INTEGRATED DRY NO_x/SO_2 EMISSIONS CONTROL SYSTEM

CALCIUM-BASED DRY SORBENT INJECTION

(Test Period: April 30 to November 2, 1993)

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ABSTRACT

The DOE sponsored Integrated Dry NO_x/SO_2 Emissions Control System program, which is a Clean Coal Technology III demonstration, is being conducted by Public Service Company of Colorado. The test site is Arapahoe Generating Station Unit 4, which is a 100 MWe, down-fired utility boiler burning a low sulfur Western coal. The project goal is to demonstrate up to 70 percent reductions in NO_x and SO_2 emissions through the integration of: 1) down-fired low-NO_x burners with overfire air; 2) Selective Non-Catalytic Reduction (SNCR) for additional NO_x removal; and 3) dry sorbent injection and duct humidification for SO_2 removal. The effectiveness of the integrated system on a high-sulfur coal will also be investigated.

This report documents the fifth phase of the test program, where the performance of the dry sorbent injection of calcium was evaluated as an SO_2 removal technique. Dry sorbent injection with humidification was performed downstream of the air heater (in-duct). Calcium injection before the economizer was also investigated. This fifth test phase focused on a parametric investigation of the following parameters: boiler load, calcium-to-sulfur ratio (Ca/S), and approach to adiabatic saturation temperature.

The in-duct calcium sorbent and humidification retrofit resulted in SO_2 reductions of 28 to 40 percent, with a Ca/S of 2, and a 25 to 30°F approach to adiabatic saturation temperature. These SO_2 reductions are similar to other full-scale demonstrations conducted under similar operating conditions. The majority of the SO_2 reduction was obtained in the duct or entrained phase, while lower amounts occurred across the fabric filter. Adverse fabric filter cleaning resulted from the humidification process, requiring a manual cleaning to restore proper operation.

The results of the economizer calcium injection tests were disappointing with less than 10 percent SO_2 removal at a Ca/S of 2. Poor sorbent distribution due to limited access into the injection cavity was partially responsible for the low overall removals. However, even in areas of high sorbent concentration (local Ca/S ratios of approximately 6), SO_2 removals were limited to 30 percent. It is suspected that other factors (sorbent properties and limited residence times) also contributed to the poor performance.

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LIST OF DEFINITIONS

acfm	Actual Cubic Feet per Minute
B&W	Babcock & Wilcox
Ca/S	Calcium-to-Sulfur Ratio
CEM	Continuous Emission Monitor
DCS	Distributed Control System
DOE	U. S. Department of Energy
DRB-XCL®	Dual Register Burner - Axially Controlled Low-NO_x
dscfm	Dry Standard Cubic Feet per Minute, measured at 1 atmosphere and 60°F
DSI	Dry Sorbent Injection
EPRI	Electric Power Research Institute
FERCo	Fossil Energy Research Corp.
FFDC	Fabric Filter Dust Collector
gpm	Gallons Per Minute
ID	Induced Draft (fan)
LNB	Low-NO_x Burner
MMD	Mass Mean Diameter
MWe	MegaWatts (electrical)
OFA	OverFire Air
PLC	Programmable Logic Control
ppm	Parts Per Million
ppmc	Parts Per Million Corrected to 3 percent O_2 level
PSCC	Public Service Company of Colorado
psig	Pounds per Square Inch Gauge
RATA	Relative Accuracy Test Audit
scfm	Standard Cubic Feet per Minute, measured at 1 atmosphere and 60°F
SNCR	Selective Non-Catalytic NO_x Reduction
WDPF	Westinghouse Distributed Processing Family, control system at Arapahoe
T_{app}	Approach to Adiabatic Saturation Temperature

EXECUTIVE SUMMARY

This test report summarizes the technical activities and results for one phase of a Department of Energy sponsored Clean Coal Technology III demonstration of an Integrated Dry NO_x/SO_2 Emissions Control System for coal-fired boilers. The project is being conducted at Public Service Company of Colorado's Arapahoe Generating Station Unit 4 located in Denver, Colorado. The project goal is to demonstrate up to 70 percent reductions in NO_x and SO_2 emissions through the integration of existing and emerging technologies, including: 1) down-fired low-NO_x burners with overfire air; 2) Selective Non-Catalytic Reduction (SNCR) for additional NO_x removal; and 3) dry sorbent injection and duct humidification for SO_2 removal.

Due to the number of technologies being integrated, the test program has been divided into the following test activities:

- Baseline tests with the original combustion system
- Baseline tests with the original combustion system and SNCR
- Low-NO_x Burner (LNB)/Overfire Air (OFA) tests
- LNB/OFA/SNCR tests
- LNB/OFA/Calcium Injection tests
- LNB/OFA/Sodium Injection tests
- LNB/OFA/SNCR Dry Sorbent Injection tests (integrated system)
- High-Sulfur Coal tests with the integrated system.
- Air Toxics Tests

This report presents the results of the calcium injection tests performed after the combustion system retrofit on the Arapahoe Unit 4 boiler. The SO_2 removal performance of the dry sorbent injection system was evaluated with in-duct humidification of the gas. Humidification was performed by atomizing water into the flue gas, thereby reducing the average gas temperatures closer to the adiabatic saturation point. Calcium injection was performed at two locations: in the duct downstream of the air heater, and in the convective pass upstream of the economizer. The calcium injection/humidification test program was conducted over a ten-week period from April 30 to July 2, 1993. Additional testing with calcium was performed during later air toxics testing performed in October of 1993.

The primary operating parameter for sorbent injection processes is the calcium-to-sulfur ratio (Ca/S), which relates the amount of sorbent injected relative to the mass flow of sulfur in the flue gas. In the cases when humidification was utilized, the primary operating variable was the approach to adiabatic saturation temperature (T_{app}) of the flue gas. Saturation temperatures of the flue gas ranged from 112 to 118°F, depending on boiler operating conditions. The humidification system was used to vary T_{app} from 20 to 70°F. Parametric variation of the Ca/S ratio, approach to adiabatic saturation, and boiler load were performed for the calcium injection tests.

With a 25 to 30°F approach to adiabatic saturation and a nominal Ca/S injection ratio of 2, the SO_2 removals with in-duct humidification and calcium injection ranged from 28 to 38 percent (Figure S-1). SO_2 removals decrease with decreases in humidification (i.e., higher T_{app}). For this installation, an approach to adiabatic saturation temperature of 30°F is considered to be the lowest practical operating condition for extended operating periods. Figure S-1 compares Arapahoe data with the SO_2 removals obtained at the Ohio Edison Edgewater duct humidification demonstration during an earlier clean coal project (McCoy et al, 1992). The results obtained during the current work are comparable to those at Edgewater.

Detailed SO_2 measurements at the fabric filter inlet duct and individual compartments were utilized to analyze the SO_2 removal process. Test data indicated that the majority of the SO_2 removal occurs prior to entering the fabric filter. In one case, 29 percent SO_2 removal was measured in the entrained phase at the inlet of the fabric filter, while only an additional 5 percent SO_2 removal was measured at the outlet of the fabric filter. SO_2 distribution in the fabric filter on a compartment-by-compartment basis indicated that higher SO_2 removals occur in the first four compartments of the fabric filter. These distribution patterns may be related to sorbent/ash/humidification/flue gas distribution patterns in the duct or the fabric filter.

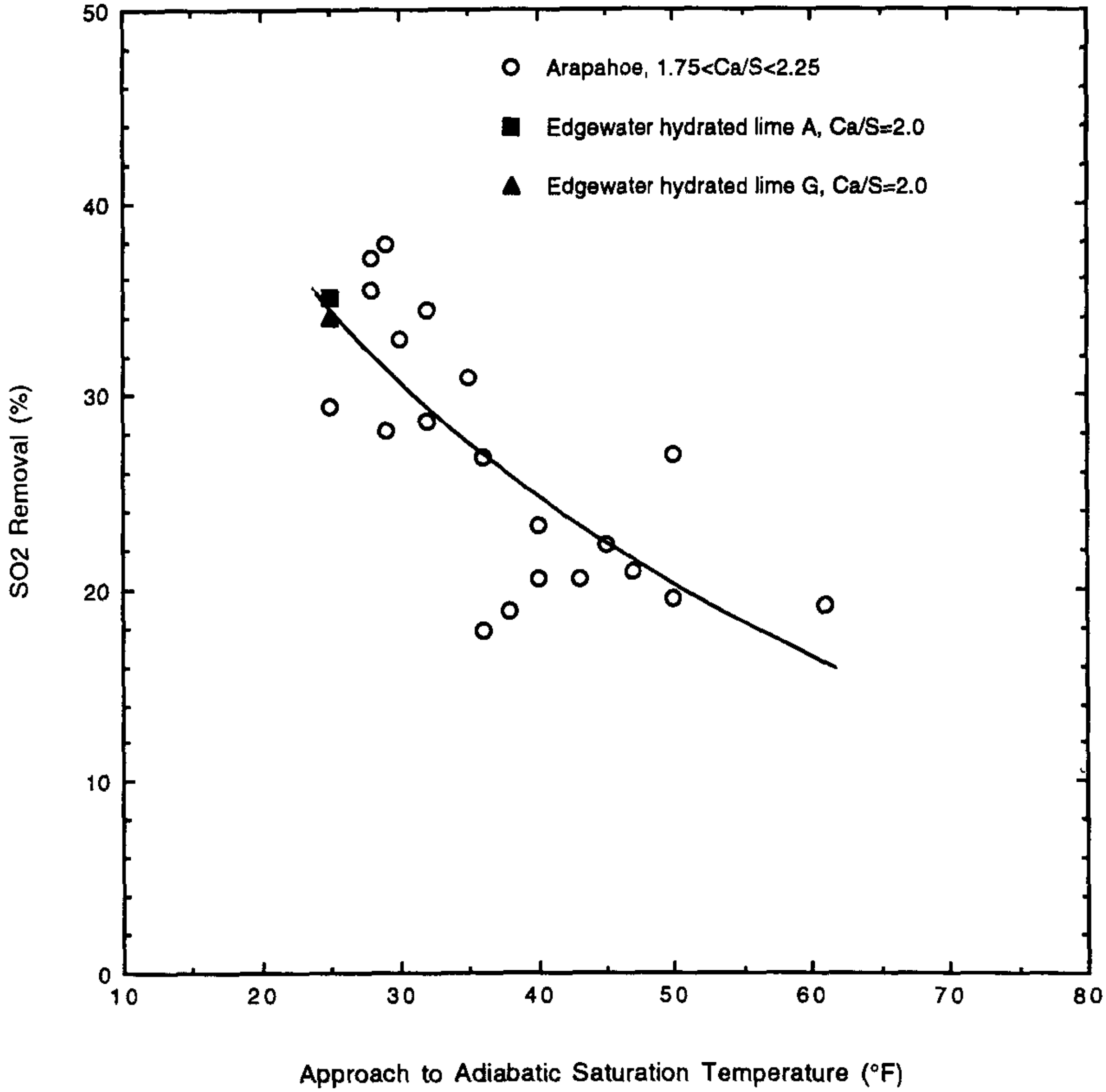

Figure S-1. Comparison of SO_2 Removal versus Approach to Adiabatic Saturation Temperature for Arapahoe and Edgewater Data (McCoy et al., 1992). (Note: The Edgewater data are conditions without sodium addition to the humidification water.)

Although there was some deposition in the duct resulting from the humidification and calcium injection processes, the deposits were considered manageable. Calcium/ash deposits were noted in two locations downstream of the humidification grid, at a flow diversion air foil and at the start of the duct slope leading to the fabric filter inlet. These deposits formed piles of hard, agglomerated calcium and ash, that could not be conveyed by the gas flow.

After the air toxics testing performed in October of 1993, when a 30°F approach to adiabatic saturation temperature was maintained continuously for a period of two days, fabric filter cleaning was found to be impaired. At full load or high gas flow conditions, the fabric filter pressure drops were not sufficiently reduced by cleaning, resulting in continuous cleaning of the fabric filter. The impaired cleaning indicated that ash deposits were not being sufficiently removed by normal reverse gas cleaning cycles. Excessive moisture or water on the fabric filters was suspected as the problem. Possible causes of the ash accumulation are that the 30°F approach to adiabatic saturation at steady state conditions was too low for the Arapahoe Unit 4 system, or that transient operations (i.e., load following and the operation of the humidifier controls) may have temporarily exceeded the set points and led to excessive moisture on the bags. All bags were manually cleaned by lowering and reinstalling the bags to remove the adhering ash accumulation. The fabric filter cleaning cycle returned to normal after the manual cleaning procedure.

The effectiveness of economizer injection at Arapahoe Unit 4 was compromised by limited access to the convective pass cavity at the required flue gas temperature window. As a result, distribution of sorbent into the duct was poor and large areas of flue gas were essentially untreated. Although temperatures were in the optimal range (950 to 1150°F), overall SO_2 removals ranged from only 5 to 10 percent at a Ca/S ratio of 2.0. Although SO_2 removals of slightly above 30 percent were measured in the area adjacent to the sorbent injectors, the local stoichiometry in this region was estimated at 6.0. Thus, it appears that high levels of SO_2 removal are not attainable with economizer injection at Arapahoe Unit 4, even in areas with high sorbent concentrations. It is suspected that insufficient residence time at the optional temperature window, and a relatively low sorbent-specific surface area also contributed to the poor overall performance.

1.0 INTRODUCTION

This report presents the results from one phase of the Public Service Company of Colorado (PSCC) and the Department of Energy (DOE) sponsored Integrated Dry NO_x/SO_2 Emissions Control System program. The DOE Clean Coal Technology III demonstration program is being conducted by Public Service Company of Colorado at PSCC's Arapahoe Generating Station Unit 4, located in Denver, Colorado. The intent of the demonstration program at Arapahoe Unit 4 is to achieve up to 70 percent reductions in NO_x and SO_2 emissions through the integration of existing and emerging technologies, while minimizing capital expenditures and limiting waste production to dry solids that are handled with conventional ash removal equipment. The technologies to be integrated are: 1) a down-fired low-NO_x burner system with overfire air; 2) Selective Non-Catalytic Reduction (SNCR) with urea and ammonia-based compounds for additional NO_x removal; and 3) dry sorbent injection (calcium- and sodium-based compounds) and duct humidification for SO_2 removal. Figure 1-1 shows a simplified schematic of the integrated system as implemented at Arapahoe Unit 4.

During the demonstration program, these emissions control systems are being optimized and integrated with the goal of achieving up to 70 percent reductions in NO_x and SO_2. It is anticipated that the emissions control system will achieve these reductions at costs lower than other currently available technologies. It is also anticipated that these technologies will integrate synergistically. For example, an undesirable side effect of sodium-based sorbent injection for SO_2 control has been oxidation of NO to NO_2, resulting in plume colorization. Pilot-scale testing, sponsored by the Electric Power Research Institute (EPRI), has shown that the presence of NH_3 can reduce the NO_2 emissions resulting from sodium-based dry sorbent injection. In the integrated system, the byproduct NH_3 emissions from the urea injection system will serve to minimize NO_2 formation. An additional objective of this program is to test the effectiveness of the integrated system on a high-sulfur coal.

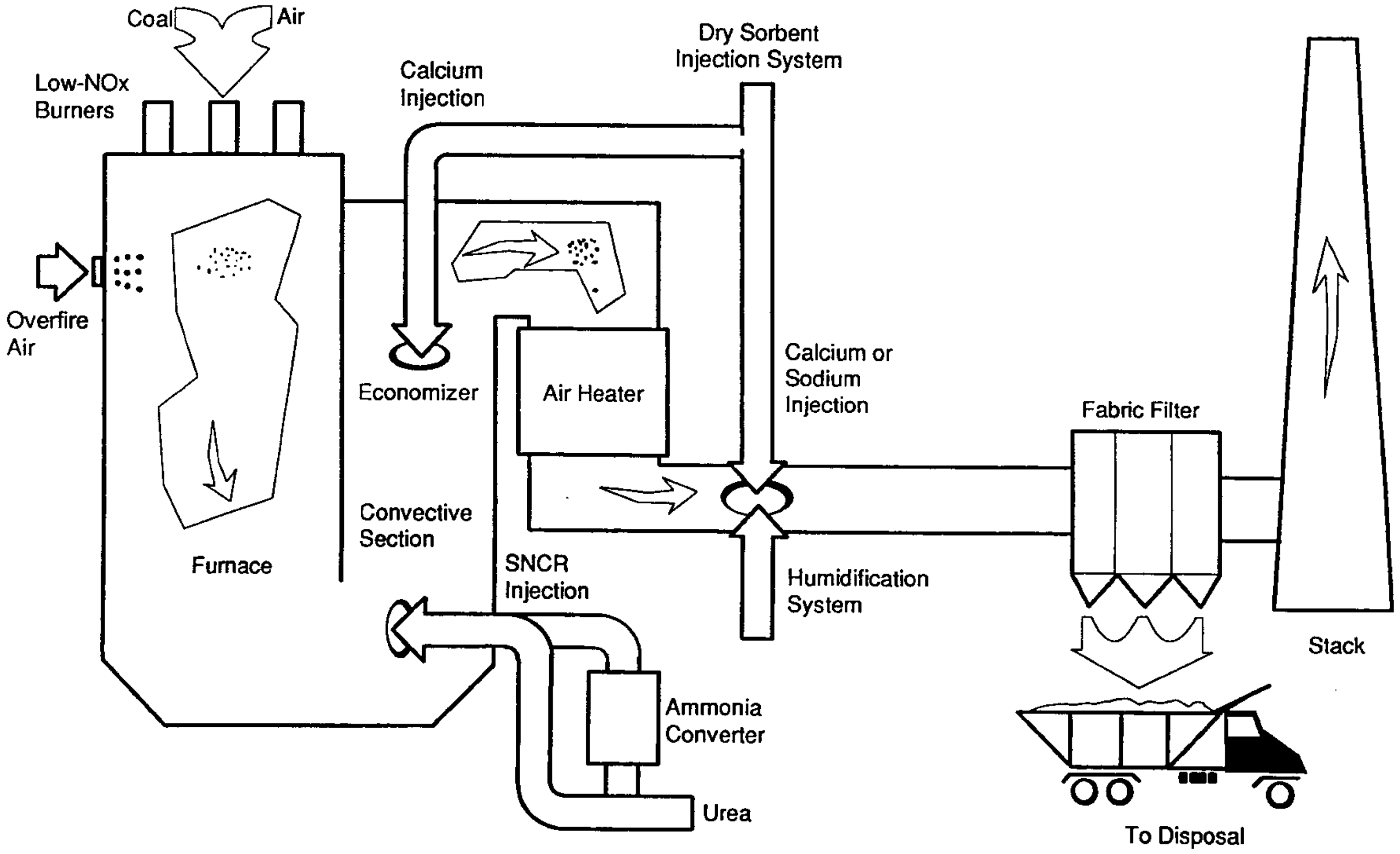

Figure 1-1. Arapahoe Unit 4 Integrated Dry NO_x/SO_2 Emissions Control System

Due to the number of technologies being integrated, the test program has been divided into the following test activities:

- Baseline tests of the original combustion system. These results provide the basis for comparing the performance of the individual technologies as well as that of the integrated system. (completed, Shiomoto, et al., 1992)
- Baseline combustion system/SNCR tests. Performance of urea and aqueous ammonia injection with the original combustion system. (completed, Smith, et al., 1993a)
- Low-NO_x burner (LNB)/overfire air (OFA) tests. (completed, Smith, et al., 1993b)
- LNB/OFA/SNCR tests. NO_x reduction potential of the combined low-NO_x combustion system and SNCR. (completed, Smith, et al., 1993c)
- LNB/OFA/calcium-based sorbent injection. Economizer injection and duct injection with humidification. (subject of this report)
- LNB/OFA/sodium injection. SO_2 removal performance of sodium-based sorbents.
- Integrated Systems test. NO_x and SO_2 reduction potential of the integrated system using LNB/OFA/SNCR/dry sorbent injection using calcium- or sodium-based reagents. Integrated system performance.
- High-sulfur coal tests. NO_x and SO_2 reduction potential of the integrated system while using an eastern bituminous coal. Dry sorbent injection will be calcium-based using the most efficient injection location determined from previous testing.

In addition to investigation of NO_x and SO_2 emissions, the test program also investigated air toxic emissions. Air toxic emission levels were measured during the testing of the low-NO_x combustion system, and during the LNB/OFA/SNCR tests with urea. Air toxics emission levels were also measured during the calcium injection tests, and additional tests will be conducted during the sodium injection tests to determine the potential air toxics removal of these two pollution control technologies. The air toxics test results will be documented in separate Environmental Monitoring Reports.

This report presents the results of the dry sorbent injection tests with calcium-based sorbents. These tests included both economizer injection and duct injection with humidification.

2.0 PROJECT DESCRIPTION

The following subsections will describe the key aspects of the technologies being demonstrated, and the project participants.

2.1 Process Description

The Integrated Dry NO_x/SO_2 Emissions Control system consists of five major control technologies that are combined to form an integrated system to control both NO_x and SO_2 emissions. NO_x reduction is accomplished through the use of low-NO_x burners, overfire air, and SNCR, while dry sorbent injection (using either calcium- or sodium-based reagents) is used to control SO_2 emissions. Flue gas humidification will be used to enhance the SO_2 removal capabilities of the calcium-based reagents. Each of these technologies is discussed briefly below.

2.1.1 Low-NO_x Burners

NO_x formed during the combustion of fossil fuels consists primarily of NO_x formed from fuel-bound nitrogen, and thermal NO_x. NO_x formed from fuel-bound nitrogen results from the oxidation of nitrogen which is organically bonded to the fuel molecules. Thermal NO_x forms when nitrogen in the combustion air dissociates and oxidizes at flame temperatures. Thermal NO_x is of primary importance at temperatures in excess of 2800°F.

To reduce the NO_x emissions formed during the combustion process, Babcock and Wilcox (B&W) Dual Register Burner-Axially Controlled Low-NO_x (DRB-XCL®) burners were retrofit to the Arapahoe Unit 4 boiler. Most low-NO_x burners reduce the formation of NO_x through the use of air staging, which is accomplished by limiting the availability of air during the early stages of combustion. This lowers the peak flame temperature and results in a reduction in the formation of thermal NO_x. In addition, by reducing the oxygen availability in the initial combustion zone, the fuel-bound nitrogen is less likely to be converted to NO_x, but rather to N_2 and other stable nitrogen compounds. The B&W DRB-XCL® burner achieves increased NO_x reduction effectiveness by incorporating fuel staging in addition to air staging. Fuel staging involves the introduction of fuel downstream of the flame under fuel-rich conditions. This results in the generation of hydrocarbon radicals which further reduce NO_x levels. The fuel staging is accomplished through the design of the coal nozzle/flame stabilization ring on the burner. Additionally, combustion air to each burner is accurately measured and regulated to provide a balanced fuel and air distribution for optimum NO_x reduction and combustion efficiency. Finally, the burner assembly is equipped with two sets of adjustable spin vanes which provide swirl for fuel/air mixing and flame stabilization.

2.1.2 Overfire Air

Low-NO_x burners and overfire air reduce the formation of NO_x by controlling the fuel/air mixing process. While low-NO_x burners control the mixing in the near burner region, overfire air controls the mixing over a larger part of the furnace volume. By diverting part of the combustion air to a zone downstream of the burner, initial combustion takes place in a near stoichiometric or slightly fuel rich environment. The remaining air necessary to ensure complete combustion is introduced downstream of the primary combustion zone through a set of overfire air ports, sometimes referred to as NO_x ports. Conventional single-jet overfire air ports are not capable of providing adequate mixing across the entire furnace. The B&W dual-zone NO_x ports, however, incorporate a central zone which produces an air jet that penetrates across the furnace and a separate outer zone that diverts and disperses the air in the area of the furnace near the NO_x port. The central zone is provided with a manual air control disk for flow control, and the outer zone incorporates manually adjustable spin vanes for swirl control.

The combined use of the low-NO_x burners and overfire air ports is expected to reduce NO_x emissions by up to 70 percent.

2.1.3 Selective Non-Catalytic Reduction

NO_x reduction in utility boilers can also be accomplished by Selective Non-Catalytic Reduction (SNCR). This process involves the injection of either urea or ammonia (anhydrous or aqueous) into the combustion products where the gas temperature is in the range of 1600 to 2100°F. In this range, NH_2 is released from the injected chemical which then selectively reacts with NO in the presence of oxygen, forming primarily N_2 and H_2O. A SNCR system is capable of removing 40 to 50 percent of the NO from the flue gas stream.

Urea and ammonia each have their own optimum temperature and range within which NO_x reduction can occur. An example of such a temperature "window" is shown conceptually in Figure 2-1. At temperatures above the optimum, the injected chemical will react with O_2 forming additional NO_x, thereby reducing the NO_x removal efficiency. At temperatures below the optimum, the injected chemical does not react with NO, resulting in excessive emissions of NH_3 (referred to as ammonia slip). Chemical additives can be injected with the urea to widen the optimum temperature range and minimize NH_3 emissions.

The SNCR chemical of primary interest for the present program is urea. The urea is generally injected into the boiler as a liquid solution through atomizers. The atomizing medium can be either air or steam, although air is used in the current installation. The urea and any additives are stored as a liquid and pumped through the injection atomizers. At Arapahoe Unit 4, a system has also been installed to catalytically convert the urea solution to ammonium compounds.

2.1.4 Dry Reagent SO_2 Removal System

The dry reagent injection system consists of equipment for storing, conveying, pulverizing and injecting calcium- or sodium-based reagents into the flue gas between the air heater and the particulate removal equipment, or calcium-based reagents upstream of the economizer. The SO_2 formed during the combustion process reacts with the sodium- or

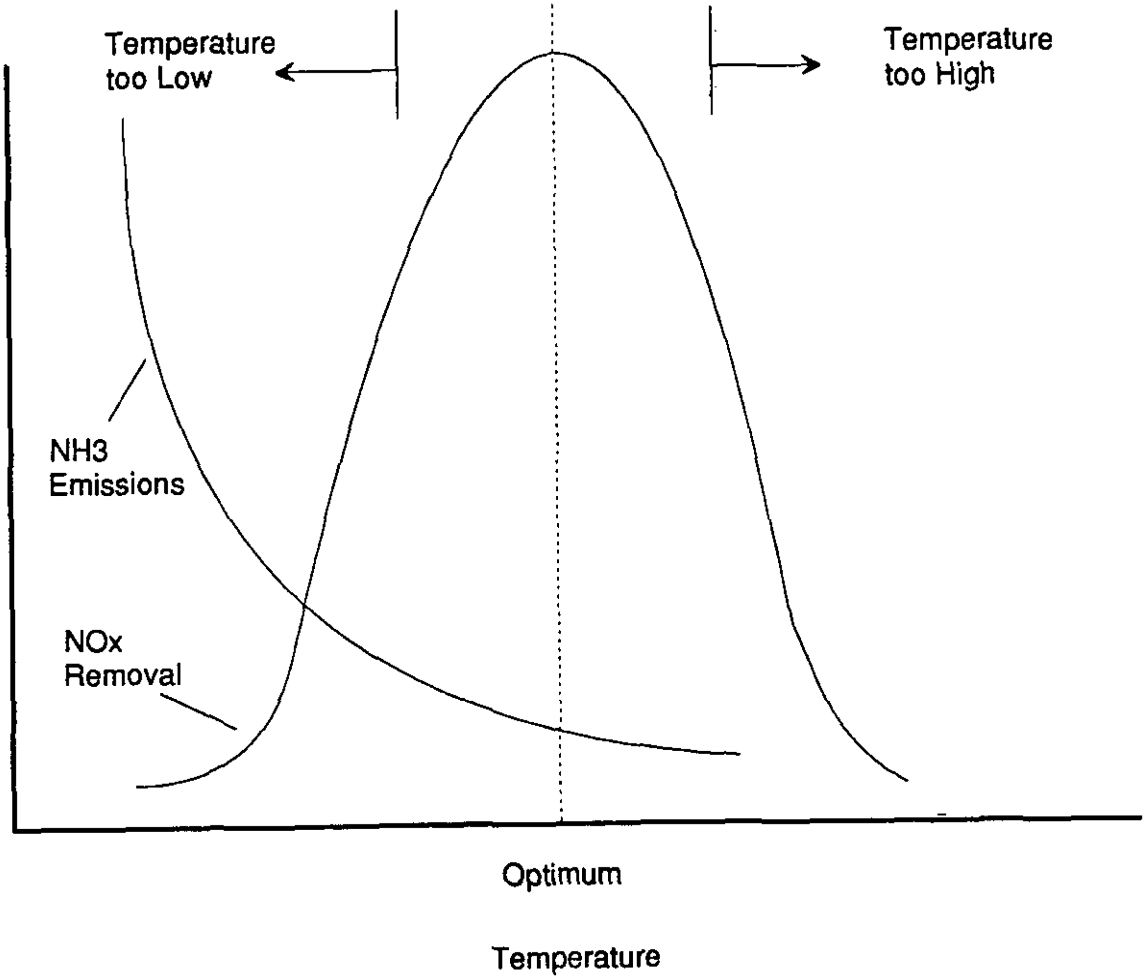

Figure 2-1. Conceptual Temperature Window for the SNCR Process

calcium-based reagents to form sulfates and sulfites. These reaction products are then collected in the particulate removal equipment together with the flyash and any unreacted reagent and removed for disposal. The system is expected to remove up to 70 percent of the SO_2 when using sodium-based products while maintaining high sorbent utilization.

Although dry sodium-based reagent injection systems reduce SO_2 emissions, NO_2 formation has been observed in some applications. NO_2 is a red/brown gas; therefore, a visible plume may form as the NO_2 in flue gas exits the stack. Previous pilot-scale tests have shown that ammonia slip from urea injection reduces the formation of NO_2 while removing the ammonia which would otherwise exit the stack.

In certain areas of the country, it may be more economically advantageous to use calcium-based reagents, rather than sodium-based reagents, for SO_2 removal. SO_2 removal using calcium-based reagents involves dry injection of the reagent into the furnace at a point where the flue gas temperature is approximately 1000°F. Calcium-based materials can also be injected into the flue gas ductwork downstream of the air heater, but at reduced SO_2 removal effectiveness.

2.1.5 Humidification

The effectiveness of the calcium-based reagent in reducing SO_2 emissions when injected downstream of the air heater can be increased by flue gas humidification. Flue gas conditioning by humidification involves injecting water into the flue gas downstream of the air heater and upstream of any particulate removal equipment. The water is injected into the duct by dual-fluid atomizers which produce a fine spray that can be directed downstream and away from the duct walls. The subsequent evaporation causes the flue gas to cool, thereby decreasing its volumetric flowrate and increasing its relative and absolute humidity. It is important that the water be injected in such a way as to prevent it from wetting the duct walls and to ensure complete evaporation before the gas enters the particulate removal equipment or contacts the duct turning vanes. Since calcium-based reagents are not as reactive as sodium-based reagents, the presence of water in the flue gas, which contains unreacted reagent, provides for additional SO_2 removal. Up to 50 percent SO_2 removal is expected when calcium-based reagents are used in conjunction with flue gas humidification.

2.2 Project Participants

PSCC is the project manager for the project, and is responsible for all aspects of project performance. PSCC has engineered the dry sorbent injection system and the modifications to the flyash system, provided the host site, trained the operators, provided selected site construction services, start-up services and maintenance, and is assisting in the testing program.

B&W was responsible for engineering, procurement, fabrication, installation, and shop testing of the low-NO_x burners, overfire air ports, humidification equipment, and associated controls. They are also assisting in the testing program, and will provide for commercialization of the technology. NOELL, Inc. was responsible for the engineering, procurement and fabrication of the SNCR system. Fossil Energy Research Corp. is conducting the testing program. Western Research Institute is characterizing the waste materials and recommending disposal options. Colorado School of Mines is conducting research in the areas of bench-scale chemical kinetics for the NO_2 formation reaction with dry sorbent injection. Stone & Webster Engineering is assisting PSCC with the engineering efforts. Cyprus Coal and Amax Coal are supplying the coal for the project, while Coastal Chemical, Inc. is providing the urea for the SNCR system. Air Toxics testing was performed by Carnot, Inc.

3.0 DRY SORBENT INJECTION AND HUMIDIFICATION SYSTEM DESCRIPTION

The dry sorbent injection (DSI) system consists of a redundant sorbent system designed for the delivery of calcium- or sodium-based materials into the duct work between the boiler air heater and the fabric filter fly ash collection system. The redundant system includes two separate sorbent systems, including storage silos, feeders, mills, and delivery systems. In addition to the duct injection location (≈280°F), additional injectors were installed upstream of the boiler economizer and used to test calcium-based sorbent injection at higher flue gas temperatures (≈1000°F).

The DSI and the duct humidification systems were added to the existing Arapahoe Unit 4 boiler and flue gas duct work and required no major modifications beyond adding the access into the existing flow system. The original Unit 4 electrostatic precipitators had been removed and a new reverse gas fabric filter and induced draft (ID) fans were installed in 1985. The retrofit fabric filter was relocated in back of the common stack for Units 3 and 4 and required a long duct that connected the fabric filter inlet with the existing air heater exit. This air heater exit duct provided the site for the duct sorbent injection and humidification. The economizer sorbent injection site required additional injectors which were installed in a suitable cavity in the convective section of the boiler.

3.1 Process Chemistry

The detailed chemistry between $Ca(OH)_2$ and SO_2 is dependent on the temperature region in which the calcium hydroxide and SO_2 come in contact. For instance, for furnace injection of $Ca(OH)_2$ at temperatures of nominally 2000°F, the calcium hydroxide must first decompose to CaO, and it is the CaO that reacts with SO_2 for form calcium sulfate.

In the case of economizer $Ca(OH)_2$ injection, the detailed chemistry is not well understood. The work by Bortz, et al., (1986) suggests that the SO_2 removal occurs primarily through a direct reaction between $Ca(OH)_2$ and SO_2 (Eqn. 3-1 below), along with the major competing reactions (Eqn. 3-2 and Eqn. 3-3). Reaction 3-4 between $CaCO_3$ and SO_2 is a minor reaction.

$$Ca(OH)_2+SO_2 \rightarrow CaSO_3+H_2O \quad \text{(Eqn. 3-1)}$$

$$Ca(OH)_2+CO_2 \rightarrow CaCO_3+H_2O \quad \text{(Eqn. 3-2)}$$

$$Ca(OH)_2 \rightarrow CaO+H_2O \quad \text{(Eqn. 3-3)}$$

$$CaCO_3+SO_2 \rightarrow CaSO_3+CO_2 \quad \text{(Eqn. 3-4)}$$

The design challenge is to locate the temperature window where reaction 3-1 dominates over reactions 3-2 and 3-3.

