.3	50.1	0.69	29.39	0.1	0.86
719	60.5	47.2	1.09	25.81	0.0	0.81
1440	50.0	---	0.41	33.60	0.9	0.91

TABLE 4-3

Parker-Hannifin Slurry Nozzle Test Data
(Measurements at 5 ft from Atomizer without shield)
September 15, 1989

Nozzle Serial No.	Water Flow lb/hr	Air Pressure psig	Air to Liquid Ratio	Measured SMD µm	% Above 130 µm	Obscuration
60007 (slurry)	1440	80	0.43	51.90	19.3	0.90
	1080	80	0.58	44.67	10.1	0.87
	720	80	0.86	34.77	2.7	0.83
60011 (slurry)	1440	80	0.43	54.57	18.8	0.87
	1080	80	0.58	48.68	13.8	0.84
	720	80	0.86	38.25	3.7	0.82
	1440	100	0.53	51.76	17.9	0.93
	1080	100	0.70	43.32	7.4	0.93
	720	100	1.05	33.33	2.4	0.92
60008 (water)	1080	65	0.43	54.08	23.0	0.88
	840	65	0.55	46.98	13.1	0.83
	600	65	0.77	37.90	4.4	0.79

As can be seen from Figures 4-1 and 4-2, the Lechler supersonic nozzle outperformed the other two nozzles in the areas of mean droplet size and larger drop population.

In terms of the mean droplet size the B&W MK-7 I-Jet is quite comparable with the Lechler, with the Lechler being slightly better. At 5 ft. downstream the Parker-Hannifin nozzle shows a much poorer result. In earlier tests, the Parker-Hannifin nozzle showed marked improvement in droplet size at 21 inches and 36 inches from the nozzle. At those closer distances the Parker-Hannifin nozzle still had droplet SMD higher than the other nozzles but the difference was less.

As shown in Figure 4-2, the Lechler nozzle produces extremely small quantity of drops larger than 130 μm. This characteristic makes the Lechler a good selection from the duct wall deposit point of view.

Spray Pattern

Although the spray diameter was not measured, from visual observations it was estimated that the Lechler nozzle has a fully developed diameter of about 18 inches, the B&W MK-7 I-Jet has about 26 inches and the Parker-Hannifin about 30 inches. A narrow spray pattern is desirable to help minimize wall wetting and duct deposits.

4.3 In Situ Measurements

4.3.1 Measurement Methodology

In situ measurements of droplet size distributions produced during water humidification testing and during slurry injection testing were carried out at the DITF on three occasions. During May and July of 1990 measurements were made of water sprays produced by both Parker-Hannifin external mix nozzles and by Lechler supersonic nozzles. In December, 1991, more in situ droplet size distribution measurements were made in sprays of water, reagent slurry, and reagent slurry/recycle ash mixtures produced by the same Lechler supersonic nozzles that were tested in 1990. All tests were conducted with an array of six nozzles. Because the Parker-Hannifin nozzles were not used for slurry testing no measurements were made with these nozzles in the last test series. Additional information on these in situ measurements is available in Topical Report No. 2.[1]

For these tests a variety of air pressures and water flow rates were used and all tests were made with normal flue gas flows in the duct. Two measurement devices were used to perform the measurements: the SRI Video Droplet Analyzer (VDA) and an Insitec in-situ optical particle sizing device, described by Insitec as a Particle Concentration Size and Velocity Probe (PCSV-P or PCSV).

SRI VDA. The SRI VDA is an imaging system that provides on-line droplet diameter measurement based on real-time measurement of the height (diameter) of droplet images obtained by a synchronized high speed strobe illuminator/video camera combination. The camera and illuminator are mounted in a probe which can be inserted through a 4-inch or larger diameter port, making it possible to make in-situ measurements in a flowing gas stream. A combination of shrouds and purge air are used to keep the optical windows clean and dry. The purge air also provides limited cooling of the camera, lenses, and illuminator electronics but the system is not capable of prolonged operation in hot gas streams. However, at the DITF, the sprays being measured provided sufficient external cooling of the probe that continuous operation was possible.

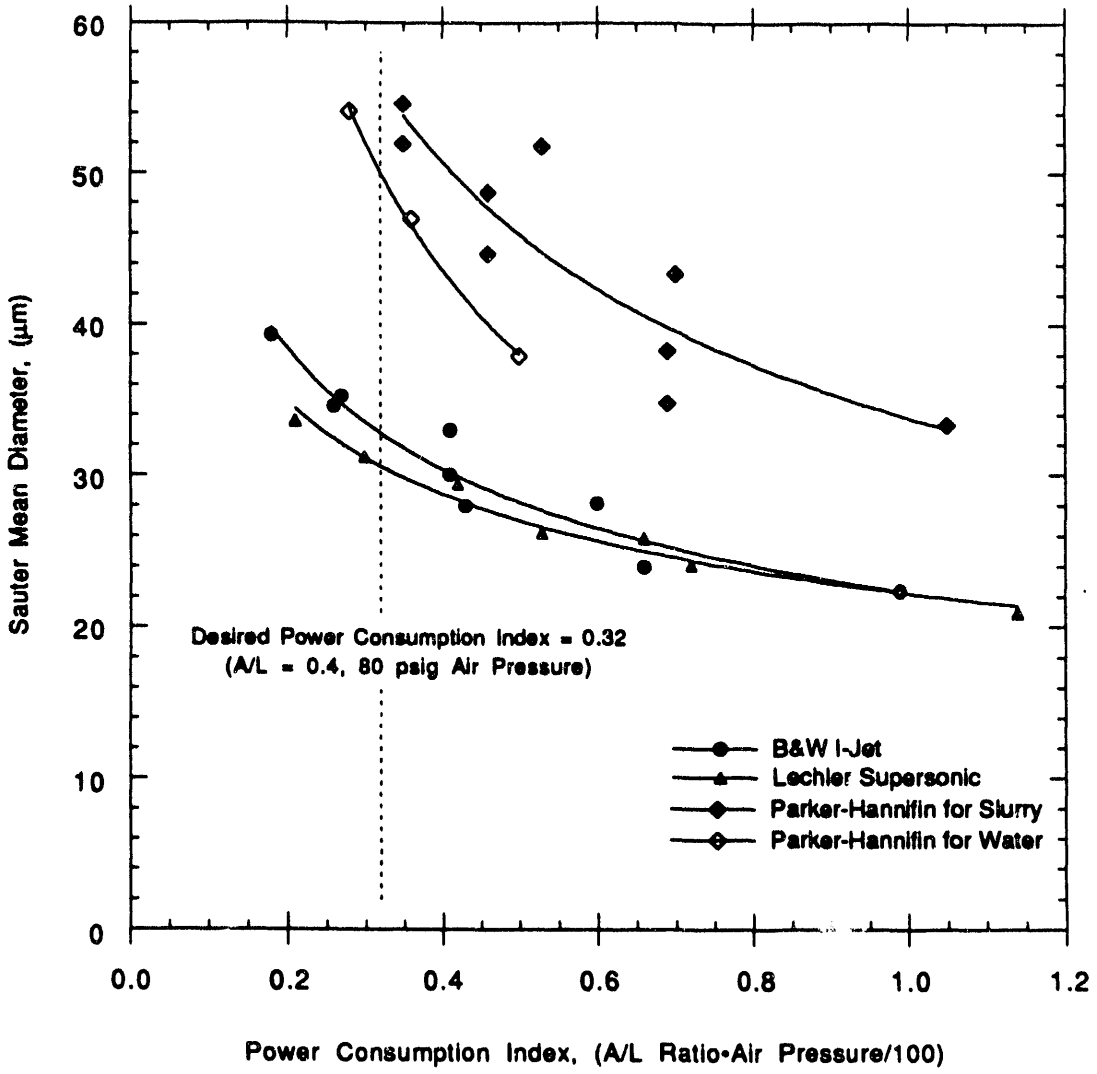

Figure 4-1. Sauter Mean Diameter as a function of the Power Consumption Index for B&W I-Jet, Parker-Hannifin and Lechler nozzles.

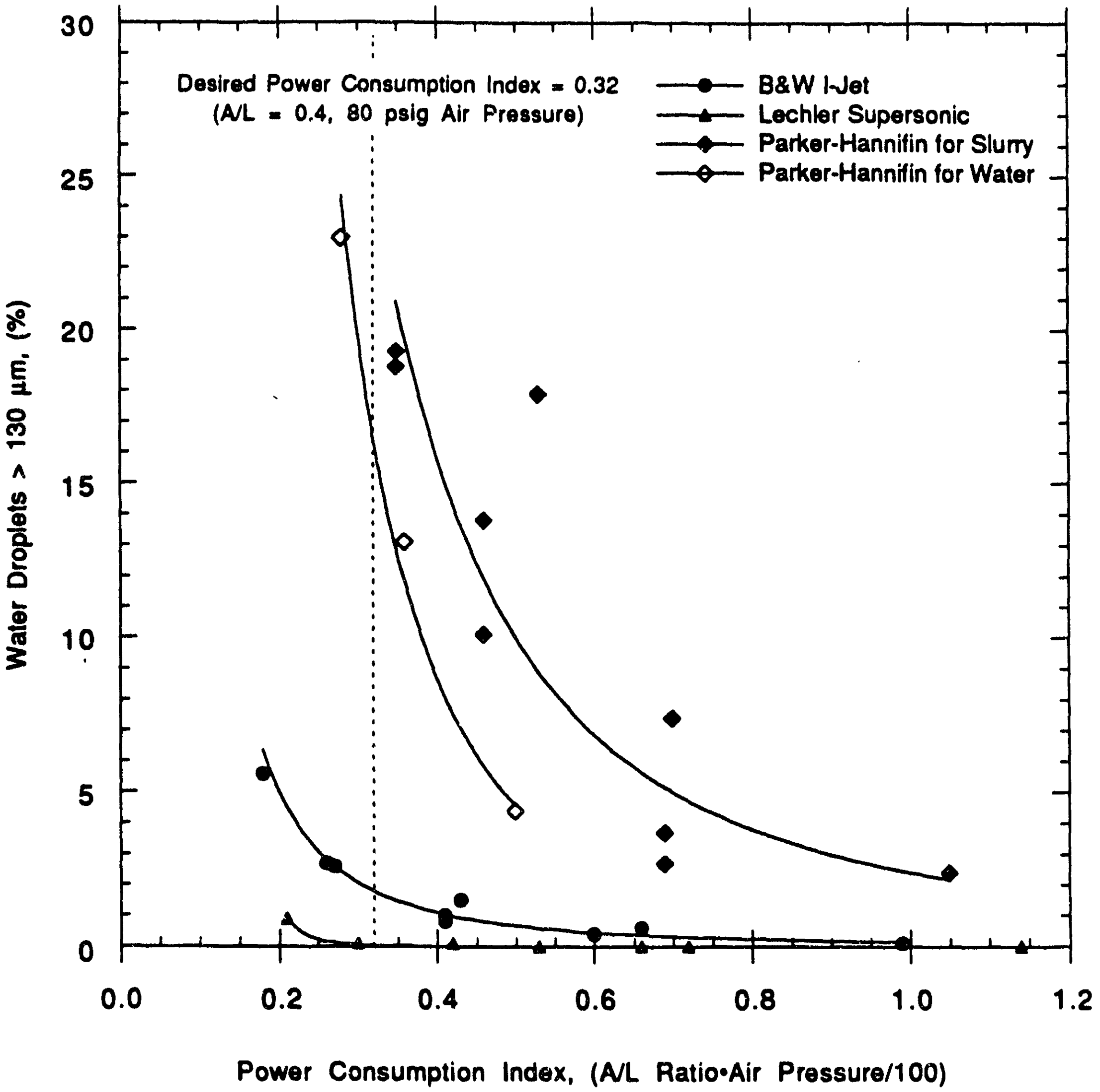

Figure 4-2. Water droplets greater than 130 μm as a function of the Power Consumption Index for B&W I-Jet, Parker-Hannifin and Lechler nozzles.

The VDA was configured to provide data over the size range of 3 to 450 μm for the DITF nozzle tests. However, because of the high gas velocities in the duct, blur from particle motion was about 10 μm which resulted in a loss of data at the small end of the VDA's nominal sizing range. Consequently reliable data were obtained with the VDA over the more restricted range of 25 to 450 μm rather than the full range for which it was configured.

PCSV-P. The Insitec PCSV-P is a dual range in-situ optical single particle counting device that provides data on particle sizes, concentration, and velocity in either or each of its two operating modes. The small particle mode is set up to provide data over a nominal size span of 0.5 to 2.5 μm while the large particle mode is setup to provide data over a nominal range of 3 to 40 μm. Data can be taken in only one of the two modes at any one time, but mode switching is automated and fast so data can be taken sequentially in the two modes in a fairly short period of time. As with the VDA, a combination of purge air and shrouds is used to keep the optical windows clean and dry. Cooling provided by an external water jacketed sheath permits use of the instrument at temperatures far greater than that of normal flue gases. The instrument response is sensitive to the refractive index and shape of the particles being measured; consequently, the indicated sizes can differ somewhat from the true sizes. Provision is made in data analysis to account for the difference between absorbing and transparent particles in instrument response. This takes care of the major effect of refractive index.

In order for the PCSV-P to work properly only one particle can be in the sensing zone at any one time. For most aerosols the number concentrations fall off as size increases. Thus, if the concentrations in a size range are high the detection requirement can be met only by increasing the lower detection threshold for that range. Thus, data can be taken at high concentrations, but only by restricting the range of measurement, losing the ability to obtain data for the smaller sizes in the desired range for the affected configuration. The concentrations produced by the nozzles in these tests were high enough to restrict the range of the large particle mode to about 13 to 40 μm. Insitec's data analysis algorithm uses an interpolation scheme to fill in for missing data between the upper sizing limit of the small particle mode and the lower limit of the large particle mode. The accuracy of the interpolation in matching the true distribution is open to question.

In the first two test series the VDA and the PCSV were both used. In the third series of tests only the VDA was used because it was found in the first two series of tests that because of the high particle concentrations encountered the PCSV provided little data than could not be obtained with the VDA. In addition, based on experience obtained during water spray tests, it was felt that in heavy slurry sprays the purge air system in the PCSV would be overwhelmed.

4.3.2 Sampling Strategy

During a test series two types of measurements were conducted. In the first, single point measurements were made at a fixed location (the center of the duct) as close to the plane of the nozzles as was possible (5 ft downstream) for various liquid flow rates and air pressures. Traverses were made to provide comparative data to verify that the single point data was representative in-so-far as droplet size distribution measurements were concerned. The second series of tests was intended to provide more quantitative data regarding droplet concentration as a function of distance downstream of the plane of the nozzles. For these tests traverses of the duct were made at downstream distances of 5, 8, and 24 ft. For tests with water, the fly ash background was measured and subtracted from the data as reported here. Because water sprays collect fly ash to an unknown extent, these data may be somewhat over corrected.

4.3.3 Test Results

In Situ Water Droplet Measurements. Tables 4-4 and 4-5 present the results of combined VDA and PCSV measurements made 5 ft downstream of the plane of the nozzles for Parker-Hannifin and Lechler nozzles, respectively. The test matrix included water flows of 6, 8, 10, and 11 gpm and a variety of air pressures. For the Parker-Hannifin nozzles, the measured Sauter Mean Diameter (SMD) ranged from 20 μm (6 gpm at 110 psig) to 45 μm (11 gpm at 80 psig). For the Lechler nozzles, measured SMD ranged from 25 μm (6 gpm at 80 psig) to 40 μm (11 gpm at 60 psig).

For both types of nozzles non-uniform duct coverage was indicated by transport rates that, if projected from the single point measurements to the whole duct, were often greater than the actual water flow rate to the nozzle lances. The estimated transport rates decreased with increasing air pressure at any water flow rate. This might reflect higher evaporation rates because of smaller droplet sizes and/or an increase in spray cone angle. In general, SMD increased with increasing water flow and decreased with increasing air pressure.

Tables 4-6 and 4-7 present the results of VDA measurements made at downstream distances of 5, 8, and 24 ft from the plane of the nozzles for Parker-Hannifin and Lechler nozzles, respectively. Under the conditions of these tests the sampling planes represented evaporation times of 0.10, 0.17, and 0.54 s.

For the Parker-Hannifin nozzles, these results indicated that approximately one-third of the water sprayed was still liquid after about 0.5 s of evaporation time. For the Lechler nozzles, these results indicated that approximately one-fourth to one-third of the water sprayed was still liquid after about 0.5 s of evaporation time. However, for both types of nozzles the indicated mean droplet diameters at the sampling planes closest to the nozzles may be too large and the water transport rates too low because of the lack of data for very small droplet sizes. This lack of data may not be as serious at the farthest sampling plane since, in any case, the smaller size droplets must have been highly depleted at that location.

In Situ Slurry Droplet Measurements. Table 4-8 presents the results of VDA measurements made at downstream distances of 5, 8, and 24 ft from the plane of the nozzles for Lechler nozzles during tests conducted in December, 1991 with water, reagent slurry and reagent slurry/recycle ash mixtures. As these results show, compared to the results in Table 4-7 for water, at 24 ft downstream, the SMD of remaining droplets containing water and reagent slurry or reagent slurry/recycle ash were from 20 to 40 μm greater than the SMD measured for water alone. Also, as might be expected, the SMD of reagent slurry/recycle ash mixtures were greater than that measured for reagent slurry alone.

It should be also noted that the estimated transport rate (Recovered Flow Rate in Table 4-8) is low, compared to the transport rates reported during the two earlier test series. It is believed that during these tests the nozzles on the upper nozzle lance were oriented somewhat differently from the way they were located during the first two test series and that this is responsible for the lower recovered flow rates.

Table 4-4 Results of Size Distribution Measurements for Parker-Hannifin Nozzles, Combined VDA and PCSV Data Taken at the Center of the Top Port, 5 ft downstream.

Water Flow, gpm	6	8	10	11
Air Pressure, psig	Sauter Mean Diameter, µm			
80	31.1	38.8	40.8	44.5
100	23.5	28.9	33.4	38.1
110	19.1	27.0	28.1	28.1
	Calculated Water Flow*, gpm			
80	6.0	7.9	11.0	13.8
100	4.7	6.9	9.4	10.1
110	4.1	5.7	5.7	7.2

* From single point size distribution and velocity measurements.

Table 4-5. Results of Size Distribution Measurements for Lechler Nozzles, Combined VDA and PCSV Data Taken at the Center of the Top Port, 5 ft Downstream.

Water Flow, gpm	6	8	10	11
Air Pressure, psig	Sauter Mean Diameter, µm			
60	---	37.5	35.0	---
80	26.3	28.1	27.2	29.2
	Calculated Water Flow*, gpm			
60	---	13.2	15.7	---
80	6.9	8.2	9.1	9.1

* From single point size distribution and velocity measurements.

Table 4-6. Results of Size Distribution Measurements for Parker-Hannifin Nozzles, VDA Traverse Data Taken at Port Sets 2, 3, and 4.*

Water Flow, gpm			6	10
Downstream				
Port Set #	Distance (ft)	Time of Flight (sec)	Sauter Mean Diameter, µm (Air Pressure = 100 psig)	
2	5	0.10	35.2	39.2
3	8	0.17	34.6	40.3
4	24	0.54	38.5	46.7
			Calculated Water Flow*, gpm	
2	5	0.10	3.8	6.2
3	8	0.17	3.0	4.8
4	24	0.54	2.0	3.5

* Data taken in top and bottom ports, 2 points per port.

Table 4-7. Results of Size Distribution Measurements for Lechler Nozzles, VDA Traverse Data Taken at Port Sets 2, 3, and 4.*

Water Flow, gpm		6			10		
Downstream		Sauter Mean Diameter, µm (Air Pressure = 80 psig)					
Port Set, #	Distance, ft	Background Correction**			Background Correction**		
		None	Average	Highest	None	Average	Highest
2	5	31	32	34	36	37	38
3	8	37	40	44	35	38	41
4	24	33	36	42	44	48	56
		Calculated Water Flow*, gpm					
2	5	2.6	2.4	1.9	4.7	4.7	4.0
3	8	2.9	3.2	2.6	3.4	3.9	3.3
4	24	2.1	2.1	1.5	3.2	3.6	3.0

* Data taken in top and bottom ports, 2 points per port.
** See text for explanation of background correction procedure.

Table 4-8. VDA Test Results, Reagent Slurry, Reagent Slurry/Recycle Ash Injection[1]

Date	Injected Liquid	Downstream Location ft	Downstream Location sec.	VDA Optics[2] Magnification	Inlet Temp. °F	SO_2 Level ppm	Ca/S Ratio	Approach °F	A/L Ratio[3]	Sauter Mean Diameter µm	Measured Flow Rate at Nozzle, gpm	Recovered[4] Flow Rate at VDA, gpm	Droplet Conc. liters/m³	Estimated Dry Mass Conc. grains/acf
12/18	Water	5	0.10	High	342	3205	--	42	1.46	30	9.0	1.09	0.00360	2.79
12/18	Water	8	0.17	High	342	3205	--	42	1.46	40	9.0	1.46	0.00480	2.79
12/18	Water	5	0.10	Low	342	3205	--	42	1.46	67	9.0	1.15	0.00379	2.79
12/18	Water	8	0.17	Low	342	3205	--	42	1.46	68	9.0	1.76	0.00578	2.79
12/20	Slaked Lime	5	0.10	Low	308	2078	1.73	41	1.06	75	11.3	2.84	0.00773	5.14
12/20	Slaked Lime	8	0.17	Low	308	2078	1.73	41	1.06	64	11.3	2.53	0.00689	5.14
12/20	Slaked Lime	24	0.54	Low	308	2078	1.73	41	1.06	68	11.3	4.91	0.01340	5.14
12/17	Slurry/Recycle	24	0.54	High	337	2955	1.41	40	0.89	85	14.0	7.40	0.02290	8.53
12/19	Slurry/Recycle	24	0.54	Low	306	2093	1.68	27	0.91	78	13.2	7.33	0.02280	6.51
12/20	Slurry/Recycle	24	0.54	Low	307	2064	1.27	37	1.06	73	11.3	5.02	0.01370	6.28

1. All Tests conducted with six 2.88 gpm Lechler Nozzles
2. VDA Range at Low Magnification: 20 - 3000 µm (80 - 2000 µm for best accuracy).
   VDA Range at High Magnification: 3 - 450 µm (10 - 200 µm for best accuracy)
3. All tests at 80 psig pressure.
4. Two point traverse in top and bottom ports(4 points total).

5.0 SULFUR DIOXIDE REMOVAL EXPERIMENTS

Studies of SO_2 removal were subdivided between: (1) dry injection of calcium hydroxide with humidification, and (2) injection of slaked lime slurries.

Tests were conducted to measure SO_2 removal with reagent dry $Ca(OH)_2$ sorbent (Mississippi Lime^{TM}), reagent dry $Ca(OH)_2$ mixed with dry recycle ash, and with dry recycle ash alone. Both co-planar and non-coplanar injection of water and sorbent were tested. ESP performance was evaluated for selected process conditions.

The second major series of tests to measure SO_2 removal and ESP performance was conducted with the injection of various slurry mixtures. These slurries included slaked lime slurry, mixtures of slaked lime slurry and recycled waste ash, and a slurry of recycled waste ash alone. For all of these tests, the liquid portion of the slurry was water and the slaked lime sorbent was produced on site with a detention-type slaker using a pebble lime feed stock supplied by the Mid Ohio Valley Lime Company of Marietta, OH. The physical properties of the dry and slaked lime sorbents were reviewed in Topical Report No. 2.[1]

5.1 Dry Sorbent Injection

Dry sorbent injection tests were performed with upstream humidification and downstream humidification. With upstream humidification (the non-scavenging mode), dry sorbent is injected after water droplets have fully evaporated and the approach temperature has been reached. Thus, the sorbent does not contact (or scavenge) any water droplets present in the flue gas. With downstream humidification (the scavenging mode), dry sorbent is injected upstream of the water sprays, and the sorbent has a chance to react with SO_3 present in the flue gas before humidification and, after humidification, to contact (and become moistened by) water droplets. Because moist sorbent reacts much more readily with SO_2, the scavenging mode offers the possibility of higher SO_2 removal.

Coplanar injection is a variation of the scavenging mode. The sorbent is injected at the point of humidification, typically in a place where it must pass through the water spray before it can disperse throughout the duct. This arrangement should increase SO_2 removal because there is a better chance for more of the sorbent to contact water droplets than with the non-scavenging mode or downstream humidification. The potential disadvantage of this technique is that because the sorbent does not disperse throughout the duct before reaching the humidification zone, the sorbent will have no opportunity to react with SO_3 present in the incoming flue gas. Submicron-sized sulfate aerosols are formed when flue gas containing SO_3 is humidified. Because corona quenching has been observed in the first field of an ESP during duct injection tests where the injected dry sorbent did not scavenge the incoming SO_3,[7] the possibility exists that the gain in SO_2 removal realized from coplanar injection might be offset by degraded ESP performance.

A coplanar injection nozzle was designed, built, and installed in the horizontal test duct of the DITF. Figure 5-1 shows a schematic drawing of the installation. As Figure 5-1 shows, this 5.75 in. diameter nozzle discharged the dry sorbent approximately 3 in. from the plane defined by the ends of the humidification nozzles. The nozzle was sized so that the exit velocity at the tip of the nozzle would be 60 ft/s (isokinetic to a flue gas flow of 50,000 acfm in the 50 in. wide by 40 in. high duct). The

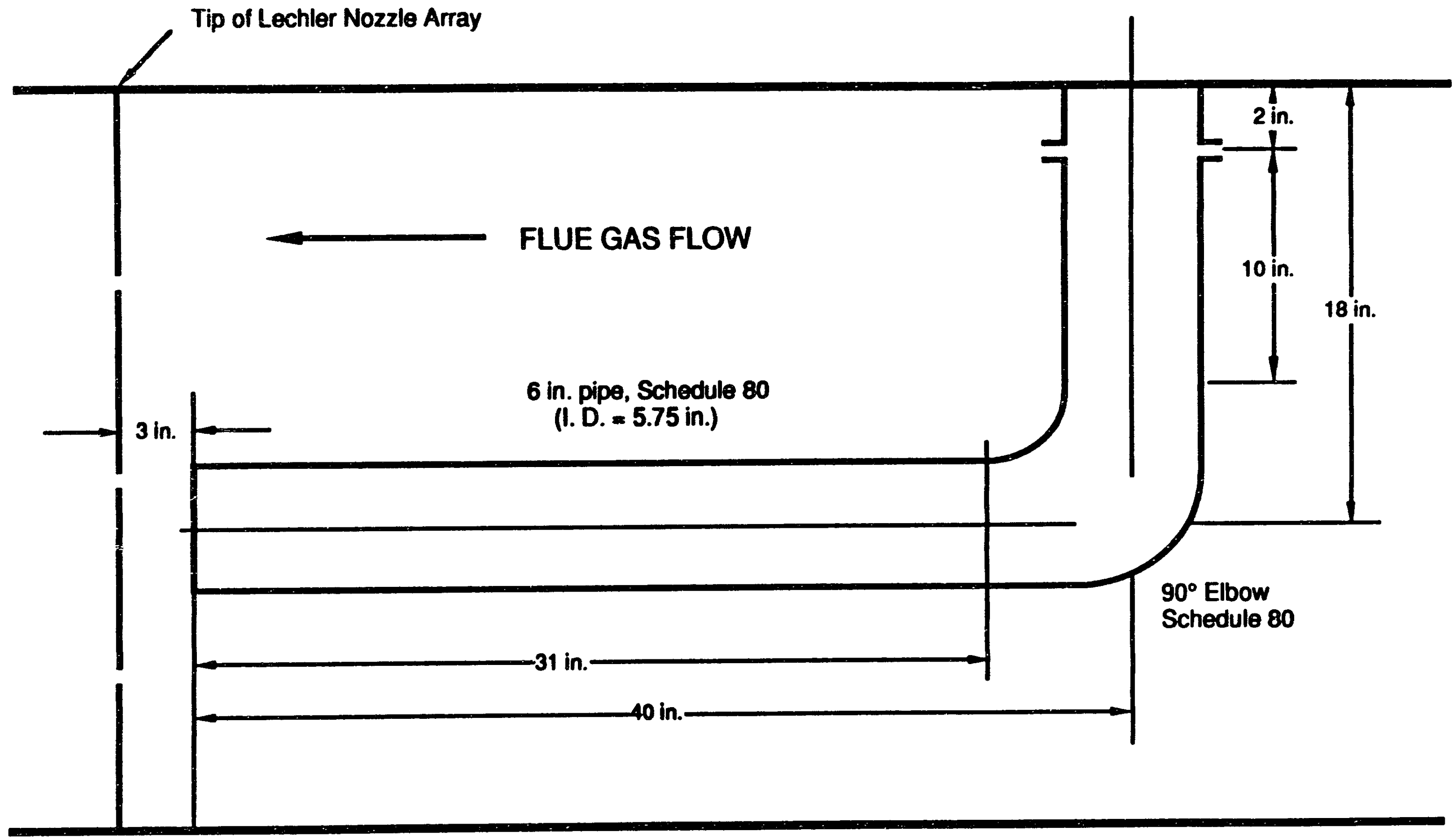

Figure 5-1. Schematic diagram of the installation of the coplanar dry injection nozzle in the horizontal test duct at the DITF.

array of humidification nozzles was composed of three nozzles on each of two lances, one above and the other below the point where the dry sorbent was injected. The top lance was depressed 1.25° from the horizontal and the lower lance was elevated 5° from the horizontal. The outer nozzles on each lance were pointed inward by 5°. This arrangement had been determined empirically to minimize wall wetting that occurred in earlier tests with water and slurry as reported in Topical Report No. 2.[1] The same Lechler Supersonic nozzles were used for humidification and for slurry injection throughout these tests (2.88 gpm capacity, Model 199.005.23).

Since better SO_2 removal results were obtained with co-planar injection than with non-coplanar injection, this discussion will focus on the co-planar experiments. Parametric tests to measure SO_2 removal were performed at nominal Ca/S ratios of 1.0, 1.5, and 2.0 at approach temperatures of 25, 35, and 45°F. A long-term test was conducted to evaluate ESP performance with dry sorbent injection at a nominal Ca/S ratio of 2.0 and approach temperatures of 45 and 35°F. No recycle ash was injected during these tests.

Three types of tests with recycle ash were performed:

- Injection of dry recycle ash collected during previous slurry tests.
- Injection of dry recycle ash from dry injection tests.
- Injection of dry sorbent recycle with reagent dry sorbent.

Tables 5-1 and 5-2 and Figures 5-2 through 5-4 summarize the SO_2 removal data obtained in these tests. Inlet SO_2 concentrations were in the range of 1960 to 2020 ppm. The results reported in these tables are usually hourly averages of data made after steady state conditions were reached for the particular test. When possible, these averages were computed during periods that quench probe runs were made so that sorbent utilization based on gas phase removal data could be compared with the results of solids analyses carried out on the quench probe samples and ESP hopper samples taken at the same time as the quench probe samples. Heat balance calculations for these tests are presented in Appendix A of Topical Reports 3 through 6.[2]

As indicated above, nominal approach temperatures of 25, 35, and 45°F were used for these parametric tests. Unfortunately, these tests were approximately 60% complete when it was determined that the J-type thermocouple array at the ESP inlet reported an inlet temperature that could be offset from the correct value by as much as 10°F. This problem was quickly corrected and most of the lost temperature information was recovered from other manual measurements of the ESP inlet temperature made for quench probe runs or for ESP inlet mass train measurements. However, much of the intended 35°F approach data turned out to have been closer to 40°F.

The results of experiments with reagent dry sorbent (Mississippi Lime™ $Ca(OH)_2$) are summarized in Table 5-1 and Figures 5-2 through 5-4. Tests performed with the injection of dry recycle ash from earlier slurry tests, coplanar dry injection tests, or from combined reagent $Ca(OH)_2$ and dry recycle ash are summarized in Table 5-2 and Figures 5-3 and 5-4. Table 5-1 also presents the results of solids analysis of selected quench probe and ESP hopper samples. Generally, sorbent utilization determined from the analysis of the quench probe samples agrees well with sorbent utilization calculated from the gas phase data. As would be expected, sorbent utilization determined from solids analyses of the ESP inlet hopper samples were higher (usually from one to three percent) than sorbent utilization

Table 5-1. SO_2 Removal Data Obtained During Coplanar Dry Sorbent Injection Tests

TEST IDENTIFICATION			GAS PHASE DATA						UTILIZATION FROM ANALYSIS, %			
			SO_2 Removal, %			Gas Phase Utilization, %			Q. Probe	ESP Hoppers		
Test Number	Ca/S Ratio	Approach to Sat, °F.	End of Horiz. Duct	ESP Inlet	ESP Outlet	End of Horiz. Duct	ESP Inlet	ESP Outlet	ESP Inlet	Inlet	Middle	Outlet
46-DS-03	0.94	21	24	24	30	25	25	31		28.4	30.6	46.3
46-DS-02	1.43	25	25	33	36	18	23	25		25.5	27.8	36.7
46-DS-01	1.96	24	33	41	47	17	21	24		27.6	29.6	40.5
47-DS-03	1.01	37	16	17	21	15	17	21				
45-DS-03	1.05	39	17	16	21	16	15	20				
45-DS-03	1.05	38	17	17	20	16	16	19				
47-DS-02	1.55	37	19	21	28	12	13	18				
47-DS-01	1.91	35	25	25	33	13	13	17				
48-DS-03	2.02	37	25	27	35	12	13	17				
47-DS-01	2.04	39	21	22	29	10	11	14				
48-DS-04	2.04	35	24	25	33	12	12	16				
43-DS-04	0.99	44	11	13	17	11	13	17	13.2	15.4	28.4	28.9
43-DS-04	1.00	44	14	14	19	14	14	19	12.6	15.4	28.4	28.9
43-DS-02	1.48	45	17	18	23	12	12	15				
43-DS-03	1.54	43	17	22	23	11	14	15	12.0	14.9	20.6	36.4
45-DS-02	1.56	47	17	20	25	11	13	16				
43-DS-03	1.57	43	17	18	25	11	12	16	11.8	14.9	20.6	36.4
45-DS-02	1.60	47	23	22	27	14	14	17				
45-DS-01	1.91	45	22	22	30	12	12	16				
45-DS-01	1.93	45	23	23	31	12	12	16				
43-DS-01	1.97	40	24	24	32	12	12	16	10.6	13.9	20.8	31.0
43-DS-01	2.02	40	24	26	35	12	13	17	11.4	13.9	20.8	31.0
48-DS-01	2.03	44	20	21	30	10	10	14				
48-DS-02	2.06	45	20	21	31	9	10	15				

Table 5-2. SO_2 Removal Data Obtained During Coplanar Dry Sorbent Injection Tests with Recycle Ash Alone and Fresh Sorbent plus Recycle Ash

TEST IDENTIFICATION					GAS PHASE DATA					
		Ca/S Ratio			SO_2 Removal, %			Gas Phase Utilization, %		
Test Number	Source of Recycle Ash	Overall	Recycle Ash	Approach to Sat, °F.	End of Horiz. Duct	ESP Inlet	ESP Outlet	End of Horiz. Duct	ESP Inlet	ESP Outlet
Recycle Ash										
50-DSR-02	Dry Sorbent	1.17	1.17	25	25	26	32	22	23	28
49-DR-03	Dry Sorbent	1.09	1.09	36	14	16	21	14	16	21
47-DR-02*	Slurry	1.14	1.14	36	22	24	30	19	21	26
49-DR-01	Dry Sorbent	1.05	1.05	46	11	12	14	11	12	13
49-DR-02	Dry Sorbent	1.18	1.18	46	11	12	14	10	10	13
47-DR-01	Slurry	1.18	1.18	46	19	20	26	16	17	22
Sorbent and Recycle Ash										
50-DSR-02	Dry Sorbent	2.04	0.85	25	36	38	49	18	19	24
50-DSR-03	Dry Sorbent	2.09	0.85	27	35	37	48	17	18	23
50-DSR-01	Dry Sorbent	2.03	0.85	36	29	31	40	14	15	20

* Analysis of solids samples from this test indicated utilizations of 41.0% for the Quench Probe sample and 43.2, 44.2, and 46.7% for samples from the ESP inlet, middle, and outlet hoppers.

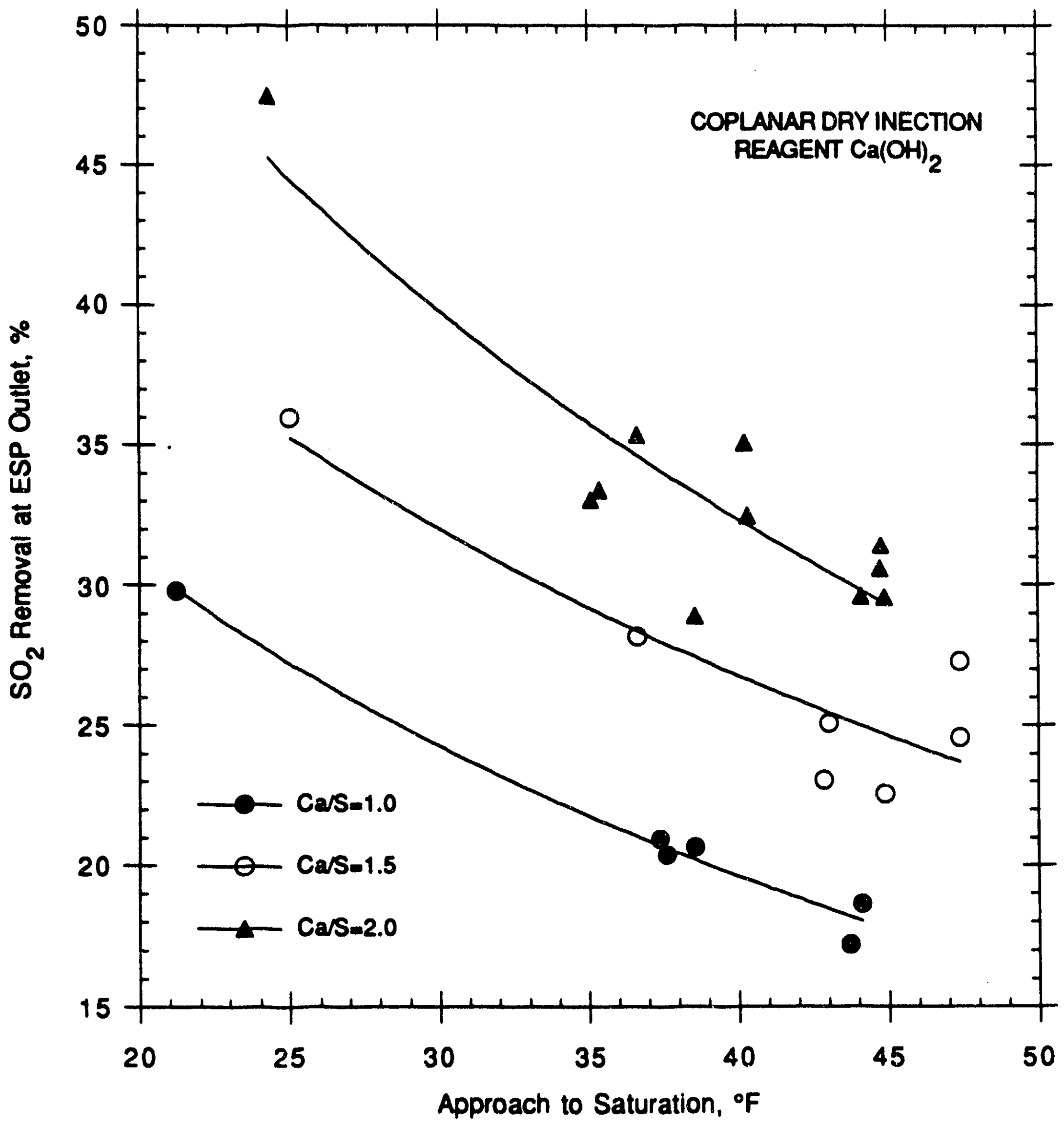

Figure 5-2. Percent of SO_2 removed at the ESP outlet as a function of the approach to saturation. Coplanar dry injection with reagent $Ca(OH)_2$.

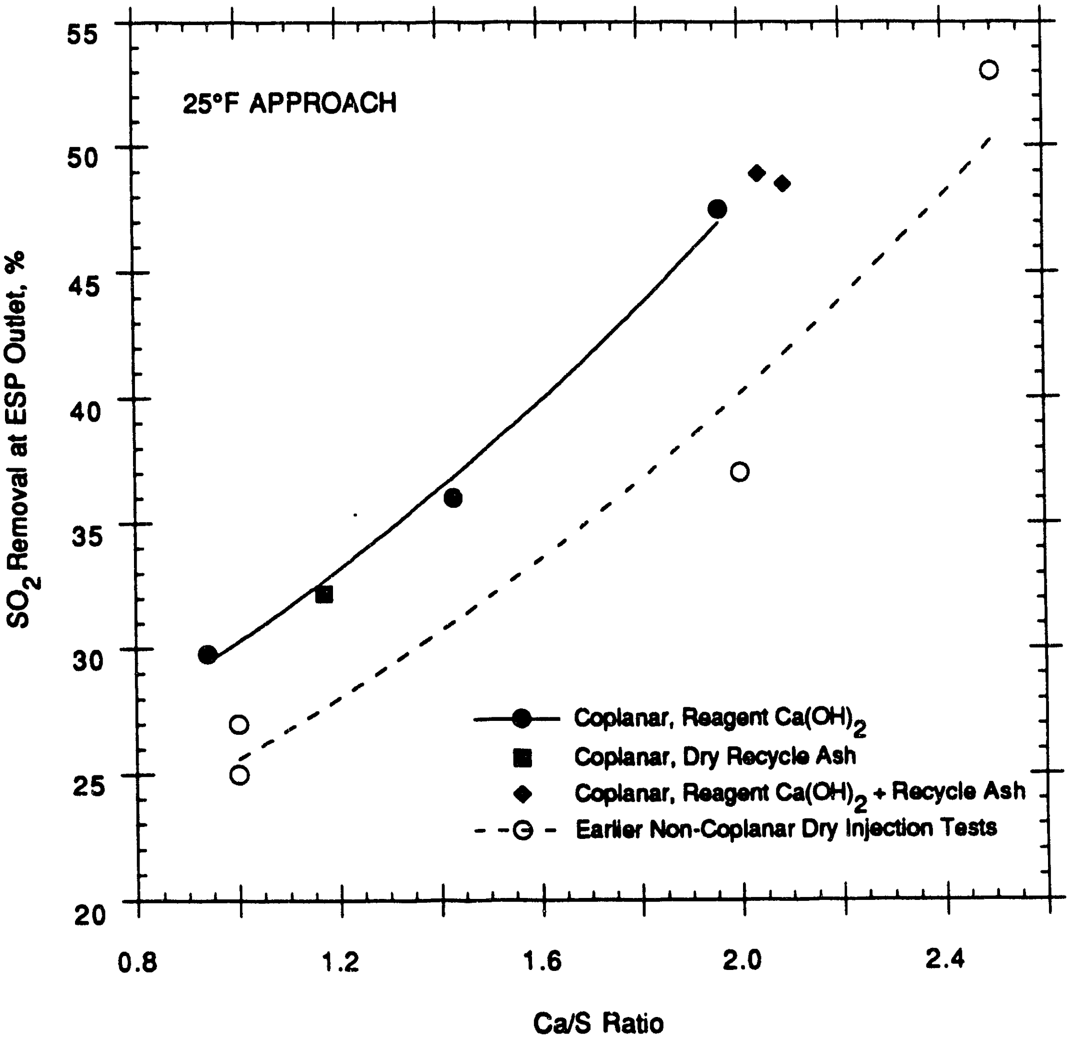

Figure 5-3. Percent of SO_2 removed at the ESP outlet as a function of the Ca/S ratio at a 25° F approach to saturation. Coplanar dry injection with reagent $Ca(OH)_2$ and reagent $Ca(OH)_2$ with recycle ash. Non-coplanar dry injection data at a 25° F approach shown for comparison.

