DOE/PC/81009-T33
(DE90005529)
Distribution Category UC-105

U.S. Department of Energy
Pittsburgh Energy Technology Center
Henry Pennline, DOE Project Officer

DESULFURIZATION OF FLUE GAS BY THE CONFINED ZONE DISPERSION PROCESS

FINAL REPORT

October 1989

Contract No. DE-AC22-85PC81009

Bechtel Job No. 17939

ILLUSTRATIONS

TABLES

ABBREVIATIONS, ACRONYMS, AND DEFINITIONS

acfm	actual cubic feet per minute
ADT	acid dew point
AST	approach to saturation temperature
AVC	automatic voltage control
bhp	brake horsepower
CEM	continuous emissions monitor, term used to designate SO_2-O_2 monitor
CL	calcitic lime
conc	concentration
CPC	Consumers Power Company
CZD	confined zone dispersion
DOE	U.S. Department of Energy
d/s	downstream
EMV	effective migration velocity
ESP	electrostatic precipitator
Eff	efficiency
FGD	flue gas desulfurization
gpm	gallons per minute
HHV	higher heating value
ID	induced draft
Injection	spraying lime slurry or water into flue gas flowing in a duct
kscfm	thousand standard cubic feet per minute
L	lime
LFR	lime feed ratio, moles of lime (both Ca and Mg) fed per mole of SO_2 entering
MWe	megawatts, electric equivalent
NO_x	nitrogen oxides
NWIR	normalized water injection rate
O_2	oxygen
OH	hydroxide concentration
O&M	operating and maintenance
PEDA	Pennsylvania Energy Development Authority
PENELEC	Pennsylvania Electric Company
PETC	Pittsburgh Energy Technology Center
PHDL	pressure hydrated dolomitic lime (also called Type S lime)
PRDA	Program Research and Development Announcement
P&ID	piping and instrumentation diagram
P&ID	process and instrumentation diagram
SCA	specific collection area
scf	standard cubic feet
scfm	standard cubic feet per minute
SO_2	sulfur dioxide
SO_3	sulfur trioxide
SSCo	Spraying Systems Company
T/R	transformer/rectifier
u/s	upstream
VI	voltage current
W	water
WC	water column, the head difference in a water manometer

All temperatures are in degrees F, unless specified otherwise.

Section 1

SUMMARY

This document is the final report for U.S. Department of Energy (DOE) Project DE AC22 85PC81009, Desulfurization of Flue Gas by the Confined Zone Dispersion Process. Bechtel National, Inc. was responsible for carrying out the project under the direction of the Pittsburgh Energy Technology Center (PETC) of the DOE.

The Confined Zone Dispersion (CZD) process involves injecting a finely atomized slurry of reactive lime into the ductwork of a coal-fired utility boiler. The principle of the confined zone is to form a wet zone of slurry droplets in the middle of the duct confined in an envelope of hot gas between the wet zone and the duct walls. The lime slurry reacts with part of the sulfur dioxide (SO_2) in the gas, and the reaction products dry to form solid particles. An electrostatic precipitator (ESP) downstream from the point of injection captures the reaction products, along with the fly ash entrained in the flue gas.

The purpose of this project was to prove the CZD process concept by testing it on a limited scale, and then demonstrating the process on a large scale. The scope of work included projecting the cost of commercial implementation. Specific performance objectives, as defined by DOE for this project, were to remove 50 percent of the SO_2 at a total projected cost of less than $500 per ton of SO_2 removed.

The test facility for the DOE-supported proof-of-concept tests was on a scale equivalent to a 7 MWe generating plant. These tests were carried out at the Campbell Station of Consumers Power Company (CPC) in West Olive, Michigan, using flue gas from the station's Unit 1. Work on the project began in September 1985, and the proof-of-concept tests took place between September 1986 and July 1987.

The large-scale demonstration was made on a scale of 70 MWe in one of the two flue gas trains of the 140 MW Unit 15 at the Seward Station, Seward, Pennsylvania, of Pennsylvania Electric Company (PENELEC). This testing was initially supported by Bechtel, PENELEC, and the Pennsylvania Energy Development Authority (PEDA). Additional support to extend the testing was provided by DOE and New England Power Service. The tests that were sponsored by DOE were authorized in September 1987 and carried out during September and October of 1987.

Part 2 of this report describes the proof-of-concept tests at Campbell Station, and Part 3 describes the large-scale demonstration at Seward Station.

Part 4 describes how data from the two test sites were correlated, and presents conceptual designs for two full-scale retrofit installations. The rationale and data supporting the conclusions are also given in Part 4.

In this section, the activities and the results of the project are summarized. Because of the many differences in the scale, scope, conditions, and constraints between the proof-of-concept tests at Campbell Station and the large-scale demonstration at Seward Station, these two programs are summarized separately. Combined data analyses and full-scale cost projections are also briefly discussed in Section 2, and the conclusions and principal findings from both test programs are listed in Section 3.

1.1 PROOF-OF-CONCEPT TESTS

The proof-of-concept tests at Campbell Station (described in Part 2) included the design, construction, and operation of the test facility as required to carry out the test program. After shakedown of the system, the proof-of-concept tests consisted of 4 months of days-only parametric tests and about 2 months of around-the-clock operation. The performance of the electrostatic precipitator (ESP) was evaluated during this latter period.

1.1.1 Test Facility

The test facility withdrew a slipstream of about 20,000 acfm of flue gas from Campbell Unit 1 just downstream from one of the air heaters. The gas was conducted to a straight run of test duct 130 feet long and 3 feet in diameter where lime slurry was injected. The gas then entered a pilot-scale ESP. From this ESP, the gas passed through an induced draft (ID) fan which returned it to the Unit 1 ductwork, where it passed through the full-scale precipitator.

Lime, either pressure hydrated dolomitic or normally hydrated calcitic, was delivered in bulk either dry or as a freshly slaked slurry. Batches of slurry were prepared from the dry hydrate by making them up to the concentration desired in a slurry makeup tank. Slurries were degritted through liquid cyclones and stored for use in either of two 5,000-gallon feed tanks.

Slurry was injected into the 3 ft dia. test duct through two spray nozzles. These were air atomizers mounted in the center of the duct, pointing downstream, and located 40 feet apart.

On-line measurements included the following:

- Gas velocity, temperature, and pressure upstream of lime injection
- Gas temperature and pressure at the downstream end of the test section
- The SO_2 and oxygen (O_2) concentrations upstream of the spray nozzles and downstream of the ESP. The upstream SO_2/O_2 probe could be moved to a point just ahead of the ESP to measure SO_2 removal across the ESP
- Opacity downstream of the ESP
- Flows of lime slurry and atomizing air

1.1.2 Shakedown

Startup work began in mid-September of 1986 and continued to mid-December of 1986. During this period, the system was checked out and made operable and the operating team was mobilized and trained. The equipment was modified and improved as operating experience indicated.

Flue gas coming from the host unit usually ranged between 270°F and 310°F and between 1,300 and 1,700 ppm SO_2. The test facility could not control the temperature or the SO_2 concentration of the incoming gas. Therefore, downstream temperature in the test duct was controlled by varying the rate of slurry injection into the upstream spray nozzle. The changes in slurry injection and variation in the entering SO_2 concentration caused the lime feed ratio (LFR), the molar ratio of lime to SO_2, to vary somewhat during the course of each test.

Tests during the shakedown period identified an acceptable spray nozzle: Spraying Systems Company's (SSCo's) Casterjet nozzle with their 5-50 tip. With air supplied at 90 psig, atomization was fine enough and the spray angle was such that deposition on the duct walls could be minimized.

To control deposition, however, it was necessary to limit the injection rate through the upstream nozzle to about 1.5 gpm, and through the downstream nozzle to 1.2 gpm. At these injection rates, the entering gas velocity was limited to about 35 ft/sec when the gas was cooled to a typical operating temperature of 160°F.

1.1.3 Parametric Tests

Four months of parametric tests began in January 1987. These tests normally lasted 3 hours, but several took from 12 to 18 hours. After each test, the duct was opened and any deposits were noted, and cleaned out. Test conditions were varied to determine how to achieve 50 percent removal of SO_2 and to control deposition in the duct.

The effects of controllable variables were also explored. The variables and their observed effects are as follows.

Downstream Temperature. This temperature was varied from 140°F to 180°F. The lower temperature increased SO_2 removal, but also increased deposition in the duct. Both of these phenomena are the results of longer liquid phase residence time. A good compromise was 160°F, about a 35°F approach to saturation temperature (AST).

Lime Slurry Concentration. This value was varied from 8 to 22 percent. Deposition in the duct decreased as slurry concentration increased; lime utilization also decreased but SO_2 removal was higher because of the higher LFR.

Gas Velocity. Gas velocity upstream from injection was varied from 20 to 60 ft/sec. No effect on SO_2 removal could be observed as a function of velocity alone. To maintain the downstream temperature constant as gas velocity increased, the slurry injection rate was increased proportionately. Increased slurry injection was accompanied by coarser atomization and deposition on the duct walls, which may have obscured the effect of gas velocity on SO_2 removal.

Type and Source of Lime. Two types of hydrated lime from five sources were tried. The two limes that performed best were pressure hydrated dolomitic lime (PHDL) supplied in dry form by the Rockwell Lime Co. of Manitowoc, Wisconsin, and a calcitic lime (CL) wet slaked at the nearby Sims Station in Grand Haven, Michigan. The calcitic lime resulted in higher removal and caused less deposition in the duct at the tested conditions.

Lime Feed Ratio (LFR). The number of moles of lime injected per mole of entering SO_2 was varied from 0.5 to 3.5. Increasing the LFR increased SO_2 removal but reduced lime utilization. Utilization ranged from 12 to 50 percent for PHDL and from 26 to 60 percent for CL.

LFR and downstream temperature were the two variables that had the most effect on SO_2 removal.

The parametric tests showed that 50 percent SO_2 removal with PHDL and a downstream gas temperature of 160°F required an LFR of approximately 2, giving a lime utilization of 25 percent. With the wet slaked calcitic lime at this temperature, 50 percent SO_2 removal required an LFR of approximately 1.1, giving a utilization of 45 percent.

Preliminary tests with gas tubes showed moderate NO_x removals. However, subsequent tests with a chemiluminescent analyzer showed negligible removal.

By measuring distances downstream from the spray nozzles where wet solids stuck to a probe inserted into the gas stream, it was possible to estimate approximate drying times. (These measurements were approximate because the solids changed from very wet to very dry over a distance of several feet.) These drying times for the indicated drop in flue gas temperature were:

- From 280°F-300°F to 200°F 0.7 to 1.2 sec
- From 200°F to 160°F 1.2 to 1.4 sec

Most of the SO_2 removal occurred before the droplets of lime slurry dried. Measurements of SO_2 removal across the ESP showed that less than 5 percent (absolute) of the SO_2 removal occurred as the dry solids traveled to the ESP and were captured there.

1.1.4 Duration Tests

The purpose of this series of tests was to operate the system continuously for prolonged periods to observe deposition and nozzle wear, and to provide stable operating conditions for the ESP tests. Table 1-1 lists various tests which demonstrated low deposition with about 50 percent or more SO_2 removal at 160°F and a gas velocity of 20 ft/sec.

Table 1-1

LOW DEPOSITION DURATION TESTS

Date	Lime Slurry	Duration (hr)	SO_2 Removal	LFR	Lime Utilization	Deposits (% fed)
5/7	PHDL, 15%	20	50	2.3	22	4.4
5/8	PHDL, 19.6%	20	47	2.7	17	5.5
5/12,13	CL, 11.1%	20	42	1.0	42	4.8
5/19,20	CL, 12%	20	46	1.4	33	1.1
5/29,30	CL, 12%	20	50	1.1	44	0.7
6/2,3	CL, 17%	18	61	1.8	34	0.4

At a gas velocity of 20 ft/sec, slurry injection rates were approximately 1.2 gpm through the upstream nozzle and 0.8 gpm downstream. Higher gas velocities required higher injection rates and resulted in more wall deposition for prolonged operation.

1.1.5 Analysis of SO_2 Removal Data

The data were organized into three separate data sets, and each set was analyzed separately using a personal computer-based regression program. These sets were: PHDL injected though one nozzle, PHDL injected through two nozzles, and freshly slaked CL injected through two nozzles.

Both rational and empirical expressions were examined to correlate the data. The rational expressions do not allow SO_2 removal to exceed 100 percent and SO_2 removal is zero when LFR equals zero.

For all three data sets, the rational expressions showed a strong dependence of SO_2 removal on both LFR and AST. Gas inlet temperature was also identified as an important variable. Inlet SO_2 concentration was identified as an important variable for the CL data set, but not for the PHDL data sets. However, since inlet SO_2 is a factor in LFR, also used in the correlation, this result is inconclusive.

Plots of calculated versus actual SO_2 removal for the rational correlations showed a slight bias in that calculated removal tended to be high at low actual removal and low at high actual removal. This suggests improved correlations could be found.

The empirical correlations reflected relationships between the independent variables rather than the variables' true contribution to SO_2 removal. Thus, they were difficult to interpret and did not extrapolate. The rational correlations are felt to be better than the empirical correlations for understanding the process despite the bias.

Plots of the rational correlations showing SO_2 removal versus LFR showed that SO_2 removal rises faster and higher for freshly slaked CL than for

PHDL, and that PHDL injected through two nozzles outperformed PHDL injected through one nozzle.

Plots of lime utilization versus lime concentration for PHDL and CL show that lime utilization decreases with increasing lime concentration. Since, by definition, lime utilization times LFR equals SO_2 removal, this implies that, at a given LFR, SO_2 removal will decrease with increasing lime concentration (assuming other variables are held constant).

This phenomenon explains why SO_2 removal performance of PHDL was better when injected through two nozzles than through a single nozzle with another nozzle for water injection. For a given operating condition, the concentration of lime injected through a single nozzle had to be higher than that injected through two nozzles because the additional water injected through the second nozzle was not used to dilute the lime. This increase in feed solids results in poorer lime utilization and therefore, poorer SO_2 removal performance.

Additional analysis of the Campbell data could be expected to improve its correlation. However, it was felt that a more useful correlation could be obtained by analyzing the combined data set from both the Campbell and Seward sites as later described.

1.1.6 ESP Tests

Two series of ESP tests were carried out: the first in November 1986 during shakedown of the system, and the second from May to July 1987, at the end of the test program. The test runs for the first series were shorter than those for the second series. The objective was to determine how injection of lime into the ductwork affected ESP performance and whether injection is likely to increase particulate emissions. The results were contradictory.

The first series of tests showed that the lower temperature and higher moisture content of the gas with injection improved collection enough to offset the higher particulate loading so that emissions did not increase significantly. The second, and more extensive, series showed the opposite:

that lime injection impaired ESP performance and caused emissions to increase. Table 1-2 shows typical ESP performance at a gas velocity upstream from injection of 45 to 50 ft/sec.

Table 1-2

ESP TESTS

Date	Lime Injection	ESP Temperature (°F)	Removal Efficiency	Emissions, (gr/dscf)
First Series, November 1986				
11/18	No injection	275	94.8	0.050
11/22	PHDL, 12%	165	99.0	0.034
Second Series, May to July 1987				
6/8	No injection	284	98.1	0.058
Several	CL, 12%, average	160	86.3	0.761
7/27	PHDL, 15%	159	87.5	0.937

The validity of the second series of tests showing poorer performance with lime injection is questionable. It is likely that incompletely dried slurry resulting from poor atomization caused excessive electrical leakage during these tests. It is felt that further testing must be performed to confirm ESP performance during CZD treatment of flue gas.

1.2 LARGE-SCALE TESTS

The large-scale test program at the Seward Station of PENELEC (described in Part 3) included the design, installation, and operation of the CZD test system. The CZD system was retrofitted onto one of two parallel flue gas ducts on the 140 MW Unit 15. After shakedown of the system, the activity consisted of 2 months of parametric lime injection tests and 1 month of continuous lime injection tests. ESP performance was evaluated during this latter period.

1.2.1 Test Facility

The flue gas was treated in approximately 35 feet of a straight ductwork section (8 feet wide x 11 feet high) situated between two sets of turning vanes. The ductwork section and turning vanes were located between two existing ESPs. At a nominal flue gas velocity of 64 ft/sec, the duct section had only 0.5 second of residence time. After slurry injection, the dried reaction products and fly ash were collected in the second existing ESP.

PHDL and dry CL were received in self-unloading trucks and pneumatically transferred to a lime silo. The dry lime was slurried with water in a 2,500-gallon lime sump equipped with an agitator. The slurry was pumped from the sump to a vibrating screen to remove fine grit and then stored in either of two 10,000-gallon agitated lime feed tanks.

Two centrifugal feed pumps, operating in series, pumped lime from the feed tanks through a pump-around loop that passed close to a valved manifold which distributed lime to the atomizing nozzles. A separate valved manifold distributed atomizing air to the nozzles.

On-line measurements included the following:

- Gas velocity and temperature upstream of lime injection
- Gas temperature before and after the downstream ESP
- SO_2, NO_x, and O_2 concentrations upstream of the spray nozzles and downstream of the ESP and the ID fan
- Flow of lime slurry and atomizing air
- Temperature profiles in the duct cross section at several distances downstream of the injection point

1.2.2 Shakedown Tests

The shakedown tests began in June of 1987 and continued into August of 1987. During this period, the system was checked out and made operable, and the operating team was mobilized and trained. Water atomization tests were performed to determine the pressure and flow characteristics of the atomizing nozzles and the orientation constraints of the multiple atomizer array.

Prior to the Seward testing, several nozzle atomizers were tested at the University of California, Davis, to calibrate the nozzles and to determine the effects of air and water rates on fineness of atomization. Nozzle performance results were also available from the pilot-scale CZD testing at the Campbell Station of Consumers Power Company (CPC). These two test programs identified the Spraying Systems Company's (SSCo) Casterjet nozzle as an acceptable atomizer for the Seward tests.

The next step involved testing the calibrated nozzles in the flue gas duct to determine the best configuration and the minimum ratio of atomizing air to water required to avoid wetting the duct and turning vanes. The testing started with a single nozzle and evolved to a nine-nozzle array.

Because of the short duct and limited residence time, a much higher air-to-water ratio than expected was required to provide the fine atomization necessary for rapid evaporation. The air and discharge orifices of the nozzle were enlarged to provide this higher ratio.

1.2.3 Lime Injection Tests

Two months of parametric lime injection tests began in August 1987 and were followed by a month of continuous lime injection tests in October.

The parametric tests, which normally lasted several hours, investigated the effects of lime concentration on the extent of flue gas desulfurization, lime utilization, and lime injection rate. The continuous lime injection tests investigated the long-term effects of lime injection on the atomizers, duct deposits, and ESP performance.

The lime injection tests confirmed that fine atomization and restricted lime feed rates were necessary to dry the atomized droplets sufficiently to avoid deposition on the turning vanes located about 35 feet downstream of the nozzles. These restricted feed rates limited the maximum SO_2 removal. The following results were obtained.

Duct Temperature Profiles. Temperature profiles taken in the duct cross section at several distances from the injection point confirmed that a true confined zone, a moist interior surrounded by hot gas, could be obtained.

PHDL Injection. With PHDL injection, SO_2 removal ranged from 6 to 30 percent, depending on the slurry flow rate and slurry concentration. The LFR ranged from 0.11 to 1.34. NO_x removal ranged from 8 to 21 percent and increased with increasing slurry concentration. Lime utilization, based on combined SO_2 and NO_x removal, ranged from 23 to 90 percent.

Slurry Concentration. Sulfur dioxide removal increased and lime utilization decreased with increasing slurry concentration.

Calcitic Lime. With CL, either freshly slaked or a slurry prepared from dry hydrate, SO_2 removal, NO_x removal, and lime utilization were significantly lower than corresponding values for the PHDL. The unexpected lower performance for the freshly slaked lime may have been caused by eroded nozzle tips. Time was not available to repeat the freshly slaked CL tests with erosion resistant tips.

Duct Deposits. It appeared that duct deposits could be prevented by limiting injection rates to the point where the atomized droplets dried before they reached the first interior duct surface, the turning vanes. However, since this was a manually controlled operation, it was not possible to follow load closely, particularly at night. Consequently, there were times when the injection rate was excessive, resulting in low downstream temperatures with some deposition on the vanes and surrounding areas. Poor atomization resulting from eroded atomizers also caused some deposits.

1.2.4 Analysis of SO_2/NO_x Data

The test data for PHDL were arranged into groups according to weight percent slurry concentration. A plot of SO_2 removal versus gallons per minute of slurry injected was made identifying each group with a unique symbol. It was found that a straight line could be drawn from the origin through the data points for each group.

These plots show that the Seward test data exhibit a positive linear relationship of SO_2 removal versus slurry injection rate. The plots also showed that, at a given injection rate, SO_2 removal increases with slurry concentration.

Lime utilization data were plotted to determine how lime utilization is related to lime type and lime concentration for SO_2 and NO_x removal. From these plots, the Seward test data show the following relationships:

- o Both CL and PHDL utilization decrease with increasing lime concentration for both SO_2 and NO_x removal.
- o PHDL utilization is higher compared with CL for either SO_2 or NO_x removal at a given lime concentration.

As noted earlier, the short residence time available in the test duct at Seward limited the lime injection rate to a point where a maximum of only 30 percent SO_2 removal could be obtained. A full-scale commercial system with a longer straight run of duct would not be limited in this way. Furthermore, the ductwork configuration at Seward is suitable for installation of a second set of atomizers upstream of the set used, which would approximately double the residence time. This would allow more slurry to be injected and result in higher SO_2 removal.

The plots described above were extrapolated to project the slurry injection rate and concentration required for 50 percent SO_2 removal. By this extrapolation, the injection of about 55 gpm of 7.5 percent PHDL would remove 50 percent of the SO_2 at Seward.

This extrapolation is probably conservative. Using two-stage injection and increasing residence time would permit more injection points, better gas/spray dispersion, a larger and more uniform confined zone, and a closer approach to saturation temperature for the treated gas. These factors should provide better lime utilization thereby obtaining 50 percent SO_2 removal at an injection rate lower than 55 gpm.

Two-stage injection is expected to provide much higher NO_x removals compared with that obtained in the single-stage injection tests during the Seward test program.

1.2.5 ESP Tests

Particulate removal efficiency testing of the downstream ESP with and without lime slurry injection was conducted to determine the capability of the ESP to handle the additional grain loading when lime was injected into the system. An existing online opacity monitor mounted in the stack was also used to indicate ESP performance during the testing.

During the short-term parametric tests, the opacity decreased and remained lower during lime injection and then increased when injection was stopped. During the long-term continuous injection tests, the opacity decreased at the start of injection and remained low initially, but then rose after 5 to 10 hours' operation to a level exceeding the original opacity prior to the start of injection. Off-power rapping was successful in restoring opacity to acceptable levels, but was required intermittently.

Particulate removal efficiency tests were performed for fly ash alone (no injection), during injection of PHDL and during CL injection. Only one slurry injection rate per test was evaluated. The average particulate removal efficiency was slightly higher during the CL injection and slightly lower during the PHDL injection compared with fly ash alone. The average emissions were the same during CL injection but higher during PHDL injection compared with fly ash alone.

The CZD testing was conducted with the ESP in an as-found condition. No attempt was made to optimize the mechanical/electrical condition prior to testing. Analysis of the ESP operating characteristics during the testing suggests that the precipitator had some deficiencies with the automatic voltage controllers and rapping systems.

The capability of off-power rapping to reduce opacity levels suggests that a well-tuned ESP, with automatic controls for voltage and rapping, and with discharge electrode rapping, may be capable of maintaining acceptable opacity levels during lime injection. As with the tests at Campbell Station, it is felt that further ESP testing is needed.

Section 2

ANALYSES AND PROJECTIONS

2.1 COMBINED DATA ANALYSES

Widely different test conditions at Campbell and Seward made it difficult to analyze the data on a common basis. Compared with Campbell, Seward had these principal differences:

- Extremely short residence time
- Much larger duct cross section
- Higher gas velocity and gas flow rate
- Finer and more uniform atomization
- Higher total injection rates
- Lower inlet SO_2 concentration
- Lower SO_2 removals
- High approach to saturation temperatures
- Capability to establish a confined zone
- Relatively less duct deposits

One approach did successfully correlate the combined data set and appears to provide reasonable extrapolations. This approach had three major characteristics:

- The injection rates and gas flows for the two systems were normalized to make them directly comparable.
- Significant measured variables were included directly in the correlation formula.
- A coefficient, K, was added to the correlation formula to account for the effect of unmeasured variables, system differences, and lime type.

The injection rates and gas flows were normalized by dividing the water portion of the slurry feed rate in gallons per minute (gpm) by the gas flow rate in thousand standard cubic feet per minute (kscfm). This quantity was called the normalized water injection rate (NWIR). Other measured variables used in the correlation formula were: feed solids in weight percent (Wt %), the arithmetic average of the inlet and outlet SO_2 concentrations in wet parts per million by volume (Avg SO_2), and approach to saturation temperature (AST) in °F.

The form of the correlation equation chosen was:

$$\text{Percent } SO_2 \text{ removal} = K\,(NWIR)^a (Wt\ \%)^b (Avg\ SO_2)^c (AST)^d$$

The SO_2 removal data were grouped into three data sets: Seward PHDL, Campbell PHDL, and Campbell CL. Each data set was regressed separately using a personal computer-based regression program to obtain the values of the exponents and the coefficient, K, that provided the best fit. Fit was measured by the square of the correlation coefficient, R^2, provided by the regression program. An R^2 value of 1 is a perfect fit; 0 is completely random.

Using the initial regressions as a guide, additional regressions for each data set were made using fixed values for the exponents. The objective was to find single values for each exponent that, when used to correlate each set, did not significantly affect the data fit. The final result was the correlation of each data set to the equation where the measured variables had the same exponents and the only difference was the value of the coefficient, K. The value of K, obtained this way, was a measure of the difference in performance between the test systems. The results are shown in Table 2-1.

Table 2-1

CORRELATION RESULTS

Data Set	a	b	c	d	K	R^2
Seward PHDL	0.65	0.45	-0.4	-0.4	27.3	0.877
Campbell PHDL	0.65	0.45	-0.4	-0.4	19.1	0.774
Campbell CL	0.65	0.45	-0.4	-0.4	24.4	0.654

A comparison of calculated versus actual removal for the Seward and Campbell PHDL correlations with the same exponent values is shown in Figure 2-1.

The range of the variables used in this correlation is shown in Table 2-2.

Table 2-2

RANGE OF VARIABLES

Variable	Seward	Campbell
NWIR, gal/kscf	0.06 - 0.15	0.2 - 0.36
Wt %	1.6 - 16	7.5 - 21
Avg SO_2, ppmv wet	600 - 780	800 - 1200
AST, °F	95 - 130	25 - 55

The correlation provides reasonably accurate predictions of SO_2 removal when the variables are within these ranges. However, the accuracy of extrapolations outside these ranges is unknown, and they should be performed with caution.

The difference in performance for the Seward and Campbell test systems can be measured by examining the values of K obtained for the PHDL data sets. The value of K for the Seward PHDL data set is approximately 43 percent higher than that for the Campbell PHDL data set. This means that system differences provided a 43 percent higher performance at Seward compared with Campbell. This implies that operation of a large-scale system similar to Seward at the same test conditions used at Campbell would produce SO_2 removal results approximately 43 percent better than those obtained during the actual Campbell tests.

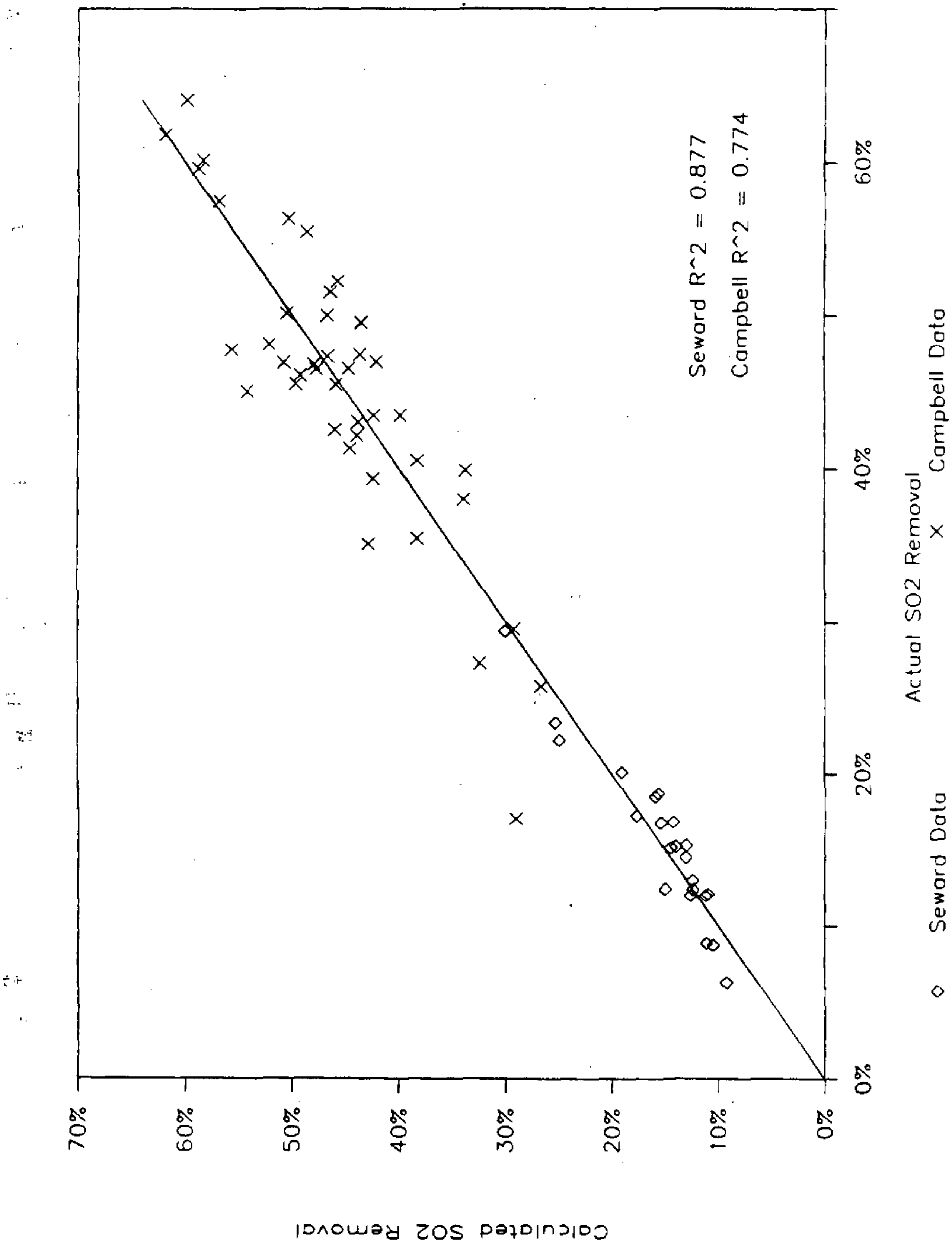


Figure 2-1 Calculated vs Actual SO_2 Removal for Fixed Exponent Case

Comparing the value of K for the Campbell PHDL and CL data sets shows that the SO_2 removal performance for calcitic lime was about 28 percent higher than that for PHDL, at the conditions tested. No useful large-scale system data were collected for CL, and we therefore have no evidence that the improved performance of CL over PHDL will also be observed in large-scale installations. Further testing is needed to confirm if calcitic lime will produce significantly better SO_2 removal in a full-scale system.

2.2 FULL-SCALE PROJECTIONS

Conceptual designs for two full-scale retrofit installations, a generic 500 MWe unit and J. H. Campbell Unit 1 of CPC, were prepared. The designs include a process flow diagram showing flows of material and energy, and the sizes, duties, and materials for the principal items of equipment. Capital and operating costs were estimated from the designs.

2.2.1 SO_2 Removal

The level of SO_2 removal for the full-scale projections is specified at 50 percent. The correlation developed for the combined Campbell and Seward SO_2 removal data was used to predict lime concentrations required for 50 percent SO_2 removal. The value of K (27.3) obtained for the Seward PHDL data was used. This value takes into account the better SO_2 removal performance of the full-scale system produced by the ability to establish a true confined zone. The lime type was chosen as PHDL because this is the only type for which data were available from both test sites. A sensitivity analysis for lime type CL, using the same K factor, and the use of another K factor were conducted for comparison.

The levels of the independent variable in the correlation equation were determined as follows.

<u>AST</u>. The outlet temperature chosen for the projections is 170°F, the temperature required to keep the turning vanes deposit-free at Seward. At an assumed saturation temperature of 125°F, this provides an AST of 45°F. With an inlet temperature of 280°F, and assuming an ideal confined zone, 71 percent

of the gas flow would be confined in the center zone of the duct and cooled to the saturation temperature of 125°F. This gas would be surrounded by an envelope of inlet flue gas at 280°F, amounting to 29 percent of the gas flow. When these two zones are completely mixed together downstream, they would produce a blended outlet temperature of 170°F.

NWIR. The value of this variable was calculated from a heat balance based on the flue gas characteristics. For a given flue gas, once the outlet temperature is specified, NWIR varies directly with the gas inlet temperature.

Average SO_2. The arithmetic average of the inlet and outlet concentrations of SO_2 in the gas was calculated from a material balance.

Wt%. The correlation equation was solved for Wt% using the values of the other variables as specified above.

2.2.2 NO_x Removal

At the Campbell test site, NO_x removal tests were inconclusive. At the Seward test site, NO_x removal reached 17 percent with one stage of injection. This amount could improve with the addition of a second stage of injection. The specified NO_x reduction for the full-scale projections is 50 percent. The DOE guidelines require that a penalty be assessed for processes which do not inherently reduce NO_x emissions by a minimum of 50 percent. Because 50 percent NO_x removal was not demonstrated, this penalty was assessed and no credit was taken for CZD NO_x removal.

2.2.3 Deposits

During the full-scale tests, it appeared that deposits could be prevented if the atomized droplets dried before they impinged on the interior duct surfaces. Fine-spray nozzles with erosion resistant tips and suitable instrumentation for the required process control were included in the projections to provide for adequate droplet drying. No special mechanical devices to dislodge or remove deposits were included. If additional CZD testing shows a need for mechanical devices, the projections should be modified accordingly.

2.2.4 ESP Performance/Upgrading

The capability of an existing ESP to handle the additional loading resulting from lime injection was not conclusively determined during the CZD testing. Some tests indicated ESP emissions were no greater during lime injection than without; others indicated emissions increased during lime injection. The reasons for the increased emissions could not be conclusively identified, so it was not possible to specify corrective measures.

No ESP modifications to upgrade performance have been included in the full-scale projections. However, new ESP conveyors and waste solids storage silos have been included to handle the increased quantities of waste solids.

2.2.5 Atomizing Air Pressure and Flow Rate

The testing at both sites showed that high atomizing air pressure provided fine atomization which improved drying and SO_2 removal. A practical limit of 90 psig was established at both sites and will be used for the projections. A minimum of 30 scf atomizing air per gallon of slurry was required in the Seward testing to maintain good temperature profiles and dry downstream turning vanes. A design value of 30 scf/gallon of feed was used for the projections.

2.2.6 500 MWe Reference Plant

The reference power plant specified for this retrofit study is a pulverized coal-fired plant consisting of two 500 MWe boiler units (i.e., Unit 1 and Unit 2). The plant is assumed to be located near Milwaukee, Wisconsin. For the purpose of this evaluation, only Unit 1 is to be retrofitted for a 50 percent reduction of SO_2 using the CZD process.

Table 2-3 lists power plant design information provided by the DOE guidelines. Table 2-4 provides the projected process design characteristics.

Table 2-3

500 MWe REFERENCE PLANT
KEY BOILER DESIGN DATA AND FLUE GAS CHARACTERISTICS

Characteristics	Specifications
Plant rating, MW net	500
Estimated remaining life, yr	30
Net plant heat rate, Btu/kWh	10,000
Capacity factor, %	65
Sulfur content of coal, %	4
Average heating value of coal, Btu/lb	10,100
Gas flow rate, acfm/MW	4,000
Gas temperature, °F	280
Boiler efficiency, %	88
Average coal burn rate, tph	247
SO_2 emission, tph	18.77
NO_x emission, tph	2.22

Table 2-4

500 MWe REFERENCE PLANT
PROCESS DESIGN CHARACTERISTICS

Process Design Parameters	Specifications
SO_2 removal, %	50
Spray down temperature, °F	170
Approach to saturation temperature, °F	45
Normalized water injection rate, gal/kscf gas	0.265
Inlet SO_2 concentration, ppmv, wet basis	2,780
Outlet SO_2 concentration, ppmv, wet basis	1,318
Average SO_2 concentration, ppmv, wet basis	2049
Lime feed ratio, 1/2 [moles $Ca(OH)_2 \cdot Mg(OH)_2$]/mole SO_2 entering	1.46
Lime utilization, %	34.3
Lime purity, %	95.5
Lime slurry concentration, Wt%	24.3
Atomizing air pressure, psig	90
Atomizing air flow, scfm/gpm slurry	30
Raw Material and Utility Requirements	
PHDL, 95.5% $Ca(OH)_2 \cdot Mg(OH)_2$, tph	29.6
Process water, gpm	354
Electricity, kW	4000
Process Effluents	
SO_2, tph	9.4
NO_x, tph	1.1
Fly ash, tph	31.6
Reaction products (includes unreacted lime), tph	36.4
Grit, tph, wet	1.66
Waste water, gpm	none

A cost estimating methodology developed by the DOE was used. This method:

- o Levelizes total retrofit capital requirements using standardized assumptions and economic factors developed by EPRI as well as simplifications determined to be suitable by DOE
- o Levelizes all costs to 1982 base-year dollars
- o Levelizes capital costs for dissimilar acid rain precursor (i.e., SO_2 and NO_x) control approaches at different stages of technical maturity
- o Calculates the total retrofit capital requirement and first year operating and maintenance costs, from which a total levelized retrofit cost can be calculated

Information required to generate the estimates was obtained from equipment vendors, published cost data, and Bechtel inhouse cost files. Capital costs were estimated by a modular factor cost estimating approach. Process equipment sizing and cost were developed by Bechtel. Operating costs were calculated based on estimated reagent and utility consumption, and the DOE-specified operating cost criteria.

The total retrofit capital requirement was estimated at $47.01/kW, including NO_x nonremoval penalty. The estimated first year operating and maintenance costs are $31.34/kW-yr. The calculated SO_2 removal cost is $357/ton SO_2. In terms of 30-year levelized busbar electricity cost, it becomes 14.0 mills/kWh.

Substitution of lime type CL for PHDL using the same correlation factor, K, has a moderate impact on the 500 MWe conceptual design. Although the same weight of hydrated lime is used for both lime types, the CL design utilizes unhydrated lime delivered to the plant site. This usage considerably reduces the dry lime storage facilities. Offsetting this is the need for onsite equipment to hydrate the CL. The CL is also less expensive than the PHDL.

From the point where the CL is hydrated, the equipment requirements, i.e., storage and feed tanks, transfer and feed pumps, atomization system, air compressors and instruments and controls, are nearly identical for both CL and PHDL.

The net effect of the changes reduces the capital and operating costs for the design. The estimated total retrofit capital requirement reduces to \$42.1/kW, including NO_x nonremoval penalty. The estimated first year O&M costs reduce to \$25.1/kW/yr. The calculated SO_2 removal cost is \$292/ton SO_2 and the 30-year levelized busbar electricity cost becomes 11.3 mills/kWh.

The effect of an increase of 25 percent in the value of the correlation factor, K, on the 500 MWe conceptual design was investigated. Additional full-scale testing of the CZD process with two-stage injection is expected to provide a better confined zone pattern and show an improvement in SO_2 removal performance which will increase the value of K. The amount of the expected improvement can not be predicted at this time; 25 percent represents one possibility.

The increase in the value of K produces more than a proportional reduction in the lime requirements because the lime utilization also increases. The reduction in lime requirements substantially reduces the dry lime storage and handling equipment. The lime slurry handling equipment, including the atomization system is not significantly affected.

A 25 percent increase in K for the 500 MWe conceptual design using PHDL reduces the estimated total retrofit capital requirements to \$38.5/kW, including NO_x nonremoval penalty. The estimated first year O&M costs become \$19.6/kWh-yr. The calculated SO_2 removal cost is \$236/ton SO_2 and the 30-year busbar electricity cost becomes 8.9 mills/kWh.

2.2.7 J. H. Campbell Unit 1, Consumers Power Company

Campbell Unit 1 of Consumers Power Company is a base-loaded pulverized coal-fired boiler, located in West Olive, Michigan. It burns medium-sulfur coal, and the SO_2 emissions are uncontrolled. Fly ash is removed by two electrostatic precipitators in series - 1E and 1W. Key boiler design data and flue gas characteristics are as shown in Table 2-5.

Process design characteristics for Campbell Unit 1 are presented in Table 2-6.

Table 2-5

J. H. CAMPBELL UNIT 1
KEY BOILER DESIGN DATA AND FLUE GAS CHARACTERISTICS

Characteristics	Specifications
Unit rating, MW net	260
Estimated remaining life, yr	30
Net plant heat rate, Btu/kWh	9,520
Capacity factor, %	80
Coal as fired	
Moisture, %	11.3
Ash, %	10.7
Sulfur, %	2.2
Higher heating value (HHV), Btu/lb	11,178
Flue gas temperature, °F	280-330
Flue gas flow, acfm @ 300°F	863,700
Flue gas SO_2 concentration, ppmv	1,617
Particulate emissions control device	2-stage ESP 1st stage 95% 2nd stage 97%

Table 2-6

J. H. CAMPBELL UNIT 1
PROCESS DESIGN CHARACTERISTICS

Process Design Parameters	Specifications
SO_2 removal, %	50
Flue gas temperature at injection point, °F	300
Spraydown temperature, °F	170
Approach to saturation temperature, °F	45
Normalized water injection rate, gal/kscf gas	0.284
Average SO_2 concentration, ppmv, wet basis	1189
Lime feed ratio, 1/2 [moles $Ca(OH)_2 \cdot Mg(OH)_2$]/mole SO_2 entering	1.32
Lime utilization, %	38
Lime purity, %	95.5
Lime slurry concentration, Wt%	13.6
Atomizing air pressure, psig	90
Atomizing air flow, scfm/gpm	30
Raw Material and Utility Requirements	
PHDL, 95.5% $Ca(OH)_2 \cdot Mg(OH)_2$, tph	6.58
Process water, gpm	160
Electricity, kW	1,600
Process Effluents	
SO_2, lb/hr	4,620
Fly ash, tph (ESP 1E)	9.00
Reaction products (includes unreacted lime), tph (ESP 1W)	8.70
Grit, lb/hr, wet	740
Waste water, gpm	none

The cost estimating methodology used for this case follows the EPRI Technical Assessment Guide for a Class II level of analysis. Major equipment costs are based upon Bechtel inhouse information, adjusted to current cost index, and vendors' telephone quotes. Other materials are by ratio to major equipment costs on plant parameters. Construction labors are from labor/material ratios for similar work, adjusted for site conditions and using expected average labor rates. The base year for the cost estimate in 1988.

The total estimated retrofit capital requirement is $29.49/kW; the first year operating cost is $18.07/kW-yr; the 30-year levelized busbar costs is 6.5 mills/kWh. The calculated SO_2 removal cost is $360.38 per ton of SO_2 removed, including both capital charge and O&M costs.

As discussed for the 500 MWe conceptual design, additional full-scale CZD testing is expected to show an improvement in SO_2 removal performance. This would result in a reduction in the estimated costs for Campbell Unit 1 similar to those presented for the 500 MWe case.

Section 3

CONCLUSIONS

The following conclusions and principle findings can be drawn from the results of the CZD testing.

1. Overall SO_2 removals above 50 percent are possible with either PHDL or CL.

2. The injection of atomized lime slurry in a large duct can be controlled in a confined zone dispersion which minimizes duct deposition while enhancing SO_2 removal performance. Temperature profiles of the duct cross section during injection can be used to define the shape of the confined zone.