The lower flue gas temperatures at the duct injection location are not favorable for flue gas-solid reactions shown above. At the lower temperatures, $Ca(OH)_2$ captures SO_2 more efficiently in the presence of water. The following equations show the two most important reactions between $Ca(OH)_2$ and SO_2 at duct injection temperatures.

$$Ca(OH)_2+SO_2+1/2O_2+H_2O \rightarrow CaSO_4+H_2O \quad \text{(Eqn. 3-5)}$$

$$2Ca(OH)_2+2SO_2 \rightarrow 2CaSO_3 \bullet 1/2H_2O+H_2O \quad \text{(Eqn. 3-6)}$$

3.2 Existing Boiler Equipment

Arapahoe Unit 4 utilizes a single tubular air heater for heating the secondary air. The boiler flue gases exit the air heater in a single, short and very wide duct. The air heater exit duct work immediately transitions into a narrower and taller duct. Figures 3-1 and 3-2 show the side and top views of duct/fabric filter/stack arrangement for Unit 4. The air heater exit is approximately 150 feet from the inlet of the fabric filter, while the transition duct accounts for 36 feet of the total. Flow diverting vanes are used in the transition duct, while flow straighteners are used in the duct immediately downstream of the transition point. The balance of the duct is 114 feet long and has moderate changes in profile and elevation into the fabric filter. The location of the duct sorbent and humidification injection is just downstream of the flow straighteners, approximately 103 feet from the fabric filter inlet, where the duct is 17' 3" wide by 9' 9" tall. Approximately

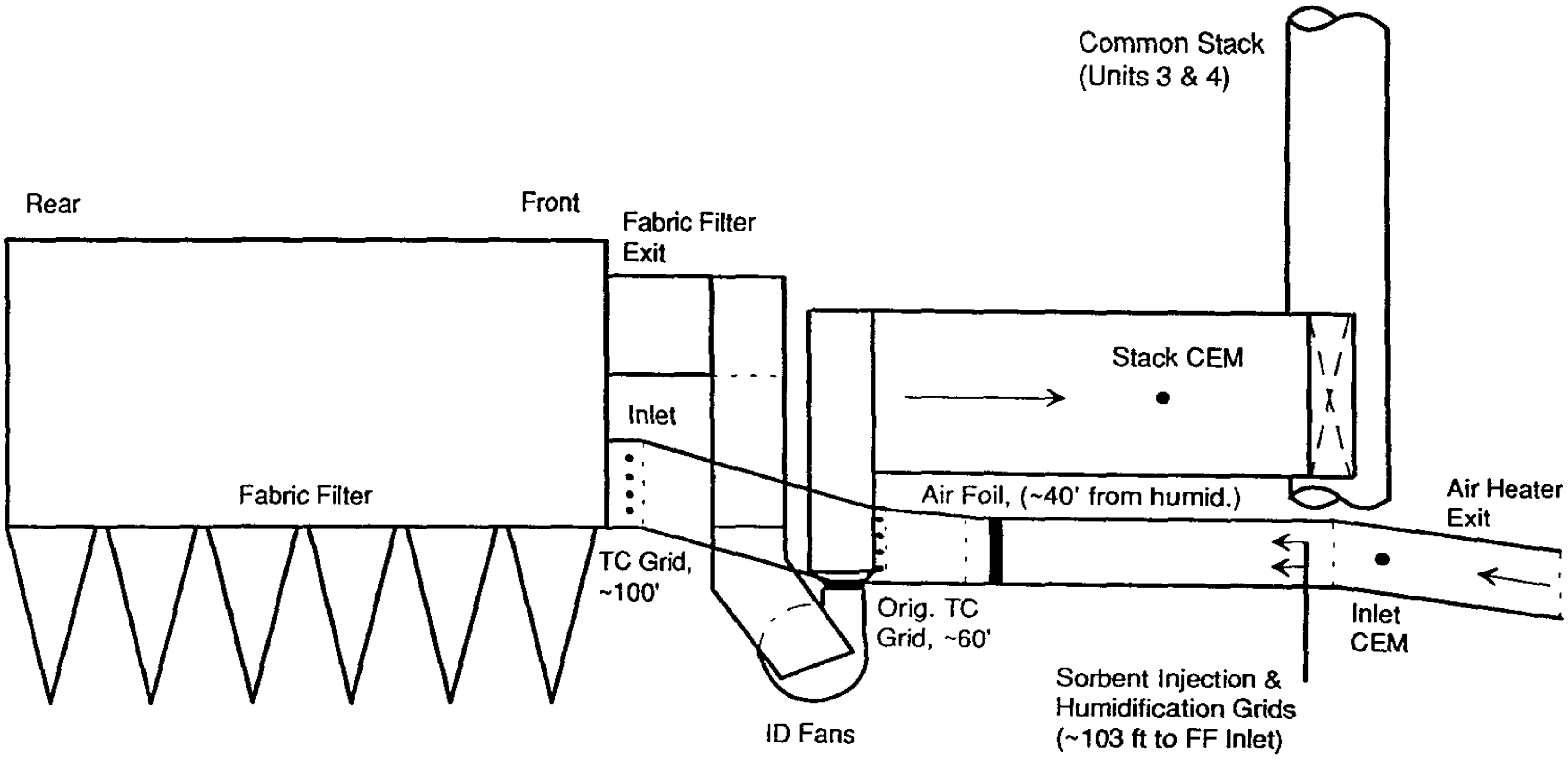

Figure 3-1. Side View of Equipment Downstream of the Arapahoe Unit 4 Air Heater

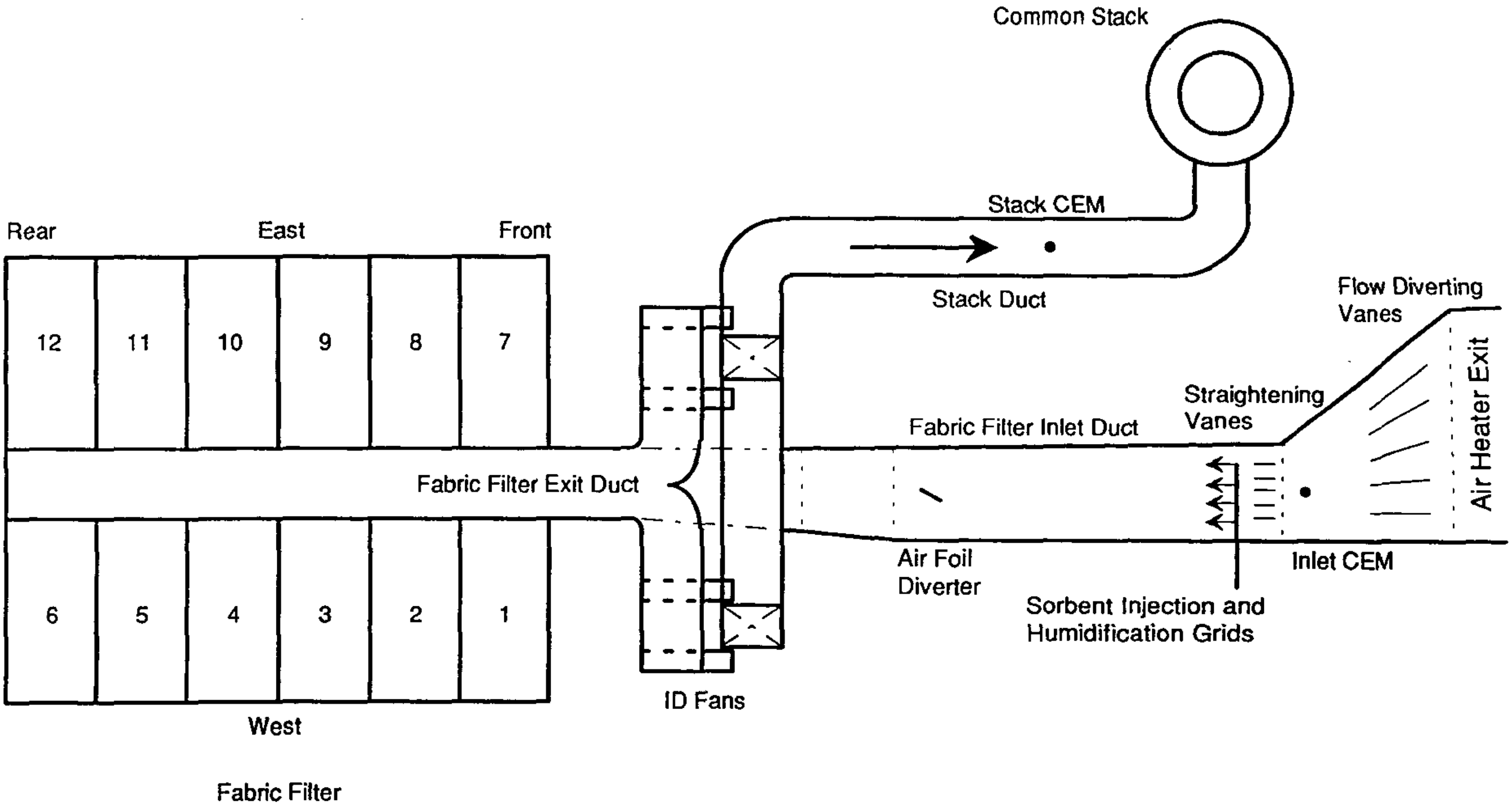

Figure 3-2. Top View of Equipment Downstream of the Arapahoe Unit 4 Air Heater

halfway to the fabric filter, the duct work transitions into a 15' wide by 11' 6" tall duct. In this second transition duct, a single, vertical air foil was installed near the center of the duct, to divert gas from the west to the east side of the duct. According to plant personnel, this air foil was intended to eliminate ash drop-out or deposition on the bottom of the duct on the east side. The air foil is part of the existing boiler equipment and was not installed as part of this test program. The air foil assembly also includes a horizontal stiffener that connects the center of the foil with the west wall. After this second transition point and the air foil location, the duct starts to rise up to the fabric filter inlet elevation. As the duct rises in elevation, it also gradually changes to conform with the 12' wide by 14' tall fabric filter inlet dimensions.

The Arapahoe Unit 4 fabric filter is an Ecolaire Environmental Company reverse gas fabric filter with 12 compartments and is designed for a gas flow of 600,000 acfm at 290°F. The compartments are arranged in a 2 wide by 6 long pattern around the centrally located inlet duct. Each compartment consists of 252 woven fiberglass bags that are 12 inches in diameter and 34 feet long. The original operating pressure drop was specified as 6.6 inches of H_2O at the design conditions, although the operating practice at the plant initiates a cleaning cycle when the pressure drop reaches 4.0 inches of H_2O. At full load, normal O_2 levels, and with all compartments operative, the fabric filter pressure drop decreases to approximately 2 inches of H_2O immediately after a cleaning cycle. Each compartment gas inlet pulls flue gas from the bottom of the fabric filter inlet duct into the upper level of the ash hoppers, just below the tube sheet. The flue gases flow up into the bags and the clean gas exits into a common duct located near the top of the compartments. Poppet valves and dampers control the gas flow and cleaning for each compartment.

After the cleaned flue gases exit the fabric filter, the duct splits for the two ID fans, then recombines into a single duct to return back to the common stack for Units 3 and 4. The single duct between the ID fans and the stack was used for all gas sampling at the fabric filter exit or "stack" location, since the common stack was not suitable for monitoring Unit 4.

3.3 Humidification System

The humidification system lowers the flue gas temperature by spraying a finely atomized water spray from an array of atomizers. Reducing the flue gas temperature to within 20 to 40°F of the adiabatic saturation temperature has been attributed with enhanced SO_2 removal when injecting calcium-based sorbents downstream of the air heater. The humidification system includes a set of atomizer lances installed in the duct, a variable speed water pump, two large atomizing air compressors, a thermocouple grid to monitor the gas temperatures and a control system to control the humidification process (Figure 3-3). The humidification lances and the flow controls were designed and constructed by B&W, although some major components, such as the water pump and the large air compressors were procured by PSCC. The location of the humidification atomizer grid is in the air heater exit duct, just downstream of the flow straighteners and near the beginning of a long straight run of duct (Figure 3-1). The humidification grid location is also the site for the sorbent injectors for the duct injection system. Initial design data obtained by B&W indicated that the flue gas flow at this location was very uniform.

The humidification atomizers are a dual-fluid design, utilizing high pressure air to atomize the water into very fine droplets. Atomizers are arranged on lances, with six atomizers per lance. Each lance also incorporates an aerodynamic shell around the atomizer assemblies that is purged with clean gas (fabric filter outlet gas is used at Arapahoe Unit 4). The purge gas is used to prevent ash deposition when the humidification system is not in use. A set of seven lances was installed into both the east and west side walls of the duct, for a total of 84 atomizers arranged in a 12-wide by 7-high grid (Figures 3-4 and 3-5). Water is supplied to the 14 lances from two common water headers, although additional shut off valves and controls are installed to prevent water flow if atomizing air flow was insufficient to any lance. Water is supplied from a city water supply and controlled with a variable speed pump. A magnetic flow meter and temperature indicator provide the signals supplied to the system controls. The water is also strained to prevent plugging of the atomizers.

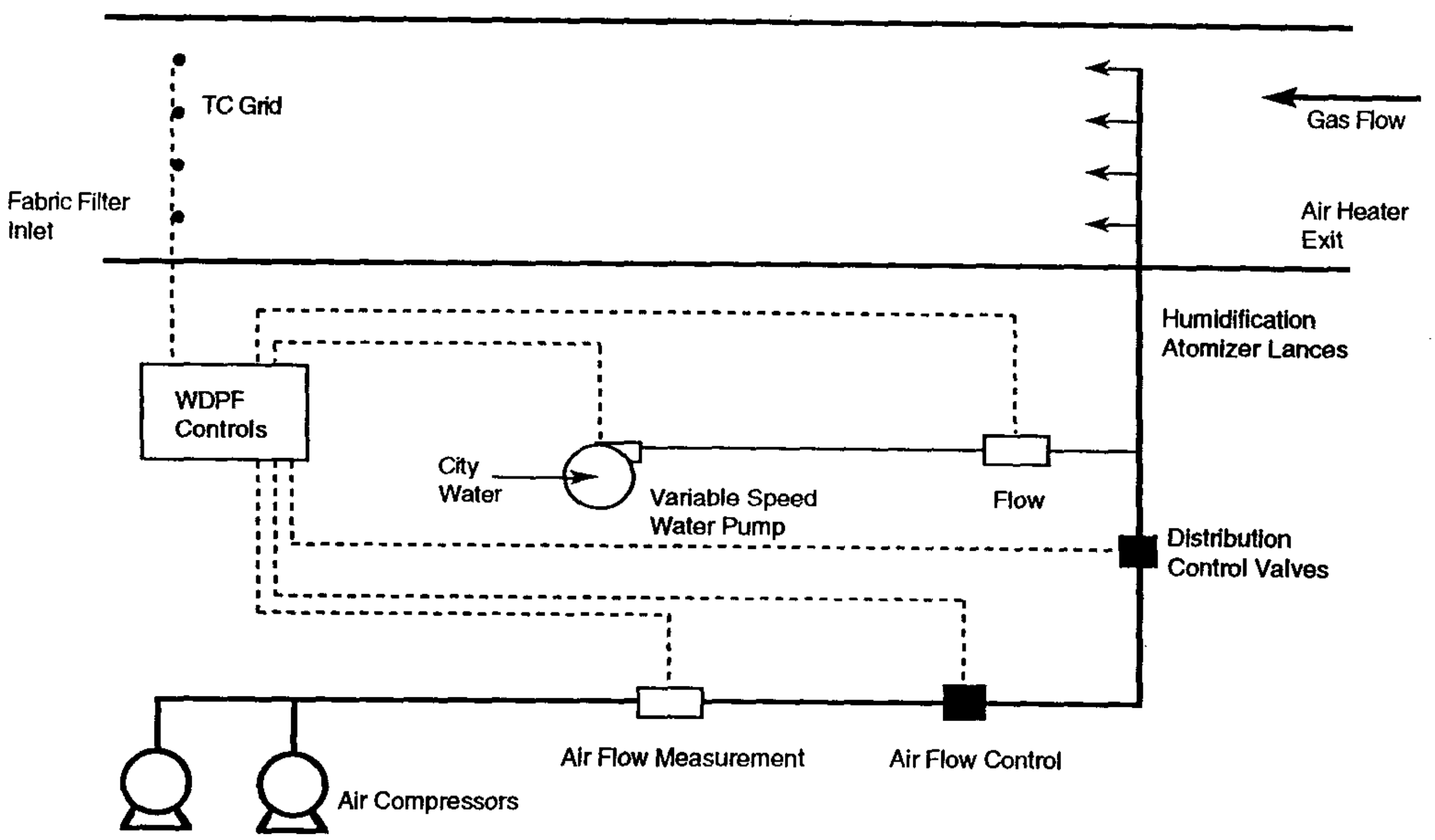

Figure 3-3. Simplified Diagram of the Humidification Injection and Control System

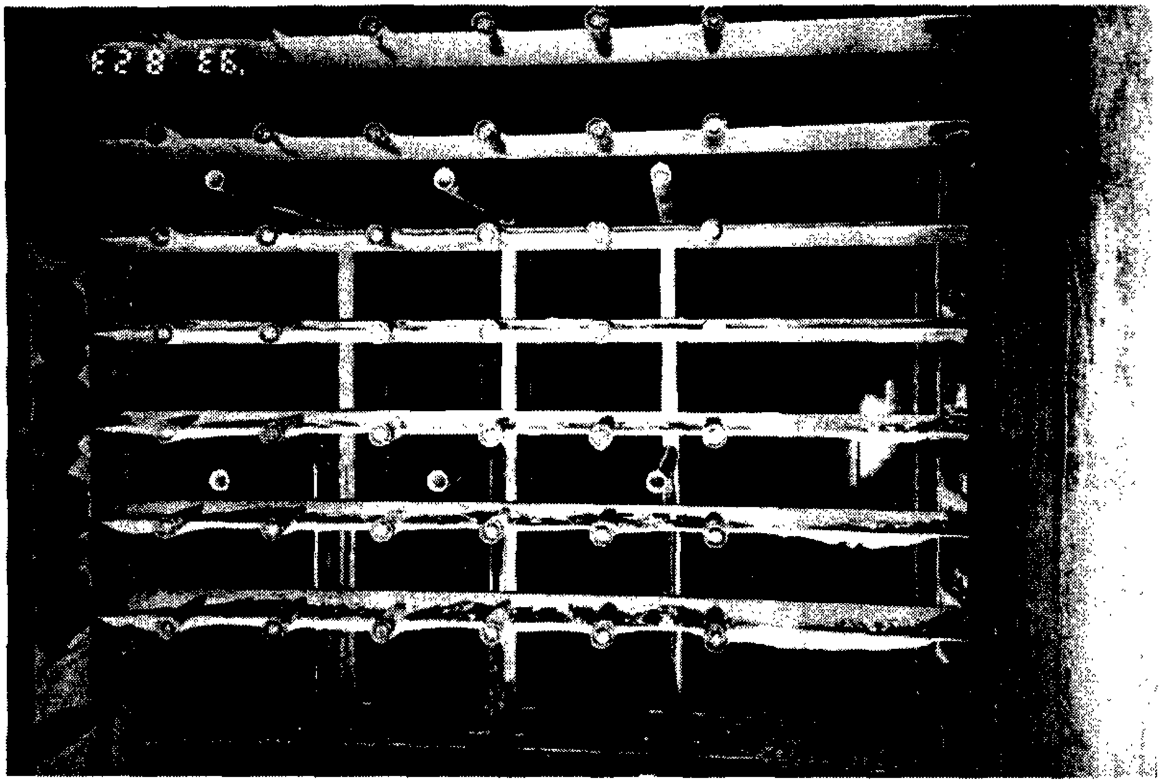

Figure 3-4. Humidification and Sorbent Injection Grids (East Half)

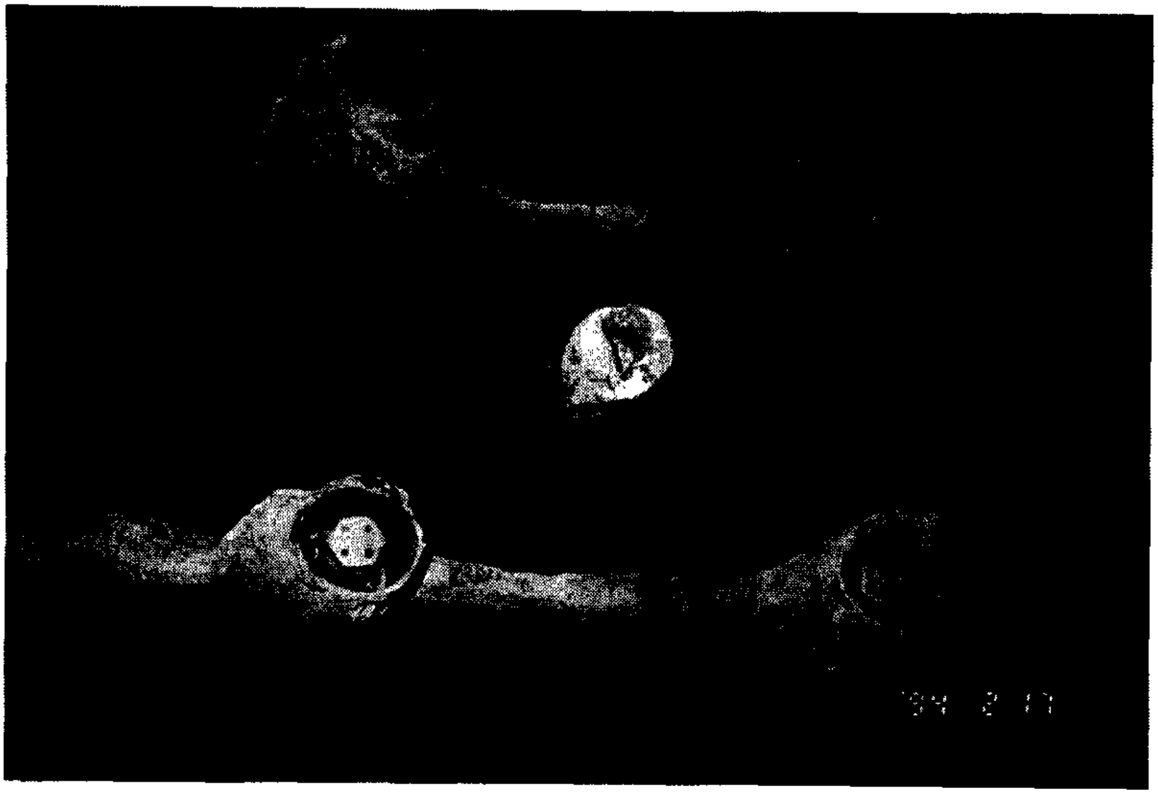

Figure 3-5. Humidification Atomizers and Sorbent Injector

High pressure compressed air is supplied to the lances from a set of headers with two sets of air flow control valves. These header control valves provide a moderate amount of water flow balance control by modulating the relative atomizer air pressure to the lances. Since a dual-fluid atomizer has some interaction between the air and water flows and pressures, reducing the air pressure to a given lance will increase the water flow, and vice versa. The two control valves provide a limited range of air pressure control and could be used to help balance the lance water flows in the vertical direction (top to bottom) by reducing air pressure to the top lances. Each lance also includes strainers to prevent atomizer plugging.

Two large compressors provide up to 7000 scfm of 140 psig atomizing air, when both are in operation. The air pressure can be modulated by a flow control valve, although the valve was 100 percent open for most tests. Compressor air flow rates (measured with a vortex shedding flowmeter), as well as pressure and temperature measurements are supplied to the control system to provide corrected air flow rate calculation. Additional strainers prevent large particles from entering the flow system. A single compressed air line supplies atomizing air to the headers on both the east and west sides of the duct. All piping after the protective strainers is stainless steel to prevent rust.

A grid of 12 flue gas thermocouples located downstream of the lances monitor the effects of the humidification system. Each individual thermocouple can be displayed on the control monitor, although the average gas temperature is used for control purposes. Alarms and water shut off controls are provided for the individual, as well as average, grid temperatures. The humidified gas temperature (fabric filter inlet grid temperature) is controlled by modulating the water flow rate. The initial humidification system installation included a thermocouple grid located approximately one-half of the way between the lances and the inlet to the fabric filter. This site was at the rear of the second transition duct, just before the duct work begins the rise to the fabric filter inlet elevation. Early tests indicated that the original thermocouple grid location was too close to the humidification grid and the temperature measurements were being biased down by wet or damp ash/sorbent deposition on the thermocouples. The grid was relocated to a point just upstream of the fabric filter inlet to minimize the erroneous measurement problems. Under low approach temperature conditions however, a few of the thermocouple probes still showed signs of wet ash accumulation. Shields were added to the upstream surfaces of these probes to prevent direct deposit accumulation on the thermocouples. These modifications provided improved measurement of the average fabric filter inlet temperature and the approach to saturation of the flue gas.

Monitoring and control of the humidification system is provided on a single screen of the Westinghouse WDPF (Westinghouse Distributed Processing Family) boiler control system. In addition to monitoring the flow, pressure and temperature of the water and atomizing air supply systems, the screen monitors the fabric filter inlet grid temperatures and provides control of the water flow rate. Automatic average grid temperature control is provided by modulating the water flow rate; while in manual mode, the water flow rate is controlled with pump speed. With the exception of the start-up and shut-down of the large air compressors and some manual isolation valves for the air and water supplies, the system is primarily controlled from a humidification control screen on the DCS.

3.4 Dry Sorbent Injection System

The dry sorbent injection system (DSI) at Arapahoe Unit 4 utilizes two identical preparation and injection systems to provide the required capacity at high sorbent flow rates and redundancy at lower flow rates. The two systems are entirely separate up to and including the sorbent injectors in the duct. The DSI system at Arapahoe Unit 4 also allows sorbent injection in either the air heater exit duct or upstream of the economizer by manual piping changes. Figure 3-6 outlines one of the two sorbent preparation and injection systems and its major components. Each system includes a storage silo, variable speed screw feeder, a rotary air lock, blower for conveying air, a pulverizer to grind the sorbent, a distributor to split the sorbent stream and the six injectors.

3.4.1 Dry Sorbent Storage and Handling

The two sorbent preparation and injection systems (labeled A and B for the testing) are identical in capacity and operation. Each has separate controls and can be independently

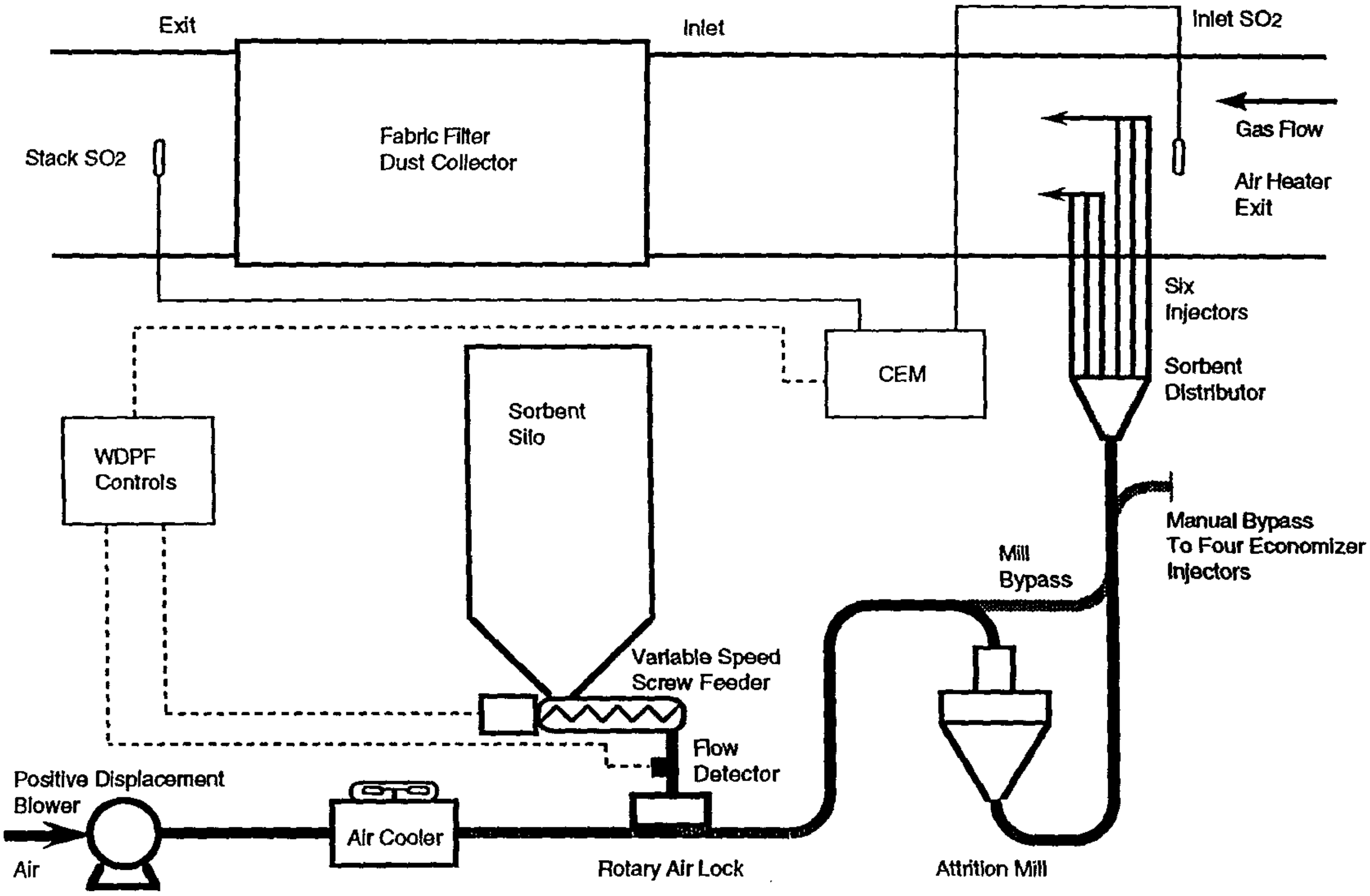

Figure 3-6. Simplified Diagram of One Sorbent Handling System and the Process Controls

operated from a control screen on the DCS. The following descriptions will characterize one of the two identical systems.

Sorbent is stored in a silo with a capacity of approximately 6100 cubic feet. Sorbents are transported by truck and pneumatically loaded into the top of the silo. The silo is vented at the top through a small fabric filter system which prevents fugitive dust emissions. An ultrasonic level indicator provides continuous silo level measurements; however in practice, the dust levels in the silo generally prevent accurate indications during operation. Manual methods of determining the silo sorbent levels are typically used.

A slide gate is installed at the bottom of the silo hopper to provide isolation from the feeder, when necessary. Directly below the slide gate are a variable speed drive and screw feeder. The volumetric screw feeder provides the sorbent flow control for the system and can be operated with local controllers in the sorbent preparation building or from the DSI control screen. The control of each feeder has an automatic control for SO_2 removal with a trim to control the NO_2 emission level, however in normal use during the test program, the feeder speed was manually set to obtain the desired Ca/S ratio. The initial setup of the screw feeder had limited maximum flow rate capacity with low density materials and, mid-way through the dry sorbent program, the screw feeder sprockets were changed to double the speed. Since the variable speed drive was not affected, the new feed rates were approximately doubled.

The screw feeder delivers sorbent directly into the top of a rotary air lock, which provides the necessary isolation between the sorbent feed and the conveying air systems. The air lock is strictly used for isolation, not feed rate control, and is therefore operated at a constant rotational speed. The air lock is vented to relieve the higher pressure from the conveying air and help prevent pressurization of the bottom of the silo and screw feeder. The vent line extends up to the top of the silo and into the fabric filter venting system. A flow detection probe installed between the exit of the screw feeder and the inlet of the air lock is used to detect the loss of sorbent flow. When properly calibrated for the sorbent type, the probe determines loss of flow and displays an alarm on the DSI control screen.

The conveying air system passes just below the rotary air lock, which allows the sorbent to drop into and be dispersed with the air. The air is supplied from a positive displacement blower that operates at a constant speed and air flow rate. The blower air pressure is monitored to determine if plugging occurs or if sorbent flow is abnormal. The air supply pressure is limited to 10 psig by a relief valve installed downstream of the blower. An air-to-air heat exchanger installed downstream of the blower cools the carrier air whenever the sorbent pulverizers are used. This heat exchanger cools the air and reduces the mill exit air temperatures to prevent overheating of the sorbent. After the air cooler, the air flows under the rotary air lock and picks up the sorbent flow.

After the sorbent and air are mixed, the flow can be directed into the Entoleter attrition mill to increase the fineness of the sorbent particles. Since the calcium-based sorbents are generally very fine, the mills were not put into service and the air coolers were not used during the current phase of testing. A bypass line can be installed to allow the calcium/air mixture to bypass the mill. The mills will be utilized during the subsequent phase of testing with sodium-based sorbents.

After exiting the mill or the mill bypass line, the sorbent and carrier air are piped to one of the injection locations, either the duct or the economizer. The injection system at each is very similar, although the number of injectors differs. Most of the testing was performed at the air heater exit duct location and will be described here, although the economizer system is physically similar. A distributor is installed on the top of the air heater exit duct to split the sorbent flow to each injector. A single pipe supplies the sorbent from the preparation system and the flow is evenly split into six injection streams for either system. At the outlet of the distributor is a separate pinch valve on each line, that can isolate the injector from the system. During the testing, the pinch valves were used to isolate a single injector line for calibration purposes. After a short period of time, the pinch valves failed due to erosion and subsequent leakage problems. The rubberlined pinch valves were replaced with ball valves which have provided a much greater resistance to erosion.

3.4.2 Air Heater Exit Duct Sorbent Injection

The duct injection location was the focus of the dry sorbent testing at Arapahoe Unit 4 and was utilized for the majority of the tests. The air heater exit location is shown on Figure 3-1 and is located just downstream of the flow straighteners. This injection location provides approximately 103 feet of duct work prior to entry into the fabric filter. Immediately after the sorbent and humidification injection location, the duct remains relatively constant in cross section for roughly one-half of the distance to the fabric filter.

Calcium- or sodium-based sorbents are injected into the flue gas stream at the same plane as the humidification system through a grid of 12 atomizers arranged in a 2 high by 6 wide array. The injection atomizers from each of the two systems (A and B) are interspersed within the grid, so that operation with only a single system provides sorbent injection across the entire duct. The A and B systems alternate injectors in a checkerboard fashion within the 12 point grid, with each system comprising six injectors, three on each side of the duct (Figure 3-7).

Each injector is of a simple two-inch pipe construction, with the pipe exit oriented downstream of the flue gas flow. This atomizer orientation allows cocurrent sorbent/ conveying air flow with flue gas flow. The injection atomizers are located at the exit plane of the humidification water atomizers, and between two adjacent humidification lances in the vertical direction (Figures 3-4 and 3-5). The atomizers enter the air heater exit duct from the top and turn 90 degrees within the duct to point downstream prior to injection.

3.4.3 Economizer Sorbent Injection

Initially, it was planned that the economizer sorbent injection location be at the economizer inlet, where the north wall access across the width of the boiler backpass would have provided the ability to attain good dispersion and mixing of the sorbent.

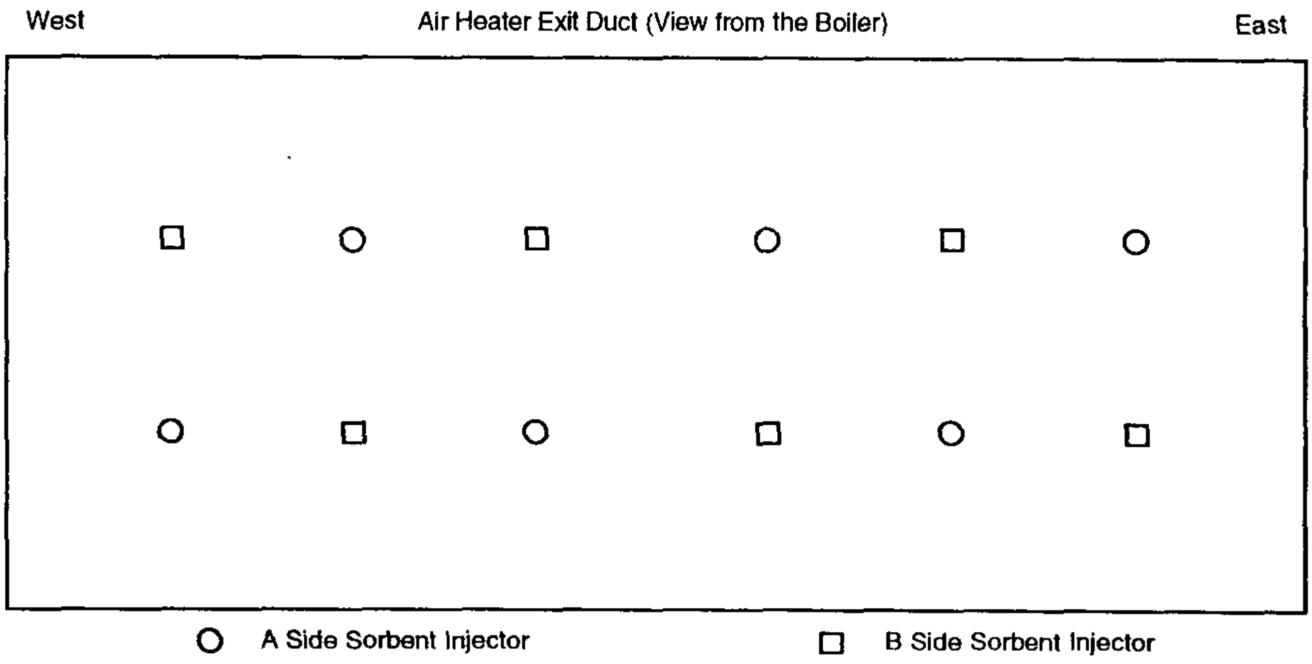

Figure 3-7. Approximate Locations of Duct Injectors from the A and B Side Sorbent Systems

However, flue gas temperature measurements indicated that an injection location between the two tube banks of the primary superheater would provide the optimum (950 to 1150°F) temperature zone. Unfortunately, a superheater header runs the length of the north wall of the boiler back pass at this location, and as a result it was necessary to install the injectors on the side walls of the boiler. Figure 3-8 shows the economizer injection location on an elevation view of the boiler, and Figure 3-9 shows the flue gas temperatures measured at a depth of approximately 5 feet from the west wall as a function of boiler load. Figure 3-9 also shows the temperature measured at the originally planned injection location (economizer inlet) for comparison.

Changing the injection location from the duct to the economizer requires plant maintenance personnel to remove and reinstall different piping connections to redirect the sorbent flow. In the economizer injection configuration, the distributors for the A and B sorbent systems are located on opposite sides of the boiler, with the A system being on the west and the B system on the east. This configuration requires that both systems be in operation in order to inject sorbent into the east and west halves of the boiler. In addition, each system is reduced to four injectors, due to the limitation of the available access areas. Figure 3-10 shows the economizer injector locations relative to the boiler plan area.

Relocating the injectors to the side walls was expected to result in difficulties in adequately dispersing the sorbent, since the plan area of the injection location is much wider than it is deep. However, once testing began, it was discovered that the distribution of sorbent was much worse than anticipated. Tests showed that the injectors, which protrude just a few inches into the flue gas stream, were only treating the area immediately adjacent to the side walls. Midway through the economizer injection tests, longer injectors were installed on the west side of the boiler in an effort to better distribute the reagent. These new injectors (Figure 3-11) not only allow deeper penetration into the boiler, but two holes on either side of each injector also provide coverage of the flue gas near the wall. The location of the side holes on adjacent injectors are spaced as shown in Figure 3-11 in order to provide optimal coverage of the flue gas between the injectors.