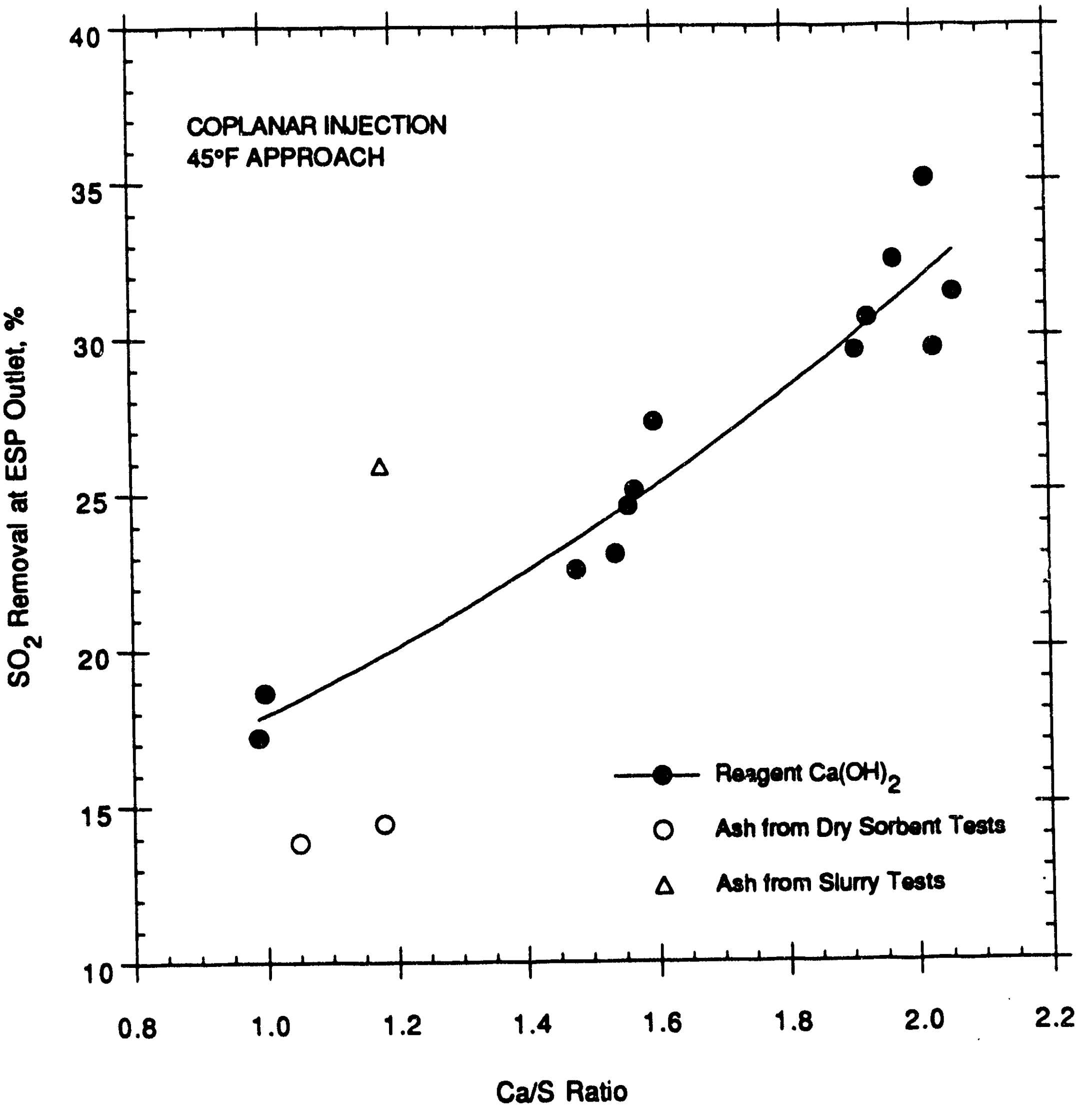

Figure 5-4. Percent of SO_2 removed at the ESP outlet as a function of the Ca/S ratio at a 45°F approach to saturation. Coplanar dry injection with reagent $Ca(OH)_2$ and reagent $Ca(OH)_2$ with recycle ash.

calculated from the gas phase data. At the ESP outlet, SO_2 removal data are also shown in Figures 5-2 through 5-4. Figure 5-2 shows how SO_2 removal increases with decreasing approach temperature and increasing Ca/S ratio, for reagent $Ca(OH)_2$ sorbent. Some of the scatter in these data may be due to the aforementioned inaccuracy in the temperature measurement at the ESP inlet. Figure 5-3 presents SO_2 removal as a function of Ca/S ratio at a nominal 25° F approach and includes data from recycle testing as well as data from earlier tests with reagent $Ca(OH)_2$ where the sorbent was injected upstream of the humidification nozzles (scavenging mode). Generally, SO_2 removal was unaffected by the type of sorbent used. It should be noted, however, that the recycle ash used for these tests was generated during other coplanar dry sorbent injection tests, and approximately 52% of this material was $Ca(OH)_2$. Coplanar injection increased SO_2 removal over that obtained when sorbent was injected in the scavenging mode by 5 to 10%, depending on the Ca/S ratio. This is most probably due to the better contact of sorbent and water provided by coplanar injection, especially at lower approach temperatures.

Figure 5-4 presents SO_2 removal as a function of Ca/S ratio at a nominal 45° F approach and includes data from recycle tests (no reagent $Ca(OH)_2$) conducted with recycle ash preserved from earlier slurry injection (35% $Ca(OH)_2$ in the recycle ash) and from coplanar dry sorbent injection (52% $Ca(OH)_2$ in the recycle ash). In this case, the source of the recycle ash affected SO_2 removal. When recycle ash from dry sorbent tests was injected lower amounts of were SO_2 removed than were removed with reagent sorbent. When recycle ash from slurry tests was injected much higher amounts of SO_2 were removed than were removed with reagent sorbent. However, the calcium utilization with dry injection of slurry recycle ash is still significantly lower than for slaked lime slurry injection under comparable conditions.

5.2 Slurry Injection

Extensive parametric testing of the injection of slaked lime slurries and the injection of slurries made from various mixtures of recycled ash and slaked lime slurry was carried out at the DITF. The experimental effort was concentrated on this process mode as a result of superior SO_2 removal and ease of operation compared with dry injection.

Also, as part of these slurry injection tests, four other limited series of tests were performed in which the data are reported separately. These test series consisted of:

- An evaluation of the effect of air/liquid ratio on SO_2 removal and wall deposition for both the six Lechler nozzle array and for a single 12 gpm Lechler nozzle,
- Injection of dry recycle ash through the coplanar nozzle while a slaked lime slurry was injected through the six Lechler nozzle array,
- Evaluation of a two-stage process in which a single 2.88 gpm Parker-Hannifin nozzle (dual fluid-external mix) was installed on a lance located 30 ft downstream of the array of six Lechler nozzles to determine the effect of downstream humidification on SO_2 removal with slurry injection, and,
- Investigation of the effect on SO_2 removal of $CaCl_2$ addition to slaked lime slurries and to mixtures of recycle ash and slaked lime slurry.

For this report, the results all of the tests were scrutinized and test results were excluded from the data summaries presented here if there were questions as to the accuracy of SO_2 measurements, gas flows or flue gas temperatures. Generally, liquid slurry flow was accurately delivered and measured. However, when humidification water was added to slurry injected through the Lechler nozzle array (to maintain a given Ca/S ratio and vary approach temperature) it was found that it was not possible to stabilize humidification water flow because the available flow controller was sized to deliver higher water flows at lower discharge pressures than were used in the slurry pumping system.

At the humidification water flows that were typical (< 2 gpm), humidification water flow frequently varied to the point that values recorded by the data acquisition system were incorrect. Many of the heat balance calculations for tests performed from March through May, 1991 (the period when humidification water was in regular use) reflect this inaccuracy by showing a poor heat balance because of nonexistent or abnormally low humidification water flow.[2] After May, 1991 when it was realized that metering low water flows was a problem and that the addition of humidification water could also reduce the effective solids content of the slurry to a point where wall wetting could be a problem (because of increased drying times), this practice was halted.

Tables 5-3 and 5-4 summarize all of the SO_2 removal tests performed with reagent or slaked lime slurry injection that were performed at the DITF. Table 5-3 shows the results of SO_2 removal tests included in Topical Report No. 2 and Table 5-4 presents the results of SO_2 removal tests conducted from February, 1991 to the end of testing.[1,2] Table 5-4 also includes SO_2 removal and gas phase utilization data for both the end of the horizontal duct (1 sec of residence time) and for the ESP inlet (1.5 sec of residence time). Before February, 1991 SO_2 removal data was not reported at the end of the horizontal duct.

Figure 5-5 summarizes SO_2 removal data at the ESP inlet as a function of Ca/S ratio, and Figure 5-6 contains an analogous summary of SO_2 removal data measured at the ESP outlet. Finally, gas phase utilization determined at the ESP inlet and outlet are presented as a function of Ca/S ratio in Figures 5-7, 5-8, 5-9 and 5-10. Figure 5-7 contains a line for coplanar dry sorbent injection derived from the data in Figure 5-3. A comparison of this line with the comparable slurry data indicates the superior performance of slurry injection at comparable approach temperatures.

Inspection of these figures shows that even though every effort was made to insure that these data were correctly measured there is still some scatter, particularly in SO_2 removal measured at the ESP inlet. For example, at the ESP inlet data from test 43-SL-01 show much higher SO_2 removals than appear to be consistent with other data at a 20-25°F approach. Because these data clearly conflict with other data taken at different times the results from this particular test should probably be disregarded.

Likewise, in the approach range of 30-40°F, there appears to be a difference in SO_2 removal measured from tests 42-SL-04, 43-SL-02, and 54-SL-01 and the rest of the data. During tests 42-SL-04 and 43-SL-02 much higher SO_2 removals were measured than are suggested by the rest of the data and during test 54-SL-01 much lower SO_2 removals were measured than are suggested by the rest of the data. Again, because these data clearly conflict with the preponderance of other data in this range of approach temperatures the results of these tests should probably be disregarded.

Table 5-3. Results of SO_2 Removal Tests Carried out at the DITF

Test #	Ca/S Ratio	Approach (°F)	Inlet SO_2 (ppm)	--- SO_2 Removal, (%) ---		--- Gas Phase Util. (%) ---	
				ESP Inlet	ESP Outlet	ESP Inlet	ESP Outlet
28-SL-07	1.03	25	1790	46	52	44	51
28-SL-04	1.43	25	1909	54	64	38	45
28-SL-04	1.54	25	1805	56	67	36	44
28-SL-04	1.60	23	1773	58	70	36	44
28-SL-04	1.60	24	1780	57	70	36	44
25-SL-02	3.27	21	1156	78	90	24	27
28-SL-07	0.98	28	1852	45	50	46	51
28-SL-07	1.01	27	1781	45	51	44	51
25-SL-04	1.44	30	2734	50	71	35	50
25-SL-04	1.45	28	2764	52	71	36	49
28-SL-01	2.10	27	1775	62	80	29	38
28-SL-01	2.15	28	1700	60	79	28	37
28-SL-06	0.99	35	1875	43	51	43	51
28-SL-06	1.03	35	1799	44	50	42	49
28-SL-06	1.07	35	1702	44	52	41	49
28-SL-02	1.49	35	1804	45	56	30	38
28-SL-03	1.49	35	1873	49	59	33	40
28-SL-03	1.49	35	1869	52	61	35	41
28-SL-02	1.51	35	1788	46	59	30	39
27-SL-02	1.93	35	1875	55	66	29	34
24-SL-02	1.95	35	1788	54	68	28	35
24-SL-02	2.86	32	1167	60	75	21	26
25-SL-05	1.27	40	2764	44	58	35	46
25-SL-03	1.45	37	2146	48	63	33	43
29-SL-02	1.97	38	1766	53	61	27	31
29-SL-02	2.02	37	1773	56	67	28	33
29-SL-02	2.06	37	1752	55	66	27	32
27-SL-02	2.09	38	1738	53	67	26	32
20-SL-03	2.20	38	1205	49	56	22	26
20-SL-01	2.32	38	1186	51	60	22	26
24-SL-01	2.88	39	1253	56	68	20	24
28-SL-05	1.04	43	1803	37	41	35	40
28-SL-05	1.05	43	1780	36	40	34	38
28-SL-05	1.05	44	1790	37	42	36	40
25-SL-01	1.83	43	1770	49	63	27	34
27-SL-01	2.15	43	1692	49	61	23	29
27-SL-01	2.15	45	1679	47	60	22	28
20-SL-05	2.23	42	1216	51	61	23	27
20-SL-02	2.43	43	1213	50	59	20	24
26-SL-01	1.52	50	1771	36	42	23	28
26-SL-02	1.75	46	1794	45	55	26	32
29-SL-01	1.85	49	1878	47	55	26	30
29-SL-01	1.91	47	1836	50	61	26	32
21-SL-01	1.98	48	1252	50	62	25	32
20-SL-02	2.29	48	1271	47	57	20	25
21-SL-01	2.34	47	1064	49	62	21	27
25-SL-06	1.30	56	2790	36	44	28	34
26-SL-03	1.64	56	1804	41	47	25	29
21-SL-01	2.00	53	1247	45	60	23	30
21-SL-01	2.01	52	1227	48	60	24	30
21-SL-01	2.08	55	1201	48	61	23	29
21-SL-01	2.15	53	1151	49	63	23	29
21-SL-01	2.17	51	1129	50	62	23	29
21-SL-01	2.22	56	1159	52	62	23	28
21-SL-01	2.29	51	1137	55	66	24	29

Table 5-4. Results of SO_2 Removal Tests with Reagent Lime Slurry Carried out Since 2/91

Test #	Ca/S	Approach	Inlet SO_2	---------- SO_2 Removal, (%) ---------			---- Gas Phase Utilization, (%) -----		
	Ratio	(°F)	(ppm)	End H Duct	ESP Inlet	ESP Outlet	End H Duct	ESP Inlet	ESP Outlet
35-DSR-04	1.02	23	2112	46	46	56	45	46	55
34-SL-04	1.02	24	1990	47	48	58	46	47	57
38-SL-03	1.29	25	1983	40	41	52	31	32	40
38-SL-01	1.58	23	1991	53	55	71	33	35	45
68-SL-01	1.62	23	3289	–	49	60	–	30	37
39-SL-03	1.78	23	1982	–	58	76	–	33	43
39-SL-01	1.79	24	2009	–	57	72	–	32	40
38-SL-02	1.79	22	1973	56	57	74	31	32	41
38-SL-02	1.82	24	1946	54	57	74	30	31	40
38-SL-04	1.91	26	1992	–	54	67	–	28	35
38-SL-04	1.92	25	1994	–	53	68	–	28	35
34-SL-01	2.00	26	2020	56	57	76	28	28	38
33-SL-03	2.01	27	1350	61	62	74	30	31	37
43-SL-01	2.01	24	1992	61	71	79	30	35	39
43-SL-01	2.05	24	1979	–	75	81	–	37	40
37-SL-02	2.06	22	2095	53	59	75	26	28	36
43-SL-01	2.07	24	1982	–	75	83	–	36	40
43-SL-01	2.08	24	1986	–	75	84	–	36	40
34-SL-02	2.10	25	2007	57	60	79	27	29	38
33-SL-05	2.14	19	1843	57	59	78	27	27	36
37-SL-03	2.15	24	1954	53	57	74	25	26	34
38-SL-03	2.16	25	1990	56	59	76	26	27	35
37-SL-02	2.17	22	2008	56	61	76	26	28	35
77-SL-03	2.22	25	2084	59	61	81	26	27	36
37-SL-04	2.22	22	1978	58	61	75	26	27	34
78-SL-02	2.34	25	2626	55	58	77	23	25	33
37-SL-04	2.41	22	1884	58	62	79	24	26	33
78-SL-01	4.91	26	1077	70	79	92	14	16	19
53-SL-03	1.62	34	1927	43	45	54	27	28	33
68-SL-01	1.70	31	3260	–	47	59	–	28	35
53-SL-01	1.72	37	1964	46	47	57	27	28	33
54-SL-03	1.78	37	2116	44	46	55	25	26	31
54-SL-01	1.80	39	2023	39	40	48	22	22	27
53-SL-02	1.81	34	1978	49	50	60	27	28	33
54-SL-03	1.84	38	2096	44	47	55	24	25	30
51-SL-01	1.85	35	2035	50	52	64	27	28	34
54-SL-03	1.85	36	1989	46	48	58	25	26	32
51-SL-02	1.85	37	2028	52	54	65	28	29	35
42-SL-04	1.92	36	1983	–	60	64	–	31	34
42-SL-04	1.94	36	1977	–	60	65	–	31	33
54-SL-03	1.97	38	1988	47	50	57	24	25	29
57-SL-03	1.98	36	2017	49	51	63	24	26	32
54-SL-03	1.99	39	2008	48	48	57	24	24	29
42-SL-02	1,99	33	1954	–	57	63	–	28	32
42-SL-04	1.99	35	1922	–	60	67	–	30	33
42-SL-02	1.99	34	1981	–	59	66	–	29	33
42-SL-02	2.01	33	1955	–	58	66	–	29	33
57-SL-02	2.02	36	2017	48	49	63	24	24	31
54-SL-03	2.07	40	1958	49	50	59	24	24	28
54-SL-03	2.08	40	1947	51	52	61	24	25	30
54-SL-03	2.08	39	1962	50	50	60	24	24	29
54-SL-03	2.10	32	1875	46	48	58	22	23	28
57-SL-04	2.11	36	2059	51	53	67	24	25	32
52-SL-01	2.13	36	1986	52	53	64	24	25	30
76-SL-01	2.13	39	2071	46	48	63	22	23	30
57-SL-01	2.18	35	2014	50	52	64	23	24	29
65-SL-01	1.49	44	2496	38	40	46	26	27	31
65-SL-02	1.57	49	2396	37	39	47	24	25	30
39-SL-04	1.60	47	2001	–	38	46	–	24	29
65-SL-01	1.66	44	2452	40	41	48	24	25	29
65-SL-01	1.69	43	2458	40	41	49	23	24	29
74-SL-01	1.73	41	2078	39	42	48	23	24	28
34-SL-03	1.82	43	1973	43	46	58	24	25	32
52-SL-03	1.83	42	1943	51	53	62	28	29	34
52-SL-02	1.84	41	1968	49	51	61	27	28	33
33-SL-04	1.93	43	1870	53	52	63	27	27	33
33-SL-04	1.93	47	1882	48	47	58	25	25	30
54-SL-03	2.13	42	1906	50	52	61	23	24	29
33-SL-01	2.21	45	1357	48	51	62	22	23	28
33-SL-02	2.25	45	1263	47	49	58	21	22	26

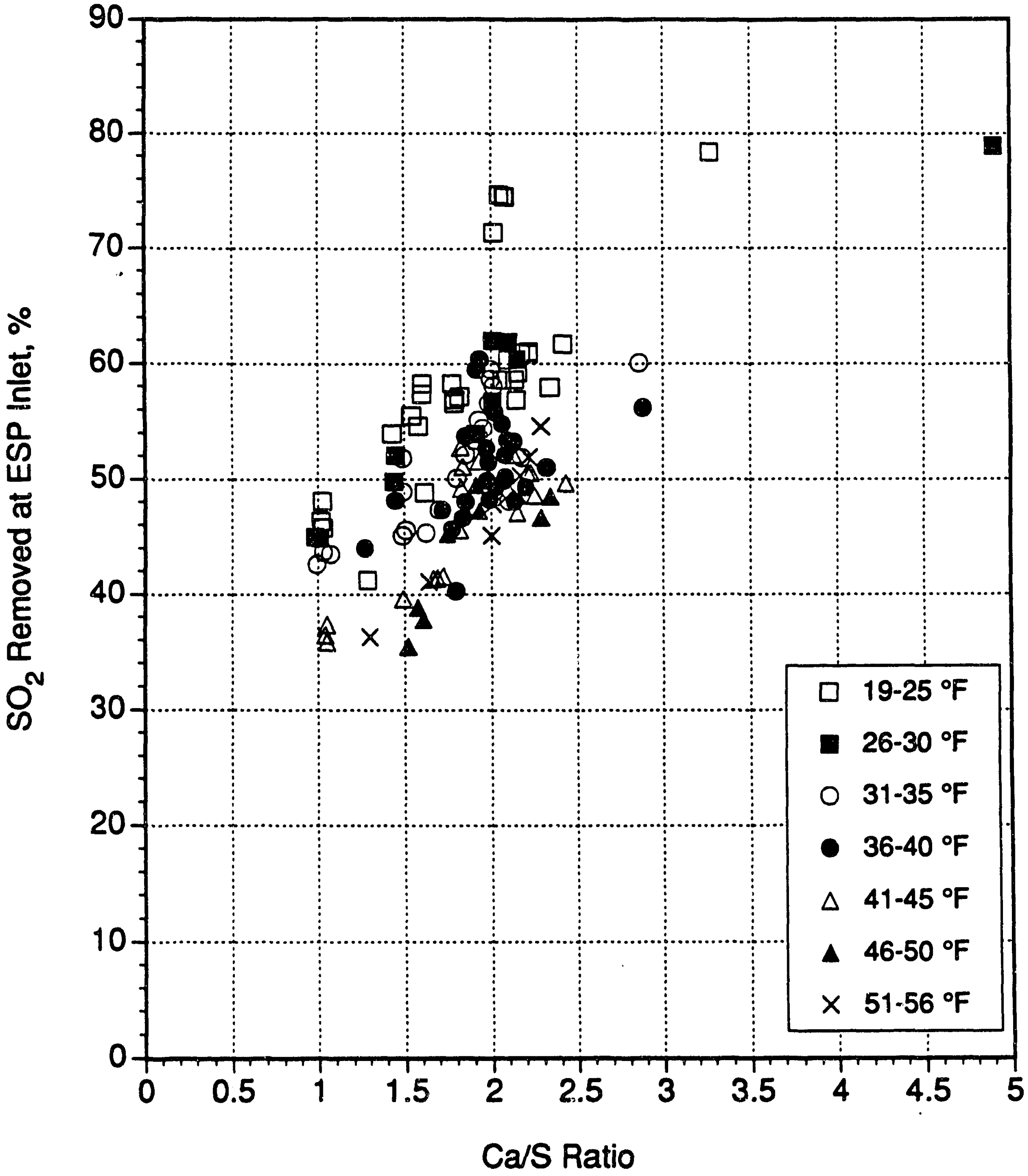

Figure 5-5. Percent of SO_2 removed at the ESP inlet as measured by the gas sampling system. Summary of all data at all approach temperatures.

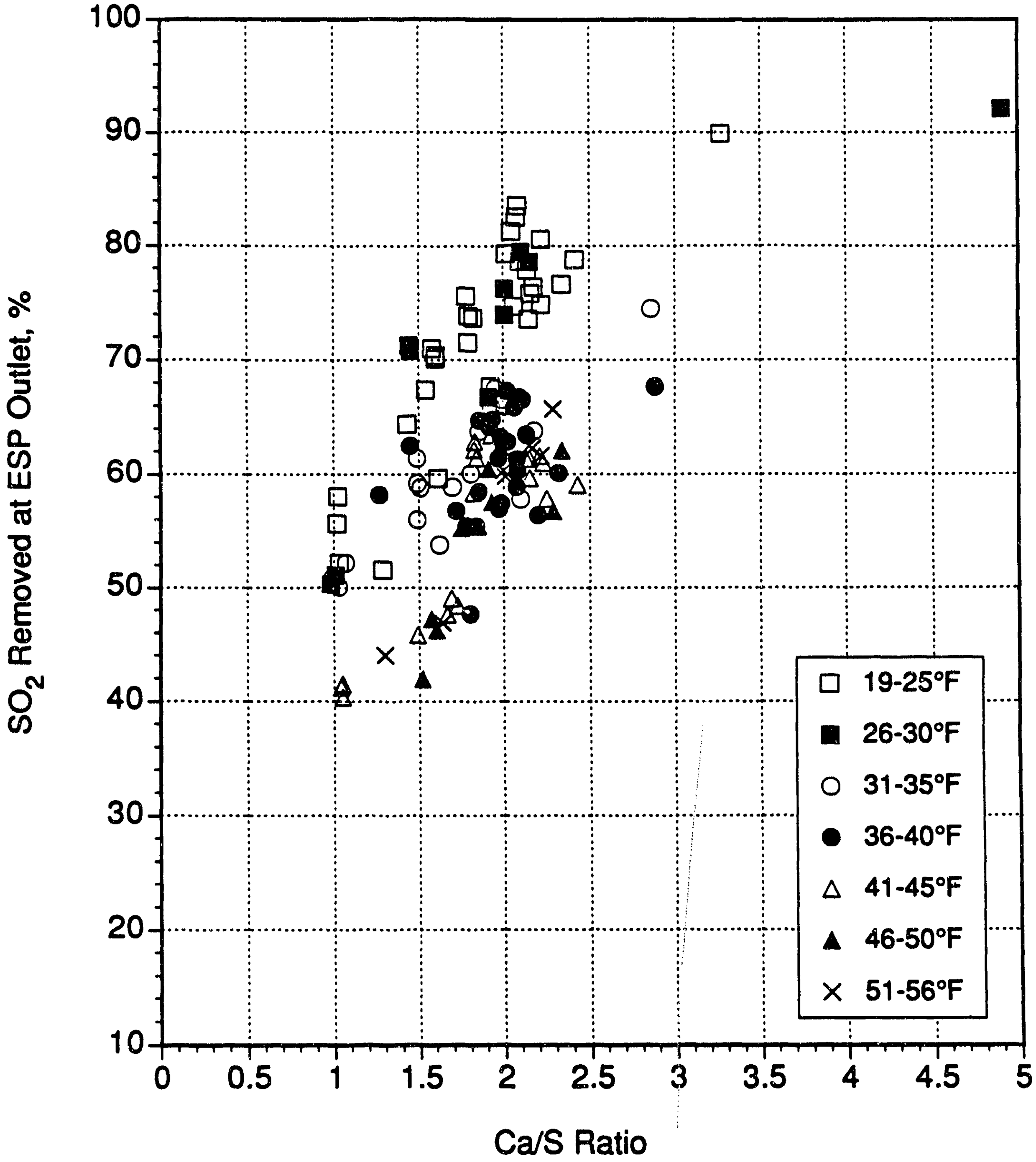

Figure 5-6. Percent of SO_2 removed at the ESP outlet as measured by the gas sampling system. Summary of all data at all approach temperatures.

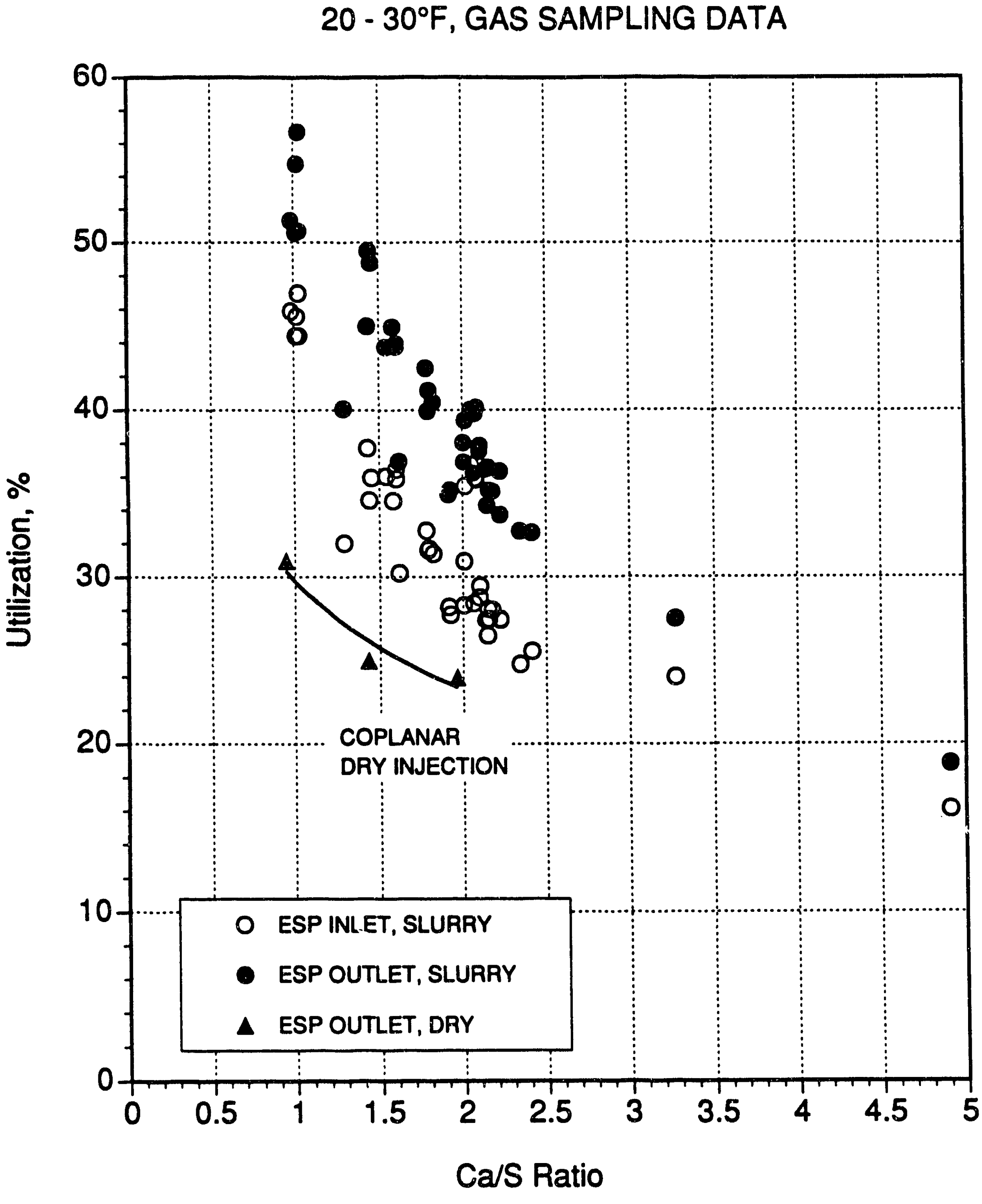

Figure 5-7. Percent of sorbent utilized at the ESP inlet and outlet as determined by the gas sampling system. Summary of test data for approach temperatures from 20 to 30° F.

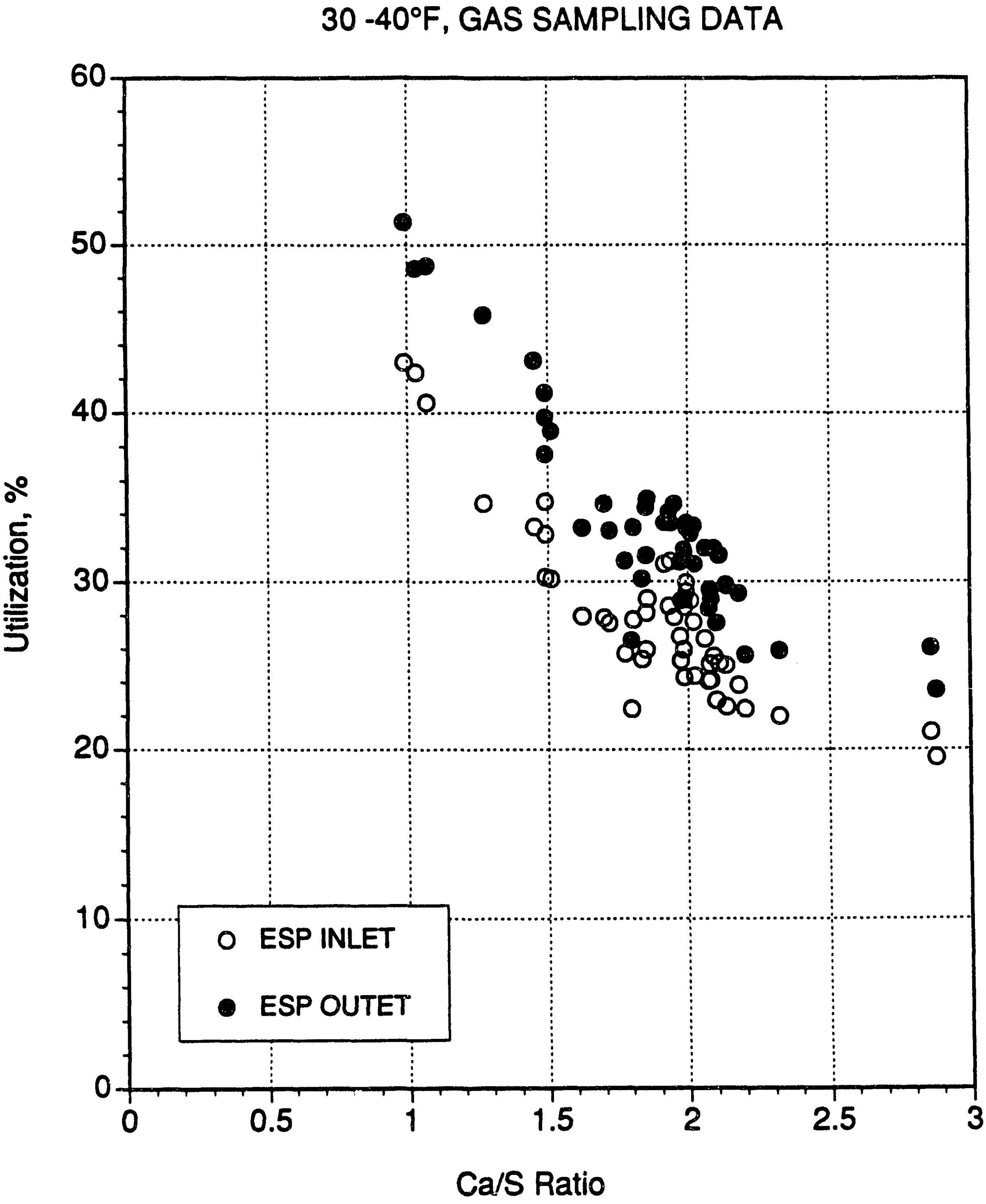

Figure 5-8. Percent of sorbent utilized at the ESP inlet and outlet as determined by the gas sampling system. Summary of test data for approach temperatures from 30 to 40°F.

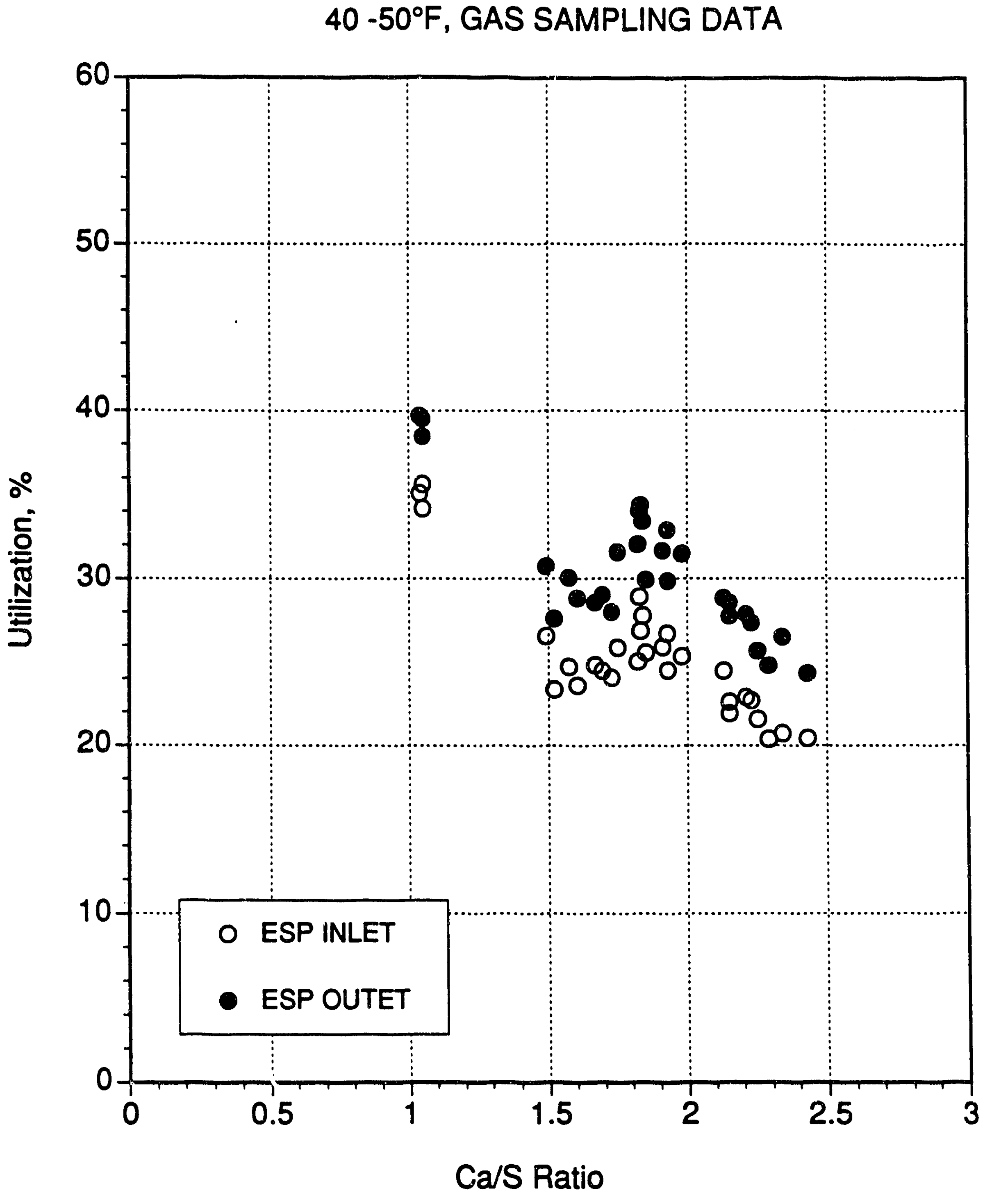

Figure 5-9. Percent of sorbent utilized at the ESP inlet and outlet as determined by the gas sampling system. Summary of test data for approach temperatures from 40 to 50°F.

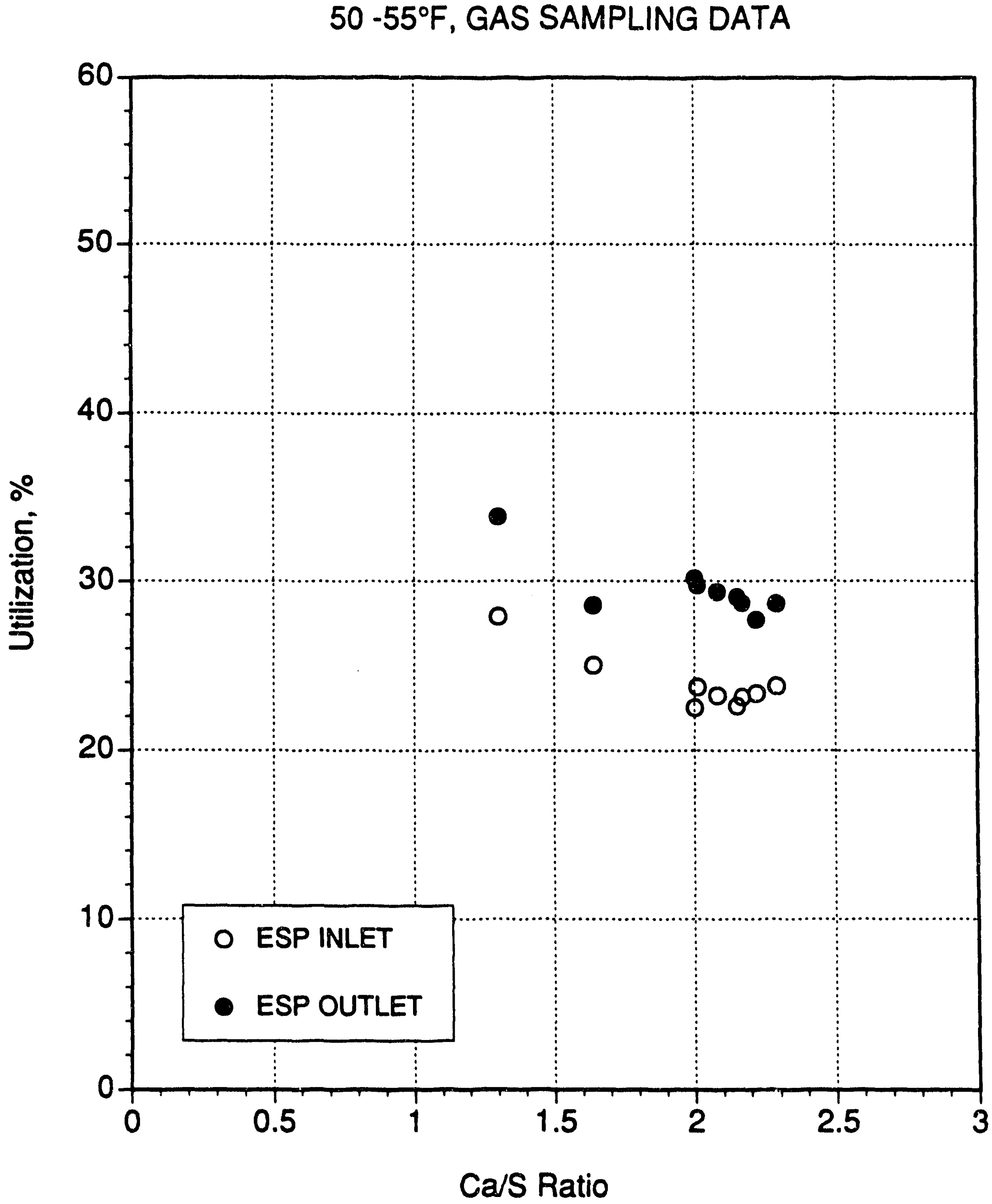

Figure 5-10. Percent of sorbent utilized at the ESP inlet and outlet as determined by the gas sampling system. Summary of test data for approach temperatures from 50 to 55°F.

5.2.1 Sorbent Utilization as a Function of Particle Size

During test 34-SL-02 (March 12, 1991) as part of a separate test series devoted to measuring ESP emissions as a function of SCA with reagent slurry injection, a composite ESP hopper sample was prepared for analysis, and a portion of this sample was segregated by size with a BAHCO particle size classifier. Ten size fractions were obtained. Each size fraction, as well as the composite sample, was then analyzed to measure sorbent utilization.

The results of these analyses are reported in Table 5-5. As this table shows, most of the mass in the sample was greater than 25 μm in size. This largest size fraction also had the lowest calcium content (and sorbent utilization) suggesting that most of the reagent slurry was 25 μm in size or less. Calcium content appeared to be uniformly distributed throughout the other size fractions with a tendency to increase as particle size decreased. On the other hand, sorbent utilization was greatest in a size range from 2.3 to 7.7 μm. It should be noted the particle size data represent the fractionation achieved by an air classification procedure on the dried slurry residue, and thus the results may not be indicative of the dried slurry residue particle size distribution in suspension in the duct.