3. Injected lime slurry has to dry before contacting any surfaces inside the duct; otherwise, deposits will form. Operation without deposits for SO_2 removals above 25 percent appears to require residence times greater than 0.5 second based on Seward results.

4. An inadequate residence time created by a short duct can be partially compensated for by increased fineness of atomization which increases droplet surface area and, therefore, increases evaporation rate.

5. PHDL was less erosive to the nozzle discharge orifice than were hydrated or freshly slaked CL.

6. High lime utilizations of about 50 percent at 50 percent SO_2 removal are possible, particularly at low SO_2 concentrations. Utilization is inversely related to lime concentration.

7. The electrostatic precipitator (ESP) contributes less than 5 percent (absolute) to SO_2 removal.

8. Intermittent off-power rapping was successful in restoring stack opacity to acceptable levels during continuous lime injection at the full-scale test site. While this practice is not suitable for normal power plant operation, it suggests that improving the mechanical and electrical condition of an exiting ESP may make it capable of removing the added particulate matter introduced by lime injection.

9. The combined SO_2 removal data from the Campbell and Seward test sites were correlated to a single correlation formula that appears to provide reasonable extrapolations. Additional full-scale CZD testing with increased residence time and a closer approach to saturation temperature is expected to provide data that will show an improvement in the SO_2 removal performance for the correlation.

10. The correlation was used to project design bases for two full-scale retrofit installations; a generic 500 MWe unit and J. H. Campbell Unit 1 of CPC. The total projected costs to remove 50 percent of the SO_2 were $357 and $360 per ton of SO_2 removed, respectively, for the 500 MWe unit and Campbell Unit 1. These costs are below the DOE performance objective of $500/ton of SO_2 removed. Additional CZD testing with two-stage injection and a better confined zone pattern is expected to show improved SO_2 removal performance which will substantially lower these SO_2 removal costs.

11. NO_x removals of up to 17 percent were demonstrated during the full-scale Seward testing. These removals are expected to increase with additional CZD testing using two-stage injection. If a credit were taken for the acid reduction potential of the NO_x removal, the SO_2 removal costs would be further reduced.

12. Additional testing is required to further explore the limits of lime injection rate and SO_2 removal, to clarify performance of CL and PHDL as a function of residence time in a confined zone, and to more thoroughly assess the effect of lime injection on ESP performance.

13. Additional ESP testing is expected to be favorable, and the projected advantages of the CZD process appear real. Therefore, the process should prove to be extremely attractive and economical.

PART 2

Campbell Station Tests

CONTENTS

ILLUSTRATIONS

TABLES

Table		Page

ABBREVIATIONS, ACRONYMS, AND DEFINITIONS

acfm	actual cubic feet per minute
ADT	acid dew point
AST	approach to saturation temperature
AVC	automatic voltage control
bhp	brake horsepower
CEM	continuous emissions monitor, term used to designate SO_2-O_2 monitor
CL	calcitic lime
conc	concentration
CPC	Consumers Power Company
CZD	confined zone dispersion
DOE	U.S. Department of Energy
d/s	downstream
EMV	effective migration velocity
ESP	electrostatic precipitator
Eff	efficiency
FGD	flue gas desulfurization
gpm	gallons per minute
HHV	higher heating value
ID	induced draft
Injection	spraying lime slurry or water into flue gas flowing in a duct
kscfm	thousand standard cubic feet per minute
L	lime
LFR	lime feed ratio, moles of lime (both Ca and Mg) fed per mole of SO_2 entering
MWe	megawatts, electric equivalent
NO_x	nitrogen oxides
NWIR	normalized water injection rate
O_2	oxygen
OH	hydroxide concentration
O&M	operating and maintenance
PEDA	Pennsylvania Energy Development Authority
PENELEC	Pennsylvania Electric Company
PETC	Pittsburgh Energy Technology Center
PHDL	pressure hydrated dolomitic lime (also called Type S lime)
PRDA	Program Research and Development Announcement
P&ID	piping and instrumentation diagram
P&ID	process and instrumentation diagram
SCA	specific collection area
scf	standard cubic feet
scfm	standard cubic feet per minute
SO_2	sulfur dioxide
SO_3	sulfur trioxide
SSCo	Spraying Systems Company
T/R	transformer/rectifier
u/s	upstream
VI	voltage current
W	water
WC	water column, the head difference in a water manometer

All temperatures are in degrees F, unless specified otherwise.

Section 1

INTRODUCTION

As part of a program to develop more cost-effective approaches to the control of acid rain precursors, the Department of Energy (DOE), in 1985, requested proposals for carrying out proof-of-concept tests of new technology to reduce emissions of SO_2 and NO_x from existing power plants. The DOE's objective was to stimulate development of lower cost processes suitable for retrofitting onto older plants. The specific goal was to remove at least 50 percent of the SO_2 at a total cost of less than $500 per ton of SO_2. The proof-of-concept test facilities were to be on a scale equivalent to 5 MWe.

Bechtel was awarded Contract DE-AC22-85PC81009 by DOE, Pittsburgh Energy Technology Center to perform proof-of-concept testing. Bechtel's concept, called the Confined Zone Dispersion (CZD) process, involves injecting a finely atomized slurry of reactive lime into the ductwork between a boiler's air heater and its precipitator.

The test facility was located at the J. H. Campbell Station of Consumers Power Company in West Olive, Michigan. Unit 1 at the Campbell Station supplied a slip stream of flue gas to the facility. Work on the project began in September 1985, and the proof-of-concept tests took place between September 1986 and July 1987.

Section 2

SUMMARY

The proof-of-concept (or pilot-scale) tests at Campbell Station included the design, construction, and operation of the test facility as required to carry out the test program. After shakedown of the system, these tests consisted of 4 months of days-only parametric tests and about 2 months of around-the-clock operation. The performance of the electrostatic precipitator (ESP) was evaluated during this latter period.

2.1 TEST FACILITY

The test facility withdrew a slipstream of about 20,000 acfm of flue gas from Campbell Unit 1 just downstream from one of the air heaters. The gas was conducted to a straight run of test duct 130 feet long and 3 feet in diameter where lime slurry was injected. The gas then entered a pilot-scale ESP. From this ESP, the gas passed through an induced-draft (ID) fan which returned it to the Unit 1 ductwork, where it passed through the full-scale precipitator.

Lime, either pressure hydrated dolomitic or normally hydrated calcitic, was delivered in bulk either dry or as a freshly slaked slurry. Batches of slurry were prepared from the dry hydrate by making them up to the concentration desired in a slurry makeup tank. Slurries were degritted through liquid cyclones and stored for use in either of two 5,000-gallon feed tanks.

Slurry was injected into the 3 ft dia. test duct through two spray nozzles. These were air atomizers mounted in the center of the duct, pointing downstream, and located 40 feet apart.

On-line measurements included the following:

- o Gas velocity, temperature, and pressure upstream of lime injection
- o Gas temperature and pressure at the downstream end of the test section

- The SO_2 and oxygen (O_2) concentrations upstream of the spray nozzles and downstream of the ESP. The upstream SO_2/O_2 probe could be moved to a point just ahead of the ESP to measure SO_2 removal across the ESP
- Opacity downstream of the ESP
- Flows of lime slurry and atomizing air

2.2 STARTUP

Startup work began in mid-September of 1986 and continued to mid-December of 1986. During this period, the system was checked out and made operable and the operating team was mobilized and trained. The equipment was modified and improved as operating experience indicated.

Flue gas coming from the host unit usually ranged between 270°F and 310°F and between 1,300 and 1,700 ppm SO_2. The test facility could not control the temperature or the SO_2 concentration of the incoming gas. Therefore, downstream temperature in the test duct was controlled by varying the rate of slurry injection into the upstream spray nozzle. The changes in slurry injection and variation in the entering SO_2 concentration caused the lime feed ratio (LFR), the molar ratio of lime to SO_2, to vary somewhat during the course of each test.

Tests during the shakedown period identified an acceptable spray nozzle: Spraying Systems Company's (SSCo's) Casterjet nozzle with their 5-50 tip. With air supplied at 90 psig, atomization was fine enough and the spray angle was such that deposition on the duct walls could be minimized.

To control deposition, however, it was necessary to limit the injection rate through the upstream nozzle to about 1.5 gpm, and through the downstream nozzle to 1.2 gpm. At these injection rates, the entering gas velocity was limited to about 35 ft/sec when the gas was cooled to a typical operating temperature of 160°F.

2.3 PARAMETRIC TESTS

Four months of parametric tests began in January 1987. These tests normally lasted 3 hours, but several took from 12 to 18 hours. After each test, the duct was opened and any deposits were noted, and cleaned out. Test conditions were varied to determine how to achieve 50 percent removal of SO_2 and to control deposition in the duct.

The effects of controllable variables were also explored. The variables and their observed effects are as follows.

2.3.1 Downstream Temperature

This temperature was varied from 140°F to 180°F. The lower temperature increased SO_2 removal, but also increased deposition in the duct. Both of these phenomena are the results of longer liquid phase residence time. A good compromise was 160°F, about a 35°F approach to saturation temperature (AST).

2.3.2 Lime Slurry Concentration

This value was varied from 8 to 22 percent. Deposition in the duct decreased as slurry concentration increased; lime utilization also decreased but SO_2 removal was higher because of the higher LFR.

2.3.3 Gas Velocity

Gas velocity upstream from injection was varied from 20 to 60 ft/sec. No effect on SO_2 removal could be observed as a function of velocity alone. To maintain the downstream temperature constant as gas velocity increased, the slurry injection rate was increased proportionately. Increased slurry injection was accompanied by coarser atomization and deposition on the duct walls, which may have obscured the effect of gas velocity on SO_2 removal.

2.3.4 Type and Source of Lime

Two types of hydrated lime from five sources were tried. The two limes that performed best were pressure hydrated dolomitic lime (PHDL) supplied in dry form by the Rockwell Lime Co. of Manitowoc, Wisconsin, and a calcitic lime

(CL) wet slaked at the nearby Sims Station in Grand Haven, Michigan. The calcitic lime resulted in higher removal and caused less deposition in the duct at the tested conditions.

2.3.5 Lime Feed Ratio (LFR)

The number of moles of lime injected per mole of entering SO_2 was varied from 0.5 to 3.5. Increasing the LFR increased SO_2 removal but reduced lime utilization. Utilization ranged from 12 to 50 percent for PHDL and from 26 to 60 percent for CL.

LFR and downstream temperature were the two variables that had the most effect on SO_2 removal.

The parametric tests showed that 50 percent SO_2 removal with PHDL and a downstream gas temperature of 160°F required an LFR of approximately 2, giving a lime utilization of 25 percent. With the wet slaked calcitic lime at this temperature, 50 percent SO_2 removal required an LFR of approximately 1.1, giving a utilization of 45 percent.

Preliminary tests with gas tubes showed moderate NO_x removals. However, subsequent tests with a chemiluminescent analyzer showed negligible removal.

By measuring distances downstream from the spray nozzles where wet solids stuck to a probe inserted into the gas stream, it was possible to estimate approximate drying times. (These measurements were approximate because the solids changed from very wet to very dry over a distance of several feet.) These drying times for the indicated drop in flue gas temperature were:

- From 280°F-300°F to 200°F — 0.7 to 1.2 sec
- From 200°F to 160°F — 1.2 to 1.4 sec

Most of the SO_2 removal occurred before the droplets of lime slurry dried. Measurements of SO_2 removal across the ESP showed that less than 5 percent (absolute) of the SO_2 removal occurred as the dry solids traveled to the ESP and were captured there.

2.4 DURATION TESTS

The purpose of this series of tests was to operate the system continuously for prolonged periods to observe deposition and nozzle wear, and to provide stable operating conditions for the ESP tests. Table 1-1 lists various tests which demonstrated low deposition with about 50 percent or more SO_2 removal at 160°F and a gas velocity of 20 ft/sec.

Table 2-1

LOW DEPOSITION DURATION TESTS

Date	Lime Slurry	Duration (hr)	SO_2 Removal	LFR	Lime Utilization	Deposits (% fed)
5/7	PHDL, 15%	20	50	2.3	22	4.4
5/8	PHDL, 19.6%	20	47	2.7	17	5.5
5/12,13	CL, 11.1%	20	42	1.0	42	4.8
5/19,20	CL, 12%	20	46	1.4	33	1.1
5/29,30	CL, 12%	20	50	1.1	44	0.7
6/2,3	CL, 17%	18	61	1.8	34	0.4

At a gas velocity of 20 ft/sec, slurry injection rates were approximately 1.2 gpm through the upstream nozzle and 0.8 gpm downstream. Higher gas velocities required higher injection rates and resulted in more wall deposition for prolonged operation.

2.5 ANALYSIS OF SO_2 REMOVAL DATA

The data were organized into three separate data sets, and each set was analyzed separately using a personal computer-based regression program. These sets were: PHDL injected though one nozzle, PHDL injected through two nozzles, and freshly slaked CL injected through two nozzles.

Both rational and empirical expressions were examined to correlate the data. The rational expressions do not allow SO_2 removal to exceed 100 percent and SO_2 removal is zero when LFR equals zero.

For all three data sets, the rational expressions showed a strong dependence of SO_2 removal on both LFR and AST. Gas inlet temperature was also identified as an important variable. Inlet SO_2 concentration was identified as an important variable for the CL data set, but not for the PHDL data sets. However, since inlet SO_2 is a factor in LFR, also used in the correlation, this result is inconclusive.

Plots of calculated versus actual SO_2 removal for the rational correlations showed a slight bias in that calculated removal tended to be high at low actual removal and low at high actual removal. This suggests improved correlations could be found.

The empirical correlations reflected relationships between the independent variables rather than the variables' true contribution to SO_2 removal. Thus, they were difficult to interpret and did not extrapolate. The rational correlations are felt to be better than the empirical correlations for understanding the process despite the bias.

Plots of the rational correlations showing SO_2 removal versus LFR showed that SO_2 removal rises faster and higher for freshly slaked CL than for PHDL, and that PHDL injected through two nozzles outperformed PHDL injected through one nozzle.

Plots of lime utilization versus lime concentration for PHDL and CL show that lime utilization decreases with increasing lime concentration. Since, by definition, lime utilization times LFR equals SO_2 removal, this implies that, at a given LFR, SO_2 removal will decrease with increasing lime concentration (assuming other variables are held constant).

This phenomenon explains why SO_2 removal performance of PHDL was better when injected through two nozzles than through a single nozzle with another nozzle for water injection. For a given operating condition, the concentration of lime injected through a single nozzle had to be higher than that injected through two nozzles because the additional water injected through the second nozzle was not used to dilute the lime. This increase in feed solids results in poorer lime utilization and therefore, poorer SO_2 removal performance.

Additional analysis of the Campbell data could be expected to improve its correlation. However, it was felt that a more useful correlation could be obtained by analyzing the combined data set from both the Campbell and Seward sites as later described.

2.6 ESP TESTS

Two series of ESP tests were carried out: the first in November 1986 during shakedown of the system, and the second from May to July 1987, at the end of the test program. The test runs for the first series were shorter than those for the second series. The objective was to determine how injection of lime into the ductwork affected ESP performance and whether injection is likely to increase particulate emissions. The results were contradictory.

The first series of tests showed that the lower temperature and higher moisture content of the gas with injection improved collection enough to offset the higher particulate loading so that emissions did not increase significantly. The second, and more extensive, series showed the opposite: that lime injection impaired ESP performance and caused emissions to increase. Table 1-2 shows typical ESP performance at a gas velocity upstream from injection of 45 to 50 ft/sec.

Table 2-2

ESP TESTS

Date	Lime Injection	ESP Temperature (°F)	Removal Efficiency	Emissions, (gr/dscf)
First Series, November 1986				
11/18	No injection	275	94.8	0.050
11/22	PHDL, 12%	165	99.0	0.034
Second Series, May to July 1987				
6/8	No injection	284	98.1	0.058
Several	CL, 12%, average	160	86.3	0.761
7/27	PHDL, 15%	159	87.5	0.937

The validity of the second series of tests showing poorer performance with lime injection is questionable. It is likely that incompletely dried slurry resulting from poor atomization caused excessive electrical leakage during these tests. It is felt that further testing must be performed to confirm ESP performance during CZD treatment of flue gas.

Section 3

PROJECT DESCRIPTION

On February 2, 1985, the Pittsburgh Energy Technology Center (PETC) of the Department of Energy (DOE) issued a Program Research and Development Announcement, (PRDA) RA-22-85PC81001, soliciting proposals to carry out proof-of-concept tests of novel processes for flue gas desulfurization (FGD). These FGD processes were to be capable of removing at least 50 percent of the SO_2 from the flue gas of coal-burning utility boilers. They were also to have the potential of being economically retrofitted onto existing boilers, and the by-products were to be either useful or at least suitable for disposal as nonhazardous wastes. The total estimated cost of the SO_2 removal was to be less than $500 per ton of SO_2 removed. PETC specified that the scale of the proof-of-concept tests was to be approximately equivalent to a 5 MWe power plant.

On April 1, 1985, Bechtel responded to this PRDA with a proposal to design, build, and operate a test facility based on the company's proprietary Confined Zone Dispersion (CZD) process. The facility was to be located at Consumers Power Company's (CPC's) Campbell Station in West Olive, Michigan. Unit 1 at the Campbell Station would supply a slip stream of flue gas to the facility. CPC agreed to this arrangement in a letter of intent, a copy of which Bechtel included in its proposal. On June 12, 1985, PETC notified Bechtel that the latter's proposal was one of those selected for negotiation, and Contract DE-AC-22-85PC81009, signed on September 23, 1985, authorized work to begin. A Work Plan, drafted by Bechtel, was submitted to PETC on November 22, 1985.

3.1 IMPLEMENTATION

A formal agreement with CPC was signed on February 19, 1986. CPC was unable to accept any liability for the test facility or any costs that would affect its rate structure. To preclude any action that required modification of Campbell Station's environmental permits, no process wastewaters could be discharged by the test facility, and all solid wastes had to be disposed of off site. In addition, measures to minimize emissions of dust were mutually developed by Bechtel and CPC.

CPC assisted the project in many ways. It helped apply for environmental permits, and provided general support and assistance throughout the program. Campbell Station provided utilities, office space, and other services.

Bechtel National, Inc. personnel from San Francisco managed the project and performed the process design, shakedown, testing, and reporting. Detailed design, most of the procurement, and management of construction was done by Bechtel Eastern Power Company, from its office in Ann Arbor, Michigan. Subcontractors from western Michigan performed the construction.

During a scheduled outage of Unit 1 late in November 1985, penetrations were made in the unit's ductwork. Manually operated shutoff dampers were welded onto the penetrations, and the damper openings were sealed with cover plates and insulated. With these dampers in place, another outage was not needed to connect the test duct.

Most of the process design was completed by December 1985. This included specifying the sizes, duties and general layout of major items of equipment; major instruments and controls; and materials of construction for the process equipment.

Procurement of long-lead items such as the electrostatic precipitator (ESP), the ID fan, and the on-line monitor for SO_2 and O_2 began in November 1985. With the execution of a subcontract for installing the process equipment (which included piping, wiring, and insulation) in July 1986, procurement for building the facility was completed. However, procurement of supplies continued throughout the test program. The facility was dismantled and the site was restored in August 1989.

3.1.1 Detailed Design and Construction

Detailed design began in December 1985 and was essentially finished by June 1986. This work included preparation of bid specifications for subcontractors, a number of working drawings for equipment and structures, a process and instrumentation diagram (P&ID), wiring diagrams, and detailed layouts. Specifications for restoring the site were also prepared.

Three principal subcontracts were awarded for the construction work:

- Footings, foundations, and concrete work
- Design, provision of materials, and erection of the process building
- Erection and installation of process equipment, piping, and wiring

A Bechtel superintendent supervised the construction, but subcontractors performed the work. The construction superintendent was responsible for quality control and verified that the subcontractors completed their work satisfactorily. Work at the site began in May 1986, and the construction superintendent turned the facility over to the operating team on October 8, 1986.

3.1.2 Final Program Activities

The shakedown work began in mid-September 1986, and the test program was completed on July 28, 1987. Shakedown and test program activities are described in Sections 4, 5, 6, and 7.

On completion of the test program, the facility was secured and mothballed, with all the tools and supplies stored in the process building until disposition instructions for the equipment were received from the DOE. Dismantling and site restoration were completed in August 1989.

While the project was active, Bechtel submitted technical progress reports to PETC each month. These reports describe each month's activity. During the test program, they also included a brief description and an analysis of each month's results and a detailed tabulation of the operating and test data. The reader is referred to these monthly technical reports for the raw test data.

3.2 PROCESS AND FACILITY DESCRIPTION

3.2.1 Design Considerations

The test facility was designed to be simple and versatile. Flexible hoses were connected to pumps to allow the suction and discharge points to be changed as required. An example of this flexibility is seen in the lime handling and supply system where either lime slurry pump could take suction from any of the lime slurry feed tanks and discharge to the grit tank, the wastewater sump, or the pump-around loop.

The test duct was located about 12 feet above grade to avoid existing structures close to Unit 1, to allow a straight run of test duct in excess of 100 feet, and to minimize the length of the connections. The diameter of the test duct was chosen to be 3 feet. At a gas flow of 50 ft/sec, the test scale would be equivalent to about 7 MWe, somewhat larger than required by the PRDA. The larger duct size lessened the problems of deposits inside the duct and permitted workers to go inside for inspection and cleaning.

Since the facility would have to operate in winter, all lime slurry preparation and handling equipment and the principal instruments and controls were enclosed in a heated building.

Operation of the test facility could not interfere with the operation of the Campbell plant since the test facility simply withdrew a slipstream of flue gas from the plant's ductwork and returned it. Isolation dampers with operating platforms and access ladders were required where the test duct connected to the ductwork of Unit 1.

No sewer connection was permitted to carry off wastewater from the test facility. All wastewater was used either to make up slurry or to moisten the waste solids discharged to the dumpster in order to control airborne dust.

Waste solids had to be disposed of off site. The ESP discharged the solids into a covered dumpster, and a contractor hauled them to a Class 2 disposal site as required.

3.2.2 Overview

As noted, the test facility was designed to (1) withdraw a slipstream of flue gas from ductwork of Unit 1 and then (2) inject a finely atomized spray of lime slurry into the flue gas as it flowed through a straight run of 3 ft dia. test duct. After leaving the test duct, the gas discharged into a pilot-scale ESP and then returned to the upstream side of the second-stage ESP in Unit 1.

Figure 3-1 is a piping and instrumentation diagram (P&ID) of the test facility; Figure 3-2 shows the layout of the facility. The duct of the test facility tied into the ductwork of Campbell Unit 1 just upstream from the first-stage ESP. The test duct entered the pilot plant building and continued as a straight run of pipe for a distance of approximately 130 feet, before curving upward and entering the pilot-scale ESP. Induced draft fan V-1 withdrew the flue gas from the Unit 1 ductwork, pulled it through the test duct and the pilot-scale ESP, and then discharged it back into the Unit 1 ductwork upstream from the plant's second-stage ESP. Manually operated dampers were installed at the start and end of the test duct where it connected to Unit 1 to shut off the flow of flue gas when the test duct was not in operation. The entire test duct was insulated with 2-inch-thick calcium silicate to minimize heat loss.

3.2.3 Lime Storage and Handling

Self-unloading bulk trailers of about 20-ton capacity delivered pressure hydrated dolomitic lime (PHDL) to the test facility as a fine powder. The trailers discharged the dolomitic lime pneumatically into storage silo T-5. During unloading, vent gas displaced from the silo passed through filter F-2, which removed particulates. The filtered vent gas was then discharged to the atmosphere. Rotary vane feeder M-2 and eductor M-40 recycled PHDL from the vent filter back to the storage silo.

Rotary vane feeder M-1 (under the silo) fed PHDL to inclined screw conveyor SC-2, which discharged the lime into 5,000-gallon slurry makeup tank T-1. Mixer MX-1 was provided in T-1 to agitate lime and water to make up a slurry of the desired concentration. During the latter part of the test program, calcitic lime was brought to the facility in slurry form by tank truck and delivered directly to T-1. This slurry was adjusted to the desired concentration for test runs.

Slurry transfer pump P-1 transferred the slurry from T-1 to slurry cyclones CDC-1A and CDC-1B, where fine grit was removed. Degritted lime flowed out the top of the cyclones into lime slurry feed tanks T-4A and T-4B. The cyclone underflow containing the grit in concentrated slurry discharged into grit sump T-2, and then flowed by gravity to grit tank T-3.

The cyclone underflow in the grit tank was washed to recover lime and to reduce the quantity of waste solids. Water was added to the grit tank to dilute the grit concentrate, and agitator MX-2, mounted on the tank, kept the slurry in suspension. Grit pump P-2 then pumped the grit slurry through cyclone CDC-2, also mounted on the grit tank. The dilute slurry of lime in the overflow went to T-1, and the washed grit in the underflow fell back into T-3.

After the grit had been washed, pump P-2 transferred the grit tank contents to a settling box. A flexible hose was connected to the discharge of P-2 to permit this transfer.

After the grit had settled out in the settling box, the supernatant was decanted into a wastewater sump located in the pilot plant building. Sludge was removed manually from the settling box and taken to the dumpster near the pilot-scale ESP.

As necessary, sump pump P-4 transferred water from the wastewater sump to the dumpster to control the dust generated by the discharge of solids to the dumpster from the electrostatic precipitator (ESP) hoppers. This water was then hauled away with the solids in the dumpster for offsite disposal. Water from the sump was also pumped as needed to tank T-1 for use in making up fresh lime slurry or to tank T-3 to wash the grit.

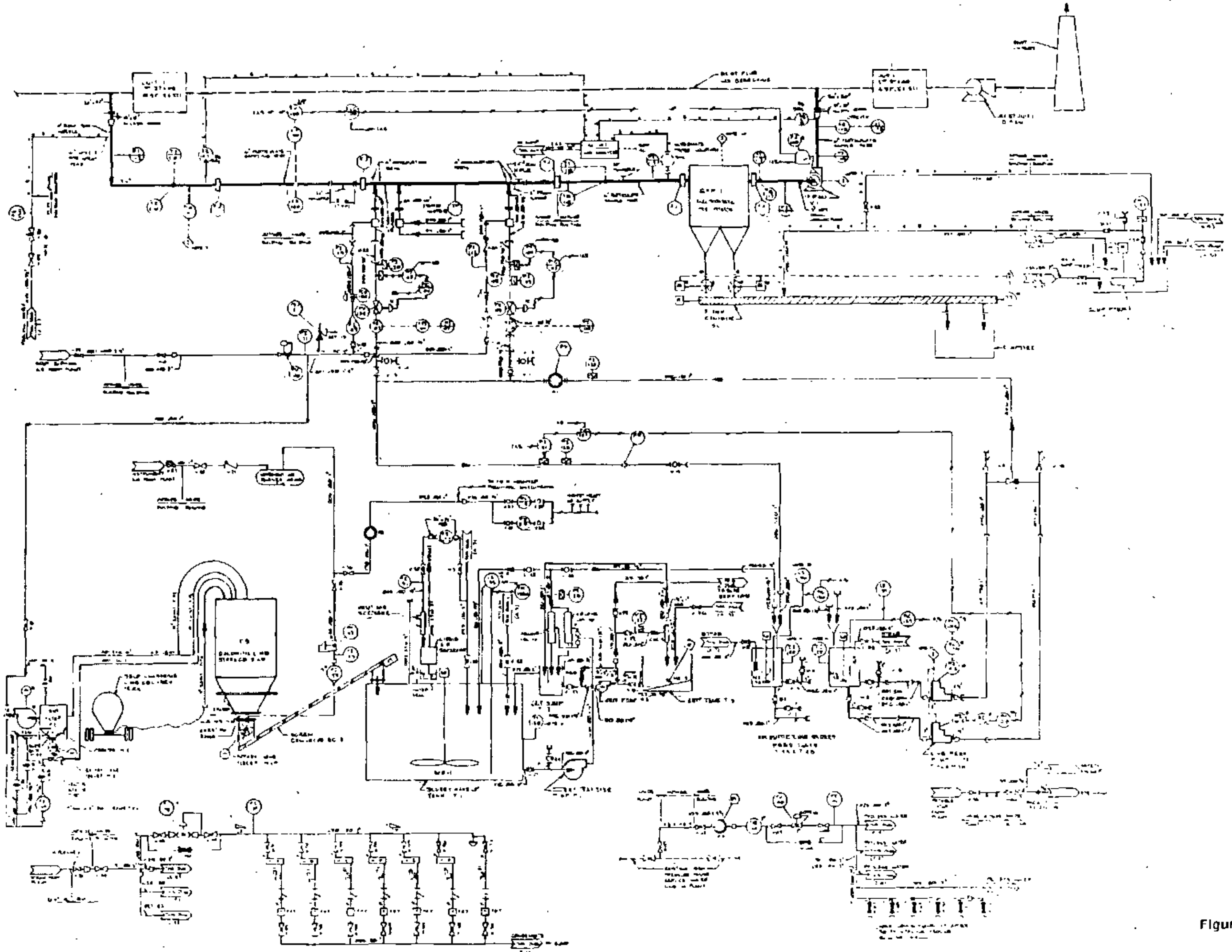


Figure 3-1 P&ID of the Test Facility

Part 2

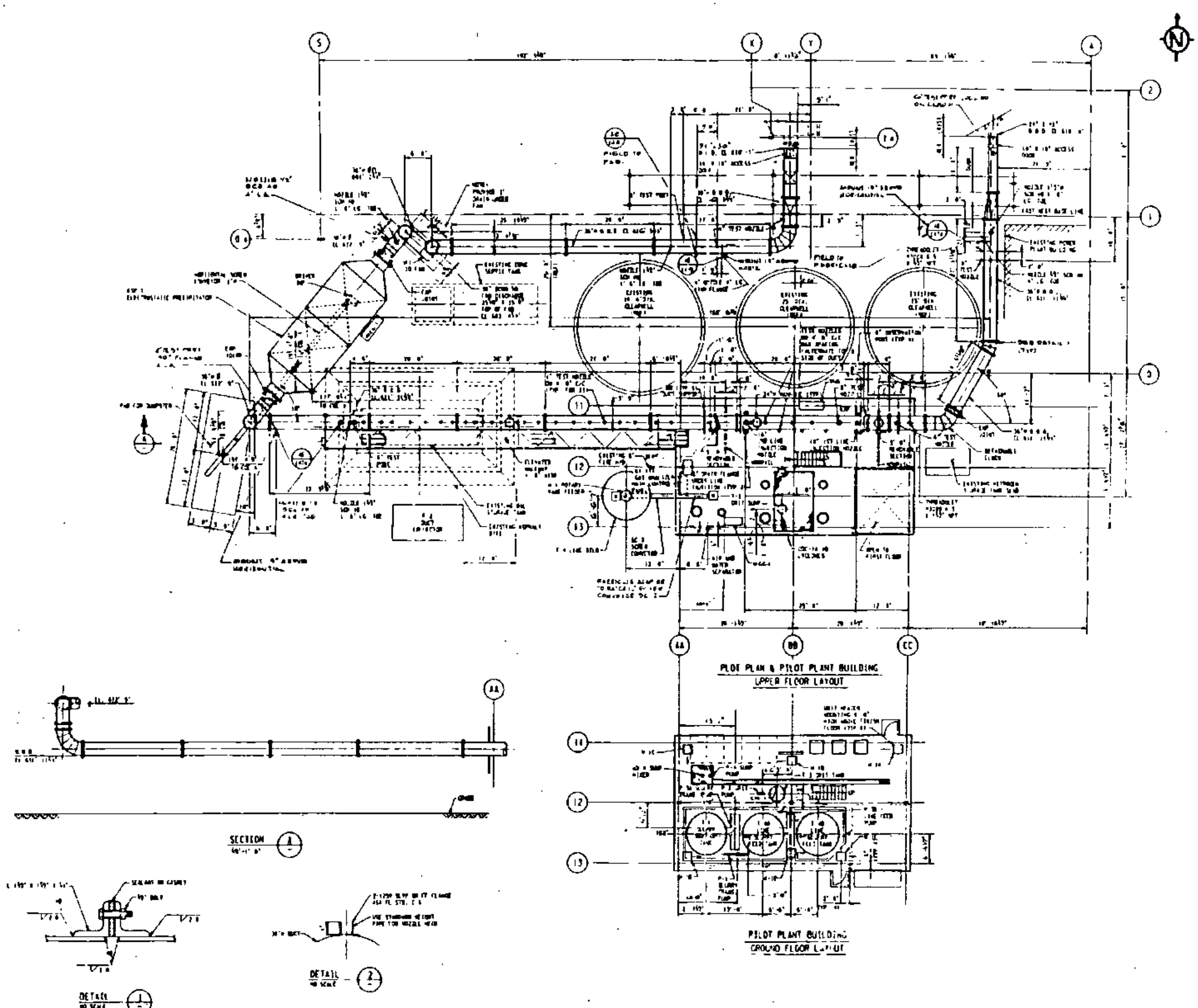


Figure 3-2 Layout of the Test Facility

Two progressive cavity pumps, P-3A and P-3B, one operating and one spare, circulated the lime slurry from either slurry feed tank through 20-mesh strainer F-1 in a pump-around loop that passed close to the two points where slurry was injected into the test duct. Pressure controller PIC-101 regulated pump speed to maintain the loop pressure needed to supply the slurry to each injection point. Orifice FO-1 throttled the excess slurry before it discharged back into the feed tank.

3.2.4 Test Duct

The 3 ft dia. test duct that tied into the ductwork of Campbell Unit 1 just upstream from its first-stage ESP ran south and then turned west into the pilot plant building. It then ran straight, passing through the building and continuing for over 130 feet, in all, until it turned to enter the pilot-scale ESP. To ensure a uniform gas flow through the test section, there was about 30 feet of duct upstream from the first slurry injection point and about 100 feet downstream from the second injection point Figure 3-3 shows a portion of the test duct.

Flow sensor FE-100 and flow controller FIC-100, located in the duct upstream from the lime injection, maintained the selected gas flow constant by regulating the inlet vanes of ID fan V-1.

Two slurry spray nozzles, using compressed air from the plant as the driving fluid, were used to atomize the slurry and inject it into the test duct. Figure 3-4 is a diagram of one of the spray nozzles used during the test.

To achieve the desired pressure at the nozzle, slurry to each spray nozzle was throttled through pressure control valve PV-102 or PV-103. Magnetic flow meter FI-107 and sonic flow meter F-108 measured the slurry flow to the upstream and downstream nozzles, respectively. The pressure of the compressed air supplied to the nozzles was regulated by pressure control valves PCV-104 and PCV-105.

An extractive on-line analyzer furnished by Lear-Siegler measured the O_2 and SO_2 concentrations of the gas in the test duct. Sample probes were located

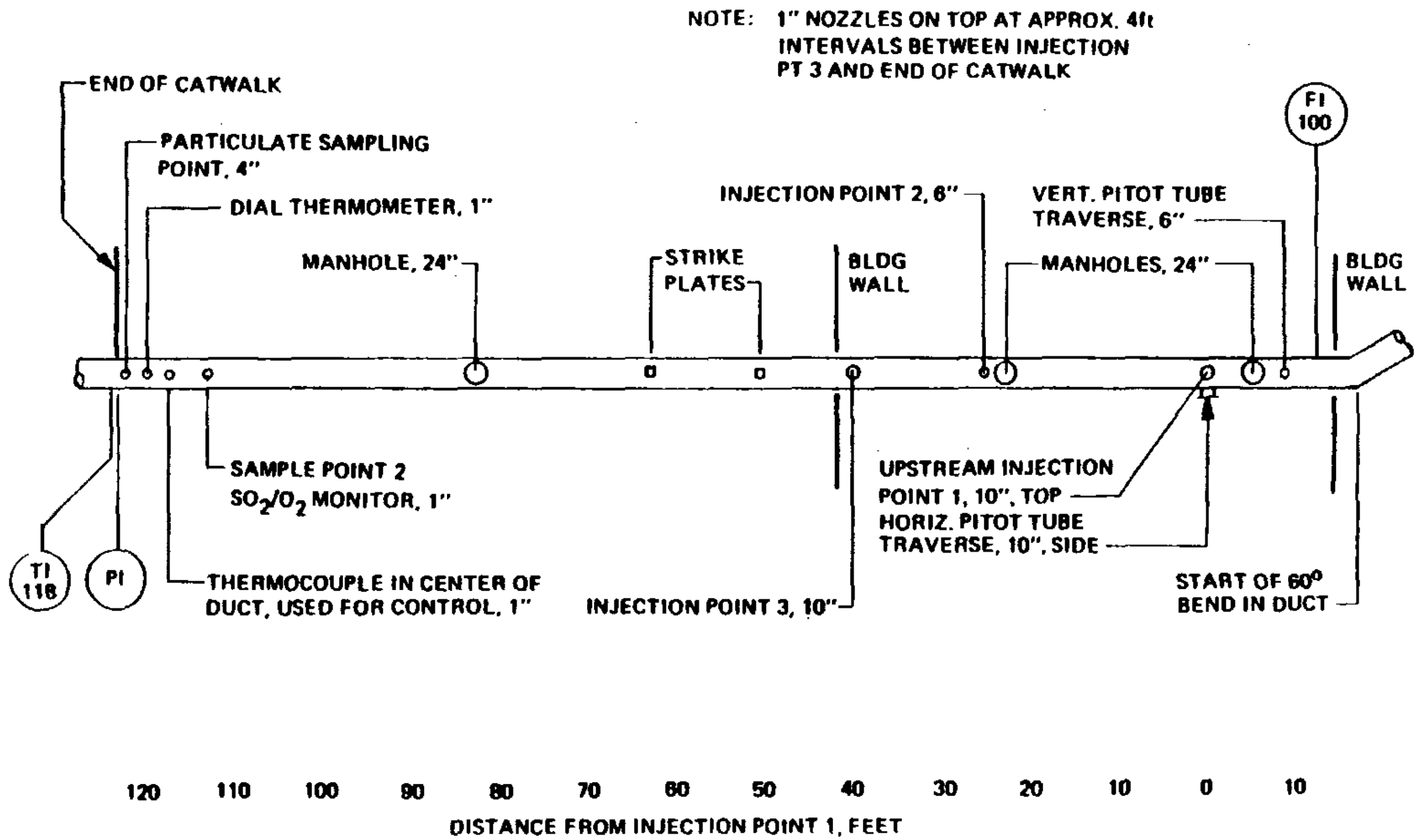


Figure 3-3 Plan View of Duct Test Section

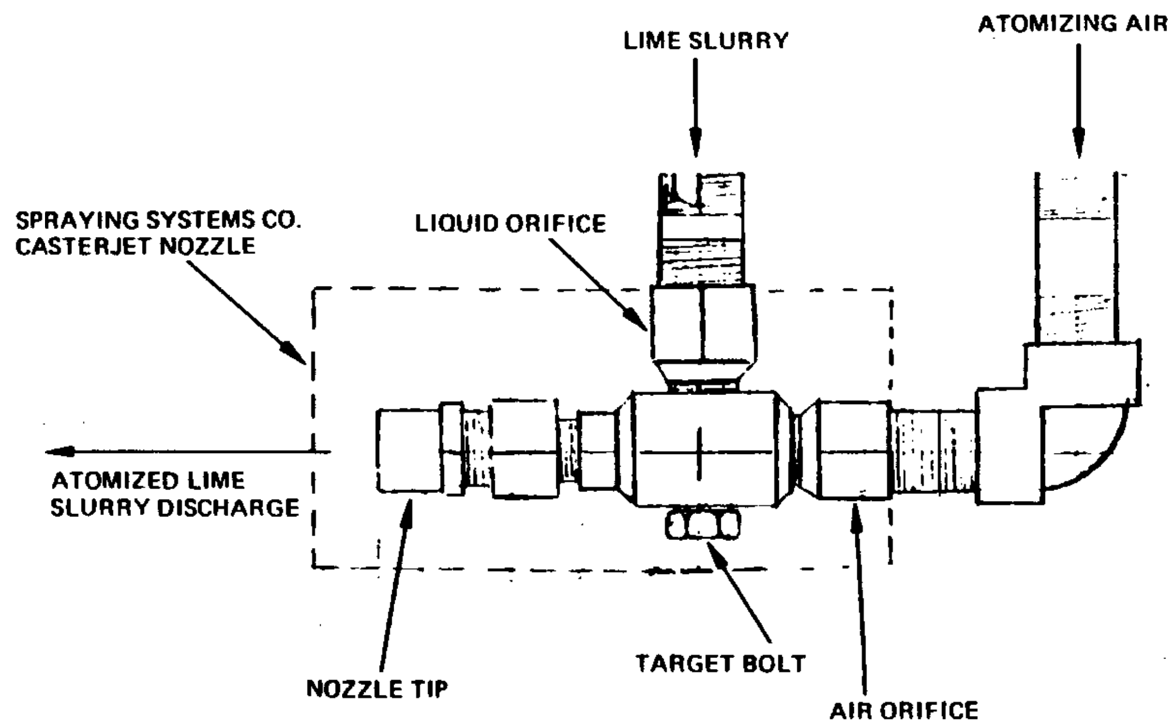


Figure 3-4 Spray Nozzle Assembly

upstream from the first lime injection point and downstream from the pilot-scale ESP. The analyzer switched between the upstream and the downstream sample point every 5 minutes. A third sample point located at the entrance of the ESP was used occasionally to measure SO_2 removal across the ESP.

The concentrations of SO_2 and O_2 were displayed at a control panel located inside the pilot plant building. Parameters such as gas flow rate, slurry flow rate, and slurry feed pressure were regulated from this control panel.

Three 24 in. dia. manholes, as shown in Figure 3-3, were installed in the straight run of test duct. These manholes provided access to the nozzles and made it possible to inspect the duct and remove deposits from the duct.

3.2.5 Pilot-Scale ESP

The pilot-scale ESP was located directly downstream from the test section of the duct. All test loop gas passed through this ESP. The ESP had two fields in series and two hoppers. At 21,000 acfm, the specific collection area (SCA) was 165 ft^2/1,000 acfm. The average velocity past the plates was close to 3 ft/sec, and the plate spacing was 12 inches.

Lodge-Cottrell division of Dresser Industries, Inc. supplied the unit. Section 7 describes the ESP more fully.

Section 4

SHAKEDOWN

The objective of the shakedown work was to ensure that the test program could be carried out in the completed test facility. This involved the following tasks:

- o Checking out the individual items of equipment and the instrumentation
- o Discovering unforeseen problems
- o Modifying the facility to resolve problems and improve the operation
- o Calibrating the instruments and controls
- o Learning how to operate the system and developing procedures to obtain the data desired
- o Mobilizing personnel and training the project team

A successful test program required a smoothly functioning facility and a project team with the needed skills and training.

As noted, equipment checkout began in the later part of September 1986. On October 8, construction work was officially completed; shakedown continued through December 22, when work was suspended for the holidays.

4.1 MODIFICATIONS TO THE FACILITY

The shakedown work indicated the need for a number of modifications:

- o To operate the duct shutoff dampers every day, platforms, and access ladders were needed.
- o The position of the dumpster that received waste solids from the electrostatic precipitator (ESP) had to be changed. A way of moving the dumpster to distribute the load was also required.
- o One length of the mixing paddles in the waste solids screw conveyor had to be replaced by a screw flight to keep the conveyor from plugging.

- The rotary valve under the upstream ESP hopper was slowed down by installing a larger driven sprocket. This reduced the load on the motor.
- A turning vane was installed in the 30° bend in the duct just upstream from the first injection point. This distributed the gas flow more evenly over the cross section of the duct.
- The two manhole openings in the duct ahead of the injection points were faired over by making saddle-shaped inserts that conformed to the inside surface of the duct.
- The downstream slurry injection point was moved from a point 25 feet downstream from the upstream point to a point 40 feet downstream from the upstream point. This reduced deposits at high upstream injection rates.
- In-line screens were installed ahead of the lime slurry cyclones to prevent large particles from clogging the fine openings in the cyclones.