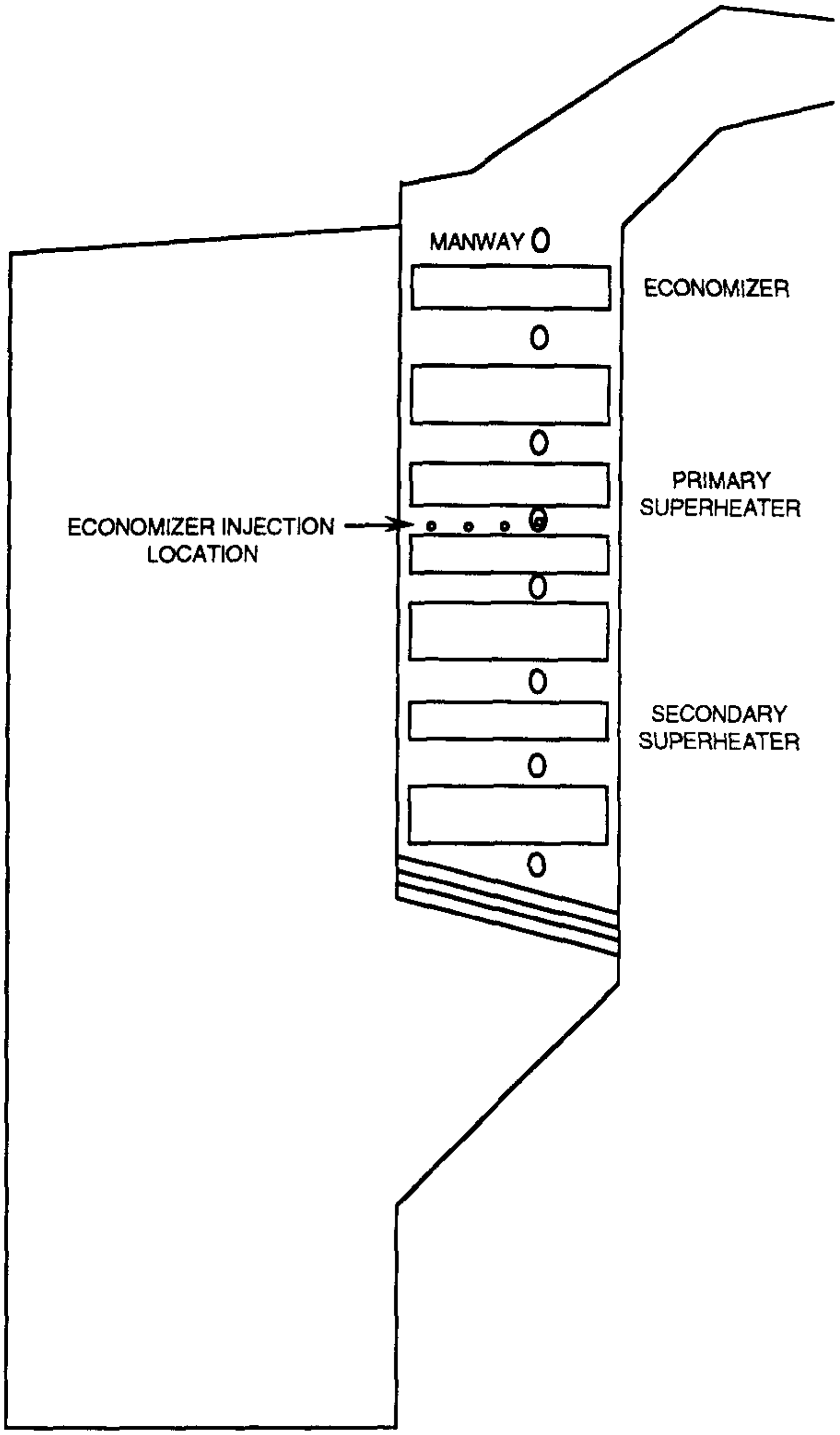

Figure 3-8. Elevation view of Economizer Injection Location

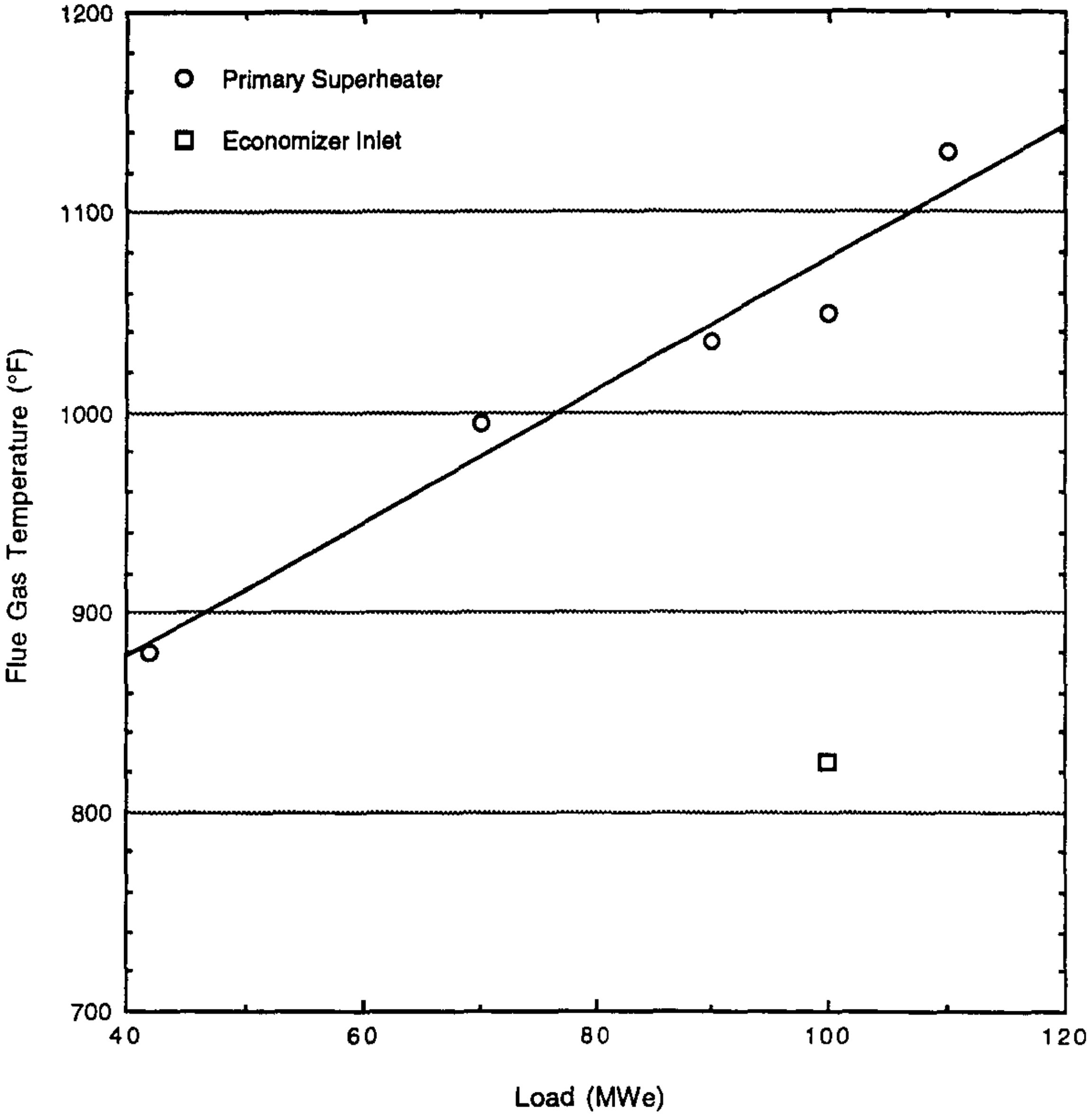

Figure 3-9. Flue Gas Temperature at Primary Superheater and Economizer Inlet Locations as a Function of Boiler Load

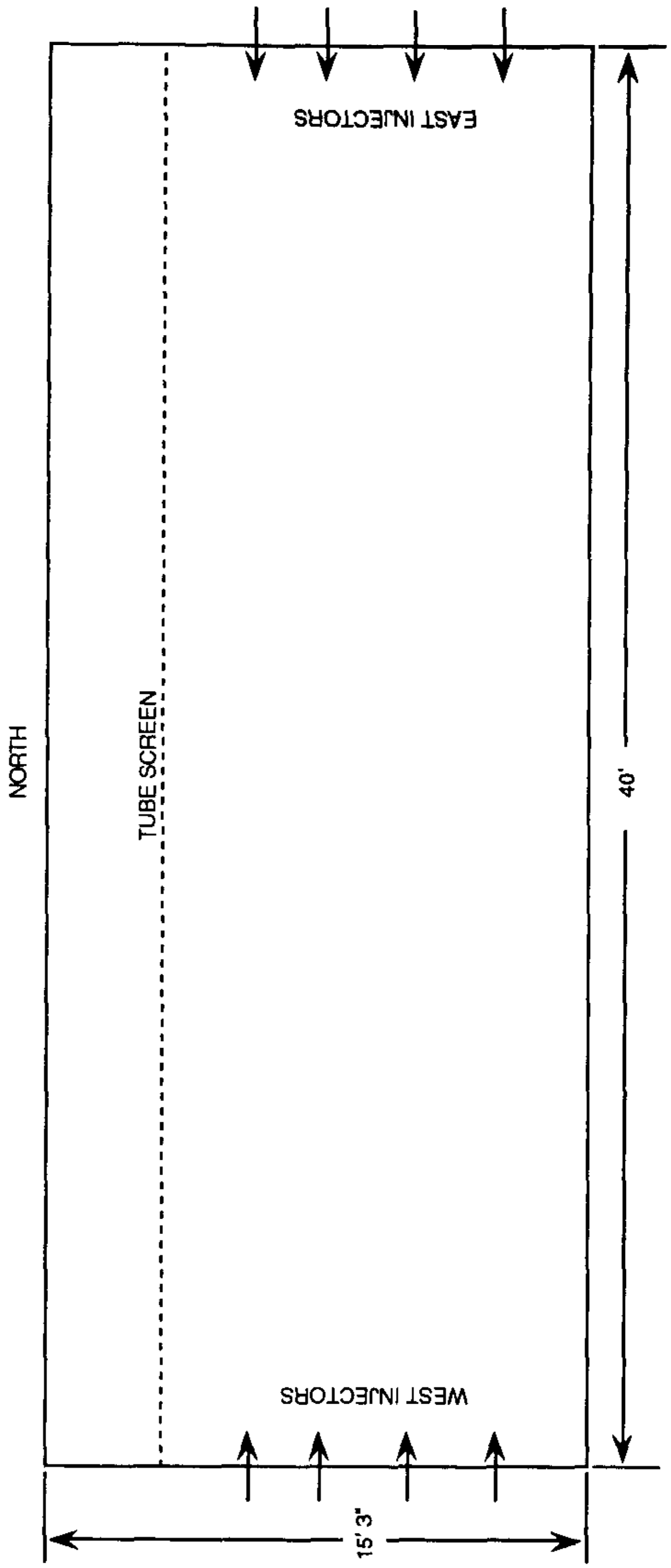

Figure 3-10. Plan View of Economizer Injection Location

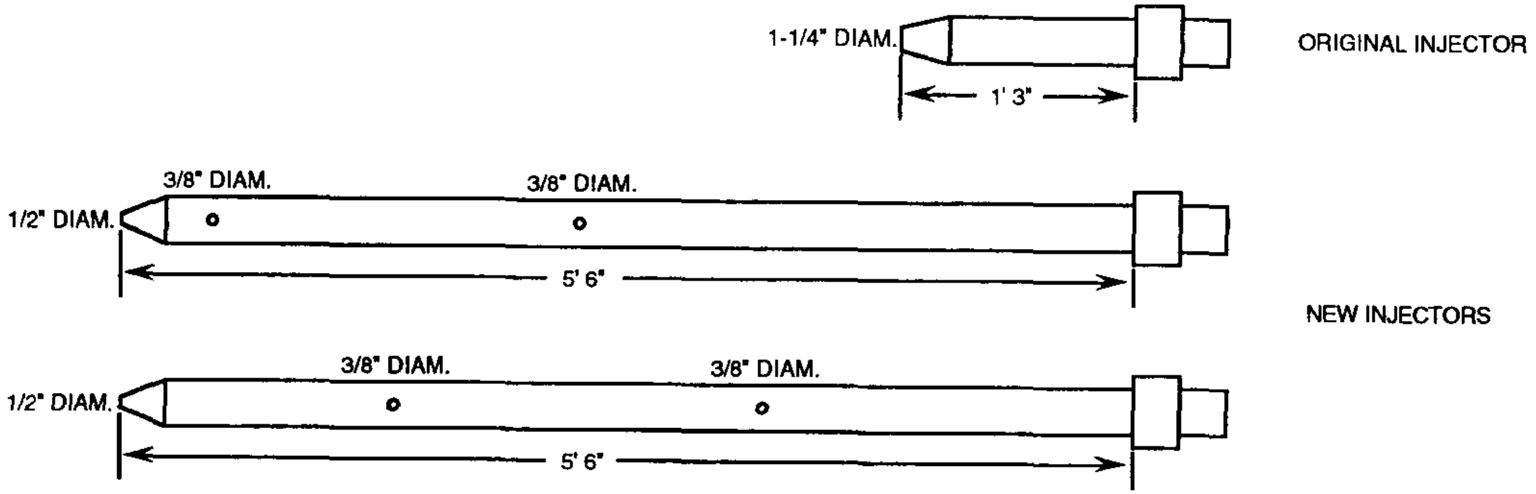

Figure 3-11. Economizer Injector Detail

3.5 Operational Problems

A number of operational problems were encountered during the calcium-based sorbent injection program and will be briefly described in this section. This experience is documented in order to avoid these problems in systems designed in the future. The problems to be discussed will be those which may be characteristic of the specific system design that could be improved with modifications, and not overall process constraints. Other problems encountered with the use or limitations of sorbent injection or humidification will be covered in later sections with the test results.

3.5.1 Humidification System Problems

Problems with the humidification system were generally limited to the control and distribution of water and not from inherent mechanical design.

Thermocouple grid temperature measurement problems were described previously and the installation of a new grid further downstream with the shielded sensors helped to reduce the effects. The wet or damp deposits on the thermocouples depressed the indicated measurement, with the measured temperature being between the wet and dry bulb temperatures. The average indicated grid temperatures will be depressed and the water flow rate will be lower than expected. The net effect will be a higher approach to adiabatic saturation temperature and lower SO_2 removals.

The ability to control the water flow through the atomizers on individual lances, to provide an even temperature distribution through the grid was limited, and could not provide the control necessary to fully balance the temperatures on the grid. Zones of low temperatures were consistently noted, but could not be altered with the available hardware configuration. These zones may have been due to biases in the water distribution, or due to variations of flue gas flow or inlet temperatures within the duct. Low temperature zones were undesirable, since these could limit the minimum approach temperatures attainable and could result in local deposition problems. The original biasing adjustments on the air pressure side of the atomizers had limited effect on varying water flow vertically among the lances. A manual water flow control valve on each lance may be one alternative to provide a better control of the water distribution.

Automatic control of the humidification system generally worked well, provided that accurate flue gas temperature measurements could be made. Arapahoe Unit 4 is a cycling unit on the PSCC system, and the unit can respond to rapid changes in load demands. During load following, over-injection of water was noted when sharp decreases in boiler load occurred. Under these circumstances, the flue gas flow was directly reduced with load, causing the humidification temperatures to drop if the water flow rate did not rapidly decrease as well. The water injection controls lagged the load reductions and caused temporary low gas temperature conditions. Over-injection of water and low gas temperatures could cause serious deposition problems as the flue gas approached the saturation temperature. These incidents did not last more than five minutes. The water flow controls used at Arapahoe are a feedback system based solely on the grid temperature. Additional tuning of the system or the addition of boiler load on a feed forward control may minimize over-injection of water.

3.5.2 Sorbent Storage and Handling Problems

A number of problems, which resulted in erratic or loss of sorbent flow, were encountered with the handling of the sorbent. Storage problems in the silo which prevented smooth flow into the screw feeder were encountered periodically. Rat holes down the center of the sorbent could impede flow by running the feeder dry, despite a considerable amount of sorbent collected on the hopper slopes. Vibrators on the silo hopper were only moderately successful, as was an "air cannon" installed on one silo hopper. Beating the hopper walls with a sledgehammer was frequently employed with some success. Some problems were simply due to the difficulty in flowing the bulk materials and were a consequence of the specific material handling properties.

Hard or compacted layers of sorbent on the silo hopper walls were seen periodically, which impeded flow down into the screw feeder. The hard sorbent layer could have been the result of moisture adsorption by the sorbent or perhaps compaction while in storage.

In any case, clearing blockages and resuming sorbent flow was often difficult due to the limited access into the hopper. Opening a port on a full silo hopper could also be dangerous, should the material begin to freely flow out of the open port.

Air leakage through the rotary air lock is suspected as a significant problem which can cause erratic feed characteristics. Air leakage from the carrier air can pressurize the outlet of the screw feeder and bottom of the silo. Sufficient sorbent levels in the silo may reduce the problem, however pressurizing the feeder and sorbent bed can disrupt the material flow and cause erratic or significantly reduced flow rates. Better air locks and improved venting systems may reduce these problems. One additional problem suspected with the air lock venting concerns the loss of sorbent carried away with vent air. With very fine materials, such as the calcium-based sorbents, a significant portion of feed material may be lost to the vent system before the sorbent is added to the carrier air. This leads to feed rate calibration errors, whenever screw feeder calibrations are performed at atmospheric pressure, while the system normally operates under carrier air pressure. Revised feeder calibration procedures were instituted to resolve these difficulties, although the root cause is the rotary air lock leakage.

3.5.3 Sorbent Injection Grids

Plugging of individual injectors or the distributor has been a recurring problem. Hard deposits within the piping may be the result of aerodynamic impaction on turns or flow irregularities, or perhaps formed from moisture from the flue gas or other ambient sources. Beating the injector lines was the first resort, but often of limited success. In other cases, disassembly was required and the hard deposits removed by hand. Injection transport lines were also filled or flushed with water to soften and remove the deposits. A few deposits have been noted at the sorbent injector tips located in the flue gas duct, although none of the injector tips have been entirely closed off. Water was not used to clean the sorbent injector lines entering the duct.

Erosion of the pinch valves located downstream of the distributor was mentioned previously, although replacement with ball valves appears to have solved this problem.

3.5.4 Determining Sorbent Feed Rate

One other issue worth mentioning at this point is the ability to accurately determine the calcium sorbent feed rate during the short term parametric tests. The project is intended as a full-scale commercial demonstration. As such, the equipment was designed accordingly. In actual long-term operation, the control system would be set at a percent SO_2 removal efficiency, and the feed rate adjusted accordingly. Overall sorbent utilization would then be determined on an integrated basis over a relatively long time period. In a commercial design, there is no need to provide the means to gravimetrically measure the instantaneous sorbent feed rate.

The lack of an instantaneous gravimetric sorbent feed rate posed some inaccuracies in determining the Ca/S molar ratio for the short-term tests. In order to determine the feed rate, calibration of the screw feeder was done two ways. As mentioned previously, a calibration was performed by shutting off the rotary air lock, and opening up an access port above the rotary air lock. The feeder was then calibrated with the discharge at atmospheric pressure. This raised a concern that when operating in the normal mode, the back pressure from leakage past the rotary air lock could affect the feed rate relative to the atmospheric calibration. To check this, a second calibration was performed while the system was on-line. For this calibration procedure, the valve for an individual injector downstream of the splitter was turned off. A fabric filter bag was attached to the flexible hose downstream of the valve. A sorbent sample was then collected and weighed from each injector line. Typically, this procedure yielded a feed rate approximately 10 to 20 percent less than the atmospheric calibration of the screen feeder. All data presented in this report is based on the more accurate injector calibration.

3.6 Typical Operating Conditions

To provide a perspective of the operating conditions for the duct humidification/calcium injection system, Table 3-1 provides a summary of typical full load operating conditions for the system.

Table 3-1 shows typical operating conditions for Arapahoe Unit 4 and the calcium injection/humidification system at full load (100 MWe) operation. The table gives typical operating conditions of the system, although these will vary with ambient conditions and other boiler related factors. The residence times were estimated with 100 MWe operation and typical humidification rates.

Table 3-1

Typical Operating Conditions for Sorbent Injection and Duct Humidification

Boiler Load:	100 MWe
Air Heater Exit	
Flue Gas Flowrate:	232,000 dscfm
Gas Velocity:	42.5 ft/sec
Dry Bulb Temperature:	280°F
O_2:	5.5% (dry)
Wet Bulb Temperature:	118°F
H_2O:	9.3%
SO_2:	400 ppm (dry @ 3%O_2)
Humidifier/$Ca(OH)_2$ Injection	
Water Flow Rate:	65 gpm
Atomizer Air/Water Rate:	0.54 lb/lb
$Ca(OH)_2$ Rate (Ca/S = 2):	35 lb/min (2100 lb/hr)
Fabric filter Outlet	
Dry Bulb Temperature:	148°F
Approach to Adiabatic Saturation:	30°F
O_2:	5.5%
H_2O:	13.2%
Approximate Residence Times (for $Ca(OH)_2$ Inj. @ 100 MWe) to	
Air Foil:	~0.9 - 1.1 sec
Original Thermocouple Grid:	~1.4 - 1.6 sec
Fabric filter Inlet:	~2.4 - 2.7 sec

4.0 MEASUREMENT METHODS

This section describes the measurement methods used to determine the humidification system operating conditions and the sorbent injection SO_2 reductions.

4.1 Gas Analysis Instrumentation

An Altech 180 continuous emission monitoring (CEM) system was purchased as part of the Integrated Dry NO_x/SO_2 Emissions Control System and installed during the low-NO_x combustion system retrofit. The CEM system utilizes a Perkin Elmer MCS 100 infrared gas analyzer which is capable of continuously analyzing eight gas species simultaneously, using either gas filter correlation or single beam, dual wavelength techniques.

The analyzer cycles through and measures all eight gas species in approximately 22 seconds. In that time, two readings are made for each gas species to be measured. The first reading is a reference value at a known wavelength and gas concentration (either 0 or 100 percent), and the second is a measured reading to determine the quantity of the desired species in the sample stream. Table 4-1 provides a listing of the full-scale range, measurement technique, and interfering species for each of the gases measured.

Table 4-1
Gas Species Measured by Perkin Elmer MCS 100 Analyzer

Measured Species	Range	Measurement Technique	Interfering Species
NO	0-500 ppm	Gas Filter Correlation	H_2O
CO	0-400 ppm	Gas Filter Correlation	H_2O
SO_2	0-400 ppm	Single Beam Dual Wavelength	NH_3, H_2O
NO_2	0-100 ppm	Single Beam Dual Wavelength	NH_3, SO_2, H_2O
CO_2	0-20 volume %	Single Beam Dual Wavelength	H_2O
H_2O	0-15 volume %	Single Beam Dual Wavelength	None
N_2O	0-100 ppm	Single Beam Dual Wavelength	CO, CO_2, H_2O
NH_3	0-50 ppm	Gas Filter Correlation	CO_2, H_2O

Using the gas filter correlation technique, the system takes a reference reading at a known wavelength and a known concentration of gas, usually 100 percent. The system then takes another reading at the same wavelength for the sample gas and records the energy absorbed by the sample. The relative difference in energy is then representative of the concentration in the sample gas.

Likewise in the single beam, dual wavelength method, a reference reading is taken at a wavelength where the desired species does not absorb energy (zero percent reference). The system then takes a measured reading at a wavelength where the desired species is known to absorb energy. The relative difference in energy is again representative of the concentration of the species in the sample stream.

Once the ratio of reference to measured energy is calculated, the energy level is corrected to account for interferences via reference tables for each specific gas. After correction for interferences, the data is zero adjusted, converted to the appropriate units, calibration corrected, and output for display and recording.

Since O_2 is not infrared active, the CEM system also contains an Ametek O_2 analyzer. The sample cell is a zirconium oxide, closed-end tube with electrodes of porous platinum coated onto the inside and outside of the tube. The cell produces a millivolt signal proportional to the relative difference of O_2 inside and outside of the cell. The millivolt signal is converted to percent O_2, scaled (0 to 25 percent), and then displayed and recorded.

All CEM analyzer and sampling system functions, including a daily automatic calibration sequence, are controlled by the MCS 100 programmable logic controller (PLC). The measured gas concentration data is displayed on a dedicated 486-based computer, which also provides data logging, manipulation and reporting capabilities.

A Relative Accuracy Test Audit (RATA) was performed on March 5, 1993, in order to verify the accuracy of the CEM system. The audit was performed by TRC Environmental Corp. in accordance with the requirements established in 40 CFR, Part 60, Appendices A and F. Complete documentation of the audit is contained in a separate report (Smith, et al., 1993b), and the results are summarized in Table 4-2.

Table 4-2
CEM RATA Results

Parameter	Relative Accuracy %
CO_2 (%, wet)	2.64
Moisture (%)	7.86
O_2 (%, wet)	17.81
NO (ppm, wet)	1.53
NO (lb/MMBtu, wet*)	5.93
NO (ppm, dry)	1.02

* Calculated on an O_2 basis

Acceptance criteria for RATA evaluation of component instruments of the CEM is 20 percent. Based upon the results, all individual parameters were found to be within the acceptance criteria.

4.2 Gas Sampling System

As shown in Table 4-1, the MCS 100 is configured to measure NH_3. Although this feature was not utilized during the current series of tests, this capability imposes some special requirements upon the design of the CEM sampling system. In order to maintain the integrity of the sample, the entire sampling system (probe, sample line, pump, flowmeter, and sample cell) must be maintained at 230°C (445°F). Due to these heat tracing requirements, the CEM system is configured to sample from only two different single-point locations. One at the exit of the air heater in the duct leading to the fabric filter, and one downstream of the fabric filter and ID fans, in the duct leading to the common stack for Units 3 and 4. The air heater exit location is at a point just upstream of the flow straightening vanes and the sorbent injection/humidification lances (see Figure 3-1). The air heater exit location is used to determine the initial boiler exit gas conditions, while the stack or fabric filter outlet sample location is used for the determination of effects after the humidification and sorbent injection. Calculation of the SO_2 removal between the air heater exit and the stack locations includes correction for dilution from ambient air inleakage and the dilution resulting from the vaporization of the humidification water.

In order to obtain a representative composite gas sample from the boiler, as well as provide the ability to look at discrete areas of the flue gas flow, Fossil Energy Research Corp. provided a sample gas conditioning system which would allow sampling from additional unheated sample probes. Although the MCS 100 was utilized as the gas analysis instrumentation, the measurement of NH_3 at the additional sampling locations was not possible due to the lack of high temperature heat tracing. A schematic of the sample gas conditioning system is shown in Figure 4-1. The system can accommodate up to 24 individual sample lines. Up to 12 of these can be composited together and then analyzed. Each of the individual sample streams is dried in a refrigerated dryer where the gas is cooled and the moisture is dropped out in a trap. Each stream then passes through a metering valve and rotameter, after which all the streams are blended together in a manifold and directed to a pair of sample pumps. The rotameters are used to balance the individual flows in order to provide an accurate composite blend. Downstream of the pumps, a portion of the composited sample is diverted to a final pass through the condenser (where the increased pressure aids in the removal of any remaining moisture), through a final particulate filter, and then to the Altech CEM for analysis.

The locations of the unheated sample probes during the current phase of testing were identical to that for the previous LNB/OFA and LNB/OFA/SNCR tests, namely: 12 at the exit of the economizer, 6 at the exit of the air heater, and one in the fabric filter outlet duct leading to the stack. Additional sample locations were provided for the fabric filter compartment outlet and the fabric filter inlet gas measurements that were performed manually. The sample probe grid in the horizontal duct at the economizer exit is shown in Figure 4-2. Although this duct is 40 feet wide, it is only 7 feet deep, so an array of probes positioned two high by six wide was deemed adequate to obtain a representative gas sample. The short probes were located at one-fourth of the duct depth, and the

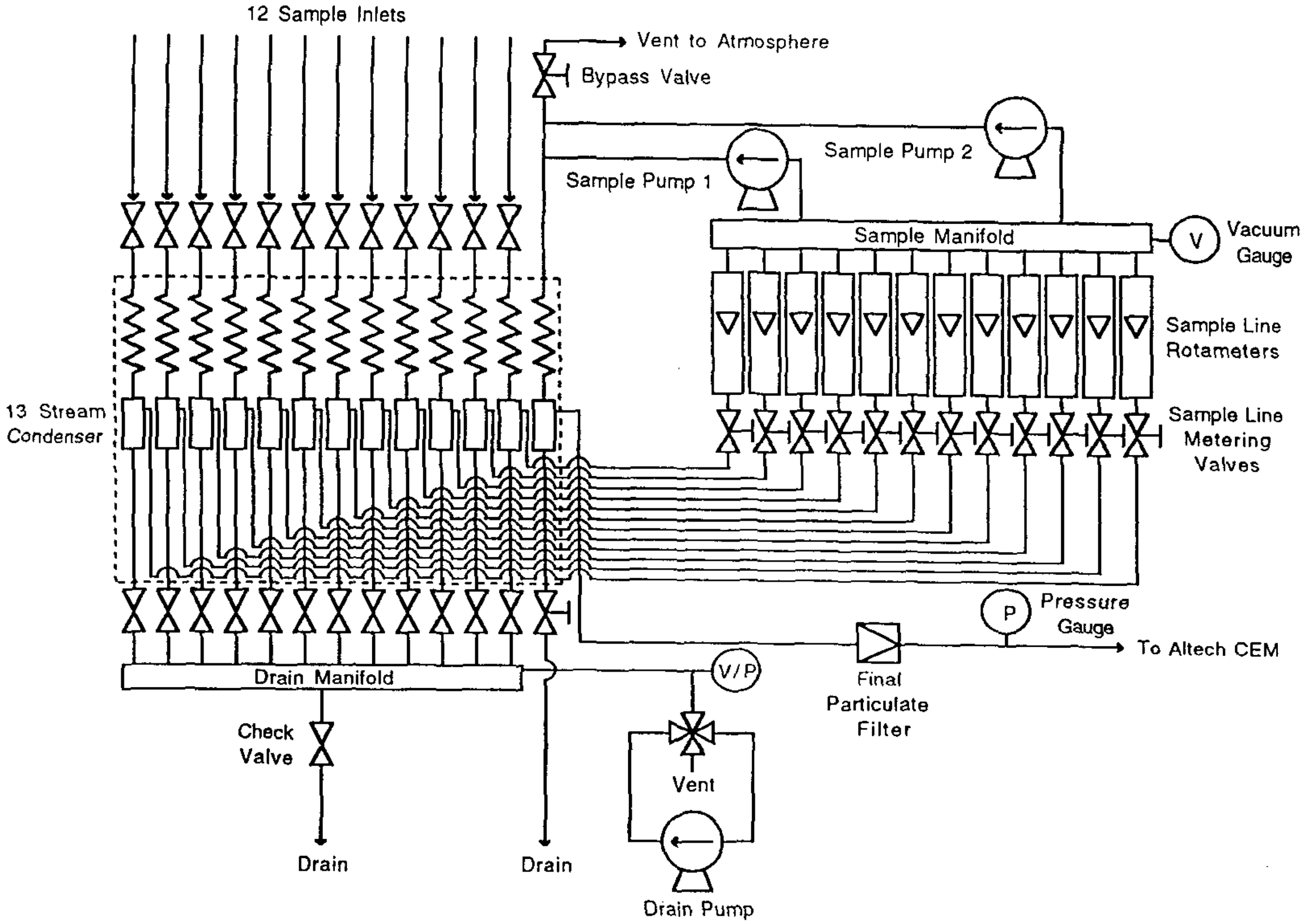

Figure 4-1. Sample Gas Conditioning System

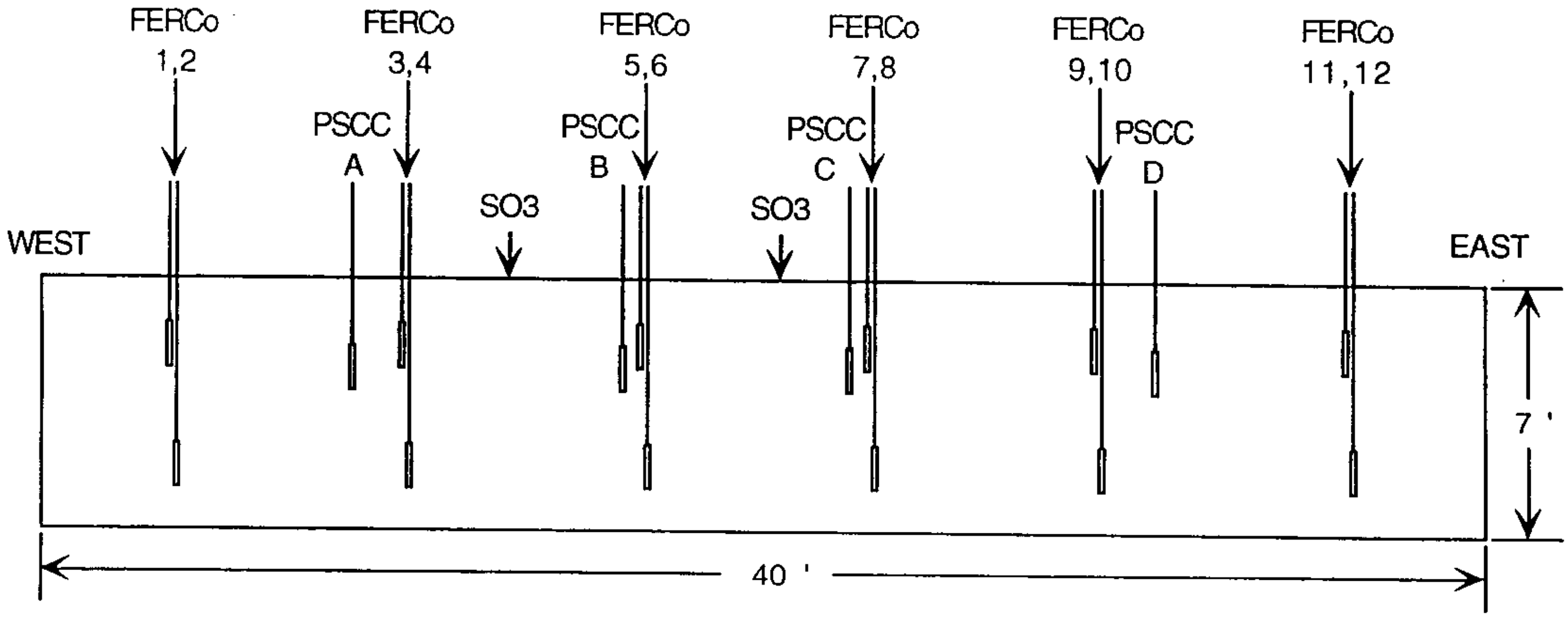

Figure 4-2. Economizer Exit Sampling Locations

longer probes at three-fourths of the duct depth. This spacing vertically divided the duct into equal areas. The use of two probe depths also provided the opportunity to ascertain any vertical stratification of gas species within the duct. Individual sample probes consisted of stainless steel tubing with sintered metal filters on the ends. The sample lines which transported the gas to the sample conditioning system, consisted of polyethylene tubing which was heat traced and insulated to prevent freezing during the winter months.

Figure 4-2 also shows the location of the four PSCC O_2 probes at the economizer exit which are used for boiler trim control. The PSCC equipment uses *in situ* probes that determine the O_2 concentration on a wet basis. These probes (numbered A, B, C and D) were located approximately three feet upstream of the Fossil Energy Research Corp. (FERCo) grid, and very near probe numbers 3, 5, 7 and 9. Two additional sampling ports were available at the economizer exit which were used for limited SO_3 measurements during the baseline burner and LNB/OFA tests.

The importance of the position of the 12-point grid relative to the four PSCC O_2 probes was realized during the baseline burner tests when it was found that the average O_2 measured from the grid was nominally one percent higher than the average indicated in the control room. This difference was attributed to the inability of the four PSCC probes to detect the elevated O_2 levels along the east and west sides of the duct which resulted from air in-leakage. A comparison between the control room and average economizer exit O_2 levels was made during the low-NO_x combustion system tests in order to determine if the retrofit had any effect on the difference between the two. This comparison also permitted correlation of the typical control room data with the results presented in this report. Figure 4-3 shows a comparison of the two average O_2 values for all the parametric tests performed during the LNB/OFA tests. The average economizer exit O_2 levels were nominally one percent higher than those indicated from the four PSCC probes. Approximately 0.3 to 0.4 percent O_2 of this difference can be attributed to the wet versus dry measurement basis between the two analyzers. The balance of the difference was due to the non-uniform O_2 distribution across the duct, and

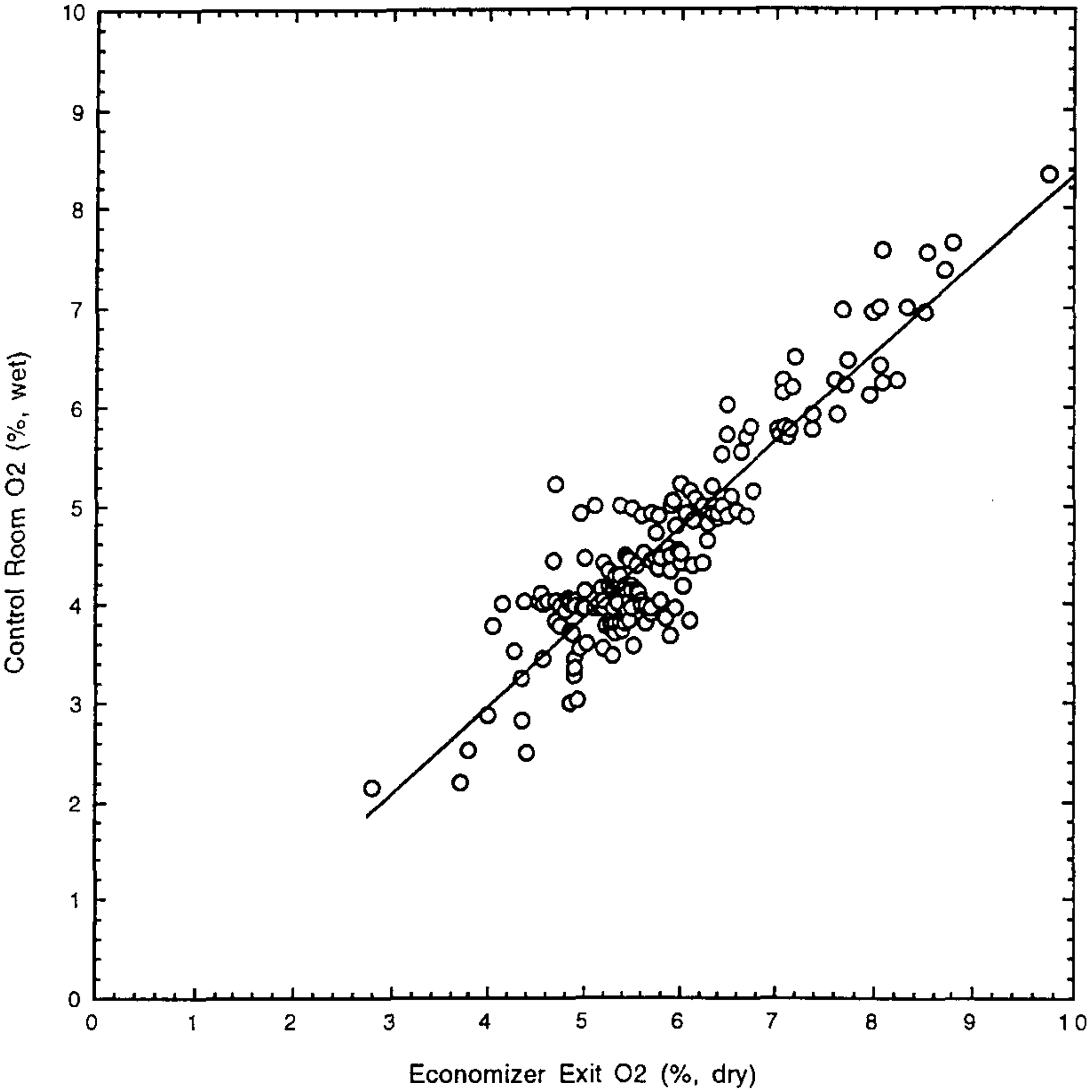

Figure 4-3. Comparison between Control Room O_2 and Economizer Exit Grid O_2 Measurements

the placement of the PSCC O_2 probes relative to the east and west walls. A significant amount of data scatter is seen in Figure 4-3, although it should be noted that variations in boiler operating parameters, such as the number of mills in service or overfire air flow, can affect the O_2 distribution, and thereby affect the difference in the average O_2 measured by each method.

The economizer grid probes were not used to determine the SO_2 emissions reductions from the sorbent injection or humidification processes; however, the grid was used to determine the actual boiler O_2 levels and used in the calculations for total flue gas flow. This measurement point was also used for accurate determination of average boiler NO_x emissions. Additional gas sample probes were installed at the air heater exit and the stack (fabric filter outlet duct) locations. These cold line probes at the air heater exit and stack were generally not utilized for the dry sorbent and humidification test programs. Only a limited number of probes were utilized at these test locations; six at the air heater exit and a single probe at the stack location. Figure 4-4 shows the location of the probes at the air heater exit. These sample probes and tubing were similar to the installation at the economizer exit. The staggered probes were installed at one-fourth and three-fourths duct depths, similar to the economizer exit. The figure also shows the location of the heated probe for the CEM system at the exit of the air heater. This probe was not in the same plane as the six-point grid, but approximately 3 feet upstream. At the stack sampling location, the heated probe for the CEM system was approximately 20 feet upstream of the unheated probe installed during the baseline burner tests. Only a single probe was used for both the CEM and the unheated probe locations since both were downstream of the fabric filter and induced draft fans where little stratification of the flue gas stream was expected. Figure 4-5 shows the installation of the heated CEM probe in the fabric filter outlet duct.