5.2.2 Sorbent Utilization at the ESP Inlet

The first topical report concerning slurry injection presented data which appeared to show a systematic difference between calcium utilizations obtained at the ESP inlet with the quench probe compared with inlet data from the gas sampling system.[1] It has since been determined that the discrepancy between sorbent utilization as determined from gas phase measurements and from solids analysis of single-point quench probe samples or ESP hopper samples could be resolved by timely measurement of slurry properties (% solids, $Ca(OH)_2$ content, density) and accurate knowledge of inlet flue gas flow. It was also found that the water content in the incoming flue gas tended to vary, making accurate knowledge of the water content in the incoming flue gas (to determine adiabatic saturation temperature) imperative.

Temporal variations in slurry composition were normal for tests that lasted long enough to require that the slaker be operated during the test to generate more reagent slurry. $Ca(OH)_2$ content in the slurry could change from the beginning to the end of the test by as much as 1% on an absolute basis. After this was realized, a practice was made of obtaining slurry samples whenever solids samples were taken or during periods of stable operation when it was planned to perform heat balance calculations.

The Servomex PSA 402C water analyzer turned out to be a very useful addition to the DITF gas sampling system because it provided a consistently accurate measurement of the water vapor concentration in the flue gas. Because water vapor concentration in the flue gas from the Unit 5 boiler could change with boiler load or with coal variation (wet coal, in particular), the adiabatic saturation temperature could change and the approach to saturation would rise or fall while the ESP inlet temperature was held constant by the PLC (which controlled the slurry flow rate to meet a desired ESP inlet temperature). As will be shown below, this type of change in adiabatic saturation temperature did occur during testing.

Another possible source of error that could have caused the ESP inlet gas phase utilization values to disagree with those values determined from analysis of quench probe samples was the choice of location where the quench probe samples were taken. Because quench probe samples are taken at one flow rate, traversing with the quench probe (and sampling at the local duct flow rate) was not

Table 5-5. Results of Solids Analyses Carried out on a Composite ESP Hopper Sample from Test 34-SL-02, 3/12/91.[1]

Size Cut (µm)	Cumulative Weight %	Δ Weight %	Ca^{+2} (%)	SO_3^{-2} (%)	Utilization (%)
1.5	1.11	1.11	31.7	20.6	32.5
2.3	3.08	1.97	31.3	22.0	35.2
4.4	10.14	7.06	29.7	21.5	36.2
7.7	19.81	9.67	29.7	21.0	35.4
10.8	28.98	9.17	30.3	19.9	32.9
17.7	42.30	13.32	29.6	18.9	32.0
22.4	48.53	6.23	29.0	18.0	31.1
25.0	51.97	3.44	29.1	18.4	31.7
25 ≤ 250	100.00	48.03	16.1	7.5	23.3
> 250[2]			14.2	8.6	30.3
Blend	All		24.0	13.7	28.6
Size Weighted Avg.	All		23.2	13.9	30.0

1. Gas Phase Utilization of 29% at ESP inlet, 38% at the ESP Outlet.
2. Greater than 60 Mesh.

feasible. Thus, a point in the center of the duct was chosen to obtain the quench probe samples. If this was not a representative point in terms of flue gas flow or mass concentration then quench probe samples would be nonrepresentative.

To determine if the quench probe samples were representative, a series of quench probe runs were planned at different points in the sampling plane at the ESP inlet test location. These tests would also determine if accurate knowledge of flue gas flow and slurry composition would help reconcile the differences in solids and gas phase utilization that had been observed in the past.

During Week 54 of testing (Test 54-SL-03, August 2, 1991), a series of nine quench probe runs were made at the ESP inlet sampling location. Each run was made at one of three sampling ports (top, middle, bottom) and/or traverse points (in, near the far duct wall, midpoint of the duct, or out, close to the near duct wall), making a nine-point grid. During these runs the nominal test conditions were held to a 35°F approach, 2000 ppm of SO_2 at the system inlet, and a Ca/S ratio of 2.0. During each quench probe run ash/sorbent samples were taken from each ESP hopper and a sample of slurry was obtained. Table 5-6 presents the results of this test and compares the results of sorbent utilization calculated from chemical analyses of the quench probe catches and three selected ESP inlet hopper samples with sorbent utilization calculated from averaged gas phase data.

The data from Table 5-7 show that the water vapor content in the flue gas dropped throughout the day, from 9.9% between 1015 and 1045 hours to 8.2% between 1730 to 1745 hours. Although the ESP inlet temperature was maintained from 168°F to 170°F throughout the day, the change in water vapor content caused the adiabatic saturation temperature to drop by about 5°F over the test. Thus, the nominal 35°F approach temperature increased from 36°F to 42°F by the end of the test. The effect of increasing approach temperature was offset, for the most part, by an increasing Ca/S ratio. Because of changes in the composition of the reagent lime slurry throughout the day, the Ca/S ratio increased from 1.85 to 2.13 by the end of the test.

Table 5-6 presents mass loadings measured for each quench probe run along with sorbent utilization as determined from chemical analyses of the quench probe catch and three selected ESP inlet hopper samples as well as sorbent utilization calculated from gas analysis data recorded during each quench probe run. The agreement between sorbent utilization as determined from chemical analyses and from gas phase data is, with two exceptions, very good. The exceptions are noted in the table in boldface. From the gas sampling data sorbent utilization averaged between 24% and 26% throughout the test. With the exception of the quench probe runs from the middle and bottom sampling ports where the sampling point was as far out as possible sorbent utilization from the quench probe runs also varied from 24% to 26%. In the case of the two quench probe runs that did not agree with the gas phase data, sorbent utilization was from 3.5% to 4.3% less than that determined by solids analysis and was closer to that measured for the ESP inlet hopper samples. In all other tests, quench probe samples were taken at the geometrical midpoint of the duct (the middle point in Table 5-6).

These data suggest that when variations in slurry properties are taken into account it is possible to obtain good agreement between sorbent utilization as determined from gas analysis or from solids analysis of quench probe catches. Thus, in subsequent testing, slurry samples were taken whenever solids samples were taken and/or whenever the system had stabilized so that heat balance calculations could be meaningful. Likewise, in the analysis of previous data, the heat balance calculations shown in the appendices of the topical reports 3 through 6 were recalculated, when possible, to reflect the most recent slurry analysis.[2]

Table 5-6. Comparison of Sorbent Utilization from Solids Analysis and from Gas Phase Measurements for Test 54-SL-03, 8/2/91.

Time	Quench Probe Run Data			Solids Analysis Data		Gas Phase Data [1]	
	Sample Location Port	Sample Location Point in Port	Mass Loading (gr/acf)	Quench Probe[2] % Utilization	ESP Inlet Hopper % Utilization	ESP Inlet % Utilization	ESP Outlet % Utilization
1605 - 1618	Top	In	5.96	24.2		24.1±0.7	29.0±0.5
1648 - 1705	Top	Middle	4.53	24.8		25.1±0.6	29.6±0.8
1726 - 1740	Top	Out	4.20	24.4	26.4	24.5±1.1	28.9±1.1
1251 - 1321	Middle	In	5.07	24.8		25.3±1.3	28.9±0.6
1357 - 1427	Middle	Middle	5.50	24.0	26.4	24.3±0.8	28.9±0.7
1500 - 1524	Middle	Out	5.03	28.4		24.1±1.3	28.4±0.8
1013 - 1045	Bottom	In	6.43	26.0		26.0±0.7	31.6±0.8
1114 - 1130	Bottom	Middle	5.97	24.8	28.8	25.7±0.7	31.2±0.7
1202 - 1213	Bottom	Out	4.45	28.9		25.4±1.0	30.2±1.1

[1] Data averaged over the time period shown, ± one standard deviation.

[2] Quench Probe samples obtained at ESP Inlet test station during the time period shown.

Table 5-7. Results for Test 54-SL-03, 8/2/91.

Time	Ca/S Ratio	Approach (°F)	Inlet SO_2 (ppm)	Inlet Water (%)	Slurry % $Ca(OH)_2$	ESP Inlet		ESP Outlet	
						Δ SO_2, (%)	Util. (%)	Δ SO_2, (%)	Util. (%)
1013-1045	1.85	36	1990	9.9	18.58	48	26	58	32
1114-1130	1.78	37	2120	9.7	18.80	46	26	55	31
1202-1213	1.84	38	2100	9.6	19.22	47	25	55	30
1251-1321	1.97	38	1990	9.3	19.67	50	25	57	29
1357-1427	1.99	39	2010	9.1	19.90	48	24	57	29
1500-1524	2.07	40	1960	8.8	19.89	50	24	59	28
1605-1618	2.08	39	1960	8.5	19.82	50	24	60	29
1648-1705	2.08	40	1950	8.4	19.77	52	25	61	30
1726-1740	2.13	42	1910	8.2	19.70	52	24	61	29

These data also suggest that sorbent utilization as determined from inlet ESP hopper samples is somewhat higher than that measured from quench probe catches or for gas phase data. This is certainly reasonable because the ESP inlet field is rapped every 3 minutes so, aside from material that falls out directly into the first ESP hopper, ash and sorbent collected in the first field of the ESP are exposed to flue gas for up to three minutes before being collected in the hopper.

5.2.3 Air/Liquid Ratio Tests with Lechler Nozzles

The 2.88 gpm Lechler nozzles used for most of the SO_2 removal tests at the DITF were usually operated at an inlet air pressure of from 70 to 80 psig. Early tests with water at the DITF revealed that high inlet air pressures were required to minimize wall wetting. These Lechler nozzles are designed to reach supersonic (choked) flow at an air pressure of 60 psig, but at flow rates of 9 to 12 gpm (1.5 to 2.0 gpm per nozzle) higher inlet air pressures were required to keep from wetting the duct walls. Operation at such high inlet pressures meant that the air-to-liquid (A/L) ratio for these nozzles averaged from 0.8 to 1.1 instead of the design value of 0.5. These high values of A/L ratio were mainly an artifact of operating the nozzles at less than their rated flow. However, concern was expressed on the part of other DOE contractors in the Duct Injection program that nozzles of this type would be unsuitable for full-scale applications because of the energy needed to compress the large volume of air that operation at these A/L ratios requires.

Therefore, a series of tests were planned to determine if the Lechler nozzles could function at or near their design A/L ratio. Three separate tests were conducted. During Week 57 of testing (August 19-22), a series of tests were performed where the A/L ratio was reduced to as low as 0.5 by reducing the pressure of the compressed air to the nozzles. Later, during week 68 of testing (November 6), a more realistic test was performed when the slurry flow rate to the nozzles was raised to the point where an A/L ratio of 0.61 was achieved. Finally, during week 71 of testing (November 25-27), a single special 12 gpm Lechler nozzle (Model 199.030.23) was tested at A/L ratios of from 0.48 to 0.61.

During week 57 of testing SO_2 removal tests were performed with the six Lechler nozzle array at nozzle air pressures of 70, 60, and 50 psig at a nominal Ca/S ratio of 2.0 and an approach temperature of 35° F. These air pressures correspond to A/L ratios of 0.7, 0.6, and 0.5, respectively. These tests were conducted with the standard nozzle configuration: a total of six Lechler supersonic nozzles arranged with three nozzles per lance. The inner and outer nozzle on each lance was canted 5° toward the center of the duct; the upper lance was depressed by 2° and the lower lance was horizontal.

The results of these tests are summarized in Table 5-8. The first test (at a nominal A/L ratio of 0.7) was repeated because an air hose in the duct burst at some point during the test. The SO_2 removal data from Table 5-8 and the fact that there were no deposits in the horizontal duct at the conclusion of the test suggest that the hose burst at the end of the test. For this brief test series the major conclusion that can be reached is that A/L ratio apparently does not affect SO_2 removal or sorbent utilization, at least down to an A/L ratio of 0.5 for Lechler nozzles.

Unfortunately, the spray pattern of the Lechler nozzles is apparently affected by air pressure. As indicated above, at an A/L ratio of 0.7 there were no duct deposits of note. However, after testing for a little over four hours at an A/L ratio of 0.6 it was found that the turning vanes at the end of the horizontal duct (1 second of residence time downstream of the nozzles) were about 30% plugged.

Table 5-8. Air/Liquid Ratio Test Summary.

Test #	Approach (°F)	SO_2 at Inlet (ppm)	Nozzle Flow (gpm)	Ca/S Ratio Lime Slurry	Air Pressure (psig)	Air/Liquid Ratio	ΔSO_2, % ESP Inlet	ΔSO_2, % ESP Outlet
57-SL-01[1]	35	2010	13.0	2.18	70	0.72	52	64
57-SL-02[1]	36	2020	12.6	2.02	70	0.73	49	63
57-SL-03[1]	36	2020	12.8	1.98	60	0.63	51	63
57-SL-04[1]	36	2060	13.5	2.11	50	0.50	53	67
68-SL-01[2]	31	3260	17.3	1.70	80	0.61	47	59
71-SL-01[3]	44	2080	10.9	1.69	80	0.61	45	52
	36	2070	11.8	1.83	80	0.56	51	61
	26	2060	13.4	2.30	80	0.48	60	76
71-SL-02[3]	41	2010	11.6	2.09	80	0.54	52	63
71-SL-03[3]	37	2050	11.5	2.00	80	0.57	51	64

1. Six 2.77 gpm Lechler nozzles.
2. Full flow test for six 2.77 gpm Lechler nozzles.
3. Single 12 gpm Lechler nozzle.

Still, there was no appreciable deposit of sorbent on the surfaces of the duct itself. At an A/L ratio of 0.5, after testing for slightly over five hours, it was found that the turning vanes at the end of the horizontal duct were approximately 60% plugged. In this case there were heavy sorbent/ash deposits downstream of the turning vanes "growing" on the downstream side of the vanes. Also, a layer of sorbent and ash approximately 6 in. deep had accumulated on the horizontal duct floor after the first hopper. It appears that the spray pattern of the nozzles becomes more centralized as the air pressure (or A/L ratio) is decreased. In situ particle size distribution tests would be required to confirm this hypothesis.

These tests addressed the question of A/L ratio by varying air pressure. Later, during week 68 of testing, the slurry flow rate was increased to the point where an A/L ratio of 0.61 was achieved at 80 psig of inlet air pressure (Test 68-SL-01). The results of this test are also presented in Table 5-8. For this test it was necessary to run the DITF without dilution to increase the inlet temperature and flue gas flow to as high as was possible. Although slurry flows of 17.3 gpm were measured (for an A/L ratio of 0.61), the slurry flow rate could have been higher. This is because the flow meter used to measure and control slurry flow was operated at its maximum possible flow (20 mA on a 4-20 mA loop). However, the heat balance calculations for this test indicated that very little additional water would have been required. As far as this brief test can indicate, no effect of A/L ratio on SO_2 removal was observed.

Although these nozzles did operate at a lower A/L ratio than usual (for day-to-day testing), when the horizontal duct was inspected after test 68-SL-01 was concluded a large solids deposit was found on the duct floor between the first and second hopper. It is encouraging that these nozzles did operate at lower A/L ratios at their rated flow but more testing would have been required to determine how to minimize duct deposits under those operating conditions.

During week 71 tests with reagent slurry injection were also conducted to demonstrate the ability to scale this nozzle up and to evaluate the behavior of a 12 gpm Lechler nozzle at design flow. Figure 5-11 shows how the single Lechler nozzle was mounted in the horizontal test duct. Externally and internally this nozzle appears to be quite like the smaller 2.88 gpm Lechler nozzle, but considerably larger. These tests showed that the larger Lechler nozzle could be operated at A/L ratios in the neighborhood of 0.5. The results of these tests are shown in Table 5-8. In general, it was found that when the large Lechler nozzle was operated up to its design flow (an A/L ratio of about 0.55) no problems with duct deposits were encountered and no effect on SO_2 removal was observed compared with the smaller nozzle.

However, when the design flow was exceeded, duct deposits were created. As with the small Lechler nozzles further tests would have been required to determine if these deposits could be minimized. In particular, it would have desirable to repeat these tests with a higher solids content recycle ash-slurry mix because higher solids content slurries tend to dry more quickly.

5.2.4 Reagent Slurry Injection with Downstream Humidification

In an attempt to investigate modes of operation that would permit low approach temperatures to be reached at low-to-moderate Ca/S ratios, two-stage humidification experiments were conducted during week 39 of testing (April 15-19). In this set of experiments, a single 2.88 gpm Parker-Hannifin nozzle was installed approximately 30 ft downstream of the main nozzle array. Approach temperatures of 35°F and 45°F were maintained at the main nozzle lance, and humidification water was added at the Parker-Hannifin nozzle to reach the desired approach temperature.

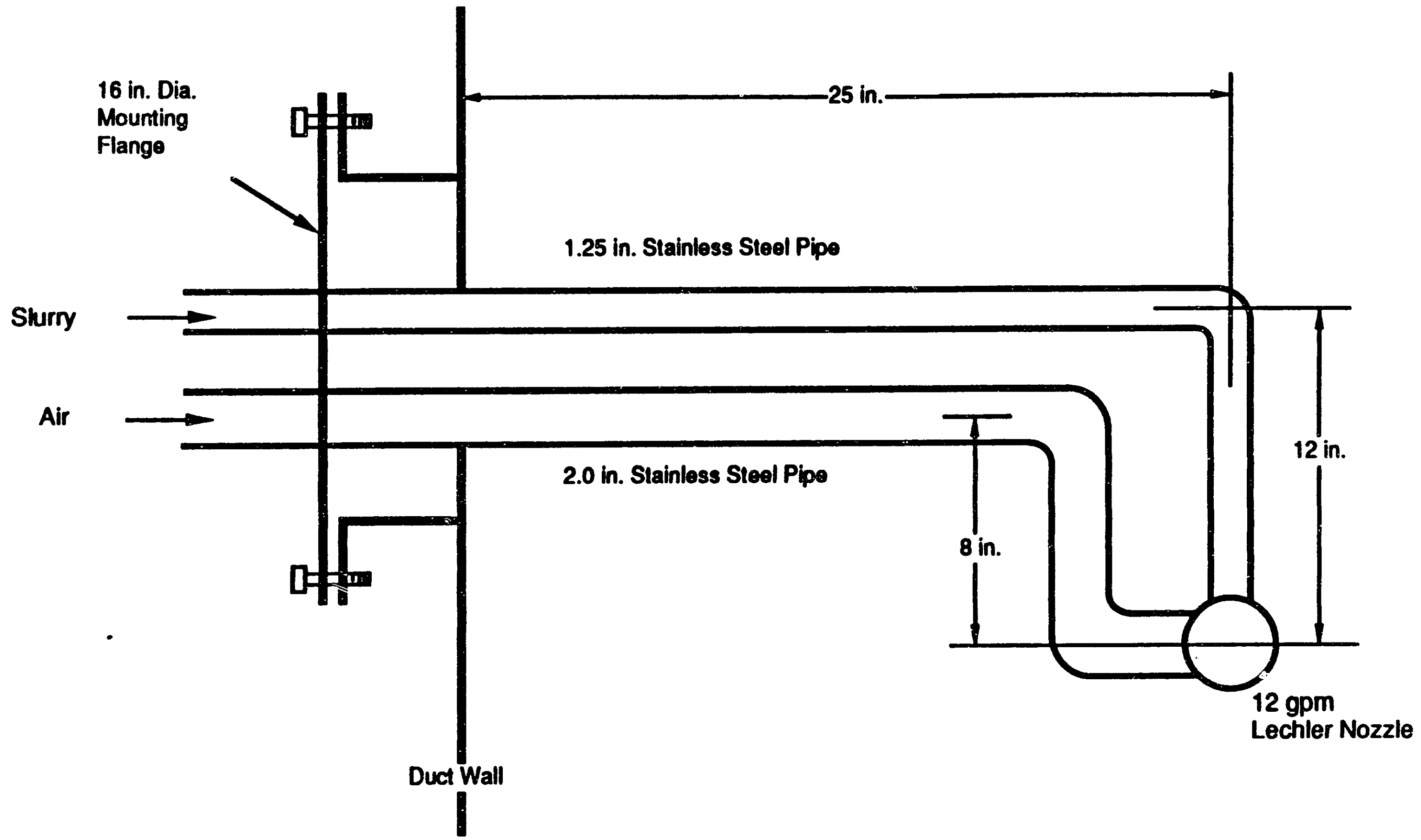

Figure 5-11. Schematic diagram of the installation of the 12 gpm Lechler nozzle in the horizontal test duct at the DITF.

These tests were quite successful in that very low approach temperatures were reached and held without wall wetting. During the most strenuous test of this procedure it was possible to operate the main nozzle lance at an approach of 45°F and to use the Parker-Hannifin nozzle to reduce the approach temperature to 10°F. When this was first attempted the approach temperature was maintained at approximately 10°F for over an hour. Subsequent inspection of the duct revealed no duct wall deposits. One disadvantage of this approach is that the Parker-Hannifin nozzles tend to plug whenever even a slight bit of debris enters the nozzle in the water line. This water is not filtered, and while it is not potable, it is usually clear. When this experiment was repeated the nozzle plugged almost immediately on start-up and the DITF had to be brought off line so that the nozzle could be cleaned.

Table 5-9 and Figure 5-12 summarize the results of these tests. As Figure 5-12 shows, at a nominal Ca/S ratio of 1.8, adding humidification water to reduce the approach to saturation from 45°F to 10°F increases SO_2 removal by approximately 15% at the ESP inlet and by almost 25% at the ESP outlet. Likewise, adding humidification water to reduce the approach to saturation from 45°F to 25°F increases SO_2 removal by approximately 10% at the ESP inlet or outlet. However, if humidification water is added at the main lance rather than downstream, much higher SO_2 removals are possible than with downstream humidification.

At a 25°F approach with water added at the main lance to maintain the Ca/S ratio at a nominal value of 1.8, the results of these tests show that the amount of SO_2 removed is essentially the same as is removed when an approach of 10°F is achieved with downstream humidification. Clearly, the more effective method to increase SO_2 removal is to add humidification water at the main lance.

5.2.5 Injection of Reagent Slurry with Recycle Ash Addition

The process of recycling rather than discarding waste sorbent/ash solids as a means of increasing calcium utilization is common practice at spray dryer installations in the utility industry. Recycling spent solids is especially important in the economics of duct injection because slurry droplet size and in-duct residence times tend to lower calcium utilization when compared to conventional spray dryers. However, encouraging results were obtained from experiments conducted at the DITF with reagent slurry/recycle ash mixtures.

Two types of experiments were conducted with reagent slurry/recycle ash mixtures. The first of these were "single pass" experiments in which waste ash from an earlier experiment with reagent slurry was either injected as a dry solid (through the coplanar dry injection nozzle) or was mixed with reagent slurry and injected into the duct. If the recycle ratio, R, is expressed as the ratio of the mass of recycle ash solids to the mass of pebble lime feed, R values ranging from 1.0 to 5.5 were investigated in these tests. The second type of experiments that were conducted were typical of the type of operation that is usual at full-scale spray dryer installations. In these experiments, a constant portion of the spent ash and sorbent collected in the ESP was reintroduced (recycled) into the reagent slurry while the rest of the spent ash and sorbent was discarded as would be the case in a continuous or multi-pass operation. These tests were continued until the amount of $Ca(OH)_2$ in the spent ash and sorbent equilibrated.

Table 5-9. Results of SO_2 Removal Tests with Downstream Humidification Provided by a Single Parker-Hannifin Nozzle, 30 ft Downstream of the Point of Slurry Injection.

Test #	Ca/S Ratio	------ Approach, (°F) ----		Inlet SO_2 (ppm)	---------- ESP Inlet --------		---------- ESP Outlet ------	
		Slurry Only	With Added Water		ΔSO_2, (%)	Util. (%)	ΔSO_2, (%)	Util. (%)
39-SL-01	1.94	35	23	1970	50	26	65	34
39-SL-02*	1.79	24	--	2010	57	32	72	40
39-SL-02	1.81	45	25	1990	50	28	65	36
39-SL-03*	1.78	23	--	1980	58	33	76	43
39-SL-04	1.75	47	26	1950	48	27	63	36
39-SL-04	1.77	47	10	1920	61	35	80	45
39-SL-05	1.77	45	23	1990	50	28	66	37
39-SL-05	1.76	45	15	2000	59	33	75	43
39-SL-05	1.77	45	9	1990	58	33	75	42

* Humidification water to reach approach added at main lance, no water added downstream. With reagent slurry flow alone, the approach temperature would have been ≈ 45°F.

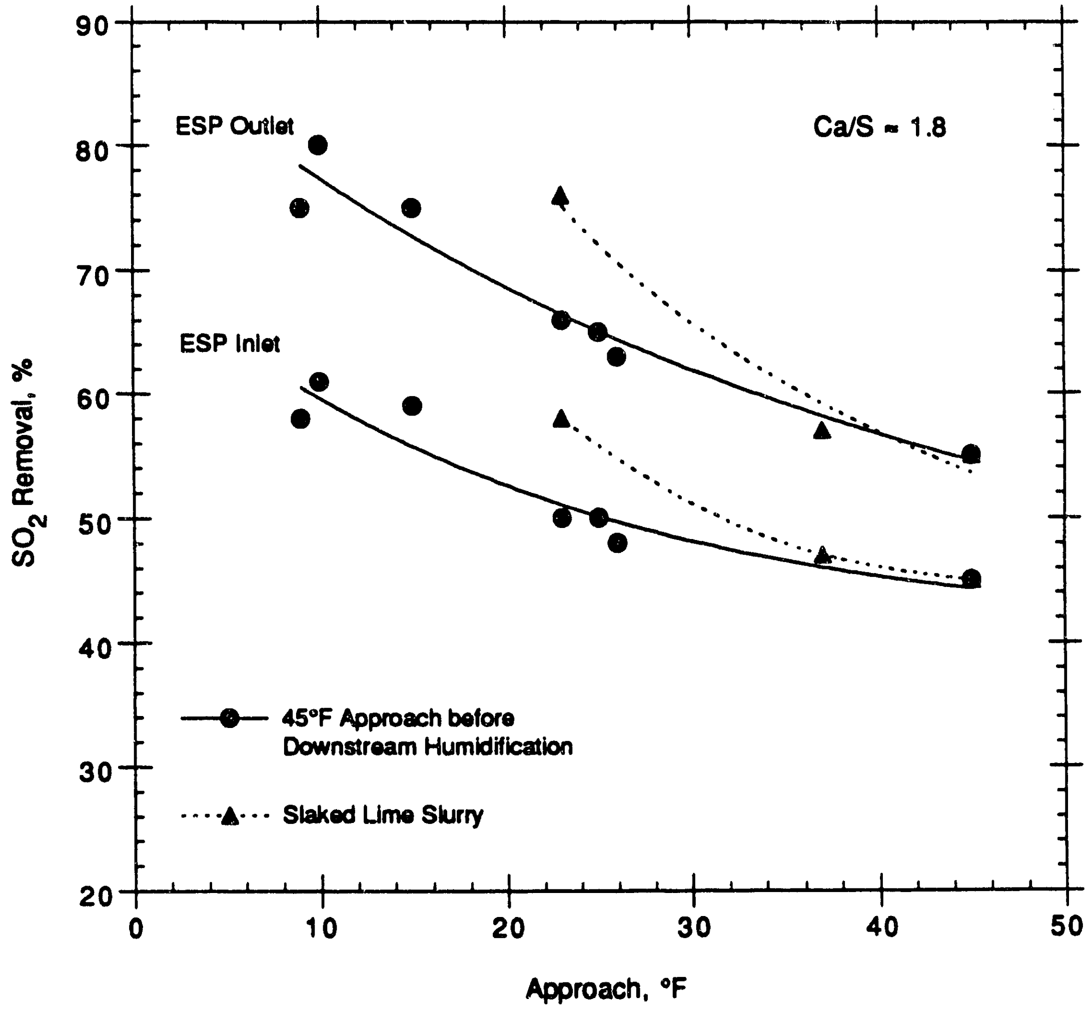

Figure 5-12. Percent of SO_2 removed at the ESP inlet and outlet for approach temperatures from 10 to 45°F. Summary of test data for reagent slurry injection with and without downstream humidification at a Ca/S ratio of 1.8.

5.2.5.1 Coplanar Injection of Dry Recycle Ash with Humidification from Reagent Lime Slurry

During week 35 of testing (March 20-21) while work was under way to start slurry/recycle ash injection dry recycle solids (from reagent slurry injection tests) were blown in through a recently fabricated coplanar dry injection nozzle positioned midway between the upper and lower nozzle lances during reagent slurry injection. This coplanar nozzle was later used during the series of dry injection tests reported above.

Two tests were performed (36-SDR-03 at a 45°F approach and 36-SDR-04 at a 25°F approach). During both of these tests reagent slaked lime slurry was first injected and SO_2 removal was measured before dry sorbent was added at the coplanar nozzle. Table 5-10 summarizes the results of these measurements. More detailed information on these tests is available from the heat balance calculations in Appendix C of Topical Report 3.[2] As might be expected, the result of adding dry recycle ash was greater at an approach of 25°F. At a 45°F approach, SO_2 removal was increased by 3% at the ESP inlet and at the ESP outlet SO_2 removal was increased by 6%. At a 25°F approach SO_2 removal was increased by 5% at the ESP inlet, and at the ESP outlet SO_2 removal was increased by 7%.

5.2.5.2 Single Pass Reagent Slurry/Recycle Ash Tests

From weeks 51 through 54 of testing (July 12-30) single pass reagent slurry/recycle ash tests were conducted at the DITF. As indicated above spent sorbent and ash from previous tests with reagent lime slurry was mixed with reagent lime slurry and injected into the horizontal test duct. The six Lechler nozzle array was used for all of these tests. Recycle ratios (based on the ratio of mass of recycle ash to mass of pebble lime required to generate the reagent slurry) of from 1.0 to 5.5 were tested. The results of these tests are presented in Tables 5-11 and 5-12. Test results in these tables are sorted on approach temperature. Table 5-11 shows that relatively high SO_2 removals were achieved.

Table 5-12 presents the results of chemical analyses (to determine sorbent utilization) performed on ESP hopper samples from recycle slurry tests carried out during weeks 51 through 54 of testing. Most of these analyses were performed on ESP inlet hopper samples but two ESP outlet hopper samples were also analyzed. Table 5-12 also shows the results of sorbent utilization as determined from averaged gas phase data at the inlet and outlet of the ESP for the same tests during the times the solid samples were collected.

In general it should be expected that solids samples from the ESP inlet hopper would dominate the mass of collected ash. Also, because the inlet ESP hopper samples are collected after being exposed to the flue gas for several minutes longer than solids collected from quench probe samples, the results of sorbent utilization measured for the ESP inlet hopper samples should be compared with gas phase sorbent utilization measured at the ESP outlet. When this comparison is made the results generally agree, but with some exceptions.

There are at least two reasons for this disagreement. First, the available $Ca(OH)_2$ in the recycle ash tended to vary significantly from day to day (as much as 7%). It is possible that the percentage of $Ca(OH)_2$ in the recycle ash varied during the test. Second, as was shown previously, slurry properties can change during a test. Table 5-12 also shows that there was little change in sorbent utilization (from solids analyses) from the ESP inlet to the ESP outlet which is not reflected in the gas phase

Table 5-10. Summary of Reagent Slurry/Dry Recycle Ash Tests.

Test #	Date Time	Ca/S Ratio		Recycle Ratio	Approach (°F)	Inlet SO_2 (ppm)	ΔSO_2, %	
		Overall	Recycle				ESP Inlet	ESP Outlet
	3/20/91							
35-DSR-03[1]	1316-1415	1.00	--	--	49	2000	33	38
35-DSR-03[2]	1600-1700	1.72	0.64	1.88	45	2060	36	44
35-DSR-03[2]	1700-1800	1.66	0.61	1.88	46	2050	36	44
	3/21/91							
35-DSR-04[1]	1145-1200	1.02	--	--	23	2110	46	56
35-DSR-04[2]	1215-1245	1.72	0.65	1.98	23	2000	51	63

1. First part of test, slurry only.
2. Second part of test, slurry plus coplanar injection of dry recycle ash.

Table 5-11. Results of Single Pass Reagent Slurry/Recycle Ash Tests.

	----- Ca/S Ratio ----					------ SO_2 Removal -----	
Test #	Reagent Slurry	Overall	Approach (°F)	Recycle Ratio	Inlet SO_2 (ppm)	ESP Inlet (%)	ESP Outlet (%)
53-SR-02	0.86	1.59	24	3.3	2000	58	73
53-SR-05	0.69	1.72	26	5.5	1930	55	67
53-SR-01	0.73	1.55	28	3.5	1970	56	70
53-SR-04	0.97	1.66	29	2.0	1900	55	64
53-SR-03	0.62	1.35	33	4.7	2020	50	58
52-SR-01	0.81	1.38	35	3.3	1990	49	56
54-SR-01	1.15	1.44	36	1.0	2000	48	58
54-SR-02	0.85	1.29	37	2.0	2040	46	56
52-SR-02	0.80	1.43	37	3.7	1970	52	62
51-SR-01	0.64	1.03	39	2.2	2010	43	55

Table 5-12. Comparison of Sorbent Utilization from Solids Analyses and from Gas Phase Data for Single Pass Reagent Slurry/Recycle Tests.

Test	------ Ca/S Ratio ------		Approach (°F)	Recycle Ratio	Utilization at ESP Inlet, %		Utilization at ESP Outlet, %	
	Reagent Slurry	Overall			Solids Analysis	Gas Phase*	Solids Analysis	Gas Phase*
53-SR-02	0.86	1.59	24	3.3	50.6	36.3±1.6	49.0	46.0±2.1
53-SR-05	0.69	1.72	26	5.5	45.7	31.9±2.7	43.0	39.2±2.1
53-SR-01	0.73	1.55	28	3.5	46.4	36.1±1.9	–	45.1±1.6
53-SR-04	0.97	1.66	29	2.0	35.3	33.1±1.6	–	38.2±1.6
53-SR-03	0.62	1.35	33	4.7	48.5	36.7±1.5	–	43.2±1.7
52-SR-01	0.81	1.38	35	3.3	–	35.5±2.7	–	41.4±2.8
54-SR-01	1.15	1.44	36	1.0	39.2	33.4±1.0	–	40.3±1.2
54-SR-02	0.85	1.29	37	2.0	37.4	35.9±1.6	–	43.3±2.1
52-SR-02	0.80	1.43	37	3.7	46.4	36.2±1.1	–	43.3±1.3
51-SR-01	0.64	1.03	39	2.2	43.6	41.5±3.6	–	53.3±5.4

* Gas phase data were averaged over a time period of approximately one hour and show ± one standard deviation. Solids samples were taken during that period of time.

data. This disparity may be due to the short duration of these tests (typically four to five hours). The ESP outlet fields are rapped every hour. The combination of an infrequent rapping schedule and overnight operation of the DITF to generate fresh recycle (a practice that was followed during these tests) ash may have led to nonrepresentative ash/sorbent residue that remained in the ESP outlet hopper.

To compare sorbent utilization with and without the addition of recycle ash, it is necessary to know how utilization of $Ca(OH)_2$ in recycle ash compares to the utilization of $Ca(OH)_2$ in reagent lime slurry. The available data are shown in Figure 5-13. The utilizations plotted on the vertical axis in this figure are based on ratios of SO_2 removal at the ESP outlet to the total $Ca(OH)_2$ available to react (the sum of $Ca(OH)_2$ in reagent lime slurry and $Ca(OH)_2$ in the recycle ash, if present). The Ca/S ratios on the horizontal axis in the figure are similarly based on the rate of injection of $Ca(OH)_2$ from reagent lime slurry and the rate of addition of $Ca(OH)_2$ from recycle ash, if available. There is considerable scatter in these data from any simple algebraic relationship. In principle, part of the scatter might be attributed to variations in the approach temperature (here the range was from 23°F to 40°F), but the points found most distant from the others were not attributable to exceptional approach temperatures. This suggests that at a given value of the Ca/S ratio sorbent utilization is essentially the same, with or without the addition of recycle ash.

An example comparing operation of the DITF with and without recycle is as follows:

> Under conditions that typically prevail at the DITF, the injection of a slurry of fresh $Ca(OH)_2$ at a Ca/S ratio of 1.0, without recycle, will cause an SO_2 removal of 50%, as shown on Figure 5-13. In this instance, the waste sorbent will obviously have a utilization of 50%.
>
> Under the same conditions, except for a recycle ratio of 2.5, the injection of a combination of reagent $Ca(OH)_2$ and recycled $Ca(OH)_2$ will produce an overall Ca/S ratio of 1.20, assuming that the utilization of sorbent in each form remains at 50%. However, the removal of SO_2 will increase from 50.0% to 59.9%, and the utilization of sorbent in the discharged waste will also increase to 59.9%. Thus, for a given expenditure of lime, recycle would increase the tonnage of SO_2 removed by the factor of 0.599/0.500, or about 1.2.

5.2.5.3 Continuous or Multi-Pass Reagent Slurry/Recycle Ash Tests

Two test series were completed in which the DITF was operated in a mode that emulated full-scale operation with continuous recycle ash addition. Test parameters for these two test series were chosen to evaluate conditions under which duct injection could be considered to be competitive at the full scale. Previously, another of DOE's contractors in the area of duct injection technology had identified, on a preliminary basis, conditions under which duct injection could be a competitive SO_2 removal technology at the 50% removal level and at the 90% removal level.

At the 50% level of SO_2 removal, an approach of 40°F, reagent Ca/S of 1.0, and recycle ratio of 2.3 was required (a low Ca/S ratio case). At the 90% level of SO_2 removal, an approach of 25°F, reagent Ca/S of 1.8, and recycle ratio of 1.7 were required (a high Ca/S ratio case). These tests were designed to determine if it was possible to operate at these conditions and obtain the necessary levels of SO_2 removal. The economic analyses assumed and the tests were conducted with 2000 ppm of SO_2

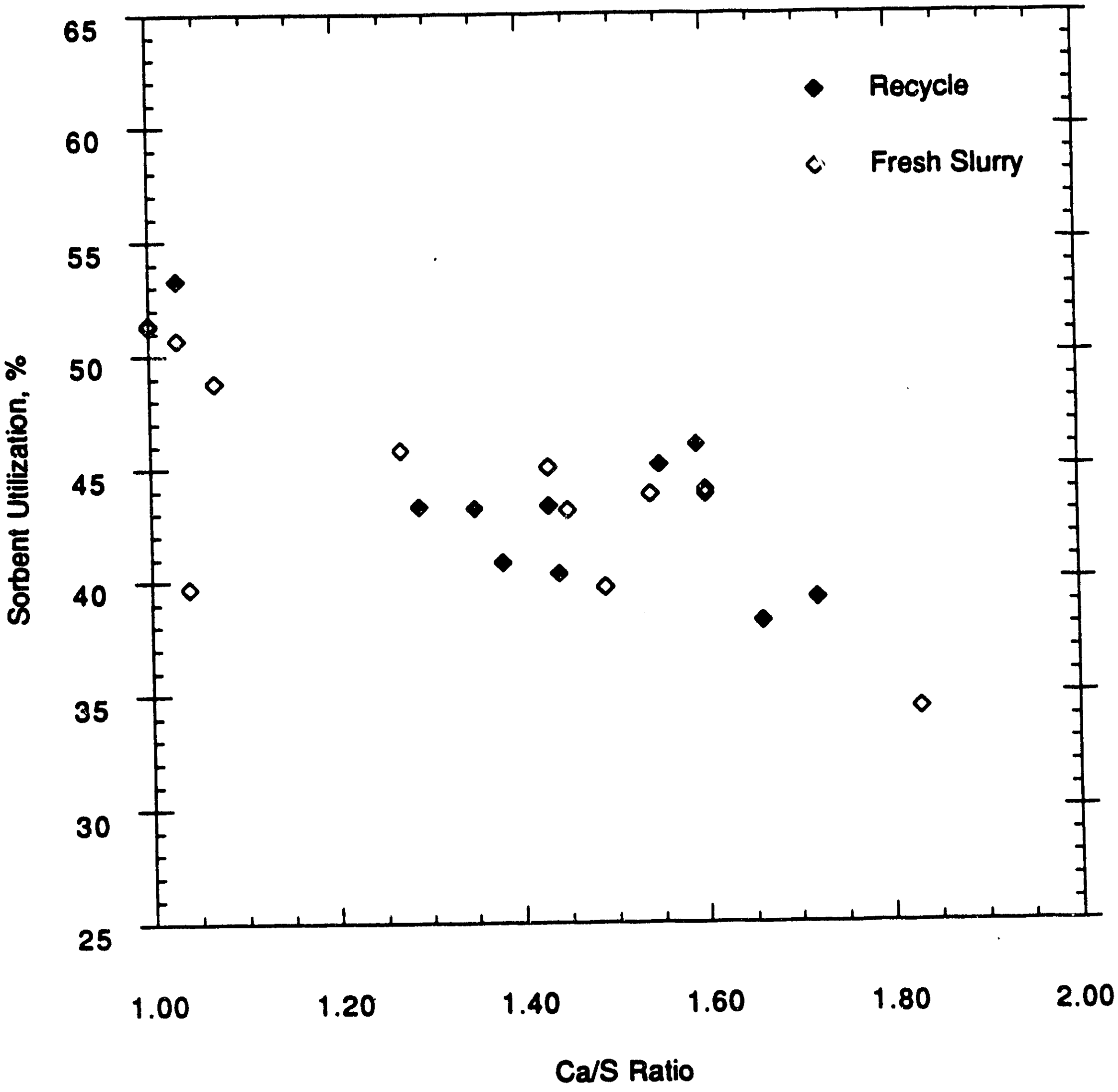

Figure 5-13. Comparison or sorbent utilization based on gas-phase data from reagent slurry injection tests conducted with and without the addition of recycle ash.

at the system inlet. Because the DITF has separate recycle ash and waste ash silos, spent sorbent and ash could be deposited to only one of these silos at a time, and it was not actually possible to continually feed a portion of the recycle ash into the recycle ash silo.
Therefore, the amount of recycle ash required for steady state operation was predetermined from mass balance considerations and spent sorbent and ash from the ESP was intermittently fed to the recycle ash silo for a time sufficient to supply the amount needed. Also, in order not to prolong the test, it was desirable to keep the level in the recycle ash silo as low as practically possible. Each test series was continued until the $Ca(OH)_2$ level in the recycle ash that was mixed with the fresh lime slurry remained constant and equal to the level of $Ca(OH)_2$ produced in the waste ash.

The low Ca/S test case was performed twice. The first time was during weeks 66 through 68 of testing (October 22 to November 5, 1991). It was decided to use this set of operating conditions again for a long-term ESP test during weeks 81 and 82 of testing (February 3-13, 1992) and during this time the low Ca/S ratio test was repeated. The high Ca/S ratio test case was performed during weeks 68 and 69 of testing (November 7 through 15, 1991).

Table 5-13 presents results for each of these tests. Also in this table are the measured and predicted (based on mass balance considerations) $Ca(OH)_2$ content in the recycle ash for each test. The predicted value of $Ca(OH)_2$ content shown in Table 5-13 is the value to which the system would equilibrate if it continued to be operated at the specific overall and reagent Ca/S ratio, approach, and recycle ratio measured during that test. At the beginning of each test series the predicted and measured values of $Ca(OH)_2$ generally did not agree. This is because the recycle ash stock at the start of each test was left over from previous testing. Generally, a very low level of spent ash and sorbent was kept in the recycle ash silo so that the time to use that ash up (and replace it with more ash from the current test) was kept to a minimum. As the test proceeded the difference between predicted and measured $Ca(OH)_2$ in the ash tended to decrease.