4.2 OPERATING PROCEDURES

Operating procedures were developed that enabled the system to run at near-constant conditions for reasonable periods of time. This activity constituted a large part of the shakedown effort. Deposition of solids in the duct limited the length of the test periods; the initial work focused on mitigating this problem.

To explore factors responsible for deposition and to determine acceptable operating conditions, the system was operated for 3 to 4 hours each day. Then, the system was shut down and inspected, conditions inside the duct were observed, and the subsequent course of action was decided upon. The primary parameters that were varied included: types of spray nozzles, injection rates of water and slurry, and gas flow. As this work progressed, the SO_2/O_2 monitor was put in service, and ways of increasing SO_2 removal were explored.

The following procedures and conditions, which avoided excessive deposition and achieved SO_2 removals approaching 50 percent, were selected:

- Spraying Systems Casterjet nozzles with a 5-50 tip were used, with air and liquid orifices 0.191 in. dia. and 0.163 in. dia., respectively.

- The nozzle was carefully adjusted to point parallel to the duct centerline. This adjustment was extremely critical. It was best done by getting inside the duct and observing the pattern of water sprayed from the nozzle and then pointing the nozzle to wet the duct walls evenly.

- The flow of slurry or water to the nozzles was limited to 1.2 gpm through the downstream nozzle and about 1.5 gpm through the upstream nozzle to minimize duct deposits.

- For SO_2 removals close to 50 percent, the downstream or spraydown temperature had to be about 160°F, and the lime feed ratio (LFR) about 2.0 moles of hydroxide (OH) per mole of SO_2 entering. With the limitation on liquid injection rates, this meant that gas flow could not exceed about 30 ft/sec and that slurry had to be injected through both nozzles in series. Single-stage slurry injection at SO_2 removals close to 50 percent caused major wall depositions.

- Since the downstream nozzle had a greater tendency to deposit solids on the duct walls, flow to it was kept constant and flow to the upstream nozzle was varied to keep the downstream temperature constant.

- The buildup of solids was progressive: deposits on the duct walls increased the amount of impingement of spray droplets, thereby accelerating deposition. For this reason, the system was shut down every day and the duct inspected and cleaned.

4.3 DATA ACQUISITION

The routine operating information included the data obtained from measurements needed to control the system and to assess its performance. Information on the analytical and calibration procedures used can be found in the appendices. The following data were normally recorded by the operator at 10- to 30-minute intervals.

- Time

- Gas temperature into the duct, in the downstream end of the duct (upstream from the ESP), and downstream from the ESP (upstream from the induced-draft [ID] fan)

- Gas flow into the duct

- Gas opacity downstream from the ID fan

- Atomizing air to each nozzle - pressure and flow

- Liquid or slurry to each nozzle - pressure and flow
- Lime slurry pump-around loop - pressure, upstream and downstream from the screen
- Sulfur dioxide concentration in the gas, upstream from the injection and downstream from the ID fan (also in the downstream end of the duct in later tests). Gas was sampled alternately at these two points on a 10-minute cycle.
- Oxygen concentration in the duct at the same locations and frequency as SO_2 concentration
- Voltage and current of each ESP field
- Slurry feed tank level, at approximately 1- to 2-hour intervals. The slurry flow meters were not reliable enough to measure injection rates for performance calculations, so timed differences in tank levels were used instead.

Besides the above entries, each data sheet indicated the date of the test, objectives or special conditions, nozzle identification and location, lime type, slurry concentration and alkalinity, and any other significant remarks, occurrences, or observations.

These data allowed LFR, SO_2 removal, and lime utilization to be calculated for each set of observations. Figure 4-1 is an example of a data sheet.

4.4 ESP TESTS

During the shakedown period, the performance of the ESP was tested for 5 days, from November 18 to 22, to verify that the ESP was operating satisfactorily. These tests consisted of simultaneously determining the concentration of particulate matter in the gas upstream and downstream from the ESP while the system operated at constant conditions. Tests were carried out with and without injection of lime.

Without injection, the particulate removal efficiency of the ESP was approximately 95 percent. As expected, injection of lime slurry and the resulting lower temperature improved the performance of the ESP enough to offset the increased loading of solids and maintain the emissions about the same as they were with no injection. Therefore, the ESP operation, with and

2/12/87

Parametric Test No 20-1

Time	Temp	Gas Flow,pac	Air P/F	liq P/F	header P/P	SO_2 us, ds	O_2 us, ds	ESP kv, ma	thermo @ 94'
	Nozzles: us		#1	SSCo .232/.191		with 8-60 Tip			
		ds	#3	SSCo .191/.163		with 5-50 tip			
	Lime Slurry		7.7% Solids, 1.041 SG,			Alk = 0.022 # eq OH⁻/gal			
11:27	water on to ds nozzle								
11:33	lime on to ds nozzle			Tank A level			96.6"		
11:36	water on to us nozzle								
11:40	lime on to us nozzle								
12:03	302	90/1.0	88/57	43/3.18	58/57	1590	5.9	58/70	
	162		90/40	49/1.23		920	6.9	55/66	157
12:10		Tank A level			93.7"				
12:18	302	90/1.0	89/57	43/3.18	58/57	1630	6.0	60/76	
	159		90/40	49/1.25		880	7.0	55/69	154
12:33	302	90/0.0	89/57	42/3.11	59/58	1610	5.9	60/72	
	159		90/40	49/1.25		930	6.8	55/69	157
12:48	303	90/0.0	89/62	42/3.12	58/57	1670	5.8	60/73	
	160		90/40	49/1.19		890	7.1	55/68	157
1:03	304	90/.25	89/60	40/2.96	55/54	1640	5.9	60/72	
	162		90/40	49/1.26		940	6.9	55/68	157
1:18	303	90/.5	90/60	40/2.96	55/54	1580	6.3	61/72	
	162		90/40	49/1.25		920	7.0	55/69	157
1:33	303	90/.5	90/62	40/2.94	55/54	1630	6.0	61/73	
	162		90/40	49/1.23		930	6.8	55/69	157
1:48	303	90/.5	89/61	40/2.94	55/54	1630	5.9	61/70	
	162		90/40	49/1.25		910	7.0	55/69	157
2:03	303	90/.5	89/60	40/2.94	55/54	1610	6.2	61/72	
	163		90/40	49/1.26		920	6.9	55/69	157
2:18	303	90/1.0	88/60	40/2.95	55/54	1620	5.9	61/72	
	161		89/40	49/1.29		880	7.1	55/68	156
2:33	lime off both nozzles. Tank A level 79.5								

Total Feed rate from time steady state reached

$$\frac{93.7 - 79.5}{143} \times 44.2 = 4.39 \text{ gpm}$$

Figure 4-1. Typical Data Sheet for Parametric Tests without lime injection, was judged to be satisfactory. Section 7 presents the results of these tests in more detail.

The waste products collected by the ESP were a mixture of fine coal ash, reaction products consisting of sulfates and sulfites of calcium and magnesium, and unreacted lime. The waste was a fine, dry, free-flowing powder. No problems were encountered in discharging the material from the ESP hoppers.

Section 5

SO_2 REMOVAL TESTS

Numerous tests to remove sulfur dioxide from flue gas using the Confined Zone Dispersion (CZD) process were conducted from January through July of 1987. These tests were performed to evaluate specific parameters and duration aspects observed during the CZD process. The results of these tests are described in this section.

5.1 PARAMETRIC TESTS

The goal of the parametric tests was to determine how certain operating variables affect the performance of the CZD process and to optimize the performance. The parametric tests were carried out from January 1987 through April of 1987.

5.1.1 Approach

The way in which the performance was evaluated, the independent variables studied, and the test procedures followed are described below.

Measures of Performance. Three measures of performance were determined:

- Deposition of Solids in the Duct. The objective was to be able to operate the system for prolonged periods without interference from accumulations of solids in the duct. Since deposition must be minimal for a successful commercial process, this measure received the highest priority.
- Sulfur Dioxide Removal. The objective was 50 percent removal of SO_2.
- Lime Utilization. The objective was high utilization of the lime, but this was given a lower priority at the present stage of development than the other two measures.

Test Procedure. The parametric tests normally lasted for 3 hours, with conditions kept as constant as possible during that time. However, because the temperature of the incoming gas and the concentrations of SO_2 and O_2 in the gas could not be controlled, test conditions often varied to some extent.

The operating procedure involved maintaining gas flow through the system all night to keep the electrostatic precipitator (ESP) warm. The ESP was kept warm so that it could be energized without drawing excessive current. During the night, gas flow was turned down and power to the ESP was turned off. In the morning, the gas flow was increased to the maximum for about 10 minutes to blow out the fly ash that had settled out in the duct overnight. This procedure would remove the fly ash but not the test deposits. The induced-draft (ID) fan was then shut off, the shutoff dampers connecting the system to the large ducts on Unit 1 were closed, and the three manholes in the straight run of duct were opened. After the duct had been purged and cooled with a ventilating fan, the inside of the duct was inspected to determine the extent of the deposits from the preceding test and the cause of those deposits. The deposits were then cleaned out. The quantity of deposits from the upstream and downstream nozzles was measured by counting the number of 5-gallon buckets of solids that were removed. A bucket contained 30 to 40 pounds of dry solids.

While the gas flow was off, the windows on the opacity monitor were cleaned and the instrument was zeroed.

When the duct was clean, the manholes were bolted closed, the shutoff dampers were opened, and the ID fan was started. Gas flow was maintained at a high level to keep fly ash from settling out in the duct and to warm up the system. After about 30 minutes, the ESP was energized.

The SO_2 and O_2 monitor was usually calibrated at this time. Then, when the system was ready, the gas flow was adjusted to the desired rate and injection of lime slurry began.

Two nozzles were nearly always used for injection, with either water or lime slurry injected upstream through Point 1 (see Figure 5-1), and lime slurry

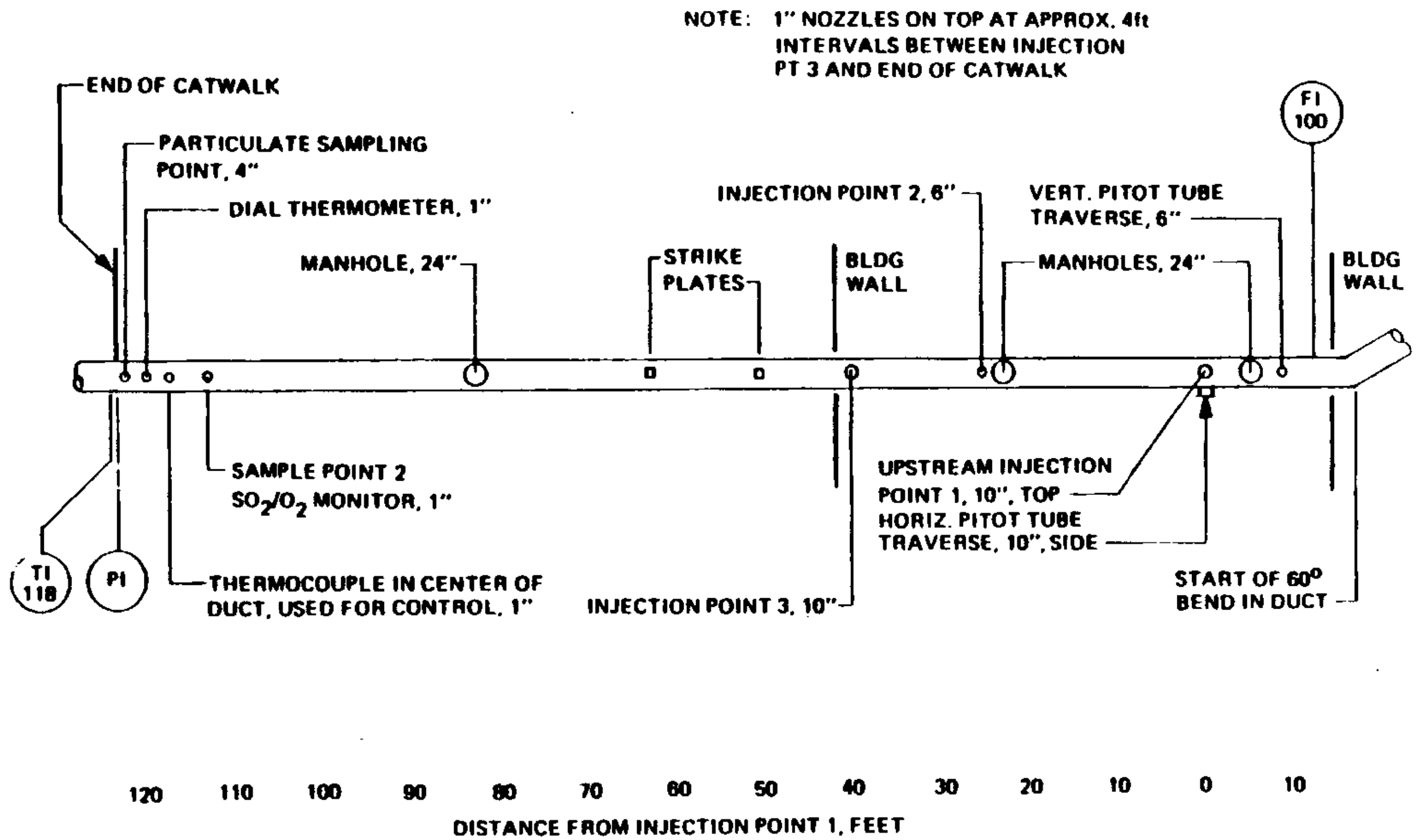


Figure 5-1 Plan View of Duct Test Section

through the downstream nozzle. Until January 15, Point 2, 25 feet downstream from Point 1, was used for the downstream nozzle; subsequently, Point 3, 40 feet downstream from Point 1, was always used.

During a test, the incoming gas flow was kept constant, as was the flow of slurry through the downstream spray nozzle. The downstream temperature, measured about 120 feet downstream from Point 1, was kept at the desired level by manual regulation of the flow of water or slurry to the upstream nozzle. The downstream temperature was measured with a thermocouple having a shield 1/8 inch in diameter. The junction was located at the center of the duct. Although the temperature over the duct cross section at this point was reasonably uniform, air leaks from nozzles on the top often caused lower temperatures at the top. For this reason, TI 118, which penetrated only 6 inches into the duct, was not normally used for control.

Data from the instruments were recorded at 10- to 30-minute intervals during a test.

Flow meters FC 107 and FC 108, which measured liquid flow to the spray nozzles were used for control, but the average slurry flow rate was determined by measuring the feed tank level and noting the time periodically. Figure 4-1 showed a typical entry.

After lime was injected for 3 hours (usually), the test was terminated by shutting off the slurry to the nozzles, turning down the gas flow, and deenergizing the ESP. The system was then left in this condition overnight.

Appendix F shows how SO_2 removal, lime feed ratio (LFR), and lime utilization were calculated from data taken during a test. In most cases, these measures of performance were calculated for the data taken at each time of observation and then averaged for the 3-hour test.

Since the SO_2/O_2 monitor switched from one to the other of the two sample points every 5 minutes, a set of readings usually took about 10 minutes to record. Changes in incoming gas temperature and in SO_2 and O_2 concentrations during this 10-minute interval caused some scatter in the data.

Parameters Studied. The parameters or independent variables studied to improve performance were the following:

- Nozzle Types and Assemblies. To minimize deposition, it was essential that the slurry be atomized into the finest droplets possible. To avoid impingement of these droplets on the walls of the small-diameter duct, the spray angle had to be narrow.

- Slurry Concentration. Concentrations from 8 to 22 percent were tested. The 20-mesh slurry screen tended to clog with lime at the higher concentration.

- Gas Outlet Temperature. A close approach to the adiabatic saturation temperature, which was about 125°F (see Appendix F), was necessary for high SO_2 removal and high lime utilization as it is in spray dry FGD systems. Gas outlet temperature was 160°F in most of the tests and ranged from 150°F to 180°F in the others.

- Gas Velocity. The gas velocity in the ductwork is normally 50 to 60 ft/sec in power plants at full load, and falls off as load decreases. The gas outlet temperature in most power plants decreases with load as well. Gas velocities from 20 to 60 ft/sec were studied in this series of tests.

- Lime Slurry Injection Rate. To keep the temperature downstream constant, the injection rate was varied with changes in gas flow and with incoming gas temperature. Increasing the slurry flow to a nozzle decreased the ratio of air to slurry and thus caused the spray droplets to increase in size. Consequently, the slurry injection rate affected the droplet size and therefore drying rate and deposition.

- Atomizing Air Pressure. With a given spray nozzle assembly, higher air pressures resulted in higher air flows and finer atomization. In most tests, the air pressure was kept as high as possible (90 psig); but in some tests, lower pressures were employed in order to observe their effect.

- Other Limes. Pressure hydrated dolomitic lime was used in most of the parametric tests, but samples of several other limes were tested as well.

5.1.2 Results

Test data have been arranged to compare results that show the effect of each parameter that was varied. The way each of the parameters cited above was varied is described below. Also described are the effects of parameter variation on solids deposition and SO_2 removal. Correlations relating parameter levels to SO_2 removal are presented in Section 6, in this part, and in Section 6 of Part 3.

Evaluation of Nozzles. Fifteen different combinations of spray nozzles and nozzle assemblies were tested. Table 5-1 lists the nozzle combinations; Table 5-2 summarizes the results of testing them. The most important criterion of performance in evaluating nozzles was the amount of solids that they deposited in the duct. To minimize deposition in this small-diameter duct, very fine atomization and a narrow spray angle were required.

Only three of the nozzle combinations definitely succeeded in depositing less than 60 pounds of solids in the duct during a 3-hour test with slurry injected at the rate of about 1.2 gpm. These combinations, identified as Types 3A, 4, and 5 in Table 5-1, were all the Spraying Systems Casterjet model with a 5-50 tip. The size of the air orifice was the only difference between them.

Nozzle Type 9 showed promise, but the fine passages clogged up on the second trial and, as a result, the nozzle was considered unsuitable. Nozzle Type 10 also showed promise in the test on February 9, but in a second test on February 23 under the same conditions, except for a higher air pressure, considerably more solids were deposited. Only when a higher slurry concentration was used on March 31 was the initial result reproduced. Additional details on the performance of these nozzles are contained in Appendix D, "Duct Inspections," of the Monthly Technical Progress Reports.

From Table 5-2 it can be seen that deposition is decreased by:

- Higher downstream gas temperature. Compare tests on January 20, January 29, and January 30
- Higher concentrations of lime slurry. Compare tests on February 14 and February 16 with those on February 9, February 23, and March 31
- Lower rates of slurry injection. Compare tests on January 19, January 20, January 27, and January 28; compare the test on January 29 with that on January 31, and the one on February 14 with that on February 16

Table 5-1

NOZZLES TESTED

Type	Description
1	Spraying Systems Co. (SSCo) CJ nozzle with air/liquid orifices 0.150/0.144 in. dia. and a tip with a sharp 0.30 in. dia. circular orifice
2	Same, but orifices 0.185/0.163 and 0.375 orifice tip
3	Same, but orifices 0.232/0.163 and 0.375 orifice tip
3A	Same, but 5-50 tip
4	Same, but orifices 0.185/0.163, 5-50 tip
5	Same, but orifices 0.191/0.163, 5-50 tip
6	Same, but orifices 0.185/0.163, 5-30 x 60 tip
7	Same, orifices 0.191/0.163, 5-30 x 60 tip
8	Delavan 31325 nozzle, SL-5 tip (air and liquid orifices are fixed in this nozzle)
9	Turbotak 6-orifice nozzle
10	Turbotak single orifice nozzle
11	SSCo 0.232/0.191 with 8-60 tip
12	Heat Systems Sonimist nozzle, 1100-1
13	SSCo 0.232/0.163 with 15200 tip
14	Parker Hannifin two-fluid nozzle

Table 5-2
EVALUATION OF NOZZLES

Date	Duration (hr)	Gas: Velocity (ft/sec)	Gas: Temp d/s (°F)	Nozzle Type: u/s	Nozzle Type: d/s(a)	Fluid conc. (%): u/s	Fluid conc. (%): d/s	Flow (gpm): u/s	Flow (gpm): d/s	Atom. Air Flow (scfm)	SO_2 Removal (%)	Lime Feed Ratio	Lime Util. (%)	Deposits (lb): u/s	Deposits (lb): d/s	Remarks
1/6	2.5	30	180	6	4	W	L, 15.2	0.8	1.22	46	23	0.75	31	0	Fair	
1/8	2.6	40	180	6	4	W	L, 15.2	1.3-1.7	1.33	44	21	0.67	31	10	200	Injection rate high at start
1/14	2.7	30	180	6	4	W	L, 15.2	0.7-0.9	1.22	46	23	0.90	27.1	0	40	
1/15	2.3	30	180	6	4	W	L, 15.2	0.9-1.1	1.02	47	22	0.84	41	0	30	
1/16	2.4	43	180	6	4	W	L, 15.5	1.4	1.15	47	20	0.65	30	0	20	
1/19	2.2	30	180	4	5	W	L, 15.5	0.8	1.08	50	19(b)	0.9	25	0	Trace	
1/20	2.3	50	180	4	5	W	L, 15.5	1.2-1.4	1.18	49	11(b)	0.8	18	0	0	
1/27	2.1	30	180	5	5	W	L, 15.6	0.6	1.52	49	32(b)	1.1	37	60	10	Includes fly ash settled out in duct overnight
1/28	2.2	30	180	5	5	W	L, 15.6	0.6-0.8	2.09	45	38	1.3	29	0	560	
1/29	2.5	30	170	5	5	W	L, 15.6	0.6-0.9	1.17	48	24	0.82	29	0	55	
1/31	2.5	30	170	5	5	W	L, 15.6	1.0-1.5	1.57	48	37	1.1	34	0	200	
1/30	2.4	30	160	5	5	W	L, 15.6	1.1-1.3	1.17	48	30	0.81	39	10	95	
2/2	3.0	30	160	5	5	W	L, 15.6	0.7-1.0	1.5	47	40	1.1	38	0	320	
2/6	4.1	27	160	5	5	L, 15.6	L, 15.6	1.1-1.4	1.2	48	50	2.0	25	10	20	
3/2	3.0	30	160	5	5	W	L, 21	1.1-1.4	1.29	46	31	1.3		0	20	
1/21	3.4	30	180	5	3A	W	L, 15.6	0.6-0.9	1.09	64	23(b)	0.9	29	0	5	
1/22	2.5	50	180	5	3A	W	L, 15.6	1.4-1.7	1.26	62	24(b)	0.8	35	0	5	
1/26	2.4	50	180	5	3A	W	L, 15.6	2.0-2.2	1.18	61	14(b)	0.7	23	0	10	
1/7	2.5	30	180	6	2	W	L, 15.2	0.5-0.6	1.15	47	27	1.0	27	0	600	Nozzle misaligned, includes solids from previous test
1/9	2.4	30	180	6	2	W	L, 15.2	1.2-1.3	1.15	47	26	0.65	29	0	400	
1/10	2.4	40	180	6	2	W	L, 15.2	2.0-2.2	0.7	46	NA	NA	NA	40	400	SO_2/O_2 monitor down

(a) Downstream nozzle at Point 2 through 1/15, and at Point 3 on 1/16 and thereafter
(b) SO_2 analysis by sniffer

TB 018 11-2487(1) Rev 7 BLC

Part 2

Table 5-2 (Cont'd)

Date	Duration (hr)	Gas Velocity (ft/sec)	Gas Temp d/s (°F)	Nozzle Type u/s	Nozzle Type d/s	Fluid conc. (%) u/s	Fluid conc. (%) d/s	Flow (gpm) u/s	Flow (gpm) d/s	Atom. Air Flow (scfm)	SO_2 Removal (%)	Lime Feed Ratio	Lime Util. (%)	Deposits (lb) u/s	Deposits (lb) d/s	Remarks
1/12	2.3	30	180	6	2	W	L, 15.2	1.0-1.2	1.23	47	26	0.29	29	40	260	Wet droplets impinged on both sides of duct
1/24	2.6	30	180	5	3	W	L, 15.6	0.5-0.8	1.18	67	31[b]	0.97	34	0	200	Impingement on both sides of duct
1/17	2.2	30	180	6	6	W	L, 15.5	0.8-1.0	1.15	47	20	0.85	24	0	200	Impingement from wide spray angle
1/23	2.4	30	180	5	8	W	L, 15.6	1.0-1.2	1.15	30	NA	NA	NA	0	160	Impingement from wide spray angle; solids settled in bottom from oversized drops
2/3	3.0	30	180	5	9	W	L, 15.6	0.6-0.9	1.11	54	25	0.94	26	0	50	
2/4	3.0	30	170	5	9	W	L, 15.6	0.7-1.1	1.28	48	34	1.4	25	0	350	Nozzle partly clogged; possibly misaligned also
2/9	3.2	30	180	5	10	W	L, 15.6	0.4-0.6	1.25	52	22	0.89	25	0	55	Atomizing air 73 psig
2/23	3.0	30	160	5	10	W	L, 15.5	1.3-1.6	1.2	65	25	0.88	28	20	60	
2/14	3.0	30	160	5	10	W	L, 8.4	1.3-1.6	1.2	65	23	0.43	53	20	150	
2/16	3.0	30	160	5	10	W	L, 8.4	0.6-0.8	1.5	61	25	0.60	42	0	280	
3/7	3.0	30	160	5	10	L, 21	L, 21	1.3-1.6	1.2	62	45	3.1	14	0	40	
3/31	2.8	30	160	5	10	W	L, 21	0.8-1.0	1.2	46	38	1.3	29	0	60	Atomizing air 70 psig
4/22	3.0	30	160	5	10	W	CL, 15[c]	1.8-2.0	1.09	41	40	0.8	50	50	375	Atomizing air 70 psig, deposits suggest slight misalignment; injection rate erratic at start
2/21	3.0	30	160	5	12	W	L, 15.5	1.3-1.7	1.2	86	36	0.77	47	20	280	Atomizing air 86 psig; spray angle too wide, line passages clogged
4/3	0.5	30	160	5	13	W	L, 20.5	0.8-1.1	1.2	73	30	1.3	24	5	180	Spray angle too wide; droplets impinged all around
4/25	3.0	30	160	5	14	W	L, 15	1.2-1.7	1.3	43	37	1.0	36	60	1060	Spray angle too wide; atomization appeared too coarse

(c) One nozzle only

TB 018 11-2487(2) Rev 6 BLC

Legend: u/s = upstream
d/s = downstream
W = water
L = PHDL
CL = wet slaked calcitic lime

Part 2

Additional data showing the effects of these three variables are presented later in this section.

Effect of Lime Slurry Concentration. Test results showing the effect of varying lime slurry concentration are presented in Table 5-3. Because all the conditions except slurry concentration were the same in each pair or group of tests, the LFR in each group increased in proportion to the slurry concentration. The increase in LFR caused SO_2 removal to rise and lime utilization to fall with increased slurry concentration. The change in LFR and its effect on removal and utilization masked any influence that concentration may have on SO_2 removal or the rapidity with which a droplet of slurry captured SO_2 in the gas.

Slurry concentration does affect deposition in the duct as noted above. Per Table 5-3, in every comparison but the first, the deposits were less at the higher concentrations and significantly less in several of the comparisons.

Effect of Downstream Gas Temperature. The downstream gas temperature or, more correctly, the approach to saturation, is one of the most important factors in spray dry FGD processes. Most of these tests were run at gas outlet temperatures between 150°F and 180°F. Since the adiabatic saturation temperature was about 125°F (see Appendix F), the approach to saturation thus ranged from 25°F to 55°F.

Table 5-4 shows that in every comparable group of tests a lower outlet temperature caused greater SO_2 removal and higher lime utilization. Although this effect was enhanced in some cases by a higher LFR at lower temperature, in five of the nine comparisons in Table 5-4, LFR is essentially constant; removal and utilization are considerably higher at the lower temperatures.

Deposition in the duct is also much greater at lower gas outlet temperatures, as would be expected from the slower drying at a closer approach to saturation. In Table 5-4, this effect is shown most clearly by the weight of deposits from the downstream spray nozzle.

Table 5-3
EFFECT OF LIME CONCENTRATION

Date	Duration (hr)	Gas: Velocity (ft/sec)	Gas: Temp d/s (°F)	Nozzle[a] Type u/s	Nozzle[a] Type d/s	Fluid conc. (%) u/s	Fluid conc. (%) d/s	Flow (gpm) u/s	Flow (gpm) d/s	SO_2 Removal (%)	Lime Feed Ratio	Lime Utilization (%)	Duct Deposits (lb) u/s	Duct Deposits (lb) d/s	Remarks
2/12	3	50	160	11	5	L, 7.7	L, 7.7	2.9	1.2	40	0.9	44	240	10	
2/11	2.9	50	160	5	5	L, 15.6	L, 15.6	2.8	1.2	52	1.7	31	490	130	
2/18	3	30	160	5	5	L, 8.4	L, 8.4	0.9	1.2	30	0.8	36	10	220	
2/19	3	30	160	5	5	L, 15.5	L, 15.5	1.3	1.2	42	1.8	23	0	40	
2/14	3	30	160	5	10	W	L, 8.4	1.3-1.6	1.2	23	0.43	53	20	130	
2/23	3	30	160	5	10	W	L, 15.5	1.3-1.6	1.2	25	0.9	28	20	60	
2/25 & 26	13.3	30	160	5	5	L, 15.5	L, 15.5	1.3-1.6	1.2	46	1.9	24	50	300	
3/10 & 11	13.5	30	160	5	5	L, 21	L, 21	1.2-1.7	1.2	50	2.7	18	60	60	
4/11	3	30	160	5	5	W	L, 8	1.0-1.2	1.3	22	0.5	40	30	250	
4/8	3.3	30	160	5	5	W	L, 15	0.8-0.9	1.3	25	0.9	27	0	135	
4/6	3.3	30	160	5	5	W	L, 20.5	0.9	1.1	28	1.1	25	5	25	
4/16	2.5	30	160	5	5	CL, 8.3	CL, 8.3	1.5-1.7	1.2	42	0.9	46	15	20	
4/21	2.3	30	160	5	5	CL, 15	CL, 15	1.7-1.9	1.2	67	2.1	33	10	15	

TB 018 11-2487(3) Rev 4 BLC

(a) Downstream nozzle at Point 2 through 1/15, and at Point 3 on 1/16 and thereafter

Legend: u/s = upstream
d/s = downstream
W = water
L = PHDL
CL = wet slaked calcitic lime

Part 2

Table 5-4
EFFECT OF DOWNSTREAM GAS TEMPERATURE

Date	Duration (hr)	Gas Velocity (ft/sec)	Gas Temp d/s (°F)	Nozzle[a] Type u/s	Nozzle[a] Type d/s	Fluid, conc. (%) u/s	Fluid, conc. (%) d/s	Flow (gpm) u/s	Flow (gpm) d/s	SO_2 Removal (%)	Lime Feed Ratio	Lime Utilization (%)	Duct Deposits (lb) u/s	Duct Deposits (lb) d/s	Remarks
1/30	2.4	30	160	5	5	W	L, 15.6	1.1-1.3	1.2	31	0.8	39	10	95	
1/29	2.5	30	170	5	5	W	L, 15.6	0.6-0.9	1.2	24	0.8	29	0	55	
1/21	2.4	30	180	5	3A	W	L, 15.6	0.6-0.9	1.1	15[b]	0.9	17	0	5	
2/2	3.0	30	160	5	5	W	L, 15.6	0.7-1.0	1.5	40	1.1	38	0	320	
1/31	2.5	30	170	5	5	W	L, 15.6	1.0-1.5	1.6	37	1.1	34	0	200	
1/27	2.1	30	180	5	5	W	L, 15.6	0.6	1.5	32[b]	1.1	29	Clean	Clean	
2/10	0.5	30	180	5	5	L, 15.6	L, 15.6	0.8	1.2	27	1.6	17	NA	NA	Lowered gas out temperature during test
2/10	0.8	30	160	5	5	L, 15.6	L, 15.6	1.4	1.2	43	1.9	23	0	30	
2/5	1.6	30	170	5	5	L, 15.6	L, 15.6	1.1	1.2	30	1.8	18	NA	NA	Lowered gas out temperature during test
2/5	0.9	30	160	5	5	L, 15.6	L, 15.6	1.4	1.2	47	2.3	20	10	15	
2/27	3.0	30	150	5	5	W	L, 15.5	1.3-1.5	1.2	42	1	44	20	200	
2/24	3.0	30	160	5	5	W	L, 15.5	1.3-1.4	1.3	30	0.9	34	10	200	
3/4	3.0	30	150	5	5	W	L, 21	1.1-3.0	1.2	47	1.3	36	70	100	
3/6	3.8	30	150	5	5	W	L, 21	1.3-1.6	1.2	41	1.4	30	40	120	Repeat of 3/4
3/2	3.0	30	160	5	5	W	L, 21	1.1-1.4	1.2	31	1.3	23	0	20	
3/5	2.9	30	150	5	5	L, 21	L, 21	1.3-1.4	1.2	57	2.9	20	0	20	
3/3	3.0	30	160	5	5	L, 21	L, 21	0.9-1.5	1.2	46	2.6	18	0	15	
3/12	3.0	30	150	5	5	L, 21	L, 21	2.0-2.3	1.0	57	4.1	14	240	10	Gas in 310°
3/16	3.0	30	160	5	5	L, 21	L, 21	1.0-1.2	1.0	42	2.6	16	0	15	Gas in 270°
3/14	3.0	30	170	5	5	L, 21	L, 21	1.3-1.5	1.0	31	3.1	10	0	10	Gas in 300°
4/9	3.0	30	140	5	5	W	L, 15	1.3-1.5	1.2	43	0.9	50	40	360	
4/8	3.3	30	160	5	5	W	L, 15	0.8-0.9	1.3	25	0.9	27	0	135	

TB 018 11-2487(4) Rev 5 BLC/RPS

(a) Downstream nozzle at Point 2 through 1/15, and at Point 3 on 1/16 and thereafter
(b) SO_2 analysis by sniffer, one pair of readings only; assumed O_2 in/out 5.5/7 5%

Legend: u/s = upstream
d/s = downstream
W = water
L = PHDL
CL = calcitic lime

Part 2

Effect of Gas Velocity. Gas velocity, like lime concentration, was not a truly independent variable in this system, and its effect is therefore difficult to discern. An increase in gas velocity brings more SO_2 into the system, and unless this is matched by increasing the slurry injection rate, the LFR decreases. Thus, a change in gas velocity causes either LFR or slurry injection or both to change. Table 5-5 compares tests at different gas velocities.

In three of the comparative groups in Table 5-5, the LFR is nearly constant (January 6 and January 8, February 20 and February 19, February 6 and February 11), but the results are contradictory. The SO_2 removal is about the same in the first case, higher at lower velocity in the second case, and lower at the lower velocity in the third case. It does not appear that gas velocity by itself has a strong influence on SO_2 removal.

With regard to deposition, there were more deposits at the higher gas velocities in some cases, but these can be explained by higher slurry injection rates in these cases. The slurry injection rate is discussed further below.

Effect of Lime Slurry Injection Rate. Because it affects the LFR, slurry injection rate is not a truly independent variable. Also, increasing the injection rate through a given nozzle increases the size of the spray droplets considerably. In these nozzles, the atomizing air flow is constant at low to moderate slurry injection rates, and then air flow falls off as slurry flow increases further. Thus, the ratio of air to liquid decreases sharply with slurry flow, and this causes poorer atomization and larger droplets.

The effect of larger droplets on SO_2 capture is not expected to be great, as the decreased liquid-gas interfacial area offsets the longer drying time. The changes in SO_2 removal shown in Table 5-6 can be reasonably explained by changes in LFR or by experimental uncertainty. However, increased injection rates do significantly increase deposition in this small duct, as discovered during the shakedown. With the type 5 spray nozzles using air at 90 psig, deposition in this duct increased greatly as injection rates were raised past

Table 5-5
EFFECT OF GAS VELOCITY

Date	Duration (hr)	Gas: Velocity (ft/sec)	Gas: Temp d/s (°F)	Nozzle[a]: Type u/s	Nozzle[a]: Type d/s	Nozzle[a]: Fluid conc. (%) u/s	Nozzle[a]: Fluid conc. (%) d/s	Nozzle[a]: Flow (gpm) u/s	Nozzle[a]: Flow (gpm) d/s	SO_2 Removal (%)	Lime Feed Ratio	Lime Utilization (%)	Duct Deposits (lb) u/s	Duct Deposits (lb) d/s	Remarks
1/6	2.5	30	180	6	4	W	L, 15.2	0.8	1.2	23	0.8	31	ND	ND	
1/8	2.6	40	180	6	4	W	L, 15.2	1.3-1.7	1.3	21	0.7	31	15	200	
1/15	2.3	30	180	6	4	W	L, 15.2	0.9-1.1	1.1	34	0.9	41	0	30	
1/16	2.4	43	180	6	4	W	L, 15.5	1.4	1.2	20	0.6	30	0	20	
1/19	2.2	30	180	4	5	W	L, 15.5	0.8	1.1	21[b]	0.9	25	0	0	
1/20	2.3	50	180	4	5	W	L, 15.5	1.2-1.4	1.2	14[b]	0.8	18	0	0	
1/21	3.4	30	180	5	3A	W	L, 15.6	0.6-0.9	1.1	26[b]	0.9	29	0	5	
1/22	2.5	50	180	5	3A	W	L, 15.6	1.4-1.7	1.3	26[b]	0.8	35	0	5	
1/28	2.4	50	180	5	3A	W	L, 15.8	2.0-2.2	1.2	17[b]	0.7	23	0	10	
2/20	3.0	15[c]	160	—	5	—	L, 15.5	0	1.2	50	1.7	29	0	30	
2/19	3.0	30	160	5	5	L, 15.5	L, 15.5	1.3	1.2	42	1.8	23	0	40	
3/2	3.0	30	160	5	5	W	L, 21	1.1-1.4	1.2	31	1.3	23	0	20	
3/9	3.0	47	160	5	5	W	L, 21	2.5-2.7	1.2	8	0.9	9	160	60	Accuracy of SO_2 removal, LFR, and util. questionable; water flow to u/s nozzle fluctuated considerably
4/1	3.0	13[c]	160	—	5	—	L, 20.5	0	0.9	35	2.2	16	0	10	
4/8	3.3	30	160	5	5	W	L, 20.5	0.9	1.1	28	1.1	25	5	25	
2/6	0.4	30	160	5	5	L, 15.6	L, 15.8	1.4	1.2	44	1.8	25	5	20	Total test duration 4 1 hours
2/11	2.9	50	160	5	5	L, 15.6	L, 15.8	2.8	1.2	52	1.7	31	490	130	
4/15	3.0	20	160	5	5	L, 15	L, 15	0.8-1.0	0.8	42	2.0	21	0	5	
2/25 & 26	13.4	30	160	5	5	L, 15.5	L, 15.5	1.3-1.6	1.2	46	1.9	24	50	300	
4/10	3.0	40	160	5	5	L, 15	L, 15	1.6-1.8	1.6	39	1.8	22	50	240	

TB 018 11-2487(5) Rev 6 BLC/RPS

(a) Downstream nozzle at Point 2 through 1/15, and at Point 3 on 1/16 and thereafter
(b) SO_2 analysis by sniffer. One pair of readings only
(c) One nozzle only; varied gas flow to control temperature

Legend: u/s = upstream
d/s = downstream
W = water
L = PHDL
CL = wet slaked calcitic lime

Part 2

Table 5-6
EFFECT OF LIME SLURRY INJECTION RATE

Date	Duration (hr)	Gas		Nozzle[a]						SO_2 Removal (%)	Lime Feed Rate	Lime Utilization (%)	Duct Deposits (lb)		Remarks
		Velocity (ft/sec)	Temp d/s (°F)	Type		Fluid conc. (%)		Flow (gpm)							
				u/s	d/s	u/s	d/s	u/s	d/s				u/s	d/s	
1/19	2.2	30	180	4	5	W	L, 15.5	0.8	1.08	10[a]	0.9	25	0	0	
1/27	2.1	30	180	5	5	W	L, 15.6	0.8	1.52	32[a]	1.1	29	Low	Low	Fly ash not blown out; fan damper arm off
1/28	2.2	30	180	5	5	W	L, 15.6	0.6-0.8	2.09	39	1.3	29	0	560	
1/30	2.5	30	160	5	5	W	L, 15.6	1.1-1.3	1.17	31	0.8	39	10	95	
2/2	3.0	30	160	5	5	W	L, 15.6	0.7-1.0	1.52	40	1.1	38	0	320	
1/29	2.3	30	170	5	5	W	15.6	0.6-0.9	1.17	24	0.8	29	0	55	
1/31	2.5	30	170	5	5	W	15.6	1.0-1.5	1.57	37	1.1	34	0	200	
1/26	2.4	50	180	5	3A	W	L, 15.6	2.0-2.2	1.18	4	0.7	6	0	10	
1/22	2.3	50	180	5	3A	W	L, 15.6	1.4-1.7	1.26	16[a]	0.8	21	0	5	
2/7	3.1	50	180	5	5	W	L, 15.6	1.0-1.9	2.0	27	0.9	28	10	300	
2/14	3.0	30	160	5	10	W	L, 8.4	1.3-1.6	1.2	23	0.4	53	20	130	
2/16	3.0	30	160	5	10	W	L, 8.4	0.6-0.8	1.5	25	0.6	42	0	280	
3/24	3.0	30	160	5	5	L, 21	L, 21	2.1-2.3	0.8	58	3.1	19	240	5	
3/16	3.0	30	160	5	5	L, 21	L, 21	1.0-1.2	1.0	42	2.6	16	0	15	Accuracy of SO_2 removal, LFR, and util. questionable
3/26	3.0	30	160	5	5	L, 21	L, 21	1.3-2.0	1.2	48	3.0	16	0	10	Slurry heated to 155°
3/28	2.9	30	160	5	5	W	L1, 15	0.6-1.0	1.2	28	1.0	28	0	60	L1 – dry hydrated calcitic lime
3/27	4.9	30	160	5	5	W	L1, 15	0.4-0.8	1.5	34	1.1	31	0	240	L1 – dry hydrated calcitic lime

TB 018 11 2487(6) Rev 5 BLC/RPS

(a) SO_2 analysis by sniffer, one pair of readings only; assumed O_2 in/out 5.5/7.5%

Legend: u/s = upstream
d/s = downstream
W = water
L = PHDL
CL = wet slaked calcitic lime

Part 2

1.2 gpm to 1.5 gpm. Table 5-6 shows this clearly when tests on the following dates are compared: January 30 and February 2, January 29 and January 31, February 14 and February 16, and March 26 and March 27. On March 24, the injection rates of 2.1 to 2.3 gpm through the upstream nozzle caused heavy deposition.

Effect of Atomizing Air Pressure. Since increased air flow improves atomization in a two-fluid spray nozzle, the maximum air pressure available in this system, 90 psig, was used in nearly all of these tests. One group of comparative tests at different pressures was run, and the results of these tests are shown in Table 5-7. The air pressure was varied to the downstream nozzle and was kept constant at 90 psig to the upstream nozzle. Unfortunately, the incoming gas temperatures were quite different in these three tests so that upstream injection rates and therefore LFR values were also different. The different SO_2 removals reported in Table 5-7 probably reflect the different LFR values rather than any effect of the air pressure.

Deposition from the downstream nozzle showed some increase as atomizing air pressure decreased from 90 to 70 psig. Deposits from the upstream nozzle were greater at the high upstream injection rates used.

Performance of Other Limes. As noted, all the parametric test results discussed so far in this section used the pressure hydrated dolomitic lime (PHDL) supplied by the Rockwell Lime Co. However, four samples of lime from other sources were tested, as shown in Table 5-8. The first group of tests indicated in Table 5-8 used the same PHDL from Rockwell Lime Co. as noted above, and these data are included for comparison. The other four samples were a wet slaked calcitic lime as used at the nearby Sims Station, another sample of PHDL from U.S. Gypsum, and two other samples of hydrated calcitic lime that were obtained in dry form and individually slurried; one from U.S. Gypsum, the other from a local source.