In addition to the gas sample sites for the Altech and the FERCo systems, additional gas measurements were obtained from the individual fabric filter compartments. A separate fabric filter gas sample stream was added to the FERCo sample system and subsequently analyzed with the Altech CEM. Since accurate SO_2 emissions would be

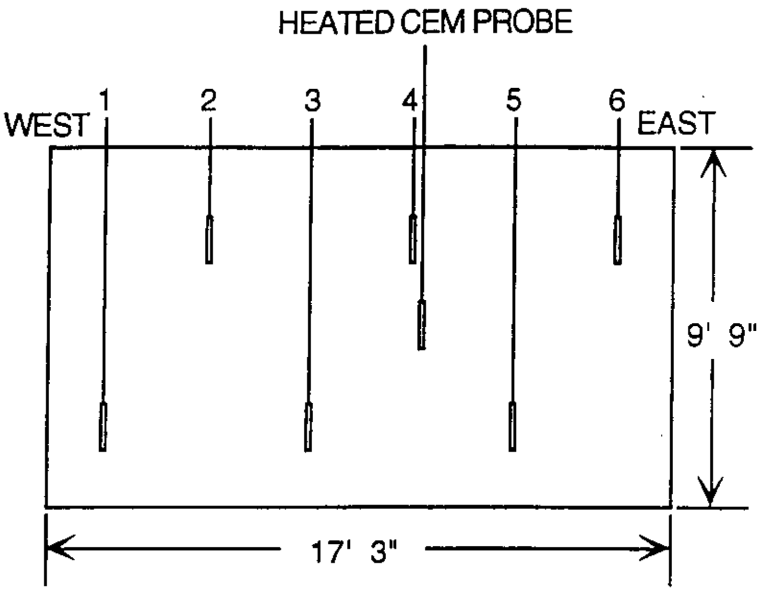

Figure 4-4. Air Heater Exit Sampling Locations

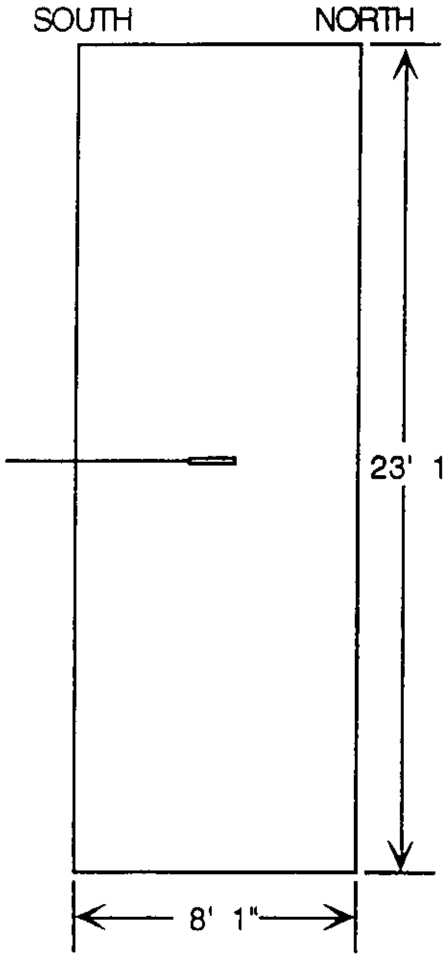

Figure 4-5. Fabric Filter Outlet Duct Sampling Location

required from the fabric filter compartment samples, a non-bubbling condenser and water dropout were added to the sample line just outside of the compartment sample location. Initially, existing gas taps installed for monitoring compartment pressure drop were used to obtain a compartment gas sample from the top of the tube sheet on the clean gas side. During a boiler outage, a teflon line was installed in the top of each compartment that was used to pull a sample from the center of the compartment clean gas outlet opening. A fitting was installed on the door of each compartment to access this compartment gas sample. The compartment gas samples were acquired manually and required that the sample line and water dropout be moved and reconnected for each compartment during this measurement. This data was utilized to analyze the SO_2 removals and indirectly determine the sorbent distribution on a compartment-by-compartment basis. A comparison between the CEM stack sampling location and the average of the compartment samples showed very good agreement, and indicated that the compartment gas sampling technique was valid.

4.3 Approach To Adiabatic Saturation Temperature

The measurement of the flue gas temperature and its approach to adiabatic saturation is a key variable in characterizing the humidification and SO_2 removal process with calcium-based sorbents. The use of a thermocouple grid should permit an accurate evaluation of the flue gas temperature, given sufficient residence time and an even distribution of water, flue gas and temperature.

However, the problems with wet or partially wet thermocouples resulted in lower than actual gas temperature indications (i.e., a temperature between the true wet bulb and dry bulb temperature). The data resulting from a test under these conditions would indicate low SO_2 removals, since the actual approach to adiabatic saturation temperature would be higher than indicated by the thermocouple grid. Correctly evaluating the actual flue gas and approach temperatures was considered a high priority item for evaluating the test results. To partially solve the problem, the thermocouple grid was moved further downstream and shields were placed in front of the thermocouples most susceptible to wetting. While this improved the gas temperature measurement, the grid still did not accurately indicate the dry bulb temperatures.

Several means of verifying the actual flue gas temperature and the amount of humidification were used early in the test program. One means of checking the thermocouple grid was to monitor the steady state fabric filter outlet temperatures. Since the humidification system was restarted for each test day during the parametric testing, a number of hours were required for the fabric filter and all associated flue gas duct work to equilibrate to the reduced temperatures. Two fabric filter exit temperatures were available, one was a single thermocouple and signal transmitter located at the fabric filter exit and the second was a thermocouple system located in the stack duct, close to the Altech monitor. Although there were some questions regarding the accuracy of the transducer signals at the stack location, as well as concerns about the flue gas temperature increase associated with the energy input from the ID fans, the data indicated that grid measurement errors were occurring. Temperature traverses of the stack duct were also performed to verify the fabric filter exit temperatures. Finally, additional thermocouples were installed at the ID fan inlet ducts (four total) to provide a better means of monitoring fabric filter exit temperature. All of these verifications indicated that the equilibrium fabric filter exit temperatures were higher than the average measurement by the thermocouples at the inlet grid during steady state tests at high humidification rates. This is shown in Figure 4-6. While measuring the temperature at the exit to the fabric filter is sufficient for the parametric tests which are conducted at steady state conditions, it is not adequate for load following.

Wet bulb temperature measurements were performed to verify the humidification effect of the flue gases. The wet bulb temperature is used in psychrometry to determine the saturation temperature of an air/water mixture, and in conjunction with the normal or dry bulb temperature, can be used to determine the relative humidity. Wet bulb temperatures were manually performed by wrapping a cloth around a thermocouple and wetting the wick prior to insertion into the flue gas duct. Wet bulb measurements verified that the calculated saturation temperatures for the flue gases were accurate. Wet bulb

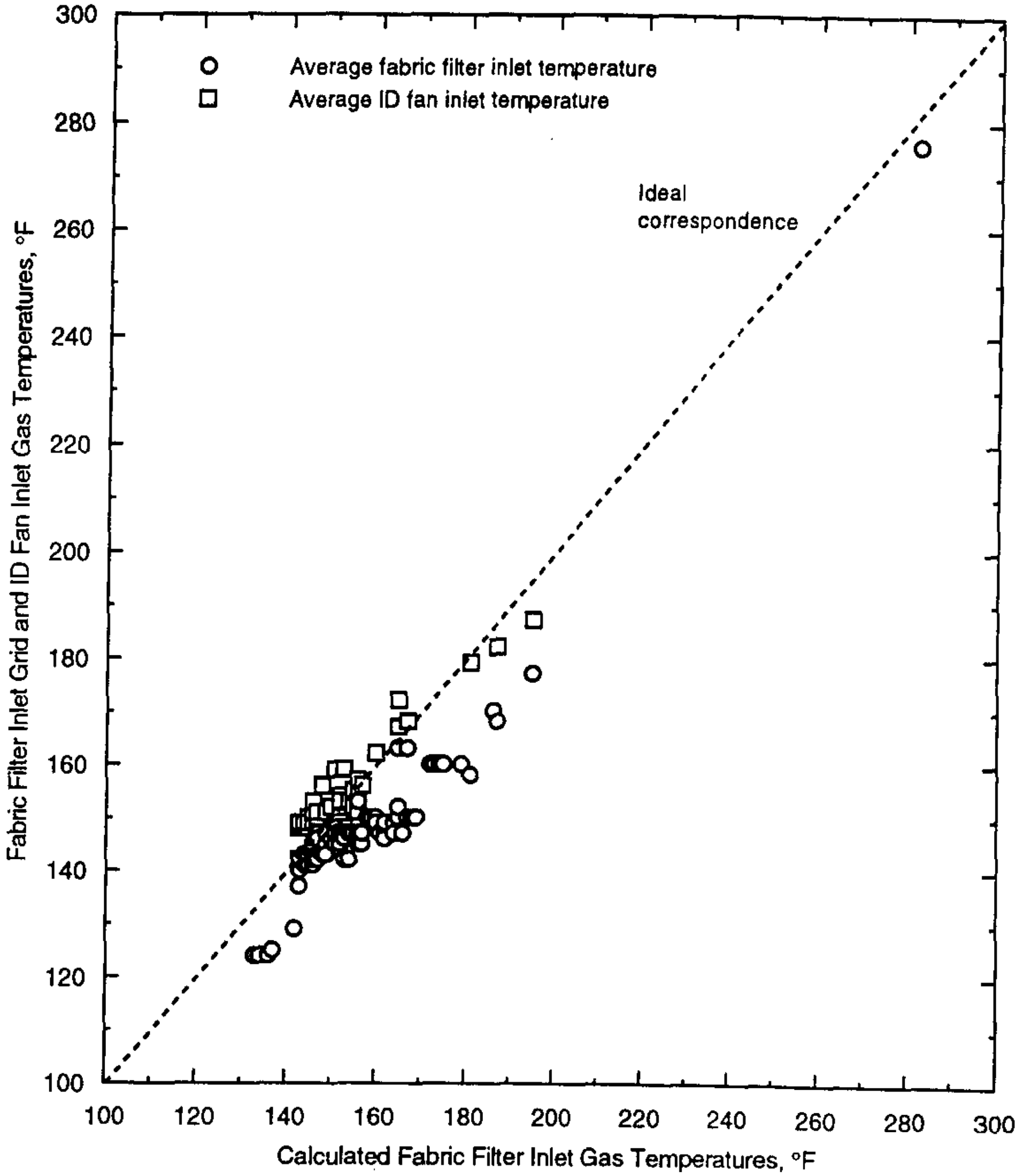

Figure 4-6. Comparison of the Calculated Humidification Gas Temperature with the Fabric Filter Inlet Grid and ID Fan Inlet (Fabric filter Exit) Temperatures

temperature measurements were within one degree Fahrenheit of the calculated saturation temperatures and verified the use of the calculation methodology. Psychometric calculations were performed to model the humidification process and verify the water flow rate and the average fabric filter inlet grid temperature measurements. Assuming an adiabatic humidification process and applying continuity for the water vapor and flue gas, as well as conservation of energy between the inlet flue gas, liquid water and the humidified flue gas streams were the basis of the calculation. The equations required water flow rate and temperature, air heater outlet water vapor content and temperature, and boiler load and O_2 level inputs to determine the humidified gas temperatures. Flue gas flow rates were based upon gas flow measurement tests at known boiler O_2 levels and corrected for the test conditions of actual boiler load and O_2. Inlet conditions were obtained from boiler gas temperature and Altech H_2O and O_2 measurements, while the evaluation of the boiler O_2 level was determined from the 12 point economizer exit grid average. The calculation also included a correction for heat rate that becomes important at low loads.

The calculations determined the flue gas saturation temperature and the humidified gas temperature, given the boiler and water input parameters. The calculations also confirmed that when the humidification water flow rates were high, the measured grid temperatures were being biased below the dry bulb temperature. The equations were used to determine the calculated water flow rates for the desired humidification temperature or approach temperature set point. Verification of the calculations were also indicated by the steady state fabric filter outlet temperature measurements and the manual wet bulb temperature measurement.

During the test program, the calculations were relied upon to determine the operation point of the humidification system and to determine the approach to adiabatic saturation temperature of the flue gas. Errors from the fabric filter inlet grid were unavoidable at high water flow rates, but the set point temperatures could be biased to provide the desired test conditions, while maintaining automatic controls for the water injection. In this report, the calculated values were utilized for determining the humidification process operation and for all data interpretation. However, the data summary in the appendix includes the calculated dry bulb temperature as well as the measured values throughout the system.

5.0 DUCT INJECTION TEST RESULTS

This section will present the results of the duct injection/humidification tests. In presenting the results, the calcium hydroxide properties will be presented first (Subsection 5.1). This will be followed by the SO_2 removal and performance of the duct injection system (Subsection 5.2). Then, detailed measurement in the duct and individual fabric filter compartments will be presented (Subsection 5.3). Subsection 5.4 will discuss the chemical analysis of solids taken from the fabric filter hoppers. Finally, Subsection 5.5 will discuss the overall operability of the system, including duct deposition and fabric filter operating problems.

5.1 $Ca(OH)_2$ Characteristics

The calcium hydroxide used for the test program, both duct and economizer injection, was obtained from Pete Lien & Sons, in Rapid City, S.D. The chemical composition and physical characteristics of the calcium hydroxide are shown in Table 5-1. The mass mean diameter (MMD) particle size (determined by sedimentation) was 2.67 microns. The particle size distribution for the sedimentation analysis is shown in Figure 5-1.

Table 5-1

$Ca(OH)_2$ Characteristics

Source:	Pete-Lien & Sons
Calcium Content:	68 wt% CaO [75.6 percent if pure $Ca(OH)_2$]
Particle Size (MMD by sedimentation):	2.67 microns
BET Surface Area:	14.8 m^2/gm

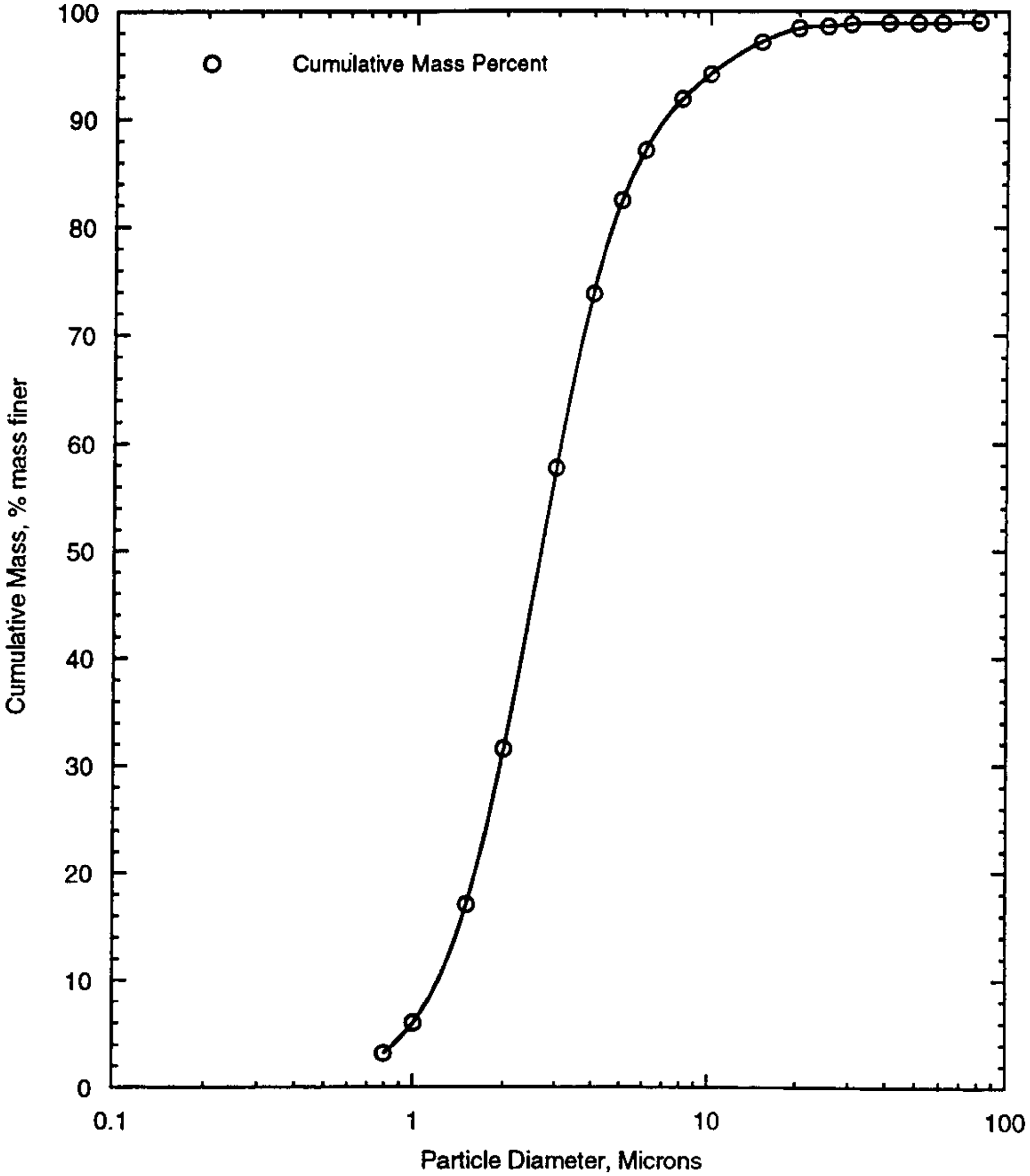

Figure 5-1. $Ca(OH)_2$ Particle Size Distribution (by Sedimentation)

5.2 SO_2 Removal Performance

The primary parameters that control the SO_2 removal of the duct injection/humidification system are 1) the approach to adiabatic saturation temperature (T_{app}), and 2) the amount of $Ca(OH)_2$ injected (i.e., Ca/S molar ratio). For the present test program, T_{app} was varied from 20 to 76°F by varying the amount of water injected. The Ca/S ratio was varied from nominally 0.4 to 2.2. The majority of the testing focused on approach to adiabatic saturation temperatures of 30 to 40°F and Ca/S ratios of nominally 2.

Before presenting the results, it should be reiterated that the approach to adiabatic saturation temperature can be determined a number of ways: 1) measured fabric filter exit temperature and wet bulb temperature, 2) measured thermocouple grid temperature at the fabric filter inlet along with the wet bulb temperature, and 3) calculated approach to adiabatic saturation based on air preheater exit temperature, flue gas flow rate, water injection rates and flue gas water vapor content. In principle, all of these methods should yield the same value if the system is at equilibrium. Section 4 discussed the relationships between these various methods. The thermocouple grid at the inlet to the fabric filter tended to get wet and read a temperature that was below the dry bulb temperature. This indicates that liquid water was still present in the duct at this location, nominally 2.5 seconds downstream of the humidifier. The most reliable methods were either the calculated approach temperature or the approach temperature based on the measured fabric filter exit temperature. Under steady state operating conditions, the relationship between these two methods was within measurement accuracy (≈1°F) at a nominal approach to adiabatic saturation temperature of 30°F. For the purpose of data presentation in this report, the calculated approach to the adiabatic saturation temperature based on a duct energy balance is used. One advantage of the calculated temperature method is that the operating conditions at the fabric filter inlet could be determined without waiting for thermal equilibrium to occur at the fabric filter exit. All of the calculated values can be found in the data summary presented in Appendix A.

Figure 5-2 shows SO_2 removal as a function of approach to adiabatic saturation temperature and Ca/S ratio for the data summarized in Appendix A. Although each test

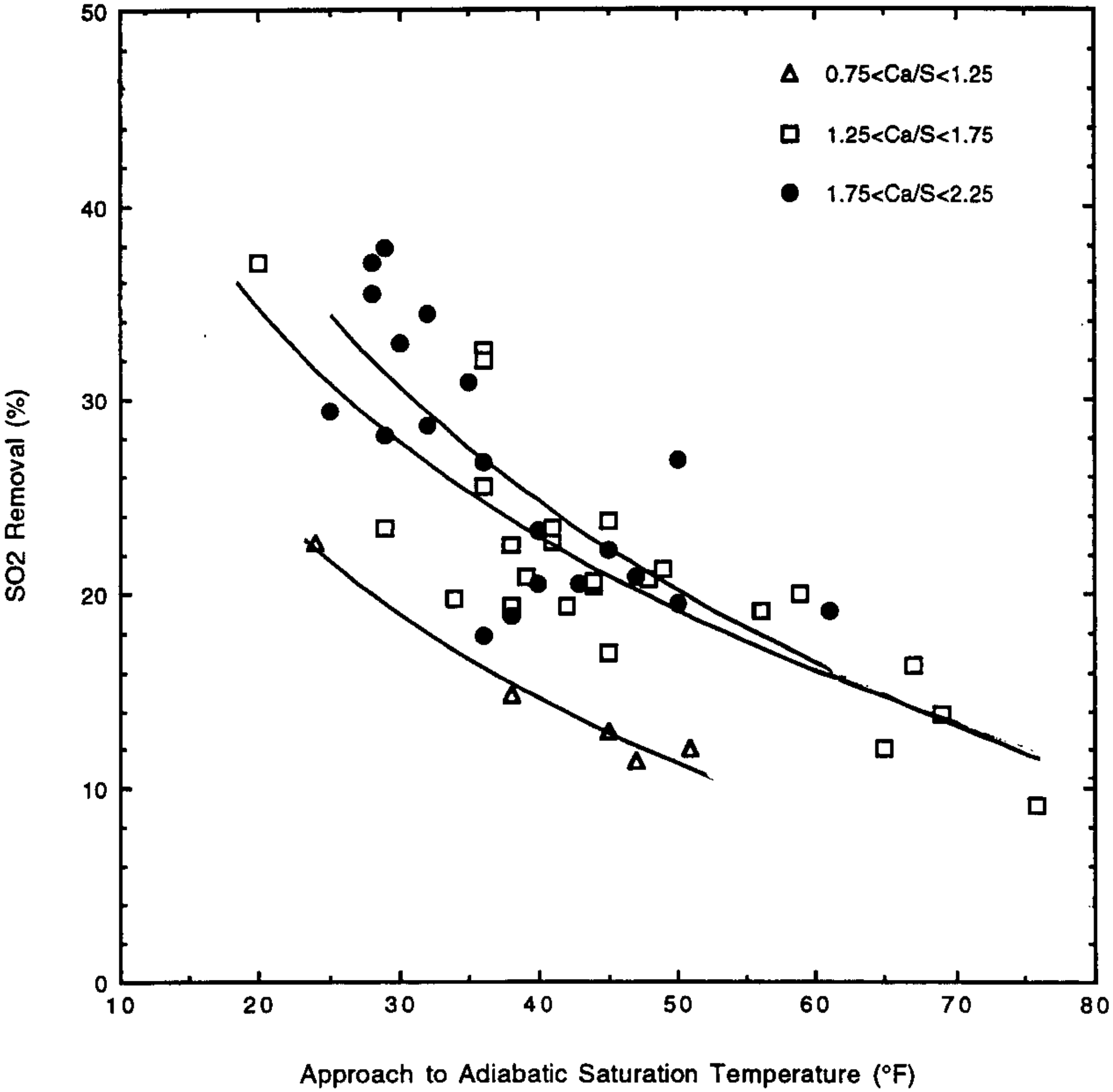

Figure 5-2. SO_2 Removal versus Approach to Adiabatic Saturation Temperature

was normally initiated with a target Ca/S ratio of 1.0, 1.5 or 2.0, maintaining a consistent sorbent feedrate throughout the duration of a test was often difficult. Thus, the Ca/S ratio calculated at the end of a test may vary as much as 10 to 15 percent from the target value. For this reason, the data in Figure 5-2 were grouped into three Ca/S ratio ranges centered at 1.0, 1.5, and 2.0. The data show that overall behavior of the SO_2 removal as a function of approach to adiabatic saturation temperature was as expected: the SO_2 removal increased at higher levels of humidification (e.g., lower T_{app}). At a high approach to adiabatic saturation temperature of 75°F, SO_2 removal was only 12 percent at a nominal Ca/S ratio of 1.5. Decreasing T_{app} to 30°F improved the SO_2 removal to 28 percent. If the humidification water flow was increased to produce T_{app} of 20°F, the SO_2 removals increased to 35 percent. However, as will be discussed in a later subsection, operating at approach to adiabatic saturation temperatures lower than 30°F may not be appropriate for this installation due to fabric filter operational problems.

The data in Figure 5-2 also show that the incremental increases in SO_2 removal decrease as the nominal Ca/S ratio approaches 2.0. When the Ca/S ratio is increased from nominally 1.0 to 1.5, the SO_2 removal increases nearly 19 to 28 percent. However, when the nominal Ca/S ratio is increased further to 2.0, the SO_2 removals only increase to 31 percent. This behavior results from the "overabundance" of sorbent at Ca/S ratios in excess of 1.5, which causes the sulfation process to be less efficient on the basis of moles of sulfur removed per mole of calcium injected.

Another point to be made regarding the data presented is the effect of boiler load. The data points shown in Figure 5-2 cover a boiler load range from 50 to 114 MWe. No trends in SO_2 removal versus approach to saturation temperature were evident as a function of load, within the typical day-to-day variation of the data.

Since the SO_2 removals were lower than initially expected, the question is raised as to how the performance of the Arapahoe Unit 4 duct sorbent injection/humidification system compares to other full-scale facilities. For comparison, the results obtained with duct injection/humidification at the Edgewater Station of Ohio Edison (McCoy, et al., 1992) are shown in Figure 5-3. During the Edgewater demonstration, the majority of the testing was performed with sodium added to the humidification water, with only limited testing performed with water and $Ca(OH)_2$ alone. However, during the Edgewater testing, data was reported for the two different $Ca(OH)_2$ materials referred to as Sorbent A and Sorbent G. Sorbents A and G had surface areas of 23.2 m^2/gm and 16.7 m^2/gm, respectively. At a nominal approach to adiabatic saturation temperature of 25°F, the two $Ca(OH)_2$ materials tested at Edgewater (without sodium addition) showed SO_2 removals of 34 and 35 percent. These results are consistent with the SO_2 removals obtained from the Arapahoe Unit 4 facility under similar operating conditions.

The effect of the amount of calcium injected, or Ca/S molar ratio, is shown in Figure 5-4. In this figure, the data points are shown for nominal 5°F differences in the approach to adiabatic saturation temperature. Lines have been drawn through the data points for approaches of 25 to 30°F and 40 to 45°F to better show the trends. As expected, the SO_2 removal increases as the Ca/S ratio increases, with the incremental increase becoming less and less at Ca/S ratios in excess of 1.5. Again, the effect of lower approach to adiabatic saturation temperature is evident in the data plotted in Figure 5-4.

5.3 Detailed Measurements

The prior subsection presented the overall performance of the duct injection/humidification system. To gain more insight into the results and the process, a series of detailed gaseous measurements were made. These measurements were made at two locations. First, SO_2 measurements were made in the duct downstream of the humidification and $Ca(OH)_2$ injection plane and upstream of the fabric filter inlet. These gas samples determine 1) the overall levels of SO_2 removal that occurred after 1.2 seconds of residence time in the duct, and 2) whether there were any major maldistributions of sorbent in the duct. In addition to the spatially resolved SO_2 measurements in the duct,

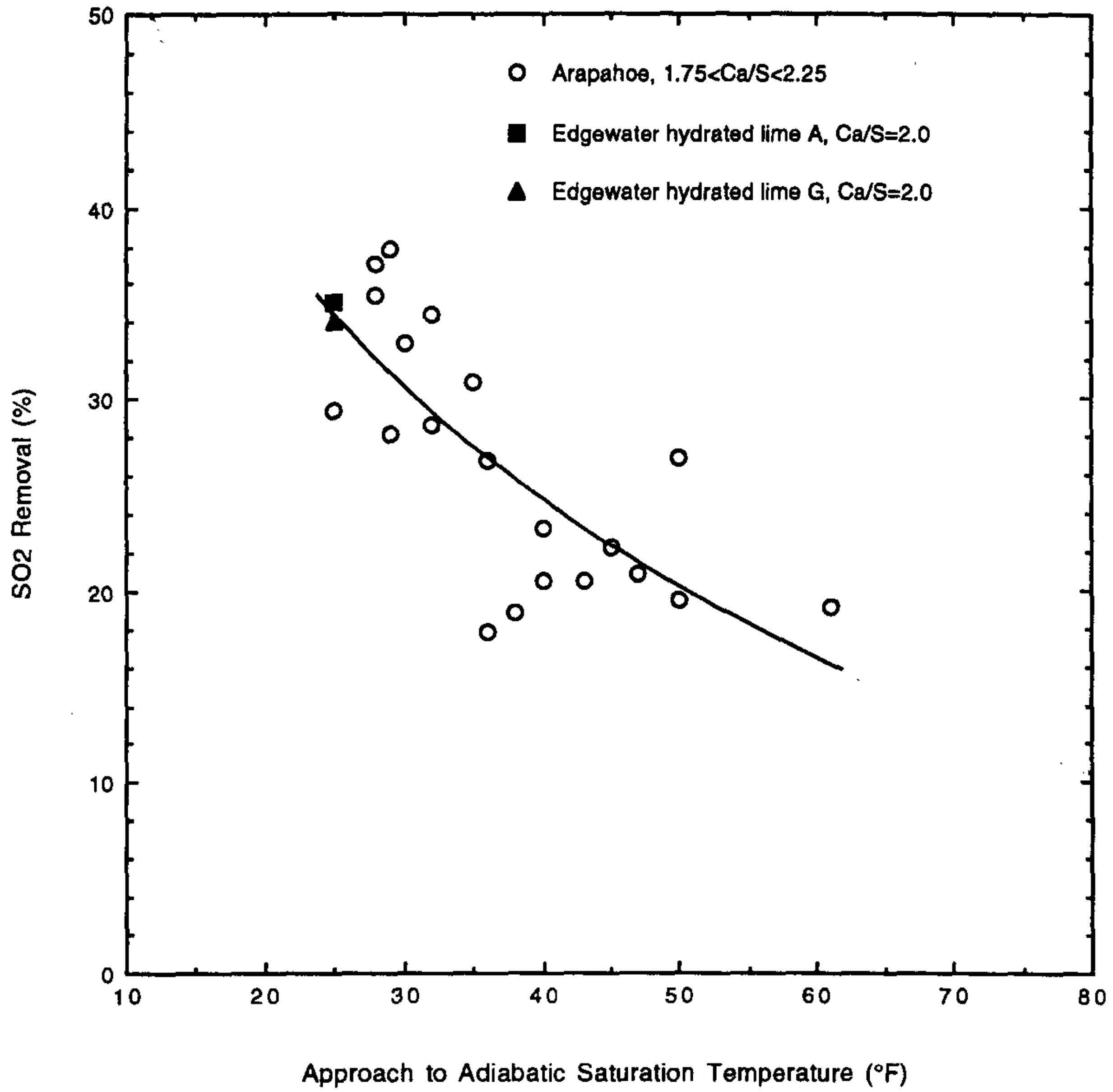

Figure 5-3. Comparison of SO_2 Removal versus Approach to Adiabatic Saturation Temperature for Arapahoe and Edgewater Data (McCoy et al., 1992)

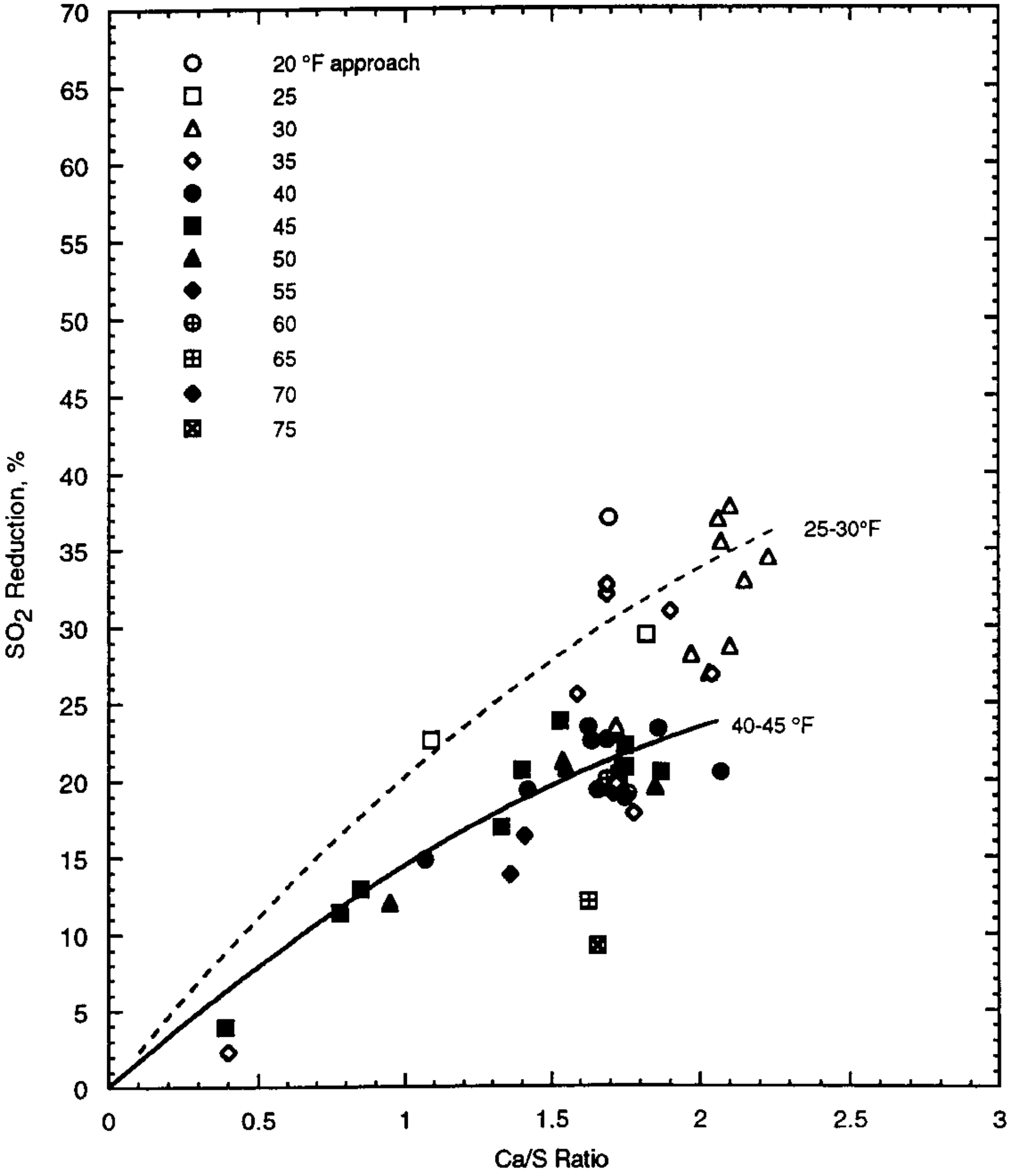

Figure 5-4. Cross Plot Between Calcium-to-Sulfur Ratio and SO_2 Removal at Various Approach to Adiabatic Saturation Temperatures for All Data

gas samples were also obtained from the exit of each fabric filter compartment. These measurements were performed to determine if there were any major compartment-by-compartment variations in the SO_2 removal. These detailed measurement are discussed below.

5.3.1 Duct SO_2 Measurements

Gas samples were obtained from the duct using the four ports located approximately 60 feet (or approximately 1.2 seconds) downstream of the humidification and calcium injection grids. These ports were formerly used for the original humidification thermocouple grid that was subsequently relocated further downstream at the fabric filter inlet. During the tests, the unit was operated at a load of 114 MWe, the humidifier operated to give a 30°F approach to adiabatic saturation temperature, and $Ca(OH)_2$ was injected at a Ca/S of 2. To obtain a representative gas sample, it is necessary that the $Ca(OH)_2$ not be allowed to react with SO_2 in the sampling system. To minimize these reactions, a sampling system patterned after one by B&W (Daum, et al., 1989) was fabricated. A sketch of the system is shown in Figure 5-5. The probe consists of a relatively large tube, 3 inches in diameter, which provides an initial gas/particle separation by virtue of the low upward velocity in the tube. The gas sample then passes through a heated probe tube and heated filter. The heated tube and filter are intended to increase the approach to saturation temperature of the gas, thus slowing the $SO_2/Ca(OH)_2$ reactions. The filtered gas sample is then dried and transported via an unheated sample line to the continuous gas analyzers.