As Table 5-13 shows, for the low Ca/S ratio case it was possible to obtain better performance than required by the economic analysis. At an approach of 41°F, reagent Ca/S ratio of 1.01, and recycle ratio of 2.07 an SO_2 removal of 55% was measured at the ESP outlet (Test 82-SR-01, February 13). For the high Ca/S ratio case, due to limitations in the amount of ash that could be delivered by the recycle ash weigh belt feeder, it was difficult to maintain a recycle ratio above 1.5. Thus, for this case, at an approach of 24°F, reagent Ca/S ratio of 1.71, and recycle ratio of 1.49 an SO_2 removal of 88% was measured at the ESP outlet. If it had been possible to reach the desired recycle ash ratio, SO_2 removal at the ESP outlet would probably have exceeded 90%.

5.2.5.4 Reagent Slurry and Reagent Slurry/Recycle Ash Tests with $CaCl_2$ Addition

Two series of tests were performed to evaluate the effect on SO_2 removal of adding $CaCl_2$ to reagent slurry and reagent slurry/recycle ash mixtures. Various amounts of $CaCl_2$ were added to the reagent slurry in a holding tank, which was then injected as is or mixed with recycle ash before injection. In this case, the main focus of these tests was to evaluate the effect of added $CaCl_2$ on SO_2 removal and when recycle ash was mixed with reagent slurry it was used mainly to reach overall Ca/S ratios that were otherwise unattainable with straight reagent slurry. Although it was possible to estimate the amount of chlorides in the waste ash from each test, the actual amount of chloride was determined by laboratory analysis of ESP hopper samples after each test was completed. Table 5-14 and Figures 5-14 through 16 present the results of these tests.

Table 5-13. Summarized Results for Continuous Reagent Slurry/Recycle Ash Tests.

Test #	Date	Approach (°F)	Inlet SO_2 (ppm)	----- Ca/S Ratio -----		Recycle Ratio	$Ca(OH)_2$ in Recycle Ash		---------- ΔSO_2 ----------	
				Overall	Reagent Slurry		Measured (%)	Predicted* (%)	ESP Inlet (%)	ESP Outlet (%)
LOW Ca/S										
66-SR-02	10/22/91	37	2030	1.45	0.88	3.57**	22.77	13.7	45	55
66-SR-03	10/23/91	41	2060	1.73	0.94	4.64**	22.77	13.6	46	60
66-SR-04	10/24/91	43	2110	1.46	0.93	3.04**	24.01	15.0	47	56
66-SR-05	10/25/91	45	2080	1.54	1.05	2.12	27.11	18.9	46	56
67-SR-01	10/28/91	39	2040	1.48	1.10	1.92	20.64	18.7	47	60
67-SR-02	10/31/91	44	2060	1.38	1.05	2.05	20.64	20.3	42	53
67-SR-03	11/01/91	43	2020	1.56	1.03	1.83	17.93	19.2	42	54
68-SR-01	11/04/91	44	2090	1.33	1.04	2.09	18.70	20.8	41	51
68-SR-02	11/05/91	29	2000	1.29	1.18	1.88	18.44	-	49	64
81-SR-01	2/3/92	40	2020	1.52	1.06	2.21	31.88	18.4	45	58
	2/4/92	39	2150	1.10	1.05	1.88	19.14	19.3	42	55
82-SR-01	2/10/92	41	2070	1.47	1.10	1.77	16.13	20.9	43	55
	2/11/92	41	2070	1.31	1.00	1.66	16.01	17.1	43	57
	2/12/92	43	2060	1.28	0.97	1.96	16.11	16.5	41	56
	2/13/92	41	2030	1.31	1.01	2.07	14.75	18.3	42	55
	2/13/92	36	2050	1.34	1.00	1.88	15.29	16.4	44	58
Test Case		40	2000	2.15	1.00	2.30	-	20.1	-	50
HIGH Ca/S										
68-SR-03	11/07/91	25	2050	2.61	1.88	1.32	23.67	28.0	64	85
69-SR-01	11/12/91	29	2020	2.51	1.98	1.46	23.60	31.8	59	79
69-SR-02	11/14/91	25	2050	2.64	1.97	1.26	22.09	28.4	66	89
69-SR-03	11/15/91	24	2050	2.35	1.71	1.49	23.63	23.6	66	88
Test Case		25	2000	2.37	1.80	1.70	-	24.8	-	90

* $Ca(OH)_2$ content at equlibrium.

** Recycle ash weigh belt feeder malfunctioned and overfed recycle ash.

Table 5-14. Summary of Results for Tests with $Ca(Cl)_2$ Addition.

Test #	------ Ca/S Ratio ------		Approach (°F)	Inlet SO_2 (ppm)	%Chloride in Spent Solids	Recycle Ratio	---------- ESP Inlet ----------		------- ESP Outlet ---------	
	Overall	Reagent					ΔSO_2, %	Utilization, %	ΔSO_2, %	Utilization, %
76-SL-01	2.13	2.13	39	2070	<0.35*	0.0	48	23	64	30
76-SL-02	2.28	2.28	35	2080	0.26	0.0	52	23	69	30
76-SL-03	2.38	2.38	37	2040	0.50	0.0	52	22	68	29
76-SL-04	1.97	1.97	35	2060	0.97	0.0	50	25	64	33
77-SL-01	1.97	1.97	34	2080	1.8	0.0	50	26	66	34
77-SL-02	2.20	2.20	35	2040	2.3	0.0	56	26	76	35
83-SR-01	1.20	0.98	25	2080	1.1	1.38	51	43	62	52
83-SR-02	1.08	0.29	35	2750	3.0	3.50	28	26	36	34
83-SR-03	1.26	1.07	27	2070	2.6	1.08	55	44	69	55
84-SR-01	1.49	0.92	25	1190	2.6	2.87	66	44	83	56
84-SR-02	2.38	1.82	35	1140	3.6	1.25	66	28	80	33
84-SL-03	1.68	1.68	37	2050	3.4	0.0	50	30	64	38

* Without $Ca(Cl)_2$ addition soluble chloride levels in ESP inlet hopper ash ranged from 0.14 to 0.35% on 11/14/91.

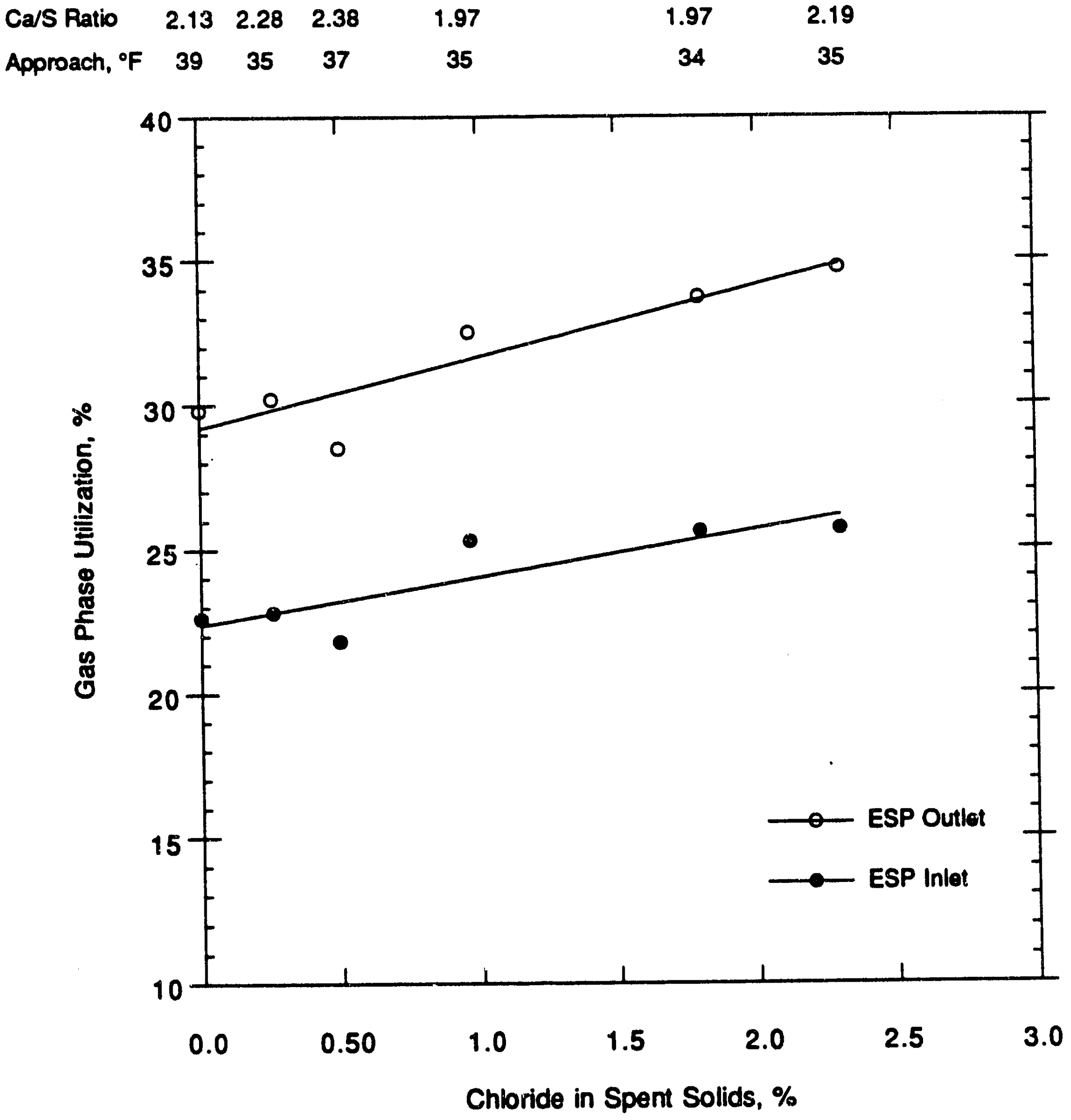

Figure 5-14. Percent of SO_2 removed at the ESP inlet and outlet for chloride levels of up to 2.2% in spent solids. A nominal Ca/S ratio of 2.0 and approach to saturation of 35°F was maintained for these tests.

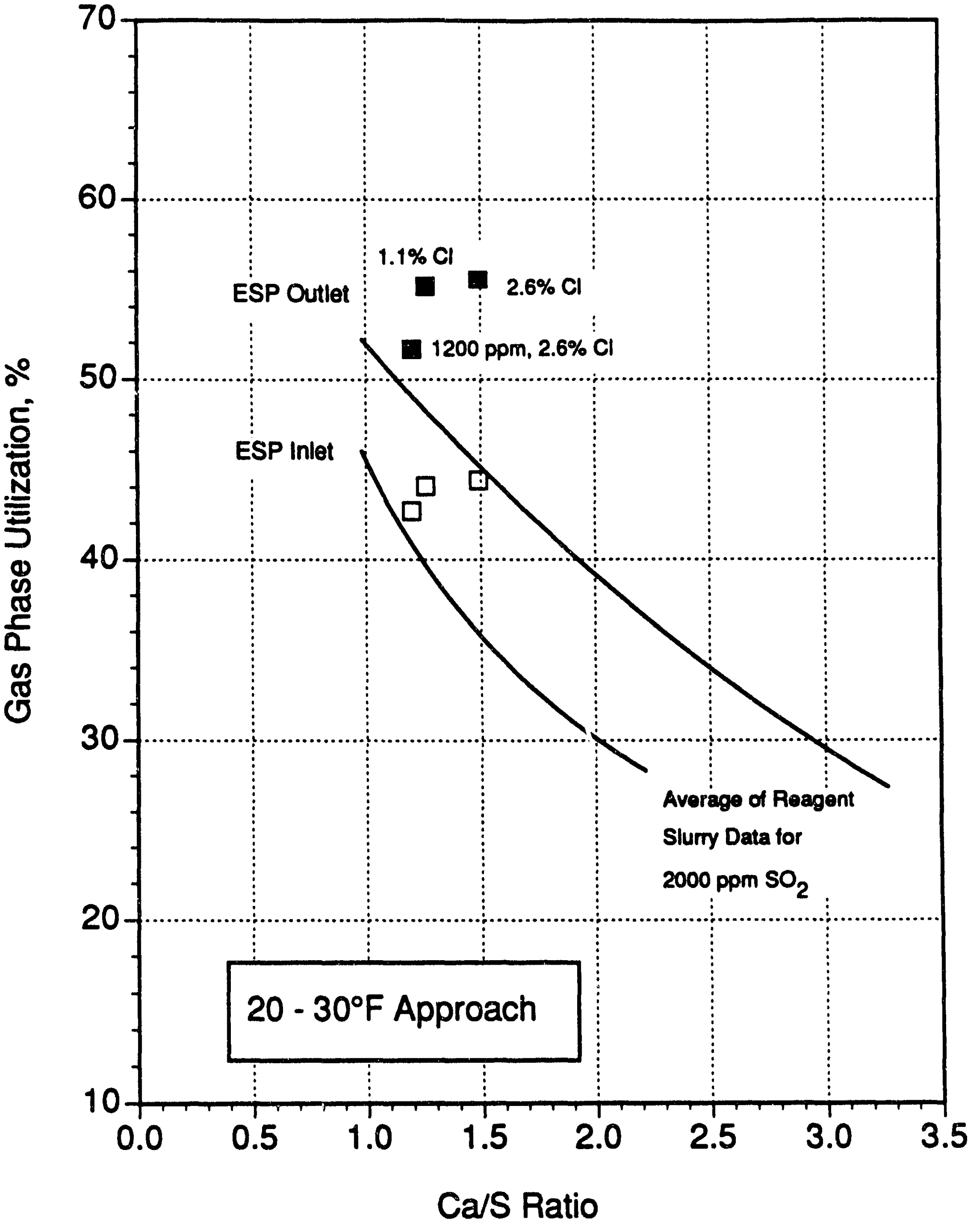

Figure 5-15. Percent of sorbent utilized at the ESP inlet and outlet for SO_2 model tests conducted with $CaCl_2$ addition. Summary of test data for approach temperatures from 20 to 30° F.

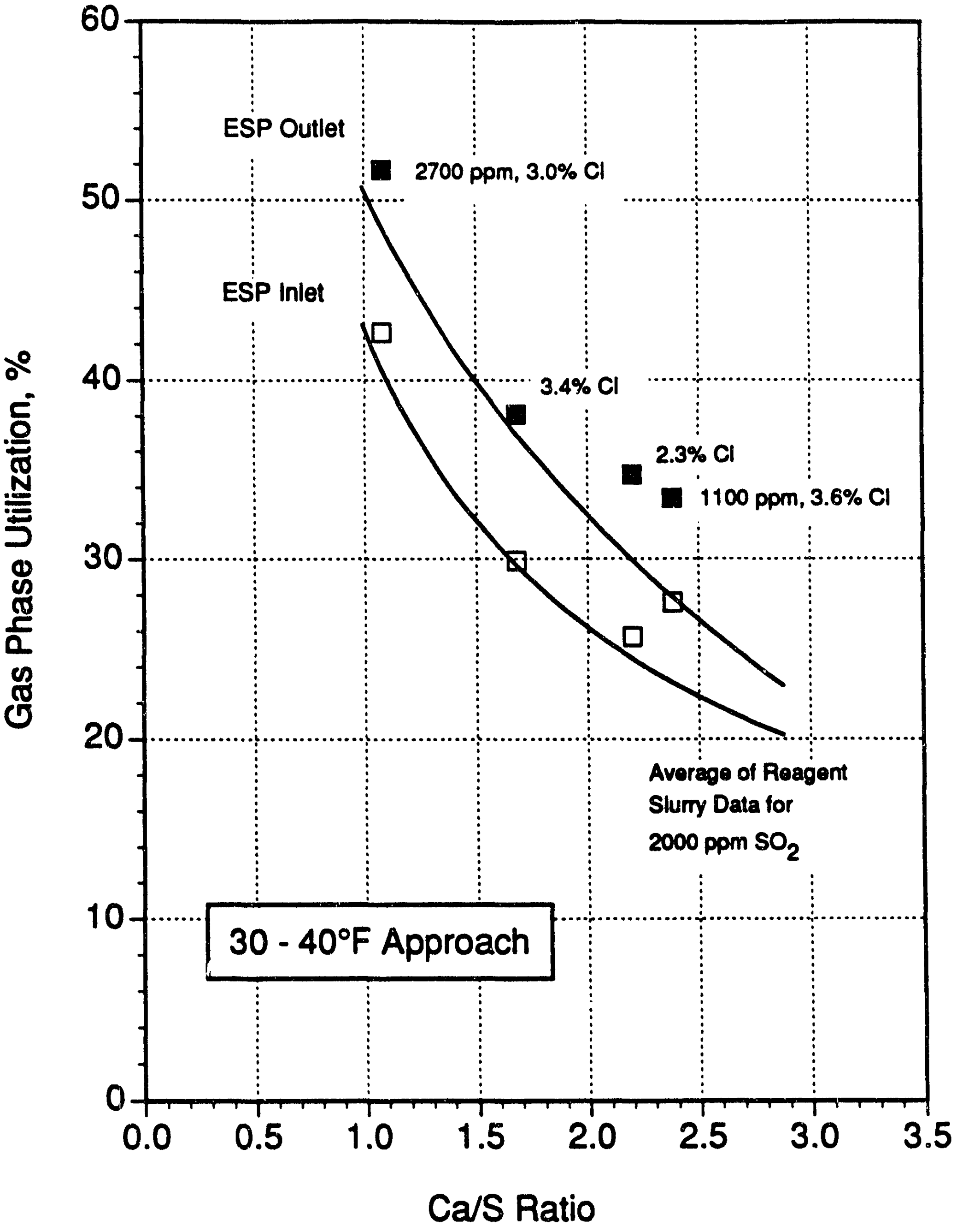

Figure 5-16. Percent of sorbent utilized at the ESP inlet and outlet for SO_2 model tests conducted with $CaCl_2$ addition. Summary of test data for approach temperatures form 30 to 40° F.

The first series of tests, performed with reagent slurry only, was carried out during weeks 76 and 77 of testing (December 30, 1991 to January 7, 1992). These tests were performed at a nominal Ca/S ratio of 2.0 and an approach to saturation of 35°F. During this series, six tests were conducted, in which up to 2.2% chloride was present in the ESP hopper ash. As Table 5-14 and Figure 5-14 show, at a 35°F approach, sorbent utilization did increase with chloride addition (an increase of 6% at the ESP outlet at 2.2% chloride), but the gain was probably not significant enough to justify the cost of the additive.

The second series of tests was performed during weeks 83 and 84 of testing. These tests were performed at a variety of Ca/S ratios, approach temperatures, and inlet SO_2 levels. The results of these tests are shown in Table 5-14 and in Figures 5-15 and 5-16. Figure 5-15 shows the gas phase utilization data taken in this series of tests in the range of approach temperatures from 20 to 30°F plotted against a curve fit to previous data taken with reagent slurry injection (without chloride addition) at an inlet SO_2 level of 2000 ppm for the same range of approach temperatures. These data show approximately the same increase in utilization at the ESP exit as was seen in Figure 5-14. Figure 5-16 shows less of an increase in utilization.

These tests suggest that either higher levels of chloride addition or much lower approach temperatures are required to significantly increase sorbent utilization. Unfortunately, it was not possible to explore this effect any further before testing at the DITF ended on February 27, 1992.

5.3 Fabric Filter Evaluations

For most potential applications, a duct injection process should include a particulate control system which maintains emissions of particulate matter at a level no greater than the emission rate without sorbent injection. Since many existing installations include relatively small electrostatic precipitators which cannot meet this requirement, it will be necessary to consider enlarging or replacing such units.

Because of their relatively compact size, pulse jet fabric filters (PJFF) have been receiving increasing attention as a potential means of reducing particulate emissions from utility boilers. It is also recognized that additional sorbent utilization can be achieved in a fabric filter installed downstream of a low-temperature sorbent injection process such as duct injection. For these reasons, a decision was made to dedicate most of the resources allocated to Testing of Advanced Configurations to a study of a simulated PJFF operating downstream from a duct injection process. A fabric filter device was installed and evaluated at the DITF. For these tests, a portable sidestream fabric filter (SSFF) was used that simulated the operation of a pulse-jet fabric filter. The SSFF allowed evaluation of SO_2 removal efficiencies, fabric pressure drop behavior, fabric cleanability, and particulate collection efficiency.

SRI fabricated the SSFF for the U.S. DOE.[6] This device is a redesigned version of a portable fabric filter originally designed and built for the Electric Power Research Institute. The SSFF has been useful in screening fabrics and evaluating flue gas conditioning agents at several full-scale utility boilers.[5]

A flue gas sample was extracted on a continuous basis and conveyed to a temperature-controlled sample chamber. A circular swatch of fabric (0.67 ft^2) was mounted vertically in the sample chamber opposite the chamber entrance. The flue gas velocity was reduced as it passed through a conical transform, which uniformly distributed the flue gas before it reached the fabric. Taps are located on each side of the fabric to monitor the pressure drop across the fabric. Ash that was removed from the fabric during cleaning or that did not have sufficient momentum to reach the fabric was collected in the ash hopper, which is located beneath the fabric holder.

The flue gas passed through the fabric and entered an inertial cyclone, which collected, with high efficiency, any ash penetrating the fabric. The flow rate through the fabric was measured by an orifice meter located downstream of the cyclone. The flue gas then flowed out of the heated sampling cabinet, through a liquid chiller, desiccant and filter assembly to clean the gas stream prior to being discharged through a vacuum pump and flow setting hardware. A schematic drawing of the SSFF is presented in Figure 5-17.

At the DITF, the SSFF was installed at the inlet to the ESP, approximately 1.5 s of residence time downstream of the point of slurry injection. A heat-traced sampling probe was located in the center of the duct and was fitted with a nozzle sized to isokinetically extract a continuous sample of gas at a flow rate of 2.7 acfm (an air-to-cloth ratio of 4.0 ft/min). Thermocouples were located at the inlet of the sample chamber and near the surface of the fabric for precise temperature control. For all tests at the DITF, a needle-felted Ryton™ fabric was used, typical of fabrics used in full-scale, pulse-jet baghouses. Operation of the SSFF was controlled by a dedicated interactive data acquisition system.

Continuous gas sampling instruments monitored the flue gas downstream of the fabric. A Western Research Model 721-AT SO_2 monitor and Servomex Model 540A oxygen analyzer extracted a continuous sample downstream of the fabric (at the exit of the liquid chiller device). To assure the flue gas stream being sampled by the gas analyzers was free of moisture, the sample line was passed through a ice-bath condenser that was placed downstream of the liquid chiller.

The SSFF can be operated with reverse-gas cleaning or with pulse-jet cleaning. For operation at the DITF, the SSFF was configured to simulate pulse-jet cleaning. This consisted of adding an external reservoir that was pressurized with compressed air and exhausted through a quick-acting solenoid valve. The pulse air was directed through a pipe and was released tangentially at the center of the clean side of the fabric, similar to the geometry in full-scale, pulse-jet baghouses. The SSFF was configured to pulse-clean on a pressure-initiated basis. Cleaning consisted of two consecutive pulses with a duration of 50 ms that were separated by a period of 10 s. In laboratory measurements, similar pulses had been measured to impart fabric accelerations of about 400 g, typical of the upper portions of bags in a full-scale pulse-jet baghouse.

During initial fabric filter operation with the sorbent/ash product, it was found that the fabric cleaned very easily, resulting in an after-cleaning pressure drop of ~1.0 in. H_2O. In a full-scale pulse-jet baghouse, only a small portion of the bags are pulsed during any one cleaning period, and the average pressure drop across the fabric is typically maintained at approximately 5 in. H_2O. Therefore, to simulate full-scale baghouse operation, initiation of on-line cleaning was set to occur at a fabric pressure drop of 9.0 in. H_2O.

Ash samples were collected from the SSFF hopper after each test condition (once or twice per day). Chemical analyses of the ash samples determined the degree of sorbent utilization. Comparison to calculated values of utilization, based on gas-phase data (SO_2 removal and Ca/S ratio), generally showed good agreement between the two techniques as shown in Figure 5-18.

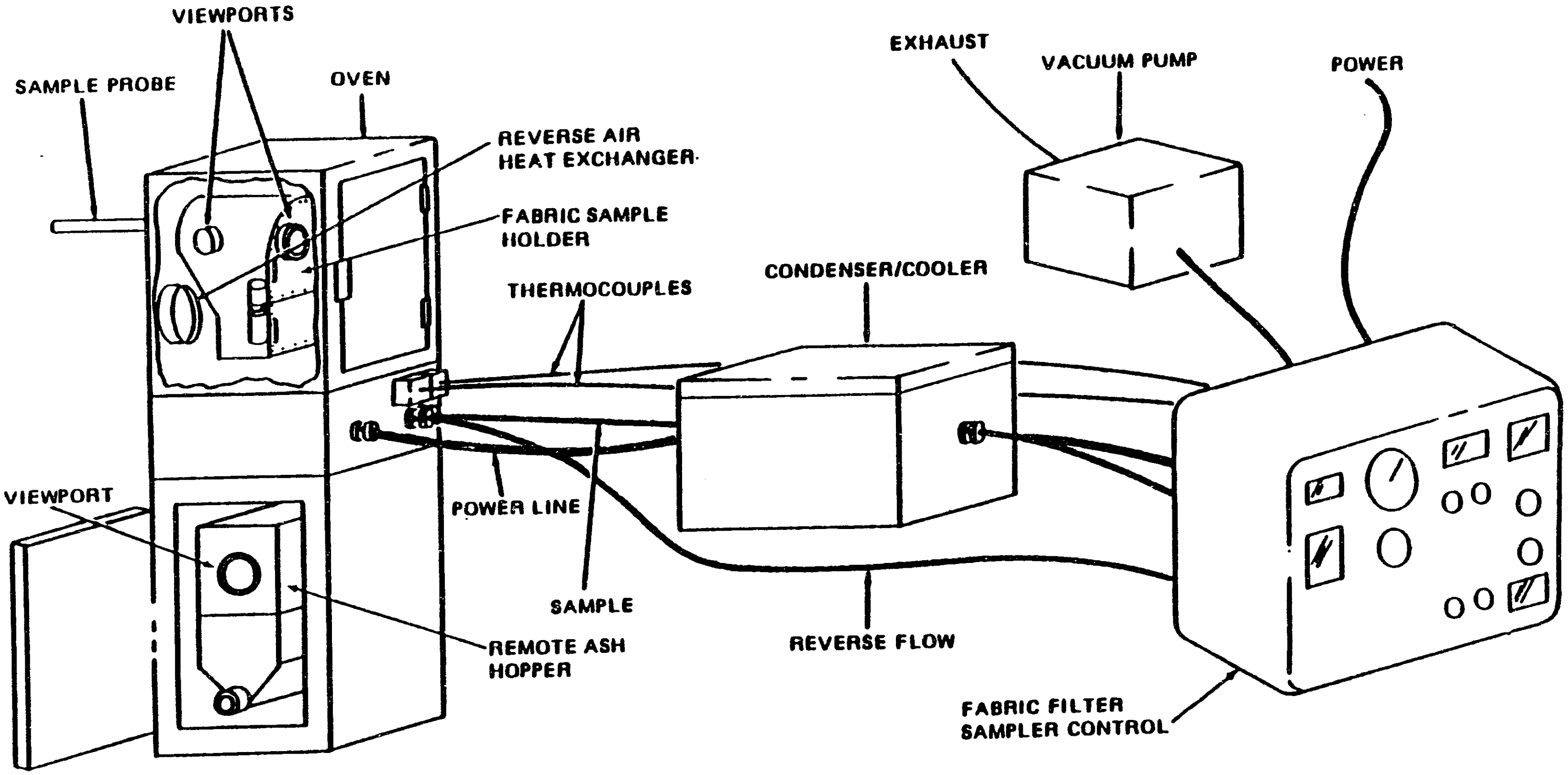

Figure 5-17. Schematic diagram of the Sidestream Fabric Filter Device.

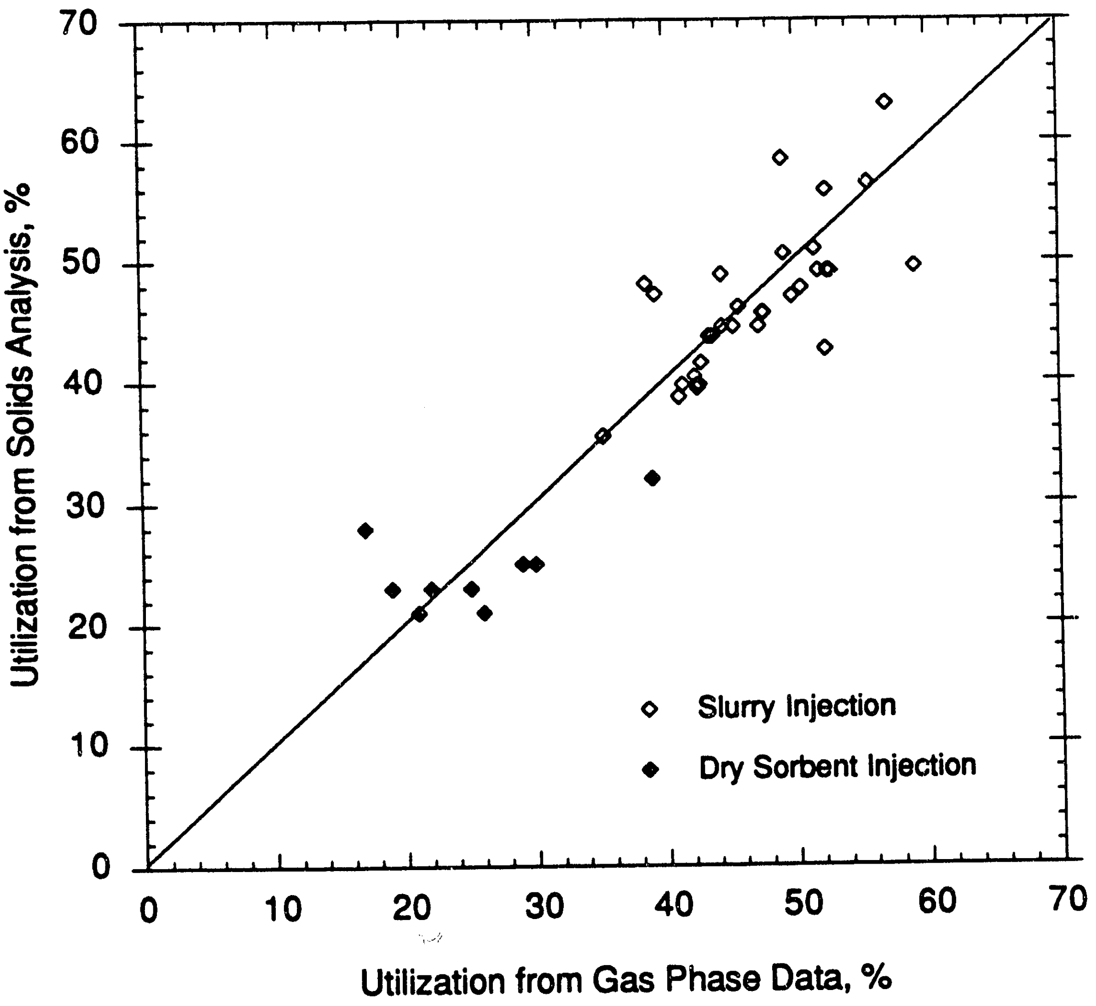

Figure 5-18. Comparison of sorbent utilization determined from gas-phase data and from chemical analyses of SSFF hopper samples. Data from tests conducted with dry sorbent injection and with slurry injection.

Several experiments and evaluations validated the SO_2 removal results. In addition to the good agreement of sorbent utilization between solid sample and gas-phase analyses, other indications supported these results.

As the fabric pressure drop increased during a filtration cycle (due to the growth of the filter cake), SO_2 concentrations downstream of the fabric filter decreased in a corresponding fashion. This implies that the filter cake was an active component in SO_2 removal.

There was also a predictable relationship between the SO_2 removals across the ESP and the SSFF. In tests with the SSFF and the duct (and ESP) operating at the same approach-to-saturation temperature, SO_2 removal through the SSFF was consistently 5-10% more than the removal across the ESP for all test conditions.

An experiment was devised to determine if any significant SO_2 removal could be attributed to losses through the sampling system. With the SSFF operating at an approach-to-saturation temperature of 15°F, and ~0 ppm of SO_2 downstream of the fabric, a constant flow rate of SO_2 from a gas cylinder (the equivalent of 101 ppm in the diluted gas stream) was injected downstream of the fabric at the immediate exit of the heated sample chamber. An SO_2 concentration of 97 ppm was measured at the SO_2 monitor (downstream of the condensers), indicating less than 5 ppm loss of SO_2 through the sampling system.

Results which were obtained with the SSFF are subdivided as follows: a) Sections 5.3.1 through 5.3.3 present data with the SSFF maintained at essentially the same temperature as the duct spray dryer, and b) Sections 5.4 through 5.6 present data with the SSFF cooled with a secondary cooling step to temperatures significantly lower than the duct spray dryer.

5.3.1 Dry Sorbent Injection

The SSFF was operated during tests with dry sorbent injection (hydrated lime) in which the Ca/S ratio was ~2.0 and for approach-to-saturation temperatures in the duct of 35 and 45°F above saturation. A tabular summary of SSFF test results is presented in Table 5-15. Sulfur dioxide removals (and sorbent utilizations) across the SSFF fabric filter for dry sorbent injection tests were considerably lower than comparable slurry injection tests.

5.3.2 Slurry Injection - Without Recycle

The SSFF was operated during tests with slurry injection at a variety of Ca/S ratios (1.1 to 2.3) and for approach-to-saturation temperatures in the duct of 25 to 45°F. The test results discussed in this section were obtained with the duct injection process operated without recycle.

Tables 5-16 and 5-17 list results of SSFF tests performed with slurry injection (without recycle). The data in Table 5-16 were obtained with a single-stage slurry injection process in which the SSFF was maintained at the temperature of the duct. Table 5-17 contains data obtained with slurry injection followed by water injection in the duct to maintain the duct temperature at 10 to 35°F lower than the evaporative cooling provided by water in the slurry. The SSFF was maintained at the duct temperature downstream from the point of second-stage water injection.

Table 5-15. SSFF Tests - Dry Sorbent Injection

Test ID	Ca/S	ΔTs Duct	SO$_2$ Removal, %			Utilization, % Gas-phase SSFF-avg.
			SSFF	ESP	Duct	
48-DS-01	2.01	44	34	30	21	17
48-DS-03	2.05	37	44	35	27	21

Table 5-16. SSFF Tests - Slurry Injection Without Recycle

Test ID	Ca/S	ΔTs Duct	SO$_2$ Removal, %				Utilization, % Gas-phase SSFF-avg.
			SSFF (max)	SSFF (avg)	ESP	Duct	
38-SL-03	1.13	25	60.7	55.5	49.9	41.1	49.1
38-SL-01	1.42	25	80.2	74.1	57.0	52.7	52.3
38-SL-02	1.72	25	85.4	81.9	72.5	55.9	47.6
38-SL-02	1.74	25	88.7	82.8	71.3	56.5	47.5
39-SL-02	1.76	25	83.1	80.4	70.6	57.9	45.7
34-SL-02	2.07	25	88.2	84.8	73.0	58.7	41.0
37-SL-02	2.10	25	92.0	86.5	76.3	60.7	41.1
37-SL-03	2.11	25	93.0	89.0	76.8	62.4	42.3
37-SL-04	2.20	25	98.7	93.5	77.7	62.1	42.5
37-SL-04	2.21	25	97.5	94.2	80.5	63.4	42.7
37-SL-04	2.23	25	95.2	92.2	81.1	63.4	41.4
33-SL-04	2.00	45	66.2	63.9	64.0	51.8	32.0
33-SL-04	2.00	45	64.0	61.8	63.0	51.2	30.9
33-SL-04	2.00	45	72.1	64.4	58.0	47.8	32.2

Table 5-17. SSFF Tests - Slurry Injection Without Recycle With Two-Stage Humidification

Test ID	Ca/S	ΔTs Duct		SO$_2$ Removal, %				Utilization, % Gas-phase SSFF-avg.
		Duct	SSFF	SSFF (max)	SSFF (avg)	ESP	Duct	
39-SL-02	1.77	35/25	25	77.9	69.8	66.2	51.0	39.3
39-SL-01	1.85	35/25	25	83.5	79.0	66.9	50.9	42.8
38-SL-04	1.88	35/25	25	78.4	72.4	64.2	54.1	38.6
39-SL-01	1.89	35/25	25	79.7	74.8	65.4	50.1	39.5
39-SL-04	1.71	45/25	25	75.8	72.5	64.4	50.0	42.5
39-SL-05	1.73	45/10	10	97.7	90.6	74.9	57.9	52.4

Sulfur dioxide removal for the SSFF is presented for the maximum removal attained (at the end of the filtration cycle) and the average removal (averaged over the entire filtration cycle). Although the data reported for SO_2 removal across the SSFF in subsequent graphical presentations are based on the average SO_2 removal, results for full-scale operation are expected to be closer to the maximum values.

Figure 5-19 presents a summary of SSFF data for SO_2 removal as a function of Ca/S ratio at a duct approach temperature of 25° F. Calculations of SO_2 removals are based on the DITF inlet conditions (before slurry injection). A ranking of SO_2 removals for various conditions is shown by the different curve fits. The bottom curve shows the level of SO_2 removal achieved across the duct (up to the inlet of the ESP). The other two curves show the additional SO_2 removal attributable to the particulate control device (ESP or fabric filter). The fabric filter is shown to consistently remove 5 to 10% more SO_2 (absolute basis) than the ESP for the same conditions.

5.3.3 Slurry Injection - With Recycle

The SSFF was operated during tests with reagent slurry plus recycle material injected at similar Ca/S ratios and duct approach temperatures as during the tests without recycle. More discussion concerning slurry with recycle ash is presented in a previous section. Results of the SSFF tests are presented in Table 5-18. Note that SO_2 removals of 94.4 to 97.8% were obtained at the SSFF outlet at ΔT_s values of 23-27°F with reagent Ca/S values from 1.78 to 2.06.

5.4 Dry Sorbent Reactivation

Since SO_2 removals improved significantly when the duct was operated at lower approach-to-saturation temperatures (e.g. 25 versus 45° F), a decision was made to investigate SSFF operation at lower temperatures than duct temperatures. Because of the small scale of the SSFF, it was practical to operate the SSFF at lower temperatures than the duct conditions. The temperature controller set points were lowered for the sample probe and the sample chamber, which provided cooling by as much as 35° F at the fabric, without having "cold spots" in the sample probe or sampling chamber. The SSFF could achieve these lower temperatures by utilizing the sampling probe and heated sample chamber as a passive heat exchanger. This allowed the SSFF to operate at temperatures approximating the adiabatic saturation temperature while the duct was operating at 25° F above the saturation temperature.

It should be noted that cooling the flue gas without the addition of water is not an adiabatic saturation process. Therefore, if the SSFF is cooled, for example, 25° F below the duct temperature to the calculated adiabatic saturation temperature without additional water, the flue gas is actually a few degrees above the true saturation point.

It was found that very high SO_2 removals could be achieved (over 95%) with the duct operating at an approach temperature of 25° F and the SSFF operating at an approach temperature of 10° F for a Ca/S ratio of 2 (without recycle) for an SO_2 concentration of 2000 ppm upstream of duct injection. There were no operational problems at a 25° F approach temperature (in the duct) with the SSFF operating at the saturation temperature. The filter cake remained dry and cleaned normally at the calculated saturation temperature.

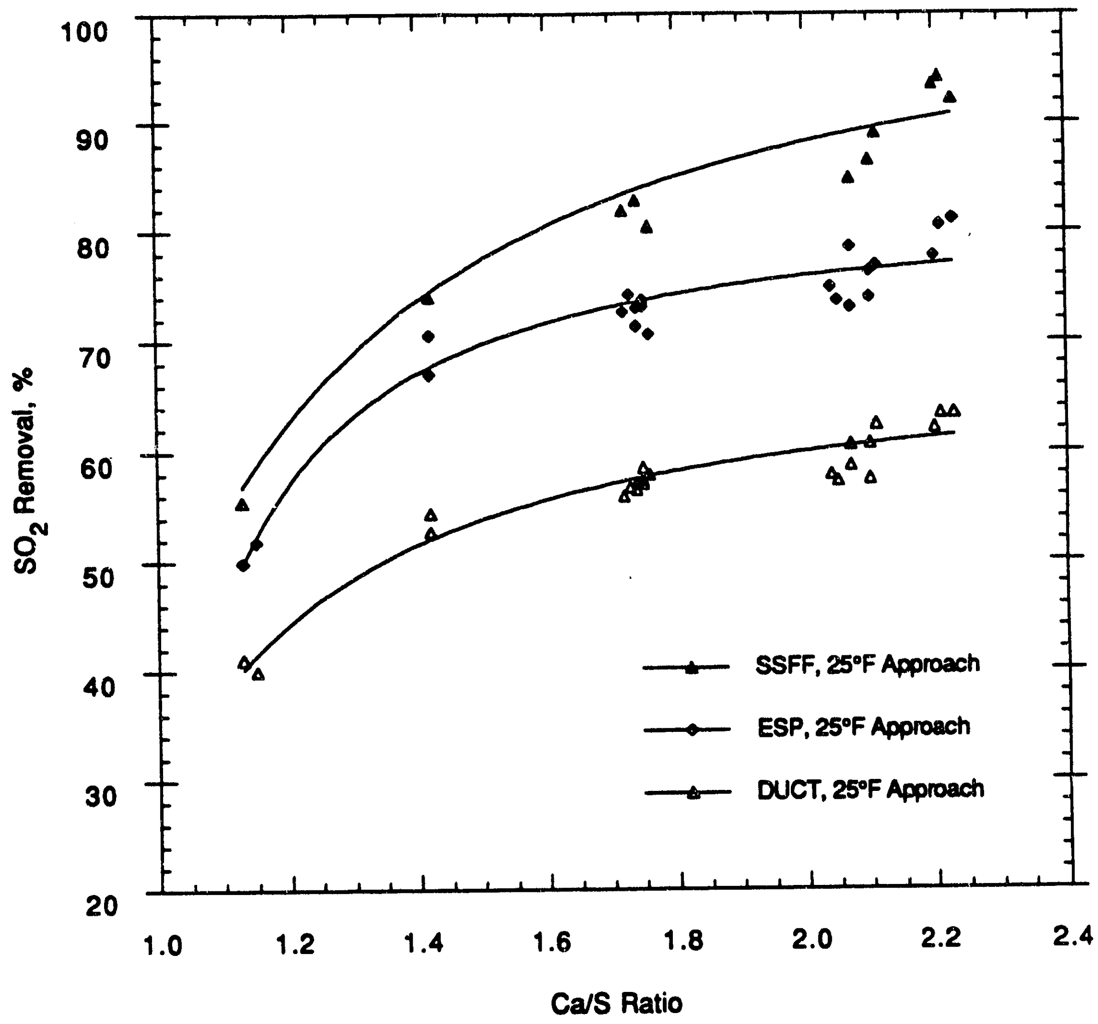

Figure 5-19. SO_2 removal as a function of Ca/S ratio for a duct approach temperature and SSFF approach temperature of 25°F. Data obtained during slurry injection testing.