Of these other lime samples, only the wet slaked calcitic lime appeared to perform better than the Rockwell PHDL. Not only were the SO_2 removal and lime utilization percentages higher, but the tendency to deposit solids in the

Table 5-7
EFFECT OF ATOMIZING AIR PRESSURE

Date	Duration (hr)	Gas		Nozzle						SO_2 Removal (%)	Lime Feed Ratio	Lime Utilization (%)	Duct Deposits (lb)		Remarks
		Velocity (ft/sec)	Temp d/s (°F)	Type		Fluid conc. (%)		Flow (gpm)							
				u/s	d/s	u/s	d/s	u/s	d/s				u/s	d/s	
3/3	2.8	30	160	5	5	L, 21	L, 21	.9-1.5	1.2	46	2.6	18	0	15	Atomizing air, d/s nozzle, 90 psig, 47 scfm
3/23	3.0	30	160	5	5	L, 21	L, 21	1.8-1.9	1.2	60	3.3	18	50	40	Atomizing air, d/s nozzle, 80 psig, 38 scfm
3/21	3.0	30	160	5	5	L, 21	L, 21	2.1-2.2	1.2	62	3.6	17	120	40	Atomizing air, d/s nozzle, 70 psig, 35 scfm

Table 5-8
PERFORMANCE OF OTHER LIMES

Date	Duration (hr)	Gas		Nozzle						SO_2 Removal (%)	Lime Feed Ratio	Lime Utilization (%)	Duct Deposits (lb)		Remarks
		Velocity (ft/sec)	Temp d/s (°F)	Type		Fluid conc. (%)		Flow (gpm)							
				u/s	d/s	u/s	d/s	u/s	d/s				u/s	d/s	
4/8	3.2	30	160	5	5	W	L, 15	0.8-0.9	1.3	25	0.91	27	0	135	PHDL from Rockwell Lime Co., baseline conditions
4/23	0.7	30	160	5	5	W	L, 15	1.4	1.1	31	0.88	35	ND	ND	PHDL from Rockwell Lime Co., baseline conditions, part of test
4/16	0.8	30	160	5	5	W	L, 15	1.4-1.6	1.15	26	0.84	31	ND	ND	PHDL from Rockwell Lime Co., baseline conditions, part of test
3/18	2.8	30	160	5	5	W	CL, 15	1.0-1.1	1.2	43	1.15	38	5	5	Wet slaked calcitic lime
4/20	3.0	30	160	5	5	W	CL, 15	1.5-1.6	1.2	38	0.94	40	20	5	Wet slaked calcitic lime
2/24	3.0	30	160	5	5	W	L, 15	1.3-1.4	1.3	30	0.88	34	10	200	PHDL from US Gypsum, O_2 analyzer inop., assume O_2 5.5/7.5%
3/19	3.0	30	160	5	5	W	L, 15	1.0-1.2	1.2	22	0.86	25	5	240	PHDL from US Gypsum, O_2 analyzer inop., assume O_2 5.5/7.5%
3/26	2.9	30	160	5	5	W	L, 15	0.8-1.0	1.2	28	1.02	28	0	60	Calcitic lime hydrate, local source
3/27	2.8	30	160	5	5	W	L, 15	0.4-0.8	1.5	34	1.08	31	0	240	Calcitic lime hydrate, local source
4/4	3.1	30	160	5	5	W	L, 15	0.7-0.9	1.1	28	0.98	29	0	30	Calcitic lime hydrate from US Gypsum

TB 018 11-2487(7) Rev 6 BLC

Legend: u/s = upstream
d/s = downstream
W = water
L = PHDL
CL = wet slaked calcitic lime

Part 2

duct appeared to be significantly less. For these reasons, the wet slaked calcitic lime was subsequently used in most of the duration tests that are described in Section 5.2.

Miscellaneous Tests. A number of miscellaneous tests were conducted to obtain preliminary information on various factors that seemed to have some possibility of significance. None of these experiments showed any important or significant effect, however. Table 5-9 gives these results, and each experiment is discussed briefly below.

Effect of Freshly Made Lime Slurry. On February 13, the performance of freshly made slurry was compared with the performance of a batch that was about 10 days old. The test was started in the usual manner using the older slurry from the large feed tank. The feed pump suction was then shifted to a barrel containing freshly made lime slurry having the same concentration as the older batch. Table 5-9 shows that no significant change in removal or utilization was observed.

Effect of Adding Organic Acid to Lime Slurry. After the barrel had been refilled once or twice for the test described above, a gallon of 4 percent acetic acid (vinegar) was added to the slurry in the barrel to test the effectiveness of an organic acid in promoting SO_2 removal. As can be seen in Table 5-9, no significant change in removal or utilization was observed from the acetic acid.

Effect of Adding Caustic to Lime Slurry. Two trials in which caustic was added to a small batch of lime slurry during a test failed to show any significant effect on SO_2 removal beyond that expected from the increase in LFR resulting from the added alkali. Table 5-9 shows the results.

The absence of any observable improvement in removal from the caustic suggests that dissolution of lime is not a rate determining step in the capture of SO_2 under the conditions of this test.

Table 5-9
MISCELLANEOUS TESTS

Date	Duration (hr)	Gas Velocity (ft/sec)	Gas Temp d/s (°F)	Nozzle Type u/s	Nozzle Type d/s	Nozzle Fluid conc. (%) u/s	Nozzle Fluid conc. (%) d/s	Nozzle Flow (gpm) u/s	Nozzle Flow (gpm) d/s	SO_2 Removal (%)	Lime Feed Ratio	Lime Utilization (%)	Duct Deposits (lb) u/s	Duct Deposits (lb) d/s	Remarks
EFFECT OF FRESHLY MADE LIME SLURRY															
2/13	0.5	30	170	5	5	W	L, 8.4	0.7-0.9	1.3	18.4	0.47	39 1	—	—	Lime slurry made up on 2/3
2/13	0.7	30	170	5	5	W	L, 8.3	0.7-0.8	1.2	18.7	0.42	44 5	—	—	Fresh slurry fed from barrel
2/13	0.3	30	170	5	5	W	L, 8.3	0.7-0.8	1.2	17.7	0 42	42 1	0	195	Vinegar (1 gal, 4%) added to barrel
EFFECT OF ADDING CAUSTIC TO LIME SLURRY															
2/10	0.5	30	160	5	5	W	L, 15.6	1.25	1.15	43	1.6	27	—	—	Initial conditions,slurry 0.0450 eq OH/gal
2/10	0.5	30	160	5	5	W	L, 15.6	1.8	1.2	47	1.9	25	—	—	3 gal caustic (0.037 eq OH/gal) added to ~ 40 gal slurry
4/23	1 6	30	160	5	5	W	L, 15	1.4	1.08	31	0 88	35	—	—	Baseline conditions, slurry 0.0435 eq OH/gal
4/23	1.5	30	160	5	5	W	L, 15	1.5-1.6	1.17	35	1.04	33	—	—	Slurry with caustic, 0 0464 eq OH/gal
4/23	0.8	30	160	5	5	W	L, 15	1.3-1.5	1.1	33	0.92	36	75	400	Return to baseline conditions
EFFECT OF ADDING FLY ASH TO LIME SLURRY															
4/13	3.0	30	160	5	5	W	L+WS, 22	1.3-1.5	1.3	31	1.0	30	45	65	Waste solids mixed with lime slurry, alkalinity 0.045 eq OH/gal
4/24	3.0	30	160	5	5	W	L+FA, 18	1.1-1.2	1.3	26	0.7	40	20	140	Fly ash in lime slurry, digested at 160°F, alkalinity 0.0277 eq OH/gal

TB 018 11-2487(8) Rev 4 BLC

Legend: u/s = upstream
d/s = downstream
W = water
L = PHDL
CL = wet slaked calcitic lime
WS = waste solids
FA = fly ash

Part 2

Effect of Adding Fly Ash to Lime Slurry. On April 13, a slurry of waste solids and lime was injected. The alkalinity of the slurry that was used to calculate LFR was determined by titration.

On April 24, fly ash (without reaction products) was slurried with lime and digested overnight at 160°F. The objective was to discover whether the products of a reaction between lime and fly ash were more reactive than lime alone.

Neither of these experiments showed any large effect on SO_2 capture, and the high solids concentration in the slurry did not appear to decrease deposition in the duct.

Effect of Duct Deposits on SO_2 Removal. The test data do not appear to indicate that deposition in the duct had a significant effect on SO_2 removal. A linear regression analysis was made of the removal versus time data for several tests where the deposition was heavy and for two tests with no deposition (see Appendix B.6 for details). In most of the cases, removal increased about 2 percentage points after a 2-hour period. This effect of deposition is not entirely consistent, however. Removal decreased with time in two of the tests with heavy deposits, but it increased more than 2 percentage points in two other tests with heavy deposits.

Since the average removal from each test was used in analyzing the data, these small increases in removal will not affect the overall conclusions, even though they do contribute to the scatter of the data.

Effect of CZD Process on Nitrogen Oxide Removal. Although removal of nitrogen oxides (NO_x) was outside the scope of this project, some easily-carried-out analyses were made (see Appendix B.7). A "sniffer" gas sampling device supplied by Gas Tech was used: it is described in detail in Appendix D.7. The "sniffer" drew a fixed quantity of gas through a small glass sampling tube packed with solid adsorbent that changed color on contact with NO_x.

In tests carried out during November 6, 1986, and January 29, 1987, it was suggested that injection of PHDL slurry might be removing a significant percentage of the NO_x from the flue gas.

To verify these indications of NO_x removal, several analyses were performed with a Thermoelectron chemiluminescent analyzer on February 10, 1987 (see Appendix G). The analyses showed no indication of any significant removal of NO_x under various conditions of temperature and injection of PHDL slurry into the gas.

These findings deserve further study, particularly in consideration of the substantial NO_x removal measured during the Seward station testing (see Part 3).

5.1.3 Discussion of Parametric Tests

A goal of this project was to demonstrate 50 percent removal of SO_2 from flue gas under operating conditions that could be sustained for long periods of time without building up excessive deposits in the duct. These conditions were intended to simulate those in a full-scale utility plant as closely as possible. Although 50 percent SO_2 removal was achieved, prevention of excessive deposition in this small duct required that slurry injection rates be limited. This condition also required limiting gas velocities to levels below those found in full-scale plants.

Limitation of Slurry Injection Rate. With injection through two nozzles in series, flow must be less than 1.2 gpm through the downstream nozzle, and somewhat more than 1.2 gpm but less than about 1.5 gpm through the upstream nozzle. This limitation on slurry injection rates also limited gas flow through the system if the LFR was to be high enough to remove 50 percent of the SO_2 at incoming concentrations of 1,400 to 1,600 ppm.

The tests on March 10 and March 11 showed this performance. A 21 percent slurry was injected at about 1.5 gpm through the upstream nozzle and 1.2 gpm downstream with an incoming gas velocity of 30 ft/sec. Sulfur dioxide removal was close to 50 percent, LFR was about 2.9, and lime utilization was

18 percent. After over 13 hours of operation, 60 pounds of solids was deposited downstream from each nozzle. To lower the amount of deposition in the system, lower injection rates and thus lower gas flows would be required.

The gas velocity at 30 ft/sec in the above test is considerably less than the 50 to 60 ft/sec in most utility ducts. It should be emphasized, however, that the short distance between the atomizer and the duct wall in this small diameter (3 feet) test duct is the primary cause of this limitation on the gas flow. In a full-scale duct, spray nozzles could be mounted further from the duct walls and spray angles could be wider without causing wet droplets to impinge on the walls.

Lime Utilization. Two limiting cases govern the rate at which a droplet of slurry captures SO_2 from the gas. The first and fastest case is when diffusion through the gas film at the gas liquid interface limits the rate. The second and slowest case is when dissolution of lime is controlling the rate (References 5-1 and 5-2).

When the gas film controls the rate, the more rapid dissolution of lime keeps the pH in the aqueous phase high enough that the liquid film on the droplet surface is alkaline and SO_2 reacts as soon as it diffuses through the gas film. With the liquid phase alkaline, the magnesium hydroxide in dolomitic lime, which is less soluble than calcium hydroxide, will not dissolve and will therefore not react.

In the other extreme, when dissolution of lime is limiting, the SO_2 must dissolve in the liquid phase and reach the film surrounding the lime particles before it can react. In this case, with free SO_2 dissolved in the aqueous phase, the pH is low and the magnesium hydroxide can dissolve and react. Also, a larger percentage of the lime will react, giving improved utilization.

High removal of SO_2 from flue gas from medium- to high-sulfur coals requires lime slurry concentrations of 12 to 15 percent or higher. The high lime slurry concentrations tend to keep the liquid phase alkaline which suppresses the dissoultion of magnesium hydroxide. Thus, in these cases, high utilizations of dolomitic lime, even of the reactive PHDL, may be harder to achieve than with reactive CL. This may be why the wet slaked CL performed better than the PHDL.

5.2 DURATION TESTS

The goal of the duration tests was to operate the system continuously and demonstrate sustained 50 percent SO_2 removal. Operating continuously also provided the opportunity to identify any problems, such as wear of the nozzles, that might not be observed during shorter tests.

5.2.1 Approach

For the duration tests, the facility was operated 24 hr/day, beginning on May 7. Operations continued with as few interruptions as possible until June 15, when a forced outage on Unit 1 terminated the activity. Testing was resumed on July 22 until the program was completed on July 28.

It was intended that the system operate continuously from May 7 until May 19 when the electrostatic precipitator (ESP) tests began. After May 19, the system was to be operated to provide conditions desired for the ESP tests that were to be made each day. This involved daily shutdowns for duct cleaning (see below).

The performance of the CZD process during this period of around-the-clock activity is discussed below. Sulfur dioxide removal, lime utilization, deposition of solids in the duct, and the behavior of critical items of equipment were again the measures of performance. Section 7 describes the ESP tests that were carried out at the same time.

The parametric tests had shown that deposits would collect in the duct unless the slurry injection rate through the downstream spray nozzle was kept below 1.2 gpm. To have the LFR high enough to achieve 50 percent removal of SO_2 with this low injection rate, gas flow through the duct had to be limited. Therefore, to allow continuous operation with 50 percent SO_2 removal, the following baseline conditions were established:

- o Incoming gas velocity - 20 ft/sec
- o Downstream temperature - 160°F
- o Slurry injected through two nozzles in series, with flow through the downstream nozzle limited to 0.8 gpm

Since the wet slaked calcitic lime had performed somewhat better than the PHDL, it was used for all the tests where lime was injected from May 12 through July 25.

As noted, the intention was to operate the system as continuously as possible from May 5 to May 19, when the ESP tests began. At first, the duct was to be opened and inspected each day until the absence of deposits showed that the system could run for longer periods without stopping. Although the system did run for 15 to 20 hours at a time without deposition, a number of unexpected equipment problems made it advisable to stop each day long enough to inspect the duct and clean it out when necessary. These problems included frequent sticking of a lime slurry control valve, failure of sonic slurry flow meter FI-108 to read accurately at low flows, wear in the atomizer nozzles, and buildup of scale in the piping and nozzles. The last two problems were caused by the longer periods of operation. By the time all these problems had been diagnosed and corrected, it was time to begin the ESP tests.

The ESP tests normally began in the afternoon when the system was started with the gas flow at 20 ft/sec and brought to the desired temperature by injecting the lime slurry. These conditions were maintained overnight. In the morning, the gas flow and injection rate were increased to the rate for the test, and particulate sampling began. Particulate sampling usually required about 4 hours for two tests. Then the system was shut down; the duct was opened, inspected, and cleaned; and the next test was ready to start. This schedule limited operating periods to about 20 hours, with gas flow at 20 ft/sec for about 16 hours and at a higher velocity for 4 hours.

The higher slurry injection rates needed to maintain the desired temperature at gas flows of 40 to 50 ft/sec caused deposits to build up rapidly in the duct. These deposits had to be cleaned out after each episode.

Besides varying the gas velocity, tests were made at several downstream temperatures and at different concentrations of lime. As noted, most of these duration tests used the wet slaked calcitic lime as a 12 percent slurry. Table 5-10 summarizes these test conditions and the results.

In a number of tests nothing was injected; in others only water was injected. The primary purpose of operating at these conditions was to compare the particulate removal in the ESP with the removal when lime was injected. But these conditions also provided an opportunity to better characterize the system as to heat loss, air in-leakage, and performance of the sampling systems on the SO_2/O_2 monitor. These tests are described in Appendix B.

When the system was restarted on July 22 after having remained idle for the preceding month, a number of problems were encountered, including clogged filters and leaking solenoid valves in the sampling systems for the SO_2/O_2 monitor. In addition, the O_2 analyzer responded sluggishly and often seemed to read too low. Since these problems were not completely resolved during the 6 days of operation, the SO_2 and O_2 concentrations observed during this period are less reliable than in prior tests.

5.2.2 Results

Table 5-10 gives the duration test conditions and summarizes the results of the duration tests. These results supplement the information acquired from the earlier parametric tests, and several items are discussed below.

The apparent SO_2 removal when nothing was injected provides a good check on the SO_2/O_2 monitor and its sampling system. The negligible removals shown in the tests on May 31, June 1; June 7, June 8; and June 13, June 14 are evidence that the monitoring system was working well. The 3 percent SO_2 removal shown on July 26 indicates that the concentration measurements were less accurate at that time.

Table 5-10

LONG DURATION TESTS - SUMMARY OF RESULTS

Date	Duration (hr)	Gas Velocity (ft/sec)	Gas d/s Temp. (°F)	Nozzle Loc/Type[a] u/s	Nozzle Loc/Type[a] d/s	Nozzle Fluid Conc. (%)	Nozzle Flow (gpm)[b]	SO_2 Removal (%)	Lime Feed Ratio	Lime Utilization (%)	Duct Deposits (lb)	Remarks
Dolomitic Lime (PHDL)												
5/7, 8	17.7	20	160	1/5	3/5	L, 15	0.6-1.3 0.8	41 50	1.8 2.3	23 22	Fair, 120	
5/8, 9	15.3	20	160	1/5	3/5	L, 19.6	0.4-1.0 0.8-0.9	47 46	2.7 2.6	17 17	Fair, 140	Increased lime conc. to 19.6%
5/9,10,11	Total 34.9	20	160 170 150	1/5	3/5	L, 19.6	0.8-1.2 0.8-1.0	53[c] 44 64	2.6 2.6 2.6	21 17 24	Fair, 420	Concentrated lime, vary downstream temperature
5/11,12	20	20	160	1/5	3/5	L, 12	0.5-0.7 0.8	38 41 42	1.5 1.6 1.3	25 26 33	Heavy, 1040	Dilute lime, base conditions
Calcitic Lime												
5/12,13	15.5	20	160	1/5	3/5	CL, 11.1	0.5-1.0 0.8	42 41 44	1.0 1.1 1.2	42 39 37	Light, 60	Dilute calcitic lime, base conditions
5/13,14,15	Total 43	20 20 20	160 160 160	1/5	3/5	CL, 12	0.7-1.3 0.8	51 54 53	1.2 1.3 1.3	42 42 41	Excessive, 2300	Dilute calcitic lime, base conditions
5/15,16	15	20	160	1/5	3/5	CL, 12	0.7-1.3 0.8	46 46	1.2 1.2	39 37	Heavy, 760	Dilute calcitic lime, base conditions
5/16,17	17.5	20	170	1/5	3/5	CL, 12	1.0 0.4-0.5	15[d] 37 35	0.3 1.1 1.2	44 34 30	Light, 40	Increased downstream temperature
5/17,18	20.8	30	160	1/5	3/5	CL, 12	1.0-1.7 1.0-1.2	27[d] 53 52 48	0.6 1.5 1.5 1.1	46 36 34 42	Fair, 460	Increased gas velocity
5/18,19	8 13.7	20 20	160 150	1/5	3/5	CL, 12	0.6-0.9 0.7-0.8	37[c] 45	1.1 1.2	35 39	Light, 80	ESP testing began

Table 5-10 (Cont'd)

Date	Duration (hr)	Gas Velocity (ft/sec)	Gas d/s Temp. (°F)	Nozzle Loc/Type[a] u/s d/s	Nozzle Fluid Conc. (%)	Nozzle Flow (gpm)[b]	SO_2 Removal (%)	Lime Feed Ratio	Lime Utilization (%)	Duct Deposits (lb)	Remarks
Calcitic Lime (Cont'd)											
5/19,20	20	20	160	1/5 3/5	CL, 12	0.7-1.1 0.8	19[d] 42 46 48	0.6 1.3 1.4 1.3	30 33 32 36	Clean, 30	
5/20 5/21	14 5	20 40	160	1/5 3/5	CL, 12	0.7-2.0 0.8-1.5	48 59[e]	1.3 1.3	38 46	Heavy, 320	
5/21 5/22	14 5	30 50	160	1/5 1/13 3/5	CL, 12	1.3-2.7 1.1-1.5	59 58[e]	1.3 1.4	44 43	Excessive, 1000	
5/22,23	14.5 4	20 30	160	1/5 3/5	CL, 12	0.8-1.9 0.8-1.2	48 63[e]	1.4 1.6	36 40	Fair, 210	
5/23,24	19.3	20	160	1/5 3/5	CL, 12	0.7-0.8 0.8	19[d] 37 35 35	0.6 1.3 1.2 1.2	31 27 30 30	Light, 70	
5/24,25	14 3.3	20 50	160	1/5 1/13 3/5	CL, 12	0.8-2.3 0.8-1.5	37 34 46[e]	1.3 1.2 1.4	28 28 34	Fair, 230	
5/25,26	14.5 3.5	20 50	160	1/5 1/13 3/5	CL, 12	0.3-2.2 0.8-1.5	40 49[e]	1.1 1.1	36 46	Heavy, 340	
5/26,27	5.5 8.5 4.5	20 20 50	160 150 150	1/5 1/13 3/5	CL, 11.7	1.5 total 1.8 total 4.5 total	44 61 59[e]	1.0 1.2 1.2	42 52 50	Heavy, 340	
5/27,28	12.5 3.4 2	20 50 50	170 170 150	1/5 1/13 3/5	CL, 12	1.6 total 3.8 4.5	39 44[e] 61[e]	1.1 1.1 1.4	36 42 45	Heavy, 820	
5/28,29	13.3 4.3	20 50	160	1/5 3/5	CL, 11.7	0.9-2.6 0.7-1.5	40 43[e]	1.4 1.6	29 27	Fair, 290	
5/29,30	15	20	160	1/5 3/5	CL, 12	Total 1.6-1.8	51 50 50	1.2 1.1 1.1	42 44 45	Clean, 20	

Table 5-10 (Cont'd)

Date	Duration (hr)	Gas Velocity (ft/sec)	Gas d/s Temp. (°F)	Nozzle Loc/Type[a] u/s	Nozzle Loc/Type[a] d/s	Nozzle Fluid Conc. (%)	Nozzle Flow (gpm)[b]	SO_2 Removal (%)	Lime Feed Ratio	Lime Utilization (%)	Duct Deposits (lb)	Remarks
5/31, 6/1	14	20	290	-	-	-		0.4	-	-		No injection
	8	30		-	-	-		(-)0.1	-	-		
6/1, 2	15.5	20	160	1/5	3/5	Water	1.6	1.5	-	-	Clean,	Water injection only
	3	30					2.2	1.2	-	-	20	
6/2, 3	13.5	20	160	1/5	3/5	CL, 17	1.6	61	1.8	34	Clean,	Higher lime
	4.5	30					2.8	68	1.8	36	20	concentration
6/3, 4	8.5	20	160	1/5	3/5	CLR, 20	1.6	64	1.4	47	Heavy,	Lime plus
	3.5	50					4.6	64	1.6	40	580	recycled solids
6/4, 5	13.5	20	160	1/5	3/5	CLR, 20	1.6	62	1.2	50	Light,	Lime plus
	4.5	30					3.0	72	1.5	48	160	recycle solids
6/5, 6	10	20	160	1/5	3/5	CL, 14	1.6	63	1.2	52	Very heavy,	Maximum gas velocity
	4	56		1/13	3/5		6.4	64	1.7	37	3600	
6/7, 8 No injection	16.5	20	apprx. 280	-		-	-	-	0.2	-	-	
	6	50						(-)0.4				
6/8, 9	16	20	160	1/5	3/5	Water	1.2	1.4	-	-	Heavy,	Water only injected; boiler upset, mill problem
	5	50		1/13	3/5		3.5	(-)0.1	-	-	640	
6/9, 10	14	20	160	1/5	3/5	Water	1.4	1.4	-	-	Heavy,	Water only injected;
	6	50		1/13	3/5		3.5	0.4	-	-	640	repeat of test 6/8, 9
6/10, 11	14	20	160	1/5	3/5	CL, 17	1.7	67	1.7	39	Very heavy,	Higher lime
	4.5	50		1/13	3/5		5.2	73	2.0	36	1200	concentration
6/11, 12	13	20	160	1/5	3/5	CL, 12	1.5	52	1.0	52	Heavy,	$CaCl_2$ added to give
	2	50					3.9	53	1.1	48	880	(Cl^-) 500 ppm
	2	56					4.6	52	1.1	46		
6/12, 13	8	20	160	1/5	3/5	CL, 12	1.7	58	1.3	45	Very heavy,	Temperature profiles
	6	30					2.9	62	1.4	46	1100	measured in duct
	5	50					4.7	55	1.2	45		
6/13, 14 No injection	16	20	apprx. 300	-		-	-	-	(-)0.8	-	-	
	5	50						(-)0.9				
6/14, 15	9	20	160	1/5	3/5	Water	1.4	1.5	-	-		Water injection only; test interrupted at 0200 hours by forced outage of Unit 1

Table 5-10 (Cont'd)

Date	Duration (hr)	Gas Velocity (ft/sec)	Gas d/s Temp. (°F)	Nozzle Loc/Type[a] u/s	Nozzle Loc/Type[a] d/s	Nozzle Fluid Conc. (%)	Nozzle Flow (gpm)[b]	SO_2 Removal (%)	Lime Feed Ratio	Lime Utilization (%)	Duct Deposits (lb)	Remarks
7/22, 23	3	50	160	1/5	3/5	Water	3.0	1.2	-	-	Heavy, 420	Water only injected
7/23, 24	10	20	160	1/5	3/5	CL, 12	1.6	51	1.1	47	Very heavy,	Upstream nozzle not
	1.5	50	160	1/5	3/5	CL, 12	4.2	53	1.3	42	1280	aligned properly
	1	50	160	1/5	3/5	CL, 12	3.9	49	1.2	42		
	2	50	160	1/5	3/5	CL, 12	4.5	59	1.4	43		
	1	50	160	1/5	3/5	CL, 12	4.5	64	1.3	48		
	2	30	160	1/5	3/5	CL, 12	2.5	66	1.1	60		
7/24, 25	10	20	160	1/5	3/5	Water	1.1	10	-	-	Heavy,	SO_2 and O_2 concns.
	3.5	30	160	1/5	3/5	Water	2.1	-	-	-	360	not reliable: sample
	3.5	30	160	1/5	3/5	CL, 12	2.5	-	-	-		lines clogged, SO_2 monitor inoperative
7/26	2.5	30	160	1/5	3/5	None	-	3.0	-	-		No injection
	2	50	160	1/5	3/5	None	-	3.0	-	-		
	3	30	160	1/5	3/5	None	-	3.0	-	-		
7/26, 27 low	2.3	20	190	1/5	3/5	PHDL, 15	1.2	17	1.4	12	Very heavy,	SO_2 removal very
	2	20	190	1/5	3/5		1.1	26	1.2	22	760	at start
	3.5	20	160	1/5	3/5		1.6	47	1.6	29		
	2	30	160	1/5	3/5		3.0	56	2.1	27		
	1.5	50	160	1/5	3/5		4.6	56	2.0	28		
7/27, 28	6	20	160	1/5	3/5	ML, 15	1.4	56	1.6	36	Heavy,	ML = Mixture of PHDL and calcitic lime
	2	20	160	1/5	3/5		1.5	62	1.9	33	440	Water to upstream
	3	30	160	1/5	3/5		1.1	38	0.8	48		nozzle, lime slurry
	2	50	160	1/5	3/5		1.8	34	0.7	53		inj. downstream only

(a) Description of the nozzle types can be found in Table 5-1
(b) Top number (or range) in this column is upstream; bottom number is downstream; a single entry is combined flow for both nozzles
(c) SO_2 removal, LFR, and lime utilization for each temperature
(d) SO_2 removal, LFR, and lime utilization with lime injection through d/s nozzle only
(e) SO_2 removal, LFR, and lime utilization for higher gas velocity

Legend:

u/s = upstream
d/s = downstream
L = slurry of PHDL
CL = slurry of calcitic lime
CLR = slurry of calcitic lime and recycled solids

The 1 to 2 percent SO_2 removal shown with water only injected on June 1, June 2; June 14, June 15; and July 22, July 23 is probably due to SO_2 capture by bicarbonate in the water. Residual alkaline material on the inner surface of the duct, and the ESP may have captured some SO_2 at these low temperatures also.

The heavy deposition in the duct on May 12 and on May 13 through May 15, compared with that on May 19 and May 20, is due in part to the longer period of operation on May 13 through May 15. Reduced atomizing air flow was another factor. Air flow to both nozzles was lower during the first two tests than it was on May 19 and May 20 and also lower than it had been in earlier tests. The reduced flow was a result of lime scale that accumulated in the air passages of the spray nozzles. This accumulation reduced the air flow from 48 scfm down to 41 scfm in each nozzle. Washing the nozzles out with vinegar on May 16 restored the air flow and that contributed to keeping the duct clean on May 19 and May 20.

Comparison of the data from May 19 to May 20 and May 29 to May 30 with those of May 20 to May 21 and May 21 to May 22 shows how higher rates of injection increased deposition.

Increasing the lime concentration decreased deposition, as found earlier. The test on May 8 should be compared with the ones on May 11 and May 12.

Nozzle wear, which had not been detected up to this point, now began to appear with the longer periods of operation. On May 16, it was observed that the target bolts on both nozzles were obviously eroded. Slurry entered these nozzles through an orifice whose axis is perpendicular to the nozzle center line. The slurry stream impinged onto the flat end of the target bolt and the spray mixed with the air that jetted in along the nozzle centerline (see Figure 3-3). When the target bolts were replaced with bolts having hardened surfaces, no further wear was observed.

Besides the target bolts, the inside edges of the nozzle tip, which had been sharp, were found to be rounded. The worst worn tip was replaced with a new one.

No wear was detected on the slurry orifice in the nozzles.

The fact that the slurry cyclones removed nearly all of the plus 100 mesh grit from all the limes used in these tests is very likely the main reason erosion in the nozzles was not found to be more severe.

REFERENCES

5-1. Partridge, G. P., Davis, W. T., Crence, R. M., and Reed, G. D., "Mathematical Model for SO_2 Removal in a Spray Dry Absorber," Combustion Flue Gas SO_2 and NO_x Control Symposium, American Institute of Chemical Engineers National Meeting, Houston, Texas, March 29 - April 2, 1987.

5-2. Kinzey, M. and Harriott, P., "Effects of Droplet Size and Residual Water on SO_2 Removal in a Spray Dryer," School of Engineers, Olin Hall, Cornell University, Ithaca, NY (1987).

Section 6

ANALYSIS OF SO_2 REMOVAL DATA

As pointed out in Section 5, it was not possible to isolate most of the variables in this process to determine their effects separately. Therefore regression analysis was used to better find out how the various parameters affect the removal of SO_2. This section describes the regression analysis: the program, the variables selected, and the results for both pressure hydrated dolomitic lime (PHDL) and freshly slaked calcitic lime (CL).

6.1 APPROACH

For the purpose of the regression analysis, data from the parametric tests were combined with those from the duration tests. For the most part, the test data using PHDL were from the parametric tests, while those for CL came from the duration tests. Appendix A tells how the data were organized for this purpose.

As described in the test procedure, the inlet gas temperature and the inlet SO_2 concentration could not be controlled, and they often varied significantly during the 3 hours or longer that a test lasted. Moreover, the measured concentrations of SO_2 and oxygen were sometimes subject to some uncertainty depending on the state of the gas sampling system. These random variations obscured the effects of less influential variables such as incoming gas temperature and gas flow rate. For these reasons, regression analysis was used to provide a more detailed and more reliable analysis of the data than was possible by comparing results of different tests.

6.1.1 Regression Analysis Program

The linear regression program that was employed is part of the Lotus 1-2-3, Release 2 software package. This regression program computes the best values of coefficients and the constant for an equation that expresses the value of a dependent variable as a series of terms made up of selected independent variables:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 \ldots$$

Here Y is the dependent variable or some function of it. The a's are coefficients calculated by the program. The X's are independent variables or functions of these variables that are calculated from the data. The best values of the coefficients (a_0, a_1, etc.) are such that the sum of the squared differences between the observed and calculated values of Y for each data point is minimized. (A data point is a complete set of one Y and the corresponding X's.)

The program was also set up to calculate the following:

- o Square of correlation coefficient, R^2, as a measure of how well the data "fits" (1 is a perfect fit; 0 is completely random)
- o Significance of R^2 compared to a previous value
- o The value of Y corresponding to the average values of each X
- o The standard error of: each coefficient, the standard X, and the Y estimate

6.1.2 Variables Selected

The fraction of SO_2 removed, RMVL, is the principal dependent variable examined. Seven independent variables were selected for analysis:

- o Lime feed ratio, LFR
- o Outlet gas temperature, Tout
- o Lime slurry concentration, OH, lb eq OH/gallon
- o Incoming gas temperature, Tin
- o SO_2 concentration of incoming gas, SO_2, dry ppmv
- o Gas flow rate, GAS, % of FI 100 scale reading (54% corresponds to 30 ft/sec)
- o Lime slurry feed rate, FR, total gallons/min to both nozzles

Actually these variables were not truly independent as LFR is proportional to the ratio of four others: (FR)(OH)/(GAS)(SO_2). Also FR was often varied with Tin to keep Tout constant during the course of a test.

Other variable factors not included in the analysis are:

- Residence time
- Lime slurry concentration in weight percent
- Nozzle type
- Atomized droplet size
- Atomizing air pressure and flow. The pressure was kept constant at 90 psig, and the flow depended on the nozzle and/or nozzle orifice

The data were organized into three separate data sets and each set was analyzed separately. These sets were: PHDL injected through one nozzle, PHDL injected through two nozzles, and freshly slaked CL injected through two nozzles.

Both rational and empirical expressions were examined to correlate the data. The rational expressions have the following characteristics:

- SO_2 removal can not exceed 100 percent
- SO_2 removal is zero when LFR is zero

6.2 ANALYSIS

6.2.1 <u>PHDL in One Nozzle</u>

The data set for PHDL slurry injected through one nozzle is shown in Table 6-1. The data on each line are average values for the run ending at the RUN END TIME shown. The PHDL was injected through the downstream nozzle, and water was injected through the upstream nozzle to control the outlet gas temperature.

The rational expression that provided the best fit (R_2 = 0.783) for these data is:

Table 6-1
CAMPBELL SINGLE-STAGE PHDL INJECTION DATA

RUN DATE	RUN END TIME	SO2 RMVL	LIME UTIL	LFR	LIME FEED RATE (gpm)	WATER INJ RATE (gpm)	LIME CONC (#eq/gal)	INLET TEMP (F)	OUTLET TEMP (F)	INLET SO2 (ppmv	GAS FLOW (%)
01/06	16:00	23.4%	31.1%	0.753	1.04	0.80	0.0437	310	183	1559	50
01/08	16:23	20.7%	31.8%	0.651	1.26	1.50	0.0437	296	180	1647	67
01/14	14:05	24.2%	27.1%	0.896	1.22	0.80	0.0437	301	180	1526	54
01/15	16:50	21.7%	25.7%	0.844	1.12	1.00	0.0437	306	180	1488	54
01/16	16:10	18.4%	28.4%	0.646	1.15	1.40	0.0435	293	174	1520	71
01/28	14:00	38.9%	29.5%	1.319	2.09	0.70	0.0431	331	175	1755	54
01/29	14:57	23.8%	28.9%	0.825	1.17	0.78	0.0431	280	166	1570	54
01/30	14:18	31.2%	38.6%	0.809	1.17	1.20	0.0431	294	155	1600	54
01/31	14:03	37.2%	33.9%	1.099	1.57	1.22	0.0431	325	166	1586	54
02/02	15:24	40.4%	37.9%	1.066	1.52	0.80	0.0431	289	155	1584	54
02/05	12:45	20.5%	21.4%	0.962	1.09	1.00	0.0450	287	166	1515	54
02/07	14:45	26.3%	28.8%	0.916	2.01	1.20	0.0450	299	180	1524	90
02/10	12:04	24.8%	25.7%	0.966	1.26	0.80	0.0450	290	180	1513	54
02/10	12:34	15.1%	17.5%	0.865	1.17	0.80	0.0450	290	217	1567	54
02/27	14:00	42.3%	43.8%	0.967	1.27	1.42	0.0433	302	150	1464	54
03/02	17:35	30.5%	22.8%	1.341	1.29	1.23	0.0593	300	160	1472	53
03/04	15:40	47.1%	35.5%	1.326	1.20	1.30	0.0593	290	150	1384	54
04/06	14:38	27.8%	24.7%	1.132	1.09	0.90	0.0580	276	160	1440	54
04/08	15:55	25.0%	27.9%	0.898	1.29	0.88	0.0416	280	160	1540	54
04/09	15:10	42.9%	49.9%	0.860	1.20	1.38	0.0416	281	140	1501	54
04/11	14:15	21.9%	40.4%	0.541	1.27	1.10	0.0217	302	160	1303	54
04/16	11:45	26.4%	30.0%	0.879	1.20	1.50	0.0440	310	160	1550	54
04/16	12:15	34.7%	37.9%	0.916	1.35	1.42	0.0440	311	160	1567	54
04/16	12:50	30.6%	35.2%	0.870	1.20	1.55	0.0440	313	160	1567	54
04/23	13:10	30.9%	35.1%	0.880	1.08	1.40	0.0435	313	160	1374	54
04/23	14:40	34.9%	33.4%	1.046	1.17	1.50	0.0464	316	160	1338	54
04/23	15:40	32.8%	34.0%	0.964	1.17	1.53	0.0464	317	160	1361	54
MINIMUM =		15.1%	17.5%	0.541	1.04	0.70	0.0217	276	140	1303	50
MAXIMUM =		47.1%	49.9%	1.341	2.09	1.55	0.0593	331	217	1755	90
AVERAGE =		29.4%	31.7%	0.935	1.28	1.15	0.0447	300	167	1512	56

(a) PHDL injected downstream, water injected upstream.
(b) Data are average values for the run ending at the RUN END TIME shown.
(c) SO2 concentration is on a dry basis.

$$\text{RMVL} = 1 - e^{-0.1234A}$$

$$\text{where } A = \frac{\left(1 - e^{-LFR}\right)(\text{Tin})}{(\text{Tout} - 125)^{0.5}} \qquad \text{eq. M11-2a}$$

Here LFR is not used directly but is expressed as $1 - e^{-LFR}$ which reflects its effect more realistically than a simple linear relationship (see Appendix F-8). Also, the outlet gas temperature term has been modified to $(\text{Tout} - 125)^{0.5}$. (Tout - 125) approximates the approach to saturation temperature (AST) which is a principal variable in spray dry FGD systems. (AST is sometimes substituted for [Tout - 125] in this section.) The exponent 0.5 was used to reduce the variable's influence in the equation at its higher values, and was determined empirically. The equation number, eq. M11-2a, identifies the case variation number for reference.

A plot of calculated versus actual SO_2 removal is shown in Figure 6-1. This plot gives a visual indication of the scatter in the data and how well the equation fits. The straight line is the locus of points having identical calculated and measured values. It is not the best line through the points shown. This plot shows a slight bias in that the calculated removal is high at low actual removal, and low at high actual removal.

Predictions of SO_2 removal versus LFR at ASTs of 35°F and 55°F for this equation are shown in Figure 6-2.

When an SO_2 term is added to the numerator of eq. M11-2a, R^2 decreases to 0.758 indicating a poorer fit of the data. Changing $(\text{Tout} - 125)^{0.5}$ to $(\text{Tout} - 125)^{1.0}$ decreases R^2 to 0.679, indicating a significantly poorer fit.