The results of the point-by-point duct measurements are shown in Figure 5-6. Note that at Point 7, the measured SO_2 was only 2 ppm (dry @ 3 percent O_2). This point is likely the location of the pile of sorbent that collected on the duct floor (see Section 5-5) and the probe was embedded in the pile. Point 7 was not included in the reported averages. For this particular test condition, the inlet SO_2 concentration upstream of the humidifier was 422 ppm (dry corrected to 3 percent O_2) and the overall SO_2 removal was 34 percent. The point-by-point measurements in the duct indicate an average SO_2 removal

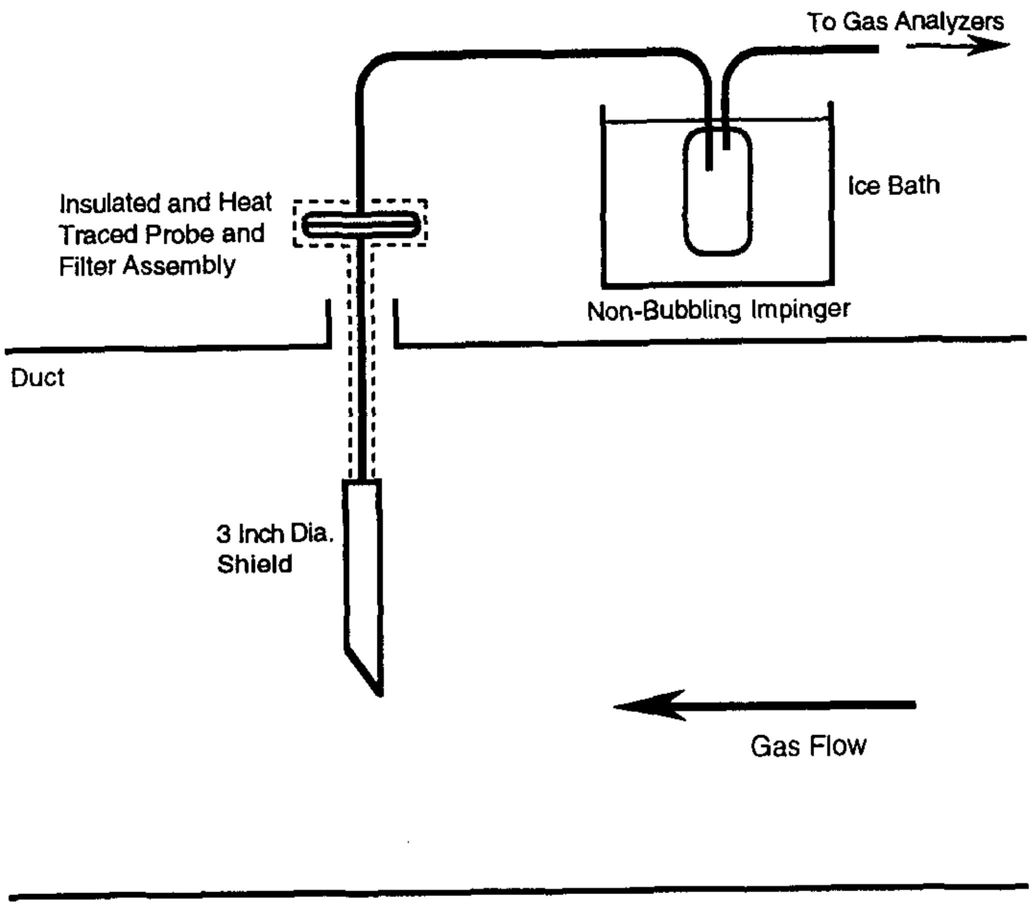

Figure 5-5. Sampling System Used for the Point-by-Point Duct Measurements

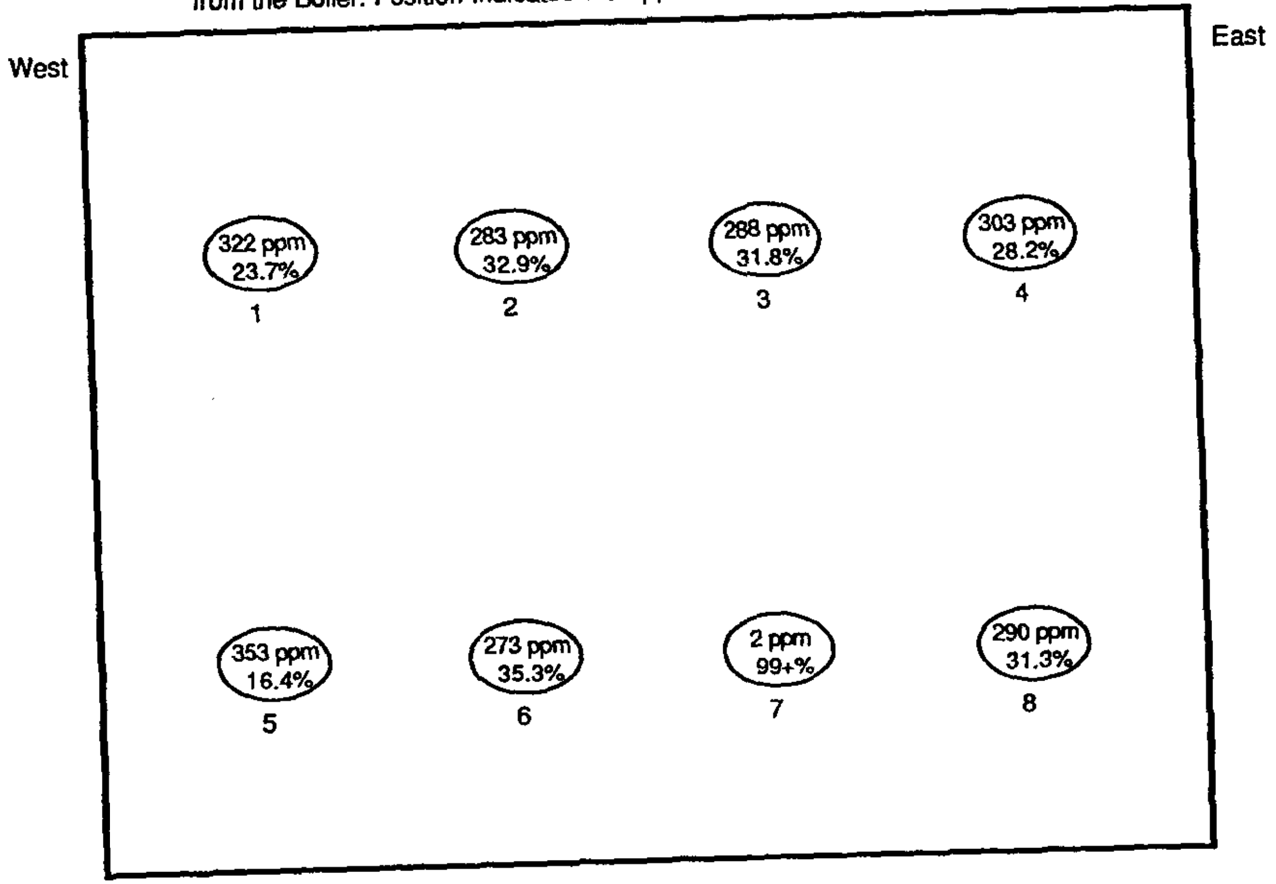
Air Heater Exit Duct at Old Thermocouple Grid Location,15' by 11.5' (View from the Boiler: Position Indicates the Approximate Sample Location in Duct)

Figure 5-6. Point-by-Point Duct SO_2 Measurements and Local SO_2 Removal for 114 MW, 30°F, T_{app} and 2.0 Ca/S Operation with 422 ppm dry @ 3% O_2 Inlet SO_2 and Overall SO_2 Removal of 34%

of 29 percent, which would suggest that most of the SO_2 removal reactions have occurred in the duct after a residence time of approximately 1.2 seconds. The point-by-point measurements also indicate lower SO_2 removals toward the outer (east and west) walls, and in particular, on the west wall of the duct.

5.3.2 Fabric Filter Compartment Measurements

Gas samples were also obtained from the exit of each fabric filter compartment to further investigate the sorbent/fabric filter interactions that may impact SO_2 removal efficiency. Gas samples were obtained by running a teflon tube from the clean gas exit port at the top of each compartment to the access compartment door. A water drop out was manually attached to the sample line on the outside of the access door, where the gas sample was dried and transported to the continuous gas analyzers.

The results of the compartment-by-compartment measurements are shown in Figure 5-7. For these tests, the unit was operated at 112 MWe, the humidifier at a 30°F approach to adiabatic saturation temperature, and the $Ca(OH)_2$ was injected at a Ca/S of 2. A tabular summary of the compartment gas sample data is also included in the figure. The upper figure shows the compartment SO_2 concentration (dry, corrected to 3 percent O_2) and the lower figure shows the calculated SO_2 removal from each compartment. For this test, the overall SO_2 removal based on the stack and inlet measurements was 36 percent. The compartment averaged SO_2 removals was 33 percent, which shows these two values are in reasonably good agreement. A number of observations can be made from the SO_2 concentration and compartment SO_2 removal data plots. The highest SO_2 removals are seen in the compartments at the entrance to the fabric filter, and decrease uniformly toward the back of the fabric filter (e.g., from south to north). The comparison between east and west compartment shows slightly higher removals on the west side of the fabric filter, although the difference was only 4 percent and may not be significant.

Test 706, 10/20/93, 2.0 NSR Calcium, 30°F

Fabric Filter Compartment Gas Profile

Compartment Gas Measurement

#	O2	SO2	NO	NOc	SO2c	SO2n	ΔSO2
1 sw	5.85	236	236	280	280	0.81	45.9
2 w	5.60	245	235	275	286	0.82	44.8
3 w	5.62	272	242	283	318	0.92	38.6
4 w	5.72	314	238	280	370	1.06	28.7
5 w	5.72	330	232	273	389	1.12	25.0
6 nw	5.75	322	232	274	380	1.09	26.7
7 se	5.45	242	234	271	280	0.81	46.0
8 e	5.42	270	232	268	312	0.90	39.8
9 e	5.50	303	233	271	352	1.01	32.1
10 e	5.40	345	230	265	398	1.15	23.2
11 e	5.48	352	228	264	408	1.17	21.3
12 ne	5.65	339	237	278	398	1.14	23.3
Ave	5.60			274	348	1.00	33.0
West	5.71			278	337	0.97	35.0
East	5.48			270	358	1.03	31.0

Average Test Gas Measurements

	O2	SO2	NO	H2O	NOc	SO2c	ΔSO2
Inlet	4.30	425	213	9.27	260	519	
Stack	5.10	243	192	12.95	262	332	36.0

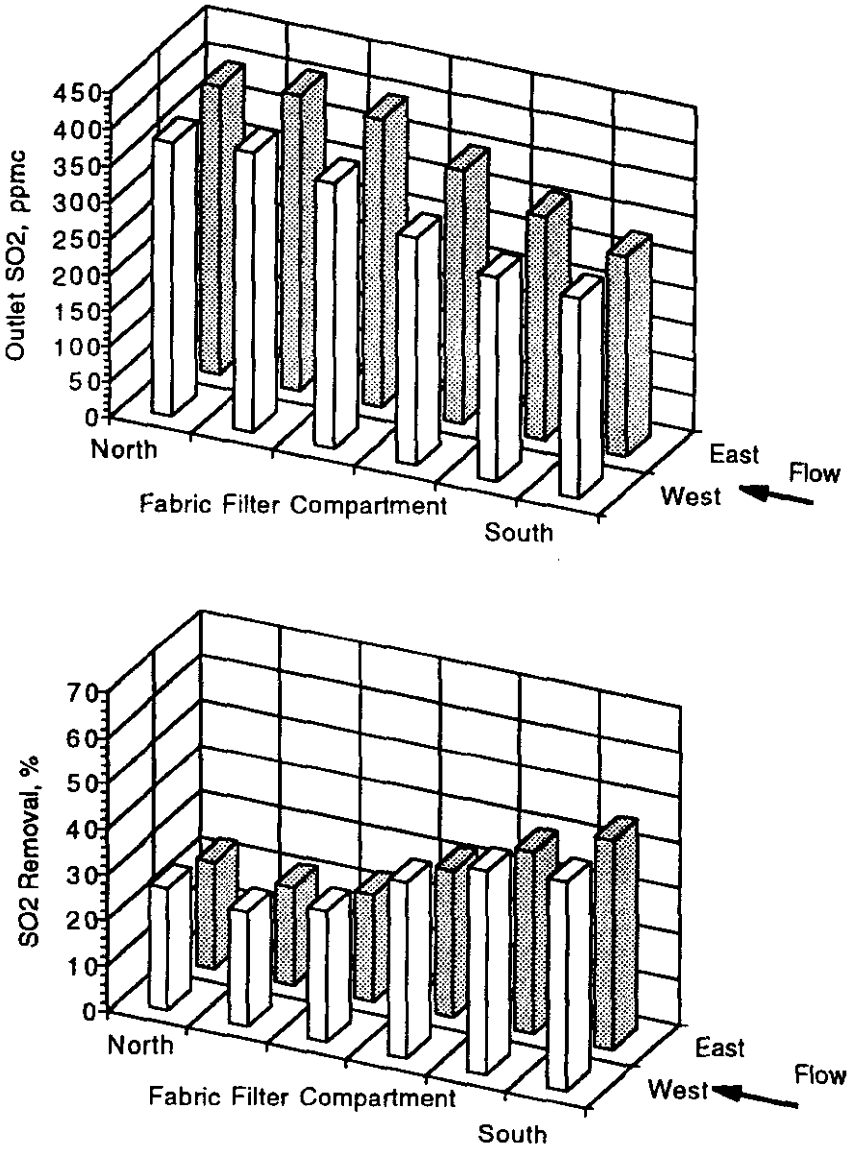

Figure 5-7. Compartment-by-Compartment Measurements (Load 112 MWe, T_{app} 30°F, Ca/S: 2)

An obvious question that arises is whether the compartment-by-compartment results shown in Figure 5-7 are consistent with the duct measurements shown in Figure 5-6. The compartment measurements indicated that the SO_2 removals from the back compartments (5, 6, 11 and 12) were in the range of 21 to 27 percent. To be consistent with the point-by-point duct measurements, the gas entering the back compartments would have to originate primarily from the outside edges of the duct where the SO_2 removals tended to be lower. Also, the higher SO_2 removals associated with the front compartments would suggest higher calcium loadings in these compartments with some additional SO_2 removal occurring within the compartments. The higher SO_2 removals may also indicate that the sorbent deposited in the front compartments is still damp, and thus more reactive than the material deposited in the back compartments.

5.4 Solids Analysis

In order to characterize the composition of the solid product of the duct injection/humidification process, laboratory analyses were performed on composite fly ash/sorbent samples obtained from the fabric filter hoppers for two separate tests. The samples were analyzed for sulfite and sulfate (via ion chromatography) to determine if the major sulfation product was $CaSO_3$ or $CaSO_4$. A previous pilot-scale study of the duct injection process (Smith, et al., 1992), showed sulfite to be the predominant product. In order to check the representativeness of the samples, each was also analyzed for calcium and iron (via atomic absorption spectroscopy). Iron was chosen as a "tracer" to indicate the relative amount of fly ash in the composite hopper samples, and the measured calcium-to-iron ratios were compared to the theoretical value for each test. The theoretical values were calculated from the sorbent and fly ash flow rates, and calcium and iron analyses of the sorbent and fly ash alone. All analyses on both composite samples were performed by Desert Analytics in Tucson, Arizona.

The results of these analyses (Table 5-2) confirmed that sulfite was the predominate product of the sulfation reaction. However, the measured Ca/Fe values were only approximately one-half of the theoretical values, indicating that the samples were not representative of the process.

Table 5-2

Solids Analysis Results for Composite Fabric Filter Hopper Samples

Test Number	SO_3 (wt %)	SO_4 (wt %)	Ca (wt %)	Fe (wt %)	Ca/Fe (measured)	Ca/Fe (theoretical)
603	1.16	0.81	8.62	1.00	8.62	18.2
608	1.08	0.69	7.44	0.82	9.13	17.8

It is believed that the technique used to collect the samples (a single sample pulled from a port on the bottom of each hopper) may have biased the analysis toward the material which was in the bottom of the hoppers before cleaning the bags. It is possible that the calcium content of material which falls from the bags during cleaning is greater than that of the material already in the hopper. A revised sampling procedure was developed, whereafter the bags in a particular compartment were cleaned, a sample was taken from the hopper bottom, as before. The hopper evacuation system was then turned on for one minute, turned off, and another sample withdrawn. This procedure was repeated until the hopper was empty; at which point, all of the samples from the hopper were thoroughly mixed together, thereby producing a composite sample which was representative of the entire fly ash/sorbent mixture accumulated in that particular hopper.

Individual hopper samples were collected in this manner during three separate tests run on October 19 and 20, 1993. During this period, the duct injection/humidification system was in operation for the third air toxics test. Portions of all twelve samples collected during one of these tests were sent to the PSCC Applied Sciences Laboratory for analysis for sodium, sulfate and sulfite. Sodium content was determined using an induced coupled plasma analysis (EPA Method 200.7). Sulfate and sulfite were determined with ion chromatography (EPA Method 300.1) and titration (ASTM Method 4500), respectively.

Tests conducted during the previous air toxics tests, showed that without sorbent injection, the fly ash alone had a nominal calcium content of 2.1 percent by weight. The results of the calcium analyses for the current test are shown in Figure 5-8, where they

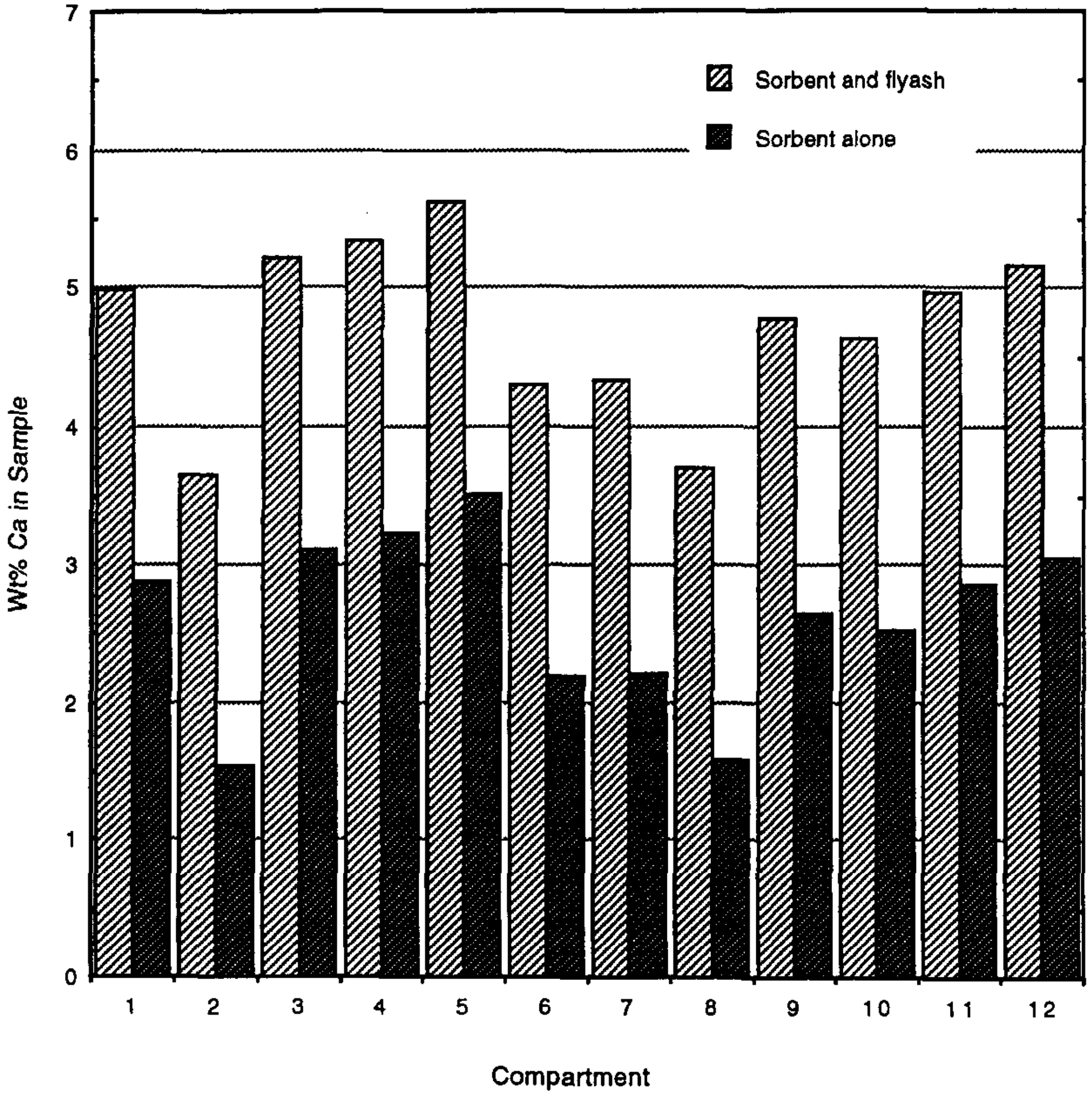

Figure 5-8. Calcium Analysis Results for Individual FFDC Hopper Sampler

have been presented as both the raw values directly from the measurement, as well as the values after subtracting the contribution from the calcium inherent in the fly ash. The results show that although there is a little variation, the calcium concentration is similar in all twelve compartments. However, this does not necessarily mean that the calcium is equally distributed among the compartments, rather only that the calcium-to-fly ash ratio is relatively equal on a compartment-by-compartment basis. Previous testing without sorbent injection has shown that the time required to evacuate each hopper after a FFDC cleaning cycle decreases dramatically between the hoppers located at the front and rear of the fabric filter. This trend indicates that the majority of the fly ash is deposited in the forward compartments. Therefore, the results shown in Figure 5-8 indicate that the sorbent is also preferentially deposited in the forward compartments.

The results of the sulfate and sulfite analyses (Figure 5-9), show that sulfite was found to be the predominate species in each compartment. These results are consistent with those shown in Table 5-2, as well as those from previous pilot-scale work (Smith, et al., 1992). Recall that the fabric filter has twelve compartments arranged in two rows of six (Figure 3-2), and that compartment number 1 is the first one on the west side, while compartment number 7 is the first one on the east side. Although, there appears to be no correlation between sulfate concentration and compartment location, the sulfite results tend to be highest in the forward compartments, and generally decrease towards the rear compartments.

A measure of the utilization of the calcium in each sample may be determined from the molar ratios of calcium and sulfur. Since one mole of calcium is required to completely react with a single mole of sulfur, the molar sulfur-to-calcium ratio is a direct measure of the utilization. Thus, a measured S/Ca ratio of 0.50 indicates 50 percent calcium utilization. Figure 5-10 shows the calculated utilizations based on the calcium concentrations corrected for the fly ash contribution. The results show that the utilizations are generally highest in the front half of the fabric filter, where the sulfite levels are also highest.

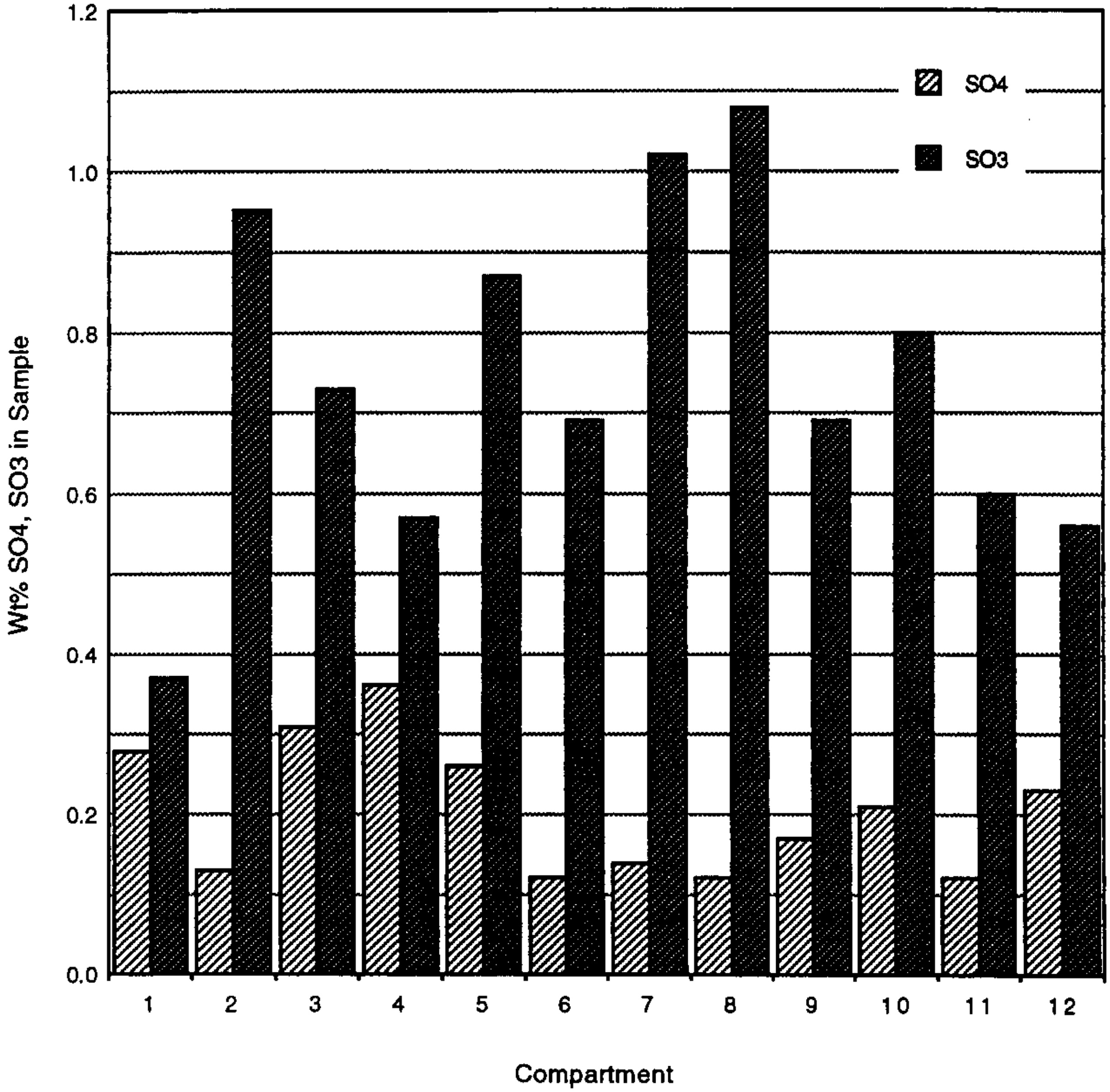

Figure 5-9. Sulfate and Sulfite Results for Individual FFDC Hopper Samples

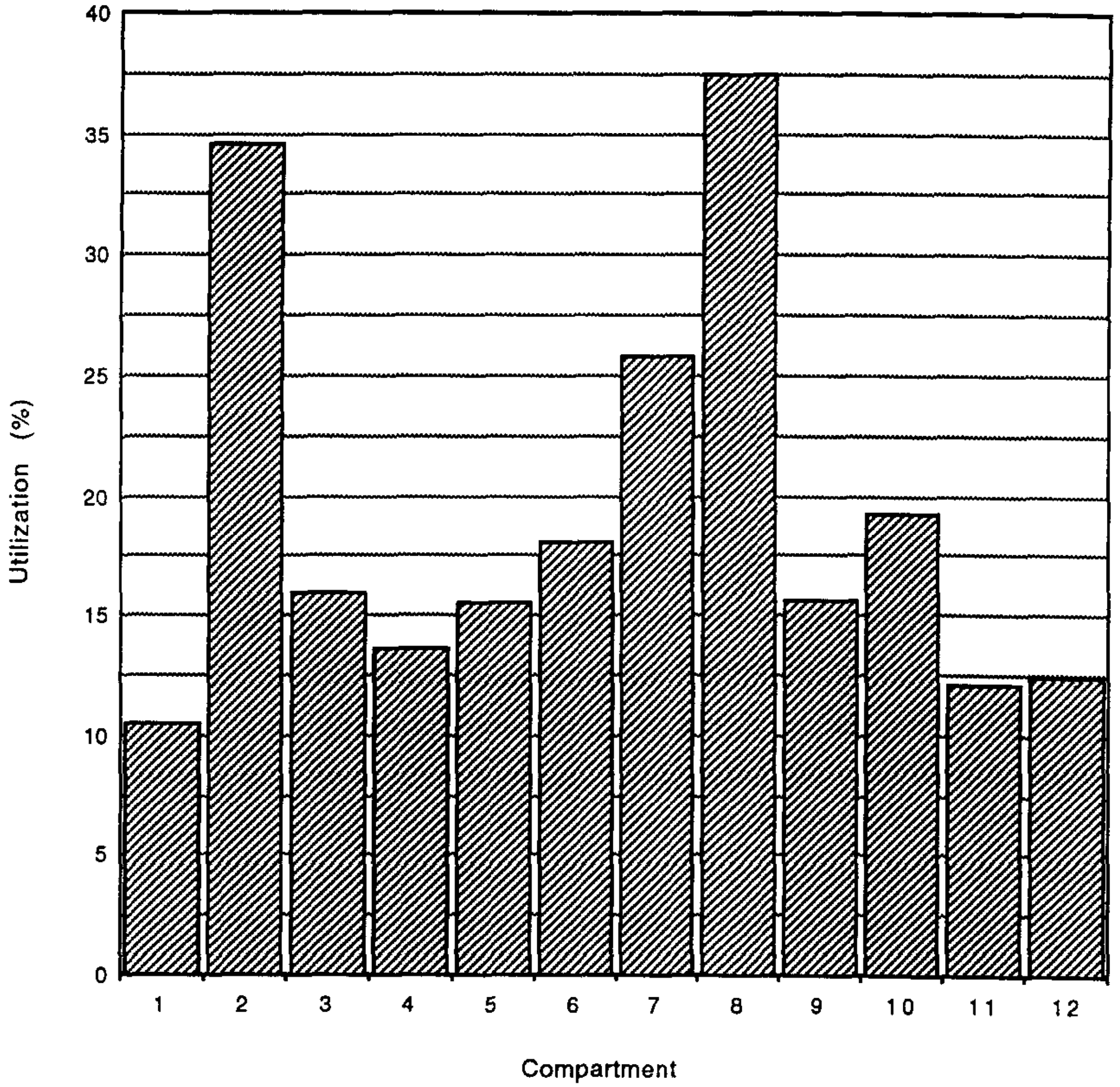

Figure 5-10. Utilization Calculations for Individual FFDC Hopper Samples

Another objective of the solids analyses was to confirm the stoichiometric ratio calculated from the sorbent feedrate and the gaseous SO_2 measurements. If the sorbent was distributed equally among the twelve compartments, calculating an overall stoichiometric ratio from the compartment-by-compartment solids analyses would be a simple matter of dividing the overall SO_2 removal by the arithmetic average of the compartment utilizations. However, more of the sorbent is deposited in the front compartments than in the rear (recall the discussion of the results presented in Figure 5-8). Therefore, the stoichiometric ratios must be calculated separately for each compartment, and then averaged, in order to provide an overall value. To do so requires the measurement of the SO_2 removal in each compartment, in addition to the utilization calculation.

Figure 5-11 presents the compartment-by-compartment SO_2 removal data which accompany the utilization calculations shown above. The peak removals occur in the first compartment on each side of the fabric filter, and then decrease as the FFDC is traversed from front to back. Since Figure 5-8 showed that the sorbent-to-fly ash ratio was relatively constant throughout the fabric filter, the increased SO_2 removals in the front compartments confirm that more of the sorbent/fly ash mixture was deposited in these areas. The arithmetic average of the SO_2 removal data is 33.0 percent. This compares to an overall SO_2 removal of 35.4 percent measured across the fabric filter. Good agreement between these two values indicates that the gas flow rates through each compartment are relatively equal. Figure 5-12 shows the stoichiometric ratio calculated on a compartment-to-compartment basis. The arithmetic average of this data (Ca/S = 1.92) is in reasonably good agreement with the feedrate calculation (Ca/S = 2.07).

5.5 Duct Deposits and System Operability

At the start of the duct injection/humidification test program, there were two concerns about the overall operability of the system. The first was the potential for deposition and sorbent buildup on the duct walls. This would be due to water drops wetting the duct walls, and the subsequent accumulation of ash and sorbent. The second concern was the impact of the duct humidification system on the overall operability of the fabric filter.

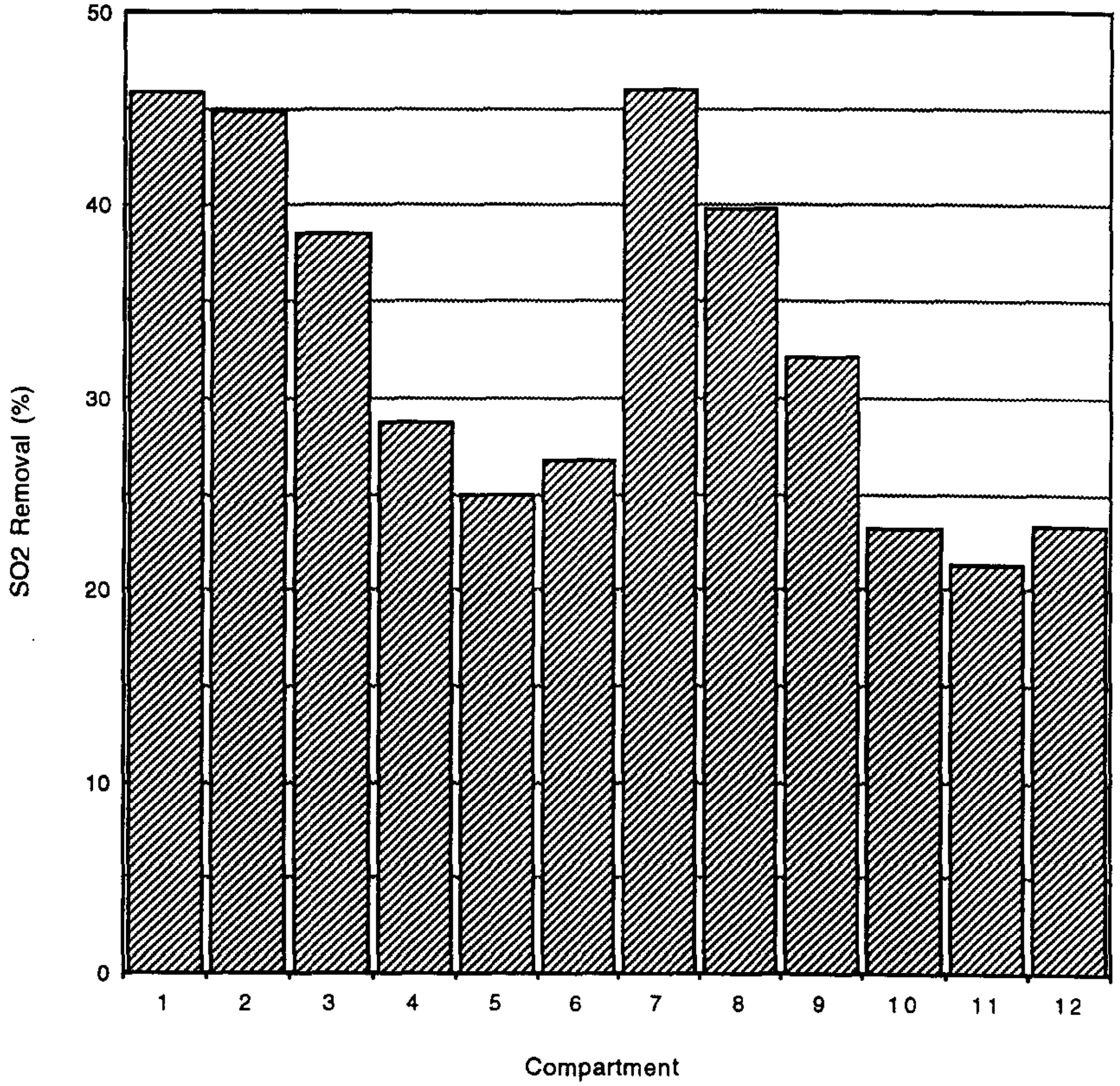

Figure 5-11. Compartment-by-Compartment SO_2 Removal Measurements

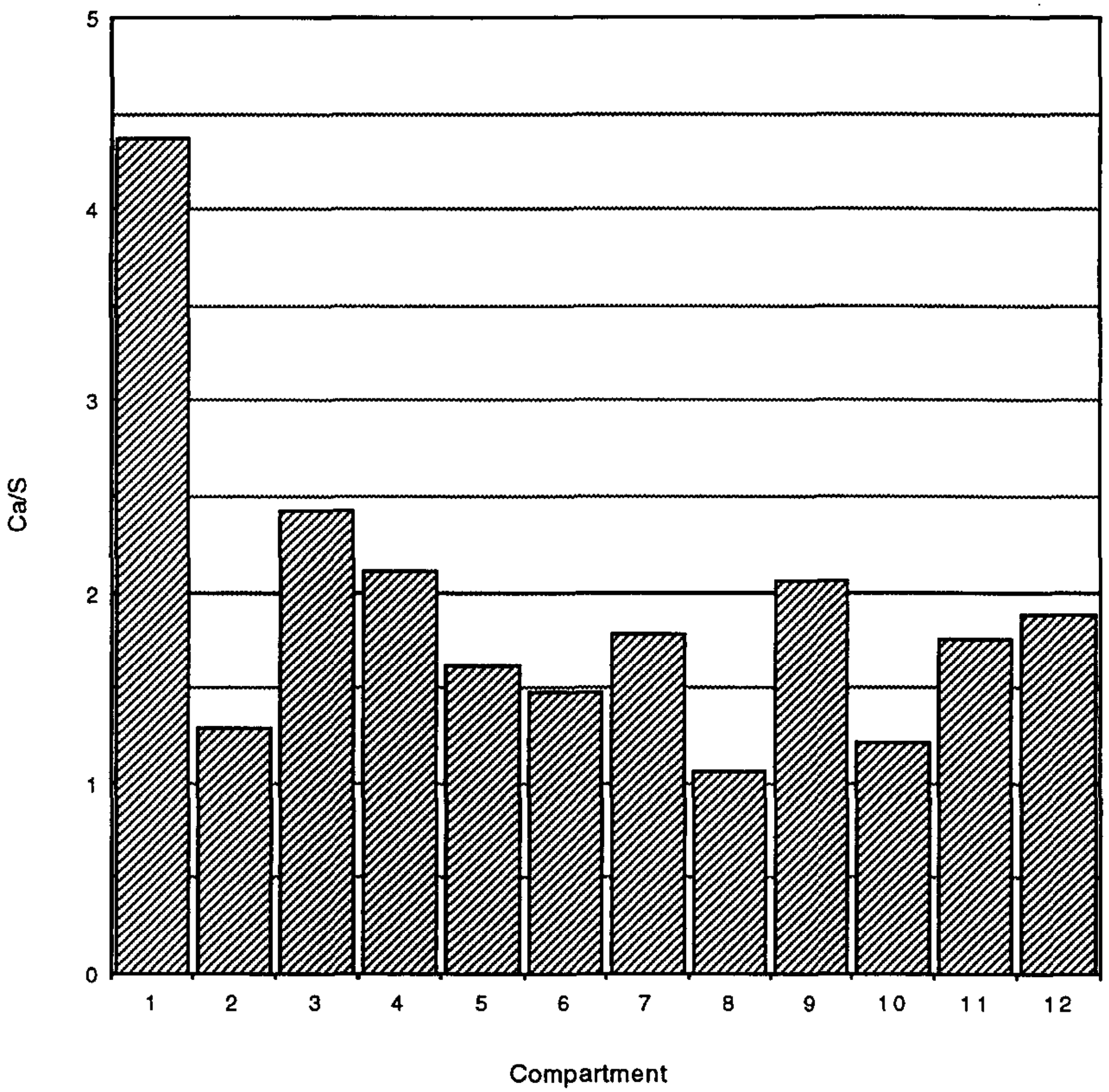

Figure 5-12. Stoichiometric Ratio Calculations for Individual FFDC Hopper Samples

transition from a horizontal run to an upward slope may have contributed to the deposit build up in this area. The deposits were not easily crumbled, and could not be blown downstream by the flue gas flow. The deposits also appeared to be a mixture of calcium and ash, and could build up to heights of 2 to 3 feet. This duct location has been a problem area for the Arapahoe Unit 4 gas flow configuration. Plant personnel indicated that after the construction of the fabric filter, fly ash deposits were known to accumulate in this area on the right side of the duct. The air foil that was subsequently installed in an attempt to eliminate the fly ash accumulation in this zone by diverting gas from the left to right side of the duct. The air foil reduced, but did not eliminate, the ash buildup in this area. The addition of sorbent injection appears to have increased the amount of buildup, but it is believed that the buildup eventually reaches an equilibrium.

The second location of sorbent/ash accumulation was at the base of the previously mentioned air foil gas diverter. During the inspections, piles on the order of 3 to 5 feet in height were noted. In this case, the deposit build ups were attributed to the obstruction created by the air foil itself. Deposits resulted from impact with the air foil or supporting cross member. These deposits solidified and grew until they fell from gravity or vibration. Since the formed deposits were relatively dense, they were not blown away by the flue gas flow, and thus accumulated at the base of the air foil. As the deposits continued to grow and fall off, the pile grew larger. It is likely this buildup would continue to grow due to the direct impact of sorbent and ash.

When possible, the deposit accumulations were broken up and vacuumed out during boiler outages. In one case, the piles were broken up and scattered on the duct floor, with the expectation that the sorbent/ash would be re-entrained and transported into the fabric filter for normal ash removal. At no time did these deposit formations impede operation of the unit or require any special operations except for their eventual removal.

While the impacts of the humidification and sorbent injection system on the duct are considered minor and manageable, there were greater impacts on the operation of the fabric filter. During the period from October 19 to October 20, 1993, the duct injection/humidification system was operated on a 24-hour per day basis to accommodate the air toxics tests. This was followed by approximately four days of single shift operation to complete some parametric tests. During this period, the system was operated at a 30°F approach to adiabatic saturation temperature. At the end of this period, after the humidifier was turned off, the fabric filter cleaning became erratic. Normally, the fabric filter pressure drop would be 2.0 inches H_2O following a cleaning cycle, with a nominal 6- to 8-hour period between cleaning cycles, depending on boiler load. At the end of this test period, the fabric filter would not clean much below 4 inches H_2O and essentially went into a continuously cleaning mode at full load operation. At reduced load, the effect was not immediately noticeable because fabric filter pressure drop was lower.