Table 5-18. SSFF Tests - Slurry Injection with Recycle

Test ID	Overall Ca/S	Reagent Ca/S	Recycle Ratio	ΔTs Duct	SO_2 Removal, %			Utilization, % Gas-phase SSFF-avg.
					SSFF	ESP	Duct	
68-SR-01	1.33	1.03	2.22	44	61.8	51.0	40.2	60.0
67-SR-02	1.38	1.05	2.05	44	63.0	53.5	43.2	60.0
67-SR-03	1.56	1.03	1.83	44	63.3	54.0	43.3	61.5
68-SR-02	1.29			25	73.8	63.0	51.9	
68-SR-02	1.29	1.18	2.15	28	69.2	63.4	49.2	58.6
68-SR-02	2.45	2.06	1.31	27	96.5	86.0	66.3	46.8
68-SR-03	2.16	1.78	1.44	27	94.4	82.4	63.4	53.0
69-SR-02	2.64	1.98	1.23	25	97.8	88.5	65.4	49.4
69-SR-03	2.45	1.82	1.35	23	97.0	89.8	64.9	53.3

The secondary cooling step upstream of the fabric filter, (without the addition of water), reactivated nearly dry sorbent and significantly increased sorbent utilization. In view of the favorable operating characteristics of the fabric filter at the low approach-to-saturation temperatures, and the very high SO_2 removals observed with the unique secondary cooling step, Southern Research Institute has applied for a patent for this process.

This process of using a secondary cooling step downstream of a slurry injection process, and upstream of a fabric filter, has been named Dry Sorbent Reactivation (DSR). A preliminary economic analysis indicates that DSR has the potential to be economically competitive with other high efficiency (90+% removal) flue gas desulfurization processes.

5.4.1 Dry Sorbent Injection

The SSFF was operated during tests with dry sorbent injection with the SSFF operating over a range of approach-to-saturation temperatures from 2 to 45°F. During these tests, the DITF operated at a Ca/S ratio of ~2.0 and the duct was operated at 35 and 45°F approach-to-saturation temperatures. A summary of the SSFF test results is presented in Table 5-19.

Figure 5-20 presents SO_2 removal versus approach temperature at the SSFF for the two temperature conditions in the duct. Sulfur dioxide removal across the SSFF increased with lower approach- to-saturation temperatures, although the SO_2 removals were lower than for comparable slurry injection tests. For an approach-to-saturation temperature of 45°F, SO_2 removal for slurry injection test was approximately 25% higher than for dry sorbent injection, as shown in Figure 5-20.

5.4.2 Slurry Injection - Without Recycle

The SSFF was operated during tests with slurry injection at a variety of Ca/S ratios and approach-to-saturation temperatures. Figures 5-21, 5-22, and 5-23 present typical data collected from the SSFF during tests with slurry injection. The figures document the pressure drop across the SSFF fabric, the fraction of SO_2 removed across the SSFF and the fraction of SO_2 removed due to the combined effect of the duct and the SSFF.

These figures illustrate the trend of increasing trends of SO_2 removal through a filtration cycle and the enhancement of SO_2 removal at reduced temperatures for the SSFF (with constant duct temperatures). A complete summary of SSFF test results with slurry injection without recycle are presented in Tables 5-20 and 5-21. To further illustrate the increased SO_2 removal with the secondary cooling step, Tables 5-20 and 5-21 contain data presented in previous tables in which the SSFF was operated at duct temperatures.

In Figure 5-21, the DITF was operated at an approach-to-saturation temperature of 45°F in the duct with a Ca/S ratio of 2.0. The SSFF was operated at different approach-to-saturation temperatures (25, 15, and 10°F). This figure shows that SO_2 removal (and sorbent utilization) increased significantly as the approach temperature at the fabric was reduced. Figure 5-22 shows that enhanced SO_2 removal was achieved for the same test conditions as Figure 5-21, except that the duct was operated at an approach-to-saturation temperature of 25°F instead of 45°F. As shown in Figure 5-22, there was practically 100% SO_2 removal with the SSFF operating at 10°F above the saturation temperature.

Table 5-19. SSFF/DSR Tests - Dry Sorbent Injection

Test ID	Ca/S	ΔTs Duct		SO_2 Removal, %			Utilization, % Gas-phase SSFF-avg.
		Duct	SSFF	SSFF	ESP	Duct	
48-DS-01	2.01	44	45	34	30	21	17
48-DS-01	2.01	44	35	39	30	21	19
48-DS-01	2.01	44	25	44	30	21	22
48-DS-02	2.07	45	20	51	31	21	25
48-DS-02	2.07	45	10	59	31	21	29
48-DS-03	2.05	37	35	44	35	27	21
48-DS-03	2.05	37	20	53	35	27	26
48-DS-03	2.05	37	10	62	35	27	30
48-DS-04	2.01	35	2	79	33	25	30

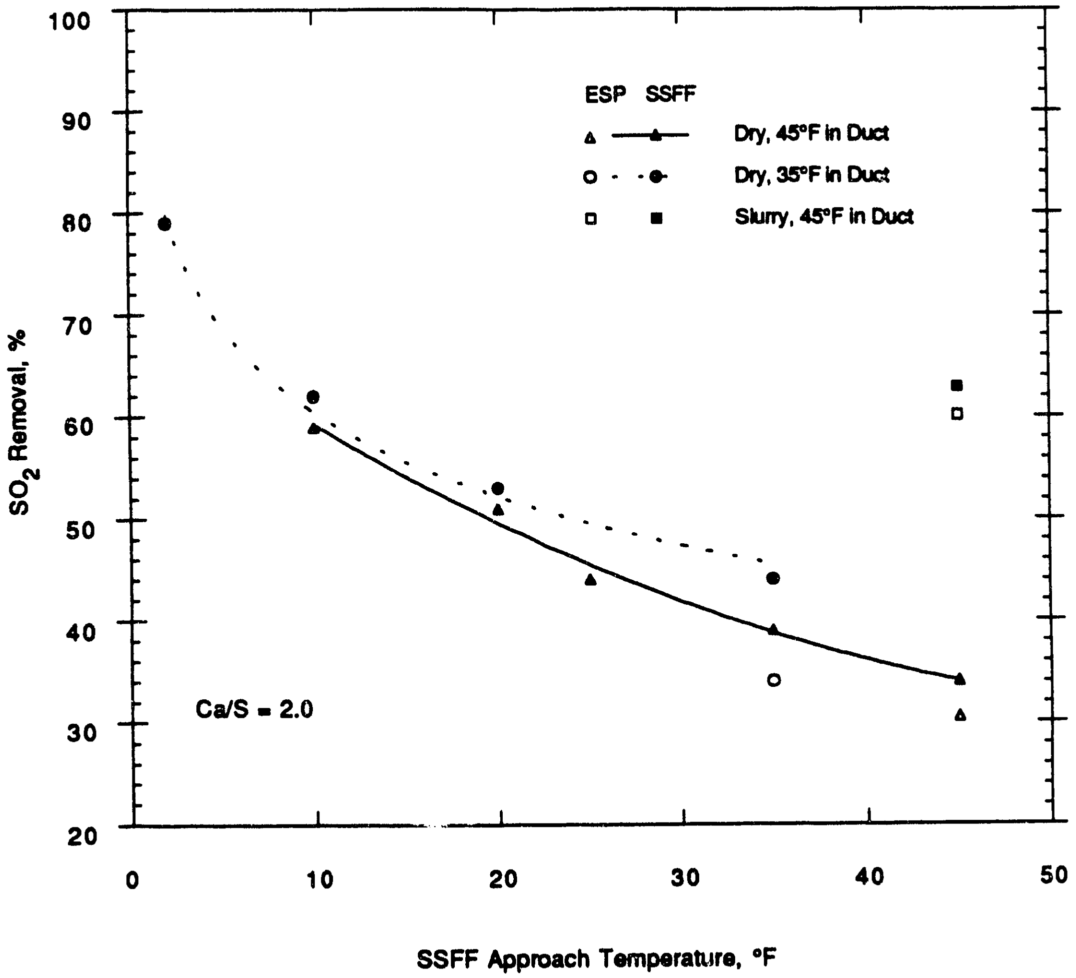

Figure 5-20. SO_2 removal averaged over a filtration period in the SSFF as a function of the approach temperature with the SSFF for approach temperatures in the duct of 35°F and 45°F and a Ca/S ratio of 2.0. Data obtained during dry sorbent injection testing

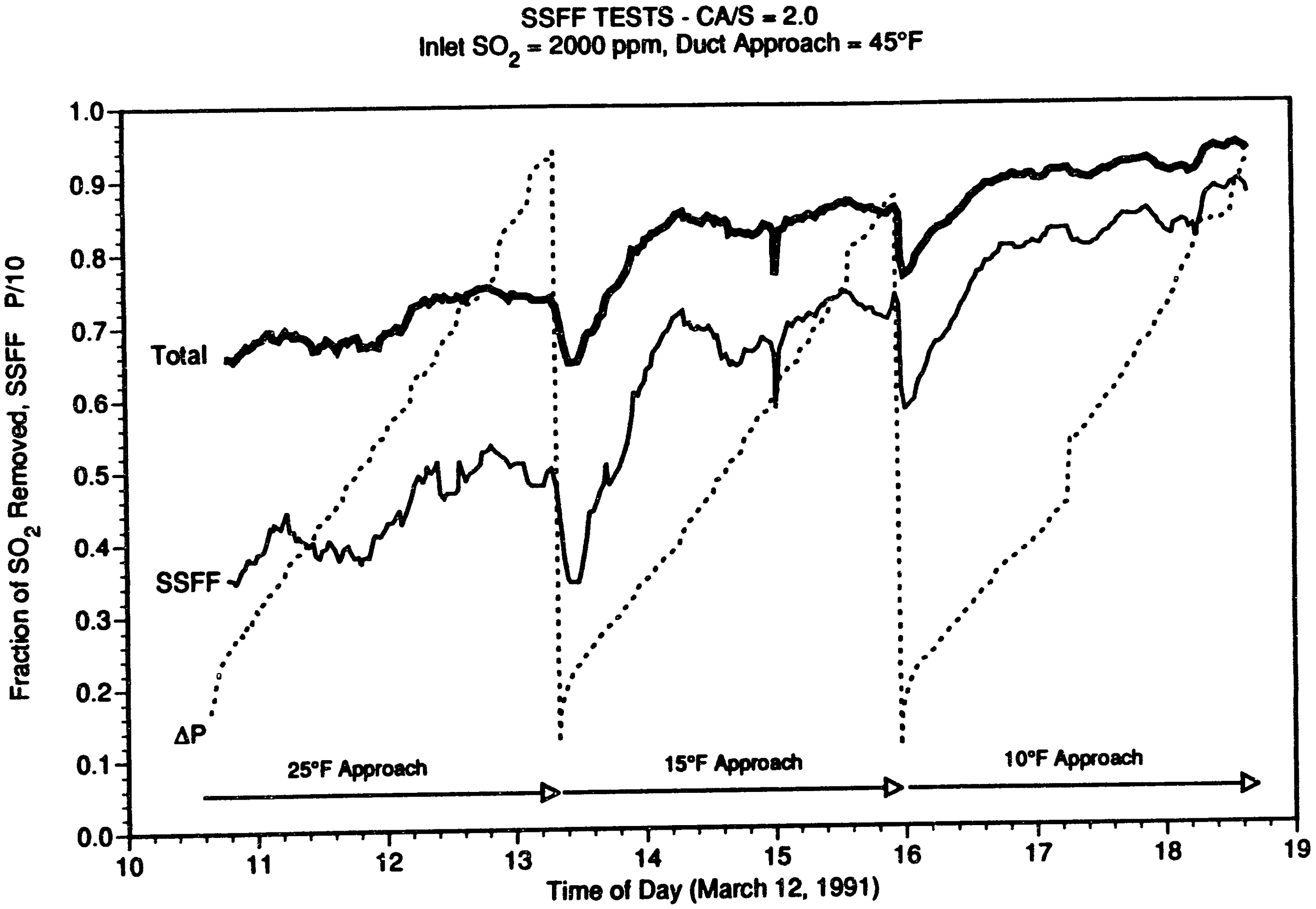

Figure 5-21. SSFF data obtained during slurry tests in which the approach temperature within the SSFF was lowered from 25 to 10°F in two steps. Data shown for duct approach temperature of 45°F.

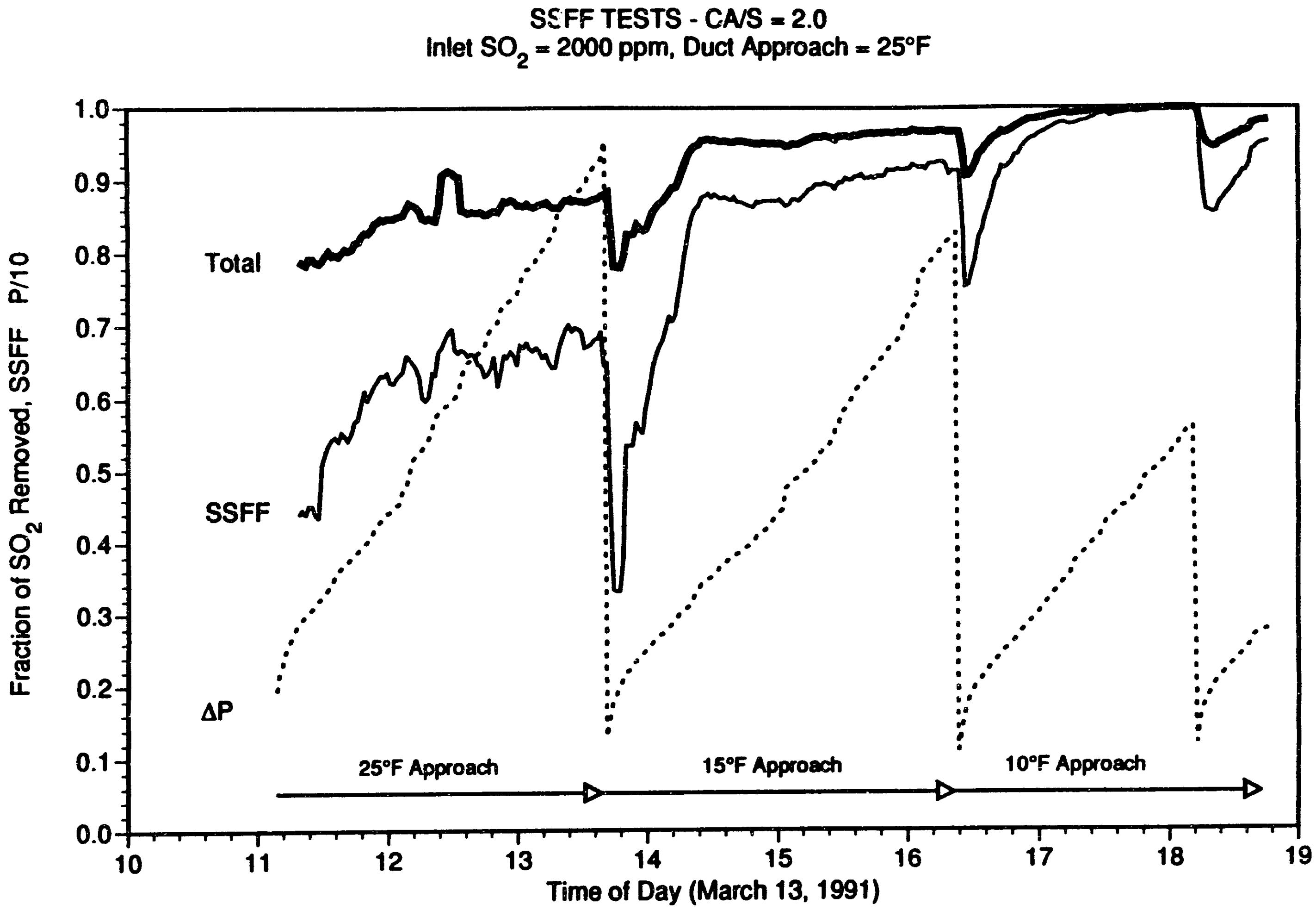

Figure 5-22. SSFF data obtained during slurry tests in which the approach temperature within the SSFF was lowered from 25 to 10°F in two steps. Data shown for duct approach temperature of 25°F.

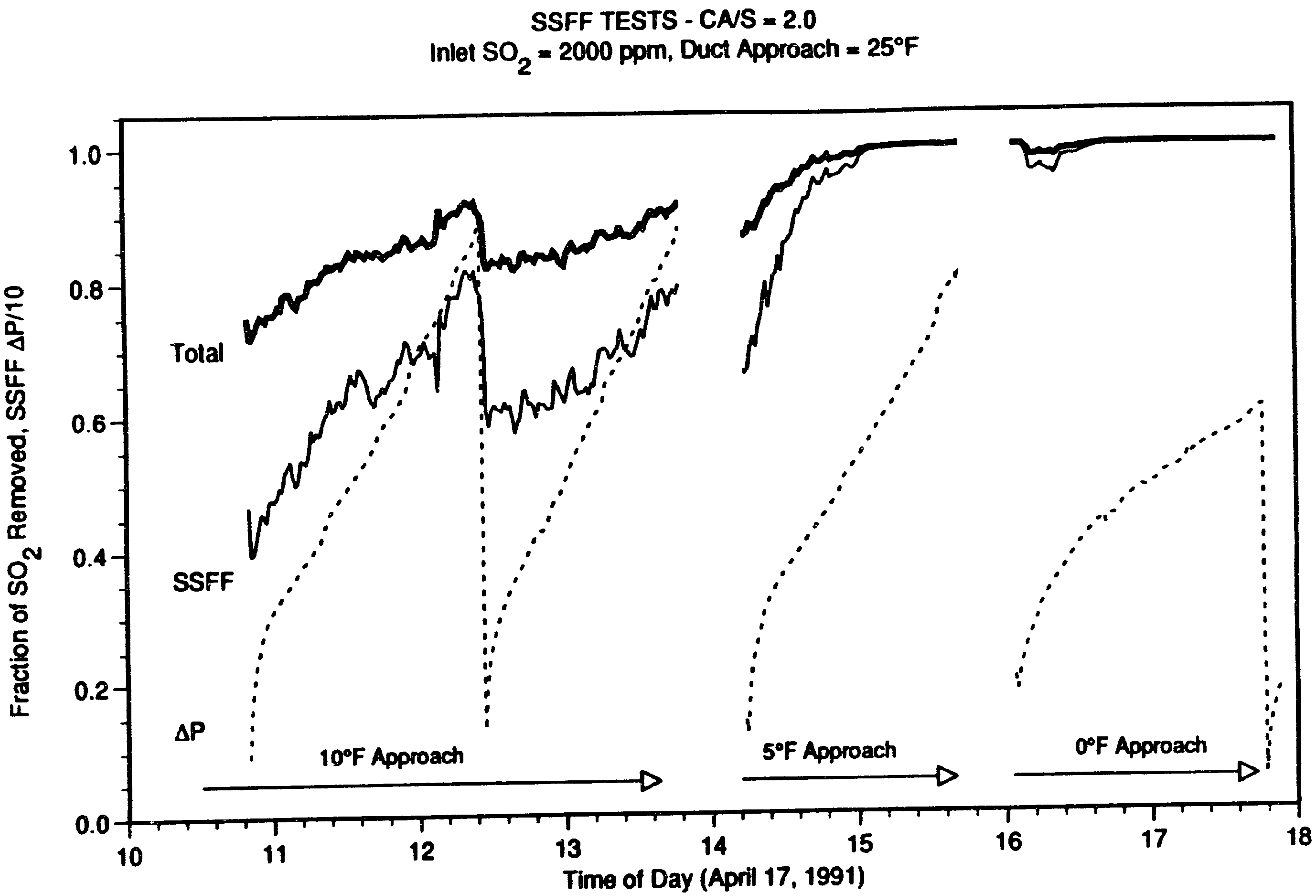

Figure 5-23. SSFF data obtained during slurry tests in which the approach temperature within the SSFF was lowered from 10 to 0°F in two steps. Data shown for duct approach temperature of 25°F.

Table 5-20. SSFF/DSR Tests - Slurry Injection Without Recycle

Test ID	Ca/S	ΔTs Duct		SO$_2$ Removal, %				Utilization, % Gas-phase SSFF-avg.
		Duct	SSFF	SSFF (max)	SSFF (avg)	ESP	Duct	
38-SL-03	1.13	25	25	60.7	55.5	49.9	41.1	49.1
38-SL-01	1.42	25	25	80.2	74.1	57.0	52.7	52.3
38-SL-02	1.72	25	25	85.4	81.9	72.5	55.9	47.6
38-SL-02	1.74	25	25	88.7	82.8	71.3	56.5	47.5
39-SL-02	1.76	25	25	83.1	80.4	70.6	57.9	45.7
34-SL-02	2.07	25	25	88.2	84.8	73.0	58.7	41.0
37-SL-02	2.10	25	25	92.0	86.5	76.3	60.7	41.1
37-SL-03	2.11	25	25	93.0	89.0	76.8	62.4	42.3
37-SL-04	2.20	25	25	98.7	93.5	77.7	62.1	42.5
37-SL-04	2.21	25	25	97.5	94.2	80.5	63.4	42.7
37-SL-04	2.23	25	25	95.2	92.2	81.1	63.4	41.4
34-SL-02	2.06	25	15	97.0	93.4	78.0	60.8	
37-SL-04	2.25	25	15	99.9	98.1	78.8	61.3	43.7
37-SL-04	2.25	25	15	99.9	97.8	78.8	62.0	43.4
38-SL-03	1.15	25	10	69.6	63.7	51.8	39.6	55.6
38-SL-01	1.42	25	10	89.2	83.8	70.6	54.4	59.1
38-SL-02	1.73	25	10	95.2	90.9	74.2	56.7	52.5
38-SL-02	1.75	25	10	94.3	92.1	73.4	58.5	52.7
38-SL-02	1.75	25	10	94.6	90.7	73.1	57.0	51.8
39-SL-02	1.75	25	10	95.2	89.8	73.7	57.4	51.5
39-SL-03	1.74	25	10	91.7	85.9	73.0	57.1	49.2
37-SL-03	2.04	25	10	99.5	96.3	74.8	57.9	47.2
37-SL-03	2.10	25	10	97.2	93.1	73.9	57.5	44.4
37-SL-03	2.05	25	10	96.4	92.8	73.6	57.3	45.3
34-SL-02	2.07	25	10	99.9	98.9	78.5	60.6	47.8
39-SL-03	1.75	25	5	99.9	97.3	75.7	58.5	55.6
39-SL-03	1.75	25	0	99.9	99.7	74.1	57.9	57.1
33-SL-04	2.00	45	45	66.2	63.9	64.0	51.8	32.0
33-SL-04	2.00	45	45	64.0	61.8	63.0	51.2	30.9
33-SL-04	2.00	45	25	72.1	64.4	58.0	47.8	32.2
34-SL-03	1.80	45	25	74.2	69.3	56.3	46.0	38.5
34-SL-03	1.80	45	15	86.0	80.3	57.4	46.9	44.6
34-SL-03	1.80	45	10	94.1	88.5	58.2	45.8	49.2

Table 5-21. SSFF/DSR Tests - Slurry Injection Without Recycle With Two-Stage Humidification

		ΔTs Duct		SO$_2$ Removal, %				Utilization, % Gas-phase SSFF-avg.
Test ID	Ca/S	Duct	SSFF	SSFF (max)	SSFF (avg)	ESP	Duct	
39-SL-02	1.77	35/25	25	77.9	69.8	66.2	51.0	39.3
39-SL-01	1.85	35/25	25	83.5	79.0	66.9	50.9	42.8
38-SL-04	1.88	35/25	25	78.4	72.4	64.2	54.1	38.6
39-SL-01	1.89	35/25	25	79.7	74.8	65.4	50.1	39.5
38-SL-04	1.88	35/25	10	88.2	83.7	67.2	53.3	44.4
39-SL-04	1.64	45	25	62.4	57.9	47.4	38.4	35.3
39-SL-04	1.71	45/25	25	75.8	72.5	64.4	50.0	42.5
39-SL-04	1.72	45/25	10	91.7	85.8	62.3	47.4	49.8
39-SL-05	1.74	45/25	10	92.1	88.1	65.8	51.2	50.5
39-SL-05	1.73	45/10	10	97.7	90.6	74.9	57.9	52.4

In Figure 5-23, the DITF was operated at an approach-to-saturation temperature of 25° F in the duct with a Ca/S ratio of 1.75. The SSFF was operated at approach temperatures of 10, 5, and 0° F. Similar to the previous graph, very high SO_2 removal was measured at low approach temperatures at the fabric. Of particular interest, the data demonstrated that filtration performance was unaffected at low operating temperatures, even at the saturation temperature. The pulse-cleaning easily removed the dustcake at all temperatures. The ash and sorbent product that was removed from the ash hopper at the termination of the 0° F approach-to-saturation temperature test condition was found to be dry and flowed freely. These observations contradict anecdotal reports of dry FGD systems with fabric filters that have suffered excursions below the water dew point that caused bag blinding or otherwise irreversible damage to the filter bags.

The fabric pressure drop curve in Figure 5-23 shows that a baghouse may actually operate at a lower drag (defined as pressure drop divided by gas flow rate) at temperatures very near the saturation temperature. The slope of the fabric pressure drop curve decreased as the temperature decreased from 10° F above saturation to 5° F above saturation, and was significantly lower at the saturation temperature. This suggests that a more porous dustcake was formed as the saturation temperature was approached.

Figure 5-24 presents a summary of SO_2 removal as a function of Ca/S ratio at a duct approach temperature of 25° F. This graph is a repeat of Figure 5-19 with the addition of the SSFF data using the secondary cooling step. A ranking of SO_2 removals for various conditions is shown by the different curve fits. The bottom curve shows the level of SO_2 removal achieved across the duct (up to the inlet of the ESP). The next two curves show the additional SO_2 removal attributable to the particulate control device (ESP or SSFF fabric filter) operated at a temperature 25° F above saturation. The upper curve shows the additional SO_2 removal across the SSFF achieved by lowering the approach temperature at the fabric from 25 to 10° F.

Figure 5-25 presents SO_2 removal as a function of the approach temperature at the SSFF fabric, with three separate curves showing the dependency on Ca/S ratio over a range of 1.42 to 2.10. These data are shown for the duct at a temperature 25° F above saturation. There is an expected increase in SO_2 removal at higher Ca/S ratios, although this benefit must be weighed against the lower sorbent utilizations realized at the higher Ca/S ratios. For the purposes of comparison data are shown for ESP operation.

Figure 5-26 presents SO_2 removal as a function of the approach temperature at the SSFF fabric, with data for a 25 and 45° F approach temperature in the duct. These data are shown for a Ca/S ratio of approximately 1.75. There is an expected increase in SO_2 removal at the lower duct approach temperature in addition to the effect of lower approach temperatures at the SSFF.

5.4.3 Slurry Injection - With Recycle

A series of SSFF tests were conducted with reagent slurry plus recycle material injected at Ca/S ratios and duct approach temperatures similar to those used during tests without recycle ash addition. Results from all SSFF tests for reagent slurry injection with recycle ash addition are presented in Table 5-22.

To illustrate the benefits of recycle, SSFF data obtained with and without recycle are presented in Figure 5-27. This figure shows SO_2 removal versus Ca/S ratio for the SSFF operating without recycle

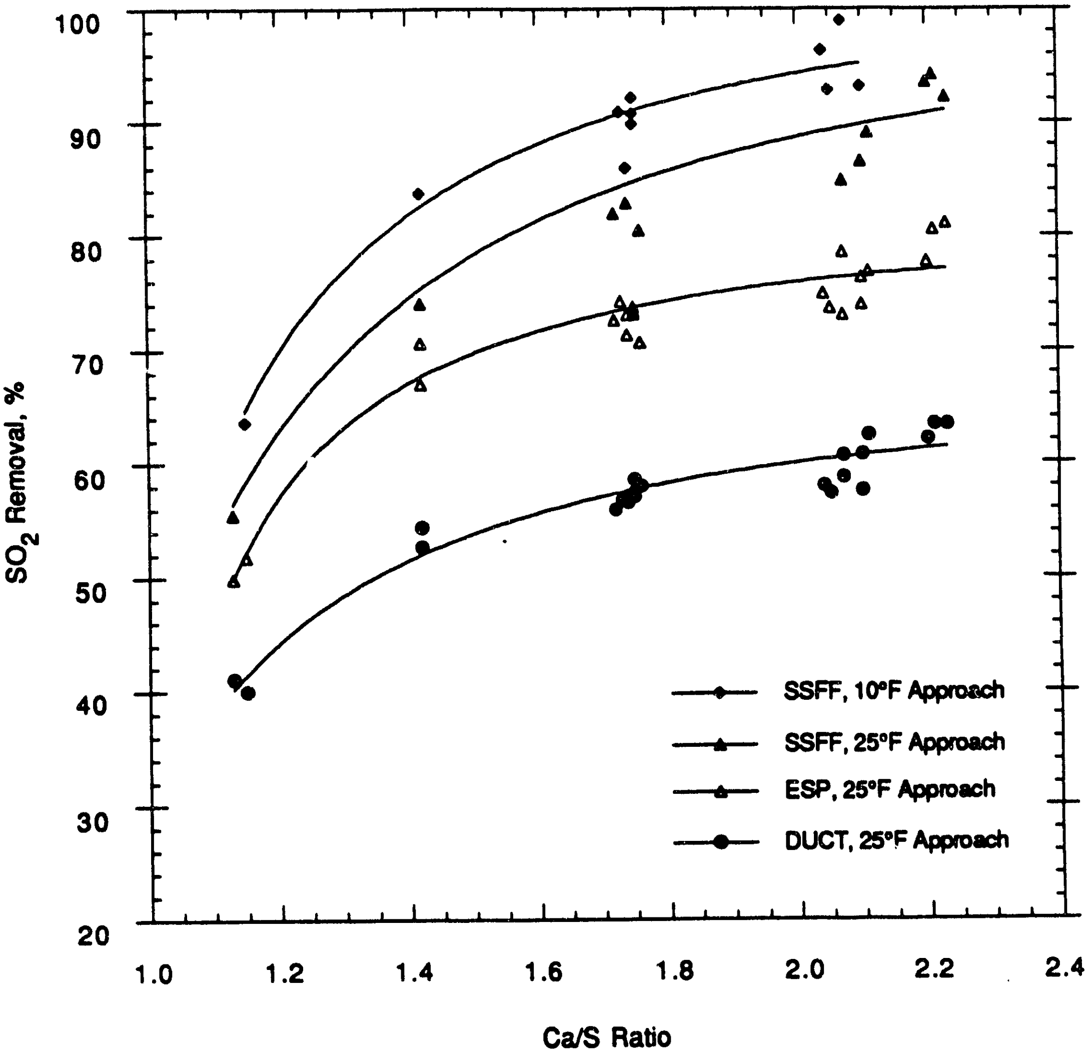

Figure 5-24. SO_2 removal as a function of Ca/S ratio for a duct approach temperature of 25°F and SSFF approach temperatures of 25 and 10°F. Data obtained during slurry injection testing.

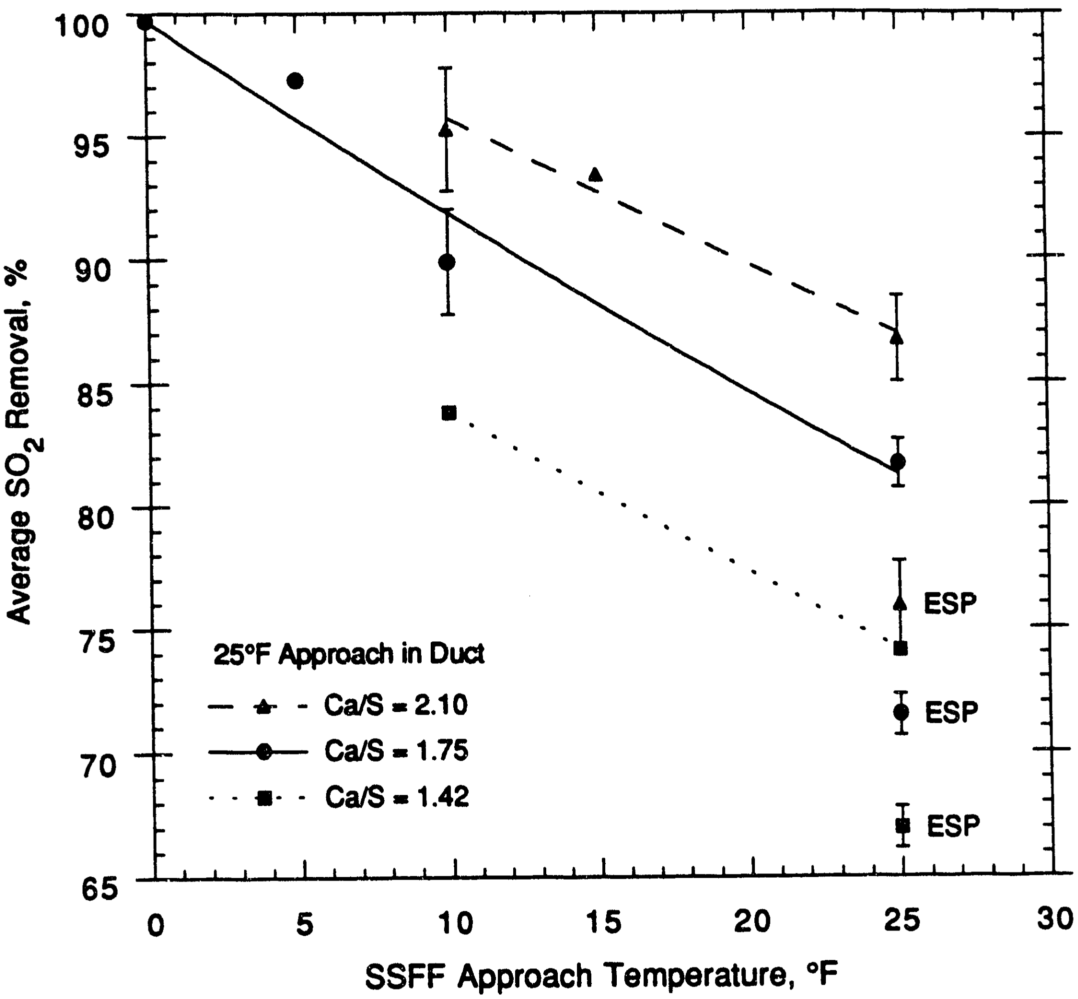

Figure 5-25. SO_2 removal averaged over a filtration period in the SSFF as a function of the approach temperature within the SSFF for three Ca/S ratios at an approach temperature of 25°F in the duct. ESP SO_2 removal data also shown. Data obtained during slurry injection tests.

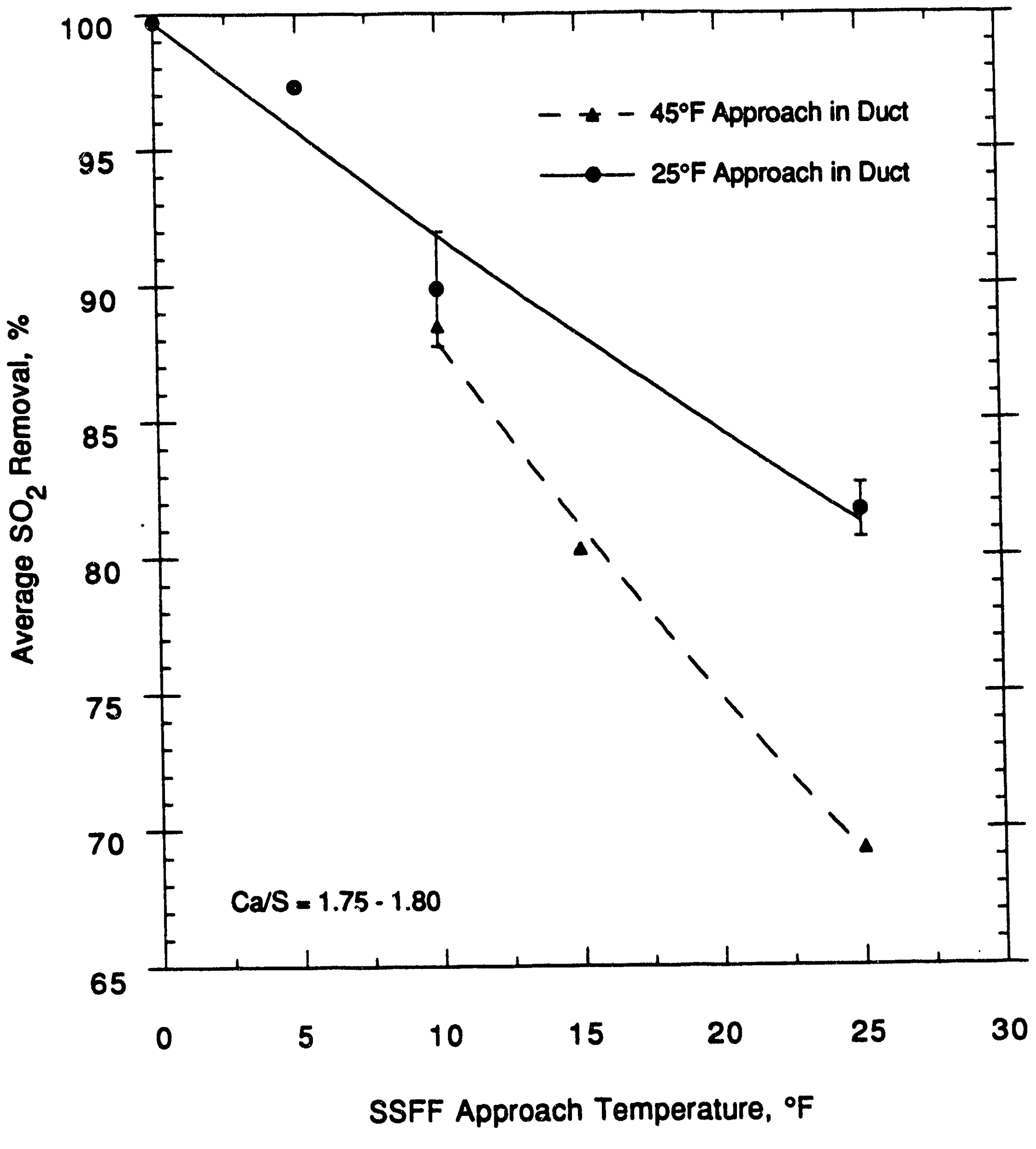

Figure 5-26. SO_2 removal averaged over a filtration period in the SSFF as a function of the approach temperature within the SSFF for approach temperatures in the duct of 25°F and 45°F. Data obtained during slurry injection testing.

Table 5-22. SSFF/DSR Tests - Slurry Injection with Recycle

Test ID	Overall Ca/S	Reagent Ca/S	Recycle Ratio	ΔTs Duct		SO_2 Removal, %			Utilization, % Gas-phase SSFF-avg.
				Duct	SSFF	SSFF	ESP	Duct	
68-SR-01	1.33	1.03	2.22	44	40	61.8	51.0	40.2	60.0
67-SR-02	1.38	1.05	2.05	44	40	63.0	53.5	43.2	60.0
67-SR-03	1.56	1.03	1.83	44	40	63.3	54.0	43.3	61.5
67-SR-03	1.48	1.14	1.72	45	20	72.6	54.3	42.7	63.7
68-SR-01	1.48	1.02	2.12	45	10	76.1	52.0	41.3	74.6
68-SR-02	1.29			25	25	73.8	63.0	51.9	
68-SR-02	1.29	1.18	2.15	28	25	69.2	63.4	49.2	58.6
*68-SR-02	1.64	1.18	2.34	33	10	83.8	63.1	48.9	71.0
68-SR-02	2.45	2.06	1.31	27	25	96.5	86.0	66.3	46.8
68-SR-03	2.16	1.78	1.44	27	25	94.4	82.4	63.4	53.0
68-SR-03	2.54	1.99	1.40	30	20	96.8	82.8	62.8	48.6
69-SR-02	2.64	1.98	1.23	25	20	97.8	88.5	65.4	49.4
69-SR-03	2.45	1.82	1.35	23	20	97.0	89.8	64.9	53.3
*69-SR-03	2.28	1.74	1.46	24	10	99.4	88.3	65.3	57.1

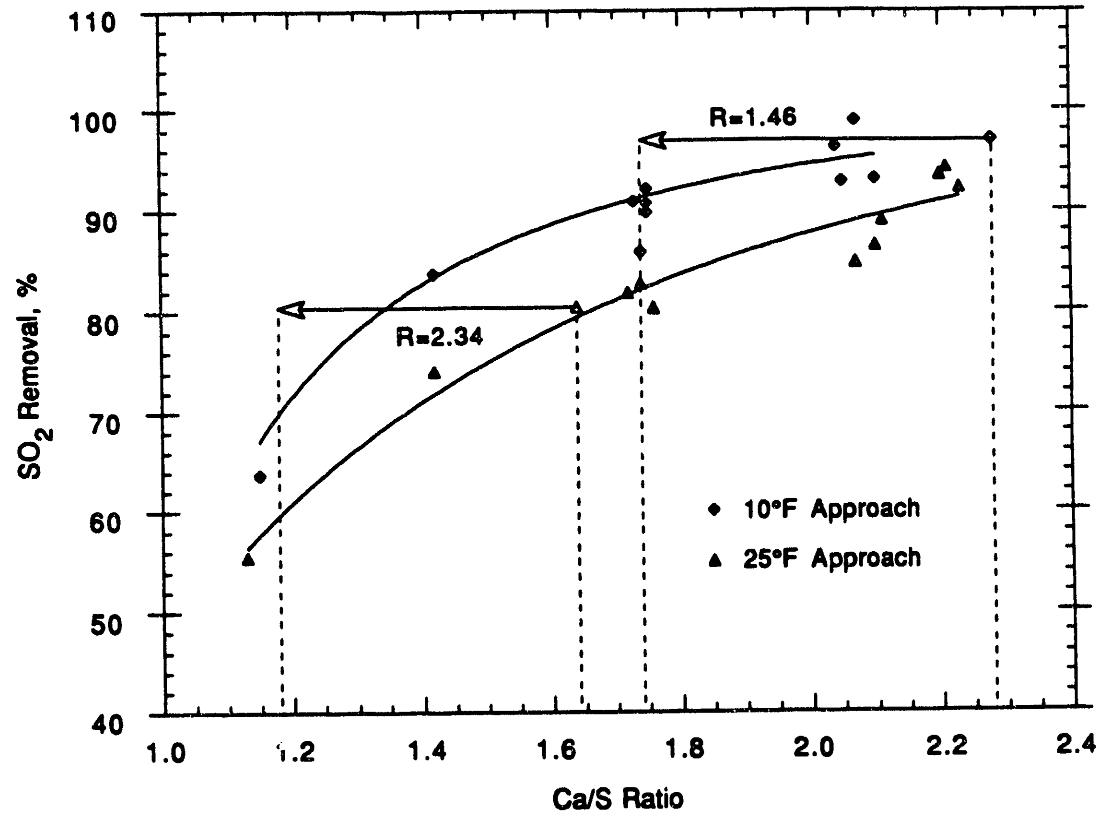

Figure 5-27. SO_2 removal across the SSFF as a function of Ca/S ratio illustrating the effect of recycle.

at a 10 and 25°F approach temperature (as shown in Figure 5-24). Sulfur dioxide removal data obtained with recycle ash addition for two test conditions are plotted versus "reagent" and "overall" Ca/S ratios. These test conditions are identified in Table 5-22 by asterisks. The reagent Ca/S ratio is the part of the sorbent mixture which has not yet been exposed to flue gas. The overall Ca/S ratio is from the combination of reagent sorbent and recycle material and is derived from the effective calcium available for reaction.

The data are shown with dotted lines from the SO_2 removal data point to the abscissa at the values of the reagent and overall Ca/S ratio. The difference between the Ca/S values illustrates the economic benefit in terms of the amount of sorbent required to achieve particular levels of SO_2 removal. However, in a full-scale continuous process, somewhat higher values of recycle ratio would be required to achieve the SO_2 removal levels illustrated by the two recycle cases in Figure 5-27. This results from the fact that the recycled sorbent material used for these tests were taken from the ESP hoppers which has more unutilized calcium than would recycle material from a fabric filter with an upstream secondary cooling step.