The empirical expression that provided the best fit ($R^2 = 0.827$) for these data is:

$$\begin{aligned}\text{RMVL} = {} & 0.167 + 0.0619\,(1 - e^{-LFR}) - 0.0516\,(\text{Tout} - 125)^{0.5} \qquad \text{eq. M3-3}\\ & + 2.98(\text{OH}) + 0.000947(\text{Tin}) - 3.66 \times 10^{-5}(SO_2)\\ & - 0.00237(\text{GAS}) + 0.147(\text{FR})\end{aligned}$$

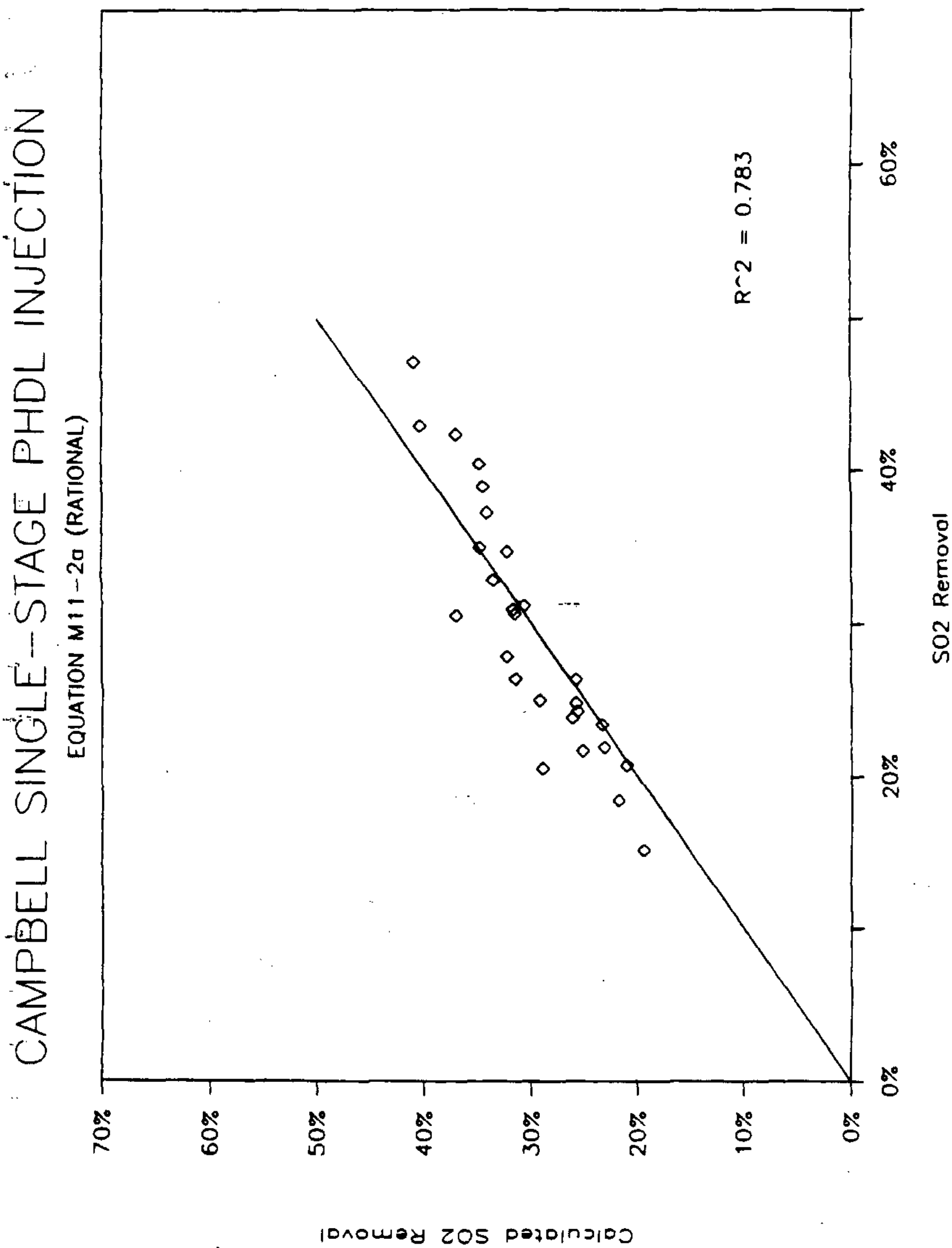


Figure 6-1 Calculated vs Actual SO_2 Removal Using Equation M11-2a

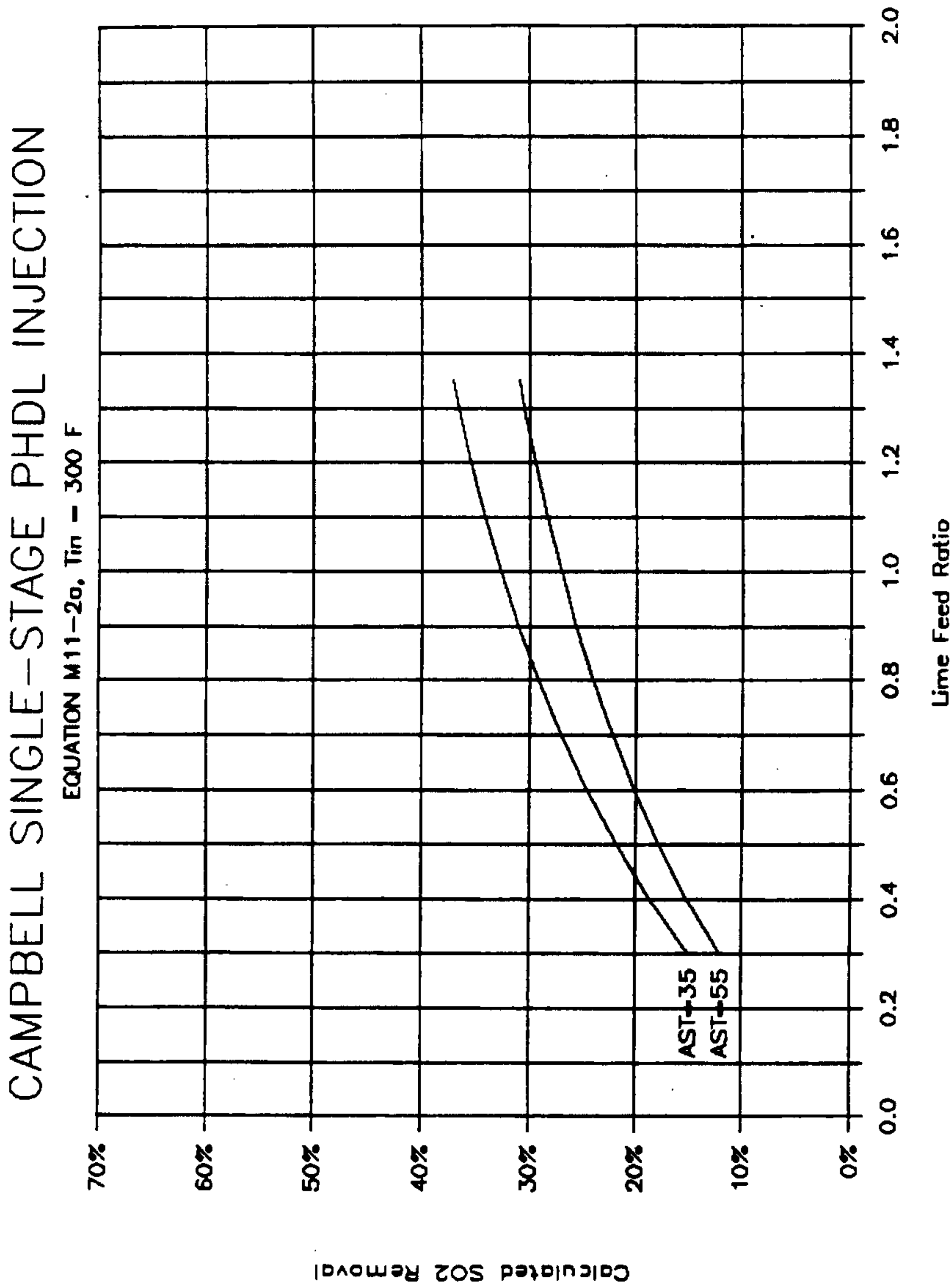


Figure 6-2 Prediction of SO_2 Removal vs LFR for AST of 35°F and 55°F Using Equation M11-2a

This case uses all seven of the independent variables. The plot of calculated versus actual SO_2 removal is shown in Figure 6-3. This plot shows less bias than the plot for the rational expression.

6.2.2 PHDL in Two Nozzles

The data set for PHDL injected through two nozzles is shown in Table 6-2.

The rational expression that provided the best fit ($R^2 = 0.723$) for these data is:

$$RMVL = 1 - e^{-0.0874B}$$

$$\text{where } B = \frac{(1 - e^{-LFR})(Tin)}{(Tout - 125)} \qquad \text{eq. D15-2a}$$

A plot of calculated versus actual SO_2 removal is shown in Figure 6-4. This plot shows a similar bias as the plot for PHDL injected through one nozzle.

Adding an SO_2 term to the numerator decreased R^2 to 0.714; adding an SO_2 term to the denominator decreased R^2 to 0.624. Substituting $(Tout - 125)^{0.5}$ for (Tout - 125) decreased R^2 to 0.650.

Predictions of SO_2 removal versus LFR at ASTs of 35°F and 55°F for this equation are shown in Figure 6-5. Figure 6-6 shows predictions of SO_2 removal at a fixed AST of 35°F with inlet temperature as a parameter.

The empirical expression that provided the best fit ($R^2 = 0.848$) for these data is:

$$\begin{aligned} RMVL = & -0.236 + 0.1625\,(1 - e^{-LFR}) - 0.1093\,(Tout - 125)^{0.5} \\ & + 3.28(OH) + 0.00268(Tin) + 1.59 \times 10^{-4}(SO_2) \\ & - 5.05 \times 10^{-4}(GAS) + 0.0188(FR) \qquad \text{eq. D3-3} \end{aligned}$$

The plot of calculated versus actual SO_2 removal is shown in Figure 6-7. Little bias is shown in this plot. Figure 6-8 shows predictions of SO_2 removal versus LFR at ASTs of 35°F and 55°F for this equation.

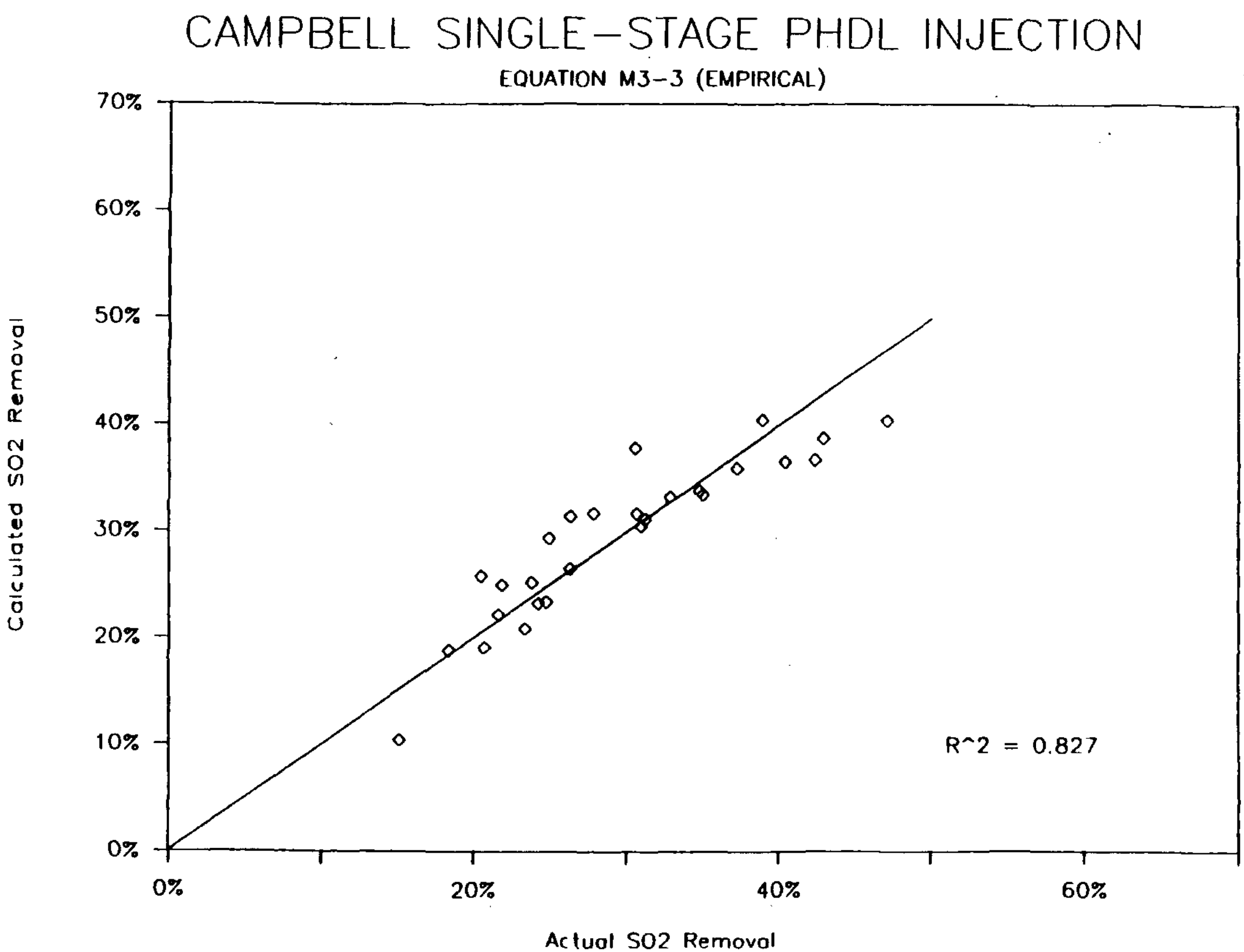


Figure 6-3 Calculated vs Actual SO_2 Removal Using Equation M3-3

Table 6-2
CAMPBELL TWO-STAGE PHDL INJECTION DATA

RUN DATE	RUN END TIME	SO2 RMVL	LIME UTIL	LFR	LIME FEED RATE (gpm)	LIME CONC (#eq/gal)	INLET TEMP (F)	OUTLET TEMP (F)	INLET SO2 (ppmv)	GAS FLOW (%)
02/05	14:45	35.4%	21.2%	1.675	2.23	0.0450	290	165	1540	54
02/05	15:45	46.5%	20.3%	2.295	2.54	0.0450	291	156	1502	54
02/05	16:20	49.5%	26.2%	2.158	1.89	0.0450	294	155	1478	48
02/06	13:00	43.5%	25.4%	1.717	2.59	0.0450	302	163	1673	54
02/06	15:34	47.3%	23.6%	2.001	2.51	0.0450	306	160	1680	48
02/10	13:04	27.3%	16.9%	1.615	2.13	0.0450	290	180	1527	54
02/10	13:34	43.0%	25.7%	1.674	2.40	0.0450	290	160	1473	54
02/10	14:32	47.4%	25.2%	1.883	2.04	0.0477	290	160	1497	48
02/11	13:21	52.2%	31.3%	1.671	4.06	0.0450	280	156	1583	90
02/12	14:18	39.9%	45.4%	0.879	4.39	0.0220	303	157	1622	90
02/18	14:15	29.5%	36.4%	0.812	2.18	0.0226	286	160	1566	54
02/19	16:10	42.2%	23.1%	1.825	2.48	0.0433	300	160	1497	54
02/20	15:35	49.5%	29.4%	1.688	1.18	0.0433	303	160	1569	26
02/25	15:40	46.5%	25.2%	1.852	2.55	0.0433	298	160	1537	54
02/26	12:30	45.5%	23.0%	1.987	2.55	0.0433	295	160	1434	54
03/03	14:10	46.1%	17.8%	2.586	2.38	0.0593	287	160	1406	54
03/07	12:45	45.0%	14.7%	3.067	2.82	0.0593	298	160	1403	54
03/07	13:45	48.1%	15.3%	3.151	2.54	0.0593	302	160	1331	54
03/10	16:45	50.1%	18.0%	2.789	2.55	0.0593	298	162	1403	54
03/21	13:10	61.8%	17.4%	3.544	3.17	0.0614	324	160	1414	54
03/23	15:00	59.6%	18.6%	3.246	3.02	0.0614	315	160	1471	54
03/24	14:40	57.5%	18.8%	3.073	3.04	0.0614	315	160	1566	54
03/28	14:10	47.7%	15.8%	3.025	2.97	0.0580	297	160	1467	54
04/01	15:20	35.0%	13.7%	2.203	0.88	0.0580	267	160	1331	24
04/10	16:15	39.3%	22.3%	1.761	3.22	0.0416	293	160	1468	72
04/14	17:55	38.0%	37.8%	1.006	2.60	0.0226	307	160	1503	54
04/15	16:10	42.5%	21.1%	2.018	1.72	0.0440	311	160	1447	36
05/07	23:30	41.3%	22.3%	1.851	1.59	0.0436	301	160	1358	36
05/08	06:00	51.5%	27.3%	1.888	1.63	0.0436	327	160	1365	36
05/08	22:30	46.9%	17.4%	2.700	1.67	0.0574	309	160	1387	36
05/09	08:00	45.5%	17.2%	2.661	1.59	0.0574	291	160	1327	36
05/10	00:10	46.8%	18.3%	2.568	1.52	0.0574	298	160	1360	36
05/10	07:40	60.1%	19.1%	3.194	1.95	0.0574	331	160	1363	36
05/10	12:15	50.0%	18.3%	2.739	1.69	0.0574	315	170	1360	36
05/10	17:45	43.5%	19.7%	2.214	1.37	0.0574	292	170	1374	36
05/11	00:55	64.0%	24.3%	2.637	1.63	0.0574	290	150	1366	36
05/12	13:05	40.6%	29.1%	1.395	1.50	0.0330	301	160	1371	36
07/27	00:20	17.0%	12.2%	1.402	1.23	0.0432	280	180	1455	36
07/27	02:50	25.8%	22.3%	1.159	1.11	0.0432	288	180	1560	36
07/27	06:20	47.0%	29.2%	1.612	1.61	0.0432	284	160	1626	36
07/27	09:55	56.4%	27.1%	2.084	2.96	0.0432	300	160	1543	54
07/27	12:00	55.5%	27.7%	2.006	4.60	0.0432	304	160	1528	88
MINIMUM =		17.0%	12.2%	0.812	0.88	0.0220	267	150	1327	24
MAXIMUM =		64.0%	45.4%	3.544	4.60	0.0614	331	180	1680	90
AVERAGE =		45.4%	22.9%	2.126	2.29	0.0478	299	162	1470	49

(a) PHDL injection only; no water injection.
(b) Data are average values for the run ending at the RUN END TIME shown.
(c) SO2 concentration is on a dry basis.

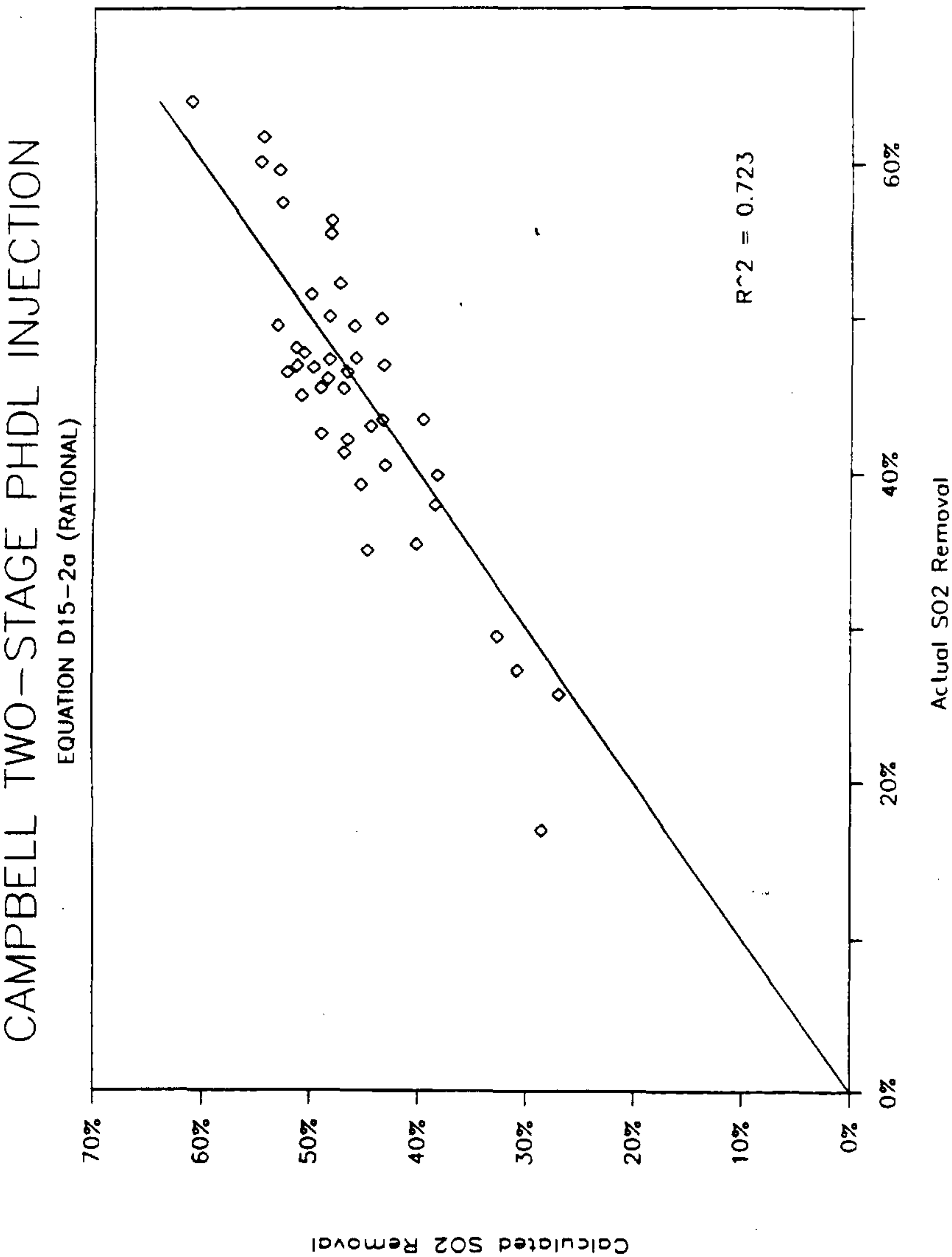


Figure 6-4 **Calculated vs Actual SO_2 Removal Using Equation D15-2a**

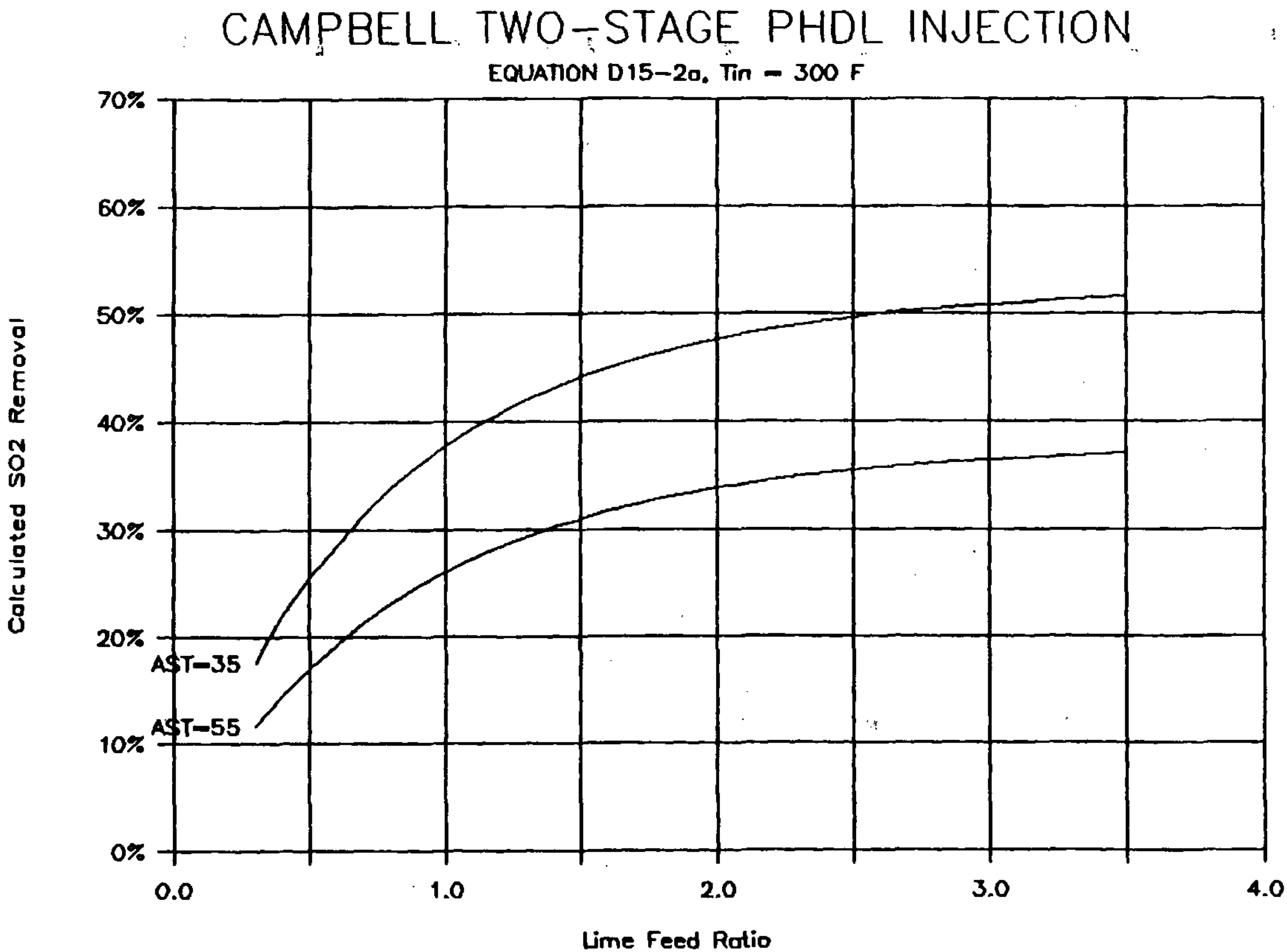


Figure 6-5 Prediction of SO_2 Removal vs LFR for AST of 35°F and 55°F Using Equation D15-2a

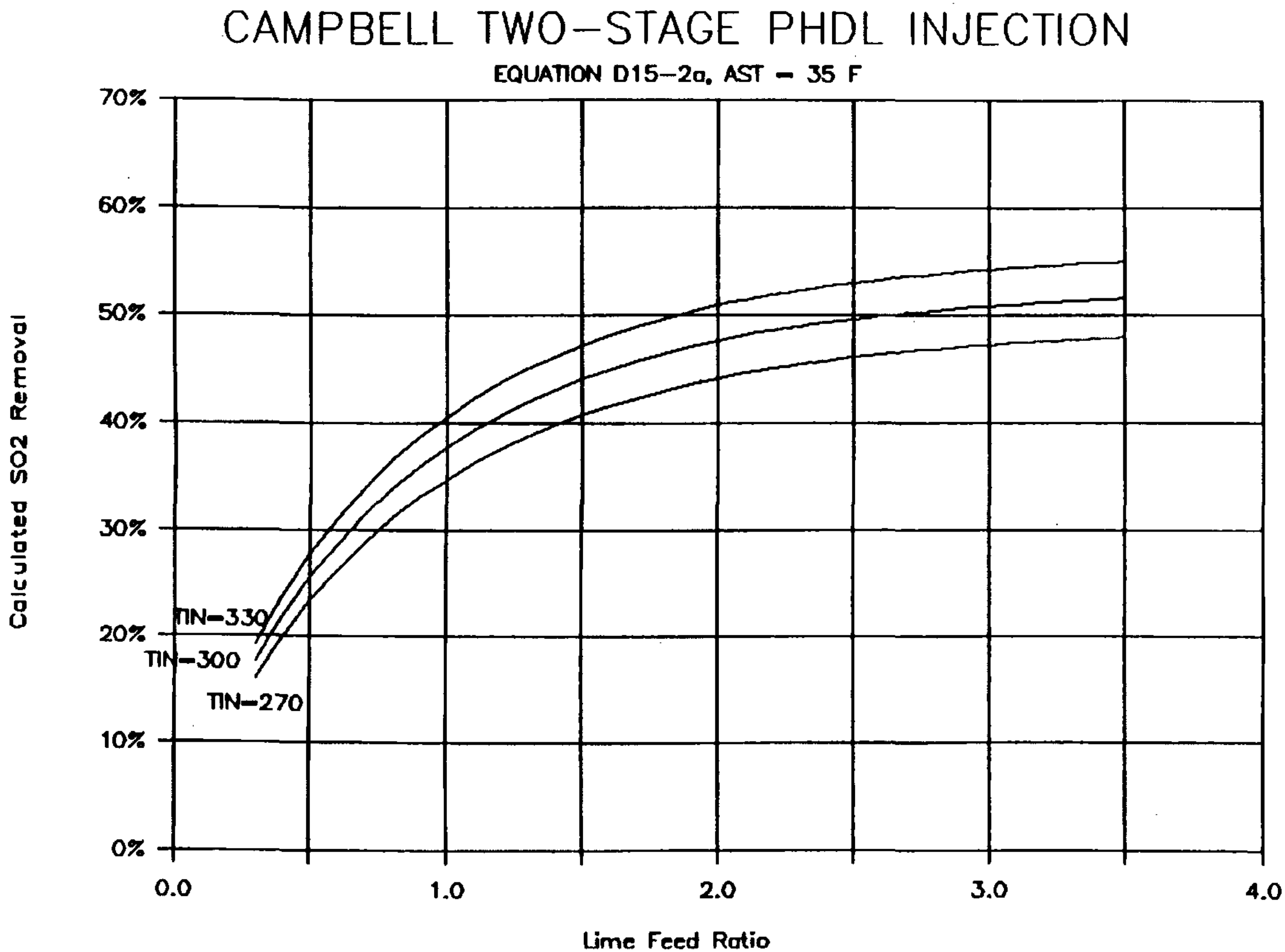


Figure 6-6 Prediction of SO_2 Removal vs LFR for Tin of 270°F, 300°F, and 330°F Using Equation D15-2a

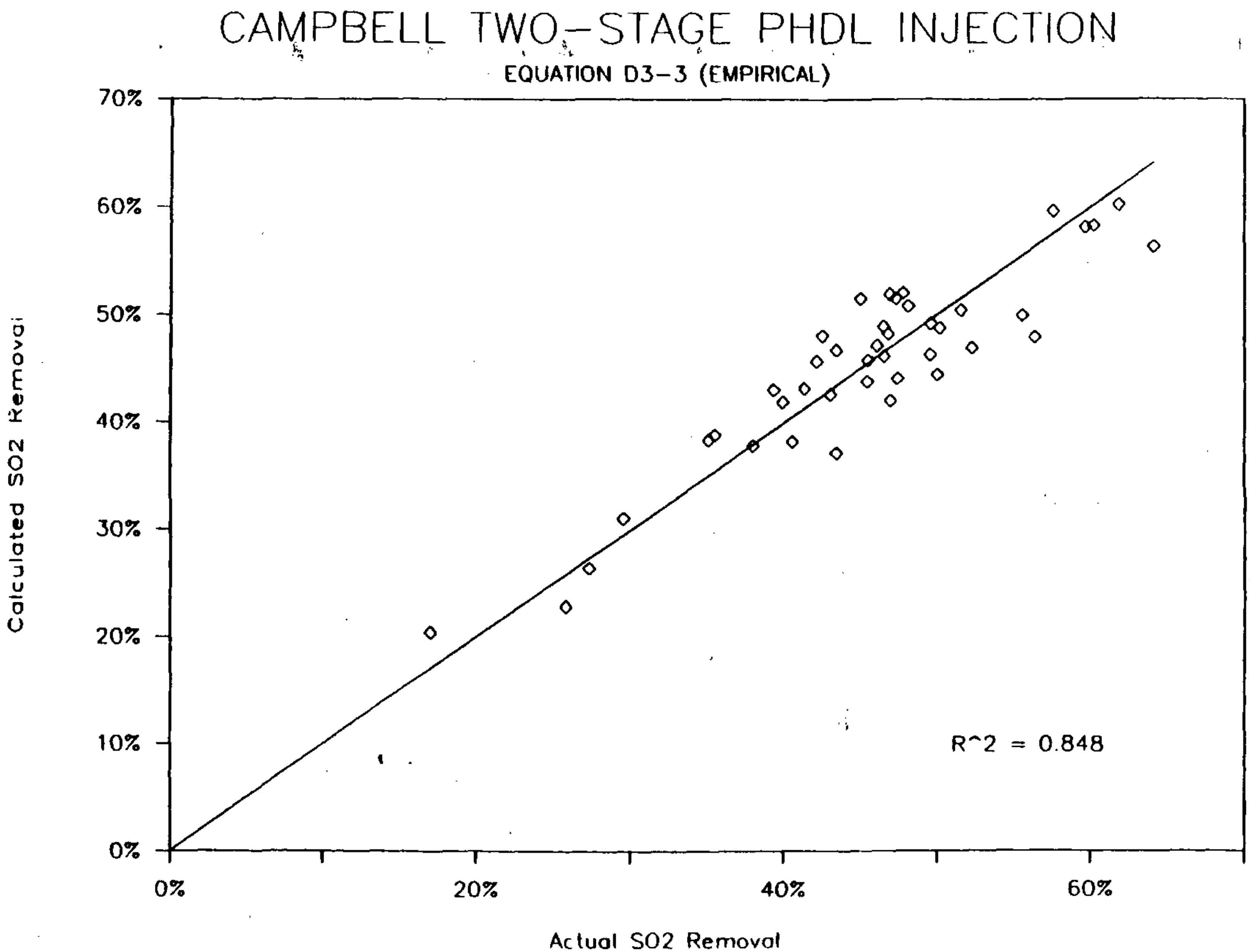


Figure 6-7 **Calculated vs Actual SO_2 Removal Using Equation D3-3**

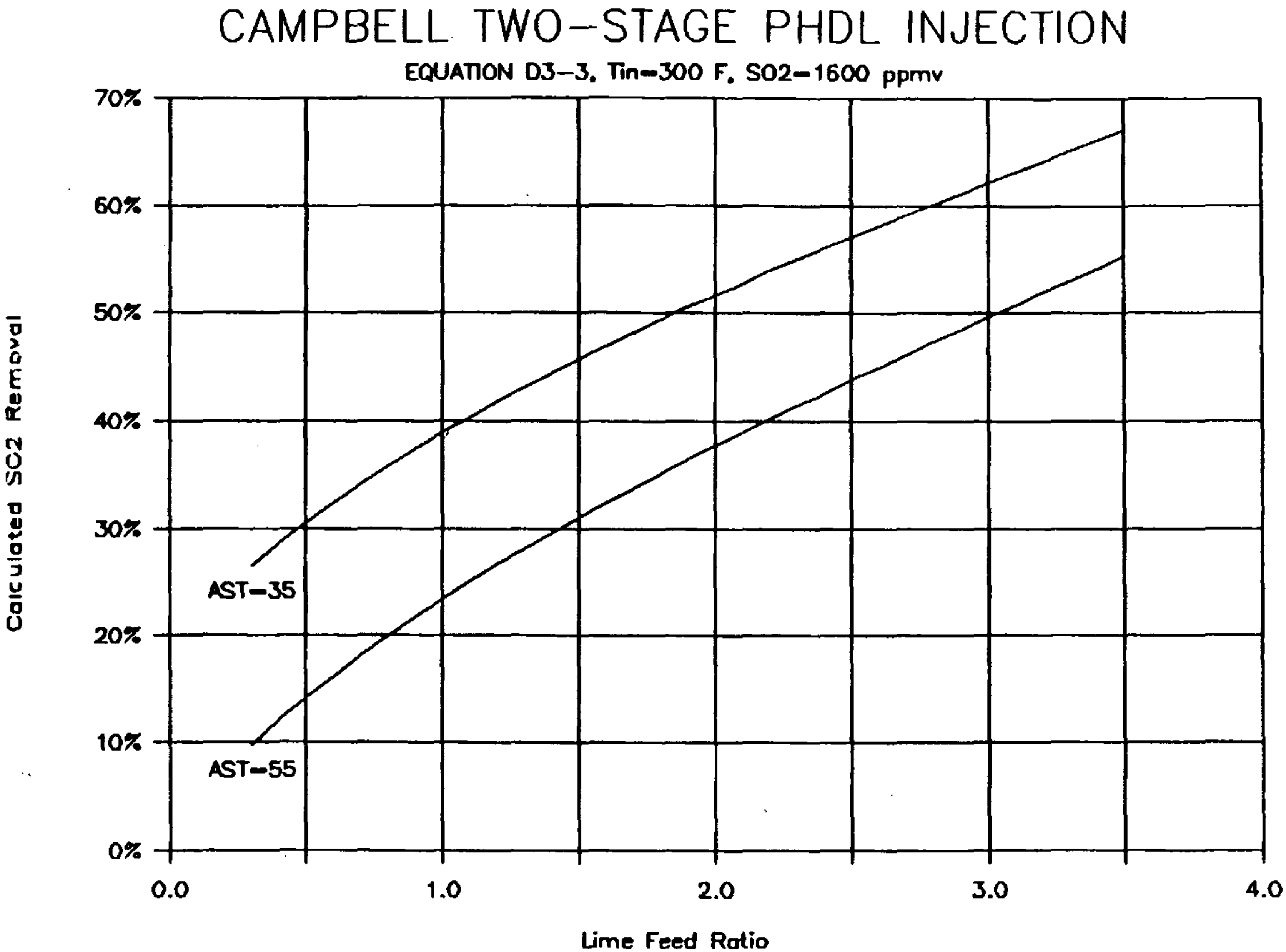


Figure 6-8 Prediction of SO_2 Removal vs LFR for AST of 35°F and 55°F Using Equation D3-3

6.2.3 CL in Two Nozzles

The data set for CL injected through two nozzles is shown in Table 6-3.

The rational expression that provided the best fit (R^2 = 0.644) for these data is:

$$RMVL = 1 - e^{-7.94 \times 10^{-6} C}$$

$$\text{where } C = \frac{(LFR)(Tin)(SO_2)}{(Tout - 125)^{0.5}} \qquad \text{eq. C10-11a}$$

Here LFR is used directly, inlet SO_2 concentration is included in the numerator, and the square root of the AST is used in the denominator.

A plot of calculated versus actual SO_2 removal is shown in Figure 6-9. This plot also shows a bias in that calculated SO_2 removal is high at low actual removal, and low at high actual removal.

Deleting SO_2 in the numerator decreases R^2 to 0.522; moving it to the denominator decreases R^2 to 0.268. Substituting (Tout - 125) for $(Tout - 125)^{0.5}$ decreases R^2 to 0.613.

Predictions of SO_2 removal versus LFR at ASTs of 35°F and 55°F for this equation are shown in Figure 6-10. Predictions of SO_2 removal versus LFR at a fixed AST of 35°F with inlet SO_2 concentration as a parameter are shown in Figure 6-11.

The empirical expression that provided the best fit (R^2 = 0.722) for the CL data set is:

$$\begin{aligned} RMVL = & -0.645 + 0.387 (1 - e^{-LFR}) - 0.0834 (Tout - 125) \\ & + 5.51(OH) + 0.00264(Tin) + 0.000274(SO_2) \\ & - 0.00214(GAS) + 0.0585(FR) \end{aligned} \qquad \text{eq. C3-3}$$

The plot of calculated versus actual SO_2 removal is shown in Figure 6-12. Figure 6-13 shows predictions of SO_2 removal versus LFR at ASTs of 35°F and 55°F for this equation.

Table 6-3
CAMPBELL TWO-STAGE CL INJECTION DATA

RUN DATE	RUN END TIME	SO2 RMVL	LIME UTIL	LFR	LIME FEED RATE (gpm)	LIME CONC (#eq/gal)	INLET TEMP (F)	OUTLET TEMP (F)	INLET SO2 (ppmv)	GAS FLOW (%)
04/18	12:46	42.7%	45.8%	0.920	2.64	0.0192	310	160	1420	54
04/21	15:10	67.0%	32.7%	2.046	3.00	0.0358	319	162	1350	54
05/13	10:10	42.7%	41.7%	1.036	1.49	0.0271	290	160	1412	36
05/13	12:40	43.7%	36.8%	1.188	1.59	0.0271	304	160	1402	36
05/13	23:45	51.1%	38.5%	1.326	1.76	0.0276	310	160	1415	36
05/14	13:15	52.4%	41.9%	1.253	1.55	0.0276	301	160	1320	36
05/15	10:45	53.3%	41.6%	1.282	1.65	0.0276	305	160	1373	36
05/16	09:40	46.2%	42.5%	1.087	1.50	0.0276	289	160	1381	36
05/17	07:45	35.6%	31.0%	1.149	1.45	0.0276	295	170	1346	36
05/18	08:00	47.9%	42.4%	1.138	2.18	0.0311	282	160	1359	54
05/18	16:45	41.5%	38.6%	1.077	1.43	0.0281	288	160	1440	36
05/18	23:45	36.0%	33.7%	1.077	1.35	0.0281	280	160	1367	36
05/19	10:30	44.8%	39.9%	1.123	1.45	0.0281	275	150	1404	36
05/20	01:30	42.1%	33.0%	1.276	1.50	0.0286	299	160	1299	36
05/20	10:30	46.4%	32.0%	1.449	1.66	0.0286	301	160	1266	36
05/20	13:48	48.5%	39.7%	1.225	1.51	0.0286	296	160	1370	36
05/21	05:10	48.4%	40.5%	1.195	1.58	0.0286	301	160	1461	36
05/21	08:10	48.0%	38.4%	1.248	1.68	0.0286	294	160	1470	36
05/21	12:00	60.9%	43.9%	1.390	3.60	0.0286	308	160	1419	72
05/22	02:35	60.5%	44.0%	1.380	2.78	0.0275	311	160	1429	54
05/22	07:35	56.9%	43.9%	1.295	2.58	0.0275	302	160	1412	54
05/22	12:30	58.6%	43.1%	1.359	4.44	0.0275	302	160	1422	88
05/23	07:40	48.3%	40.3%	1.200	1.60	0.0275	298	160	1417	36
05/23	11:25	63.3%	44.7%	1.415	2.84	0.0275	322	160	1427	54
05/24	12:04	35.7%	30.2%	1.182	1.52	0.0292	295	160	1362	36
05/25	03:55	34.8%	26.5%	1.334	1.56	0.0287	288	160	1303	36
05/25	08:50	32.8%	28.4%	1.155	1.36	0.0287	282	160	1306	36
05/26	02:20	42.0%	42.5%	0.988	1.49	0.0286	287	160	1564	36
05/26	07:20	36.5%	43.7%	0.837	0.98	0.0286	278	160	1617	29
05/26	09:10	40.8%	43.7%	0.932	1.30	0.0286	274	160	1540	36
05/26	11:05	46.8%	44.4%	1.057	3.65	0.0286	280	160	1560	88
05/26	12:40	50.7%	46.3%	1.094	3.65	0.0286	285	160	1507	88
05/26	22:45	44.4%	43.8%	1.016	1.51	0.0272	294	160	1562	36
05/27	07:15	61.0%	52.0%	1.173	1.80	0.0272	303	150	1611	36
05/27	12:30	59.3%	49.6%	1.197	4.42	0.0272	306	150	1587	88
05/27	22:55	38.5%	33.6%	1.147	1.61	0.0281	310	170	1523	36
05/28	06:55	39.0%	36.8%	1.060	1.53	0.0281	309	170	1566	36
05/28	10:10	42.6%	37.5%	1.297	3.78	0.0281	299	170	1605	79
05/28	11:20	44.1%	41.1%	1.071	3.78	0.0281	305	170	1565	88
05/28	12:55	60.8%	47.1%	1.291	4.70	0.0281	307	150	1517	88
05/29	12:05	46.8%	36.6%	1.278	4.37	0.0271	301	160	1480	88
05/29	21:25	50.6%	42.4%	1.191	1.79	0.0279	313	160	1619	36
05/30	07:25	48.8%	43.2%	1.130	1.65	0.0279	303	160	1572	36
06/02	19:45	63.9%	31.8%	2.013	1.85	0.0424	300	160	1505	36
06/02	23:45	64.9%	35.1%	1.851	1.75	0.0424	299	160	1550	36
06/03	04:45	60.4%	32.6%	1.855	1.60	0.0424	289	160	1491	36
06/03	06:15	54.2%	34.7%	1.537	1.50	0.0424	281	160	1540	36
06/03	07:15	60.6%	36.2%	1.674	1.65	0.0424	295	160	1555	36

Table 6-3 (Cont'd)

RUN DATE	RUN END TIME	SO2 RMVL	LIME UTIL	LFR	LIME FEED RATE (gpm)	LIME CONC (#eq/gal)	INLET TEMP (F)	OUTLET TEMP (F)	INLET SO2 (ppmv)	GAS FLOW (%)
06/03	10:30	70.4%	37.1%	1.896	2.77	0.0399	296	160	1500	54
06/03	11:45	64.8%	35.8%	1.811	2.77	0.0399	297	160	1570	54
06/05	23:30	64.9%	49.5%	1.315	1.73	0.0326	302	160	1658	36
06/06	07:30	62.3%	52.5%	1.186	1.63	0.0326	297	160	1624	36
06/10	22:00	67.9%	38.0%	1.793	1.80	0.0418	298	160	1623	36
06/11	06:00	66.7%	42.1%	1.585	1.67	0.0418	294	160	1646	36
06/11	07:30	62.5%	39.3%	1.596	1.60	0.0418	288	160	1553	36
06/12	01:45	54.5%	48.9%	1.116	1.66	0.0274	294	160	1579	36
06/12	08:00	50.0%	55.8%	0.896	1.36	0.0274	282	160	1601	36
06/12	10:05	52.7%	47.7%	1.106	3.90	0.0274	288	160	1520	88
06/12	12:30	52.3%	45.9%	1.140	4.57	0.0274	292	160	1520	100
06/12	21:50	58.0%	55.0%	1.055	1.70	0.0264	302	160	1542	36
06/13	01:50	58.0%	52.8%	1.099	1.70	0.0264	301	160	1481	36
06/13	05:35	60.6%	55.9%	1.088	2.60	0.0264	297	160	1525	54
06/13	07:05	64.3%	52.4%	1.227	2.87	0.0264	303	160	1493	54
06/13	09:00	54.2%	45.2%	1.199	4.25	0.0264	300	160	1483	88
06/13	12:30	56.8%	45.8%	1.242	4.75	0.0264	312	160	1600	88
07/24	07:35	51.0%	46.5%	1.097	1.69	0.0280	304	160	1658	36
07/24	09:00	52.7%	41.9%	1.257	4.23	0.0280	298	160	1480	88
07/24	10:00	49.3%	42.1%	1.170	3.91	0.0280	288	160	1470	88
07/24	12:15	59.0%	43.4%	1.361	4.46	0.0280	307	160	1443	88
07/24	13:45	63.8%	48.1%	1.328	4.54	0.0280	310	160	1507	88
07/24	14:25	65.6%	59.6%	1.101	2.48	0.0280	311	164	1615	54
MINIMUM =		32.8%	26.5%	0.837	0.98	0.0192	274	150	1266	29
MAXIMUM =		70.4%	59.6%	2.046	4.75	0.0424	322	170	1658	100
AVERAGE =		52.2%	41.9%	1.270	2.37	0.0299	297	160	1488	51

(a) CL injection only; no water injection.
(b) Data are average values for the run ending at the RUN END TIME shown.
(c) SO2 concentration is on a dry basis.
(d) CL is freshly slaked.