The exact onset of the problem was not clear because of the cyclic load operation of Arapahoe Unit 4, which has a direct impact upon fabric filter pressure drop. Effects could only be noted at sustained full load operation when the fabric filter pressure drop was at its highest. However, it was clear that the problem started with the resumption of calcium sorbent injection and humidification to a 30°F approach to adiabatic saturation temperature. Examination of the pressure drop data indicated that the bags were not being cleaned as effectively and that the post-cleaning pressure drop was higher. Inspection of a couple of fabric filter compartments revealed that large accumulations of ash remained in the bags despite the continuous cleaning cycle noted at full load.

Bag samples were removed and sent out for analysis. The bags were found to have large deposit accumulations. The level of agglomeration was found to be severe on the lower sections of the bags with a gradual reduction in the amount of deposition toward the top of the bags. However, agglomerates were present over the entire length of the bag. The nodular nature of the deposits was ascribed to moisture being absorbed by the hydroscopic calcium sulfate salts. The inability to clean the deposits with the reverse air system is thought to be due to fiberglass fibers, from the bags, being encapsulated by the deposits. Table 5-3 shows the weight and permeability of the bags for samples taken at the top, center and bottom. The values shown are as received, after cleaning, and after the bags were washed. Note that the process of removing a bag from the FFDC would

Based on the testing to date, it appears that the deposition problems in the duct are minor and manageable. However, there remain outstanding issues on the overall impact upon the fabric filter.

An occasional inspection of the sorbent injection and humidification grids, and the flue gas duct were performed during unplanned boiler outages. Several outages occurred during the duration of the test program. An inspection of the duct was conducted whenever possible during these outages. The following observations reflect the typical results of these inspections. Overall, there appeared to be little deposition on the atomizer grids. A photograph of the atomizer and injection grid, taken during one of the inspections was previously shown in Figures 3-6 and 3-7. There was slight ash buildup on some of the humidification lance surfaces, but these deposits were generally of a powdery nature and could be easily removed. The deposits on the humidification lances appeared to be fly ash and there were no areas where extensive blockage occurred.

The sorbent injectors were generally free of adhering deposits, except at the tip. Several injectors were partially plugged with material that was hard and had to be chipped off. These deposits may have resulted from exposure to water or moisture that created a cement-like deposit. The sorbent injector tips were at the low point and may have been prone to condensation of water vapor at minimum load conditions. In any case, these deposits did not cause a total blockage of sorbent flow on any injector.

For the most part, the majority of the duct was free of deposits. There were only two areas where a build up of sorbent and ash occurred; one approximately 60 feet downstream of the injection plane where the duct went from a horizontal run to an upward slope toward the fabric filter entrance, and the second at the location of the air foil located approximately 40 feet from the injection plane. The extent of the deposits is shown in the photographs in Figures 5-13 and 5-14 at the transition of the duct and the air foil locations, respectively. The deposits at the duct transition were located in the vicinity of the old thermocouple probes and were located just at the start of the duct slope. Generally, the bulk of the deposits were on the right, or east, side of the duct. The

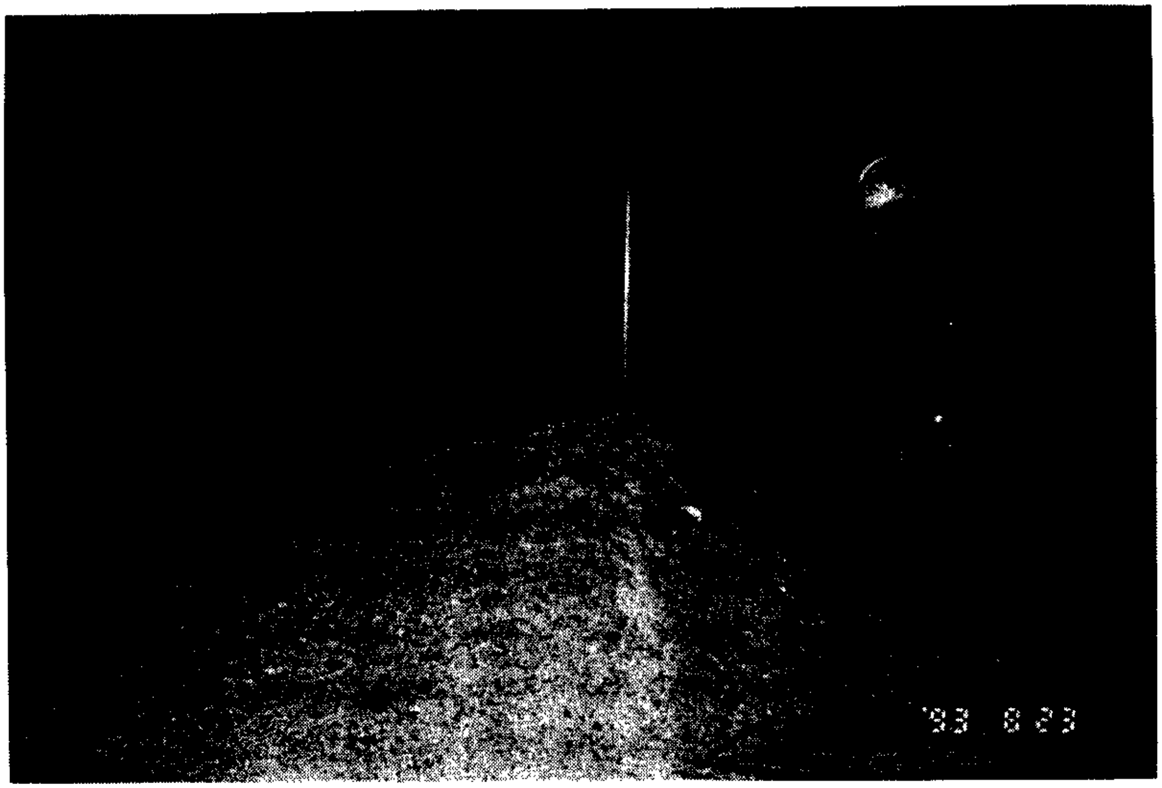

Figure 5-13. Sorbent/Ash Deposits Located ≈60 feet from the Injection Grid

Figure 5-14. Sorbent/Ash Deposits Located at the Air Foil

knock off a large amount of the buildup, and thus the as received value is not representative of the installed bag. The values also represent averages from three bag samples. Analysis of the bag material itself showed no chemical or thermal degradation (Environmental Consultant Company, 1994).

Table 5-3

Fabric Filter Bag Characteristics
(Environmental Consultant Company, 1994)

Location on the Bag		**Top**	**Center**	**Bottom**
Weight (oz/sq. yd.)	As Received	18.86	18.25	18.67
	Cleaned	15.69	15.20	15.84
	Washed	10.21	10.21	10.23
Permeability	As Received	1.8	2.0	1.8
	Cleaned	5.8	6.5	6.0
	Washed	53.3	53.9	52.3

The situation was severe enough that it required that the fabric filter cleaning and ash removal be immediately improved to lessen the impact upon fabric filter operation. Although the unit remained on-line, a single compartment was isolated and each bag was mechanically cleaned by hand. This was done by lowering each bag, which broke up the cake to a point that it separated from the fabric. After dropping a bag, it was rehung and the next bag was lowered. Due to the large number of bags, completion of mechanical cleaning required two months (November and December 1993) to complete all 12 compartments. This cleaning effort restored the performance of the fabric filter; currently the full load (100 MWe) pressure drop across the fabric filter is 1.4 to 1.6 inches H_2O after a cleaning cycle.

Table 5-4 shows a history of the weights of select bags, and one effect of the cleaning procedure. There are four marked bags in each FFDC compartment. Two each on the north and south sides of the walkway which passes through the top of each compartment. The weights of two of the four bags (one north, one south) are monitored on a

Table 5-4
History of FFDC Bag Weights

Compartment Number	Bag Number	Bag Weight (lbs)				
		Dec-92	Jun 93 (1)	Nov-Dec 93 (2)		Aug-94
1	1 North	48	50	74	24	32
	2 North			50	22	30
	1 South	46	56	66	24	30
	2 South			64	26	26
2	1 North	46	42	62	20	32
	2 North			68	24	32
	1 South	50	38	68	26	32
	2 South			70	24	30
3	1 North	38	56	66	22	26
	2 North			74	20	28
	1 South	36	58	72	24	26
	2 South			72	20	28
4	1 North	30	38	48	20	22
	2 North			52	20	20
	1 South	30	32	40	20	20
	2 South			45	18	20
5	1 North	24	40	38	18	28
	2 North			54	22	22
	1 South	28	28	32	18	24
	2 South			42	18	22
6	1 North	30	26	44	20	26
	2 North		56	60	20	24
	1 South	40	50	56	18	24
	2 South		46	52	19	22
7	1 North	70	58	78	26	40
	2 North		62	84	28	34
	1 South	66	56	72	28	36
	2 South		56	72	26	34
8	1 North	80	82	80	20	32
	2 North		68	76	22	28
	1 South	64	76	75	22	30
	2 South		78	68	20	28
9	1 North	24	50	48	22	22
	2 North		46	58	50	22
	1 South	28	38	64	20	22
	2 South		42	20	22	24
10	1 North	28	46	38	18	20
	2 North		34	43	18	20
	1 South	36	38	50	18	20
	2 South		42	60	20	20
11	1 North	24	36	36	16	20
	2 North		38	43	17	18
	1 South	24	34	36	18	20
	2 South		26	17	18	20
12	1 North	44	58	36	19	22
	2 North		58	64	20	24
	1 South	30	40	64	21	22
	2 South		40	20	20	20

(1) All bags in compartments 1, 2, 7 and 8 were hand shaken to reduce the weights. The initial weights in these compartments ranged from 68 to 96 lbs.

(2) The first number is the weight prior to lowering, raising, and shaking the bag. The second number is the weight after the cleaning proceedure.

semiannual basis by plant personnel. If the weights indicate that a cleaning problem may be developing, all four bags are checked. The December 1992 data show the weights measured before starting the calcium injection and humidification tests. The data from June of 1993 (three months after testing began) show a 15 to 20 percent increase in weights overall. The first set of numbers in the November-December 1993 column show the large increase which necessitated cleaning the bags manually. The second set of numbers shows the weights after the cleaning procedure. Finally, the August 1994 data show that, although the bag weights have increased since the manual cleaning, the weights are still less than those measured in December of 1992, before the calcium inspection tests began.

The question still remains as to whether the deposition on the bags occurred because of steady state operation of the unit at a 30°F approach to adiabatic saturation temperature, or whether transient effects caused the problems. The fact that the thermocouple grid at the inlet to the fabric filter measured temperatures below the dry bulb indicates that unvaporized water is still present at the inlet plane to the fabric filter. Inspection of the walls of the fabric filter compartments indicated areas of rust, suggesting water condensation which subsequently ran down the walls. These observations might suggest that the wet bags were due to steady state operation.

On the other hand, the problems could be due to the control system. The current control system adjusts the humidification water flow rate to maintain a set average temperature at the fabric filter inlet thermocouple grid. When the boiler load decreases, the water injection rate may be too high for a period of time until the thermocouple grid responds. This could result in short time periods when the flue gas could be saturated, resulting in the bags becoming wet. At this point, it is difficult to confidently conclude which of the above mechanisms led to the operational problems with the fabric filter. During future testing of the integrated system, the DCS humidifier control screen will either be modified, or the humidifier operated manually during load changes to eliminate the transient effects. Additional limitations to the maximum approach to saturation may also be required if a recurrence of the problem is suspected.

5.6 Alternate Sorbent Tests

A short series of tests were run with an alternate sorbent in order to assess its performance relative to the $Ca(OH)_2$ material used throughout the current test program. The alternate sorbent (called FlueSorbent) is a product developed specifically for the duct-injection process by Sorbent Technologies, Corp. (Sorbtech). The material consists of a mixture of $Ca(OH)_2$ and fine vermiculite. The vermiculite particles are much larger than the $Ca(OH)_2$ particles (approximately 200 microns compared to 4 or 5 microns), and act a both a "sponge" for added moisture, as well as a porous support for the $Ca(OH)_2$. According to Sorbtech, the material can be loaded with over 30 percent water (by weight) before it is injected, and still remain dry to the touch and free-flowing. Once inside the duct, the moisture in the vermiculite "core" evaporates through the outer $Ca(OH)_2$ layer, presumably increasing the local approach to adiabatic saturation temperature and boosting the SO_2 removals.

At Arapahoe Unit 4, the FlueSorbent was prepared onsite by blending the vermiculite and $Ca(OH)_2$ in a screw conveyor. A separate vermiculite storage silo was setup next to the DSI building, and a single screw feeder mixed both the vermiculite and $Ca(OH)_2$. A water spray into the top of the chamber added moisture during the mixing process. The moistened material was then fed through a rotary air lock, some temporary piping, and finally into the existing DSI system piping for injection into the duct. Unfortunately, the material did not feed well through either the temporary or existing piping systems. The piping system was modified in an effort to alleviate some of the problems encountered with plugging in the short-radius bends, but the problems persisted in other areas. Transport problems plagued the entire test effort start to finish, and a reportable test was not completed in the short time available. Because of the sorbent's unusual nature, a different transport system would have to be used. However, if the practical problems can be overcome, there is some indication that FlueSorbent material may perform better than $Ca(OH)_2$ alone.

6.0 ECONOMIZER INJECTION TEST RESULTS

Previous pilot-scale testing (Bortz, et al., 1986) has shown that $Ca(OH)_2$ injection in the temperature range of 1000°F has the potential of achieving SO_2 removals near 50 percent at a Ca/S ratio of 2.0. A brief test of the technology on a 150 MW lignite-fired boiler (Granatstein, et al., 1990; Feindel, et al., 1986) resulted in SO_2 removals ranging from 20 to 40 percent at Ca/S ratios of approximately 2.0. As will be discussed below, SO_2 removals with economizer injection at Arapahoe Unit 4 were substantially less than expected, when compared to the results of the earlier studies, with removals of only approximately 10 percent at a Ca/S ratio of 2.0.

The following subsections will present the results of the economizer injection tests at Arapahoe Unit 4, beginning with a description of some point-by-point gaseous traverses performed in order to determine the cause of the low SO_2 removals. This is followed by a discussion of the effects of Ca/S ratio and humidification. Finally, the results of a solids analysis of the reacted sorbent is presented.

6.1 Point-by-Point Gaseous Traverses

Initial testing at a Ca/S ratio of 2.0 without humidification resulted in SO_2 removals (measured at the outlet of the baghouse) of only 5 to 10 percent. Point-by-point gaseous traverses at the economizer exit showed that the distribution of sorbent was very poor, and only approximately one-third of the flue gas was being treated. Although SO_2 removals of 30 percent were measured near the east and west walls where the injectors were located, the local Ca/S ratio in this area was estimated to be on the order of 6.0. Longer injectors were installed in three of the four ports on the west side of the boiler in an effort to improve the distribution of sorbent in that area. It was not possible to replace the fourth injector due to clearance problems on the outside of the boiler. Figure 6-1 shows the results of the point-by-point traverses for three separate tests; one with the original injection configuration, and two with the longer injectors on the west side. All three tests were conducted at a boiler load of 80 MWe and a Ca/S ratio of 2.0. In an effort to reduce the amount of time expended during these tests, each of the twelve sampling points at the economizer exit (recall Figure 4-2) was not sampled individually,

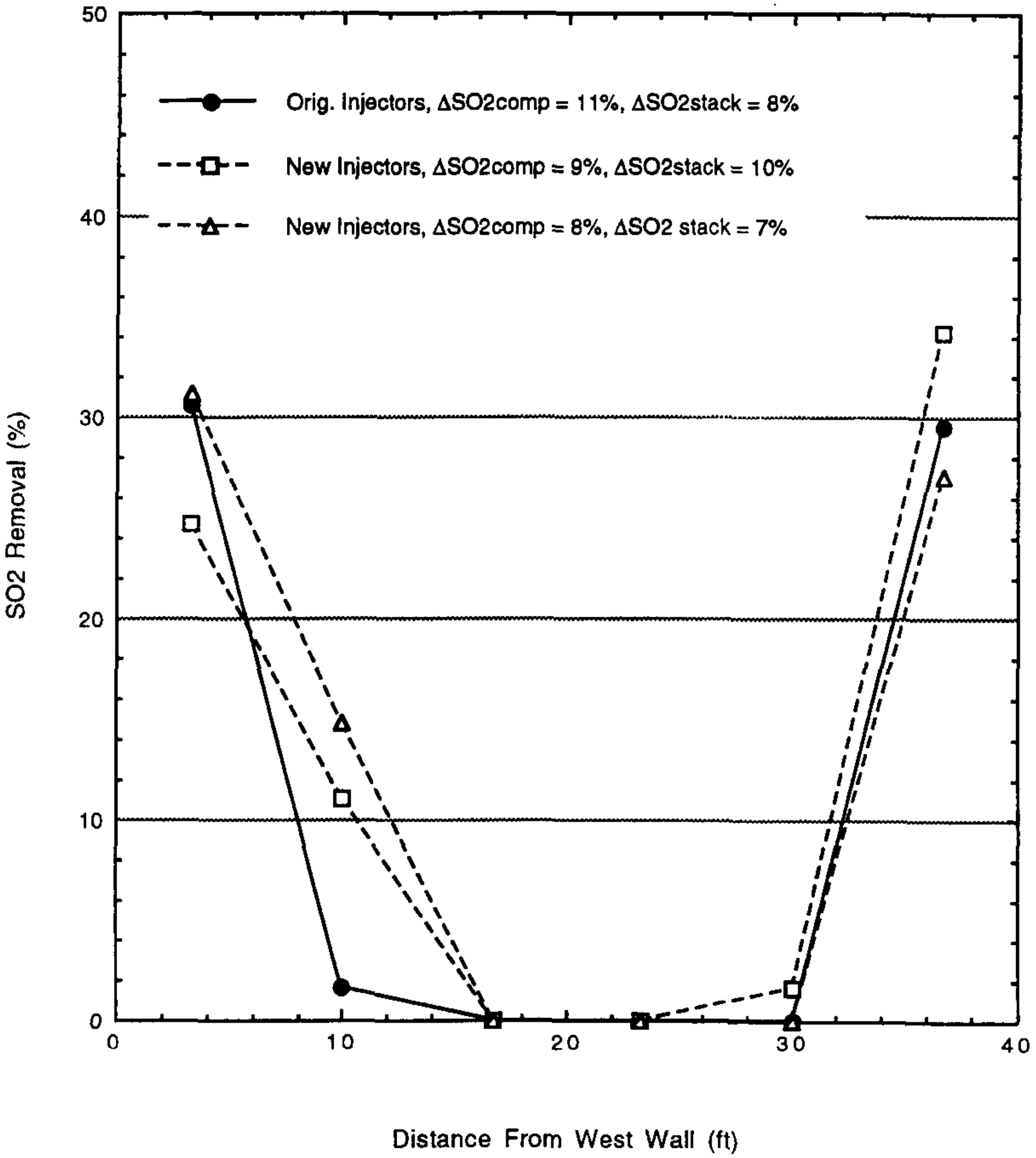

Figure 6-1. Point-by-Point SO_2 Removals with Economizer Injection (80 MWe, Ca/S = 2.0)

but the two probes in each port were composited together, thereby producing a six-point profile across the east-west direction. Included in Figure 6-1 are the SO_2 removals measured by compositing all twelve economizer exit probes together (ΔSO_2, comp.) as well as measured downstream of the baghouse (ΔSO_2, stack) for each test. The results show that the new injectors improved the distribution of sorbent on the west side of the boiler. However, the improvement was not large enough to result in a measurable increase in the overall SO_2 removals measured at either the economizer exit or stack. As discussed previously, this poor distribution was expected because of the need to inject the $Ca(OH)_2$ from the side walls.

6.2 Effect of Ca/S Ratio

The effect of the Ca/S ratio on SO_2 removal for economizer injection is shown in Figure 6-2. Two curves are shown in the figure, one for the composite SO_2 removal measured through all twelve probes at the economizer exit, and one for the local removal measured through the two probes adjacent to the west wall (Probes 1 and 2 in Figure 4-2). The Ca/S ratio designated "local" in Figure 6-2, assumes that the sorbent only penetrates one-third of the distance from the outside wall. All of the tests were conducted at a boiler load of 100 MWe with the original injectors. It should also be noted that these tests were conducted at a time when the DSI system which supplied the injectors on the east side of the boiler was out-of-service for repair; thus, injection was through the west side only. Therefore, the composite SO_2 removals shown for a particular Ca/S ratio will be lower than what would be measured when injecting through both the east and west sides, due to reduced coverage of the flue gas within the duct.

The low local SO_2 removals (18 percent at a Ca/S = 2.0) indicate that even in the region adjacent to the wall, where the distribution of the sorbent was best, high levels of SO_2 removal are not attainable at Arapahoe Unit 4 using the current $Ca(OH)_2$ material. Samples of the sorbent have been analyzed for surface area and particle size; both parameters being important for economizer injection (Bortz, et al., 1986). The BET surface area of the sorbent was 14.8 m^2/gm, and the mass mean particle size diameter was 2.7 microns (as determined by sedimentation). The BET surface area of the

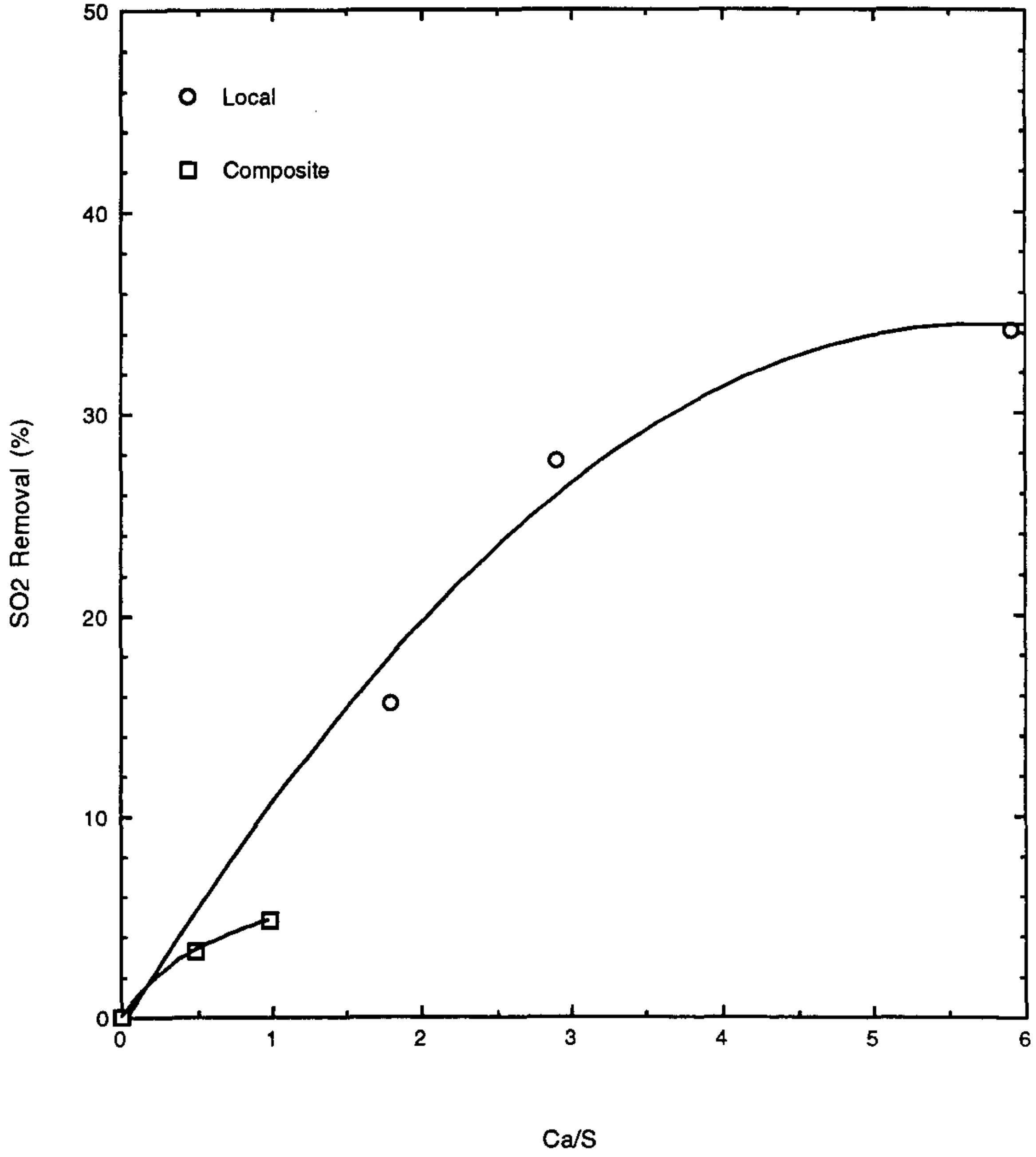

Figure 6-2. Effect of Ca/S Ratio for Economizer Injection (100 MWe, West Side Injection Only)

commercial hydrates utilized in the pilot-scale study (Bortz, et al., 1986) were in the range of 18 to 20 m^2/gm, thus the relatively low surface area of the reagent used at Arapahoe Unit 4 may have contributed to the low SO_2 removals obtained with economizer injection.

6.3 Effect of Humidification

Operation of the humidification system during economizer injection was shown to increase the SO_2 removals only slightly. These tests occurred after the humidification thermocouple grid was relocated to the inlet of the baghouse, but before the addition of the individual thermocouple shields. Therefore, the approach to adiabatic saturation temperatures calculated for these tests are likely low due to the influence of wet sorbent/ash accumulation on some of the thermocouples. At calculated approaches of 30 and 43°F, humidification increased the SO_2 removals by 3 to 4 percent as shown in Figure 6-3. All of the tests shown in the figure were conducted with injection from both the east and west sides with the original injectors at a Ca/S ratio of 2.0.

The data in Figure 6-3 also show that there is little effect of boiler load on SO_2 removal. This was expected, since the flue gas temperatures at the injection location (recall Figure 3-9) remained between 950 to 1150°F over the load range of 70 to 115 MWe.

6.4 Solids Analysis

In an effort to determine the reason for the low SO_2 removal efficiencies with economizer injection and humidification, a sample of the sorbent/fly ash mixture was obtained from the air heater exit duct at a point just upstream of the humidification grid. The sample was collected through a port which was adjacent to the east wall of the duct (Port 6 shown in Figure 4-4) where the sorbent-to-fly ash ratio was highest. The sample was sent to an outside laboratory for an ASTM Method C25 chemical analysis. The results of this analysis indicated that approximately 63 percent of the calcium in the sample was in the form of $CaCO_3$, and therefore, unreactive with respect to increased SO_2 removals with humidification. $Ca(OH)_2$ accounted for approximately 32 percent of the total calcium, and the remaining 5 percent was attributed to CaO. At economizer injection temperatures, the sulfation reactions compete with carbonation and dehydration of the

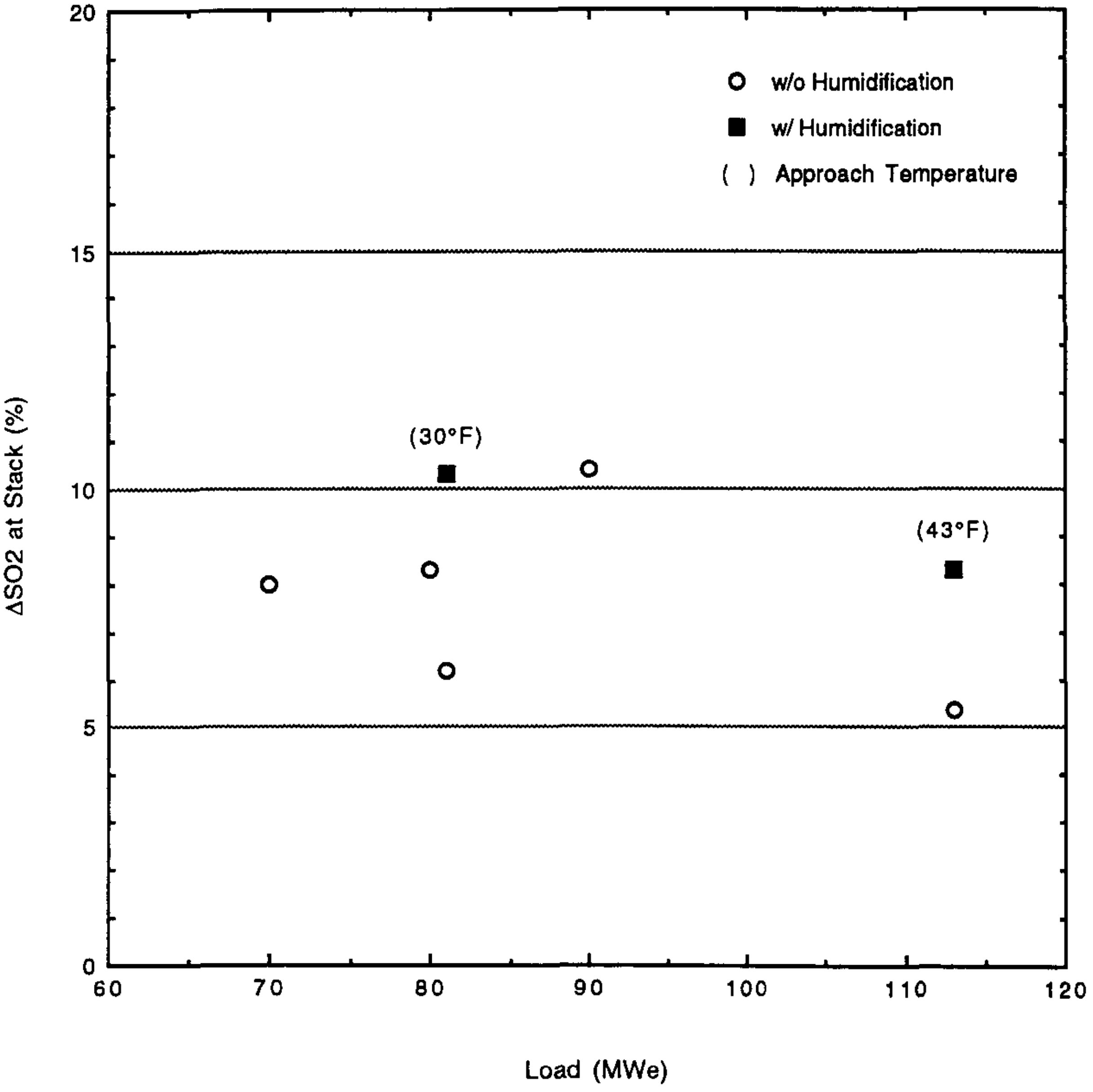

Figure 6-3. Effect of Humidification for Economizer Injection
(Ca/S = 2.0)

6.0), SO_2 removals were limited to 30 percent. The results indicate that high levels of SO_2 removal are not attainable at Arapahoe Unit 4 with the current $Ca(OH)_2$ material. It is suspected that low sorbent specific surface area and/or limited residence times also contributed to the poor overall performance.

7.3 Recommendations

Several recommendations to improve the SO_2 removal efficiency of the calcium/humidification process can be made. Some of these recommendations may further exacerbate the fabric filter deposit formation and cleaning problems noted previously.

- SO_2 removals can be enhanced by increasing the sorbent and humidification water interaction and contact. Creating larger water droplets by decreasing atomizing air flows or improving the distribution (number) of the sorbent injectors are two possibilities that would improve water/sorbent interaction. However, any variations for the humidification may have additional serious effects on deposition and fabric filter cleaning.

- Sodium addition to the humidification water has been utilized to improve SO_2 removals on full-scale demonstrations. Additional sodium will, by its very nature, remove SO_2, although additional SO_2 removals may be attained by a synergistic effect.

- Babcock & Wilcox has suggested injecting the sorbent as a slurry through the humidification atomizers as one means of improving system effectiveness. Slurry injection through the humidification grid will greatly enhance sorbent/water interaction essentially simulating a spray dryer.

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APPENDIX A

Table A-1 lists the data utilized for the trend plots for the calcium duct injection. These test points were selected because they represent steady state conditions or tests without any obvious operating difficulties.

Table A-2 lists all data recorded for the duct and economizer calcium injection tests. In addition to parametric tests, the data also includes load following, 24 hour operation that may represent non-steady state conditions.

Table A-1. Data Used For Duct Injection Trend Plots.

Test	Date	Load	Ca/S	Tapp. calc	ΔSO2
582	5/12/93	108	1.54	49	21.2
605	6/28/93	107	1.63	65	12.1
605	6/28/93	109	1.66	76	9.2
605	6/28/93	108	1.76	61	19.1
605	6/29/93	108	2.07	40	20.5
605	6/29/93	106	1.87	43	20.5
610	7/1/93	109	1.69	36	32.0
610	7/1/93	106	1.82	25	29.4
582	5/12/93	108	1.36	69	13.8
582	5/12/93	108	1.41	67	16.3
612	7/2/93	104	1.07	38	14.8
578	5/10/93	100	1.69	59	20.0
579	5/11/93	100	1.71	56	19.1
580	5/11/93	100	1.85	50	19.5
584	5/13/93	100	1.55	48	20.7
610	7/1/93	100	1.69	36	32.6
603	6/22/93	95	1.75	47	20.8
576	5/3/93	100	2.41		
579	5/11/93	100	0.95	51	12.0
584	5/13/93	99	0.78	47	11.4
610	7/1/93	98	1.09	24	22.6
605	6/28/93	91	1.69	41	22.6
605	6/28/93	91	1.74	39	20.8
605	6/28/93	91	1.33	45	16.9
605	6/29/93	86	1.63	41	23.4
600	6/16/93	80	1.86	40	23.3
604	6/22/93	80	1.78	36	17.8
599	6/15/93	80	0.40	35	2.3
601	6/17/93	80	0.85	45	12.9
602	6/21/93	80	0.39	45	3.9
610	7/1/93	78	1.42	42	19.3
612	7/2/93	79	1.40	44	20.6
581	5/12/93	70	1.73	44	20.3
586	5/14/93	70	1.70	20	37.0
583	5/13/93	70	1.66	38	19.3
604	6/22/93	50	1.75	45	22.2
604	6/22/93	59	1.53	45	23.8
606	6/29/93	60	1.64	38	22.5
606	6/30/93	58	1.75	38	18.8
608	7/1/93	60	1.72	34	19.7
609	7/1/93	60	1.72	29	23.4
611	7/2/93	61	1.59	36	25.5
705	10/19/93	112	2.06	28	37.0
706	10/20/93	112	2.07	28	35.4
707	10/20/93	112	2.10	29	37.8
709	10/26/93	102	2.03	50	26.9
712	10/27/93	101	1.97	29	28.1
715	11/1/93	112	2.23	32	34.4
717	11/1/93	113	1.90	35	30.9
719	11/2/93	114	2.04	36	26.8
720	11/2/93	114	2.10	32	28.6
721	11/2/93	114	2.15	30	32.9

Table A-2. Calcium Data, page 2

PSCC Arapahoe Unit

		GAS ANAL ECON-DRY (1-12)					GAS ANALYSIS INLET-WET ------						GAS ANALYSIS OUTLET-WET ------						
Test	Date & Time	NO	CO	SO2	CO2	O2	NO	CO	SO2	CO2	H2O	O2	NO	CO	SO2	CO2	H2O	O2	Comments
		ppm	ppm	ppm	%	%dry	ppm	ppm	ppm	%	%	%	ppm	ppm	ppm	%	%	%	
575	4/30/93:1420	235	194	424	13.53	5.25	180	154	348	12.02	8.22	4.90	192	233	332	11.73	10.48	4.90	
575	4/30/93:1500	235	194	424	13.53	5.25	180	180	347	12.05	8.20	4.90	187	281	328	11.89	10.88	4.75	
575	4/30/93:1635	235	194	424	13.53	5.25	179	184	351	12.07	8.26	4.85	187	329	329	11.54	11.54	4.60	
576	5/3/93:1615	225	166	320	13.04	5.27	195	153	268	10.87	7.69	6.30	208	663	227	11.44	11.85	5.00	
577	5/6/93:1130	199	11	263	10.28	9.20	160	14	235	9.41	6.76	8.60	164	7	232	9.25	9.38	8.55	Humid
577	5/6/93:1340	199	11	263	10.28	9.20	163	11	228	9.21	6.63	8.78	163	7	208	9.08	9.39	8.65	
577	5/6/93:1515	199	11	263	10.28	9.20	166	11	225	9.23	6.66	8.72	164	6	198	8.98	9.63	8.67	
577	5/6/93:1735	202	10	259	10.43	8.95	163	10	225	9.22	6.63	8.75	165	6	193	8.99	9.87	8.60	
578	5/10/93:0800	255	44	370	14.10	5.50	181	50	295	10.94	7.62	7.05	195	183	355	12.96	8.91	4.60	
578	5/10/93:1405	255	44	370	14.10	5.50	203	225	398	13.62	9.14	3.65	195	97	295	12.03	11.64	5.05	
578	5/10/93:1600	230	194	445	14.78	4.42	194	344	430	13.53	9.06	3.62	189	89	311	12.15	11.89	4.75	
578	5/10/93:1800	230	194	445	14.78	4.42	203	135	427	13.62	9.03	3.85	184	105	308	12.28	12.07	4.72	
578	5/10/93:2023	230	194	445	14.78	4.42	199	104	422	13.59	9.24	3.80	186	49	291	12.19	12.08	4.91	
578	5/10/93:2221	219	96	422	14.72	4.70	199	51	385	13.47	9.18	3.96	189	60	266	12.22	12.02	4.91	
578	5/11/93:0032	241	63	383	14.58	4.92	208	52	367	13.40	9.29	4.00	194	37	259	12.08	11.97	5.05	
578	5/11/93:0230	241	63	383	14.58	4.92	195	126	365	13.67	9.46	3.70	198	45	261	12.09	11.63	5.03	
578	5/11/93:0430	234	71	392	14.41	4.80	207	50	368	13.39	9.18	4.05	194	62	265	12.13	11.73	5.00	
578	5/11/93:0620	234	71	392	14.41	4.80	208	55	380	13.43	9.20	4.01	192	57	270	12.12	11.73	5.05	
578	5/11/93:0830	234	71	392	14.41	4.80	212	52	383	13.44	9.15	4.05	188	91	295	12.27	11.89	4.90	
579	5/11/93:1100	234	71	392	14.41	4.80	207	50	375	13.36	9.08	4.05	190	53	292	12.00	12.08	5.10	
579	5/11/93:1300	234	71	392	14.41	4.80	215	32	352	13.17	8.99	4.38	191	98	279	12.05	12.10	5.00	
579	5/11/93:1500	239	123	368	14.36	4.95	213	44	348	13.34	9.17	4.15	192	87	275	11.83	12.24	5.10	
579	5/11/93:1700	239	123	368	14.36	4.95	215	57	338	13.30	9.26	4.10	192	116	266	11.87	12.45	5.10	
579	5/11/93:1900	239	123	368	14.36	4.95	206	89	339	13.44	9.43	3.87	188	64	267	12.01	12.66	4.85	
580	5/11/93:2100	239	123	368	14.36	4.95	214	185	345	13.37	9.68	3.85	185	46	240	11.80	12.93	5.11	
580	5/11/93:2300	239	123	368	14.36	4.95	200	155	345	13.68	9.96	3.50	190	85	242	11.98	12.78	4.95	
581	5/12/93:0010	223	29	284	11.80	7.75	201	14	266	11.04	8.20	6.80	179	17	185	9.89	10.94	7.65	
581	5/12/93:0200	223	29	284	11.80	7.75	205	12	267	11.00	8.17	6.80	182	17	191	9.98	10.84	7.62	
581	5/12/93:0400	223	29	284	11.80	7.75	205	13	270	11.16	8.14	6.72	174	22	193	10.10	10.90	7.48	
581	5/12/93:0545	223	29	284	11.80	7.75	199	15	282	11.59	8.36	6.35	180	30	231	10.48	7.78	7.63	H2O off
582	5/12/93:1240	240	387	387.4	14.62	4.55	214	161	363	13.47	9.71	3.80	196	277	278	12.20	12.71	4.70	
582	5/12/93:1420	240	387	387.4	14.62	4.55	212	189	430	13.63	9.88	3.65	189	363	305	12.21	13.13	4.50	
582	5/12/93:2040	247	557	505	14.41	4.60	205	742	488	13.48	9.84	3.60	198	399	375	12.04	12.42	4.72	
582	5/12/93:2250	247	557	505	14.41	4.60	206	860	499	13.54	9.87	3.55	199	344	369	12.11	12.39	4.82	
583	5/13/93:0020	211	113	428	12.20	7.25	190	21	406	11.46	8.51	6.32	167	88	285	10.30	11.56	7.08	
583	5/13/93:0300	211	113	428	12.20	7.25	194	16	399	11.20	8.32	6.50	172	44	289	10.28	11.29	7.18	
583	5/13/93:0430	211	113	428	12.20	7.25	199	16	395	11.35	8.37	6.43	168	53	287	10.33	11.30	7.10	
584	5/13/93:0530	224	212	500	14.48	4.60	187	194	480	13.61	9.89	3.60	181	144	345	12.06	12.23	4.85	
584	5/13/93:0735	224	213	500	14.48	4.60	194	309	487	13.59	9.69	3.68	182	152	340	11.98	12.58	4.90	
584	5/13/93:0930	220	373	496	14.31	4.70	191	484	490	13.54	9.65	3.65	180	188	380	11.93	12.57	4.95	

PSCC Arapahoe Unit 4 Calcium/Humidification-Duct Injection, Ca(OH)2 calculations based upon 68% CaO.