5.5 NO_2 Capture Across the Fabric Filter

A brief study was conducted to determine the levels of NO_2 capture across the fabric filter at various operating conditions. It was hypothesized that fabric filter operation at low approach-to-saturation temperatures might enhance the capture of NO_2 by reaction with unutilized $Ca(OH)_2$ in the filter cake. The following disproportionation reaction is the mechanism through which capture of NO_2 is expected to occur:

$$2Ca(OH)_2 + 4NO_2 \rightleftharpoons Ca(NO_3)_2 + Ca(NO_2)_2 + 2H_2O$$

The fraction of NO_X which exists as NO_2 in flue gas is too small for this mechanism to be of practical interest unless an oxidation process were added upstream of sorbent injection. However, if essentially complete capture of NO_2 could be demonstrated in the filter cake, a combined NO oxidation and low temperature capture process for NO_2 might have practical significance.

Because of the very low levels of NO_2 naturally occurring in the flue gas stream, it was necessary to "spike" the sidestream flue gas being sampled by the SSFF with a known concentration of NO_2 gas (from a gas cylinder bottle). Quantification of the NO_2 removal was provided by injecting NO_2 gas alternately upstream and downstream of the fabric filter. Concentrations of NO/NO_X were continuously monitored with a Thermo Electron Model 10 NO_X analyzer located downstream of the fabric. A quantitative removal efficiency could be determined for a range of NO_2 concentrations when compensation is made for the flue gas dilution by the N_2 carrier of the NO_2 gas. A permeation dryer was used to remove water vapor prior to the NO_X analyzer in an effort to minimize losses of NO_2 in the sampling system.

The concentration of NO_2 contained in the gas bottle was determined to be 530 ppm, following laboratory calibration of the NO_X analyzer with a known concentration of NO gas. Subsequently, the calibration of the NO_X analyzer was set with the NO_2 gas in the NO_X mode. The instrument was rechecked periodically during the sampling period.

In view of the principle of operation of the NO_X analyzer (measurement of light energy produced when NO is oxidized to NO_2), this calibration procedure may not detect inaccuracies in absolute NO_2 values caused by failure of the converter in the instrument to reduce all NO_2 to NO. However, the trends observed in the experiments should be valid.

The following conclusions have been derived from this brief series of experiments:

- Reductions in NO_2 concentrations from 91 to 100% were observed across the filter cake when an NO_2 concentration of ~114 ppm was injected upstream of the SSFF.
- Only a small fraction (less than 50%) of the apparent NO_2 reduction could be accounted for by the sum of nitrite and nitrate ions in the collected solids.
- Penetration of NO_2 through the filter cake increased to values as high as 50% when the injected NO_2 concentration was increased to 200-300ppm.

Additional experiments are needed to provide more quantitative results and to better define the mechanism of NO_2 reduction. However, in view of the visibility problems caused by small concentrations of NO_2 in stack gas, any process involving oxidation of NO to NO_2 would need to demonstrate essentially complete capture of NO_2 to be of practical significance.

5.6 Condensables Tests

There are increasing concerns by the utility industry and regulatory agencies about the concentrations of condensable particulate matter (CPM) at the outlet of conventional control devices. EPA test method 202 prescribes the measurement of condensable particulate emissions from stationary sources, for determination of the condensable matter that condenses after passing through an in-stack filter. Fabric filter operation at low approach-to-saturation temperatures with slaked lime slurry injection is expected to enhance the collection of CPMs because the filter cake comprises a medium of active sorbent material. A simulation of a Method 202 test was performed downstream of the SSFF.

An impinger train was set up at the outlet of the fabric filter. The sampling protocol and sample recovery techniques prescribed by the EPA test methods were followed. For each measurement, the SSFF impinger train sampled for 60 minutes at 0.75 acfm yielding 40 cubic feet of gas pulled through the impingers. The samples collected were subsequently analyzed in the laboratory. Table 5-23 presents a summary of test conditions and results for data obtained on January 16 and 17, 1992.

Unfortunately, a significant level of organic material contamination was found in the collected samples which interfered with the intended determination of total mass concentrations. The contamination is believed to be the reason the measured concentrations of total mass are much larger than the sum of the measured chloride and sulfate concentrations. The contamination was suspected to be fuel oil residue from the dilution burner or lubricating oil from the compressed air system.

Even though the organic contamination compromised the results of the CPM total mass measurements, the low chloride and sulfate concentrations confirm the expected effectiveness of the low-temperature filter cake in limiting the penetration of condensable chlorides and sulfates through the SSFF.

Table 5-23. Results of CPM Tests

Run ID	SO_2, ppm SSFF Out	Sulfates		Chlorides		Total Mass mg/m^3
		mg/m^3	ppm H_2SO_4	mg/m^3	ppm HCL	
[1]CPM-2	0	0.265	0.065	0.088	0.06	8.64
[2]CPM-4	150	4.51	1.1	0.44	0.30	13.4

[1] Conditions: Ca/S = 4.0, inlet SO_2 = 1000 ppm, ΔT_s = 25°F duct and SSFF.
[2] Conditions: Ca/S = 2.3, inlet SO_2 = 2800 ppm, ΔT_s = 25°F duct and SSFF.

6.0 ELECTROSTATIC PRECIPITATOR PERFORMANCE

Precipitator performance was monitored throughout each test conducted at the DITF, and during selected test series, more complete evaluations carried out. During these test series, every effort was made to maintain the test condition for 24 hours a day so that ESP electrical operation and emissions would equilibrate at the particular test condition. When 24 hour-a-day operation was not possible, the ESP was allowed to stabilize for several hours at or near the desired test condition before electrical readings or emissions data were taken.

The performance of the ESP was evaluated during three distinct periods of testing. The first test series was conducted during weeks 33 and 34 of testing (March 5-14, 1991). During this period SO_2 removal tests were conducted at nominal Ca/S ratios of 1.0 (25°F approach) and 2.0 (25 and 45°F approach) with slaked lime slurry injection to investigate the effect of reduced specific collecting area (SCA) on ESP performance (by deenergizing the inlet and second field of the ESP). The second test series was conducted during week 48 of testing (June 18-21, 1991). During this period SO_2 removal tests were conducted with coplanar reagent dry sorbent injection, and ESP performance was evaluated at a nominal Ca/S ratio of 2.0 with approach temperatures of 35° and 45°F. The third test series was conducted during weeks 81 and 82 of operation (February 3-14, 1992). During this period SO_2 removal tests were conducted with a slaked lime slurry/recycle ash mixture and ESP performance was evaluated at a nominal reagent Ca/S ratio of 1.0 (overall Ca/S ratio of 1.4) and nominal approach temperature of 40°F. This was the low Ca/S ratio equilibrium recycle test condition discussed above. ESP performance was briefly evaluated during one other test series. During the high Ca/S ratio equilibrium recycle test (weeks 68 and 69 of testing, November 4-15, 1991) ESP performance became severely degraded with average outlet opacity reaching nearly 80% (referenced to a 25 ft stack). Unfortunately, no extensive evaluation of the ESP was planned or performed, but performance was documented. This behavior was of particular interest, because while ESP outlet emissions were quite high, ESP electrical operation was normal.

6.1 ESP Performance at Reduced SCA

During this period of testing the inlet field of the ESP was deenergized (to reach a nominal SCA of 290 ft^2/acfm), and at the end of the test the second field of the ESP was deenergized (to reach a nominal SCA of 200 ft^2/acfm). Table 6-1 summarizes ESP performance during this test, and Table 6-2 shows the average ESP electrical operating conditions measured at the conclusion of each day of testing. Figure 6-1 shows typical voltage-current curves for the ESP measured during these tests. Figure 6-2 presents the results of a laboratory measurement of the resistivity (ascending and descending temperature method) of a composite ash sample from the ESP inlet, middle, and outlet hoppers obtained during test 34-SL-02 (March 12, 1991).

The mass emission data in Table 6-1 were calculated on a lb/10^6 Btu basis using the following procedure: 1) the inlet mass concentration of fly ash to the ESP was increased by an amount equal to the dilution of fly ash concentration resulting from the effect of the dilution air injection system. 2) the efficiency of the ESP was used with the adjusted inlet loading to calculate an outlet mass concentration for each condition shown in Table 6-1, and 3) the resulting outlet mass concentrations were converted to lb/10^6 Btu as if they were measured on a boiler with a flue gas oxygen content of 5.6%. This procedure is necessary because of the excess oxygen introduced by the DITF dilution air injection system. A precipitation rate parameter, ω_k, is shown in Table 6-1 to indicate relative

Table 6-1. Summary of ESP Behavior During Tests Conducted at the DITF During March, 1991.

Test #	Date	Ca/S Ratio, Approach (°F), Inlet SO_2 (ppm)	Inlet (gr/dscf)	Mass Emissions Outlet (gr/dscf)	Mass Emissions Outlet ($lb/10^6$ Btu)[1]	Mass Efficiency (%)	ω_k (cm-sec)	SCA (ft^2/kacfm)	Inlet Flow Rate (dscfm)
33-SL-02	3/5/91	2.25, 45, 1260	5.27	0.0640	0.123	98.79	35	285	33380
33-SL-03	3/6/91	2.01, 27, 1350	4.08	0.0096	0.018	99.76	61	304	31100
33-SL-05	3/8/91	2.14, 19, 1840	8.30[2]	0.0293	0.056	99.65[2]	56	290	33740[3]
34-SL-01	3/11/91	2.00, 26, 2020	8.55[2]	0.0618	0.118	99.28	43	286	33150[3]
34-SL-02	3/12/91	2.10, 25, 2010	11.88	0.0576	0.110	99.52	46	317	30640
34-SL-03	3/13/91	1.82, 43, 1970	10.90	0.0925	0.177	99.15	56	208	29860
34-SL-04	3/14/91	1.02, 25, 1990	5.01[2]	0.1000	0.192	98.00	39	199	32060

1. See Text
2. Estimated from previous data.
3. Measured at outlet.

Table 6-2. Summary of ESP Electrical Behavior During Tests Conducted at the DITF During March, 1991.

Test #	Date	Ca/S Ratio, Approach (°F), Inlet SO_2 (ppm)	INLET FIELD		SECOND FIELD		THIRD FIELD		OUTLET FIELD	
			Voltage (kV)	Current Density (nA/cm^2)	Voltage (kV)	Current Density (nA/cm^2)	Voltage (kV)	Current Density (nA/cm^2)	Voltage (kV)	Current Density (nA/cm^2)
33-SL-02	3/5/91	2.25, 45, 1260	*	*	36.7	56	36.2	78	34.6	81
33-SL-03	3/6/91	2.01, 27, 1350	*	*	45.4	53	43.7	85	40.1	84
33-SL-05	3/8/91	2.14, 19, 1840	*	*	46.5	49	45.6	82	44.5	87
34-SL-01	3/11/91	2.00, 26, 2020	*	*	47.2	45	43.9	85	41.3	85
34-SL-02	3/12/91	2.10, 25, 2010	*	*	47.3	44	46.4	82	44.8	89
34-SL-03	3/13/91	1.82, 43, 1970	*	*	*	*	48.2	60	46.3	82
34-SL-04	3/14/91	1.02, 25, 1990	*	*	*	*	51.7	72	45.2	87

* Transformer-Rectifier set off

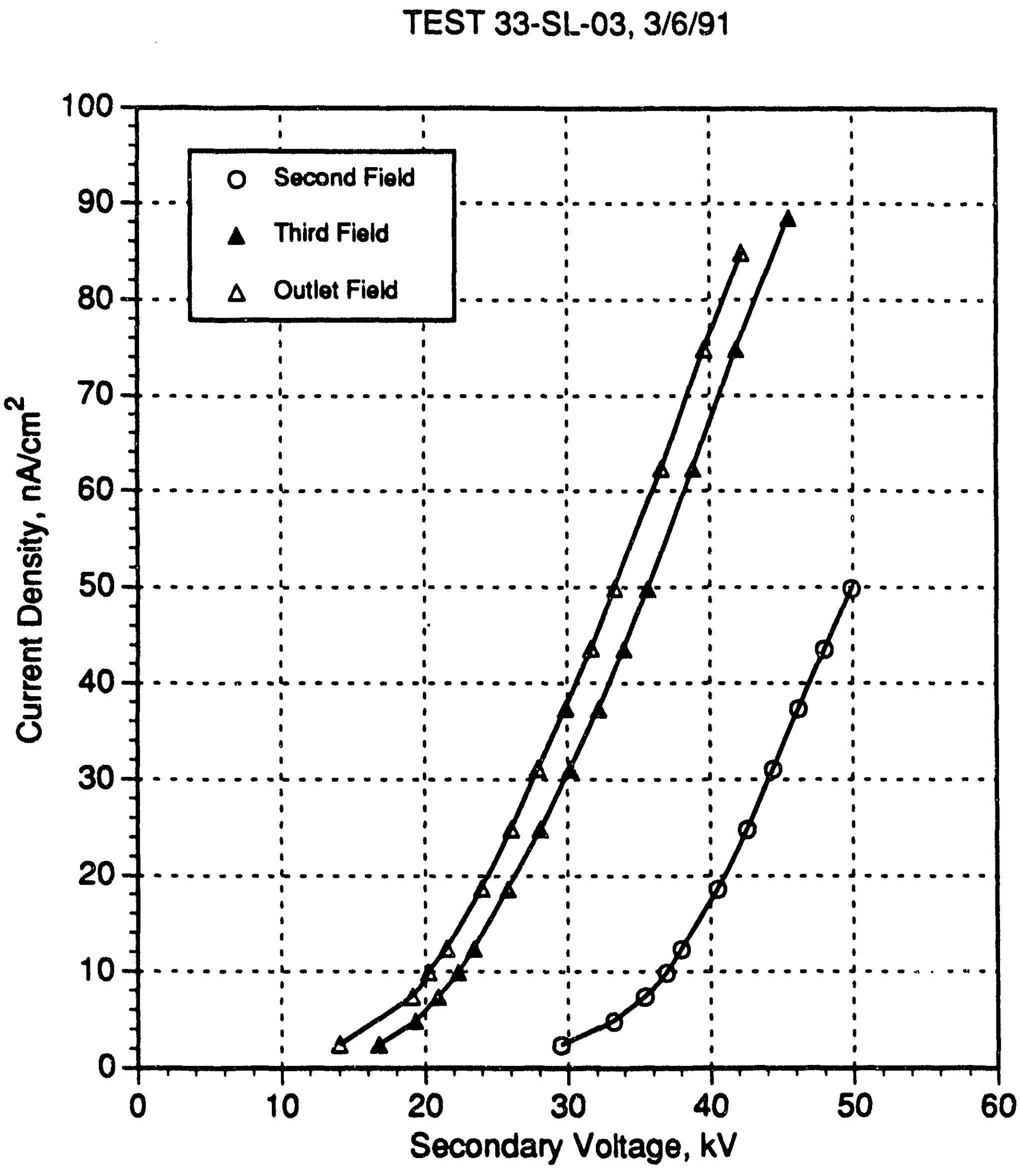

Figure 6-1. Current density as a function of applied ESP voltage for Test 33-SL-03, March 6, 1991. The first field of the ESP was deenergized.

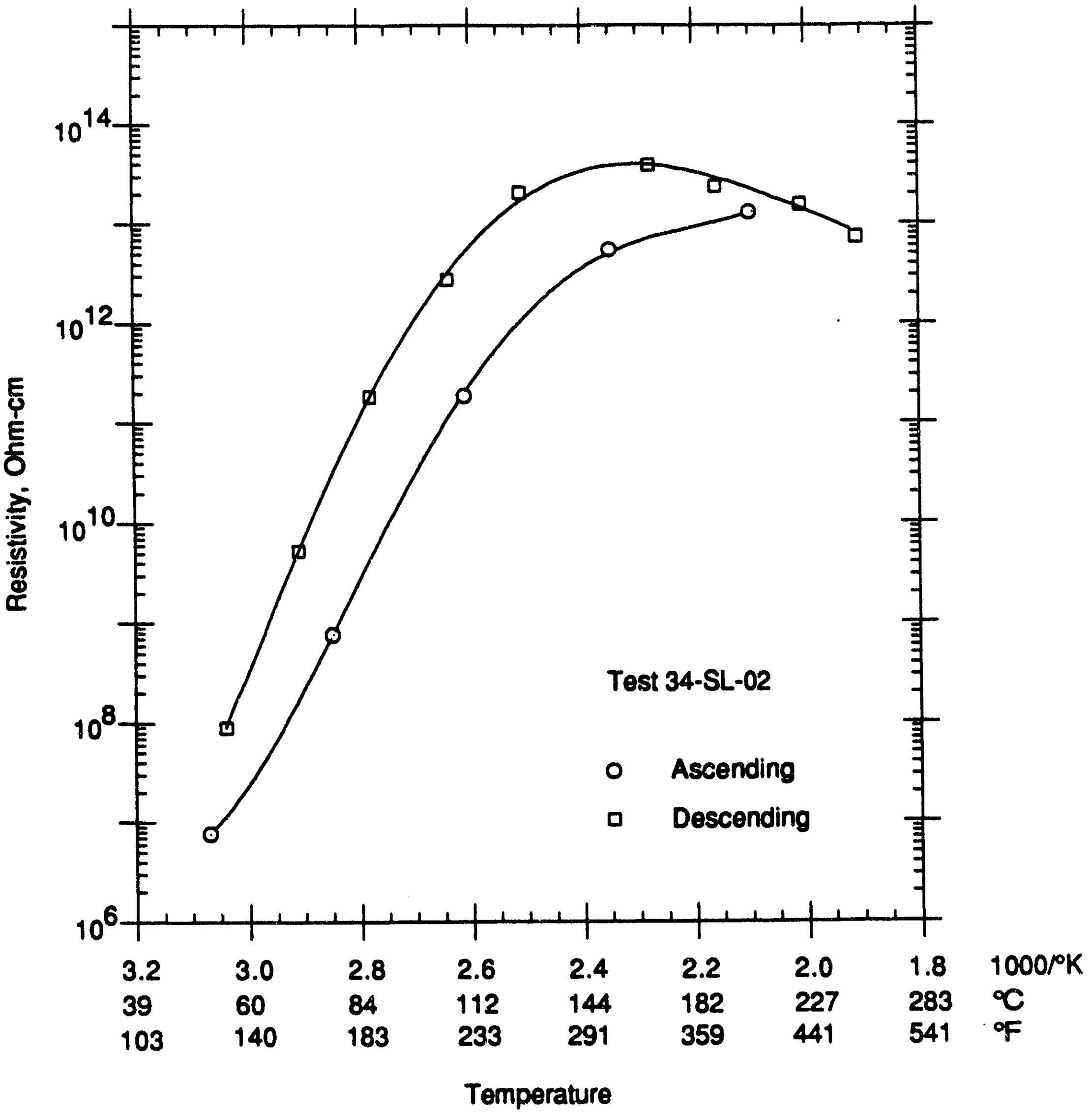

Figure 6-2. Resistivity measured in the laboratory as a function of temperature for a composited sample of ESP hopper ash from Test 34-SL-02. Data taken at 10.6% H_2O using both ascending and descending temperature.

performance. As a point of reference, ω_k values of from 27 to 62 cm/s have been reported for full-scale ESPs collecting ash downstream of spray dryers.[8]

In only two cases did the overall mass collection efficiency fall below 99%. In both cases (Tests 33-SL-02 and 33-SL-04), testing was terminated because of solids deposits that had accumulated in the horizontal test duct. Because outlet mass emissions measurements require a period of two hours and because operators at the DITF regularly used a small "poke hole" in the horizontal test duct to break up the solids deposits as they formed (to prolong the test so that the outlet emissions measurements could be completed) it is possible that ESP performance was compromised during these two tests. However, as Tables 6-1 and 6-2 show, at lower approach temperatures and at lower values of SCA the ESP appeared to perform well enough to maintain collection efficiency above 99% with the exception of the two previously cited cases. Certainly, the behavior that was observed during the E-SO_x tests at the Burger Station[8] was not duplicated. It should be pointed out, however, that the efficiencies reported in Table 6-1 may not be sufficient to avoid violations of mass emission or opacity regulations for some locations.

The laboratory resistivity curve shown in Figure 6-2 is provided to illustrate the rapid manner in which resistivity increases as the temperature of the ash/sorbent mixture increases (in the range of approach temperatures used for these tests) and to provide an example to compare with other laboratory resistivity curves in this report.

6.2 ESP Performance During Coplanar Reagent Dry Sorbent Injection

During week 48 of testing at the DITF, SO_2 removal tests were conducted with coplanar injection of dry reagent sorbent. The DITF was operated for 24 hours a day at a nominal Ca/S ratio of 2.0 and approach temperatures of 45°F (June 18 and 19) and 35°F (June 20 and 21). During this time testing was interrupted only once, during the night of June 19, to repair a hole in the horizontal test section duct caused by ash entrained in an air jet from a misaligned soot blower tube located near one of the duct hoppers. Mass concentration measurements were performed at the ESP inlet on June 18-20 and at the ESP outlet on June 19 and 20. In situ particle size distribution measurements (with modified Brink cascade impactors) were conducted at the ESP inlet on June 18-20, and at the ESP outlet on June 19 and 20.

Table 6-3 summarizes ESP performance during this test and Table 6-4 shows the average ESP electrical operating conditions measured at the conclusion of testing on June 19 and 20. The mass emission data in Table 6-3 were calculated on a lb/10^6 Btu basis using the method described above to correct for the effect of the air dilution system at the DITF. Figure 6-3 shows averaged in situ particle size distribution data measured at the ESP inlet on June 18 and 19. These data were used as part of the input data for ESP model simulations. Figures 6-4 through 6-7 show typical voltage-current curves for the ESP measured at the end of each day of testing and Figure 6-8 presents the results of a laboratory measurement of the resistivity (ascending and descending temperature method) of a composite ash sample from the ESP inlet, middle, and outlet hoppers obtained during test 48-DS-02 (June 19). In situ resistivity measurements were also performed at the ESP inlet for both approach temperatures. Table 6-5 presents the results of these measurements. Finally, Table 6-6 presents the results of ESP model calculations with input data representative of this test using the standard SRI/EPA model,[9] a version of this model that has been modified to take into account the effect of space charge,[10] and the ADA ESP Model.[11]

Table 6-3. Summary of ESP Behavior During Tests Conducted at the DITF During June, 1991.

Test #	Date	Ca/S Ratio, Approach (°F), Inlet SO_2 (ppm)	Mass Emissions			Mass Efficiency (%)	ω_k (cm-sec)	SCA (ft^2/kacfm)	Inlet Flow Rate (dscfm)
			Inlet (gr/dscf)	Outlet (gr/dscf)	Outlet (lb/10^6 Btu)[1]				
48-DS-02	6/1991	2.06, 45, 1980	11.78	0.0454	0.087	99.61	45	345	36163
48-DS-03	6/20/91	2.02, 37, 2000	11.69	0.0066	0.013	99.94	83	336	36750

1. See Text

Table 6-4. Summary of ESP Electrical Behavior During Tests Conducted at the DITF During June, 1991.

Test #	Date	Ca/S Ratio, Approach (°F), Inlet SO_2 (ppm)	INLET FIELD Voltage (kV)	INLET FIELD Current Density (nA/cm^2)	SECOND FIELD Voltage (kV)	SECOND FIELD Current Density (nA/cm^2)	THIRD FIELD Voltage (kV)	THIRD FIELD Current Density (nA/cm^2)	OUTLET FIELD Voltage (kV)	OUTLET FIELD Current Density (nA/cm^2)
48-DS-01	6/18/91	2.03, 44, 2010	57.8	2[1]	57.5	17[1]	49.9	74	49.1	82
48-DS-02	6/1991	2.06, 45, 1980	60.0	<1[1]	52.4	33[1]	45.1	39	42.3	53
48-DS-03	6/20/91	2.02, 37, 2000	69.8	9	58.1	27	54.7	50	53.5	62
48-DS-04	6/21/91	2.04, 35, 2010	70.8	7	61.6	17	51.7	42	45.2	55

[1] Spark limited operation.

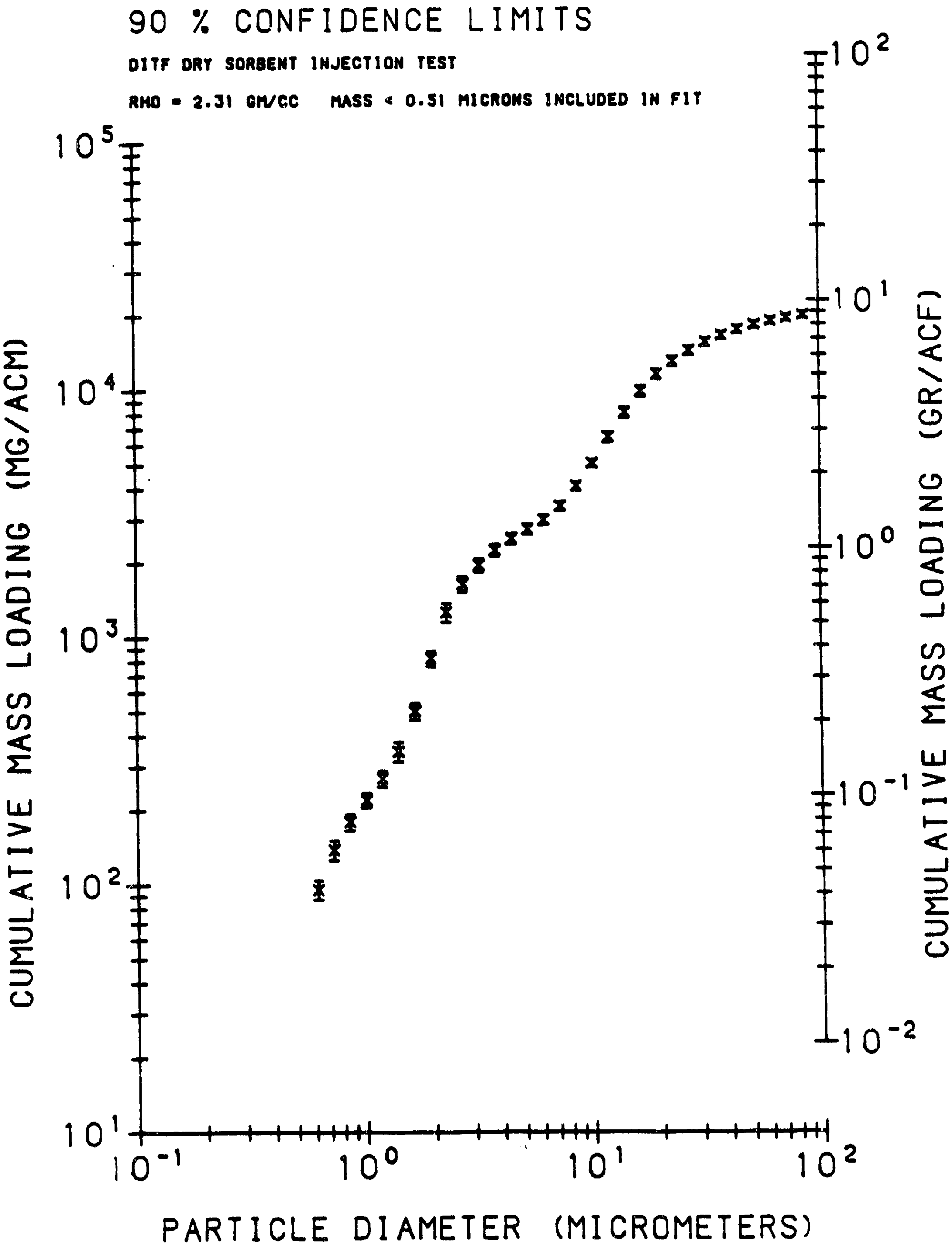

Figure 6-3. Particle size distribution measured at the ESP inlet. Average of measurements made on June 18-19, 1991. Cumulative mass basis.

TEST 48-DS-01, 6/18/91

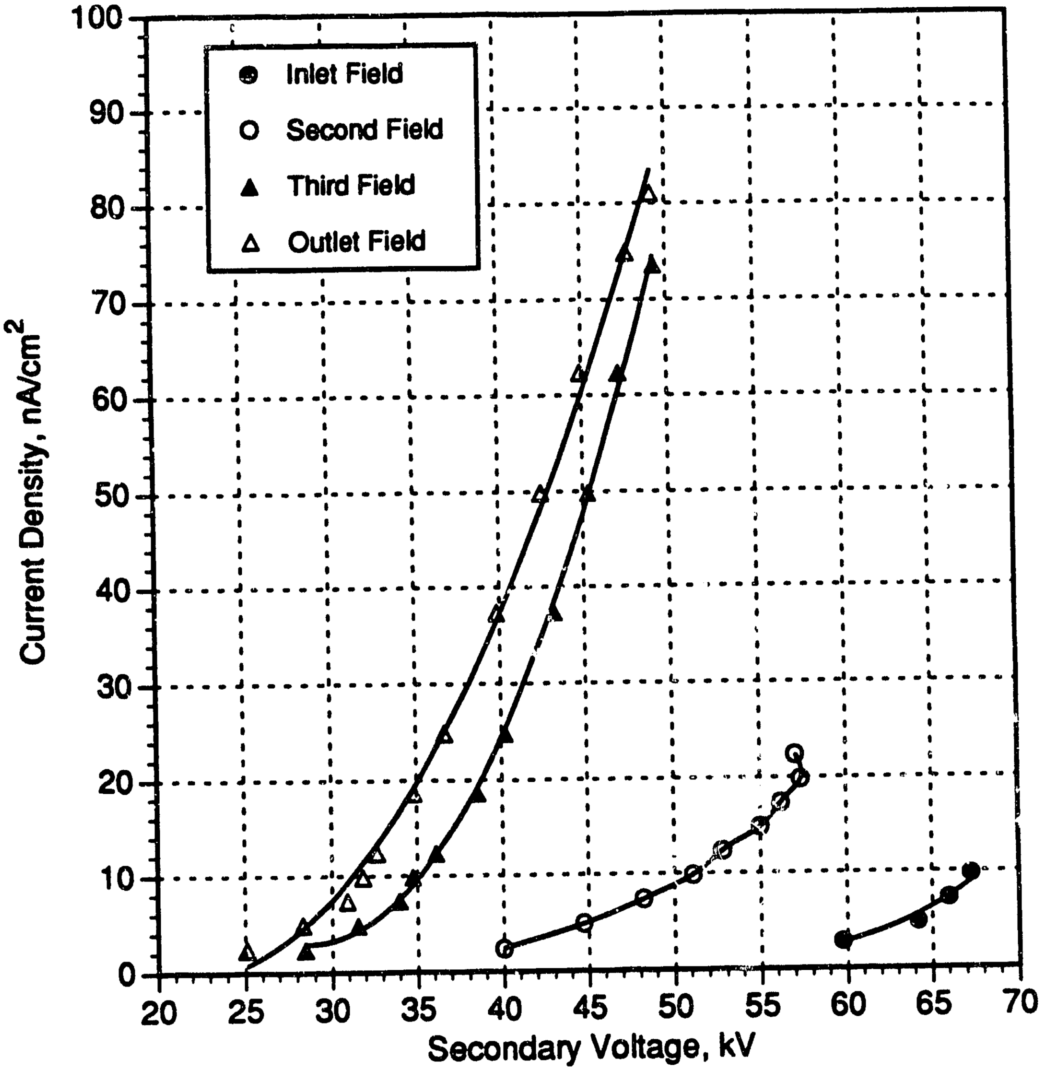

Figure 6-4. Current density as a function of applied ESP voltage at a 45°F approach to saturation. Test 48-DS-01, June 18, 1991.

TEST 48-DS-02, 6/19/91

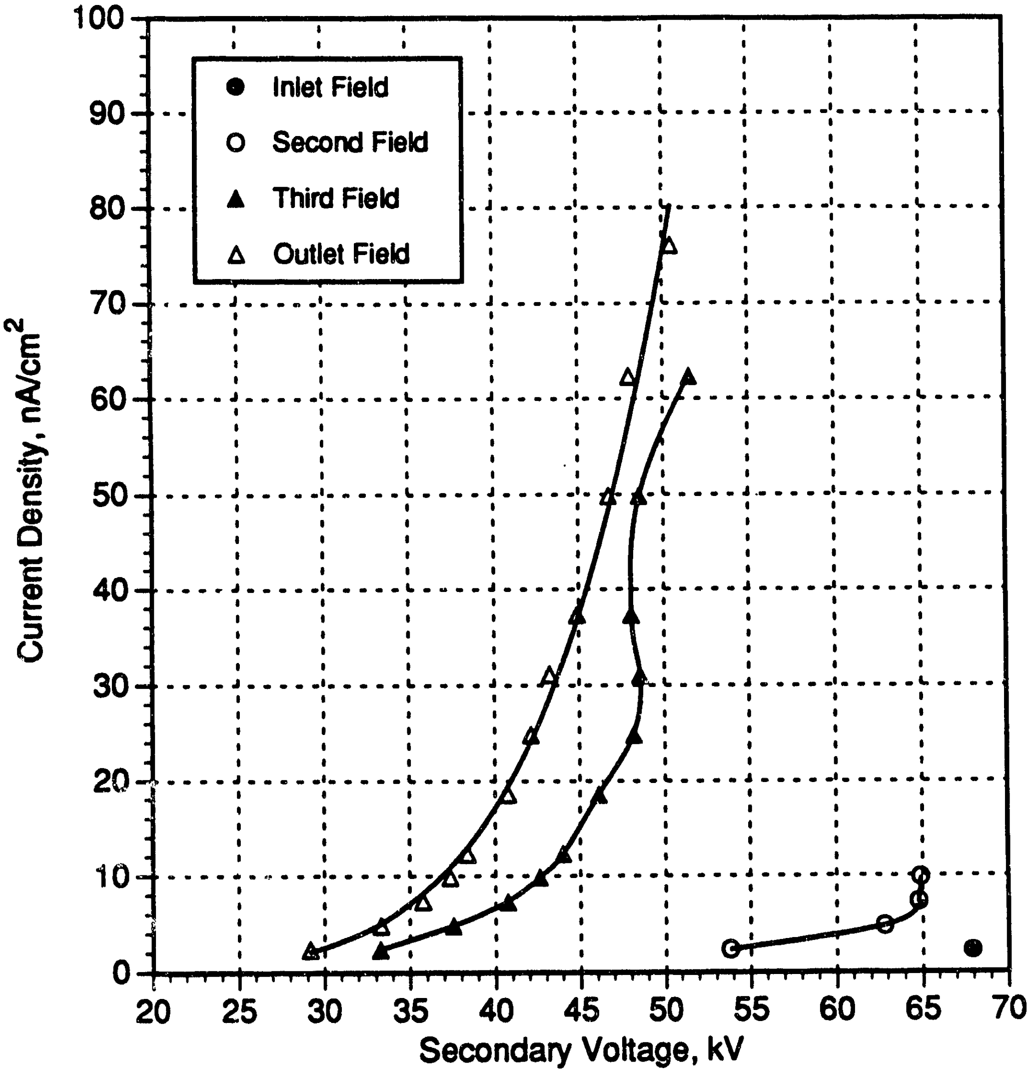

Figure 6-5. Current density as a function of applied ESP voltage at a 45°F approach to saturation. Test 48-DS-02, June 19, 1991.

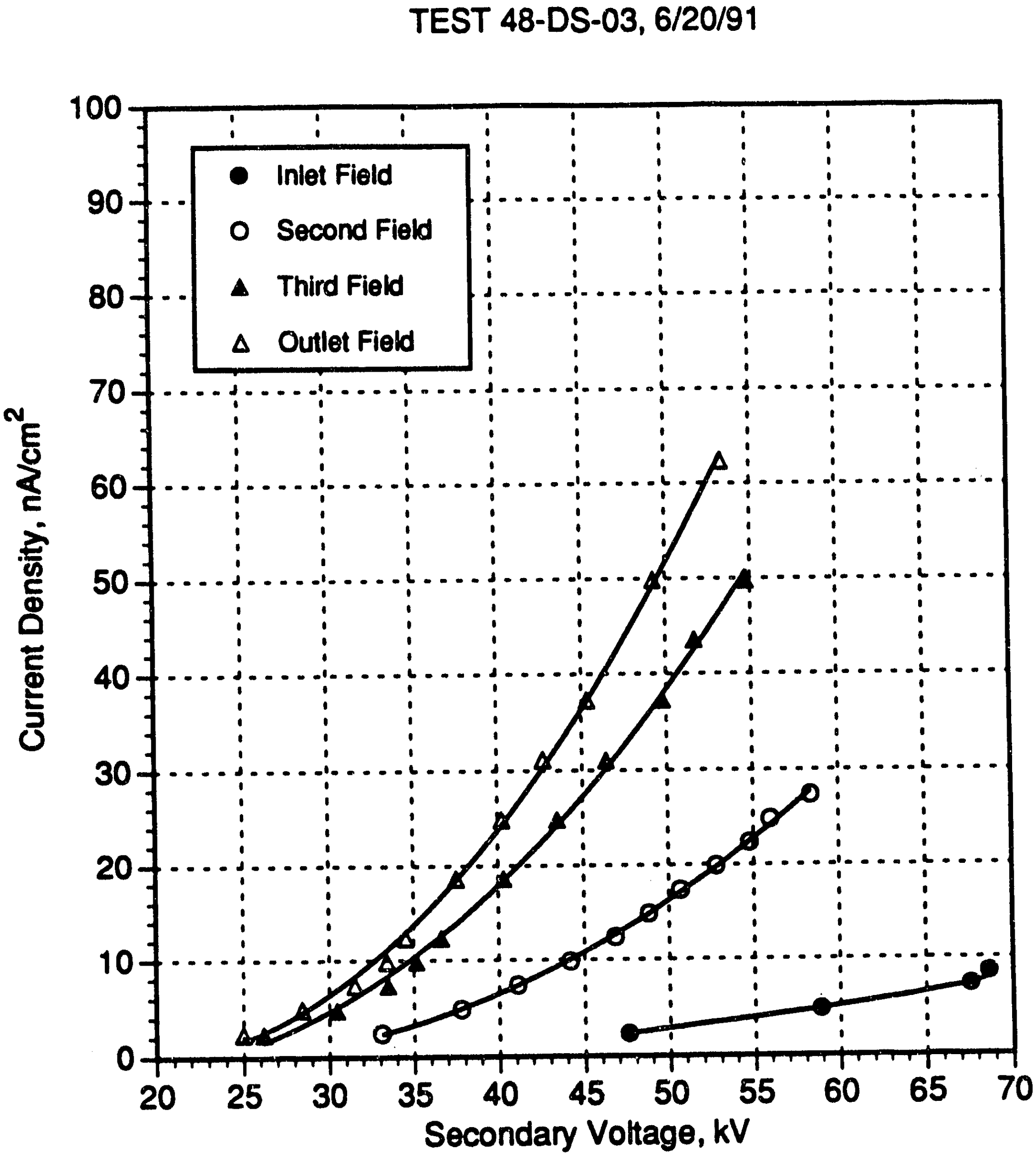

Figure 6-6. Current density as a function of applied ESP voltage at a 35°F approach to saturation. Test 48-DS-03, June 20, 1991.

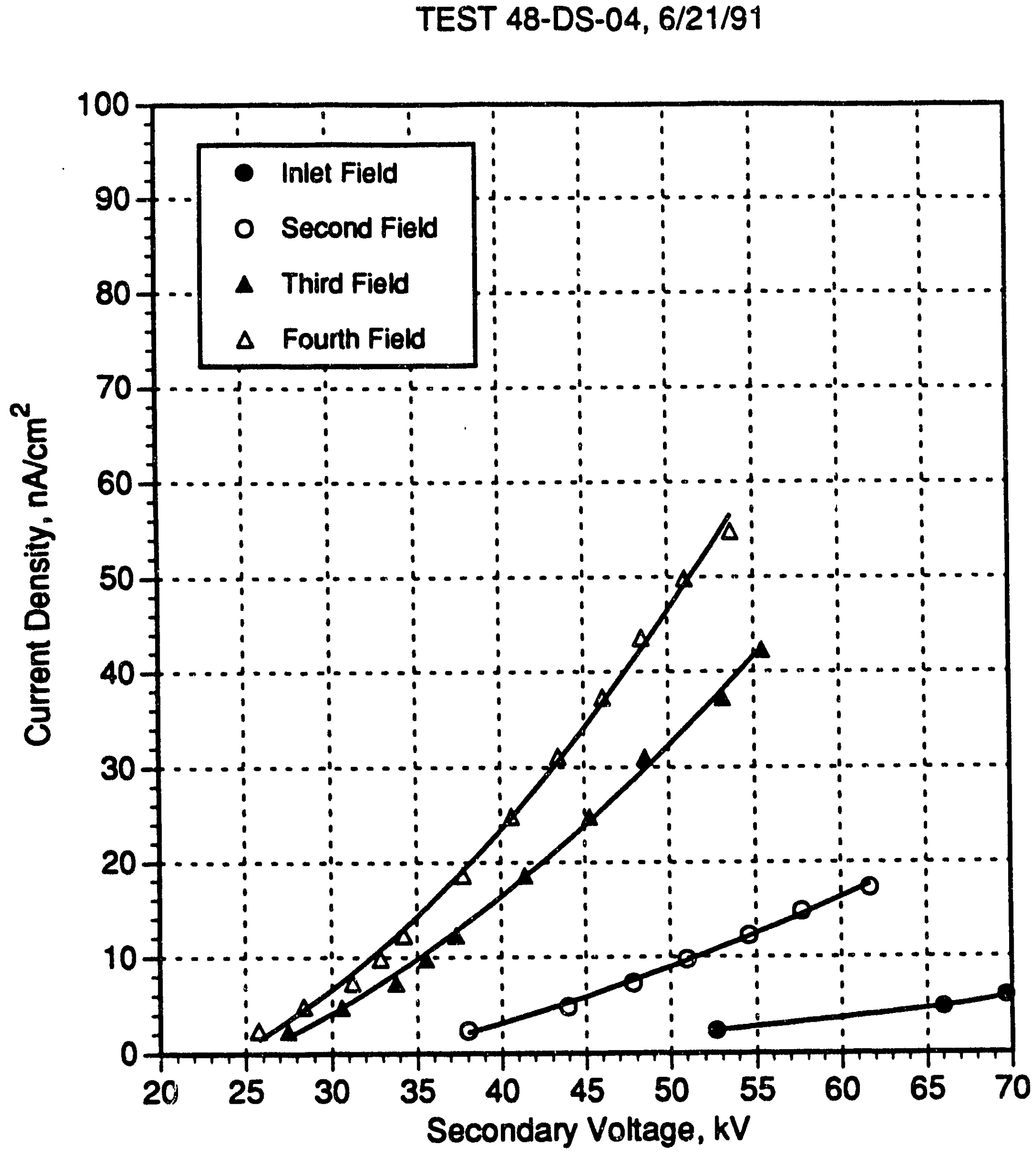

Figure 6-7. Current density as a function of applied ESP voltage at a 35°F approach to saturation. Test 48-DS-04, June 21, 1991.