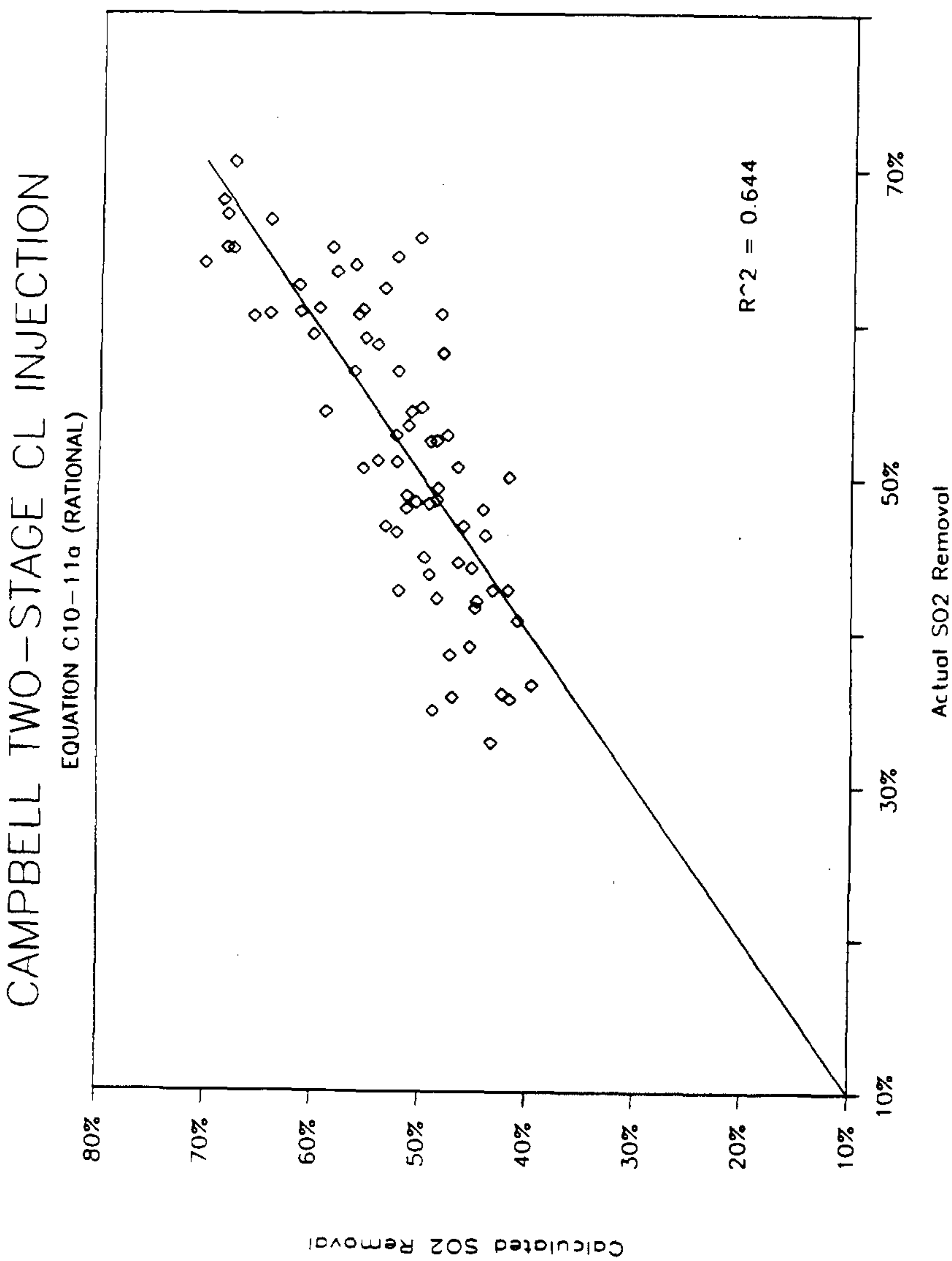


Figure 6-9 Calculated vs Actual SO_2 Removal Using Equation C10-11a

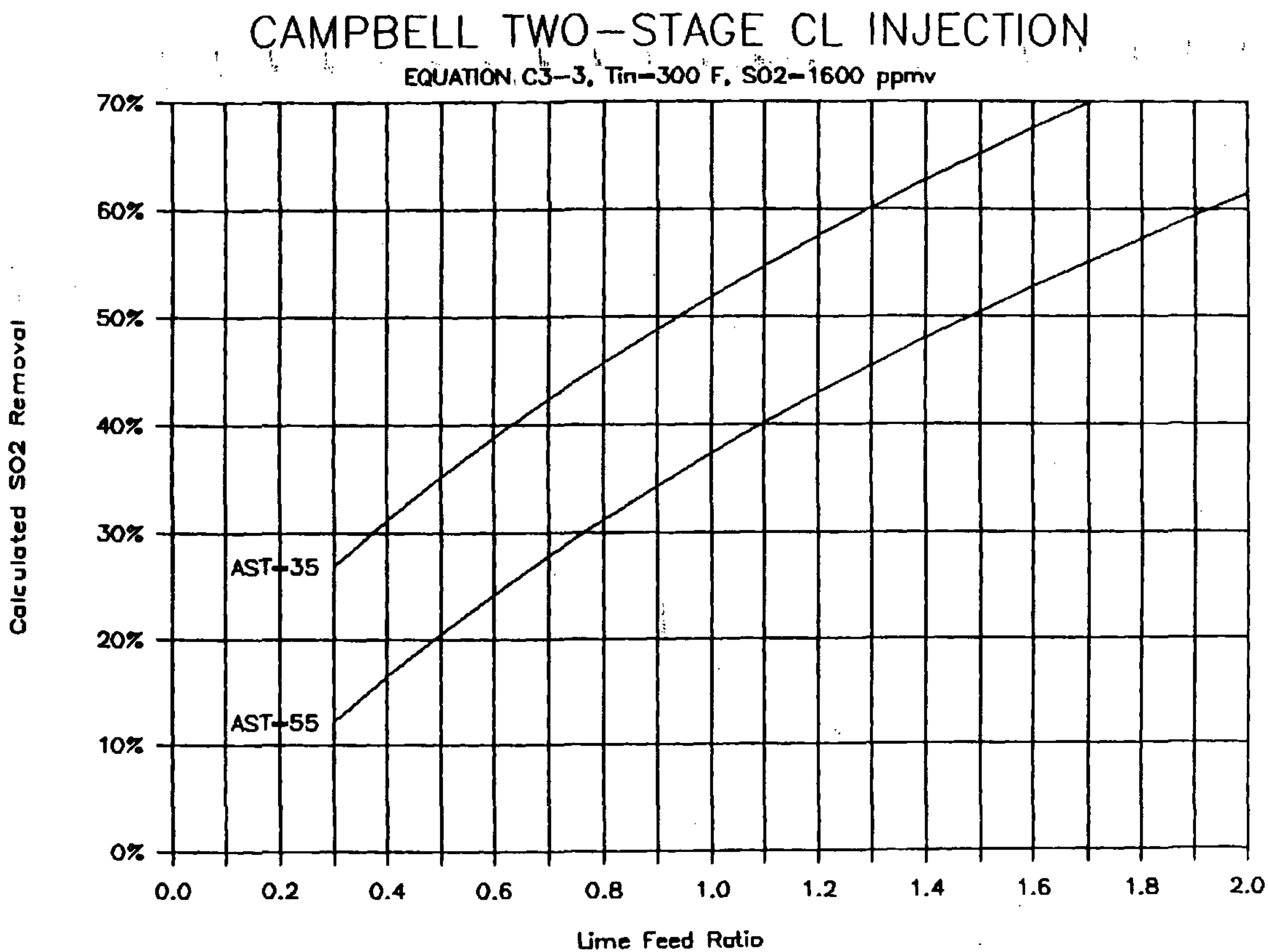


Figure 6-10 Prediction of SO_2 Removal vs LFR for AST of 35°F and 55°F Using Equation C10-11a

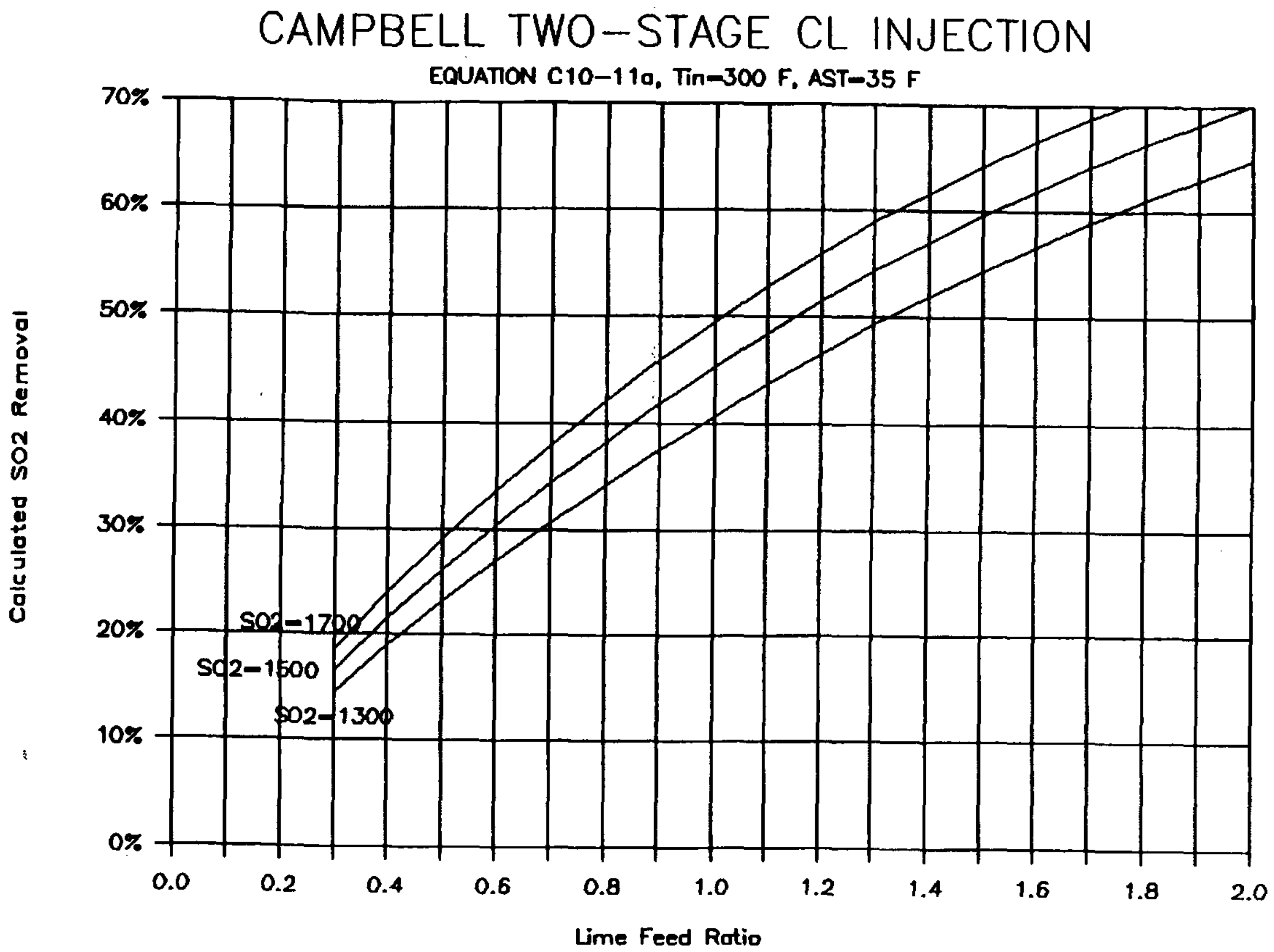


Figure 6-11 **Prediction of SO_2 Removal vs LFR for SO_2 of 1300 ppm, 1500 ppm, and 1700 ppm Using Equation C10-11a**

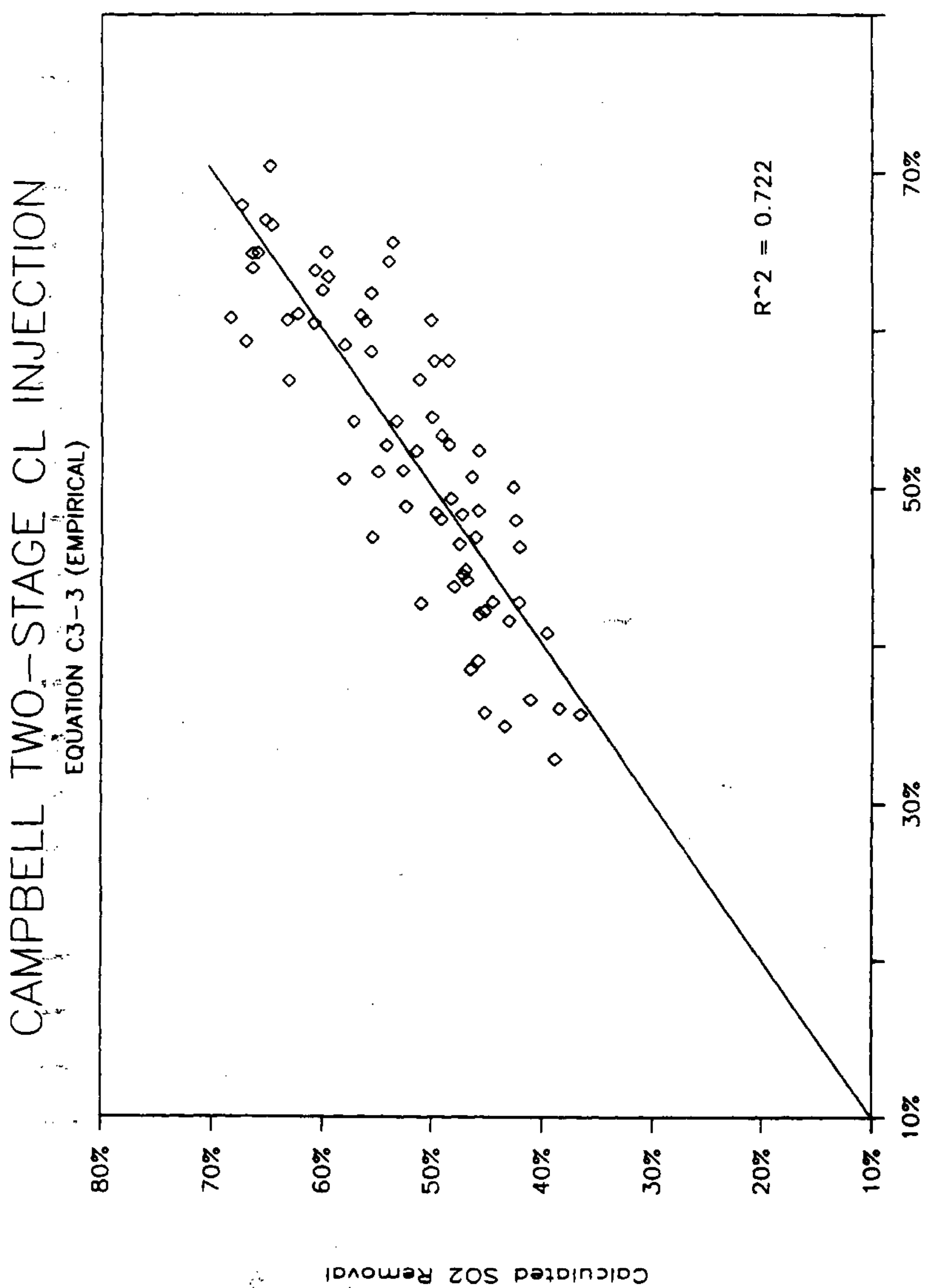


Figure 6-12 Calculated vs Actual SO_2 Removal Using Equation C3-3

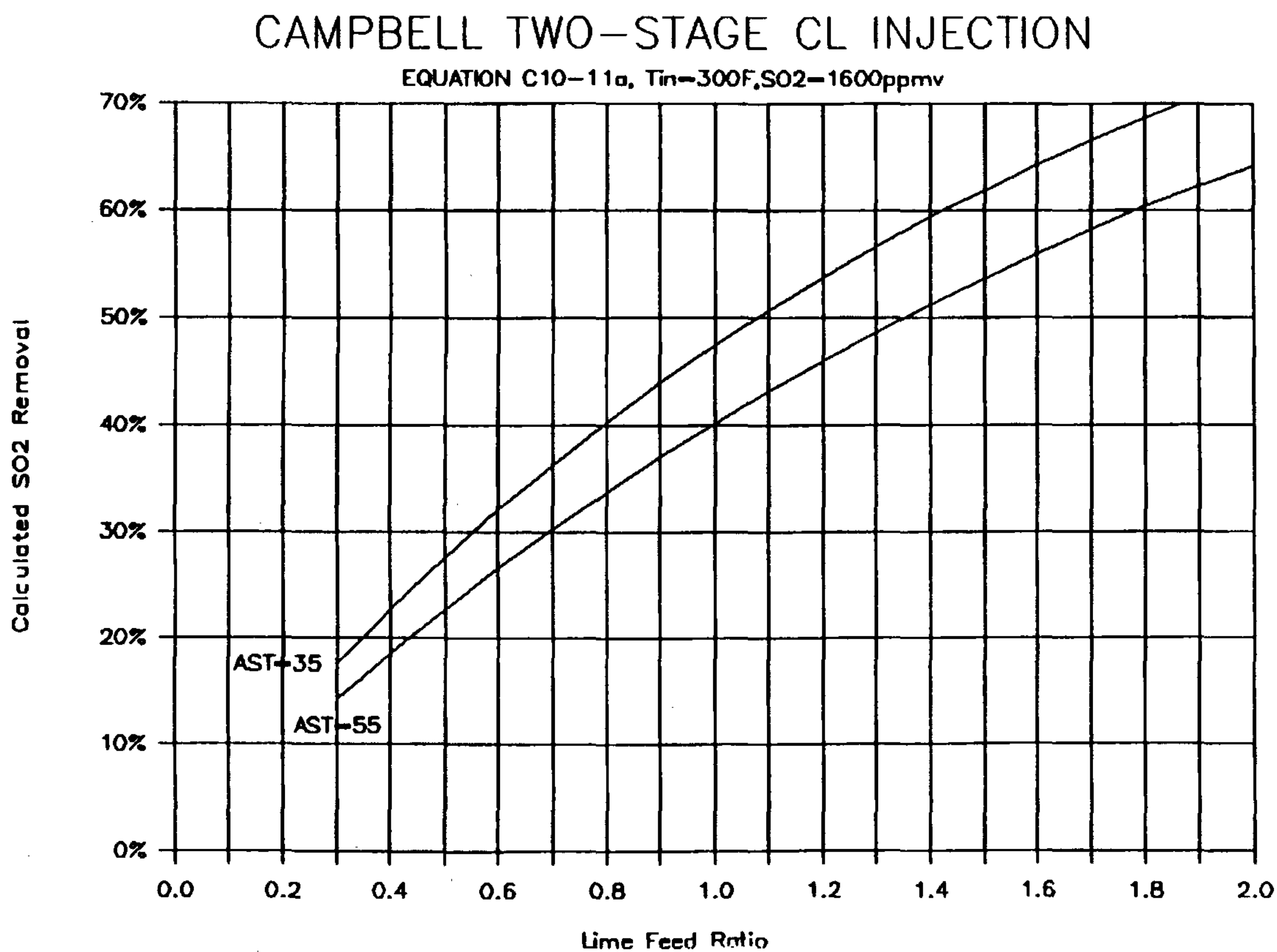


Figure 6-13 Prediction of SO_2 Removal vs LFR for AST of 35°F and 55°F Using Equation C3-3

6.3 DISCUSSION

Two important independent variables in spray dry FGD systems are LFR and outlet temperature, or more correctly AST, which is approximated by (Tout - 125) in these experiments. Figures 6-2, 6-5, and 6-10 show SO_2 removal as a function of LFR for two values of AST for the rational expressions that gave the best fit for the three data sets. A strong dependence of SO_2 removal on both LFR and AST is seen in these figures.

Figure 6-5, for PHDL injected in both nozzles, shows the strongest dependence of SO_2 removal on AST because the AST term has a power of one in the expression for this data versus a power of one-half for the expressions for the other two data sets.

Figures 6-14 and 6-15 are plots of lime utilization versus lime concentration for two-stage injection of PHDL and CL, respectively. These plots show that lime utilization decreases with increasing lime concentration. Since, by definition, lime utilization times LFR equals SO_2 removal, this implies that, at a given LFR, SO_2 removal will decrease with increasing lime concentration (assuming other variables are held constant).

This phenomenon explains why the SO_2 removal performance of PHDL was better when injected through two nozzles than through a single nozzle with another nozzle for water injection as shown by comparing Figure 6-2 and 6-5. For a given operating condition, the concentration of lime injected through a single nozzle had to be higher than that injected through two nozzles because the additional water injected through the second nozzle was not used to dilute the lime. This increase in feed solids results in poorer lime utilization and, therefore, poorer SO_2 removal performance.

A comparison of Figure 6-10 with Figures 6-2 and 6-5 shows that SO_2 removal rises faster and higher for CL than for PHDL. For the Campbell test conditions, freshly slaked CL showed superior SO_2 removal performance compared with PHDL.

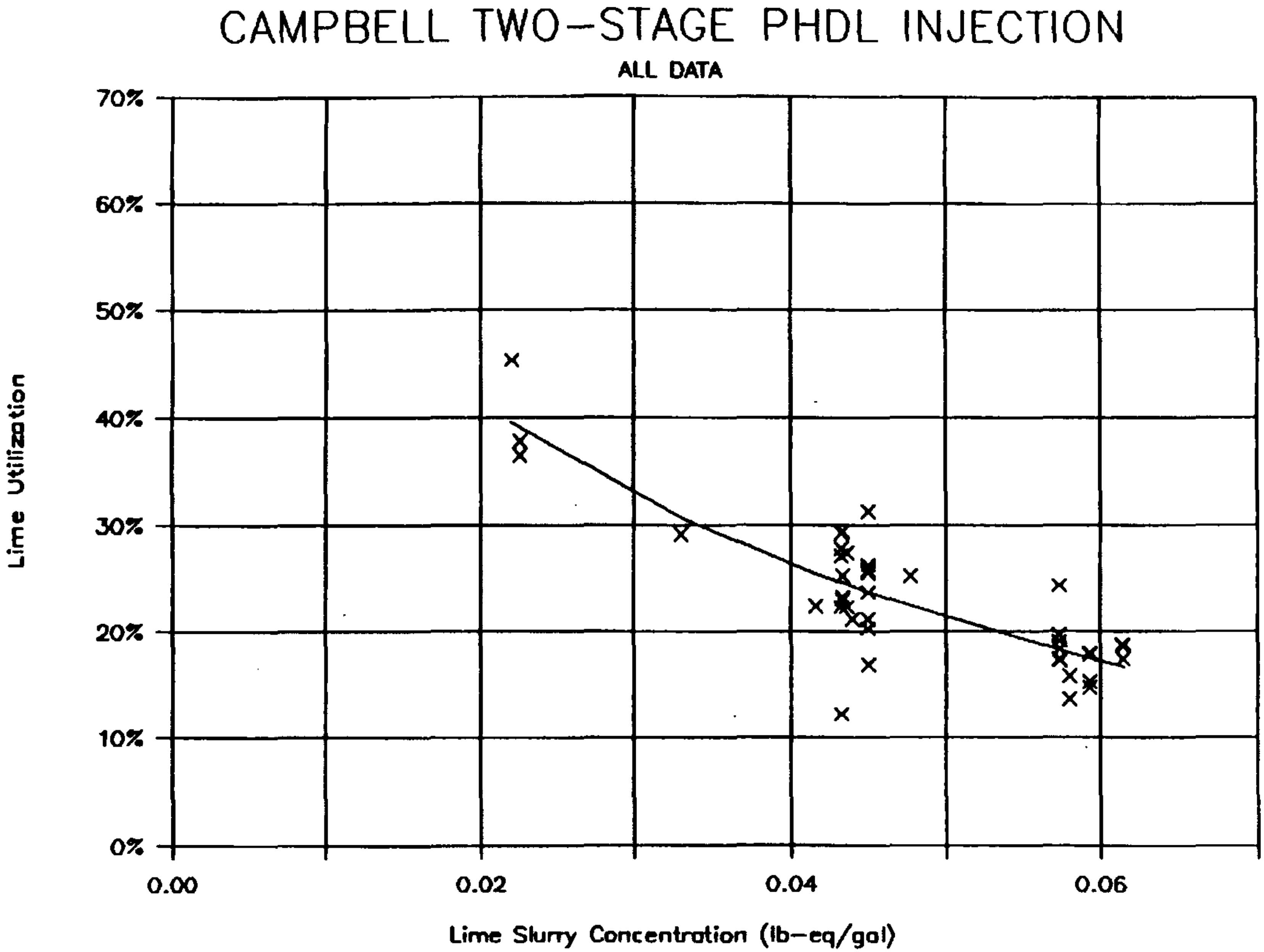


Figure 6-14 Lime Utilization vs Lime Concentration for Campbell Two-Stage PHDL Injection

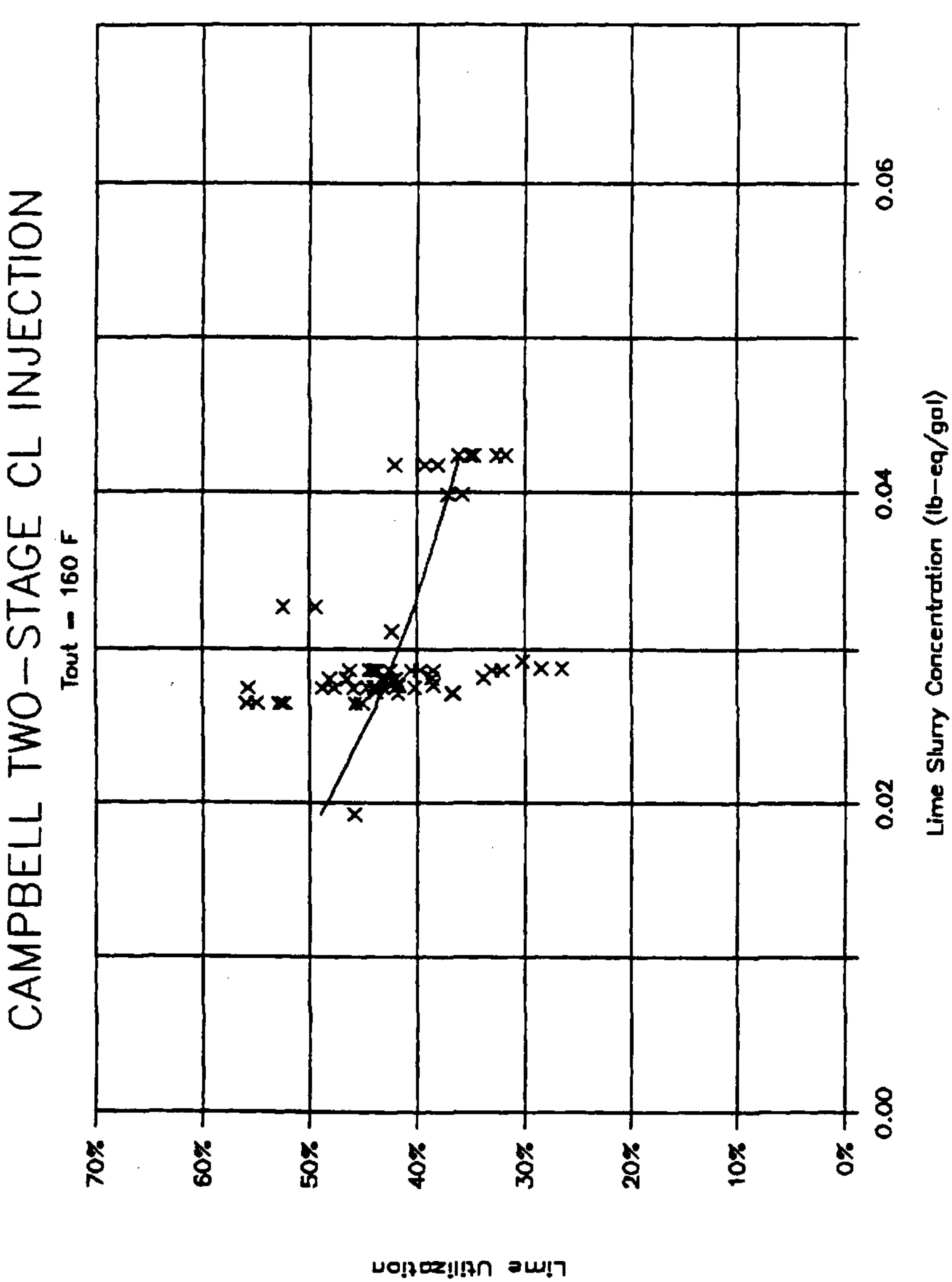


Figure 6-15 Lime Utilization vs Lime Concentration for Campbell Two-Stage CL Injection

The regression analysis also identified the gas inlet temperature as an important variable as shown in Figure 6-6.

Increasing Tin in this system has several effects that all tend to increase SO_2 removal:

- A higher Tin would allow use of a more dilute slurry to reach a given LFR. This would provide better lime utilization and better SO_2 removal performance.
- In the tests where lime slurry was injected through two nozzles, the outlet temperature was controlled by varying the flow of slurry to the upstream nozzle. Thus, when Tin rose, more slurry was injected, and this increased SO_2 removal.
- An increase in Tin increased the adiabatic saturation temperature and therefore decreased the approach to saturation since Tout was kept constant. A lower approach slowed drying and thus increased SO_2 removal.
- The mass flow of incoming gas was kept constant during a test. The gas flow indicator, FI 100, measured the mass flow and was independent of temperature. Therefore, when Tin rose, the gas density decreased and its velocity increased. The increased velocity gave better mixing of spray droplets with the gas, but this effect probably had only a very small influence on SO_2 removal.

The above considerations suggest that the observed effect of Tin on SO_2 removal may be peculiar to this particular system rather than being a general phenomenon.

The regression analysis for the rational expressions identified inlet SO_2 concentration as an important variable for the CL data set but not for the PHDL data sets. As explained earlier, LFR is not truly an independent variable since it is a function of SO_2. Since both SO_2 and a function of SO_2 are treated as variables, this analysis cannot determine the true effect of SO_2 inlet concentration on SO_2 removal.

The empirical correlations reflect relationships between the independent variables and are difficult to interpret. They also do not extrapolate.

All of the plots of calculated versus actual SO_2 removal for the rational expressions show a slight bias in that the calculated removal tends to be high at low actual removal and low at high actual removal.

The rational correlations are felt to be better than the empirical correlations for understanding the process despite the bias and the lower correlation coefficients.

6.4 ADDITIONAL ANALYSIS

Additional analyses of the Campbell data could be expected to provide improved correlations. However, at the time the analysis presented here was being performed, additional data were being obtained at the full-size CZD test program at Seward station. A decision was made to focus additional effort on analyzing the combined data set from both sites.

The reader is referred to Part 4, Section 1 where a correlation of the combined data from both the Campbell and Seward test sites is described. The correlation is used to provide preliminary design information for the full-scale projections presented in Section 2 of Part 4.

Section 7

ESP TESTS

A principal objective of this project was to assess the effect of the reaction products and any unreacted lime on the performance of electrostatic precipitators (ESPs). Certain factors were noted from previous experience with spray dry flue gas desulfurization (FGD) systems operating upstream from ESPs. When lime slurry was sprayed into the ductwork, the lower temperature and higher moisture of the gas were expected to more or less offset the effect of the higher loading of solids on ESP performance (References 7-1 and 7-2). If a CZD system also exhibited the same tendency, particulate emissions would not be changed much by retrofitting the system, and extensive modification of the ESP would not be needed.

As noted, the ESP was part of the test facility. The ESP was energized during all the lime injection tests. ESP performance was measured in two series of tests. The first series was performed in November 1986, shortly after starting up the facility. The second series of tests was carried out from May through July 1987, at the end of the program.

In situ measurements of the resistivity of the particulate matter were also made toward the end of this second series of tests.

7.1 ESP INSTALLATION

7.1.1 ESP Design Details

Lodge-Cottrell division of Dresser Industries, Inc. supplied the ESP for the Campbell test facility. This ESP was one of that company's standard units of the SP5 series of modular assemblies. The precipitator had two collector fields in series, each with its own transformer/rectifier (T/R) and bus section. Each field had 12 collector plates spaced on 12-inch centers. Each collecting plate, positioned parallel to the gas flow, was divided into five segments. This design allowed for 20 percent of each collecting field to be rapped at one time. The emitting electrodes were of rigid frame design. Specific details are listed in Table 7-1.

Table 7-1

ESP DESIGN DETAILS

Number of chambers	1
Number of fields	2
Number of T/Rs	2
Number of hoppers	2
Number of gas passages	12
Gas passage spacing	12 in.
Effective treatment length	15 ft (7.5 ft in each field)
Plate dimensions	9.75 ft high by 7.5 ft long
Total collector area	3,510 ft^2
Total effective emitting electrode length	2,670 ft
Cross section area for gas flow	117 ft^2
T/R capacity, each	60 kVdc at 80 mAdc

Figure 7-1 is a cutaway isometric drawing of the unit.

Gas from the 130-foot-long test section traveled through a 3 ft dia. duct and turned upward through a 180° bend to enter the ESP, as shown in Figures 3-2 and 3-3. Figure 7-1 shows the inlet gas splitter vanes in the inlet transition piece that distributed the gas flow over the ESP cross section.

As an example of the size of the ESP relative to the size of the test duct, if gas at 300°F comes into the test duct at 50 ft/sec and slurry is injected to cool it to 160°F, the velocity is reduced to about 45 ft/sec. The average velocity through the ESP is then 2.5 ft/sec, the time in contact with the collector plates 5.8 sec, and the specific collection area (SCA) about

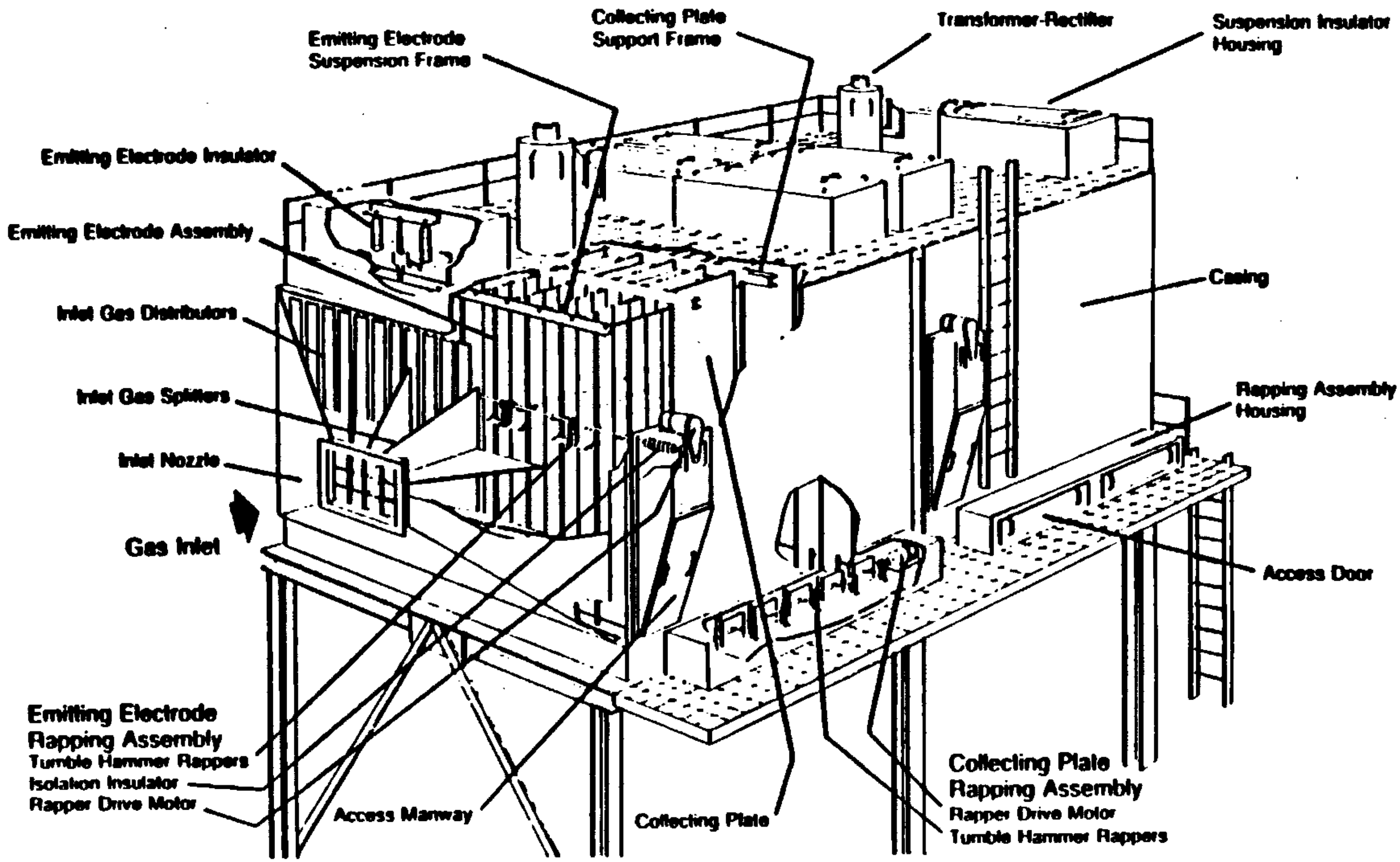


Figure 7-1 Lodge SP5 Series Modular Dry Electrostatic Precipitator

190 ft^2/1,000 acfm. Although the SCA value is representative of many existing ESPs in power plants burning medium- to high-sulfur coal, the velocity of the gas flowing past the plates is relatively low (4 to 6 ft/sec being more typical), and the contact time relatively high.

7.1.2 ESP Inlet Conditions

Flue gas for the test facility was withdrawn from the side of the ductwork of Campbell Unit 1, just downstream from an air heater, as described in Section 3. The gas in Unit 1 flowed downward through the air heater, then turned about 135° and flowed diagonally upward past the point where the test facility took its gas. Since a scoop did not extend into the large duct, gas withdrawn for the test facility did not necessarily carry the same concentration of fly ash that went to the full-scale ESP. However, since the purpose of these tests was to compare ESP performance with and without injection of lime slurry into the gas, the fact that the fly ash concentration in the gas may have been somewhat different from that in the Unit 1 ductwork was not considered important.

It is noted that Unit 1, rated at 260 MW, was base-loaded, and its output seldom fell below 180 MW, 70 percent of capacity. Therefore, while changing loads may have caused some variations in the composition and particulate loading of gas entering the test facility, these variations should not have been great. Variations in the ash content of the coal and in the percentage of excess combustion air could also have caused the fly ash concentration in the gas to vary.

Particulate concentrations were measured at the pilot ESP inlet during the tests conducted from May to July 1987. Table 7-2 lists these concentrations in order of increasing gas velocity. With no injection, the inlet ash concentration was usually lower at a higher gas flow rate through the pilot precipitator. These results may be a coincidence because a higher take-off velocity from the plant ducting would be expected to force a higher percentage of the ash to make the turn into the take-off duct. The average value of 3.35 gr/dscf is somewhat lower than the estimated concentration of 3.9 gr/dscf.

Table 7-2

CONCENTRATIONS OF PARTICULATE MATTER IN FLUE GAS ENTERING THE ESP

Test No.[a]	Inlet Gas Velocity[b] (ft/sec)	Part. Concen. into ESP (gr/dscf)	
No Injection			
23	30	3.99	Estimated concentration of fly ash in gas, 3.9 gr/dscf
24	30	4.70	
25	30	4.36	
58	30	3.73	
60	30	2.91	
36	50	3.10	
37	50	2.90	
38	50	2.10	
51	50	2.74	
52	50	3.00	
	Avg.	3.35	
Injection of Water Only			
26	30	4.24	
27	30	3.98	
56	30	2.35	
42	50	2.26	
43	50	2.03	
53	50	1.90	
	Avg.	2.79	
Injection of 10 to 12 Percent Calcitic Lime Slurry			
1[c]	20	4.10	Estimated concentration of particulates (fly ash, reaction products, unreacted lime) in gas, 3.9 + 3.2 = 7.1 gr/dscf (see Appendix F)
2[c]	20	4.88	
3	20	4.36	
4	20	4.05	
14	20	4.86	
9	30	5.99	
10	30	6.13	
5	40	5.38	
6	40	5.41	
7	50	5.48	
8	50	5.20	
12	50	5.67	
13	50	4.56	
15	50	3.89	
16	50	5.16	
21	50	5.69	
22	50	5.43	
46	50	5.75	
48	50	4.85	
49	50	5.71	
50	50	5.40	
54	50	5.67	
55	50	4.96	
47	60	4.33	
	Avg.	5.12	

(a) Tests conducted during May to July 1987.
(b) Gas velocity in test duct, upstream of any injection.
(c) These tests were performed at an ESP inlet temperature of 148°F. All other lime injection tests were performed at 160°F.

The estimate assumed 10.6 percent ash in the coal and 40 percent excess air. It also assumed that 80 percent of the coal ash appeared as fly ash (see Appendix F).

With injection of water, the inlet fly ash concentrations also tend to be lower at the higher gas velocities. In these cases, some of the fly ash was wetted by the injected water and deposited in the test duct before the point where the concentrations were measured.

When lime slurry was injected, the measured concentrations of particulate matter at the ESP inlet, as listed in Table 7-2, showed no trend with gas velocity and were all below the estimated value of 7.1 gr/dscf. Deposition of solids in the duct is probably the principal reason for the low concentrations.

7.2 ESP TEST PROCEDURES

The method used to determine the concentration of particulate matter in the flue gas was the same for both series of tests, but the operational procedures were different. These procedures are summarized in the following sections.

7.2.1 Gas Sampling and Determination of Particulate Concentration

The gas was sampled at the inlet and outlet of the ESP at the same time. The inlet samples were taken at the downstream end of the straight duct test section. The ESP outlet samples were taken just upstream of the induced-draft (ID) fan, where the gas flowed downward through a 20-foot run of straight duct.

Isokinetic samples of gas were withdrawn at each of six traverse points across the cross section of the duct. (The traverse direction for the outlet samples was in the same plane as the bend in the duct; about 20 feet upstream.) Sampling for a given test normally required 60 to 90 minutes.

The sampling procedure, determination of particulate concentrations, and calculation of ESP efficiency (the percentage of particulate matter in the flue gas at the ESP inlet that is removed by the ESP) followed EPA Method 17. Appendix D gives specific details.

7.2.2 Operational Procedures

First Series. For the first series of tests, from November 18 to 22, 1986, the system was kept warm overnight by passing a low flow of flue gas through it, with no injection. At about 0800 hours, gas flow was increased and injection of lime began. Gas sampling was started as soon as possible, after the desired gas temperature was reached and conditions stabilized.

When the first test was completed, conditions were adjusted to those desired for the second test (if a second test was to be made). The second test usually began about 2 hours later, after thermal equilibrium of the ESP had been attained.

After the tests were finished, the system was shut down, and the duct (but not the ESP) was opened, inspected, and cleaned. At the end of the day, a low flow of gas was again established to keep the system warm and dry overnight.

As noted, these tests took place early in the program, about 1 month after the shakedown started.