		Boiler		Sorbent Feed			Injector cal		ΔSO2	Humidification					Baghouse Temps					Humid calc	
Test	Date & Time	Load	O2cr	Loc.	A,w	B,e	Flow	Ca/S*	Calc	Air	Tgo	Twl	H2O	A/W	Grid	Out	IDin	Opsis	Ta	T2cr	H2Oe
		MWe	%wet		%	%	lb/min		%	scfm	°F	°F	gpm	-	°F	°F	°F	°F	°F	°F	%w
575	4/30/93:1420	100	3.90	Duct	50	50	19.2	1.02	1.3	3684			35.0	1.05	202	206					8.27
575	4/30/93:1500	100	3.90	Duct	50	50	19.2	1.02	2.8	3639			40.0	0.90	194	199					8.25
575	4/30/93:1635	100	3.90	Duct	50	50	19.2	1.01	3.4	3550			47.0	0.70	175	185					8.28
576	5/3/93:1615	100	3.50	Duct	100	100	38.4	2.41	18.0	3457	258	52	54.0	0.60	223	180				149	8.53
577	5/6/93:1130	53	7.30	Duct			0.0	0.00	-3.4	4200	248	55	30.0	1.57	160	185*		170	49	165	6.77
577	5/6/93:1340	55	7.10	Duct	45	45	17.3	1.81	4.8	4188	252	55	31.0	1.55	160			167		169	6.75
577	5/6/93:1515	55	7.00	Duct	45	45	17.3	1.85	7.1	4145	254	55	35.5	1.31	150			160		160	6.74
577	5/6/93:1735	55	7.00	Duct	45	45	17.3	1.84	9.8	4109	255	56	38.5	1.21	142			154		151	6.87
578	5/10/93:0800	105	4.10	Duct	0	0	0.0	0.00	-2.3									253			8.83
578	5/10/93:1405	100	3.70	Duct	88	88	33.8	1.68	15.3	3990	276	55	48.0	0.89	160	173		179	56	179	8.34
578	5/10/93:1600	100	3.60	Duct	88	88	33.8	1.56	18.6	3973	278	56	49.0	0.87	160	170		173	53	173	8.83
578	5/10/93:1800	100	3.60	Duct	96	96	36.9	1.69	20.0	3957	282	55	50.0	0.84	160	170		174	53	175	8.93
578	5/10/93:2023	100	3.64	Duct	96	96	36.9	1.71	22.4	3960	280	56	50.0	0.84	160	168		174	51	173	9.11
578	5/10/93:2221	100	3.57	Duct	96	96	36.9	1.86	23.0	3974	276	56	49.0	0.86	160	167		173	50	173	8.99
578	5/11/93:0032	100	3.97	Duct	90	90	34.6	1.82	21.0	4000	271	56	47.0	0.91	160	167		172	50	174	9.00
578	5/11/93:0230	100	3.94	Duct	85	85	32.7	1.76	19.1	4029	266	55	45.0	0.96	160	165		171	48	173	8.99
578	5/11/93:0430	100	3.93	Duct	85	85	32.7	1.71	20.1	4023	266	55	45.0	0.95	160	164		170	47	172	8.99
578	5/11/93:0620	100	3.93	Duct	85	85	32.7	1.66	20.7	4011	266	55	45.0	0.94	160	164		170	47	172	8.99
578	5/11/93:0830	100	4.00	Duct	85	85	32.7	1.64	14.9	3980	270	54	46.0	0.91	160	164		170	47	174	8.96
579	5/11/93:1100	100	4.00	Duct	0	90	17.4	0.90	12.3	3917	275	56	52.0	0.79	150	162		167	45	167	8.89
579	5/11/93:1300	100	4.20	Duct	0	90	17.4	0.94	13.2	3875	280	56	54.0	0.75	150	163		167	46	167	9.00
579	5/11/93:1500	100	4.00	Duct	0	90	17.4	0.96	11.5	3875	281	54	54.0	0.75	150	164		170	47	169	8.96
579	5/11/93:1700	100	3.90	Duct	0	90	17.4	0.99	11.4	3867	282	55	55.0	0.74	150	163		168	46	168	9.02
579	5/11/93:1900	100	3.96	Duct	0	90	17.4	1.00	11.6	3866	283	55	55.0	0.72	150	164		168	47	169	9.05
580	5/11/93:2100	100	3.94	Duct	90	90	34.6	1.94	20.2	3861	284	55	56.0	0.71	150	162		168	45	168	9.28
580	5/11/93:2300	100	3.95	Duct	80	80	30.8	1.76	19.1	3869	278	56	55.0	0.73	150	161		167	44	165	9.34
581	5/12/93:0010	70	5.84	Duct	56	56	21.5	1.80	21.5	4040	258	55	41.0	1.06	150	156		160	41	160	7.99
581	5/12/93:0200	70	5.83	Duct	53	53	20.4	1.70	19.6	4057	254	55	40.0	1.11	150	154		156	39	159	7.96
581	5/12/93:0400	70	5.86	Duct	53	53	20.4	1.69	20.0	4062	253	55	40.0	1.11	150	153		155	38	158	7.88
581	5/12/93:0545	70	5.86	Duct	53	53	20.4	1.66	10.0	4481	252	56	0.0		241	183		188	68	252	7.87
582	5/12/93:1240	108	3.20	Duct	95	95	36.5	1.81	14.8	3866	288	56	55.0	0.74	160	184		189	65	180	9.51
582	5/12/93:1420	108	3.20	Duct	95	95	36.5	1.54	21.2	3810	291	56	63.0	0.69	150	175		180	56	168	9.59
582	5/12/93:2040	108	3.31	Duct	95	95	36.5	1.36	13.8	3877	288	56	51.0	0.79	170	201			82	188	9.49
582	5/12/93:2250	108	3.31	Duct	100	100	38.4	1.41	16.3	3908	286	57	51.0	0.81	170	182		190	63	186	9.49
583	5/13/93:0020	70	5.25	Duct	80	80	30.8	1.74	21.2	4013	261	56	44.0	1.00	142	169		169	53	153	8.30
583	5/13/93:0300	70	5.21	Duct	75	75	28.8	1.64	19.3	4049	256	56	42.0	1.06	142	154		155	38	153	8.22
583	5/13/93:0430	70	5.23	Duct	75	75	28.8	1.67	19.2	4046	255	55	41.0	1.07	142	150		152	34	154	8.23
584	5/13/93:0530	100	3.48	Duct	100	100	38.4	1.57	18.9	3989	266	55	45.0	0.95	160	160		165	44	171	9.54
584	5/13/93:0735	100	3.50	Duct	100	100	38.4	1.55	20.7	3897	274	56	52.0	0.80	152	162		168	46	165	9.39
584	5/13/93:0930	99	3.40	Duct	0	100	19.4	0.78	11.4	3867	277	56	53.5	0.76	149	160		165	44	164	9.27

Table A-2. Calcium Data, page 4

PSCC Arapahoe Unit

		GAS ANAL ECON-DRY (1-12)					GAS ANALYSIS INLET-WET ------						GAS ANALYSIS OUTLET-WET ------						
Test	Date & Time	NO	CO	SO2	CO2	O2	NO	CO	SO2	CO2	H2O	O2	NO	CO	SO2	CO2	H2O	O2	Comments
		ppm	ppm	ppm	%	%dry	ppm	ppm	ppm	%	%	%	ppm	ppm	ppm	%	%	%	
585	5/14/93:0035	210	61	350	12.17	7.20	194	19	328	11.64	8.45	5.98	164	46	217	10.21	11.67	7.05	
585	5/14/93:0230	210	61	350	12.17	7.20	200	18	335	11.60	8.47	5.85	170	79	219	10.37	11.67	6.95	
586	5/14/93:0310	210	61	350	12.17	7.20	199	25	325	11.46	8.33	6.15	165	83	186	10.46	11.99	6.75	
586	5/14/93:0420	210	61	350	12.17	7.20	199	39	325	11.98	8.62	5.60	181	38	172	10.37	11.77	7.00	
586	5/14/93:0545	210	61	350	12.17	7.20	200	38	322	11.82	8.48	5.80	159	164	170	10.40	11.91	6.80	
586	5/14/93:0705	210	61	350	12.17	7.20	201	24	309	11.24	8.17	6.60	173	62	179	10.08	11.56	7.25	O2 changd
587	5/18/93:0907	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	242	152	365	12.32	8.99	5.10	No Sorbent
587	5/18/93:1018	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	288	155	388	13.84	0.00	5.40	EE 1-12
587	5/18/93:1039	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	248	200	247	11.81	0.00	7.40	EE 1,2
587	5/18/93:1046	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	318	69	411	14.34	0.00	4.90	EE 3,4
587	5/18/93:1055	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	298	75	430	14.89	0.00	4.40	EE 5,6
587	5/18/93:1105	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	290	310	475	16.17	0.00	3.00	EE 7,8
587	5/18/93:1115	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	313	66	410	14.34	0.00	5.05	EE 9,10
587	5/18/93:1123	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	270	17	330	11.50	0.00	8.10	EE 11,12
587	5/18/93:1135	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	293	125	380	13.93	0.00	5.35	EE 1-12
587	5/18/93:1150	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	246	125	345	12.16	8.80	5.25	Altech Out
587	5/18/93:1214	278	138	420	14.26	4.90	278	138	420	14.26	0.00	4.90	288	142	395	13.86	0.00	5.40	Base Drift
587	5/18/93:1214	288	142	395	13.86	5.40	288	142	395	13.86	0.00	5.40	249	120	355	12.01	8.54	5.40	No Sorbent
588	5/19/93:0943	261	69	392	13.14	5.30	261	69	392	13.14	0.00	5.30	223	65	360	11.65	8.75	5.00	No Sorbent
588	5/19/93:1043	261	69	392	13.14	5.30	261	69	392	13.14	0.00	5.30	255	43	378	13.34	0.00	5.10	EE 1-12
588	5/19/93:1053	261	69	392	13.14	5.30	261	69	392	13.14	0.00	5.30	210	48	342	11.73	8.81	4.91	Altech Out
588	5/19/93:1100	261	69	392	13.14	5.30	261	69	392	13.14	0.00	5.30	219	50	214	10.76	0.00	8.00	EE 1,2
588	5/19/93:1108	261	69	392	13.14	5.30	261	69	392	13.14	0.00	5.30	288	24	415	14.22	0.00	4.05	EE 3,4
589	5/19/93:1137	261	69	392	13.14	5.30	261	69	392	13.14	0.00	5.30	228	34	240	10.99	0.00	7.70	EE 1,2
589	5/19/93:1155	261	69	392	13.14	5.30	261	69	392	13.14	0.00	5.30	246	57	390	13.50	0.00	4.85	EE 1-12
589	5/19/93:1206	261	69	392	13.14	5.30	261	69	392	13.14	0.00	5.30	205	53	341	11.66	8.73	5.15	Altech Out
590	5/19/93:1239	261	69	392	13.14	5.30	261	69	392	13.14	0.00	5.30	235	35	283	11.15	0.00	7.55	EE 1,2
591	5/19/93:1620	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	187	49	341	11.79	8.84	4.95	No Sorbent
591	5/19/93:1745	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	217	30	330	12.87	0.00	5.55	EE 1-12
591	5/19/93:1756	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	206	15	205	10.84	0.00	7.70	EE 1,2
591	5/19/93:1805	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	246	16	381	13.92	0.00	4.35	EE 3,4
591	5/19/93:1814	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	225	38	402	14.05	0.00	4.10	EE 9,10
591	5/19/93:1826	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	170	25	196	10.30	0.00	8.10	EE 11,12
591	5/19/93:1837	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	224	50	422	14.84	0.00	3.40	EE 7,8
591	5/19/93:1845	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	229	26	378	13.45	0.00	4.85	EE 5,6
591	5/19/93:1854	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	215	35	330	13.20	0.00	5.20	EE 1-12
591	5/19/93:1905	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	188	25	303	11.45	8.85	5.05	Altech Out
591	5/19/93:2001	222	56	385	13.42	4.95	222	56	385	13.42	0.00	4.95	221	27	370	13.08	0.00	5.40	Base Drift
592	5/20/93:0905	249	38	392	14.02	4.55	249	38	392	14.02	0.00	4.55	214	38	348	12.04	9.30	4.45	No Sorbent
592	5/20/93:1056	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	208	21	359	11.93	9.23	4.70	No Sorbent

PSCC Arapahoe Unit 4 Calcium/Humidification-Duct Injection, Ca(OH)2 calculations based upon 68% CaO.

		Boiler		Sorbent Feed			Injector cal		ΔSO2	Humidification					Baghouse Temps					Humid calc	
Test	Date & Time	Load	O2cr	Loc.	A,w	B,e	Flow	Ca/S*	Calc	Air	Tgo	Twl	H2O	A/W	Grid	Out	IDin	Opsis	Ta	T2cr	H2Oe
		MWe	%wet		%	%	lb/min		%	scfm	°F	°F	gpm	-	°F	°F	°F	°F	°F	°F	%w
585	5/14/93:0035	69	5.37	Duct	60	60	23.1	1.68	23.8	3998	259	55	46.0	0.94	128	156		156	41	144	8.06
585	5/14/93:0230	70	5.27	Duct	60	60	23.1	1.64	24.6	4011	255	55	46.0	0.95	129	144		145	29	142	8.00
586	5/14/93:0310	70	5.19	Duct	60	60	23.1	1.66	36.1	3971	256	56	49.0	0.86	124	140		142	25	136	8.04
586	5/14/93:0420	70	5.26	Duct	60	60	23.1	1.72	37.6	3977	254	55	49.0	0.88	124	137		139	22	134	8.00
586	5/14/93:0545	70	5.26	Duct	60	60	23.1	1.71	39.4	3979	254	56	48.0	0.89	125	136		137	21	136	7.98
586	5/14/93:0705	70	5.50	Duct	60	60	23.1	1.69	35.1	3971	252	56	49.0	0.86	124	134		136	19	132	8.16
587	5/18/93:0907	108	3.60	Econ	0	0	0.0	0.00	0.1									269			
587	5/18/93:1018	108	3.60	Econ	100	0	19.1	0.87	4.7		281	59			275	263				281	
587	5/18/93:1039	108	3.60	Econ	100	0	19.1	0.87	30.4												
587	5/18/93:1046	108	3.60	Econ	100	0	19.1	0.87	2.1												
587	5/18/93:1055	108	3.60	Econ	100	0	19.1	0.87	0.7												
587	5/18/93:1105	108	3.60	Econ	100	0	19.1	0.87	-1.2												
587	5/18/93:1115	108	3.60	Econ	100	0	19.1	0.87	1.5												
587	5/18/93:1123	108	3.60	Econ	100	0	19.1	0.87	1.9												
587	5/18/93:1135	108	3.60	Econ	100	0	19.1	0.87	6.9		285	59						279		285	
587	5/18/93:1150	108	3.60	Econ	100	0	19.1	0.87	4.9												
587	5/18/93:1214	108	3.60	Econ	0	0	0.0	0.00	2.9									281			
587	5/18/93:1214	108	3.60	Econ	0	0	0.0	0.00	-1.5												
588	5/19/93:0943	100	4.00	Econ	0	0	0.0	0.00	-1.8		274	64			269	256		264		274	
588	5/19/93:1043	100	3.95	Econ	82	0	15.6	0.80	4.8		275	65			271	257		266		275	
588	5/19/93:1053	100	3.95	Econ	82	0	15.6	0.80	3.8												
588	5/19/93:1100	100	3.95	Econ	82	0	15.6	0.80	34.1												
588	5/19/93:1108	100	3.95	Econ	82	0	15.6	0.80	1.9												
589	5/19/93:1137	100	3.81	Econ	41	0	7.8	0.40	27.7		277	66			272	259				277	
589	5/19/93:1155	100	3.81	Econ	41	0	7.8	0.40	3.3									270			
589	5/19/93:1206	100	3.81	Econ	41	0	7.8	0.40	2.6												
590	5/19/93:1239	100	4.04	Econ	25	0	4.8	0.24	15.7		280	66			274	262				280	
591	5/19/93:1620	90	4.32	Econ	0	0	0.0	0.00	-0.2		271	68			268	259		267		271	
591	5/19/93:1745	90	4.33	Econ	75	75	28.8	1.70	11.0		274	68			270	258				274	
591	5/19/93:1756	90	4.33	Econ	75	75	28.8	1.70	35.7												
591	5/19/93:1805	90	4.33	Econ	75	75	28.8	1.70	4.6												
591	5/19/93:1814	90	4.33	Econ	75	75	28.8	1.70	0.8												
591	5/19/93:1826	90	4.33	Econ	75	75	28.8	1.70	36.7												
591	5/19/93:1837	90	4.33	Econ	75	75	28.8	1.70	0.0												
591	5/19/93:1845	90	4.33	Econ	75	75	28.8	1.70	2.4												
591	5/19/93:1854	90	4.33	Econ	75	75	28.8	1.70	12.9												
591	5/19/93:1905	90	4.33	Econ	75	75	28.8	1.70	10.4												
591	5/19/93:2001	90	4.33	Econ	0	0	0.0	0.00	1.1												
592	5/20/93:0905	110	3.60	Econ	0	0	0.0	0.00	0.0		282	63			274	259				282	
592	5/20/93:1056	110	3.60	Econ	0	0	0.0	0.00	-1.5	4403	284	66			277	265		278		284	

Table A-2. Calcium Data, page 6

PSCC Arapahoe Unit

		GAS ANAL ECON-DRY (1-12)					GAS ANALYSIS INLET-WET ------						GAS ANALYSIS OUTLET-WET ------						
Test	Date & Time	NO	CO	SO2	CO2	O2	NO	CO	SO2	CO2	H2O	O2	NO	CO	SO2	CO2	H2O	O2	Comments
		ppm	ppm	ppm	%	%dry	ppm	ppm	ppm	%	%	%	ppm	ppm	ppm	%	%	%	
592	5/20/93:1212	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	244	54	400	13.80	0.00	4.65	EE 1-12
592	5/20/93:1221	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	233	31	214	10.78	0.00	7.90	EE 1,2
592	5/20/93:1230	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	272	79	435	14.19	0.00	4.05	EE 3,4
592	5/20/93:1247	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	275	59	430	14.47	0.00	4.15	3,4;HiPres
592	5/20/93:1255	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	220	83	240	10.89	0.00	7.65	1,2;HiPres
592	5/20/93:1303	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	237	97	428	13.99	0.00	4.35	1-12;Hi P
592	5/20/93:1320	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	229	120	240	11.00	0.00	7.50	EE 1,2
592	5/20/93:1329	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	273	144	442	14.45	0.00	3.80	EE 3,4
592	5/20/93:1337	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	249	77	427	13.66	0.00	4.80	EE 1-12
592	5/20/93:1412	243	28	405	13.85	4.55	243	28	405	13.85	0.00	4.55	256	57	445	13.53	0.00	4.80	BaseDrift!
593	5/21/93:0047	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	184	8	380	10.41	8.32	6.60	No Sorbent
593	5/21/93:0118	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	217	12	392	11.74	0.00	6.95	EE 1-12
593	5/21/93:0126	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	185	32	296	10.98	0.00	7.90	EE 1,2
593	5/21/93:0138	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	228	14	458	12.72	0.00	5.80	EE 3,4
593	5/21/93:0144	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	170	9	209	8.37	0.00	11.00	EE 11,12
593	5/21/93:0157	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	227	9	438	12.24	0.00	6.45	EE 9,10
593	5/21/93:0210	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	214	16	387	11.73	0.00	6.90	EE 1-12
593	5/21/93:0221	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	185	10	350	10.38	8.26	6.60	Altech Out
593	5/21/93:0301	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	213	14	380	11.84	0.00	6.80	EE 1-12
593	5/21/93:0308	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	182	11	346	10.42	8.33	6.51	Altech Out
593	5/21/93:0316	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	186	25	250	11.11	0.00	7.50	EE 1,2
593	5/21/93:0324	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	165	9	181	8.41	0.00	10.80	EE 11,12
593	5/21/93:0430	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	207	26	380	11.97	0.00	6.45	EE 1-12
593	5/21/93:0436	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	177	21	347	10.62	8.36	6.30	Altech Out
593	5/21/93:0535	217	13	430	11.96	6.75	217	13	430	11.96	0.00	6.75	207	42	415	11.74	0.00	6.75	BaseDrift
594	6/8/93:1000	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	253	130	285	11.26	8.14	5.30	No Sorbent
594	6/8/93:1056	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	263	160	298	13.29	0.00	5.15	EE 1-12
594	6/8/93:1109	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	238	375	190	10.30	0.00	7.75	EE 1,2
594	6/8/93:1119	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	309	150	335	13.61	0.00	4.30	EE 3,4
594	6/8/93:1130	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	273	19	345	13.83	0.00	4.25	EE 9,10
594	6/8/93:1138	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	210	20	225	11.72	0.00	6.25	EE 11,12
594	6/8/93:1147	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	261	100	299	13.09	0.00	5.10	EE 1-12
594	6/8/93:1157	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	229	100	280	11.82	8.44	4.65	Altech Out
594	6/8/93:1456	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	212	69	260	11.27	12.40	4.70	Altech Out
594	6/8/93:1536	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	231	75	290	11.87	8.42	4.70	Altech Out
594	6/8/93:1551	272	200	315	12.93	5.30	272	200	315	12.93	0.00	5.30	258	85	330	13.14	0.00	5.10	Base Drift
594	6/8/93:1551	258	85	330	13.14	5.10	258	85	330	13.14	0.00	5.10	231	74	305	12.03	8.47	4.70	No Sorbent
595	6/9/93:0731	213	23	325	12.24	6.10	213	23	325	12.24	0.00	6.10	189	18	289	10.92	8.16	5.95	No Sorbent
595	6/9/93:0818	213	23	325	12.24	6.10	213	23	325	12.24	0.00	6.10	199	25	193	10.07	0.00	8.25	EE 1,2
595	6/9/93:0827	213	23	325	12.24	6.10	213	23	325	12.24	0.00	6.10	240	17	339	13.12	0.00	5.20	EE 3,4

PSCC Arapahoe Unit 4 Calcium/Humidification-Duct Injection, Ca(OH)2 calculations based upon 68% CaO.

		Boiler		Sorbent Feed			Injector cal		ΔSO2	Humidification					Baghouse Temps					Humid calc	
Test	Date & Time	Load	O2cr	Loc.	A,w	B,e	Flow	Ca/S*	Calc	Air	Tgo	Twl	H2O	A/W	Grid	Out	IDin	Opsis	Ta	T2cr	H2Oe
		MWe	%wet		%	%	lb/min		%	scfm	°F	°F	gpm	-	°F	°F	°F	°F	°F	°F	%w
592	5/20/93:1212	110	3.60	Econ	90	0	17.2	0.81	0.6	4398	289	69			282	271				289	
592	5/20/93:1221	110	3.60	Econ	90	0	17.2	0.81	33.6												
592	5/20/93:1230	110	3.60	Econ	90	0	17.2	0.81	-4.2												
592	5/20/93:1247	110	3.60	Econ	90	0	17.2	0.81	-3.7												
592	5/20/93:1255	110	3.60	Econ	90	0	17.2	0.81	27.0												
592	5/20/93:1303	110	3.60	Econ	90	0	17.2	0.81	-4.4		291	70								291	
592	5/20/93:1320	110	3.60	Econ	90	0	17.2	0.81	27.8												
592	5/20/93:1329	110	3.60	Econ	90	0	17.2	0.81	-4.4												
592	5/20/93:1337	110	3.60	Econ	90	0	17.2	0.81	-7.1												
592	5/20/93:1412	110	3.60	Econ	0	0	0.0	0.00	-11.6												
593	5/21/93:0047	70	5.30	Econ	0	0	0.0	0.00	0.5		255				252	243		250		255	
593	5/21/93:0118	70	5.30	Econ	73	73	28.1	1.66	7.5		255									255	
593	5/21/93:0126	70	5.30	Econ	73	73	28.1	1.66	25.1												
593	5/21/93:0138	70	5.30	Econ	73	73	28.1	1.66	0.1												
593	5/21/93:0144	70	5.30	Econ	73	73	28.1	1.66	30.7												
593	5/21/93:0157	70	5.30	Econ	73	73	28.1	1.66	0.2												
593	5/21/93:0210	70	5.30	Econ	73	73	28.1	1.66	9.0									248			
593	5/21/93:0221	70	5.30	Econ	73	73	28.1	1.66	8.4												
593	5/21/93:0301	70	5.30	Econ	73	73	28.1	1.66	11.3									249			
593	5/21/93:0308	70	5.30	Econ	73	73	28.1	1.66	10.0												
593	5/21/93:0316	70	5.30	Econ	73	73	28.1	1.66	38.6												
593	5/21/93:0324	70	5.30	Econ	73	73	28.1	1.66	41.2												
593	5/21/93:0430	70	5.30	Econ	73	73	28.1	1.66	13.5		259									259	
593	5/21/93:0436	70	5.30	Econ	73	73	28.1	1.66	11.2												
593	5/21/93:0535	70	5.30	Econ	0	0	0.0	0.00	3.5									250			
594	6/8/93:1000	113	4.00	Econ	0	0	0.0	0.00	-1.5		283							273		283	
594	6/8/93:1056	113	4.00	Econ	80	80	30.8	1.74	6.3		285				279	263				285	
594	6/8/93:1109	113	4.00	Econ	80	80	30.8	1.74	28.5									278			
594	6/8/93:1119	113	4.00	Econ	80	80	30.8	1.74	0.0									278			
594	6/8/93:1130	113	4.00	Econ	80	80	30.8	1.74	-2.7												
594	6/8/93:1138	113	4.00	Econ	80	80	30.8	1.74	24.0												
594	6/8/93:1147	113	4.00	Econ	80	80	30.8	1.74	6.3									279			
594	6/8/93:1157	113	4.00	Econ	80	80	30.8	1.74	4.3									279			
594	6/8/93:1456	113	4.00	Econ	80	80	30.8	1.74	5.4	3719	294	62	68.0	0.55	160	170		178	43	163	
594	6/8/93:1536	113	4.00	Econ	80	80	30.8	1.74	0.5									229			
594	6/8/93:1551	113	4.00	Econ	80	80	30.8	1.74	-3.4									250			
594	6/8/93:1551	113	4.00	Econ	0	0	0.0	0.00	-1.2												
595	6/9/93:0731	80	5.12	Econ	0	0	0.0	0.00	0.7		260				257	239		250		260	
595	6/9/93:0818	80	5.12	Econ	60	60	23.1	1.67	30.6		264									264	
595	6/9/93:0827	80	5.12	Econ	60	60	23.1	1.67	1.6												

Table A-2. Calcium Data, page 8

PSCC Arapahoe Unit

		GAS ANAL ECON-DRY (1-12)					GAS ANALYSIS INLET-WET ------						GAS ANALYSIS OUTLET-WET ------						
Test	Date & Time	NO	CO	SO2	CO2	O2	NO	CO	SO2	CO2	H2O	O2	NO	CO	SO2	CO2	H2O	O2	Comments
		ppm	ppm	ppm	%	%dry	ppm	ppm	ppm	%	%	%	ppm	ppm	ppm	%	%	%	
595	6/9/93:0835	213	23	325	12.24	6.10	213	23	325	12.24	0.00	6.10	212	22	344	13.17	0.00	5.30	EE 9,10
595	6/9/93:0848	213	23	325	12.24	6.10	213	23	325	12.24	0.00	6.10	146	59	210	11.05	0.00	7.35	EE 11,12
595	6/9/93:0900	213	23	325	12.24	6.10	213	23	325	12.24	0.00	6.10	209	27	290	12.21	0.00	6.15	EE 1-12
595	6/9/93:0917	213	23	325	12.24	6.10	213	23	325	12.24	0.00	6.10	185	23	270	11.09	8.11	5.80	Altech Out
596	6/9/93:1350	217	25	320	12.16	6.10	217	25	320	12.16	0.00	6.10	195	19	290	10.95	7.98	5.90	No Sorbent
596	6/9/93:1437	217	25	320	12.16	6.10	217	25	320	12.16	0.00	6.10	214	22	289	12.00	0.00	6.45	EE 1-12
596	6/9/93:1455	217	25	320	12.16	6.10	217	25	320	12.16	0.00	6.10	195	20	270	10.98	8.07	5.90	Altech Out
596	6/9/93:1542	217	25	320	12.16	6.10	217	25	320	12.16	0.00	6.10	181	15	240	10.25	12.37	5.95	Altech Out
596	6/9/93:1625	217	25	320	12.16	6.10	217	25	320	12.16	0.00	6.10	181	16	240	10.28	12.44	5.93	Altech Out
596	6/9/93:1656	217	25	320	12.16	6.10	217	25	320	12.16	0.00	6.10	191	18	273	11.11	8.19	5.80	Altech Out
596	6/9/93:1715	217	25	320	12.16	6.10	217	25	320	12.16	0.00	6.10	194	19	290	11.19	8.17	5.70	Base Drift
597	6/10/93:1053	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	211	110	290	11.14	7.89	5.90	No Sorbent
597	6/10/93:1247	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	191	593	240	12.35	0.00	6.15	EE 1,2
597	6/10/93:1259	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	241	300	321	14.49	0.00	4.20	EE 3,4
597	6/10/93:1306	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	246	90	342	13.48	0.00	5.15	EE 5,6
597	6/10/93:1315	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	253	31	360	14.04	0.00	4.65	EE 7,8
597	6/10/93:1319	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	247	20	320	12.71	0.00	5.85	EE 9,10
597	6/10/93:1328	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	190	16	165	9.24	0.00	9.20	EE 11,12
597	6/10/93:1335	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	190	225	240	11.22	0.00	7.00	EE 1
597	6/10/93:1343	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	179	860	239	12.81	0.00	5.10	EE 2
597	6/10/93:1349	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	248	190	303	14.24	0.00	3.85	EE 3
597	6/10/93:1355	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	249	35	299	13.10	0.00	5.20	EE 4
597	6/10/93:1403	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	222	250	294	12.61	0.00	5.85	EE 1-12
597	6/10/93:1412	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	196	225	265	11.44	8.27	5.40	Altech Out
597	6/10/93:1533	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	180	200	230	10.38	12.36	5.85	Altech Out
597	6/10/93:1625	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	174	200	228	10.49	12.73	5.65	Altech Out
597	6/10/93:1720	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	175	150	228	10.55	12.77	5.60	Altech Out
597	6/10/93:1751	230	175	328	12.62	6.00	230	175	328	12.62	0.00	6.00	211	265	310	12.25	0.00	6.05	Base Drift
597	6/10/93:1751	211	265	310	12.25	6.05	211	265	310	12.25	0.00	6.05	190	210	284	11.13	8.37	5.75	Altech Out
598	6/11/93:0741	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	211	53	290	11.29	8.61	5.40	No Sorbent
598	6/11/93:0838	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	230	75	295	12.70	0.00	5.80	EE 1-12
598	6/11/93:0849	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	217	8	155	8.25	0.00	10.10	EE 1,2
598	6/11/93:0857	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	261	23	248	11.45	0.00	6.95	EE 3,4
598	6/11/93:0906	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	270	21	339	13.40	0.00	5.05	EE 5,6
598	6/11/93:0912	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	254	33	360	14.36	0.00	4.25	EE 7,8
598	6/11/93:0919	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	207	154	383	15.38	0.00	3.00	EE 9,10
598	6/11/93:0929	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	172	56	220	12.26	0.00	6.15	EE 11,12
598	6/11/93:0934	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	200	57	262	11.25	8.50	5.50	Altech Out
598	6/11/93:0942	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	225	120	287	12.49	0.00	5.80	EE 1-12
598	6/11/93:0957	240	62	325	12.66	5.80	240	62	325	12.66	0.00	5.80	241	36	304	12.26	0.00	6.10	Base Drift

PSCC Arapahoe Unit 4 Calcium/Humidification-Duct Injection, Ca(OH)2 calculations based upon 68% CaO.