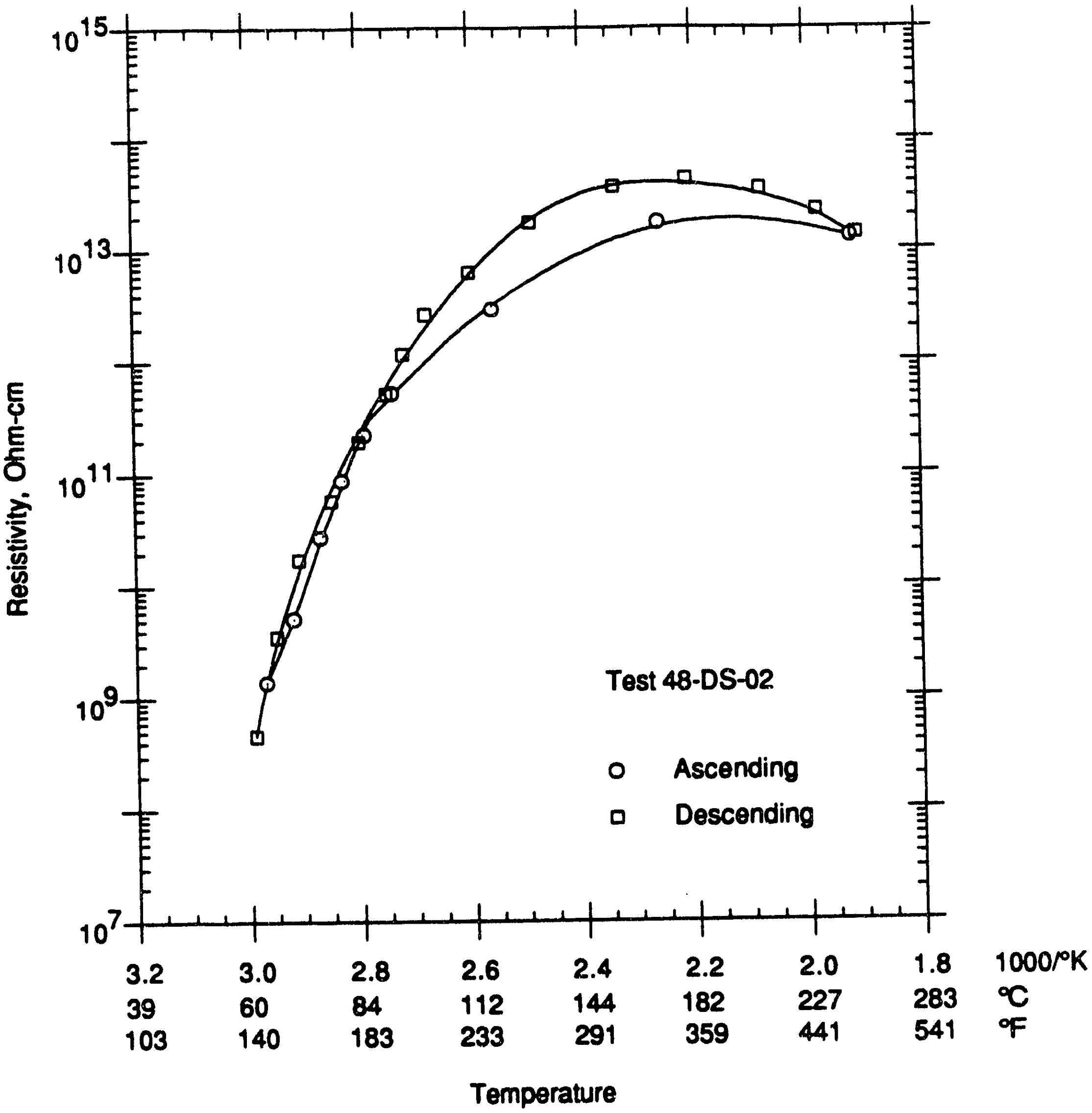

Figure 6-8. Resistivity measured in the laboratory as a function of temperature for a composited sample of ESP hopper ash from Test 48-DS-02. Data taken at 12.3% H_2O using both ascending and descending temperature.

Table 6-5. In situ Resistivity Measured at the ESP Inlet During Coplanar Dry Sorbent Injection Tests at a 35 and 45°F Approach, June 18-21, 1991.

	------------- In Situ Resistivity, Ohm-Cm	-------------
	45°F Approach	35°F Approach
Without Compressing Ash Layer	2.37×10^{11}	8.68×10^{10}
	2.13×10^{11}	1.47×10^{11}
	2.03×10^{11}	1.47×10^{11}
	9.63×10^{10}	1.93×10^{11}
	3.23×10^{11}	8.98×10^{11}
	1.86×10^{11}	1.01×10^{11}
	3.39×10^{11}	1.35×10^{11}
	2.31×10^{11}	
	3.15×10^{11}	
Average	2.38×10^{11}	1.35×10^{11}
With Ash Layer Compressed	2.94×10^{10}	1.41×10^{10}
	3.04×10^{10}	1.29×10^{10}
	4.15×10^{10}	9.86×10^{9}
Average	3.38×10^{10}	1.23×10^{10}

Table 6-6. ESP Model Results for Tests Conducted in June, 1991

Date	Test Condition	Approach °F	Measured Efficiency, %	Standard SRI Model[1]		SRI Space Charge Model[1]		ADA Model	
				Sneakage, σ_g	Efficiency, %	Sneakage, σ_g	Efficiency, %	Reentrainment, Sneakage, σ_g	Efficiency, %
6-19-91	Dry Sorbent	45	99.61	0.20, 0.25	99.67	0.15, 0.25	99.71	0.70, 0.10, 0.25 0.50, 0.15, 0.25	99.52 99.58
6-20-91	Dry Sorbent	35	99.94	0.10, 0.25	99.96	0.10, 0.25	99.90	0.00, 0.10, 0.25	99.90

[1] The SRI sneakage coefficient is defined in the model manuals as a combined factor for gas sneakage and non-rapping reentrainment. σ_g is the normalized standard deviation of the gas velocity distribution.

As Table 6-4 (Test Nos. 48-DS-01 and 48-DS-02) and the voltage-current curves for the ESP taken on June 18 and 19 show, ESP electrical performance at a 45°F approach deteriorated from one day to the next. After about eight hours of operation at a 45°F approach the baseline opacity level became uneven, and by the morning of June 19 the opacity due to rapping puffs had increased by approximately a factor of four. By this time rapping puffs from other sections of the ESP were easily detected. However, the overall opacity was still low. Unfortunately, only after this test was completed was it determined that the opacity monitor required optical realignment, and the values that were recorded during these tests were suitable only for making relative comparisons. The fact that ESP operation deteriorated significantly over a period of two days suggests that some cumulative process was occurring. It is possible that sorbent built up on the inlet field corona wires during the test. If this was so, it apparently dropped off when the DITF was brought down to repair the hole on the horizontal test duct on the night of June 19, because when testing was resumed at a 35°F approach, ESP performance had improved.

On June 20 when the approach temperature was 35°F, ESP electrical performance and emissions were markedly improved, and relative opacity decreased by a factor of two. It is possible that this improvement was due to the lowering of the approach temperature (and subsequent lowering of the resistivity of the ash/sorbent aerosol), but as Table 6-4 shows, ESP electrical performance in fields 3 and 4 deteriorated slightly from June 20 to 21.

While the ascending temperature laboratory resistivity measurements shown in Figure 6-8 suggest that lowering the ESP inlet temperature would reduce the ash resistivity by a factor of slightly greater than three (from 8.8×10^{10} to 2.7×10^{10} ohm-cm), this is probably not enough to effect the change in ESP performance that was observed. What is interesting is that the in situ resistivity measurements made at the two approach temperatures also show a decrease in ash resistivity when the approach temperature was reduced by 10°F and that the resistivity measured with the ash layer compressed was close to that measured in the laboratory.

With respect to ESP model calculations, the in situ particle size distribution measured on June 18-19 was used along with ESP operating voltage-current characteristics as input to the standard SRI/EPA ESP model, a version of that model modified to account for the effect of space charge, and the ADA ESP model. The results of these calculations are shown in Table 6-6. For all three models, more non-ideal corrections (reentrainment/sneakage) were required to force a match of measured and computed performance for a 45°F approach than at a 35°F approach. This indicates a performance degradation process was occurring which is not adequately simulated by existing model algorithms.

6.3 ESP Performance During Long-Term Low Ca/S Equilibrium Recycle Tests

During weeks 81 and 82 of testing the DITF a long-term test was planned. The test condition was chosen to emulate a "real-world" application of duct-injection technology. It was decided to operate the DITF 24 hours a day, use reagent slaked lime slurry with continuous recycling of spent sorbent, and to operate at the low Ca/S ratio condition that had been tested once before during weeks 66 through 68 of testing. For these tests the DITF was operated at a reagent Ca/S ratio of 1.0 (overall Ca/S ratio of 1.4), a nominal approach temperature of 40°F, and an inlet SO_2 level of 2000 ppm. Under these conditions, SO_2 removal at the ESP outlet averaged from 50 to 60%.

Unfortunately, because of a series of boiler tube leaks at the Unit 5 host boiler, this test was limited to a total of seven days of mainly non-consecutive testing. Thus, the goal of a long-term ESP test was not realized. However, during the last two days of testing (February 12 and 13, 1992) it was possible to operate for two extended periods (one period of 14 hours followed by a period of 28 hours). During this whole test, and particularly during the last two periods of testing, the ESP exhibited no unusual electrical behavior, but ESP emissions were observed to depend on the ESP outlet temperature. Whenever slurry injection was started, the opacity at the ESP outlet dropped at roughly the same rate as did the temperature at the exit of the ESP. At the conclusion of testing the approach temperature was reduced by 5° F (to 35° F) and testing was continued long enough to make mass emissions measurements at the ESP inlet and outlet.

During the two extended periods of testing, and during other somewhat shorter periods of testing on February 10 and 11, mass concentration measurements were made at the ESP inlet and ESP outlet, in situ particle size distribution measurements were conducted at the ESP inlet (with modified Brink cascade impactors), in situ particle size distribution measurements were conducted at the ESP outlet (with University of Washington Mark V cascade impactors), and in situ measurements of the electrical resistivity of the ash/sorbent aerosol were performed.

Because of the time required at the ESP outlet to complete a single run with a mass train or cascade impactor, both types of measurements could not be performed on the same day. Thus, mass train runs were performed at the ESP inlet and outlet on February 11 and 13 while cascade impactor measurements were performed at the ESP inlet and outlet on February 10 and 12. ESP voltage-current characteristics were measured on February 11 and 12.

Table 6-7 summarizes ESP performance during this test and Table 6-8 shows the hourly averages of ESP electrical operating conditions and opacity at the ESP outlet taken from the DAS for the two extended periods of operation on February 12 and 13. The opacity averages shown in Table 6-8 are plotted in Figure 6-9. The mass emission data in Table 6-7 were calculated on a lb/10^6 Btu basis using the method used in Table 6-1 to correct for the effect of the air dilution system at the DITF. Figures 6-10 and 6-11 show fractional efficiency-penetration curves for the ESP on February 10 and 12 calculated from the particle size data obtained at the ESP inlet and outlet for each day. Figures 6-12 and 6-13 show typical voltage-current curves for the ESP measured on February 11 and 12 and Figure 6-14 presents the results of a laboratory measurement of the resistivity (ascending and descending temperature method) of a composite ash sample from the ESP inlet, middle, and outlet hoppers obtained during test 68-SR-02 (November 5, 1991).

During this test the DITF was operated at the same conditions as for the long-term ESP test. Thus, the sorbent/ash aerosol produced during the November 5 test should have the same electrical characteristics as that generated during the long-term ESP test. In situ resistivity measurements were also performed at the ESP inlet during each day of testing. Table 6-9 presents the results of these measurements for February 11 and 13. Note that higher values of resistivity are obtained when the probe shield opening is turned about 45° F away from the direction of gas flow. This procedure tends to exclude larger particles, which may have higher residual moisture content and thus lower resistivity values. Finally, Table 6-10 presents the results of ESP model calculations with input data representative of this test using the standard SRI/EPA model, a version of this model that has been modified to take into account the effect of space charge, and the ADA Model.

As Tables 6-7 and 6-8 and Figure 6-9 show, ESP emissions tended to decrease with time. Shortly after testing commenced on February 11, while the ESP outlet temperature was still equilibrating, ESP collection efficiency was measured to be 99.23%. Four hours later the collection efficiency had

Table 6-7. Summary of ESP Behavior During Tests Conducted at the DITF During Test 82-SR-01, February, 1992.

Date	Time	Ca/S Ratio, Approach (°F), Inlet SO_2 (ppm)	Inlet (gr/dscf)	Mass Emissions		Mass Efficiency (%)	ω_k (cm-sec)	SCA (ft^2/kacfm)	Inlet Flow Rate (dscfm)
				Outlet (gr/dscf)	Outlet (lb/10^6 Btu)[1]				
2/10/92[2]	Averaged	1.4, 40, 2000	11.58	0.0726	0.139	99.37	-	-	-
2/11/92[3]	1136-1241	1.32, 41, 2050	13.68	0.1050	0.201	99.23	30.7	392	30974
	1340-1444	1.33, 43, 2050	18.64	0.0618	0.119	99.67	42.5	390	31008
	1528-1633	1.40, 40, 2070	13.72	0.0316	0.061	99.77	47.1	398	30970
2/12/92[2]	Averaged	1.4, 40, 2000	13.27	0.0745	0.143	99.44	-	-	-
2/13/92[3]	0901-1008	1.30, 40, 2070	14.51	0.0268	0.051	99.82	52.0	390	30723
	1124-1236	1.34, 42, 2070	13.23	0.0313	0.060	99.76	47.6	388	30846
	1410-1518	1.41, 36, 2030	12.61	0.0102	0.012	99.92	66.1	391	30693
	1650-1718	1.35, 34, 2060	12.65	0.0079	0.015	99.94	71.1	393	30537

1. See Text.
2. Daily average of impactor data.
3. Mass Train Data.

Table 6-8. ESP Operating Parameters, Long-Term ESP Test, 2/11/92 - 2/13/92*

DATE	TIME	INLET FIELD		SECOND FIELD		THIRD FIELD		OUTLET FIELD		OPACITY
		Voltage kV	Current Density nA/cm²	Voltage kV	Current Density nA/cm²	Voltage kV	Current Density nA/cm²	Voltage kV	Current Density nA/cm²	%
2-11	0934	40.5	34	38.2	56	40.3	81	40.3	86	78.1
	1000	45.9	37	42.1	60	43.6	83	42.5	87	71.5
	1100	46.6	37	45.1	60	46.5	77	45.3	81	7.6
	1200	46.9	37	45.2	55	47.6	71	46.7	75	1.9
	1300	45.5	36	44.7	56	47.0	72	46.7	75	2.7
	1400	46.4	37	45.3	55	47.7	70	47.6	72	0.1
	1500	47.1	37	48.9	53	48.5	67	48.3	69	5.0
	1600	49.0	37	46.5	50	49.3	64	48.9	67	0.1
	1712	48.9	37	46.8	51	49.5	63	49.1	65	0.1
	1800	49.1	37	47.1	53	49.2	65	48.8	66	3.2
	1900	50.3	38	47.7	52	49.5	63	48.9	66	0.1
	2000	49.5	38	47.5	52	49.2	64	48.6	67	1.2
	2100	48.2	37	46.6	53	47.9	69	47.6	71	0.4
	2200	49.2	37	46.7	52	48.2	69	47.7	72	1.3
	2300	49.3	37	46.7	52	48.4	68	47.8	69	0.1
2-12	1300	42.7	34	39.0	57	40.3	82	39.7	85	98.7
	1400	48.0	36	44.6	59	45.3	80	44.2	83	64.2
	1500	47.7	36	45.4	57	46.3	78	45.5	78	14.4
	1600	47.2	36	44.9	60	45.3	80	44.9	80	10.1
	1700	49.0	35	46.7	55	46.7	74	46.2	76	2.2
	1800	50.4	37	48.3	51	48.3	67	47.5	69	1.3
	1900	48.5	36	46.9	55	46.9	71	45.9	70	5.8
	2000	47.8	35	45.2	58	45.6	75	45.3	74	9.4
	2100	48.4	37	46.0	57	45.9	74	46.0	75	3.3
	2200	49.2	37	46.2	57	46.0	73	45.9	75	2.3
	2300	48.5	36	45.4	60	45.2	76	45.3	78	4.0
2-13	0000	49.7	37	46.2	56	46.1	74	45.9	76	2.6
	0100	49.3	37	46.3	56	46.2	73	46.3	75	1.2
	0200	48.4	35	44.8	59	44.8	77	45.1	79	5.3
	0300	49.5	37	46.5	54	46.7	72	46.4	75	0.7
	0400	50.1	38	47.2	53	47.4	69	47.0	72	0.6
	0500	50.4	38	47.2	53	47.3	70	47.0	72	0.6
	0600	50.1	38	47.2	56	47.6	69	47.2	71	2.5
	0700	50.8	38	47.6	53	48.0	68	47.6	70	0.1
	0800	52.1	38	48.5	50	48.7	64	48.4	66	0.1
	0900	52.0	38	48.5	50	48.2	65	48.2	66	0.1
	1000	51.9	38	48.1	52	47.5	68	47.4	69	2.8
	1100	52.0	38	47.9	53	46.9	70	47.0	72	0.1
	1200	52.2	39	47.7	51	47.0	70	46.9	72	1.1
	1300	52.6	38	47.7	46	47.6	69	47.5	71	1.1
	1400	53.7	40	48.3	42	49.4	63	48.7	66	1.2
	1500	54.2	40	48.5	42	50.0	61	49.2	64	0.2
	1600	54.5	40	48.3	42	50.4	59	49.6	64	0.1
	1700	54.9	41	48.4	42	50.2	60	49.5	63	0.1

* Hourly averages from DITF Data Acquisition System

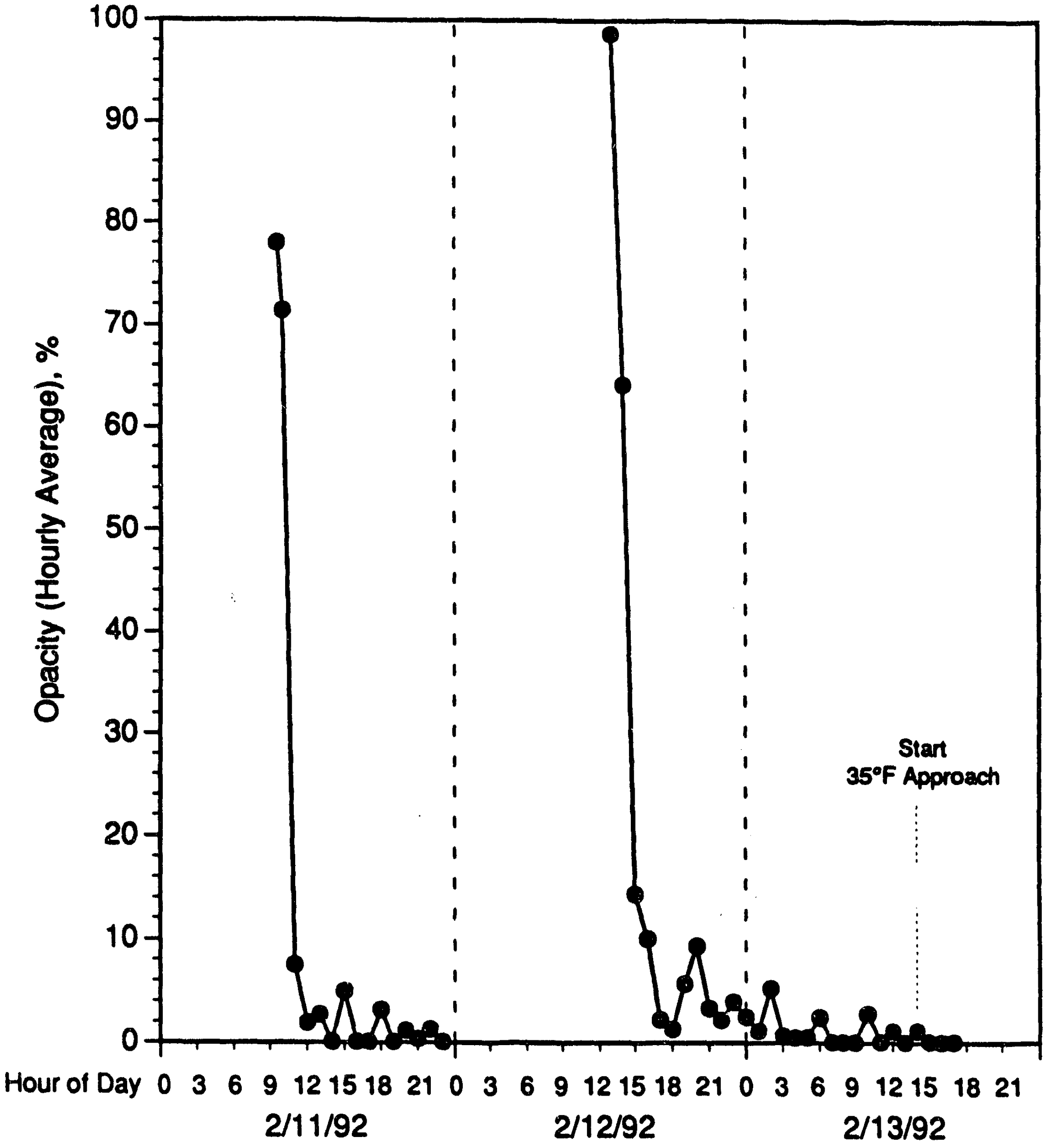

Figure 6-9. Averaged hourly opacity for March 11-13, 1992 during week 82 of testing.

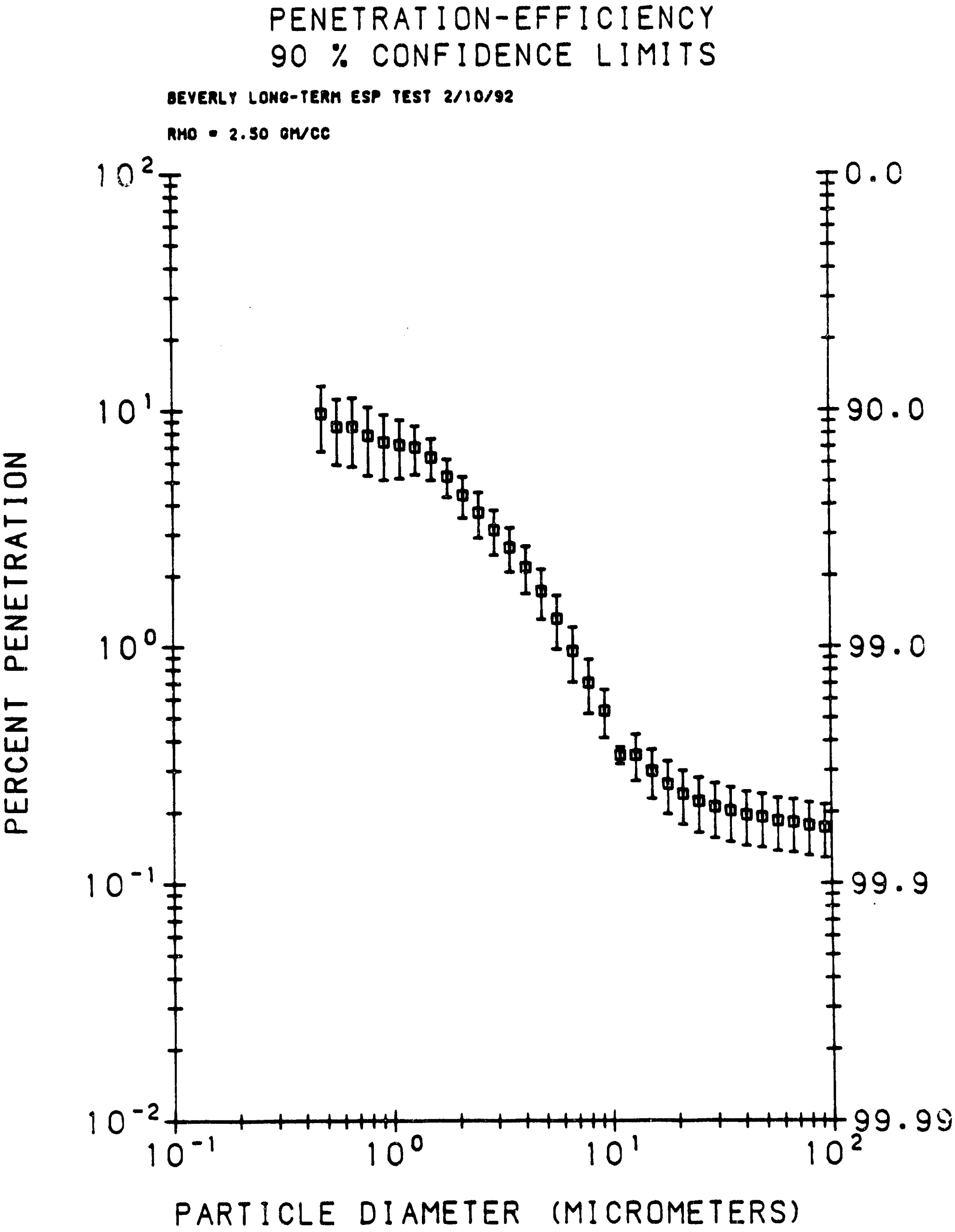

Figure 6-10. Calculated ESP penetration-efficiency from inlet and outlet in-situ impactor measurements made on February 10, 1992 during slurry/recycle ash testing.

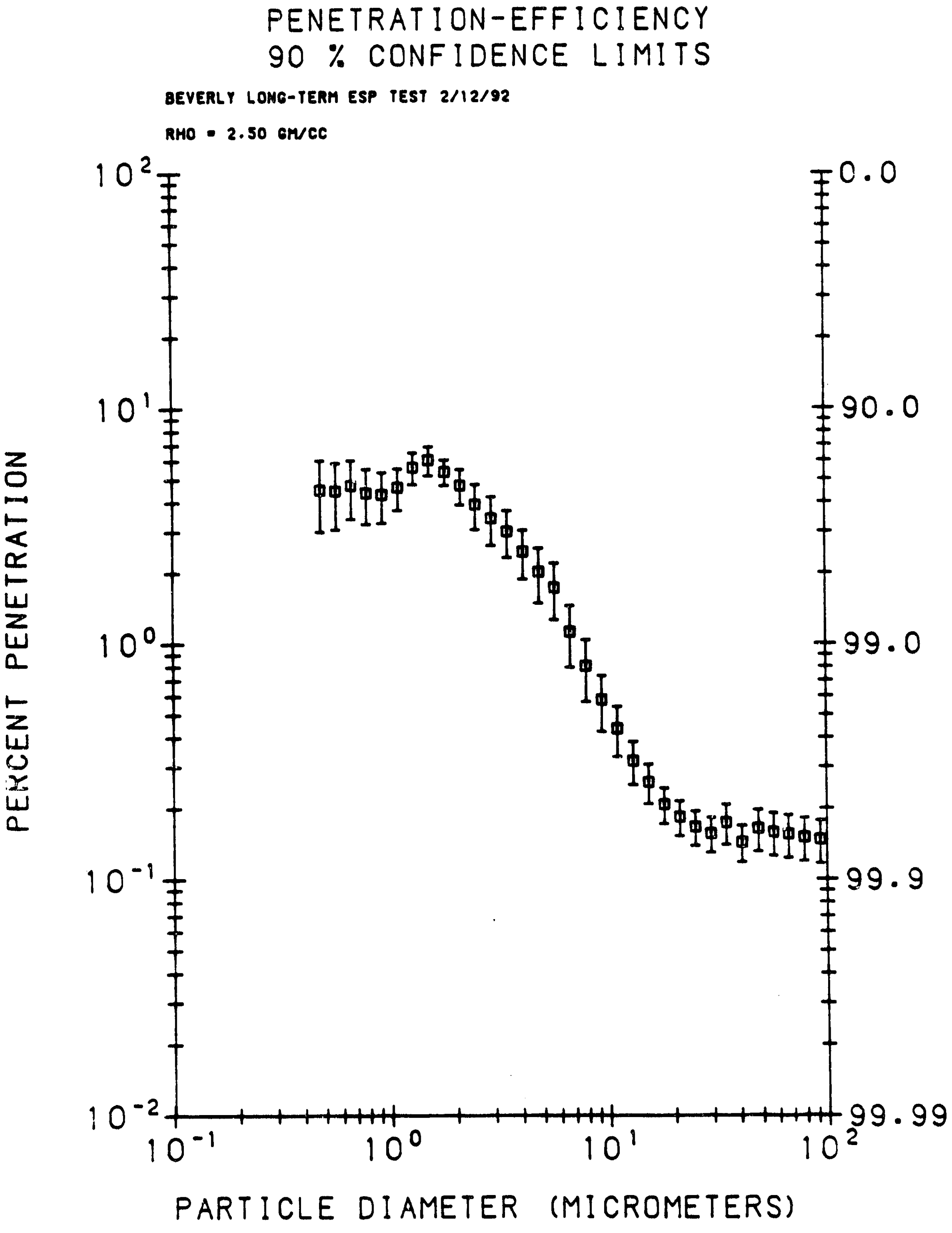

Figure 6-11. Calculated ESP penetration-efficiency from inlet and outlet in-situ impactor measurements made on February 12, 1992 during slurry/recycle ash testing.

TEST 82-SR-01, 2/11/92

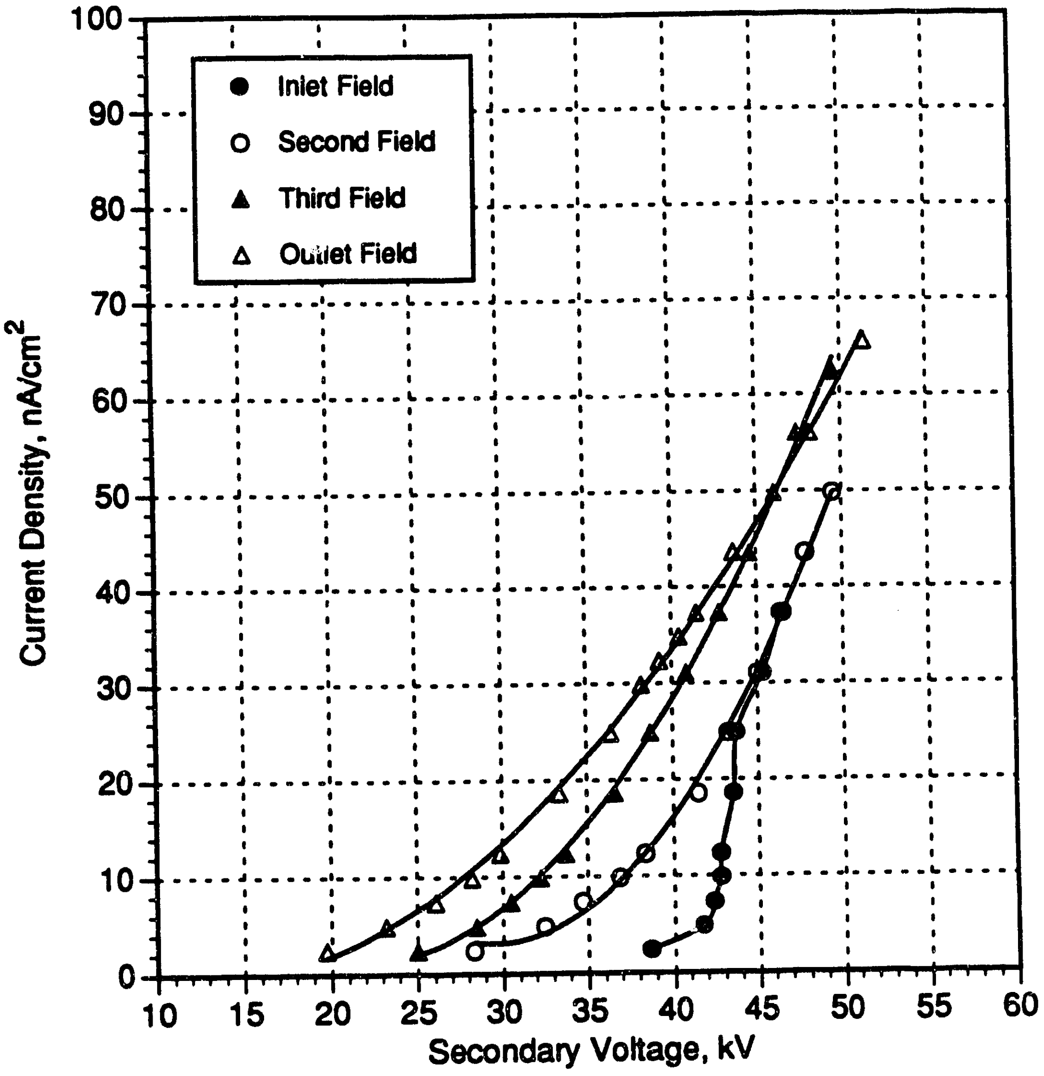

Figure 6-12. Current density as a function of applied ESP voltage at a 40°F approach to saturation during slurry/recycle ash testing. Test 82-SR-01, February 11, 1992.

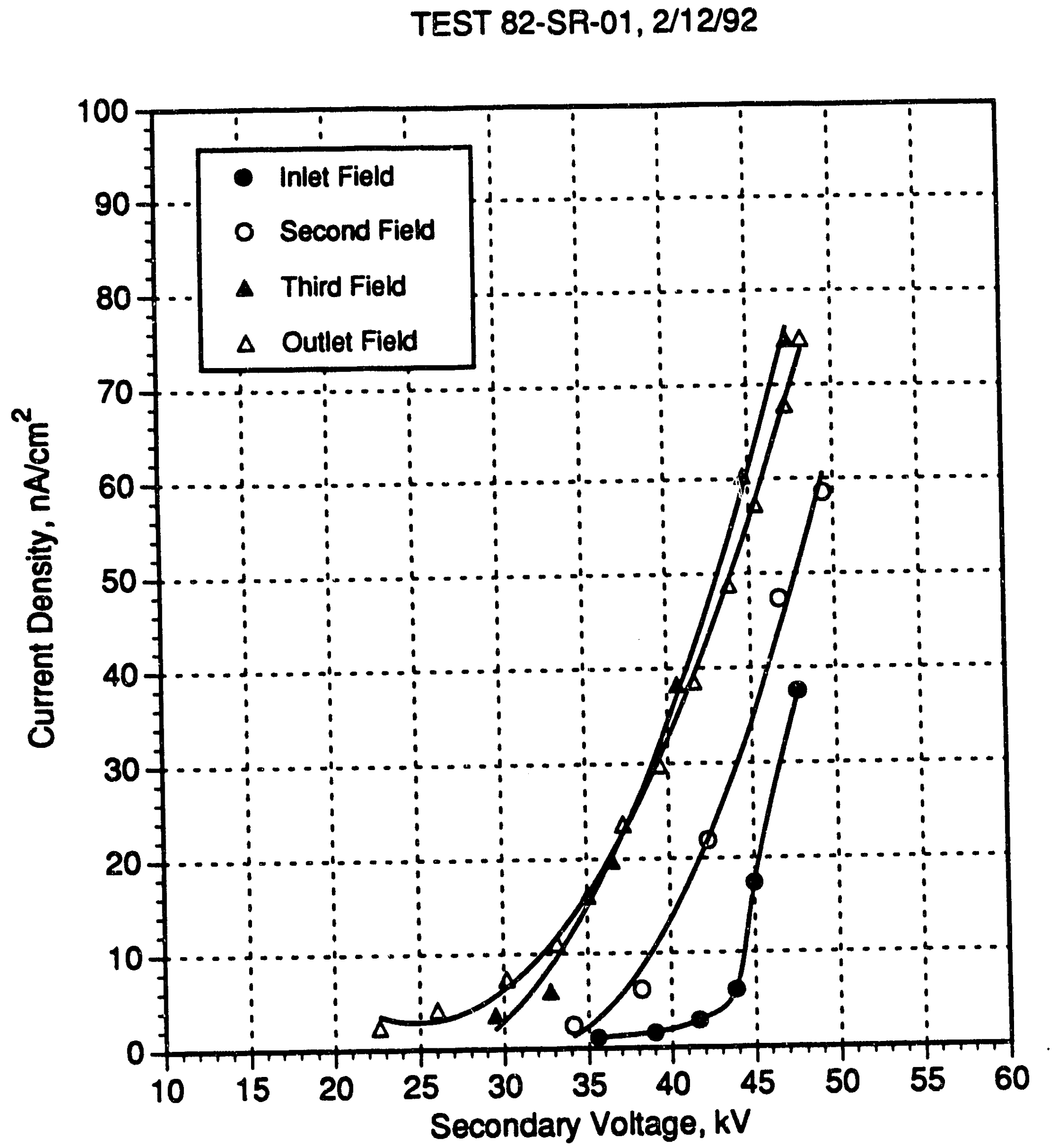

Figure 6-13. Current density as a function of applied ESP voltage at a 40°F approach to saturation during slurry/recycle ash testing. Test 82-SR-01, February 12, 1992.

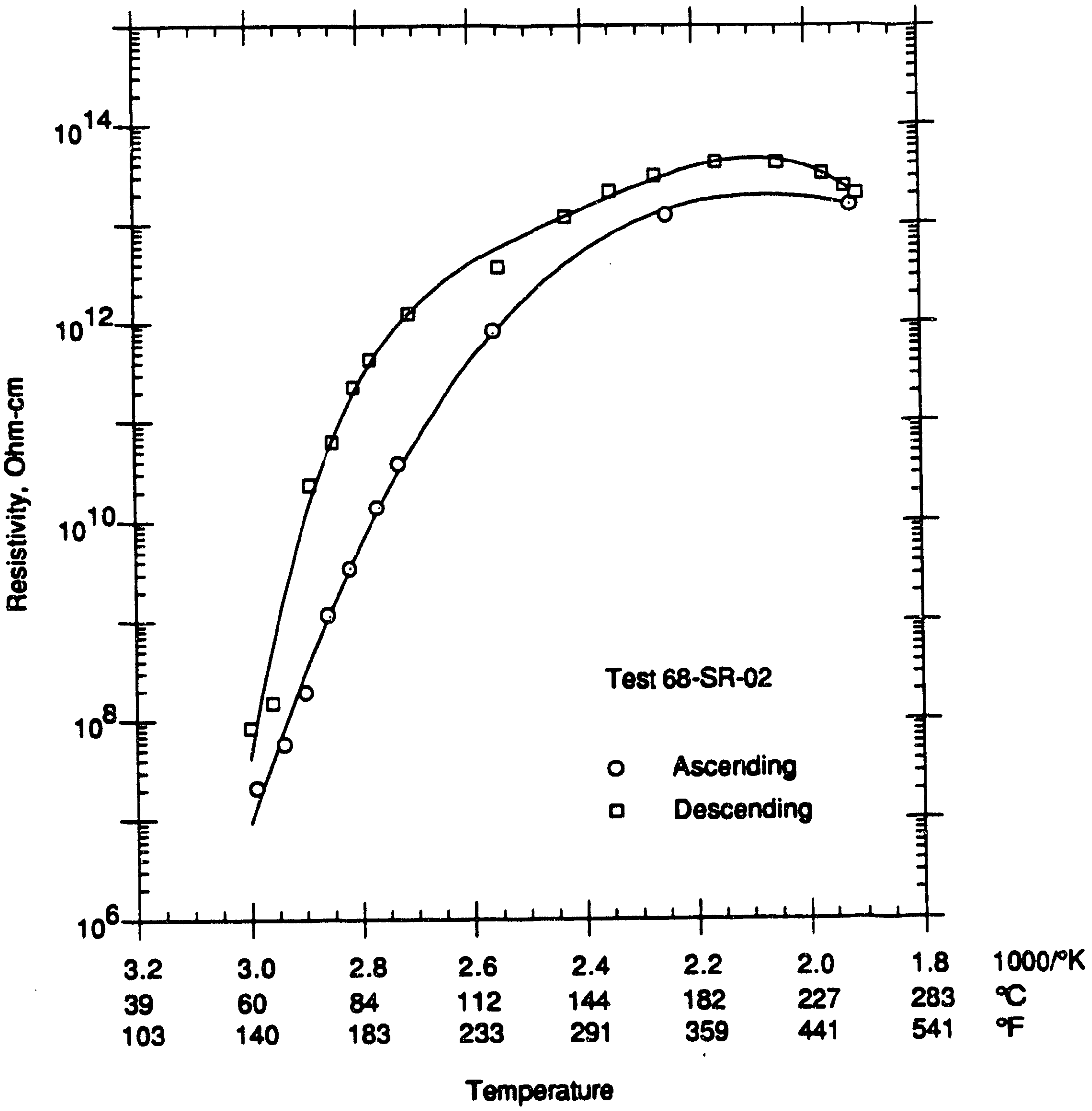

Figure 6-14. Resistivity measured in the laboratory as a function of temperature for a composited sample of ESP hopper ash from Test 68-SR-02 on November 5, 1991. Data taken at 12.3% H_2O using both ascending and descending temperature.

Table 6-9. In situ Resistivity Measured at the ESP Inlet During Slurry/Recycle Tests at a 40 and 35°F Approach, June 18-21, 1991.

Date/Time	Approach (°F)	----- In Situ Resistivity, Ohm-Cm ------	
		45° to Flow	Parallel to Flow
2/11/92			
1200-1220	39		5.50×10^{10}
1255-1355	42	1.11×10^{11}	
1420-1440	42		4.06×10^{10}
1530-1610	40	3.07×10^{11}	
Average	41	2.09×10^{11}	4.78×10^{11}
2/13/92			
0910-0945	42	6.57×10^{11}	
1025-1055	42		5.78×10^{10}
1140-1220	44	3.37×10^{11}	
1300-1330	42		5.53×10^{10}
NA	42		4.35×10^{10}
Average	42	4.97×10^{11}	5.22×10^{10}
1420-1500	37		2.79×10^{10}
NA	36		1.39×10^{10}
1545-1615	36		8.82×10^{9}
Average	36		1.69×10^{10}

Table 6-10. ESP Model Results for Tests conducted in February, 1992.

Date	Approach °F	Measured Efficiency, %	Standard SRI Model[1]		SRI Space Charge Model[1]		ADA Model	
			Sneakage, σ_g	Efficiency, %	Sneakage, σ_g	Efficiency, %	Reentrainment, Sneakage, σ_g	Efficiency, %
2-13-92	35	99.92	0.20, 0.25	99.94	0.10, 0.25	99.91	0.00, 0.10, 0.25	99.91
2-13-92	40	99.78	0.30, 0.25	99.79	0.15, 0.25	99.75	0.60, 0.10, 0.25 0.20, 0.15, 0.25	99.84 99.74

1. The SRI sneakage coefficient is defined in the model manuals as a combined factor for gas sneakage and non-rapping reentrainment.

increased to 99.77%. Likewise, on February 13, after the ESP had been on line for approximately 18 hours, the ESP collection efficiency averaged 99.79%. Table 6-8 and Figures 6-12 and 6-13 show that the ESP electrical voltage-current characteristics were near optimum.

Shortly after the approach temperature was lowered by 5°F on February 13, the average ESP collection efficiency increased to 99.94%. The lowering of the approach temperature appeared to have a beneficial effect on ESP emissions. When the approach temperature was lowered, the opacity due to rapping puffs from the last field of the ESP dropped from approximately 20% to 1% or less. This effect may have been transient, but because the test could not be extended, it was not possible to determine if this was the case or not. As Figure 6-14 shows, the ash resistivity was already low and additional lowering gained from a 5°F reduction in the approach temperature would not be expected to have a beneficial effect on collection efficiency. These values are much lower than the in-situ data. Such disagreement between laboratory and in-situ data have been observed previously.[8]

The penetration-efficiency curves shown in Figures 6-10 and 6-11 show the expected decrease in collection efficiency with decreasing particle size below 10 μm in diameter. The decrease in slope of the collection efficiency versus particle diameter curve suggests a reentrainment process for larger particle sizes.