Second Series. The second series of ESP tests began on May 19, 1987, and ended on July 22. There was a 5-week interruption from June 14 to July 23 because of a forced outage on Unit 1.

For these tests, the desired test conditions were maintained during the night preceding the test by operating with injection of lime or water, or with no injection to keep the flue gas temperature at the ESP inlet constant at the level desired for the next day's tests. However, the gas flow was kept low during the night (20 ft/sec normally) to allow a low injection rate and avoid deposition of excessive amounts of solids in the duct. At about 0800 hours, the gas flow was increased to the rate used in the test and the injection rate was raised to maintain the ESP inlet temperature constant. During lime slurry injection, the injection rate was sufficient to meet the SO_2 removal objective of at least 50 percent.

After approximately 1 hour, when it was ascertained that stable T/R conditions had been reached, VI (voltage-current) curves were taken with both T/R units on automatic voltage control (AVC). The AVC units were then set manually at the maximum sustainable level. The maximum sustainable level was either just below the level at which excessive arcing occurred, or just below the maximum voltage or current for each T/R unit, 60 kV or 80 mA, respectively.

Following this, the particulate concentration at the ESP inlet and outlet were measured simultaneously to determine the ESP efficiency. During this ESP efficiency test, electrical readings were taken from the front panels of the controllers approximately every 10 to 15 minutes. At the conclusion of the efficiency test, a second set of VI curves was taken as described.

If the efficiency test was to be replicated, the same operating conditions were held steady until preparations were complete to begin the second test (usually around 1 hour). If a change in operating conditions was called for (i.e., additional moisture or change in velocity, etc.) a suitable amount of time was allowed between tests for stabilization of the system. VI curves were then run again and the test procedure repeated.

Between one and three tests were carried out each day depending on prevailing conditions. Generally, the plant was shut down at around 1400 hours each day to facilitate entry to the test duct for cleaning out the accumulated fly ash and lime deposits.

The ESP was opened for inspection and cleaning several times during this series of tests. Cleaning consisted of rapping the plates and discharge electrodes manually, and brushing and blowing off deposits where they could be reached from the walkway between the two sections. A washdown was not attempted.

7.3 TEST RESULTS

Tables 7-3 and 7-4 summarize results of all the ESP tests carried out at the Campbell test facility. The tests are listed in chronological order with results from the first series of tests in November 1986 given in Table 7-3 and those from the second series, May to July 1987, given in Table 7-4. The tables show the effective migration velocity (EMV) of the particulate matter in the electric field. EMV is a useful parameter in evaluating the performance of ESPs in collecting different kinds of particulate matter. The EMV values were calculated using the Deutsch equation, which is universally used to predict precipitator performance.

The Deutsch equation is:

$$1 - EFF = \frac{1}{e^D}$$

$$\text{where } D = \left[\left(\frac{SCA}{1000}\right)(EMV)(0.02381)(60)\right]^k$$

EFF = collection efficiency, %/100

SCA = specific collection area, ft^2/1000 acfm

EMV = particulate effective migration velocity, cm/sec

k = a factor to account for increasing difficulty in collecting additional particulate as required collection efficiency increases (k usually approximates to 0.5 to 1.0)

For Tables 7-3 and 7-4, the value of k was taken as 0.5.

The following pages describe the test results in three separate sections: the first series of tests, the second series of tests with fly ash alone without lime injection (but with injection of water in many tests), and the second series of tests with lime injection.

7.3.1 First Series of Tests

The tests in November 1986 were carried out soon after the facility became operational. The primary purposes were to verify that the ESP was operating satisfactorily and to see if injection of lime slurry upstream of the ESP caused significantly greater emissions. Nine tests were made over a 5-day period. Of these tests, two were made with no injection, and one with injection of water only. The remaining six were made with injection of slurries of pressure hydrated dolomitic lime (PHDL) containing 15 percent solids. One test, however, used 20 percent PHDL. All ESP efficiency tests were at test duct gas velocities upstream of any injection of 45 to 50 ft/sec.

Table 7-3

ESP TEST RESTULS
FIRST SERIES OF TESTS

Date	Test No.	Gas Flow (acfm) (a)	Temp. (°F) (a)	Dust Conc. (gr/dry scf) In	Dust Conc. (gr/dry scf) Out	Effi-ciency (%)	EMV (cm/sec)	Power (watts/ 1000 acfm)	Gas Velocity (ft/sec) (b)	Contact Time (sec)	SCA (ft^2/ 1000 acfm)	Nominal Duct Velocity (ft/sec) (c)	Plate Voltage and Current 1st Fld kV	1st Fld mA	2nd Fld kV	2nd Fld mA	Remarks
No Injection, Fly Ash Only																	
11/18	1	18869	274	0.960	0.050	94.8	23.9	314.8	2.69	5.6	186	45	46	68	45	66	-
11/18	2	17980	275	1.10	0.068	93.8	20.1	339.1	2.56	5.9	195	45	-	-	-	-	-
Injection of Dolomitic Lime Slurry, 20%																	
11/19	3	15980	225	3.662	0.082	97.8	33.6	341.7	2.28	6.6	220	45	39	65	45	65	Lime to downstream nozzle only
Injection of Dolomitic Lime Slurry, 12%																	
11/20	4	16900	217	3.21	0.056	98.3	40.5	385.1	2.41	6.2	208	45	49	68	46	69	Lime to downstream nozzle only
11/20	5	15900	186	3.58	0.060	98.3	38.2	396.1	2.26	6.6	221	45	49	68	45	66	Lime to both nozzles
11/20	6	15700	168	3.44	0.058	98.3	37.6	428.8	2.24	6.7	224	45	52	70	47	66	Lime to both nozzles
11/21	7	19200	199	3.224	0.092	97.1	34.8	326.7	2.74	5.5	183	50	52	65	46	63	Lime to upstream nozzle only
11/22	8	15510	165	3.438	0.034	99.0	47.7	494.5	2.21	6.8	226	45	56	68	53	73	Lime to both nozzles
Injection of Water Only																	
11/22	9	17110	184	1.18	0.018	98.5	43.7	455.5	2.44	6.1	205	45	56	70	53	73	-

Note: One-shift operation. Temperature conditions established at start of day shift and all tests were completed 3 to 6 hours into the shift.
(a) Gas flow and temperature measured at upstream particulate sampling point, after injection
(b) Gas velocity through ESP
(c) Gas velocity in test duct, upstream of any injection

RR:H112c
Part 2

Table 7-4

ESP TEST RESULTS
SECOND SERIES OF TESTS

Date	Test No.	Gas Flow (acfm) (a)	Temp. (°F) (a)	Dust Conc. (gr/dry scf) In	Dust Conc. (gr/dry scf) Out	Effi-ciency (%)	EMV (cm/sec)	Moisture (%)	Power (watts/ 1000 acfm)	Gas Velocity (ft/sec) (b)	Contact Time (sec)	SCA (ft²/ 1000 acfm)	Nominal Duct Velocity (ft/sec) (c)	Plate Voltage and Current: Int Fld kV	Int Fld mA	2nd Fld kV	2nd Fld mA	Power Status	Remarks
Injection of Calcitic Lime Slurry, 12%																			
5/19	1	9000	148	4.098	0.024	99.4	34.1	9.0	608.9	1.28	11.7	390	20	46	55	50	59	Max.	-
5/19	2	8680	148	4.881	0.059	98.79	49.0	10.0	383.4	1.24	6.07	202	20	52	64	-	-	"	Inlet field only
5/20	3	8400	161	4.360	0.038	99.13	27.4	10.5	776.6	1.20	12.5	418	20	53	63	51	66	Max.	-
5/20	4	8640	159	4.050	0.066	98.37	42.4	11.0	335.0	1.23	6.1	203	20	51	58	-	-	"	Inlet field only
5/21	5	15390	161	5.382	0.511	90.71	12.6	11.5	375	2.19	6.84	228	40	55	52	51	57	Max.	-
5/21	6	15430	162	5.406	0.882	83.70	14.7	11.0	175	2.20	3.41	114	40	55	51	-	-	"	Inlet field only
5/22	7	20330	162	5.477	0.842	84.60	10.3	11.0	271	2.90	5.20	173	50	53	44	54	59	Max.	-
5/22	8	20150	162	5.205	0.687	86.80	12.0	11.0	400	2.87	5.20	174	50	60	73	55	68	"	-
5/23	9	12700	160	5.989	0.436	92.80	12.7	10.5	580	1.81	8.29	276	30	57	75	51	67	Max.	-
5/23	10	12210	160	6.132	1.140	81.5	10.0	11.0	339	1.74	4.32	144	30	57	73	-	-	"	Inlet field only
5/25	11	---	Invalid ---																
5/25	12	20400	161	5.667	0.711	87.5	12.8	10.5	356.9	2.91	5.16	172	50	58	60	54	72	Max.	-
5/25	13	20750	161	4.560	0.622	86.3	11.9	11.0	219.2	2.96	5.07	169	50	50	39	50	52	Reduced	-
5/26	14	7540	162	4.862	0.032	99.34	27.5	11.5	884	1.07	14	466	20	52	69	49	66	Max.	-
5/26	15	19300	161	3.886	0.912	76.53	5.9	12.0	72	2.75	5.5	182	50	41	16	40	21	Reduced (?)	-
5/26	16	19190	162	5.163	0.802	84.47		11.5	137	2.73	5.5	183	50	46	24	46	35	"	-
5/27	17	19220	151	5.618	0.797	85.8	10.6	12.9	363	2.74	5.5	183	50	56	59	53	70	Max.	-
5/28	18	21019	171	5.331	1.747	67.23	7.6	11.5	190	2.99	2.5	83	50	58	70	-	-	Max.	Inlet field only
5/28	19	19820	170	4.512	0.412	90.13	15.4	11.5	371	2.82	5.3	177	50	58	69	51	67	"	-
5/28	20	20034	151	5.921	1.642	72.27	9.5	12.5	185	2.85	2.6	88	50	56	67	-	-	"	Inlet field only
5/29	21	19980	161	5.687	0.627	88.97	14.0	11.5	427	2.85	5.3	176	50	59	75	54	76	Max.	-
5/29	22	19880	163	5.428	0.652	87.99	12.9	12.0	444	2.83	5.3	177	50	60	77	55	77	"	No rapping

RR:8313r
Part 2

Table 7-4 (Cont'd)

Date	Test No.	Gas Flow (acfm) (a)	Temp. (°F) (a)	Dust Conc. (gr/dry acf) In	Dust Conc. (gr/dry acf) Out	Efficiency (%)	EMV (cm/sec)	Moisture (%)	Power (watts/1000 acfm)	Gas Velocity (ft/sec) (b)	Contact Time (sec)	SCA (ft^2/1000 acfm)	Nominal Duct Velocity (ft/sec) (c)	Plate Voltage and Current 1st Fld kV	1st Fld mA	2nd Fld kV	2nd Fld mA	Power Status	Remarks
No Injection, Fly Ash Only																			
6/1	23	14610	282	3.99	0.0127	99.68	69.8	8.0	471	2.08	7.27	240	30	47	77	45	73	Max.	-
6/1	24	14270	281	4.70	0.279	94.06	32.9	9.0	237	2.03	3.69	123	30	45	76	-	-	"	Inlet field only
6/1	25	14740	280	4.36	0.0111	99.75	76.6	7.5	478	2.10	7.2	238	30	46	77	47	75	"	-
Injection of Water Only																			
6/2	26	12590	159	4.24	0.0025	99.94	100.0	11.5	622	1.80	8.36	279	30	55	71	52	75	Max.	-
6/2	27	13010	160	3.98	0.0072	99.82	150.0	12.0	331	1.85	4.05	135	30	57	76	-	-	"	Inlet field only
Injection of Calcitic Lime Slurry, 17%																			
6/3	28	12440	159	7.674	0.619	91.93	11.4	12.5	650	1.77	8.5	282	30	56	75	56	75	Max.	-
6/3	29	12350	158	6.810	0.437	93.58	13.5	12.5	649	1.76	8.5	284	30	57	74	52	74	"	-
Injection of Calcitic Lime and Recycled Solids, 20%																			
6/4	30	19710	159	6.765	1.111	83.76	9.4	-	426	2.81	5.3	178	50	59	70	55	78	Max.	-
6/4	31	19960	160	6.621	1.250	81.12	8.0	-	412	2.84	5.3	176	50	60	73	55	78	"	-
6/5	32	12180	159	8.101	1.049	87.05	7.4	12.0	700	1.74	8.7	288	30	57	79	52	78	Max.	-
6/5	33	12280	158	7.862	0.745	90.53	9.9	12.0	634	1.74	8.6	286	30	55	75	50	74	"	-
Injection of Calcitic Lime Slurry, 14%																			
6/6	34	22680	160	3.397	0.918	72.99	5.6	12.0	343	3.2	4.6	155	60	60	66	55	70	Max.	Heavy deposition in duct
6/6	35	22000	162	3.515	0.891	74.64	6.0	13.0	356	3.1	4.8	160	60	60	67	55	70	"	
No Injection, Fly Ash Only																			
6/8	36	21400	284	3.100	0.058	98.13	49.0	8.0	307	3.1	4.9	164	50	46	69	45	78	Max.	-
6/8	37	22230	286	2.899	0.049	98.31	53.9	8.0	290	3.2	4.7	157	50	46	67	45	76	"	-
6/8	38	22650	290	2.100	0.040	98.00	52.0	8.0	305	3.2	4.7	155	50	47	72	46	77	Max.	-
Injection of Water Only																			
6/9	39	Not included - Inlet gas temperature fluctuated greatly, and there was a great deal of unburned carbon.																	
	40	Same as 39.																	
	41	Same as 39.																	
6/10	42	19990	161	2.226	0.0073	99.68	95.2	11.0	402	2.9	5.3	176	50	54	75	54	74	Max.	-
6/10	43	20510	160	2.030	0.0024	99.88	134.0	12.0	407	2.9	5.2	171	50	55	75	55	75	"	-

Table 7-4 (Cont'd)

Date	Test No.	Gas Flow (acfm) (a)	Temp. (°F) (a)	Dust Conc. (gr/dry acf) In	Dust Conc. (gr/dry acf) Out	Efficiency (%)	EMV (cm/sec)	Moisture (%)	Power (watts/1000 acfm)	Gas Velocity (ft/sec) (b)	Contact Time (sec)	SCA (ft²/1000 acfm)	Nominal Duct Velocity (ft/sec) (c)	Plate Voltage and Current 1st Fld kV	1st Fld mA	2nd Fld kV	2nd Fld mA	Power Status	Remarks
Injection of Calcitic Lime Slurry, 17%																			
6/11	44	19720	160	6.879	1.051	84.73	10.1	11.0	400	2.8	5.3	178	50	58	70	54	72	Max.	Injection conditions unstable toward end of test, heavy deposition in duct
6/11	45	19470	158	6.249	1.212	80.61	7.6	12.0	417	2.8	5.4	181	50	59	73	54	71	"	
Injection of Calcitic Lime Slurry, 12%																			
6/12	46	19270	161	5.751	0.984	82.89	8.7	10.5	402	2.8	5.5	182	50	57	69	54	70	Max.	High gas flow suppressed electrical readings
6/12	47	22530	163	4.333	1.200	72.31	5.4	12.0	272	3.2	4.7	156	60	55	54	52	61	"	
6/13	48	19830	160	4.850	0.723	85.10	10.4	12.0	392	2.8	5.3	177	50	57	67	54	72	Max.	Rapping continuous
6/13	49	20250	161	5.711	0.779	86.40	11.7	12.5	379	2.9	5.2	173	50	57	67	54	72	"	No rapping
6/13	50	20280	162	5.402	0.652	88.0	13.2	11.1	379	2.9	5.2	173	50	57	52	52	73	"	Normal rapping
No Injection, Fly Ash Only																			
6/14	51	23970	304	2.744	0.101	96.5	39.1		218	3.41	4.4	146	50	42	61	43	63	Max.	-
6/14	52	24420	289	3.004	0.086	97.14	44.6		276	3.48	4.3	144	50	44	77	44	78	"	-
Injection of Water Only																			
7/23	53	18380	162	1.900	0.010	99.47	73.0	12.0	436	2.62	5.73	193	50	57	73	53	73	Max.	Carbon deposits in outlet thimble
Injection of Calcitic Lime Slurry, 10%																			
7/24	54	19580	159	5.668	0.826	85.43	10.5	11.5	378	2.79	5.38	179	50	57	67	51	71	Max.	
7/24	55	19340	161	4.956	1.377	72.21	4.6	11.8	253	2.75	5.45	181	50	53	50	47	48	Reduced	Power reduced to 2/3
Injection of Water at First, then Immediately Change to Lime																			
7/2	56	11450	158	2.349	0.0030	99.87	73.1	11.3	609	1.63	9.20	307	30	50	70	48	73	Max.	Water injection only
7/2	57	11550	160	4.504	0.205	95.54	16.0	11.5	635	1.65	9.09	304	30	53	74	48	73	"	Calcitic lime inject.
No Injection, Fly Ash Only																			
7/26	58	13000	261	3.729	0.028	99.25	45.0	8.9	463	1.65	8.11	270	50	43	60	44	66	Max.	Erratic boiler opn.; load rising, carbon in outlet thimble
7/26	59	19910	278	2.210	0.050	97.74	41.5	9.0	275	2.84	5.28	176	50	41	66	43	64	"	
7/26	60	13860	278	2.906	0.0151	99.49	55.5	8.8	381	1.97	7.61	253	50	43	60	43	64	"	

Table 7-4 (Cont'd)

Date	Test No.	Gas Flow (acfm) (a)	Temp. (°F) (a)	Dust Conc. (gr/dry scf) In	Dust Conc. (gr/dry scf) Out	Efficiency (%)	EMV (cm/sec)	Moisture (%)	Power (watts/1000 acfm)	Gas Velocity (ft/sec) (b)	Contact Time (sec)	SCA (ft^2/1000 acfm)	Nominal Duct Velocity (ft/sec) (c)	Plate Voltage and Current 1st Fld kV	1st Fld mA	2nd Fld kV	2nd Fld mA	Power Status	Remarks
Injection of Dolomitic Lime Only, 15%																			
7/27	61	12180	158	10.590	0.340	96.80	20.8	11.5	659	1.74	8.62	288	30	53	76	48	75	Max.	-
7/27	62	19580	159	7.519	0.937	87.53	12.3	12.5	412	2.79	5.38	179	50	57	74	52	76	"	-
Injection of Water Upstream and Mixed Lime Downstream																			
7/28	63	11614	159	11.010	0.289	97.40	22.3	12.0	648	1.65	9.09	302	30	55	73	49	73	Max.	-
7/28	64	20222	161	6.432	0.380	94.1	23.4	12.0	407	2.88	5.21	174	50	58	73	54	74	"	-

Note: Temperature conditions established in evening and maintained until morning when ESP testing began. All tests on a given day were completed within 8 hours of start of ESP testing.
(a) Gas flow and temperature measured at upstream particulate sampling point, after injection
(b) Gas velocity through ESP
(c) Gas velocity in test duct, upstream of any injection

and at ESP inlet temperatures from 275°F down to 165°F, producing ESP velocities of 2.2 to 2.7 ft/sec.

Table 7-3 shows that particulate concentrations in the gas leaving the ESP were not affected much by injecting the lime slurry. Injection of slurry improved the removal efficiency, compared with no injection, enough to offset the higher inlet loading.

The one test with only water injected to cool the gas to 184°F gave the lowest emissions of all and a removal efficiency comparable to that with lime injection.

The above results were as expected from the experience of other installations with ESPs cleaning flue gas from spray dry FGD systems.

7.3.2 Second Series of Tests - Without Injection of Lime

In the second series of tests, 20 tests were carried out without injection of lime to provide a basis for evaluating ESP performance when lime was injected. Eleven of these tests were with fly ash only - without any injection. In the other nine tests, water was injected to bring the gas temperature down to 160°F. For the tests with no injection, the gas temperature ranged from 260°F to 300°F.

Effect of Gas Velocity and SCA. For the tests with no injection, collection efficiency ranged from 99.75 percent at a gas velocity through the ESP of 2.10 ft/sec (238 SCA) to 96.32 percent at 3.41 ft/sec (147 SCA). With injection of water, the efficiency was higher: 99.94 percent at 1.79 ft/sec (279 SCA) to 99.47 percent at 2.62 ft/sec (191 SCA). Figure 7-2 shows how the efficiency fell off with gas velocity, and although the points are scattered, injection of water (fly ash plus moisture points) clearly increased efficiency. At a given mass flow of gas, part of the improvement in efficiency from injection of water is that the gas is cooled and the lower volume and lower velocity through the ESP gives more time for collection of particles. However, Figure 7-2 shows that even at the same velocity, collection from the cooler moist gas was higher. This improved performance with water injection may be partially the result of agglomeration of fine particulate into more easily collected larger particulate.

For the data in Figure 7-2, both ESP fields were energized to maximum power. Single-field-only tests with the outlet field de-energized gave an efficiency of 94.06 percent at 2.03 ft/sec with no injection in test 24. With water injection, two single-field tests (tests 27 and 41) gave efficiencies of 99.82 percent and 98.83 percent at gas velocities of 1.85 and 2.99 ft/sec, respectively. Again, moisture injection increased the efficiency.

Figure 7-3 shows that the collection efficiency both with and without water injection improved with the precipitator's SCA. This would be expected from the decrease in efficiency with gas velocity since here SCA varies inversely with gas velocity. The data plotted in Figure 7-3 are from tests at maximum power; they include tests with both one and two fields energized.

Effect of Temperature. No attempt was made to evaluate the effect of temperature (other than the gross differences with and without water injection) on either of the sets of tests without lime injection. For "fly ash + moisture," the temperature was held at a nominal 160°F.

Under "fly ash only" conditions, the temperature ranged from 260°F to 300°F, depending on prevailing boiler conditions. However, as other variables were changing over this temperature range (i.e., inlet dust loading, boiler operational conditions, precipitator gas velocity, etc.), it was not feasible to attempt any correlation with temperature.

The improved efficiency with water injection compared to no injection is due to the lower temperature, the higher moisture content of the gas, and to the agglomeration of the fine particulate.

Effect of Power Input. Fly ash collection efficiency increased by increasing the power input, as Figure 7-4 shows. The most power was absorbed in two of the tests with water injection (fly ash + moisture). These data include tests where power input was deliberately reduced.

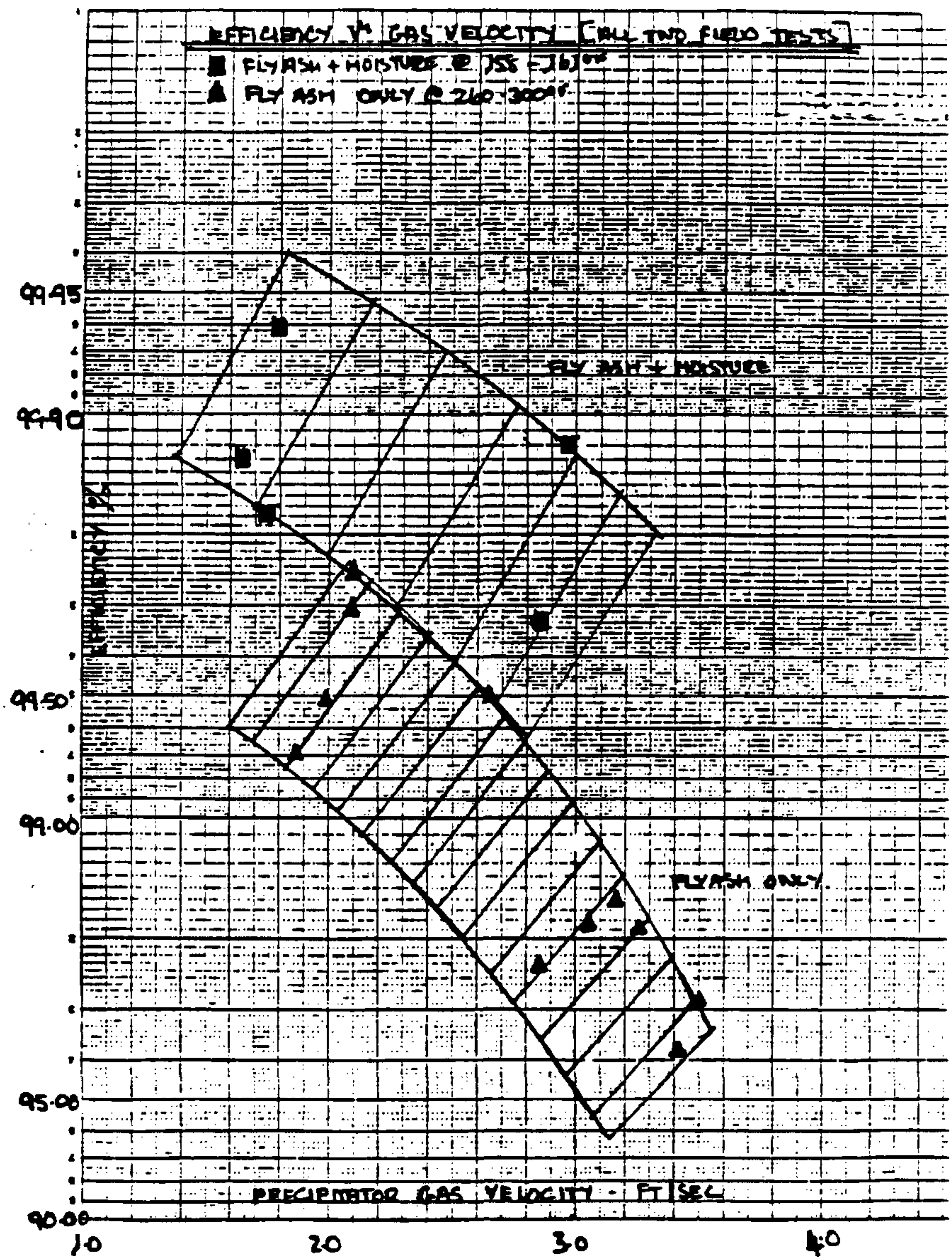


Figure 7-2 Efficiency vs Gas Velocity, All Two Field Tests

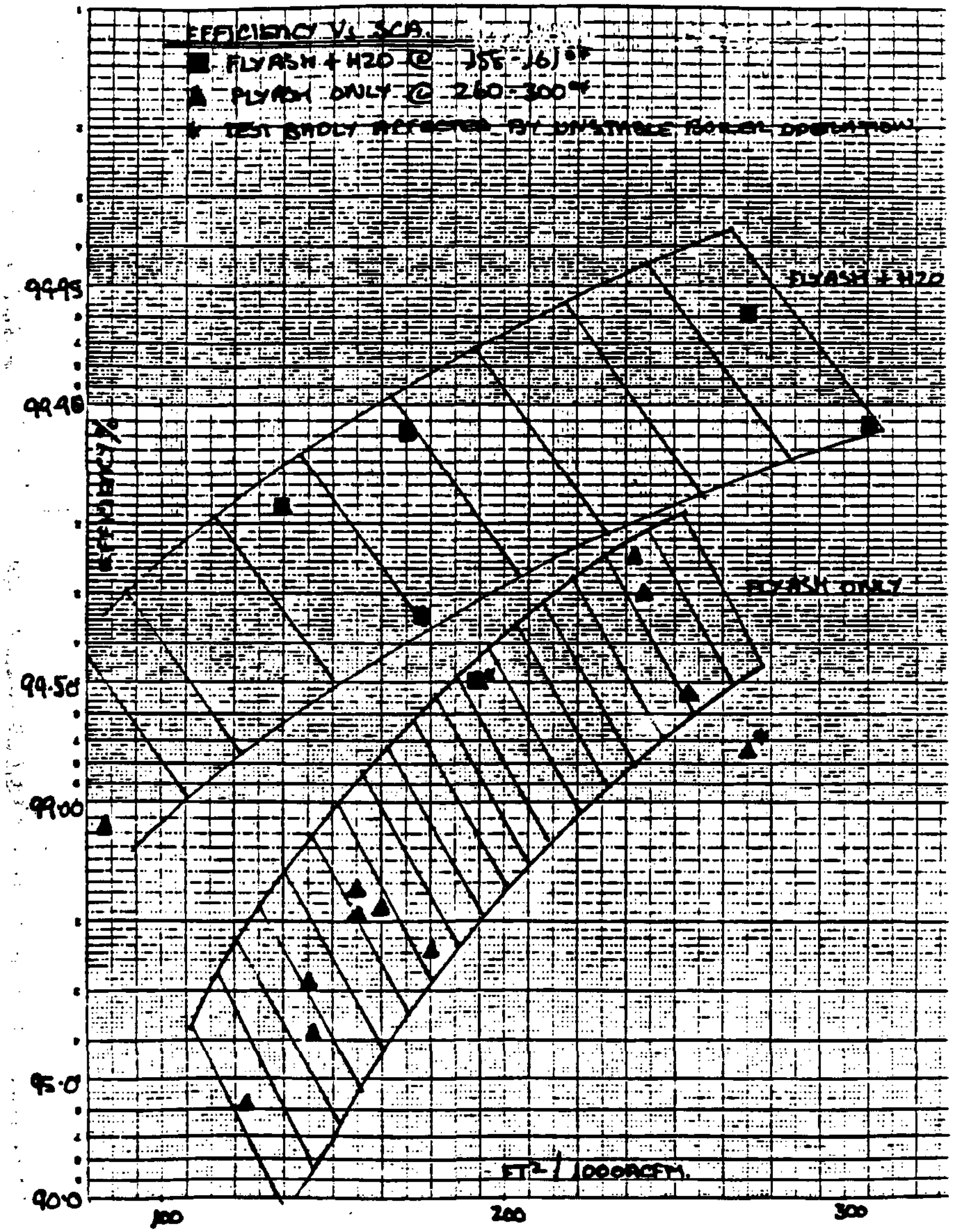


Figure 7-3 Efficiency Versus SCA

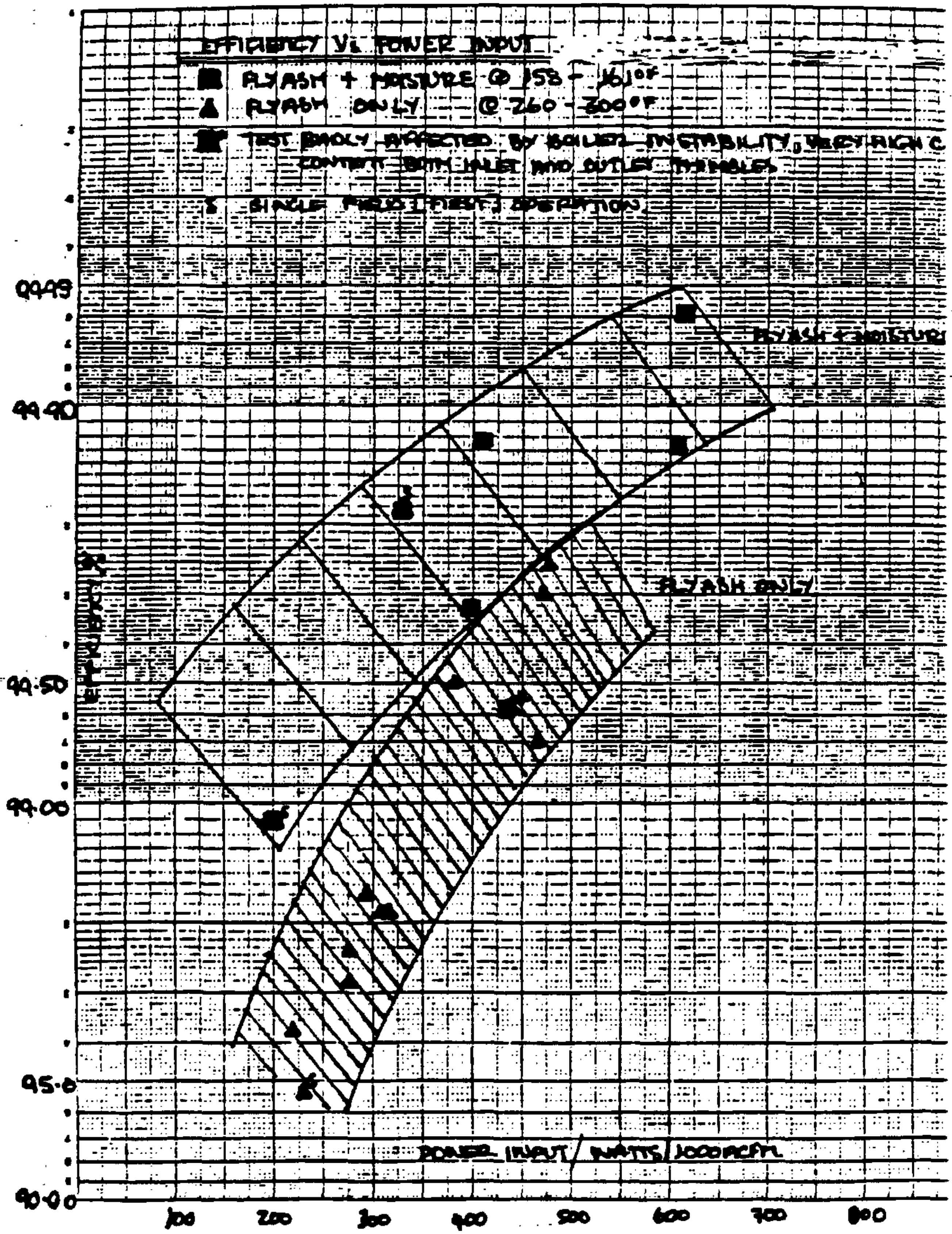


Figure 7-4 Efficiency Versus Power Input

Figure 7-4 also shows that the tests with water injection gave significantly higher removal at a given level of power. Typical performance without injection in other ESPs collecting fly ash is similar to the following results with water injection (Reference 7-3):

- 100 W/1,000 acfm, approximately 96 percent removal
- 200 W/1,000 acfm, approximately 99.5 percent removal
- 300 W/1,000 acfm, approximately 99.6 percent removal
- 400 W/1,000 acfm, approximately 99.8 percent removal

The fact that these tests without injection gave lower-than-expected collection efficiencies at given power inputs is probably due to the design or operational characteristics of this system. The poorer performance should not affect the comparisons of performance with and without injection, the primary purpose of these tests.

Effect of Rapping. During the fly-ash-based tests, an attempt was made to evaluate the effect of rapping on performance. This involved two tests on June 8, 1987, both without injection of water. Test 37 was run as a "base level" test and test 38 was run under similar conditions but with collector rapping set to "continuous" (12 raps per hour). Table 7-5 shows the results.

Table 7-5

EFFECT OF RAPPING WITHOUT WATER

Test No.	Gas Velocity (ft/sec)	Inlet Loading (gr/dscf)	Outlet Emission (gr/dscf)	Collection Efficiency (%)	EMV (cm/sec)	Power (W/1000 acfm)	Gas Temp. (°F)
37	3.17	2.899	0.049	98.31	13.13	290	286
38	3.23	2.100	0.040	98.10	12.98	305	290

As can be seen, there was no appreciable observed effect from the increase in rapping.

7.3.3 Second Series of Tests - With Lime Injection

It is evident from Table 7-4 that in the tests from May 19 to July 28, ESP performance was considerably poorer when lime was injected than when it was not. A considerable effort was made to find an explanation since these findings were so contrary to previous findings and to the results of the first series of tests at the start of the program in November 1986.

In this subsection, the results of the tests with lime injection are presented, followed by a discussion of what may have caused the lower-than-expected efficiency.

Of the 39 tests with lime injection, 31 were with calcitic lime injection. In four tests, a slurry of calcitic lime and recycled waste solids was injected. Two tests used dolomitic lime, and two a mixture of calcitic and dolomitic limes. Table 7-4 lists the reagents injected and their concentrations.

Effect of Gas Velocity and SCA - With Lime Injection. Figure 7-5 shows all of the tests with lime injection that used the maximum possible input of power. With calcitic lime injected, the collection efficiency (percentage) fell from the low 90s to the mid-80s as gas velocity increased from 1.75 to about 2.8 ft/sec through the ESP. Note in Figure 7-2 that with no injection, efficiency decreased also, but from about 99 percent to about 98 percent as gas velocity rose from 2 to about 3.2 ft/sec.

In Figure 7-5, the efficiencies for collecting the solids from dolomitic lime injection were somewhat higher, and those from calcitic lime plus recycled solids were somewhat lower, than the results with calcitic lime. (The two tests with mixed lime, tests 63 and 64 in Table 7-3, were considered as dolomitic lime.)

The three tests with calcitic lime at low velocity, at about 1.2 ft/sec in Figure 7-5, show considerably higher removal efficiencies, comparable to those with no injection.

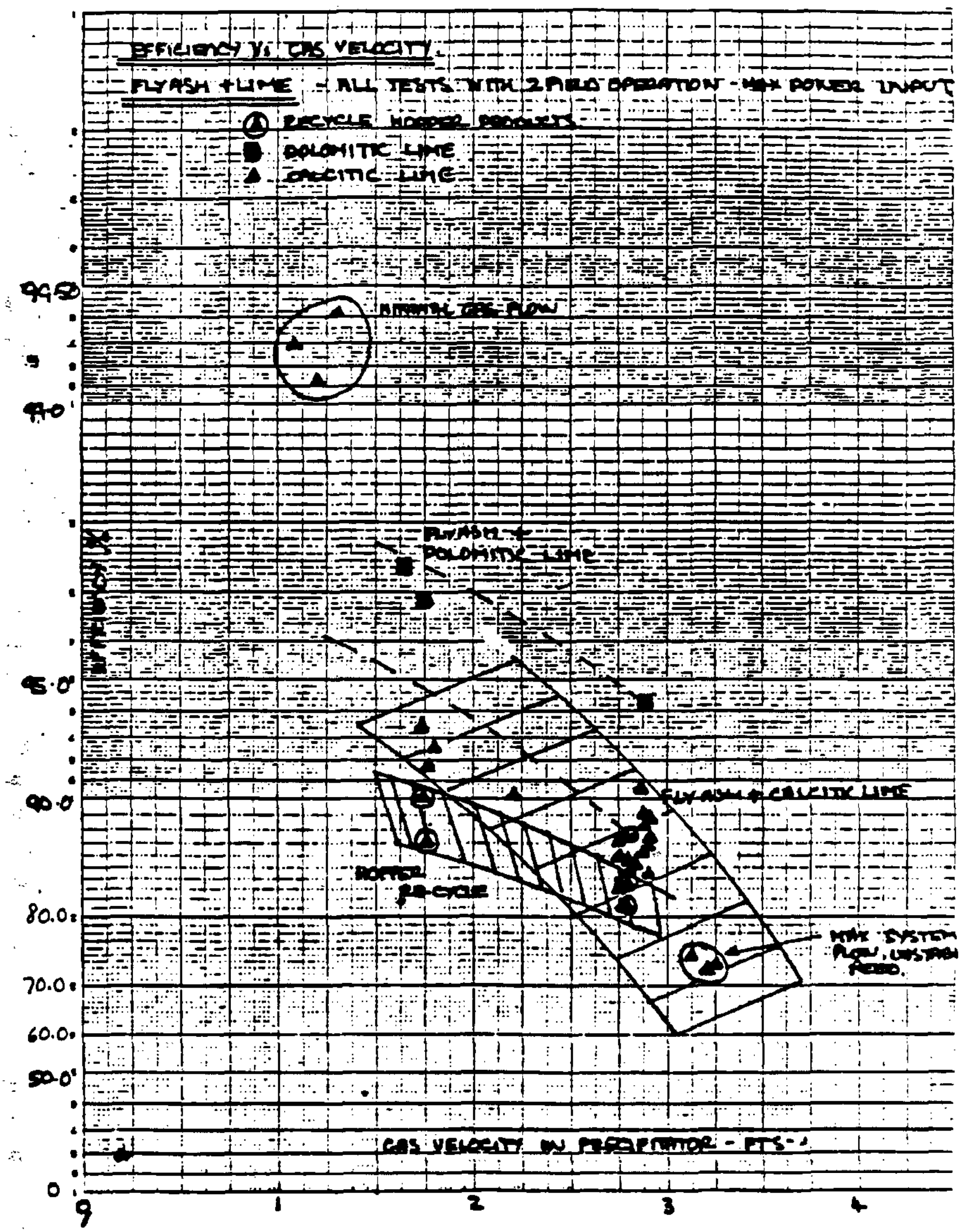


Figure 7-5 Efficiency Versus Gas Velocity

Figure 7-6 is a plot of collection efficiency versus SCA for injection with the three slurries: calcitic lime, calcitic lime plus recycled solids, and dolomitic lime (including the mixed dolomitic and calcitic limes). This plot includes test data with only the first field energized for the lower values of SCA.

Figure 7-6 shows that collection falls off rapidly as SCA decreases. This rapid falloff of performance as SCA decreases (velocity increases) could be due to several factors. Included in these factors would be nonuniform gas velocity distribution causing reentrainment of ash from the collection plates or hoppers, and carryover of wet material into the precipitator when injecting slurry. A lack of sufficient drying time could cause electrical tracking and deteriorated precipitator performance. This is discussed in subsequent sections of this report.

Figure 7-6 also indicates deteriorated performance at all velocities when injecting slurry, as compared with operation with no slurry injection (see Figure 7-3).

Effect of Gas Temperature. Most of the tests with lime injection were carried out with the gas temperature downstream of injection close to 160°F. However, several tests were made at about 170°F and 150°F. Table 7-6 shows four groups of these data with the comparable tests in order of increasing temperature. The first group, at the higher gas velocity and with both fields energized, clearly shows performance improving as temperature goes up. The second group, tests 20 and 18, shows just the opposite. The last two groups, tests 1 and 3 and tests 2 and 4, at low velocity, show a slight decrease in performance at the higher temperature.