		Boiler		Sorbent Feed			Injector cal		ΔSO2	Humidification					Baghouse Temps					Humid calc	
Test	Date & Time	Load	O2cr	Loc.	A,w	B,e	Flow	Ca/S*	Calc	Air	Tgo	Twl	H2O	A/W	Grid	Out	IDin	Opsis	Ta	T2cr	H2Oe
		MWe	%wet		%	%	lb/min		%	scfm	°F	°F	gpm	-	°F	°F	°F	°F	°F	°F	%w
595	6/9/93:0835	80	5.12	Econ	60	60	23.1	1.67	-0.5												
595	6/9/93:0848	80	5.12	Econ	60	60	23.1	1.67	29.5												
595	6/9/93:0900	80	5.12	Econ	60	60	23.1	1.67	10.5									255			
595	6/9/93:0917	80	5.12	Econ	60	60	23.1	1.67	8.3									255			
596	6/9/93:1350	80	5.11	Econ	0	0	0.0	0.00	-0.6		277	68			273	256		267		277	
596	6/9/93:1437	80	5.11	Econ	60	60	23.1	1.70	7.5		278	67						268		278	
596	6/9/93:1455	80	5.11	Econ	60	60	23.1	1.70	6.2									268			
596	6/9/93:1542	80	5.11	Econ	60	60	23.1	1.70	10.3	3857	281	63	56.0	0.69	146	201		203	30	139	
596	6/9/93:1625	80	5.11	Econ	60	60	23.1	1.70	10.3	3857			56.0	0.69	146	169		173	30		
596	6/9/93:1656	80	5.11	Econ	60	60	23.1	1.70	5.7									209			
596	6/9/93:1715	80	5.11	Econ	0	0	0.0	0.00	0.6												
597	6/10/93:1053	80	4.58	Econ*	0	0	0.0	0.00	1.3		268	70			265	255				268	
597	6/10/93:1247	80	4.58	Econ*	60	60	23.1	1.67	26.1		271	75			267	253				271	
597	6/10/93:1259	80	4.58	Econ*	60	60	23.1	1.67	12.6												
597	6/10/93:1306	80	4.58	Econ*	60	60	23.1	1.67	1.3												
597	6/10/93:1315	80	4.58	Econ*	60	60	23.1	1.67	-0.7												
597	6/10/93:1319	80	4.58	Econ*	60	60	23.1	1.67	3.4												
597	6/10/93:1328	80	4.58	Econ*	60	60	23.1	1.67	36.1												
597	6/10/93:1335	80	4.58	Econ*	60	60	23.1	1.67	21.6												
597	6/10/93:1343	80	4.58	Econ*	60	60	23.1	1.67	31.3												
597	6/10/93:1349	80	4.58	Econ*	60	60	23.1	1.67	19.2									264			
597	6/10/93:1355	80	4.58	Econ*	60	60	23.1	1.67	13.5									264			
597	6/10/93:1403	80	4.58	Econ*	60	60	23.1	1.67	11.3		275	77								275	
597	6/10/93:1412	80	4.58	Econ*	60	60	23.1	1.67	12.6												
597	6/10/93:1533	80	4.58	Econ*	60	60	23.1	1.67	16.2	3825	281	62	58.0	0.68	142	190		191	26	134	
597	6/10/93:1625	80	4.58	Econ*	60	60	23.1	1.67	17.7	3838	282	63	57.0	0.70	142	166		164	26	137	
597	6/10/93:1720	80	4.58	Econ*	60	60	23.1	1.67	18.0	3838	282	63	57.0	0.70	142	156		156	26	137	
597	6/10/93:1751	80	4.58	Econ*	0	0	0.0	0.00	5.2												
597	6/10/93:1751	80	4.58	Econ*	0	0	0.0	0.00	-1.5												
598	6/11/93:0741	80	5.14	Econ*	0	0	0.0	0.00	1.7		262	67			258	241		248		262	
598	6/11/93:0838	80	5.14	Econ*	60	60	23.1	1.70	9.2		264	68						252		264	
598	6/11/93:0849	80	5.14	Econ*	60	60	23.1	1.70	33.5									252			
598	6/11/93:0857	80	5.14	Econ*	60	60	23.1	1.70	17.4									254			
598	6/11/93:0906	80	5.14	Econ*	60	60	23.1	1.70	0.6									254			
598	6/11/93:0912	80	5.14	Econ*	60	60	23.1	1.70	-0.5									255			
598	6/11/93:0919	80	5.14	Econ*	60	60	23.1	1.70	0.5									255			
598	6/11/93:0929	80	5.14	Econ*	60	60	23.1	1.70	30.7												
598	6/11/93:0934	80	5.14	Econ*	60	60	23.1	1.70	10.7												
598	6/11/93:0942	80	5.14	Econ*	60	60	23.1	1.70	11.7		269	39						256		269	
598	6/11/93:0957	80	5.14	Econ*	0	0	0.0	0.00	4.6									257			

Table A-2. Calcium Data, page 10

PSCC Arapahoe Unit

		GAS ANAL ECON-DRY (1-12)					GAS ANALYSIS INLET-WET ------						GAS ANALYSIS OUTLET-WET ------						
Test	Date & Time	NO	CO	SO2	CO2	O2	NO	CO	SO2	CO2	H2O	O2	NO	CO	SO2	CO2	H2O	O2	Comments
		ppm	ppm	ppm	%	%dry	ppm	ppm	ppm	%	%	%	ppm	ppm	ppm	%	%	%	
599	6/15/93:0750	207	30	378	11.82	6.45													Base
599	6/15/93:0915	207	30	378	11.82	6.45	196	9	339	10.75	8.71	6.02	177	15	298	9.97	12.32	6.42	
599	6/15/93:1100	207	30	378	11.82	6.45	200	7	329	10.42	7.82	6.42	183	12	292	9.64	11.77	6.85	
599	6/15/93:1300	213	17	379	11.51	6.95	196	6	351	10.83	7.87	6.00	179	12	310	9.97	11.82	6.45	ΔLoad
600	6/16/93:0840	226	257	440	12.67	6.45	213	26	396	11.56	8.70	5.45	182	297	290	10.48	12.31	6.22	
600	6/16/93:1100	226	257	440	12.67	6.45	212	27	352	11.41	8.66	5.61	186	126	241	10.25	12.13	6.52	
600	6/16/93:1300	226	257	440	12.67	6.45	221	16	325	11.20	8.98	5.65	191	85	224	10.20	12.79	6.50	
600	6/16/93:1500	226	257	440	12.67	6.45	213	19	318	11.31	8.92	5.48	181	176	220	10.42	12.66	6.15	
600	6/16/93:1800	226	257	440	12.67	6.45	219	21	298	11.19	8.85	5.73	184	53	196	10.36	12.58	6.30	
601	6/17/93:0800	218	77	304	12.22	6.80	205	23	273	11.08	9.15	6.00	175	79	224	10.33	11.99	6.53	
601	6/17/93:0900	218	77	304	12.22	6.80	208	21	268	10.78	8.87	6.40	180	52	210	9.95	11.67	7.15	
601	6/17/93:1100	218	77	304	12.22	6.80	209	21	272	10.92	8.91	6.05	179	64	207	9.69	11.43	7.08	
601	6/17/93:1300	218	77	304	12.22	6.80	211	25	280	10.98	9.04	5.95	182	62	224	10.24	12.13	6.50	
601	6/17/93:1500	218	77	304	12.22	6.80	207	26	280	11.07	9.12	5.90	187	43	216	10.03	11.99	6.78	
601	6/17/93:1550	218	77	304	12.22	6.80	203	27	280	11.14	9.26	5.75	183	48	217	10.10	12.10	6.62	
602	6/21/93:0900	208	49	410	11.79	7.10	208	20	388	11.18	9.19	5.58	182	34	327	10.18	12.10	6.58	
602	6/21/93:1100	208	49	410	11.79	7.10	214	19	392	10.99	8.89	6.00	187	30	334	10.03	12.02	6.80	
602	6/21/93:1300	208	49	410	11.79	7.10	210	24	394	11.08	8.66	5.95	188	27	340	10.19	11.93	6.65	
603	6/22/93:0925	247	69	415	12.87	5.90	217	51	360	10.83	8.52	6.10	189	33	258	10.71	12.43	6.20	
603	6/22/93:1114	247	69	415	12.87	5.90	224	29	345	11.80	8.72	4.90	187	45	245	10.57	12.11	6.00	
603	6/22/93:1300	247	69	415	12.87	5.90	224	31	325	11.77	8.72	4.30	195	63	220	10.46	12.10	6.15	
603	6/22/93:1500	247	69	415	12.87	5.90	221	33	323	11.69	9.03	5.00	189	109	230	10.64	12.18	5.85	
603	6/22/93:1650	247	69	415	12.87	5.90	223	31	311	11.68	9.12	5.05	196	56	208	10.38	12.11	6.10	
604	6/22/93:1850	247	69	415	12.87	5.90	213	27	281	10.92	8.16	6.15	192	21	198	9.45	11.08	7.55	load follow
604	6/22/93:2100	247	69	415	12.87	5.90	214	26	273	10.78	8.71	6.20	188	22	193	9.62	11.68	7.25	
604	6/22/93:2320	165	111	249	9.44	9.80	161	78	258	9.72	7.88	7.70	142	83	163	8.03	9.97	9.45	
604	6/23/93:0100	191	130	266	10.08	9.15	168	74	262	9.99	8.07	7.30	149	107	167	8.51	10.25	8.80	
605	6/28/93:1110	274	18	262	11.61	6.38	216	15	227	10.41	10.54	4.90	221	15	175	9.65	13.47	5.90	w/Nat Gas
605	6/28/93:1240	274	18	262	11.61	6.38	229	13	233	10.54	10.59	4.90	220	14	183	9.81	13.44	5.70	
605	6/28/93:1350	274	18	262	11.61	6.38	251	16	235	10.48	10.14	5.30	235	17	190	9.85	13.08	5.85	
605	6/28/93:1500	274	18	262	11.61	6.38	251	16	243	10.54	10.17	5.22	234	16	203	10.01	13.06	5.70	
605	6/28/93:1705	274	18	262	11.61	6.38	237	18	255	10.73	10.50	4.75	215	20	190	10.08	13.87	5.30	
605	6/28/93:1905	274	18	262	11.61	6.38	253	17	241	10.48	10.43	5.05	208	35	183	10.34	14.40	4.90	
605	6/28/93:2100	250	32	330	12.05	6.80	225	19	297	10.93	8.23	6.20	204	25	230	10.32	12.20	6.25	NGas off
605	6/28/93:2300	250	32	330	12.05	6.80	227	28	298	10.80	8.30	6.30	208	32	210	10.04	11.93	6.70	
605	6/29/93:0100	250	32	330	12.05	6.80	229	18	296	10.88	8.26	6.20	209	21	217	10.05	11.80	6.72	
605	6/29/93:0300	250	26	326	11.86	6.95	227	23	292	10.60	8.01	6.00	207	18	205	9.92	11.67	6.85	
605	6/29/93:0430	250	26	326	11.86	6.95	228	18	290	10.68	8.10	6.40	213	16	206	9.88	11.62	6.90	
605	6/29/93:0700	250	26	326	11.86	6.95	228	18	288	10.71	7.99	6.60	214	19	203	9.83	11.50	6.95	
605	6/29/93:0905	250	26	326	11.86	6.95	239	19	282	10.57	7.92	6.75	215	40	202	10.20	12.01	6.55	

PSCC Arapahoe Unit 4 Calcium/Humidification-Duct Injection, Ca(OH)2 calculations based upon 68% CaO.

		Boiler		Sorbent Feed			Injector cal		ΔSO2	Humidification					Baghouse Temps					Humid calc	
Test	Date & Time	Load	O2cr	Loc.	A,w	B,e	Flow	Ca/S*	Calc	Air	Tgo	Twl	H2O	A/W	Grid	Out	IDin	Opsis	Ta	T2cr	H2Oe
		MWe	%wet		%	%	lb/min		%	scfm	°F	°F	gpm	-	°F	°F	°F	°F	°F	°F	%w
599	6/15/93:0750	80	5.70	Duct	0	0	0.0				266							256		266	
599	6/15/93:0915	80	5.70	Duct	35	0	6.7	0.41	3.6	3854	271	63	54.0	0.73	150	196		196	30	148	8.80
599	6/15/93:1100	80	6.20	Duct	35	0	6.7	0.42	1.7	3797	280	64	59.0	0.66	147	160		160	30	145	8.11
599	6/15/93:1300	80	6.10	Duct	35	0	6.7	0.40	2.3	3795	284	64	60.0	0.65	148	154		155	30	150	7.63
600	6/16/93:0840	81	5.00	Duct	70	70	26.9	1.46	17.6	3868	267	64	51.0	0.81	147	192		198	30	152	8.42
600	6/16/93:1100	81	5.00	Duct	81	81	31.2	1.88	22.1	3850	271	65	51.0	0.79	147	158		158	30	156	8.48
600	6/16/93:1300	80	4.90	Duct	75	74	28.7	1.88	21.5	3845	273	65	52.0	0.79	147	157		155	30	155	8.83
600	6/16/93:1500	80	5.00	Duct	70	69	26.8	1.82	22.6	3855	272	65	51.0	0.79	147	156		155	30	156	8.66
600	6/16/93:1800	80	5.00	Duct	67	66	25.6	1.82	26.8	3840	272	65	51.0	0.79	147	154			30	156	8.75
601	6/17/93:0800	80	5.30	Duct	60	0	11.4	0.87	10.2	3976	252	63	41.0	1.03	154	211		201	30	161	9.03
601	6/17/93:0900	81	5.20	Duct	60	0	11.4	0.85	12.4	3954	253	63	43.0	0.97	147	170		167	30	158	9.01
601	6/17/93:1100	81	5.20	Duct	60	0	11.4	0.86	13.6	3946	256	63	43.0	0.96	147	159		156	30	161	8.81
601	6/17/93:1300	81	5.20	Duct	60	0	11.4	0.84	12.0	3958	257	64	43.0	0.97	147	158		156	30	162	8.88
601	6/17/93:1500	81	5.10	Duct	60	0	11.4	0.84	13.1	3935	257	63	44.0	0.94	148	157		156	30	160	8.93
601	6/17/93:1550	81	5.20	Duct	60	0	11.4	0.85	12.9	3951	257	63	43.0	0.96	146	157		156	30	162	8.97
602	6/21/93:0900	80	5.10	Duct	36	0	6.9	0.38	4.3	3880	262	63	45.0	0.88	149	203		198	30	163	8.60
602	6/21/93:1100	81	5.20	Duct	38	0	7.2	0.38	4.2	3871	264	64	48.0	0.84	147	166		162	30	160	8.57
602	6/21/93:1300	80	5.20	Duct	40	0	7.6	0.40	3.6	3872	269	62	49.0	0.84	147	161		158	30	161	8.31
603	6/22/93:0925	96	4.10	Duct	85	85	32.7	1.59	22.9	3827	274	63	56.0	0.70	149	203		196	30	162	8.98
603	6/22/93:1114	95	4.20	Duct	92	92	35.4	1.97	18.7	3781	280	63	59.0	0.66	150	161		162	30	160	8.42
603	6/22/93:1300	95	4.20	Duct	80	81	30.9	1.91	18.2	3760	283	64	60.0	0.64	147	156		157	30	161	8.08
603	6/22/93:1500	95	4.20	Duct	72	73	27.9	1.64	20.2	3791	282	65	57.0	0.68	147	160		161	30	166	8.79
603	6/22/93:1650	95	4.10	Duct	72	73	27.9	1.69	24.0	3785	284	64	59.0	0.67	147	162		163	30	164	8.92
604	6/22/93:1850	81	5.50	Duct	63	63	24.2	1.77	16.8	3843	275	64	53.0	0.77	143	158		157	30	151	8.61
604	6/22/93:2100	80	5.65	Duct	62	62	23.8	1.79	18.8	3866	268	64	49.0	0.85	147	157		157	30	153	9.26
604	6/22/93:2320	50	7.50	Duct	42	42	16.1	1.75	22.2	4070	248	64	34.0	1.35	145	153		152	30	156	6.98
604	6/23/93:0100	59	6.90	Duct	42	42	16.1	1.53	23.8	4024	248	64	36.0	1.27	146	151		150	30	159	7.32
605	6/28/93:1110	106	4.90	Duct	70	71	27.0	2.00	12.8	3681	286	65	65.0	0.58	146	193	187		30	172	9.93
605	6/28/93:1240	106	4.80	Duct	61	62	23.5	1.70	12.7	3738	290	65	62.0	0.62	158	184	179	183	40	181	9.98
605	6/28/93:1350	107	4.80	Duct	61	62	23.5	1.63	11.5	3740	293	66	61.0	0.63	168	187	182	186	50	187	9.82
605	6/28/93:1500	109	4.60	Duct	65	66	25.1	1.66	9.2	3755	295	66	58.0	0.65	177	190	187	190	60	195	9.79
605	6/28/93:1705	108	3.60	Duct	68	69	26.2	1.72	18.2	3680	294	65	66.0	0.56	148	173	172	175	30	180	9.78
605	6/28/93:1905	108	4.10	Duct	68	69	26.2	1.78	20.1	3689	291	65	65.0	0.58	145	173	170	173	30	179	9.93
605	6/28/93:2100	91	4.70	Duct	56	56	21.5	1.33	16.9	3746	279	65	60.0	0.63	146	161	159	162	30	159	8.20
605	6/28/93:2300	91	5.20	Duct	72	72	27.7	1.69	22.6	3772	273	65	59.0	0.63	146	155	155	157	30	156	8.34
605	6/29/93:0100	91	5.30	Duct	72	72	27.7	1.71	18.8	3772	272	64	59.0	0.65	147	152	155	156	30	155	8.24
605	6/29/93:0300	90	5.30	Duct	72	72	27.7	1.79	20.1	3756	272	65	60.0	0.64	146	153	154	155	30	152	7.77
605	6/29/93:0430	91	5.20	Duct	72	72	27.7	1.73	21.4	3773	270	65	58.0	0.66	147	152	154	155	30	156	8.11
605	6/29/93:0700	91	5.20	Duct	72	72	27.7	1.72	22.9	3757	270	65	59.0	0.64	147	151	153	155	30	154	8.12
605	6/29/93:0905	94	5.10	Duct	72	72	27.7	1.68	24.4	3722	276	65	61.0	0.61	147	152	154	156	30	159	8.14

Table A-2. Calcium Data, page 12

PSCC Arapahoe Unit

		GAS ANAL ECON-DRY (1-12)					GAS ANALYSIS INLET-WET ------						GAS ANALYSIS OUTLET-WET ------						
Test	Date & Time	NO	CO	SO2	CO2	O2	NO	CO	SO2	CO2	H2O	O2	NO	CO	SO2	CO2	H2O	O2	Comments
		ppm	ppm	ppm	%	%dry	ppm	ppm	ppm	%	%	%	ppm	ppm	ppm	%	%	%	
605	6/29/93:1100	250	26	326	11.86	6.95	232	24	290	10.79	7.74	6.55	214	28	215	9.74	11.51	7.00	NGas on
605	6/29/93:1220	264	31	298	12.01	5.90	238	21	260	10.86	9.90	5.05	211	41	170	10.06	13.83	5.55	NGas on
605	6/29/93:1550	264	31	298	12.01	5.90	238	17	258	10.92	10.29	4.80	216	18	152	9.83	13.72	5.62	
605	6/29/93:1700	264	31	298	12.01	5.90	218	17	242	10.76	10.89	4.50	198	19	148	8.54	12.24	7.50	NGas off
605	6/29/93:2120	212	55	295	10.84	8.25	221	23	302	11.10	8.31	5.95	196	72	210	10.27	12.04	6.40	TCshield
606	6/29/93:2300	193	20	280	10.45	8.50	218	26	270	9.91	7.77	7.58	193	28	188	9.02	10.76	8.15	
606	6/30/93:0100	193	20	280	10.45	8.50	214	25	274	10.06	7.84	7.30	191	25	201	9.12	10.61	8.18	
606	6/30/93:0300	230	38	291	10.69	8.90	226	25	259	9.63	7.46	7.98	189	30	160	7.67	9.44	10.60	blr upset
606	6/30/93:0500	187	32	280	10.44	8.80	172	28	264	9.96	7.63	7.56	153	27	184	8.91	10.37	8.45	3mills
606	6/30/93:0630	187	32	280	10.44	8.80	174	26	264	9.96	7.68	7.55	158	21	189	8.91	10.36	8.45	
606	6/30/93:0845	187	32	280	10.44	8.80	177	24	260	9.94	7.74	7.55	157	19	188	8.86	10.52	8.42	
607	6/30/93:1045	197	32	253	9.67	9.38	188	29	232	9.10	7.64	8.50	163	26	160	8.45	10.45	8.87	load follow
607	6/30/93:1400	273	73	348	12.71	5.80	236	43	317	11.85	9.29	4.95	212	51	235	10.78	13.19	5.52	
607	6/30/93:1600	273	73	348	12.71	5.80	244	32	250	9.60	7.79	7.95	199	245	180	9.61	12.50	6.95	
607	6/30/93:1644	237	131	325	12.31	6.75	224	27	302	11.42	8.99	5.50	196	127	203	10.61	13.03	5.80	
607	6/30/93:1900	237	131	325	12.31	6.75	223	24	300	11.29	8.96	5.70	194	49	198	10.21	12.73	6.40	
607	6/30/93:2100	231	81	314	11.63	7.20	229	28	292	10.79	8.79	6.25	203	54	184	10.12	12.79	6.45	
607	6/30/93:2300	231	81	314	11.63	7.20	206	20	265	10.07	8.54	7.30	189	23	174	9.36	12.06	7.60	
607	7/1/93:0100	231	81	314	11.63	7.20	197	17	252	9.61	8.05	7.90	175	21	170	8.97	11.56	8.12	113 sat
608	7/1/93:0300	194	21	271	10.16	9.05	182	18	248	9.53	7.96	8.02	159	14	181	8.72	11.00	8.52	30Ta, 143°
608	7/1/93:0500	194	21	271	10.16	9.05	182	18	250	9.58	7.87	7.94	164	18	178	8.73	10.88	8.48	
609	7/1/93:0645	192	21	272	10.34	8.85	178	18	254	9.79	7.99	7.70	161	14	171	8.72	11.00	8.48	25Ta, 138°
610	7/1/93:1010	248	103	345	12.95	5.90	221	35	309	11.61	9.52	5.05	203	109	188	10.70	13.33	5.60	
610	7/1/93:1150	252	199	355	13.43	5.15	236	35	310	11.71	9.34	5.05	209	93	192	10.98	13.59	5.40	
610	7/1/93:1340	252	199	355	13.43	5.15	241	28	295	11.13	8.59	5.75	214	44	188	10.49	13.13	6.00	
610	7/1/93:1505	252	199	355	13.43	5.15	249	22	290	11.08	8.79	5.80	218	43	190	10.42	12.89	6.00	
610	7/1/93:1800	252	199	355	13.43	5.15	221	27	290	10.93	8.32	6.60	216	29	206	9.70	12.08	6.85	Load droppe
610	7/1/93:2300	210	18	279	10.52	8.60	207	17	266	10.19	8.72	6.95	185	16	191	9.33	12.26	7.55	
611	7/2/93:0100	195	21	272	10.32	8.96	182	18	252	9.85	8.43	7.36	165	15	163	8.85	11.65	8.20	a/w=0.5
611	7/2/93:0300	195	21	272	10.32	8.96	183	18	251	9.78	8.30	7.52	166	13	166	8.85	11.55	8.21	
611	7/2/93:0500	195	21	272	10.32	8.96	182	17	253	9.83	8.01	7.40	167	13	174	8.88	11.17	8.25	H2O upset
611	7/2/93:0645	201	16	272	10.42	8.60	187	17	258	9.98	8.17	7.40	165	13	171	9.03	11.25	8.05	
612	7/2/93:0915	201	16	272	10.42	8.60	203	17	268	10.29	8.15	7.00	190	16	195	9.47	11.64	7.30	
612	7/2/93:1120	264	36	332	12.50	6.35	233	27	292	11.15	8.55	5.83	216	24	235	10.52	12.92	5.95	
612	7/2/93:1250	264	36	332	12.50	6.35	229	25	290	10.91	8.55	6.10	207	26	225	10.35	12.75	6.10	

PSCC Arapahoe Unit 4 Calcium/Humidification-Duct Injection, $Ca(OH)_2$ calculations based upon 68% CaO.

		Boiler		Sorbent Feed			Injector cal		ΔSO_2	Humidification					Baghouse Temps					Humid calc	
Test	Date & Time	Load	O_2cr	Loc.	A,w	B,e	Flow	Ca/S*	Calc	Air	Tgo	Twl	H_2O	A/W	Grid	Out	IDin	Opsis	Ta	T2cr	H_2Oe
		MWe	%wet		%	%	lb/min		%	scfm	°F	°F	gpm	-	°F	°F	°F	°F	°F	°F	%w
605	6/29/93:1100	96	5.10	Duct	74	74	28.4	1.68	17.9	3722	279	65	61.0	0.61	147	154	156	156	30	164	7.82
605	6/29/93:1220	109	4.20	Duct	84	85	32.4	2.03	27.7	3545	288	66	75.0	0.46	147	155	156	159	30	157	9.71
605	6/29/93:1550	107	4.20	Duct	84	85	32.4	2.11	33.8	3551	292	65	74.0	0.46	149	162	162	166	30	160	9.93
605	6/29/93:1700	106	4.40	Duct	69	69	26.4	1.87	20.5	3562	293	65	73.0	0.47	150	155	154	158	30	162	10.31
605	6/29/93:2120	86	5.30	Duct	65	65	25.0	1.63	23.4	3702	272	65	60.0	0.63	147	152	153	155	30	158	7.30
606	6/29/93:2300	60	6.80	Duct	48	48	18.5	1.64	22.5	3901	256	65	41.0	1.02	144	149	150	149	30	151	7.60
606	6/30/93:0100	60	6.40	Duct	48	48	18.5	1.66	16.5	3951	250	65	38.0	1.09	147	148	148	147	30	153	7.49
606	6/30/93:0300	60	6.40	Duct	48	48	18.5	1.67	15.9	3965	246	65	38.0	1.14	147	147	148	147	30	152	7.29
606	6/30/93:0500	58	6.80	Duct	48	48	18.5	1.74	20.5	3965	248	64	38.0	1.12	147	147	149	147	30	150	7.26
606	6/30/93:0630	58	6.80	Duct	48	48	18.5	1.74	18.3	3972	247	64	37.0	1.13	147	147	148	147	30	152	7.31
606	6/30/93:0845	58	6.80	Duct	48	48	18.5	1.76	17.6	3948	249	65	38.0	1.10	147	147	149	147	30	151	7.37
607	6/30/93:1045	48	6.90	Duct	48	48	18.5	2.15	24.4	4022	241	65	32.0	1.38	146	148	149	148	30	149	7.53
607	6/30/93:1400	100	4.10	Duct	42	42	16.1	0.92	17.8	3636	280	63	65.0	0.54	148	151	152	154	30	155	9.08
607	6/30/93:1600	91	5.30	Duct	73	73	28.1	1.80	28.1	3631	280	64	66.0	0.54	146	150	153	152	30	142	9.57
607	6/30/93:1644	90	4.30	Duct	73	73	28.1	1.79	26.6	3683	279	64	61.0	0.60	145	150	151	152	30	156	8.57
607	6/30/93:1900	84	4.80	Duct	66	66	25.4	1.72	25.7	3700	275	64	59.0	0.63	145	150	151	152	30	149	8.66
607	6/30/93:2100	90	5.10	Duct	80	80	30.8	1.93	31.5	3639	276	64	65.0	0.56	146	149	152	154	30	150	8.57
607	6/30/93:2300	79	6.10	Duct	66	66	25.4	1.82	28.1	3756	265	64	54.5	0.71	147	148	151	152	30	147	9.05
607	7/1/93:0100	74	6.40	Duct	62	62	23.8	1.83	26.4	3794	260	65	51.0	0.76	146	148	150	151	30	143	8.95
608	7/1/93:0300	60	7.10	Duct	48	48	18.5	1.72	18.8	3875	249	64	42.0	0.96	142	144	146	145	30	147	7.74
608	7/1/93:0500	60	7.00	Duct	48	48	18.5	1.72	20.6	3889	247	64	41.0	1.00	143	144	145	144	30	147	7.60
609	7/1/93:0645	60	6.90	Duct	48	48	18.5	1.72	23.4	3874	247	64	42.5	0.95	137	141	142	141	25	142	7.69
610	7/1/93:1010	100	3.80	Duct	76	76	29.2	1.69	32.6	3626	279	65	66.0	0.54	147	148	152	152	30	153	9.32
610	7/1/93:1150	109	3.60	Duct	83	83	31.9	1.69	32.0	3547	287	64	72.0	0.48	147	149	152	156	30	155	9.59
610	7/1/93:1340	107	4.30	Duct	85	85	32.7	1.79	30.0	3475	289	64	79.0	0.43	146	151	155	158	30	141	9.26
610	7/1/93:1505	105	4.60	Duct	85	85	32.7	1.84	28.8	3515	287	65	75.0	0.47	148	157		163	30	145	9.52
610	7/1/93:1800	98	5.00	Duct	100	0	19.1	1.09	22.6	3525	289	65	73.0	0.48	150	157	159	162		141	9.56
610	7/1/93:2300	78	5.90	Duct	100	0	19.1	1.42	19.3	3521	272	65	57.0	0.68	151	149	154	155		158	8.08
611	7/2/93:0100	61	6.70	Duct	94	0	17.9	1.70	25.8	2917	257	65	44.5	0.86	143	145	148	147	30	149	7.83
611	7/2/93:0300	61	6.90	Duct	86	0	16.4	1.54	25.1	2921	256	65	44.5	0.86	143	143	146	145	30	148	7.81
611	7/2/93:0500	61	6.90	Duct	86	0	16.4	1.55	21.2	2910	254	64	43.5	0.86	142	146	149	149	30	148	7.44
611	7/2/93:0645	61	6.80	Duct	86	0	16.4	1.52	25.6	2890	253	64	43.0	0.88	143	142	146	144	30	146	7.83
612	7/2/93:0915	79	5.80	Duct	100	0	19.1	1.40	20.6	2906	269	65	55.0	0.65	152	147	154	154	30	159	7.55
612	7/2/93:1120	106	4.60	Duct	100	0	19.1	1.06	12.8	3318	291	64	77.0	0.48	151	150	156	158	30	155	8.56
612	7/2/93:1250	102	4.60	Duct	100	0	19.1	1.08	16.8	3348	293	65	75.0	0.51	153	150	157	157	30	156	8.74

Table A-2. Calcium Data, page 14

PSCC Arapahoe Unit 4
Ca(OH)2 Calculations

		Economizer Exit, dry (1-12)						Baghouse Inlet Gas Analysis, wet							Stack Gas Analysis, wet							
Test	Date & Time	CO ppm	NO2 ppm	CO2 %	O2 %dry	SO2 ppm	NO ppm	CO ppm	NO2 ppm	CO2 %	H2O %	O2 %	SO2 ppm	NO ppm	CO ppm	NO2 ppm	CO2 %	H2O %	O2 %	SO2 ppm	NO ppm	Comments
705	10/19/93 11:30	123	3	13.92	4.85	480	240	39	-4	12.62	9.17	4.25	438	227	83	-3	11.47	12.90	4.80	252	195	Toxics 22
705	10/19/93 12:30	97	1	13.92	4.70	475	245	69	-3	13.08	9.25	3.58	457	219	86	-3	11.53	12.82	4.70	247	197	
705	10/19/93 13:30	59	0	13.77	4.90	472	246	40	-4	12.72	8.99	4.00	431	222	45	-3	11.45	12.73	4.85	252	200	
705	10/19/93 14:30	49	0	13.53	5.05	453	247	42	-4	12.95	9.15	3.70	437	221	58	-3	11.47	12.86	4.80	239	196	
705	10/19/93 15:30	56	0	13.72	4.90	460	248	30	-4	12.69	8.99	4.10	426	235	48	-2	11.37	12.79	4.90	240	195	
705	10/19/93 16:30	79	1	13.84	4.70	460	245	66	-4	13.30	9.32	3.35	435	215	55	-3	11.57	12.77	4.80	235	192	
706	10/20/93 8:30	408	4	13.24	5.00	460	230	69	-3	12.50	9.53	4.00	440	210	266	-3	11.15	12.94	5.00	250	190	Toxics 23
706	10/20/93 9:30	99	2	13.29	5.10	457	229	52	-3	12.24	9.42	4.20	430	215	264	-3	11.14	12.98	5.05	240	190	
706	10/20/93 10:30	225	1	13.30	5.05	460	235	20	-3	12.02	9.11	4.62	417	221	109	-3	10.84	12.54	5.35	250	200	
706	10/20/93 11:40	308	1	13.38	5.05	461	234	50	-3	12.18	9.27	4.30	425	213	176	-3	10.95	12.95	5.10	243	192	
706	10/20/93 12:50	138	2	12.82	4.80	450	230	37	-3	12.24	9.28	4.22	431	215	191	-3	11.04	12.70	5.20	250	194	
707	10/20/93 14:30	204	1	13.10	5.30	451	238	35	-4	11.98	9.11	4.50	422	219	200	-4	10.84	12.62	5.25	264	200	Toxics 24
707	10/20/93 15:30	192	1	12.83	5.68	438	242	39	-4	11.79	9.04	4.70	412	221	188	-4	10.82	13.30	5.20	222	200	
707	10/20/93 16:40	198	2	12.92	5.60	449	240	47	-4	11.96	9.10	4.50	418	218	215	-3	10.89	12.98	5.25	230	194	
707	10/20/93 17:30	171	1	12.85	5.50	432	237	28	-3	11.71	8.89	4.85	392	228	179	-3	10.80	12.92	5.25	207	191	
707	10/20/93 18:40	169	1	12.07	5.35	207	240	45	-4	12.07	9.20	4.50	392	221	142	-3	10.83	12.83	5.25	219	193	
708	10/26/93 14:30	259	2	13.84	4.30	468	205	51	-4	12.60	9.16	3.80	430	188	177	-3	11.52	12.13	4.45	355	165	50 deg. approach
709	10/26/93 15:50	184	2	13.53	4.70	450	208	38	-2	12.56	9.17	3.82	423	190	14	-2	11.31	11.92	4.83	277	170	
710	10/26/93 17:10	237	1	13.80	4.43	450	205	38	-3	12.45	9.07	3.90	413	188	184	-2	11.54	12.12	4.52	260	165	
711	10/27/93 9:40	312	4	13.40	4.40	338	215	69	-3	12.40	9.09	3.85	315	198	225	-3	11.28	12.22	4.60	245	178	30 deg. approach
712	10/27/93 14:30	370	2	13.17	4.50	365	210	134	-4	11.94	8.62	4.10	325	198	224	-3	11.06	12.44	4.70	212	177	
713	10/27/93 15:10	424	1	13.21	4.60	378	210	60	-4	11.87	8.54	4.30	330	195	355	-3	11.04	12.50	4.67	200	170	
714	11/1/93 9:10	256	1	13.66	4.40	413	245	57	-5	12.56	9.06	4.05	385	230	228	-3	12.40	8.89	4.50	380	225	Base
715	11/1/93 13:40	119	2	13.70	4.90	380	260	43	-4	12.58	9.00	4.10	355	233	147	-4	11.47	12.78	4.80	220	205	
716	11/1/93 16:50	215	1	14.60	4.45	397	250	48	-4	12.74	9.02	3.90	348	220	144	-3	11.57	12.75	4.70	195	205	
717	11/1/93 17:50	166	0	14.05	4.70	365	255	42	-4	12.67	9.04	4.05	340	227	167	-3	11.78	12.86	4.40	217	195	B feeder only
719	11/2/93 11:30	220	2	14.04	4.80	360	250	51	-3	12.83	8.83	4.00	337	225	201	-3	11.70	12.38	4.70	223	205	
720	11/2/93 14:40	391	1	13.81	4.70	350	250	70	-3	12.99	8.97	3.70	330	215	215	-2	11.68	12.70	4.60	210	200	
721	11/2/93 14:40	149	2	14.00	4.55	385	240	46	-4	12.80	8.83	4.10	361	216	125	-3	11.71	12.81	4.65	220	197	good?

PSCC Arapahoe Unit 4 Calcium Injection Summary, Duct Injection Tests cont.
Ca(OH)2 Calculations based on: 68% CaO

				Sorbent Feed		Injector cal		ΔSO2		ΔNOx - - - -		ΔNO2	ΔNO	ΔNO	SO2	Economizer NO Calc - - -				Humidification				Baghouse Temps					Humid calc	
Test	Date & Time	Load	O2cr	A (w)	B (e)	Flow	Ca	Calc						ΔSO2	inlet	ΔNOx	ΔNO	ΔNO2!	ΔNO	Air	Taho	Tw	H2O	Grid	Out	IDin	Opsis	Ta	T2c	H2Oe
		MWe	%wet	%	%	lb/min	S*	%	ppmc	%	ppmc	ppmc	ppmc		ppmdc	%	ppmc	ppmc	ΔSO2	scfm	°F	°F	gpm	°F	°F	°F	°F	°F	°F	%w
705	10/19/93 11:30	112	4.20	57	69	52.2	2.02	36.8	196	5.6	15	0.2	15	0.08	532	5.5	7	0.2	0.04	3528	273	58	71.0	140	142	148	150	30	143	9.07
705	10/19/93 12:30	112	4.20	57	69	52.2	2.02	38.5	205	-2.4	-6	0.1	-6	-0.03	531	5.3	10	0.1	0.05	3535	274	58	70.5	141	142	148	149	30	144	8.84
705	10/19/93 13:30	112	4.10	57	69	52.2	2.09	34.4	177	-1.3	-3	0.7	-3	-0.02	513	4.4	8	0.7	0.04	3524	276	58	70.5	142	143	149	151	30	147	8.72
705	10/19/93 14:30	111	4.20	57	69	52.2	2.12	37.7	193	-1.1	-3	0.1	-3	-0.01	511	7.7	17	0.1	0.09	3508	278	57	72.0	141	144	149	152	30	146	8.62
705	10/19/93 15:30	112	4.20	55	66	50.1	2.02	37.0	189	6.7	19	1.6	20	0.11	511	6.9	16	1.6	0.08	3515	278	58	72.5	142	144	149	152	30	145	8.77
705	10/19/93 16:30	111	4.20	55	66	50.1	2.08	37.3	186	-3.6	-9	-0.2	-9	-0.05	499	7.3	15	-0.2	0.08	3529	276	58	69.0	142	144	149	152	30	147	8.78
706	10/20/93 8:30	112	4.20	57	69	52.4	2.04	35.8	189	-2.2	-6	0.0	-5	-0.03	528	3.8	1	0.0	0.01	3569	266	58	66.0	142	142	147	149	30	146	9.20
706	10/20/93 9:30	112	4.40	57	69	52.4	2.07	37.4	196	0.8	2	0.4	2	0.01	522	2.5	1	0.4	0.00	3542	267	58	68.0	142	141	148	150	30	145	9.15
706	10/20/93 10:30	112	4.60	57	69	52.4	2.08	33.4	173	-0.4	-1	-0.5	-2	-0.01	519	-2.3	-11	-0.5	-0.07	3540	264	58	67.0	142	141	149	151	30	143	9.13
706	10/20/93 11:40	112	4.60	57	69	52.4	2.08	36.0	187	-0.9	-2	0.0	-2	-0.01	519	2.5	2	0.0	0.01	3579	264	58	66.5	143	142	149	152	30	144	9.09
706	10/20/93 12:50	112	4.50	57	69	52.4	2.06	34.5	180	-1.7	-4	-0.5	-5	-0.03	523	-1.5	-10	-0.5	-0.06	3568	267	58	66.5	143	142	150	153	30	145	9.20
707	10/20/93 14:30	113	4.60	57	69	52.4	2.05	30.3	158	-1.6	-4	-0.2	-5	-0.03	521	1.6	-2	-0.2	-0.01	3535	267	59	68.0	142	143	150	153	30	147	8.91
707	10/20/93 15:30	112	4.60	57	69	52.4	2.10	40.3	208	0.3	1	-1.3	-1	0.00	515	5.2	8	-1.3	0.04	3486	279	56	74.5	143	145	151	155	30	149	8.75
707	10/20/93 16:40	112	4.60	57	69	52.4	2.09	38.4	198	0.1	0	0.6	1	0.00	516	6.5	12	0.6	0.06	3489	276	58	75.0	141	143	149	152	30	145	8.73
707	10/20/93 17:30	112	4.60	57	69	52.4	2.19	42.1	208	8.3	24	0.0	24	0.11	494	6.1	12	0.0	0.06	3496	276	57	74.5	143	143	149	153	30	145	8.79
707	10/20/93 18:40	112	4.60	53	64	48.6	2.06	37.7	182	2.6	7	0.1	7	0.04	484	5.7	10	0.1	0.05	3509	274	56	72.0	142	143	149	154	30	146	8.97
708	10/26/93 14:30	101	4.20	28	31	23.1	1.04	9.9	50	4.2	9	0.3	9	0.19	507	6.8	9	0.3	0.18	3847	269	58	49.0	163	169	172	172	50	165	9.10
709	10/26/93 15:50	101	4.20	49	59	44.4	2.03	26.9	134	0.3	1	-0.4	0	0.00	499	4.8	6	-0.4	0.04	3845	270	58	50.0	163	163	168	169	50	166	8.90
710	10/26/93 17:10	101	4.20	71	87	66.1	3.09	31.4	153	4.0	9	0.7	10	0.06	489	5.9	10	0.7	0.06	3843	270	57	50.0	163	163	167	168	50	165	8.99
711	10/27/93 9:40	103	4.20	15	30	16.2	0.97	14.3	53	1.2	3	-0.6	2	0.04	372	3.9	2	-0.6	0.03	3802	261	57	55.0	143	153	156	158	30	148	9.00
712	10/27/93 14:30	101	4.20	25	62	33.4	1.97	28.1	109	1.3	3	0.4	3	0.03	388	1.1	-4	0.4	-0.03	3712	277	57	63.0	144	146	151	152	30	145	8.61
713	10/27/93 15:10	101	4.20	37	98	53.1	3.05	34.1	136	4.8	11	1.0	12	0.09	398	5.3	7	1.0	0.05	3697	279	57	64.0	143	148	151	152	30	146	8.59
714	11/1/93 9:10	111	4.20	0	0	0.0	0.00	-1.5	-7	-1.3	-4	1.9	-2	0.24	461	-2.4	-11	1.9	1.61	0	282	48	0.0	276	263		273	165	282	2.41
715	11/1/93 13:40	112	4.00	32	84	45.3	2.19	31.2	133	2.2	6	0.5	6	0.05	426	8.5	18	0.5	0.13	3619	283	55	72.0	145	155	159	163	35	150	8.78
716	11/1/93 16:50	112	3.80	32	84	45.3	2.26	37.5	154	-4.5	-12	1.1	-10	-0.07	412	2.1	1	1.1	0.01	3636	280	55	71.0	145	148	153	156	30	146	8.93
717	11/1/93 17:50	113	4.10	0	100	37.9	1.90	30.9	126	6.8	18	0.8	19	0.15	407	11.8	29	0.8	0.23	3668	277	54	68.0	145	147	153	156	35	151	8.90
719	11/2/93 11:30	114	4.10	29	75	40.4	2.04	26.8	108	-0.7	-2	-0.1	-2	-0.02	401	4.9	8	-0.1	0.08	3667	275	55	67.0	146	155	159	162	35	153	8.61
720	11/2/93 14:40	114	4.10	29	74	40.0	2.10	28.6	110	-4.5	-11	0.0	-11	-0.10	385	6.6	14	0.0	0.13	3644	279	53	71.0	147	146	151	154	30	149	8.63
721	11/2/93 14:40	114	4.20	50	62	46.0	2.15	32.9	142	-0.8	-2	0.8	-1	-0.01	432	3.1	3	0.8	0.02	3631	280	54	72.0	146	146	151	154	30	147	8.80