With respect to ESP model calculations, the in situ particle size distribution measured on February 12, along with ESP operating voltage-current characteristics from February 13 was used as input to the standard SRI/EPA ESP model, a version of that model modified to account for the effect of space charge, and the ADA ESP model. The results of these calculations are shown in Table 6-10 and in Figure 6-15. Figure 6-15 shows penetration through the ESP as a function of particle size as predicted by each model. For comparison, the measured penetration curve is also plotted in this graph. Regardless of the model, it is apparent from the input data sets shown in Table 6-10 that lesser values of reentrainment sneakage are required at a 35°F approach than at a 40°F approach. Also, as Figure 6-14 shows, no model predicts the increase in particulate emissions at particle sizes of less than 5 μm to the extent indicated by the measurements.

The failure of all three models to adequately predict fine particle collection efficiency with excellent electrical operating conditions is a further indication that the collection process for sorbent particles is not well simulated by these models. A similar pattern of disagreement in fractional penetration data was observed during a test of the E-SO_x process,[8] although at much lower values of overall collection efficiency.

The apparent increase in ESP performance with decreasing temperature appears anomalous, especially in view of the low resistivity observed at these temperatures. A possible cause of this trend is that residual layers of high resistivity calcium compounds on the collection electrodes were still equilibrating with the environment as the temperature was lowered. Such a process would tend to mask the expected increase in reentrainment at low approach temperatures. However, severe reentrainment was induced during one test series with low approach temperatures and high mass loadings, and these data are discussed in the following paragraphs.

6.4 ESP Performance During High Ca/S Equilibrium Recycle Tests

During weeks 68 and 69 of testing a series of high Ca/S ratio continuous recycle tests were performed. As with the low Ca/S case described above, this test was intended to determine what SO_2

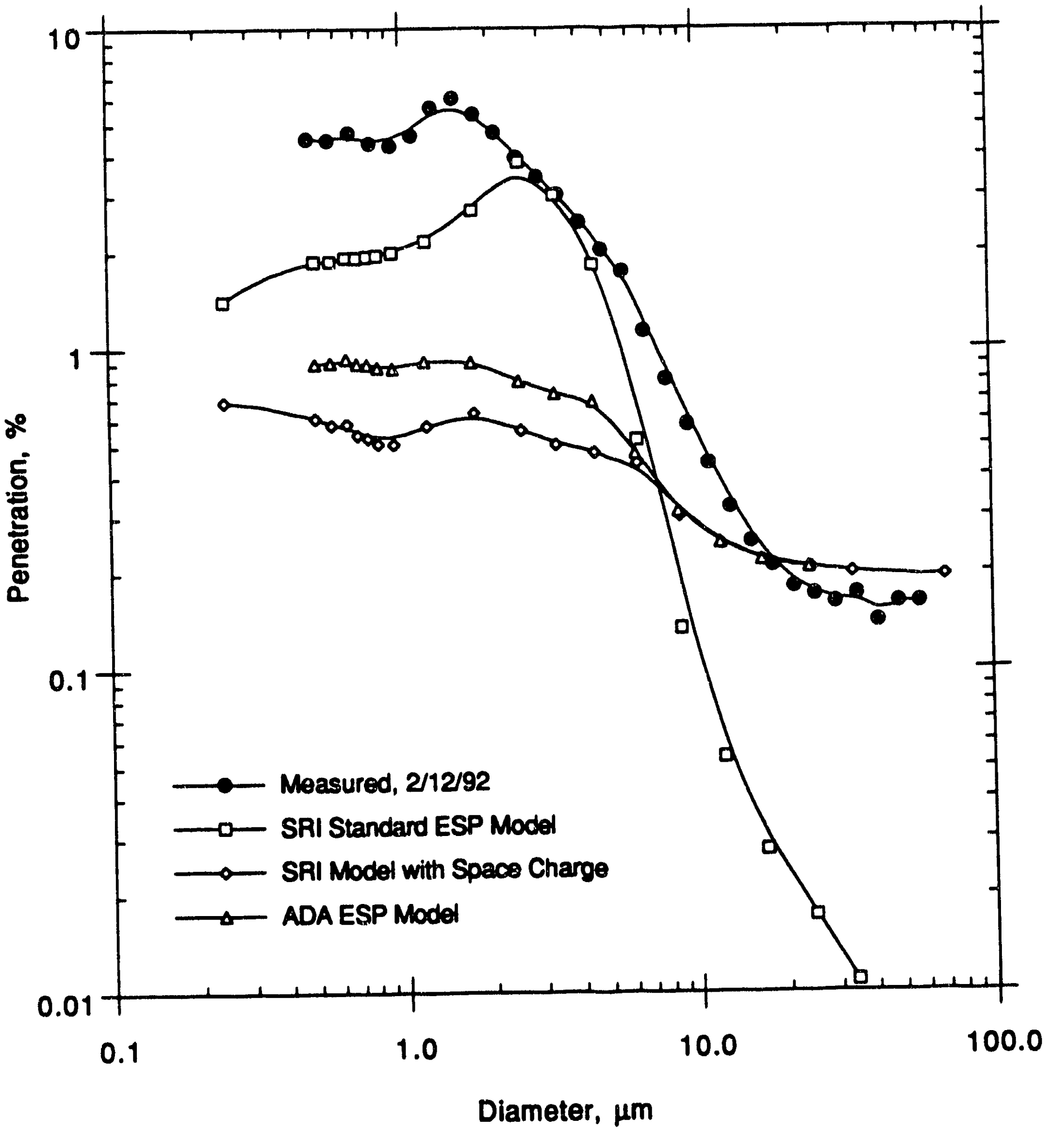

Figure 6-15. Fractional penetration predicted by the SRI ESP model, the SRI model corrected for space charge effects, and the ADA ESP model.

removals could be obtained when a portion of the spent sorbent and ash was continuously mixed with reagent slaked lime slurry. This test was continued until levels of $Ca(OH)_2$ in the spent sorbent and ash mixture that were mixed with the reagent slaked lime slurry equilibrated to the level of $Ca(OH)_2$ measured in ash exiting the ESP. For this test the DITF was operated with a nominal overall Ca/S ratio of 2.4 (reagent Ca/S of 2.0) and a 25°F approach to saturation. Under these conditions from 85 to 90% of the SO_2 was removed.

Tests began on November 7, 1991 and continued until November 15. Because the DITF was not operated for 24 hours a day, a series of separate tests was run. During this time it was not intended to perform a detailed evaluation of ESP performance because, in the past, when slaked lime slurry had been injected at low approach temperatures, ESP performance had not been observed to deteriorate.

From an electrical standpoint the ESP operated in an optimal fashion throughout this test, as is shown in Figures 6-16 and 6-17 and Table 6-11. Figures 6-16 and 6-17 show voltage-current curves taken at the conclusion of testing on November 7 and 15 and Table 6-11 shows average ESP operating points and average outlet opacity (referenced to a 25 ft stack) from the DAS. These data show no unusual electrical behavior. However, as Table 6-11 shows, the hourly average outlet opacity record suggests that ESP mass emissions were not as low as the electrical behavior would imply. The average opacity values shown in Table 6-11 are plotted in Figure 6-18. Figure 6-18 shows the typical increase in opacity associated with the start of testing (when the DAS was started at the actual beginning of a test this behavior can be seen), but also shown in this figure is a trend toward higher emissions as the test series progressed. Finally, on November 15, emissions rose to the point where the outlet opacity *averaged* about 80% for the last three hours of testing. Though the opacity monitor at the ESP outlet detected a rapping puff virtually every time any field in the ESP was rapped, ESP electrical operation was normal. Because mass emissions were observed to be increasing, mass trains were run at the ESP outlet on two occasions. The results of these measurements are shown in Table 6-11 and on Figure 6-18. These data also show that ESP collection efficiency was severely degraded.

With respect to ESP model calculations, an estimated inlet mass concentration, along with ESP operating voltage-current characteristics and outlet mass concentration measurement from November 14 was used as input to the standard SRI/EPA ESP model, that model modified to account for the effect of space charge, and the ADA ESP model. The results of these calculations are shown in Table 6-12. As the input data sets for these model calculations show, in order to duplicate the collection efficiency measured on November 14, large amounts of reentrainment had to be included.

These results suggest that the same reentrainment mechanism responsible for poor ESP performance observed in testing of the E-SO_x process[8] was active here. The reentrainment process results from electrical forces dislodging collected dust layers and deagglomerating particles of slurry residue. Although the conditions which initiate the occurrence of this process are not well understood, it is apparent that the effects on ESP collection efficiency can be severe when the process is under way.

TEST 68-SR-04, 11/7/91

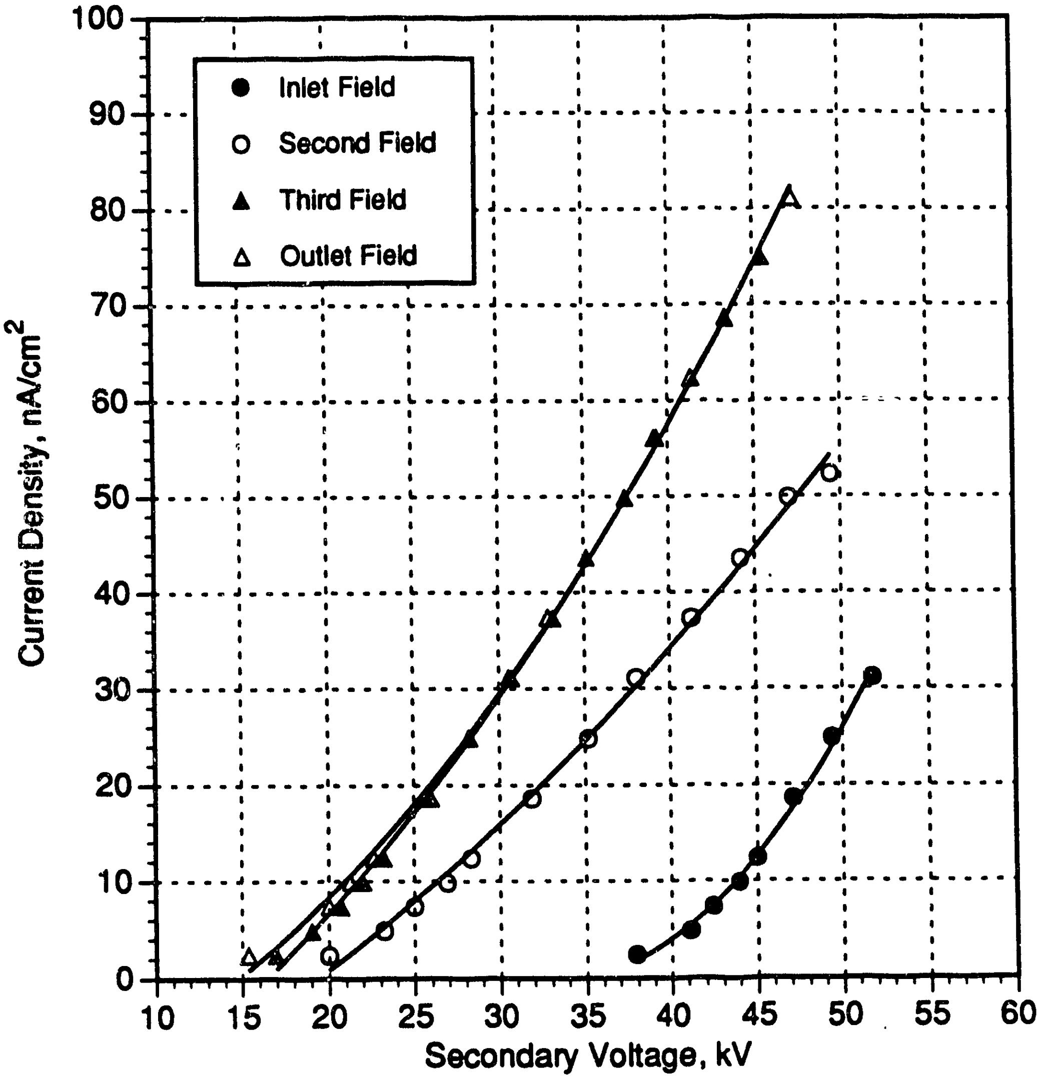

Figure 6-16. Current density as a function of applied ESP voltage at a 25°F approach to saturation during slurry/recycle ash testing. Test 68-SR-04, November 7, 1991.

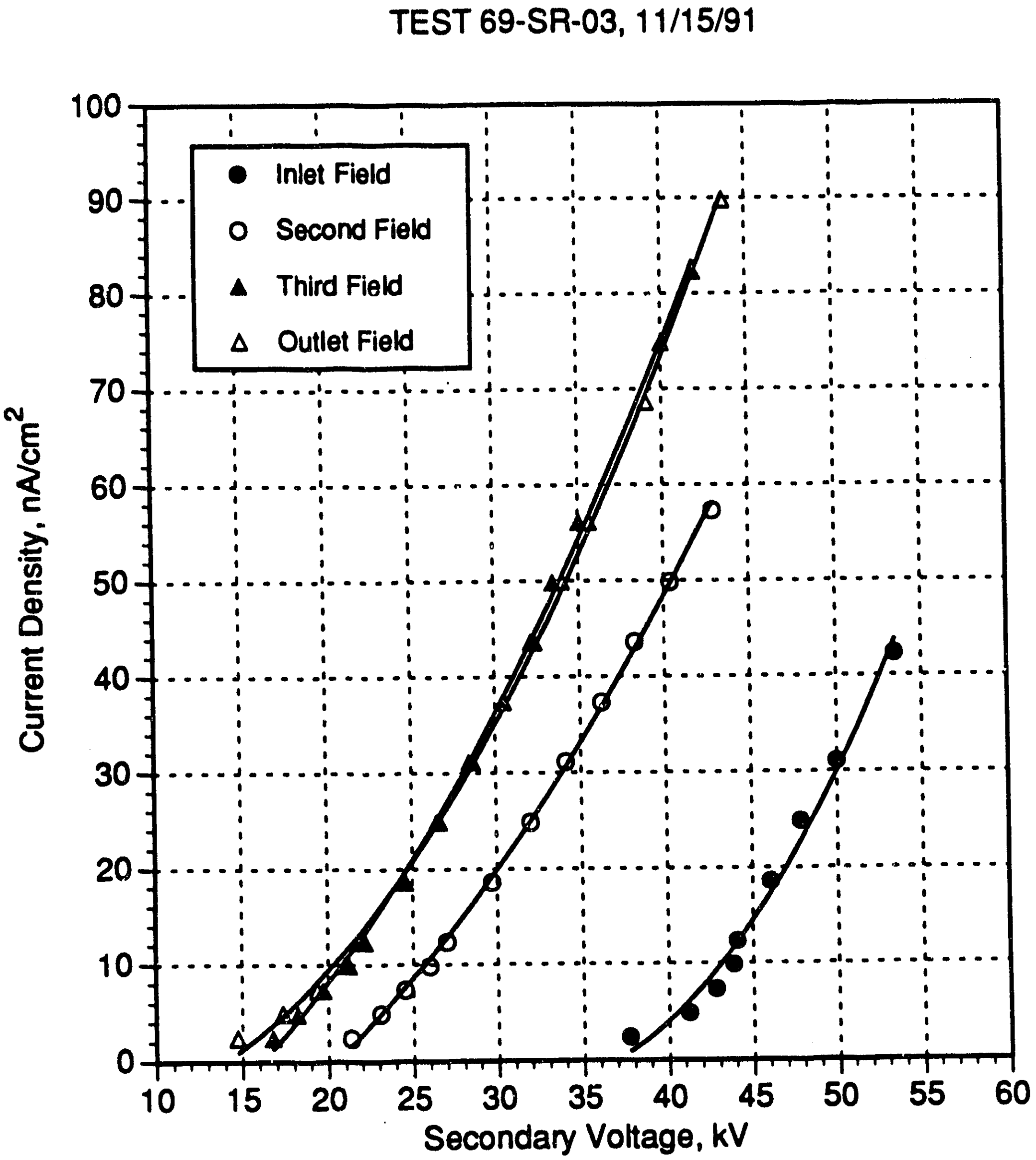

Figure 6-17. Current density as a function of applied ESP voltage at a 24°F approach to saturation during slurry/recycle ash testing. Test 69-SR-03, November 15, 1991.

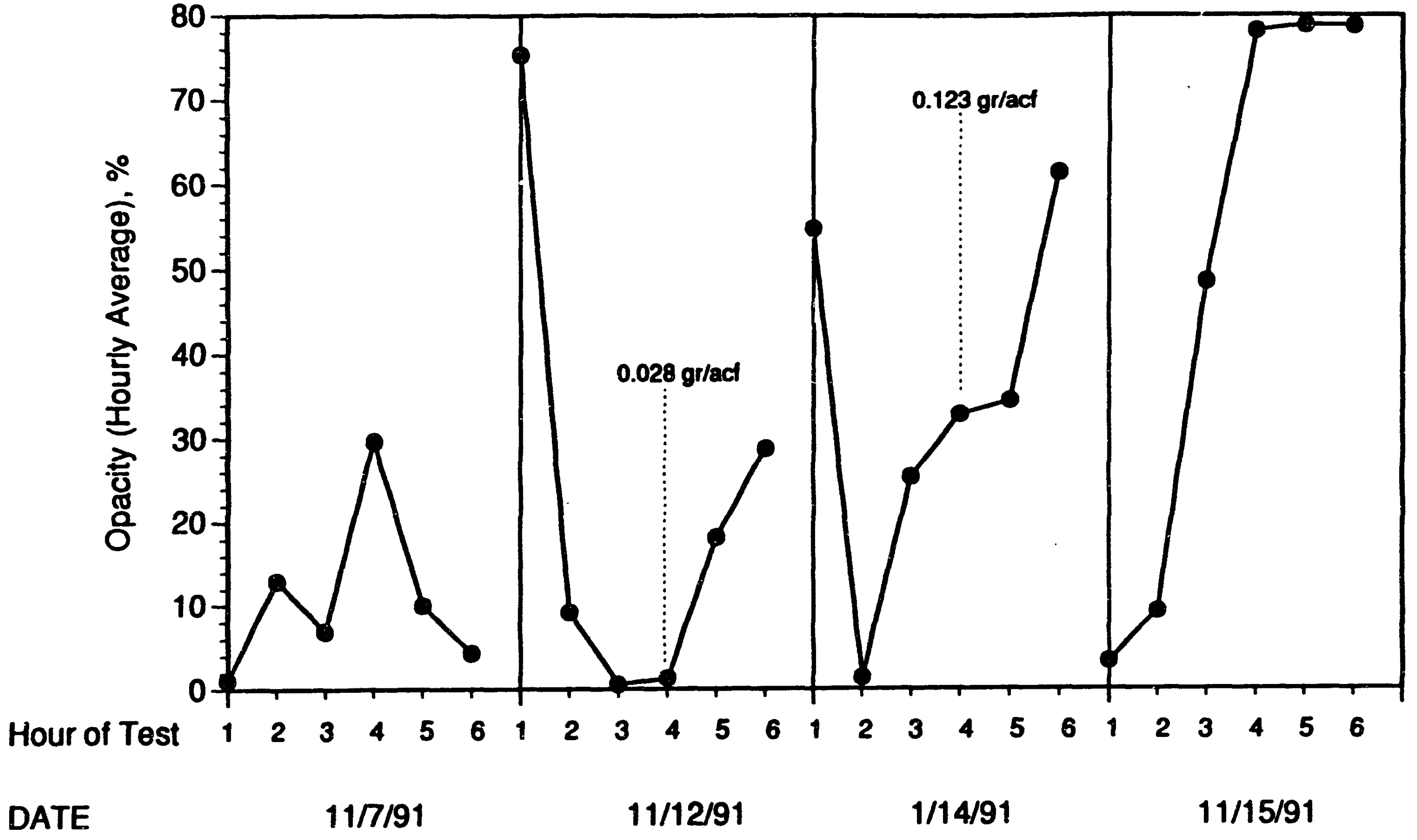

Figure 6-18. Average hourly opacity for November 7-15, 1992 during weeks 68 and 69 of testing.

Table 6-12. ESP Model Results for Tests conducted in November, 1991

Date	Approach °F	Measured Efficiency, %	Standard SRI Model[1]		SRI Space Charge Model[1]		ADA Model	
			Sneakage, σ_g	Efficiency, %	Sneakage, σ_g	Efficiency, %	Reentrainment, Sneakage, σ_g	Efficiency, %
11-14-91	25	98.64[2]	0.58, 0.25	98.63	0.28, 0.25	98.60	0.80, 0.25, 0.25	98.67

1. The SRI sneakage coefficient is defined in the model manuals as a combined factor for gas sneakage and non-rapping reentrainment.
2. Based on inlet mass concentration of 9.0 gr/acf calculated from slurry injection rate and slurry solids content.

7.0 OPERATION AND MAINTENANCE EXPERIENCE AND ISSUES

The DITF was staffed to operate continuously, five days per week in three shifts. When required, seven-day-a-week operation was accommodated by the use of overtime. Much of the testing entailed short term (i.e., 2- to 4-hour) parametric tests. A two shift mode of operation was used for that type of testing with the facility shut down from 12 to 6 A.M. This allowed access to the duct for inspection and cleaning, if necessary.

From start-up of the DITF on April 25, 1990, through shutdown on February 27, 1992, the DITF completed 80 hours of nozzle testing, 471 hours of testing with dry hydrated lime injection, 1153 hours of testing with slurry injection, and 240 hours of slurry/recycle ash injection. This includes a three month outage by the Ohio Power Company in the Fall of 1990 to rebuild the Unit 5 boiler. During this test period the DITF experienced a number of problems typical of pilot plant operation. Operation and maintenance issues that emerged during testing are discussed below for each of the major subsystems.

7.1 Process Control System Experience and Issues

The process control system which was designed for the Beverly Test Facility was microprocessor-based so as to facilitate changes in process control strategy. One of the goals of the process control system design was to produce a flexible, reliable, readily understood, user friendly-system that would be easily learned by the operating and maintenance staff on-site at the DITF. As testimony to the achievement of that intent, the on-site staff made a number of modifications to the process control system throughout the nearly two year test period to improve the data acquisition, operation and maintenance of the facility. These modifications were readily made by the on-site staff without any assistance from the original system design team. The problems were identified and effectively resolved on-site.

A series of tests was designed and executed to simulate expected disturbances or upsets in boiler and duct injection technology equipment and process conditions. The purpose of these tests was to:

- Identify reliable system control parameters for duct injection technology processes.
- Identify reliable system diagnostic parameters for duct injection technology processes.
- Provide control system design information for scale up of duct injection technology.
- Demonstrate long-term, reliable, controllable and safe operation for the duct injection technology process.

Test conditions were selected to simulate boiler load changes and the DITF process control system was reconfigured from its normal testing mode to function as a back feed control system to control the system outlet SO_2 concentration with slurry or slurry/recycle ash injection.

The DITF PLC system demonstrated an acceptable capability of controlling normal process variation. Its response to the process variation was outstanding, considering the fact that the system is designed to control a test facility and not a full-scale commercial system. These tests demonstrate that the basic philosophy of outlet SO_2 control will be a feasible and effective way to control Duct Injection in a full scale application.

During the two year testing period no specific tests were conducted solely to demonstrate failure modes. As a matter of normal activities, however, ample opportunity was realized during normal operation of the DITF to deal with failure modes.

The DITF was designed as a test facility and not as a commercial SO_2 removal system attached to an industrial or utility facility with usual levels of equipment redundancy for uninterrupted operation. As such the design default for major equipment malfunction at the DITF was shut down of the SO_2 removal system.

In a commercially viable system, complete shutdown of the SO_2 removal facility is not acceptable. In order to accommodate the failure modes referred to above, the following recommendations should be considered for system designs.

a. Utilize duct wall temperature detection systems for dewpoint approach alarm. Wet conditions in the duct almost always result in serious duct deposits.

b. Provide redundancy is ash handling, compressed air, lime slaking, lime handling systems (i.e., 2-100% or 3-50% capacity components).

c. Provide redundancy in the spray nozzle system, on-line cleaning system for nozzles, flow monitoring, pressure-drop measurement, and control to individual or groupings of nozzles to maintain availability of these critical components.

d. Provide flexibility in nozzle placement in the duct with capability to aim the nozzles away from walls where necessary to prevent impingement of spray on the walls. This will provide a means to reduce wall deposition.

In general, good engineering practice and currently available technology applied to the design of a commercial installation should accommodate most problems that are anticipated without further development necessary.

7.2 Major Subsystem Experience and Issues

7.2.1 Hydrated Lime and Slurry Preparatory Systems

During initial operation of the hydrated lime system, hydrated lime leaks were observed inside the hydrated lime building. The leaks were fixed by welding a plate beneath the belt feeder and repiping the vent system from the ends of the rotary airlock to the chute above the airlock. The belt feeder redundant slide gates were also removed since they were a source of leakage. A maximum of 1800 lbs/hr on hydrated lime, and 2000 lbs/hr of recycle have been delivered with no problems. Occasionally, the belt enclosure had to be opened and cleaned. The inlet filters for the injection blower tended to get dirtier than expected and were relocated outside the hydrated lime building. In general, the system performed well. The accuracy of the feeding system was confirmed by independent sampling.

The slurry was prepared by mixing Mid Ohio pebble lime with water at a ratio of 1:4 in a detention slaker. There was some difficulty in preparing slurry with a specified solids content since the pebble lime feeder was a volumetric type feeder. The feed rate was estimated based on the feeder speed (RPM) and it was influenced by the bulk density and the silo level. A weigh belt feeder is recommended for future installations. However, the slaker seemed to maintain a solids concentration fairly well. Frequent analyses of the slurry were performed during testing. Over all of the reagent slurry and reagent slurry/recycle ash testing,the solids content of the reagent slurry averaged 21.81 ± 1.81% and the percentage of $Ca(OH)_2$ averaged 20.40 ± 1.63%.

7.2.2 Dry and Slurry Sorbent Injection System

Humidification water for dry injection or slurry sorbent injection was added through two spray lances mounted in the flue gas duct. Each lance was connected to three dual-fluid spray nozzles. The two spray lances are attached to flange connections which are slotted to allow rotation of the lance. Initial nozzle testing showed that the ability to rotate the lance and to aim the nozzles greatly reduced low thermocouple readings, an indication of wall wetting, on the duct walls. During testing, the top lance was pointed down by 2.5 degrees and the outer nozzles were pointed in by 5.0 degrees.

The lances were constructed from Hastelloy to protect against corrosion from the flue gas. There was no indication of corrosion on the lances or nozzles during the testing.

Dry Injection System - The dry duct injection nozzle was a single nozzle which directs the air and solids mixture into the duct. A 4-inch beveled pipe injected the dry sorbent into the center of the duct approximately 2.5 feet upstream of the spray humidification nozzles.

The system ran well after the hydrated lime leakage problem was eliminated. However, because of concerns about good lime mixing, the injection nozzle was extended so that the injection point was in the same plane as the humidification nozzles. Co-planar injection improved utilization and reduced stratification, but duct deposits were still a major problem.

Slurry Injection System - An array of six Lechler nozzles was used for the majority of the slurry testing. The internal-mix Lechler nozzles are designed with erosion-resistant silicon-carbide inserts. There was no detectable wear on these inserts after almost 1100 hours of slurry testing and 240 hours of recycle slurry testing.

In general, the slurry injection system operated adequately, resulting in insignificant duct deposits under normal operating conditions of 25 to 45#F approach temperatures. Occasionally, the nozzle air passages became plugged, usually as a result of an air compressor failure. This resulted in significant duct deposits. The nozzles were cleaned in a dilute HCl solution, reinstalled in the duct, and again functioned properly.

The key to maintaining nozzle performance was keeping the nozzles clean by adequate flushing when shutting down, plus periodic inspection. Care has to be taken when cleaning the nozzle inserts. These were damaged at times during removal for cleaning.

A major problem with slurry injection at the DITF occurs when dilute slurries are used (i.e., with less than 20% solids). When dilute slurries are injected, significant deposits occur even a moderate approach temperatures. Duct deposits are minimized only when using concentrated slurries (20%

solids or more). Extended tests of up to 120 hours and approaches as close as 25°F were run with concentrated slurries without significant deposits. Extended tests with recycle ash and slurry mixtures were not possible due to recycle/slurry mixing problems discussed in Section 7.2.6.

In general, for similar test conditions, duct deposits appeared to be less significant with slurry injection than with dry injection. Co-planar dry injection did not improve this performance.

7.2.3 Duct Cleaning System

The duct cleaning system consists of a sonic horn, three soot blowers, and duct hoppers 10 to 18 feet downstream of the slurry injection points. Since dry deposits were seldom found on the roof or sides of the duct, the need for or effect of the sonic horn was not clear.

The soot blowers appeared to function efficiently only when the duct deposits were dry. Since duct deposits began to form on the far end lip of the duct hopper, one of the soot blowers, which were located upstream of the duct hopper, was relocated downstream of the duct hopper blowing against the gas flow. This appeared to hinder the formation of the dust deposits on the hopper lip. An additional five soot blowers were installed between the duct hoppers to attempt to minimize duct deposits occurring in this area.

Deposits were controlled by these systems at conditions that minimize deposition. However, under conditions which promote depositions, these systems do not control solids buildup in the duct. On these occasions, the DITF must eventually be shut down and the duct cleaned out.

7.2.4 ESP Mechanical Performance

In general, the ESP mechanically performed very well for approach to saturation temperatures ranging from 50 to 25°F. On one occasion, the collection efficiency degraded at the end of an extended test. An inspection of the ESP revealed that the seals had become detached, resulting in a heavy coating of ash in the penthouse. Further inspection also revealed that large pieces of deposits had formed a bridge between some of the corona support frames and the collection plates. When the penthouse was cleaned, seals repaired, and deposits removed, the ESP collection efficiency returned to normal.

7.2.5 Ash Collection System

This system consists of four drag chain conveyors and rotary air locks. In general, the system performed poorly. On several occasions, the collecting conveyor plugged during unloading of the duct hoppers because of the wet fly ash/sorbent mixture. The major problem with the ash collection system is unloading the duct hoppers continuously. The fly ash/sorbent mixture collected in the hoppers is lumpy and the rotary airlocks cannot break it up.

7.2.6 Recycle/Slurry Mixing

The recycle/slurry testing was initially postponed because of recycle/slurry mixing problems. The mix appeared to agglomerate and cause the strainers (located upstream the Moyno pump) to clog in less than a minute. It was also found that the recycle material contains some particles larger than the 1/8 in. opening in the strainers. A short test was done with the strainers located downstream of the pump. The preliminary results indicated that the Moyno pump was capable of deagglomerating the mix, but the strainers still clogged every 20 minutes, because of the presence of large particles in the recycled material. It was not practical to run long tests under these conditions. To eliminate this problem a pipeline delumper was installed. The delumper cutter teeth attached to a single rotor work the stream and chop the large chunks. This device required no maintenance other than cleaning. However, the strainers still needed to be shifted to the clean side every 20 to 60 minutes. The delumper is not the ultimate solution for this mixing problem but it allowed the DITF to operate in the recycle mode.

8.0 CONCLUSIONS AND RECOMMENDATIONS

- Slurry injection is clearly superior to dry injection with humidification both in SO_2 removal and in operational reliability. With slurry injection, SO_2 removal efficiencies of 50% (44°F approach to saturation) with a reagent Ca/S of 1.0 and 88% (24°F approach) with a reagent Ca/S of 1.7 were achievable using recycle. These results exceed the DOE-stated goals for the Duct Injection Technology Program. Calcium utilizations and SO_2 removals at the ESP exit with slurry injection without recycle were similar to those obtained by DOE proof-of-concept contractors in previous projects. (Dry injection with additives was not within the scope of this project.)

- The feasibility of using recycle ash from the ESP hoppers to increase calcium utilization was successfully demonstrated. Of particular significance was the finding that the reactivity of unutilized calcium in the recycle ash was the same as that observed for the calcium in slurries of slaked lime.

- Commercial spray nozzles are available to support duct injection technology. Although most testing was performed with an array of six 2.88 gpm nozzles which required operation at relatively high A/L ratios, a single 12 gpm nozzle was available for testing during the latter part of the experimental program. It was found that this large nozzle could be operated at an A/L ratio of 0.5 without forming duct deposits, and without causing any measurable change in SO_2 removal in comparison with the smaller nozzles. Since this larger nozzle is capable of treating the equivalent of 15 MWe of flue gas, it has the potential for providing an economical means of slurry injection.

- Electrostatic precipitator performance was found to be highly variable with duct slurry injection. At approach temperatures ranging from 34 to 43°F, collection efficiency ranged from 99.94% (at a 34°F approach) to a low of 99.23% (at a 41°F approach) with a specific collection area of ~390 ft^2/1000 acfm. Severe ESP performance degradation was observed at a 24°F approach with a 1.7 Ca/S ratio with recycle. Electrical reentrainment of low resistivity dust is believed to be the cause of the variable collection performance.

- Small-scale tests with a fabric filter system installed in parallel with the DITF ESP indicated that 5 to 10% more SO_2 removal could be obtained across the fabric filter than the ESP for all test conditions. Results from experiments using a unique two-stage cooling process upstream of the filter indicated that over 99% SO_2 removal across the duct and fabric filter could be achieved with a Ca/S ratio of 2.0 while good filtration performance and dust handling characteristics were maintained.

- Potential application sites for duct injection with small ESPs should consider the installation of a pulse-jet fabric filter. A follow-on proof of concept test program is needed to demonstrate this enhancement of the technology.

- Commercially available process control technology can be successfully used to control the duct injection process. The test facility control system was reconfigured using conventional techniques to successfully control the process outlet SO_2 concentration to demonstrate this capability.

- While duct deposits developed on occasion in the test facility, it is anticipated they can be avoided in a large-scale installation with a conservative approach to design and operation. The need for duct hoppers in a larger scale installation was not established based on the experience from the DITF. It was found that deposits could be controlled by soot-blowers at conditions that minimize deposits. However, at conditions which promote deposit formation (dilute slurries, clogged nozzles, very close approach temperatures), soot blowers were not effective, and the DITF had to be shut down for manual cleaning.

- The waste product generated by the process is dry and readily handled using conventional materials handling technology for recycle and disposal. The waste was classified as non-hazardous by the State of Ohio and may be disposed of in a landfill. Ash/sorbent mixtures from the DITF ESP were subjected to the Toxic Characteristic Leaching Procedure (TCLP) to measure the leachability of these samples for heavy metals. The TCLP results suggest that neither the baseline ash nor the duct injection ash could be classified as hazardous by virtue of their content of leachable metals.

- The other topical reports produced on this project contain detailed presentations of data obtained during the project.[1-4] Under a separate contract, UEC/B&W are using these and other data to develop a comprehensive process model. For this reason, the subject project does not include a correlating or modeling effort, and readers should refer to the forthcoming report on the UEC/B&W project for this information.

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APPENDIX A

DITF WEEKLY TEST SCHEDULE, Part 1

WEEK BEGINNING DATE	NO.	ACTUAL	PLANNED TASKS, ORIGINAL TEST SCHEDULE
			3.1--CHARACTERIZE SYSTEM PERFORMANCE
30-Apr	1	As Planned	Begin nozzle characterization and wall wetting evaluations
7-May	2	As Planned	
14-May	3	As Planned	
21-May	4	As Planned	
28-May	5	As Planned	
4-Jun	6	As Planned	
11-Jun	7	As Planned	
18-Jun	8	As Planned	
25-Jun	9	As Planned	Begin lime handling system check-out
2-Jul	10	As Planned	Continue lime handling system check-out
9-Jul	11	As Planned	Begin non-scavenging mode dry test
16-Jul	12	As Planned	Continue non-scavenging; begin scavenging
23-Jul	13	As Planned	Continue scavenging mode testing
30-Jul	14	As Planned	Continue scavenging mode testing
6-Aug	15	As Planned	Long-term scavenging tests
13-Aug	16	As Planned	Continue long-term scavenging tests, prepare for slurry tests
20-Aug	17	As Planned	Begin slurry testing
OUTAGE			
19-Nov	18	As Planned	Short week--Slurry system check-out, DAS changes, ESP-P5A & other instrumentation
26-Nov	19	No Slurry Testing -- Equip. Probs.	Parametric slurry testing--compare local & Bel. lime at selected conditions with 1300 ppm SO2
3-Dec	20	Limited Slurry Para. Tests	Continue para. slurry tests-additional lime comparisons if needed. Det. min. air pressure req. for nozzles.
10-Dec	21	120 Hr Test with Interruptions	Perform 120 hr test @ selected condition--include some ESP testing
17-Dec	22	120 Hr Test Continued	P-H slurry testing @ selected conditions
24-Dec	23	Debug ESP; Nozzle Pressure Tests	Short week--repeat selected conditions
31-Dec	24	Outage; Limited Slurry Tests	Short week-repeat selected conditions
7-Jan	25	Slurry Parametric	Explore short residence time testing @ selected conditions with slurry--move nozzles to downstream location
14-Jan	26	Equip. Probs; Limited Slurry Tests	Parametric ESP testing at selected slurry injection condition--probably with long residence time
		3.1 EXTENDED DUE TO EQ. PROBLEMS	3.2--SCALE-UP TESTS
21-Jan	27	Outage; Frozen Slurry Lines	Parametric tests-slurry recycle
28-Jan	28	Parametric Slurry & ESP Tests	Parametric tests--slurry recycle

DITF WEEKLY TEST SCHEDULE, Part 2

WEEK BEGINNING DATE	NO.	ACTUAL	PLANNED TASKS, ORIGINAL TEST SCHEDULE
		END 3.1, BEGIN 3.2	
4-Feb	29	Begin Slurry/Recycle Ash Tests	Parametric testing--additive one slurry for SO2
11-Feb	30	Continue Slurry/Recycle Testing	Parametric testing--additive two slurry for SO2
18-Feb	31	Outage - A/C Motor Failed	Parametric testing--additive one or two
		3.3 moved up due to requirement for review of additives	
25-Feb	32	Outage - A/C Motor Failed	Slurry recycle parametric + side stream parametric
4-Mar	33	Para. Slurry & ESP Tests, SSFF Tests	Side-stream parametric
11-Mar	34	Para. Slurry & ESP Tests, SSFF Tests	Side stream parametric--SO2 & permeability
18-Mar	35	Slurry/Recycle Ash Tests; Equip. Probs.	Side stream parametric + slurry recycle
25-Mar	36	Slurry/Recycle Ash Tests; Equip. Probs.	Side stream parametric w slurry + dry recycle
1-Apr	37	Para. Slurry Tests; SSFF Tests	Dry injection--pulse-jet side stream parametric
8-Apr	38	Para. Slurry Tests; SSFF Tests	Dry injection--different nozzle (P-H?) & modified duct cleaning
15-Apr	39	Para. Slurry Tests; SSFF Tests	Dry injection--high surface area hydrate (or different lime source)
22-Apr	40	No Tests; Equip. Probs.	Dry injection--different lime source
29-Apr	41	No Tests; Equip. Probs. Gas System	Dry injection-modified duct cleaning
6-May	42	Long Term Slurry Tests	Slurry injection--modified nozzles & upgraded duct cleaning
13-May	43	Start Dry Sorbent Testing, Coplanar injection	Slurry injection--additives parametric testing
20-May	44	Unit 5 Off-Line; Equip. Probs w/ Inlet Venturi	Slurry injection--ESP reduced SCA testing
27-May	45	Continue Dry Sorbent Inj. Tests	Slurry injection--ESP/SO2 parametric with one or two additives
3-Jun	46	Continue Dry Sorbent Inj. Tests	Slurry injection--ESP additive one
10-Jun	47	Continue Dry Sorbent Inj. Tests	Slurry injection--ESP additive two
17-Jun	48	Long-Term Dry Inj. Test, SSFF Tests	Slurry injection--ESP with modified rapping
24-Jun	49	Limited Drt Inj. Tests; Equip. Probs.	Slurry injection--recycle parametric with ESP upgrade
1-Jul	50	Dry Inj. Recycle Ash Tests	Slurry injection--sidestream parametric with additive
8-Jul	51	Resume Slurry Tests; Install Delumper	Slurry injection--sidestream parametric with additive
15-Jul	52	Limited Testing; Delumper Probs.	Slurry injection--repeat selected conditions
			3.2--SCALE-UP TESTS
22-Jul	53	Start Slurry/Recycle Ash Tests	Slurry injection--long term test of optimized configuration
29-Jul	54	Equip. Probs.; Limited Slurry/Recycle Tests	Slurry injection--long term test of optimized configuration
5-Aug	55	Equip. Probs.; Limited Slurry/Recycle Tests	Slurry injection--long term test of optimized configuration
12-Aug	56	Unit 5 Off-Line	Slurry injection--long term test of optimized configuration
19-Aug	57	A/W Ratio Tests W/ LS Noz.; Operator Injury	Slurry injection--long term test of optimized configuration
26-Aug	58	No Testing	Dry injection--long term test of optimized configuration

DITF WEEKLY TEST SCHEDULE, Part 3

WEEK BEGINNING DATE	NO.	ACTUAL	PLANNED TASKS, ORIGINAL TEST SCHEDULE
2-Sep	59	No Testing	Dry injection--long term test of optimized configuration
9-Sep	60	No Testing	Dry injection--long term test of optimized configuration
			3.5--FAILURE MODES
16-Sep	61	No Testing	Response to process condition upsets--slurry
23-Sep	62	No Testing	Response to process condition upsets-dry
30-Sep	63	No Testing, Unit 5 Off Line	Response to duct injection equipment upsets-slurry
7-Oct	64	No Testing, Unit 5 Off Line	Response to duct injection equipment upsets--slurry & dry
14-Oct	65	Limited Slurry Tests	Response to ESP equipment upsets-dry
21-Oct	66	Slurry/Recycle, Low Ca/S	Response to ESP equipment upsets--slurry
28-Oct	67	Slurry/Recycle, Low Ca/S	Response to ash handling system upset--slurry
4-Nov	68	Slurry/Recycle, Low & High Ca/S, SSFF Test	Response to ash handling system upsets-dry
11-Nov	69	Slurry/Recycle, High Ca/S, SSFF Test	Optimized failure response strategy
			4.1--MODEL VALIDATION
18-Nov	70	No Testing, Unit 5 Off Line	Validation of droplet evaporation rates--slurry
25-Nov	71	12 gpm Lechler Nozzle Tests with Slurry	Validation of droplet-sorbent collision rates
		3.5--FAILURE MODES	
2-Dec	72	Response to Process Upsets-Modify PLC	Validation of SO2 absorption rates--dry &slurry
9-Dec	73	Response to Process Upsets-Evaluation	Validation of modified ESP model-slurry
16-Dec	74	6 gpm LS Nozzles, VDA Tests, Impactors	Validation of modified ESP model--dry
23-Dec	75	No Testing, rework gas sampling system	Overall model parametric evaluation--dry
30-Dec	76	Slurry/CaCl2 Injection-Parametric Test	Overall model parametric evaluation--slurry
6-Jan	77	Slurry/CaCl2 Injection-Parametric Test	Overall model parametric evaluation--slurry
13-Jan	78	Equipment probs/Generate recycle ash	Overall model parametric evaluation--slurry
20-Jan	79	No Testing, Unit 5 Off Line	Overall model parametric evaluation--slurry
27-Jan	80	No Testing, Unit 5 Off Line	Overall model parametric evaluation--slurry
---------------			----------- Planned End of Testing ---------------
3-Feb	81	Start Long-Term ESP Test	
10-Feb	82	Conclude Long-Term ESP Test	
17-Feb	83	B&W Model Validation Tests	
24-Feb	84	B&W Model Validation Tests	
---------------		------- Actual End of Testing --------	

END

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