To decide whether this contradiction is due to random scatter in the data or to a real effect, replicated ESP tests were tabulated in Table 7-7. The first group in Table 7-7 is for conditions that correspond to the first group in Table 7-6: injection of 12 percent calcitic lime into gas flowing in the duct at 50 ft/sec. At 160°F, the average removal in these seven replicated tests was 86.3 percent. However, the standard deviation among the seven tests is

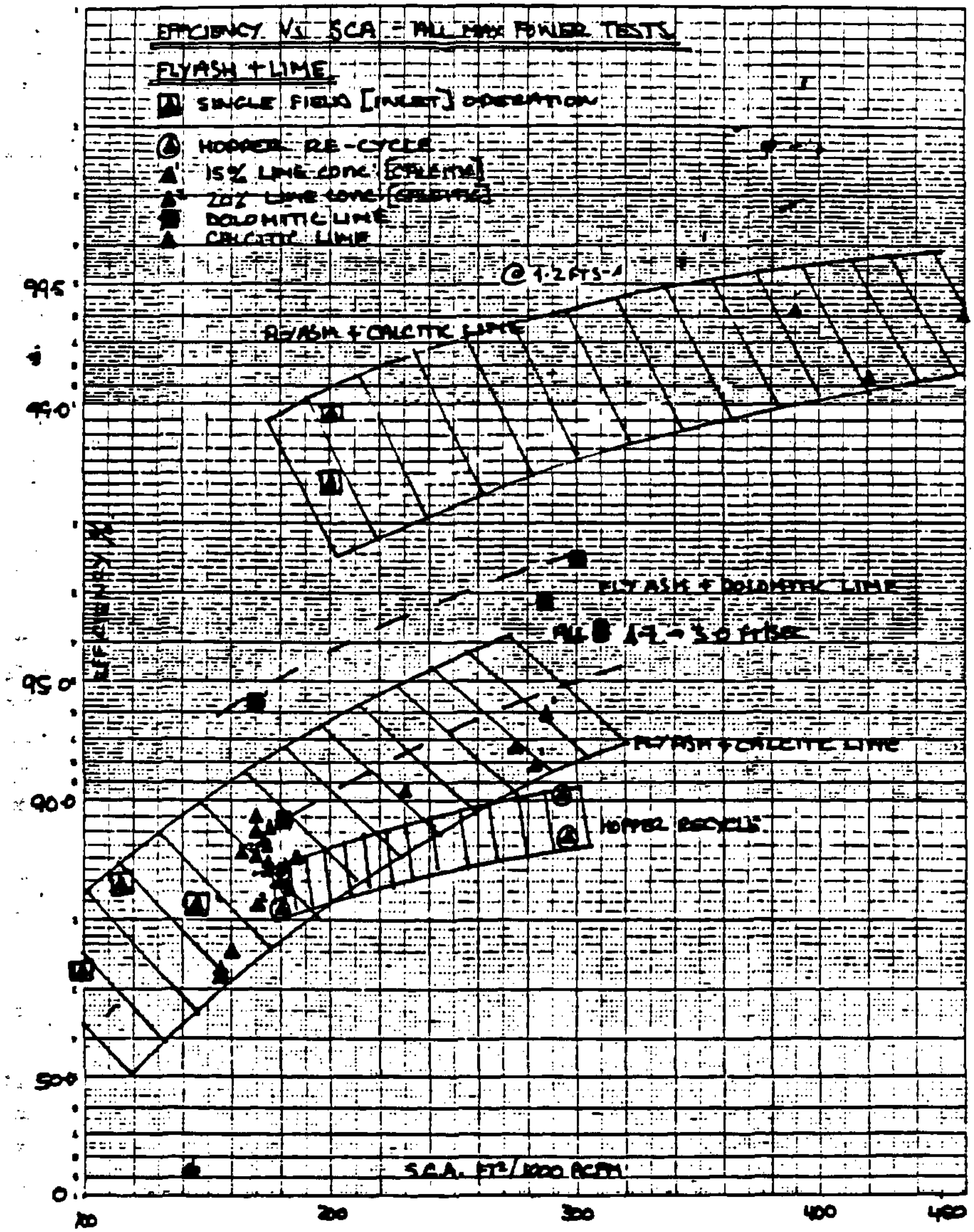


Figure 7-6 Efficiency Versus SCA, All Maximum Power Tests

Table 7-6

EFFECT OF GAS TEMPERATURE ON ESP COLLECTION EFFICIENCY

Test No.	Gas Temp. (°F)	No. of Fields	Gas Velocity (ft/sec)	Particulate Concentration (gr/dscf) Inlet	Outlet	Collection Efficiency (%)	EMV (cm/sec)
17	159	2	2.74	5.618	0.797	85.81	10.6
21	161	2	2.85	5.687	0.627	88.97	14.0
19	170	2	2.82	4.512	0.412	90.87	15.4
20	151	1	2.85	5.921	1.642	72.27	9.5
18	171	1	2.99	5.331	1.747	67.23	7.6
1	148	2	1.28	4.098	0.024	99.41	34.1
3	161	2	1.20	4.360	0.038	99.13	27.4
2	148	1	1.24	4.881	0.059	98.79	49.0
4	159	1	1.23	4.050	0.066	98.37	42.4

2.12 percent. If random errors cause the deviations, 95 percent of similar tests would be expected to show removals within 2.5 standard deviations of the average. Therefore, random variations would cause measured removals to vary between 81.0 and 91.6 percent in 95 percent of similar tests. Thus, the range of removals shown in tests 17, 21, and 19 in Table 7-6 could very well be due to random variations in the measurements.

The same conclusion applies to the three other pairs of data in Table 7-6 showing collection efficiency at different temperatures. Therefore, any effect of gas temperature on collection efficiency is too small to be evident from the data in Table 7-6. The temperature range was too limited to show any decisive effect over the range of precision of the data.

Effect of Lime Concentration. Four tests were carried out at a higher (17 versus 12 percent) concentration of calcitic lime slurry to evaluate the effect on ESP performance. Tests 28 and 29 were run at 30 ft/sec (SCA = 280), and tests 44 and 45 were run at 50 ft/sec (SCA = 180).

Table 7-7

REPLICATED ESP TESTS

Test No.	Gas Temp. (°F)	Removal Efficiency (%)	Outlet Particulate Concentration (gr/dscf)	Voltage and Current 1st Fld (kV/mA)	Voltage and Current 2nd Fld (kV/mA)
Injection 10 to 12% calcitic lime slurry; nominal inlet gas velocity, 50 ft/sec					
7	160	84.6	0.842	53/44	54/59
8	160	86.8	0.687	60/63	55/68
12	160	87.5	0.711	58/60	54/72
21	160	88.97	0.627	59/75	54/76
46	160	82.89	0.984	57/69	54/70
50	160	88.0	0.652	57/52	52/73
54	160	85.43	0.826	57/67	51/71
Avg./std. dev.		86.31/2.12	0.761/0.128		
No injection; nominal inlet gas velocity, 50 ft/sec					
36	284	98.13	0.058	46/69	45/78
37	286	98.31	0.049	46/67	45/76
38	290	98.00	0.040	47/72	46/77
51	304	96.5	0.101	42/61	43/63
52	289	97.14	0.086	44/77	44/78
59	278	97.74	0.050	41/66	43/66
Avg./std. dev.		97.64/0.69	0.064/0.024		
No injection; nominal gas velocity, 30 ft/sec					
23	282	99.68	0.0127	47/77	45/73
25	280	99.75	0.0111	46/77	47/75
58	261	99.25	0.028	43/60	44/66
60	278	99.49	0.0151	43/60	43/64
Avg./std. dev.		99.54/0.22	0.0162/0.0066		
Injection of water only					
42	160	99.47	0.010	54/75	54/74
43	160	99.68	0.0073	55/75	55/75
53	160	99.88	0.0024	57/73	53/73
Avg./std. dev.		99.68/0.21	0.0066/0.0039		

The results for tests 28 and 29 were almost the same as those from test 9 with 12 percent slurry and comparable conditions. Likewise, test 44 with 84.73 percent removal compares closely to the average removal of 86.31 percent from the seven similar tests with 12 percent slurry (see Table 7-7). Test 45 gave a lower removal, 80.61 percent, but unstable injection conditions make this result questionable. Thus, changing the lime concentration from 12 to 17 percent seems to have had little effect on the ESP.

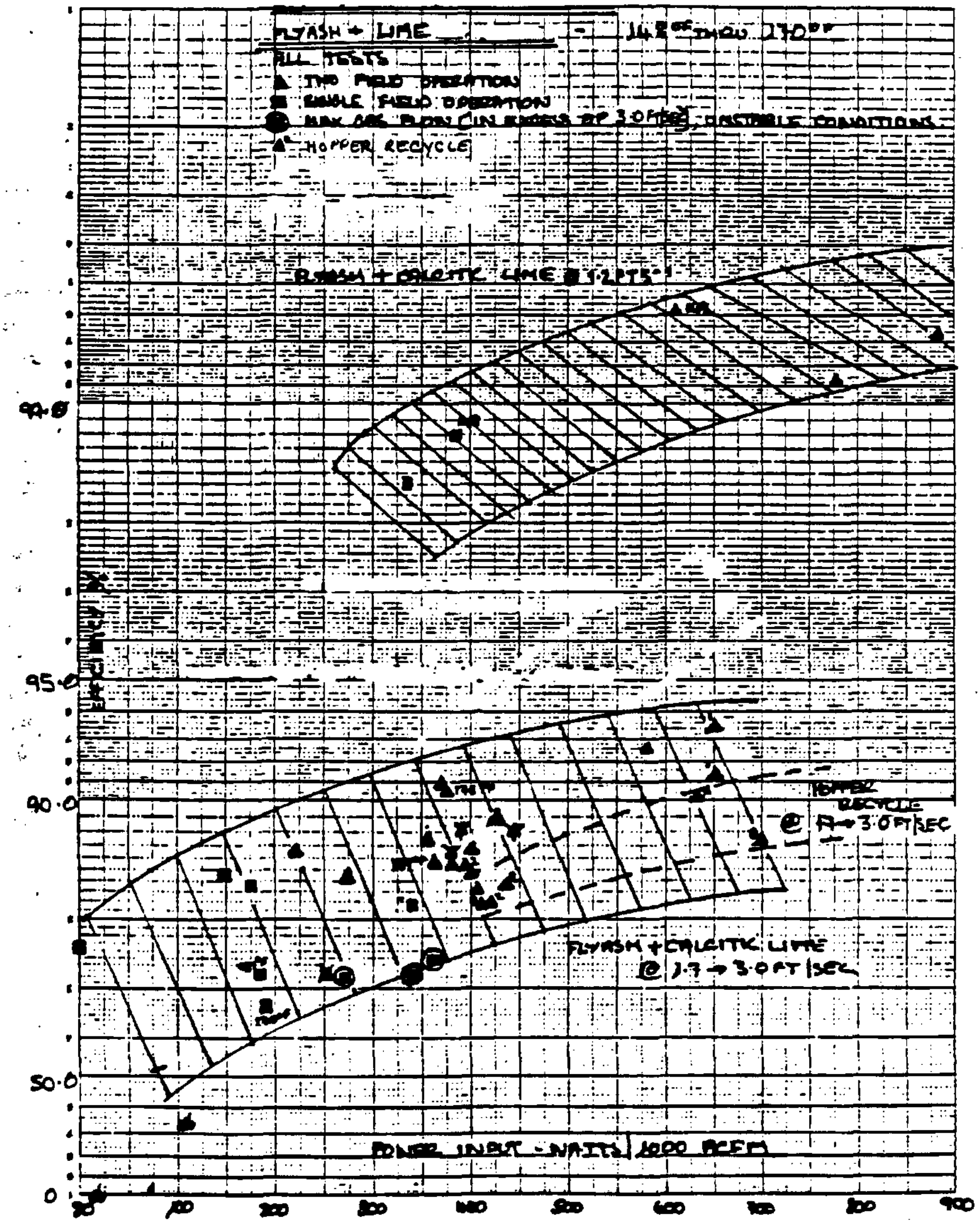
Effect of Power Input with Lime Injection. Figure 7-7 shows how collection efficiency increased with power input when lime was injected. Note that the tests at low gas velocity through the ESP (approximately 1.2 ft/sec) are again plotted separately, since their removal efficiencies were so much greater than the other tests with lime injection.

The test results shown in Figure 7-7 are for calcitic lime. Tests include one field only, those at reduced power, and those with different rapping conditions. The four tests with recycled solids mixed with the lime gave removals similar to those with calcitic lime alone.

In general, the maximum power levels were higher and the increases in efficiency with power levels were lower with lime injection than they were with fly ash alone (compare Figure 7-7 with Figure 7-4). In addition, at a specific power input the range of removal efficiencies was much lower for lime injection than without.

Figures 7-8 and 7-9 also show how collection increased with power whether lime was injected or not. They also point out that efficiencies of ESPs collecting fly ash in coal-fired power plants (Reference 7-3) are typically higher than those that were observed in these tests with fly ash alone or when lime was injected.

Effect of Rapping. Four tests were made to evaluate the effect of rapping when calcitic lime (CL) was injected. All four tests were carried out at a gas flow of 50 ft/sec, approximately 20,000 acfm at the ESP inlet (corresponding to a precipitator gas velocity of 2.7 to 3.0 ft/sec and SCA of 173 to 177), a temperature of 160°F, and with maximum power input.



Figue 7-7 Efficiency Versus Power Input

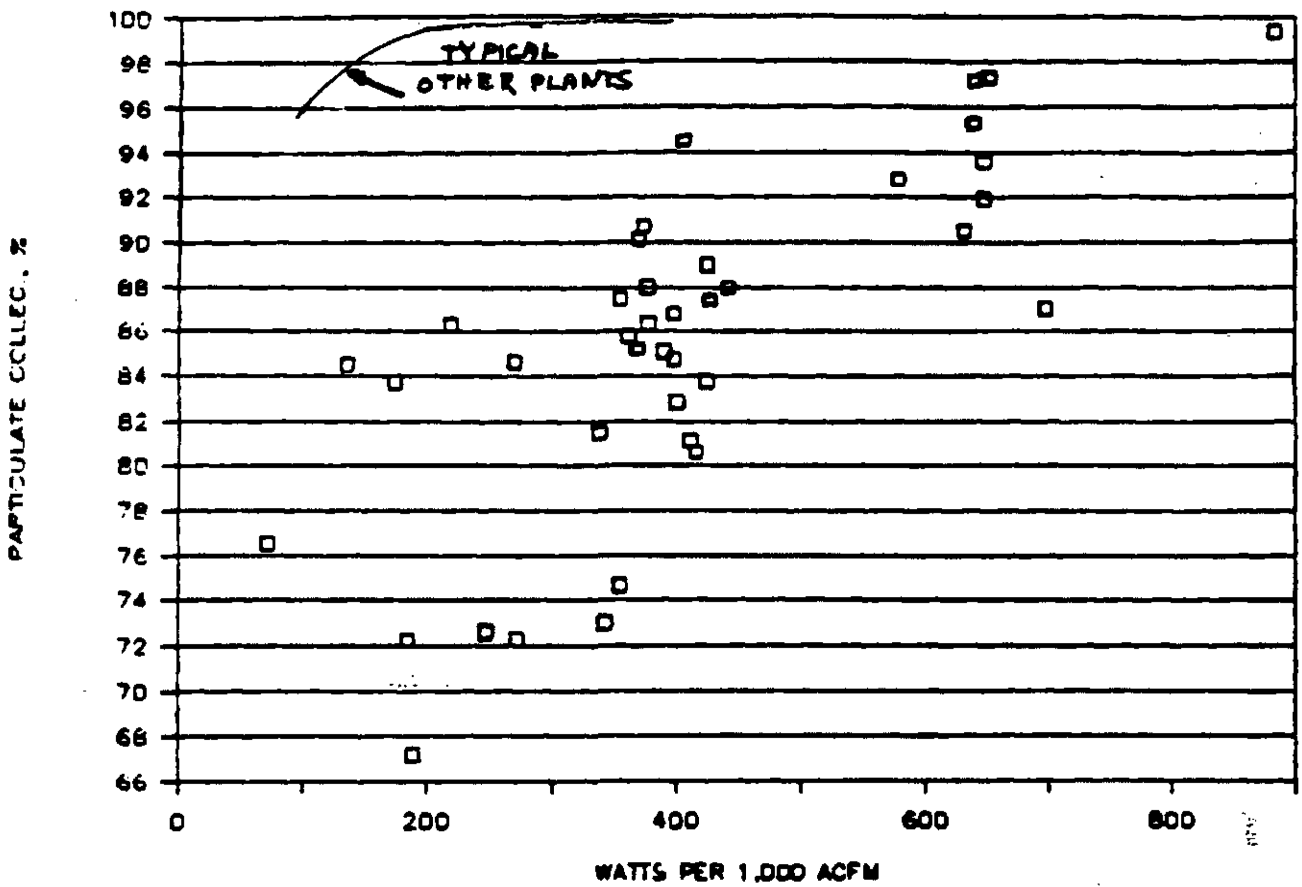


Figure 7-8 Power Versus Collection, Tests with Slurry Injection

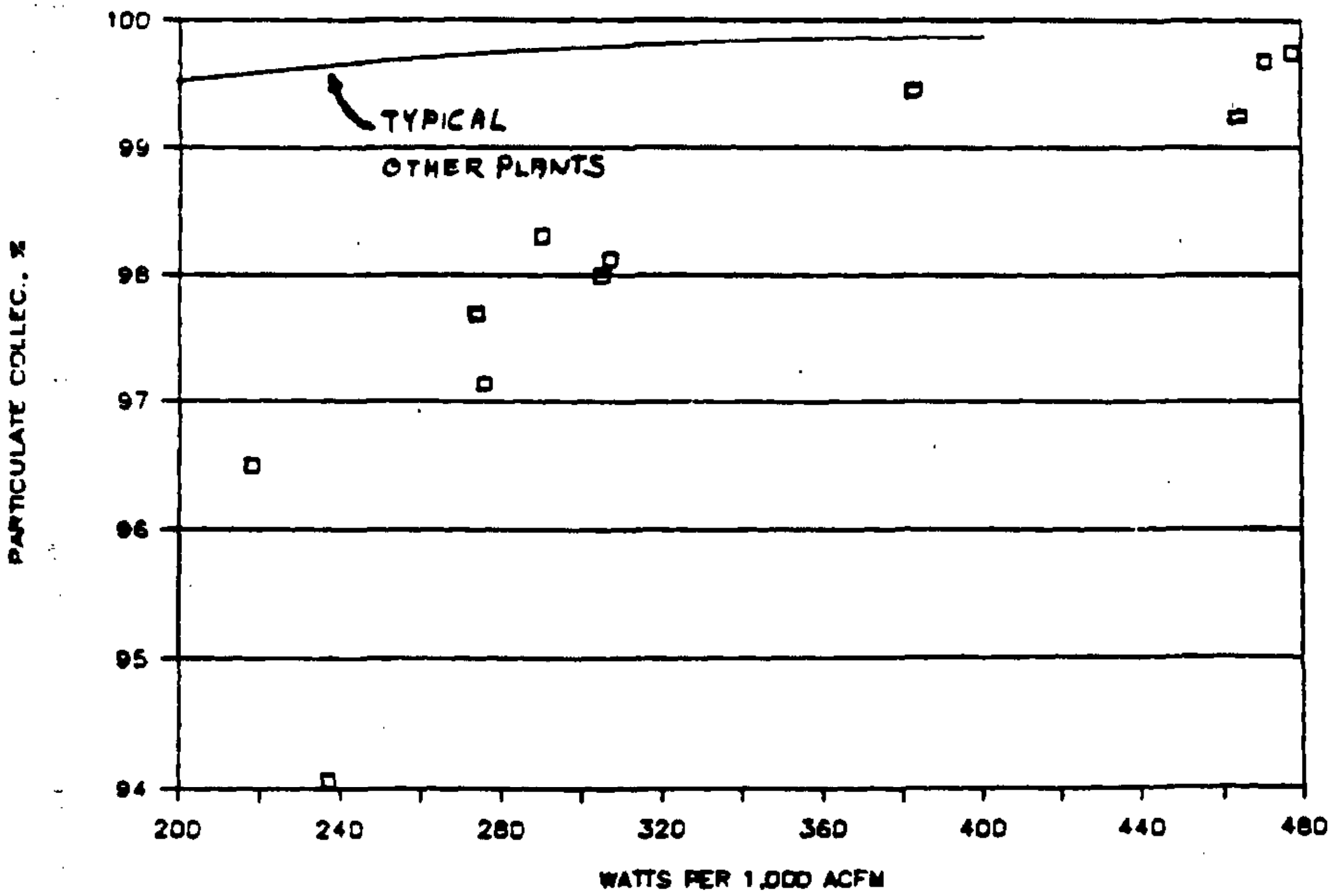


Figure 7-9 Power Versus Collection, Tests with No Injection

The tests indicated that rapping frequency did not affect performance.

Test 21 on May 29, 1987, was used as a base test under normal conditions as stated above, while test 22 was carried out with no rapping of the collector plates. Table 7-8 shows the results.

Table 7-8

COMPARISON A - EFFECT OF RAPPING

Test No.	Inlet Loading (gr/dscf)	Outlet Emission (gr/dscf)	Collection Efficiency (%)	
Test 21	5.687	0.627	88.97	Normal rapping
Test 22	5.428	0.652	87.99	No rapping

On June 13, 1987, three tests were carried out, test 48 with continuous collector rapping, and tests 49 and 50 with no rapping. Table 7-9 shows the results.

Table 7-9

COMPARISON B - EFFECT OF RAPPING

Test No.	Inlet Loading (gr/dscf)	Outlet Emission (gr/dscf)	Collection Efficiency (%)	
Test 48	4.850	0.723	85.09	Continuous rapping
Test 49	5.711	0.779	86.36	No rapping
Test 50	5.402	0.652	87.93	No rapping

Although there is some variation in inlet loading and emissions during these three tests, the performance is essentially the same. However, it might be noted that boiler load gradually climbed during the test periods and that raw gas temperatures to the system rose from an initial 290°F to 330°F. It is also noted that the inlet filter sample had a distinct "fly ash" coloration following tests 49 and 50, whereas following test 48, it had a predominately white "lime" coloration.

Particle Migration Velocity. Figure 7-10 is a plot of effective migration velocity (EMV, calculated using the Deutsch equation with k = 0.5) as a function of gas velocity for all the tests made at full power. Injection of water alone gave the highest migration velocities, 70 to 150 cm/sec. Fly ash only with no injection was next highest, from about 40 to 80 cm/sec, while most of the points for calcitic lime injection were much lower, between 5 and 15 cm/sec. The five points for lime injection falling between 25 and 50 cm/sec are the tests at 20 ft/sec (1.2 ft/sec through the ESP), that gave collection efficiencies very much higher than the rest of the lime injection tests. The three EMV values between 20 and 25 cm/sec with lime injection were from tests with dolomitic lime and with mixed lime.

From Figure 7-10, EMV seems to fall off somewhat as the gas velocity increases. Actually, according to the assumption of the Deutsch equation, EMV should remain constant as gas velocity changes.

Figure 7-11, showing EMV as a function of ESP power input, gives an excellent correlation for the tests without injection (the empirically fitted curve labeled DRY). EMV values increase with increasing power input, as they should. For the tests with calcitic lime injection, which includes all the points with EMV values below 20 cm/sec, the EMV rises much less than expected as power input increases. This fact suggests that the power was not used effectively, and that there may have been leakage across insulators, possibly caused by localized moisture in the dry solids.

Figure 7-12 shows the effect of long-term operation on performance as judged by migration velocity. Initially, performance decreased with operating time. This may have been a "conditioning effect" on the precipitator. It has been Bechtel's experience that most precipitators deteriorate for a few days from a new condition. Eventually, a steady-state condition is reached. During the Campbell testing, deterioration continued. It is suspected that power tracking or shorting somewhere in the precipitator was increasing with time.

A break in the degradation occurred after test 22 where a period of operation with no injection and a period of water spray operation occurred. However, the performance decline again continued from tests 28 through 35.

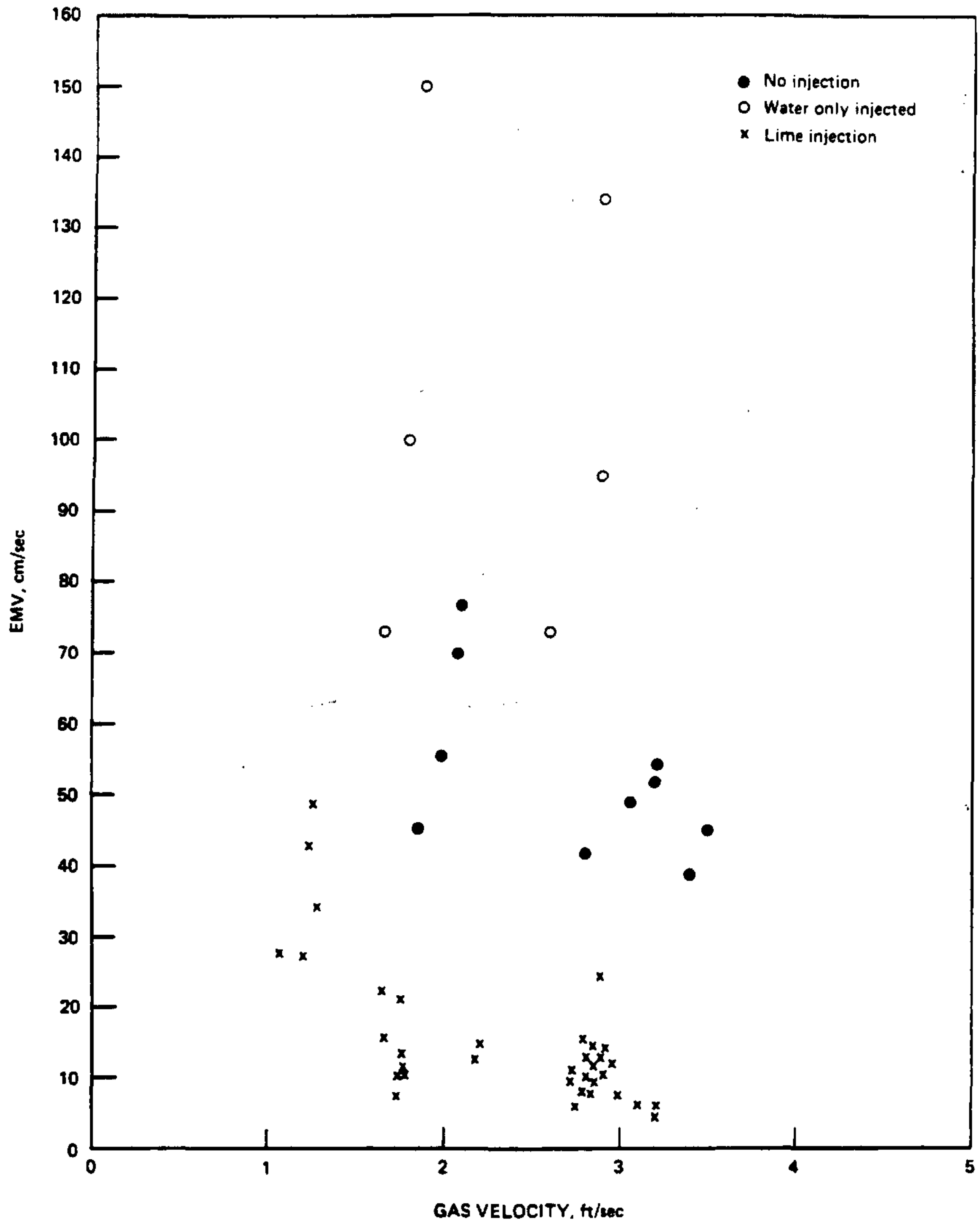


Figure 7-10 Variation of EMV with Gas Velocity

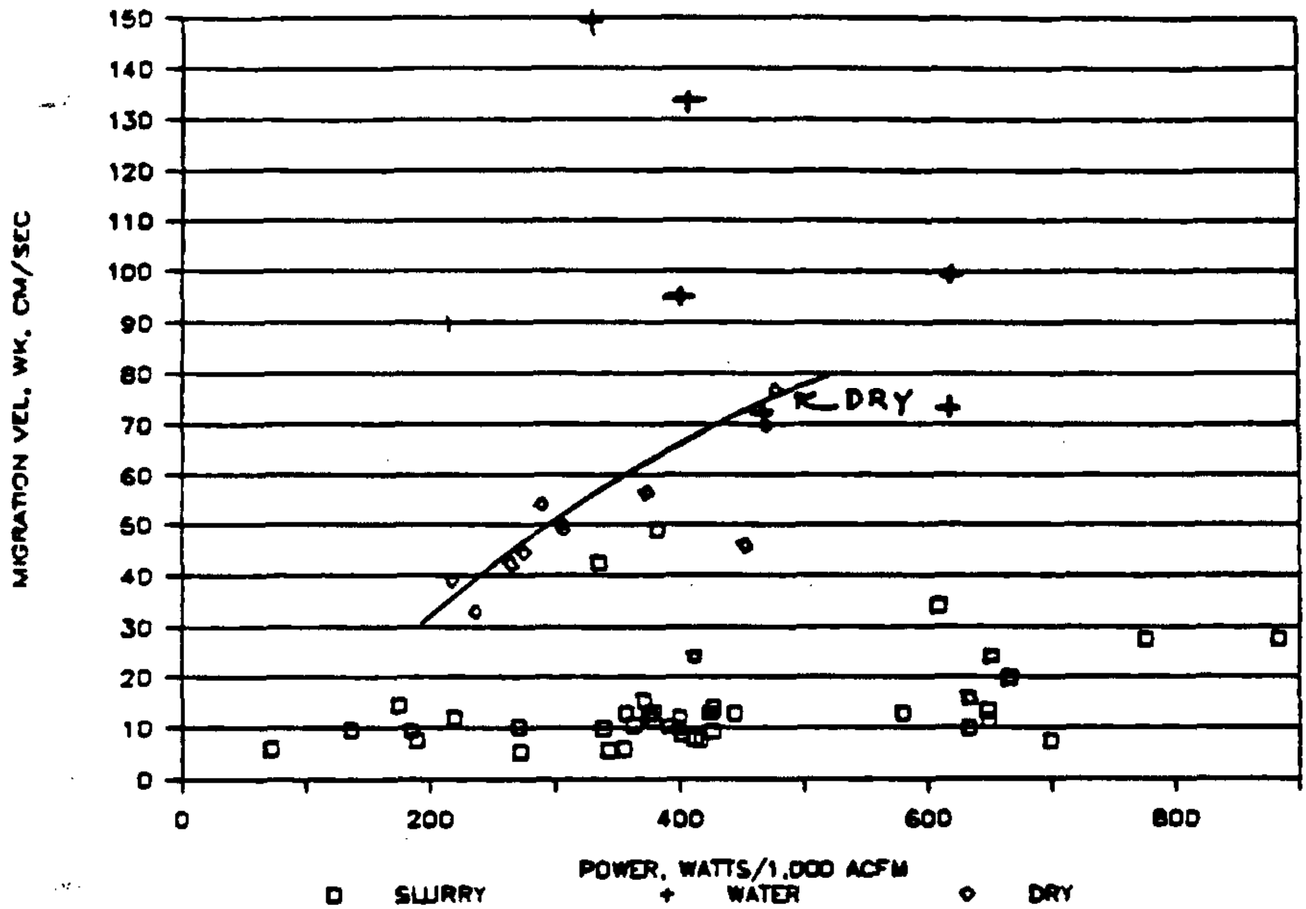


Figure 7-11 Effect of Power on Migration Velocity

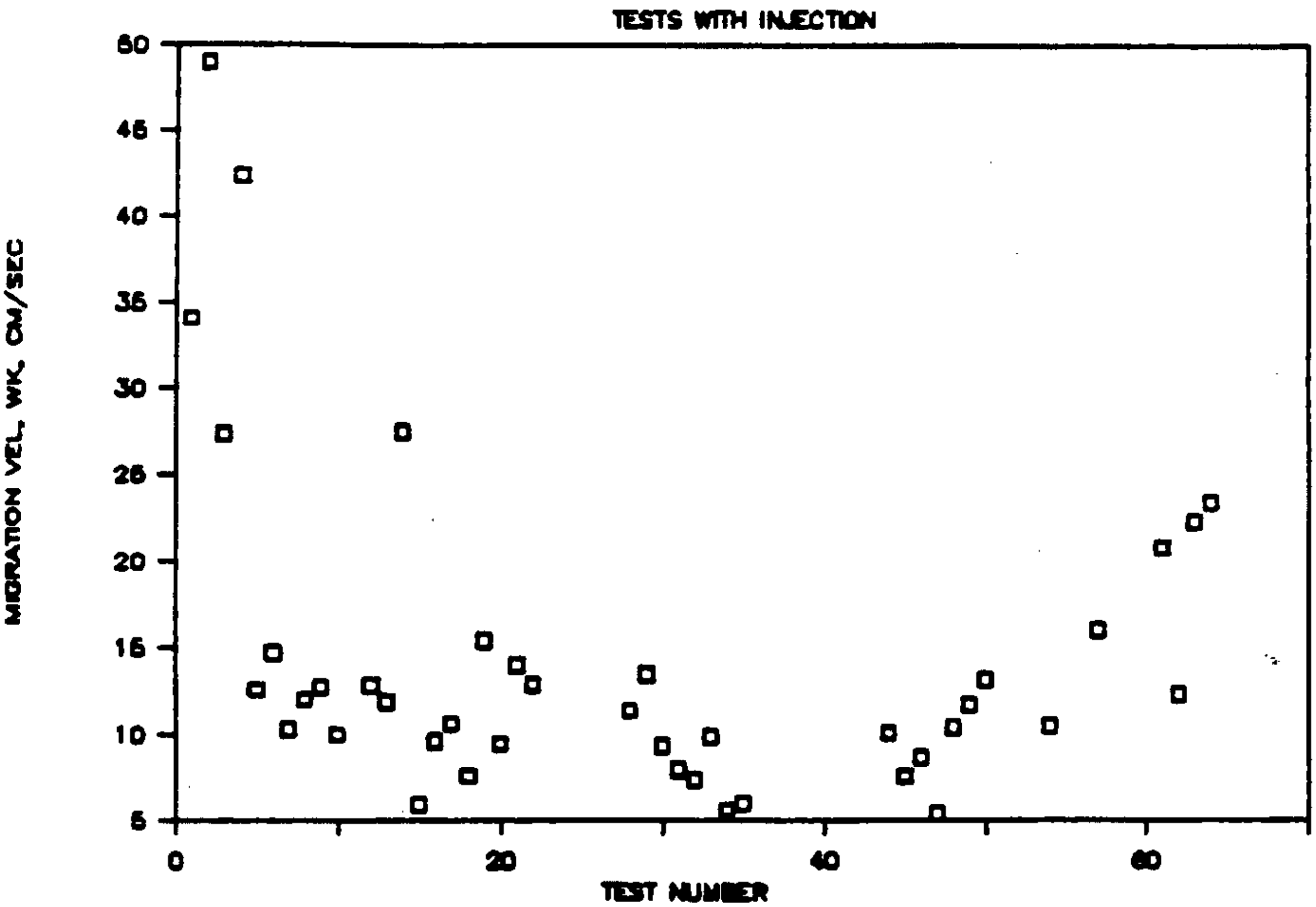


Figure 7-12 Migration Velocity History

The period of ash-only and water-only operation of tests 36 to 43 changed the performance trend. Tests 46 through 64 generally produced a trend of improving performance.

Injection of Dolomitic Lime. Two tests (61 and 62) were made with a 15 percent slurry of dolomitic lime injected. (Two other tests, tests 63 and 64, used a mixture of dolomitic and calcitic limes. These will not be considered here because lime slurry was injected only through the downstream nozzle, and water was injected upstream.)

Test 61 at 30 ft/sec removed 96.79 percent of the particulate matter. Comparisons with other similar tests using calcitic lime, all at 30 ft/sec and 160°F, are shown in Table 7-10.

Table 7-10

COMPARISON A - DOLOMITIC VS CALCITIC LIME

Test No.	Dust Concentration (gr/dscf) Inlet	Outlet	Efficiency (%)	EMV (cm/sec)	
61	10.590	0.340	96.79	20.8	Dolomitic lime, 15%
9	5.989	0.436	92.80	12.7	Calcitic lime, 12%
28	7.674	0.619	91.93	11.4	Calcitic lime, 17%
29	6.810	0.437	93.58	13.5	Calcitic lime, 17%

The other test (see Table 7-11) with dolomitic lime, test 62, at 50 ft/sec can be compared with the average of the calcitic lime tests at 50 ft/sec and 160°F.

Table 7-11

COMPARISON B - DOLOMITIC VS CALCITIC LIME

Test No.	Dust Concentration (gr/dscf) Inlet	Outlet	Efficiency (%)	EMV (cm/sec)	
62	7.519	0.937	87.53	12.3	Dolomitic lime, 15%
Av. of 7 tests	5.559	0.761	86.31	11.6	Calcitic lime, 12%

While the two comparisons show improved removal with dolomitic lime, the result is inconclusive. Improvement was very slight in one case and only two tests were made with the PHDL.

In the earlier tests with dolomitic lime, in November 1986, the ESP performance was better than in tests 61 and 62. Collection efficiency in the earlier tests ranged from 97.1 to 99.0 compared with 87.5 and 96.8 in these two later tests. Therefore, whatever adverse conditions contributed to the poor ESP performance with the calcitic lime also operated to cause poorer performance with these two dolomitic lime tests.

Effect of Conditioning Time. Tests 56 and 57 were run to see whether conditioning the ESP by keeping the conditions of the test (except for gas velocity) constant for 10 to 15 hours preceding the test was a factor in causing the low removals with lime injection. To eliminate the lime conditioning effect, water only was injected into the ESP to hold the gas at 160°F overnight. Test 56 was carried out with only water injected.

Next, just before starting test 57, which followed right after test 56, injection of 10 percent calcitic lime slurry began, with all the other conditions kept the same. The results are tabulated in Table 7-12, along with three comparable calcitic lime tests that had a 10- to 15-hour lime conditioning time, for comparison.

Although test 57 showed somewhat better performance than tests 9, 28, and 29, the significant result is that removal in test 57 was so much less than in test 56. Injection of the lime slurry caused the ESP performance to fall off almost immediately, showing that conditioning with lime injection was not responsible for the reduced ESP performance.

7.3.4 ESP Outlet Opacity

An opacity meter was installed in the duct downstream from the ESP and the ID fan. This meter had a range from 0 to 25 percent, with a light path of 3 feet across the duct diameter. Before each test, the glass was cleaned at the

Table 7-12

EFFECT OF CONDITIONING TIME

Test No.	Gas Flow (acfm)	Temp. (°F)	Dust Concentration (gr/dscf) Inlet	Outlet	Eff. (%)	EMV (cm/sec)	Vs (ft/sec)	Power (watts/1000 acfm)	Condition
56	11,450	158	2.349	0.003	99.87	73.1	1.63	609	Fly ash and water
57	11,550	158	4.504	0.205	95.54	16.0	1.64	635	Fly ash and calcitic lime, 10%
9	12,700	160	5.989	0.436	92.72	12.7	1.81	580	Fly ash and calcitic lime, 12%
28	12,440	159	7.674	0.619	91.93	11.4	1.77	650	Fly ash and calcitic lime, 17%
29	12,350	158	6.810	0.437	93.58	13.5	1.76	649	Fly ash and calcitic lime, 17%

light source, and the photo cell and the zero and span were adjusted. The glass stayed relatively clear and the zero and span showed little drift. However, because the zero adjustment would not make the instrument read zero, the indicator was "zeroed" at 5 percent.

Figure 7-13 shows how the indicated opacity varied with time in five tests where the gas flow was increased at about 0800. In every case, the opacity reading was fairly steady while the gas flow was low (20 ft/sec, except for the test on June 13, where it was 30 ft/sec prior to 0700). When gas velocity increased to 50 ft/sec, the opacity increased sharply, and then in three of the five tests it came back down a little. Occasionally, brief "spikes" were seen, some of which are shown in Figure 7-13.

Although the absolute value of the opacity is not significant, because of the uncertain zero value, at low gas velocity, actual opacity readings ranged from 6 to 9 percent. When gas velocity increased, so did opacity, and it increased more when lime was injected than when it was not.

Other data show that the opacity either held fairly steady or decreased slowly over long periods at low gas flow. However, there was some tendency for opacity to climb slowly at the high gas flows. Since it was not feasible to operate at high gas flow for more than 4 or 5 hours, the opacity was not followed beyond that period. However, the data in Table 7-4 do not show that the outlet particulate concentration was consistently higher in succeeding tests on the same day.

7.3.5 VI Curves

Voltage-current (VI) curves were taken for each ESP test, both immediately before and after each test run. Data for the VI curves were taken by running up each AVC manually, outlet field first, in increments of approximately 10 kV, and taking voltage and current readings at each point. This continued until sparking took place, the primary current limit of 15 amps being reached, or until either the maximum voltage (60 kV) or plate current (80 mA) was reached on the AVC panel.

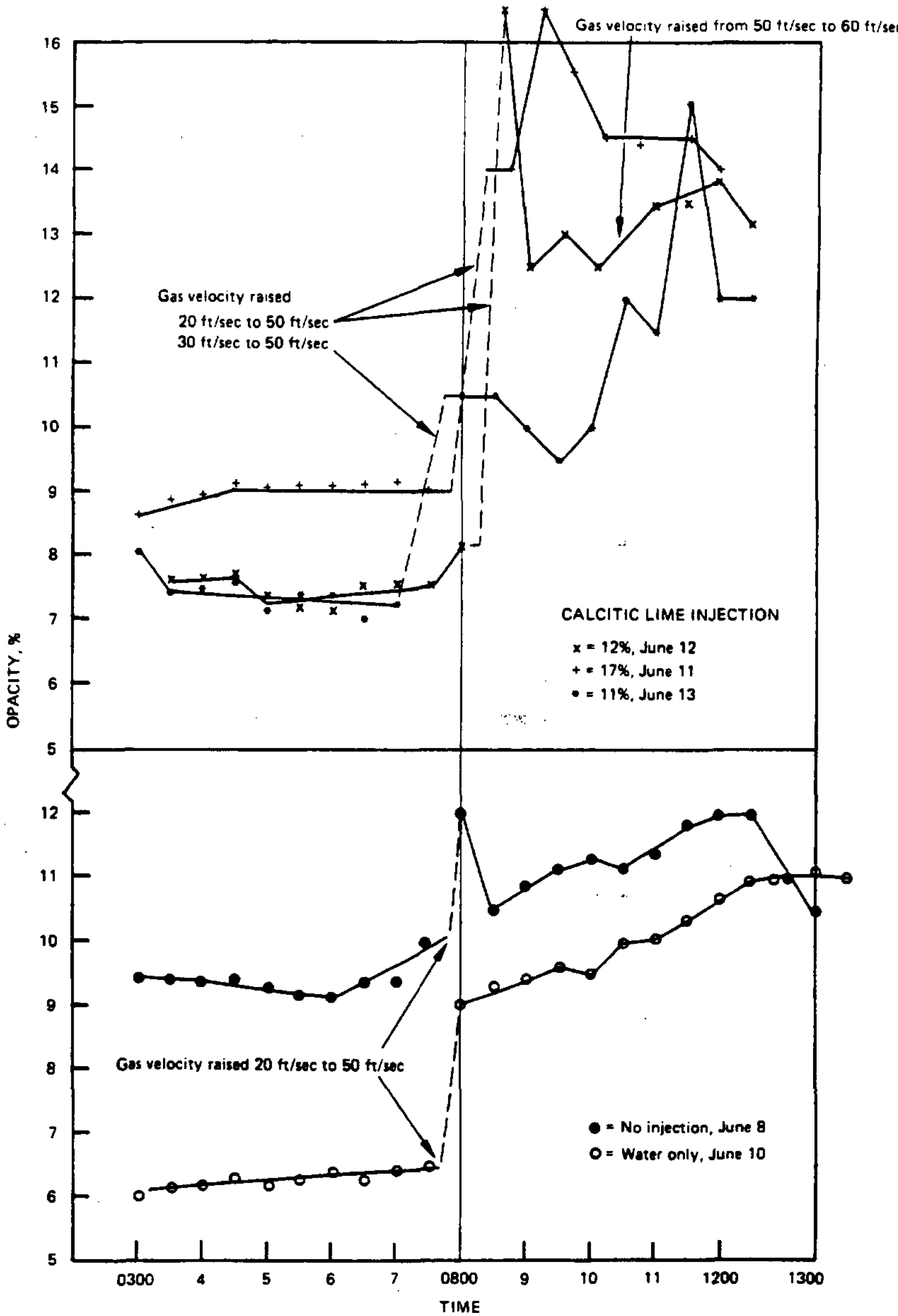


Figure 7-13 ESP Outlet Opacity vs Time

VI curves were then obtained by plotting secondary current (mA) against secondary voltage (kV).

Figure 7-14 is a set of typical VI curves for the second series of tests, taken under comparable conditions, showing the relative electrical characteristics for each injection condition tested. The curves with injection of water and those with calcitic lime slurry injected are very similar, although they rise much more steeply with no injection.

Table 7-2 shows that in the first series of tests during November 1986 when PHDL was injected through both nozzles, over 50 kV was needed to get plate currents approaching 70 mA. This is similar to the VI data for calcitic lime injection shown in Figure 7-14. However, ESP efficiency exceeded 98 percent in three of the four two-nozzle tests in November 1986, while the collection efficiency was much lower in the later series of tests.

For most tests, the VI curve for the second field (TRC-2) was somewhat steeper (i.e., more current at a given voltage) than it was for the first field. This phenomenon is exhibited by most precipitators.

Complete sets of electrical readings were taken approximately every 10 to 15 minutes during the test periods. Tables 7-3 and 7-4 show averages compiled from the readings for each test.

The AVC units were run in "manual" setting for all tests in the second series. The "control" point for each test condition was selected by first running the "pretest" VI curve; then setting the AVCs to a level just below that at which any instability was evident. The other limiting factor was the size of the transformer/rectifier sets themselves, which, as noted, placed limits on the voltage and current.

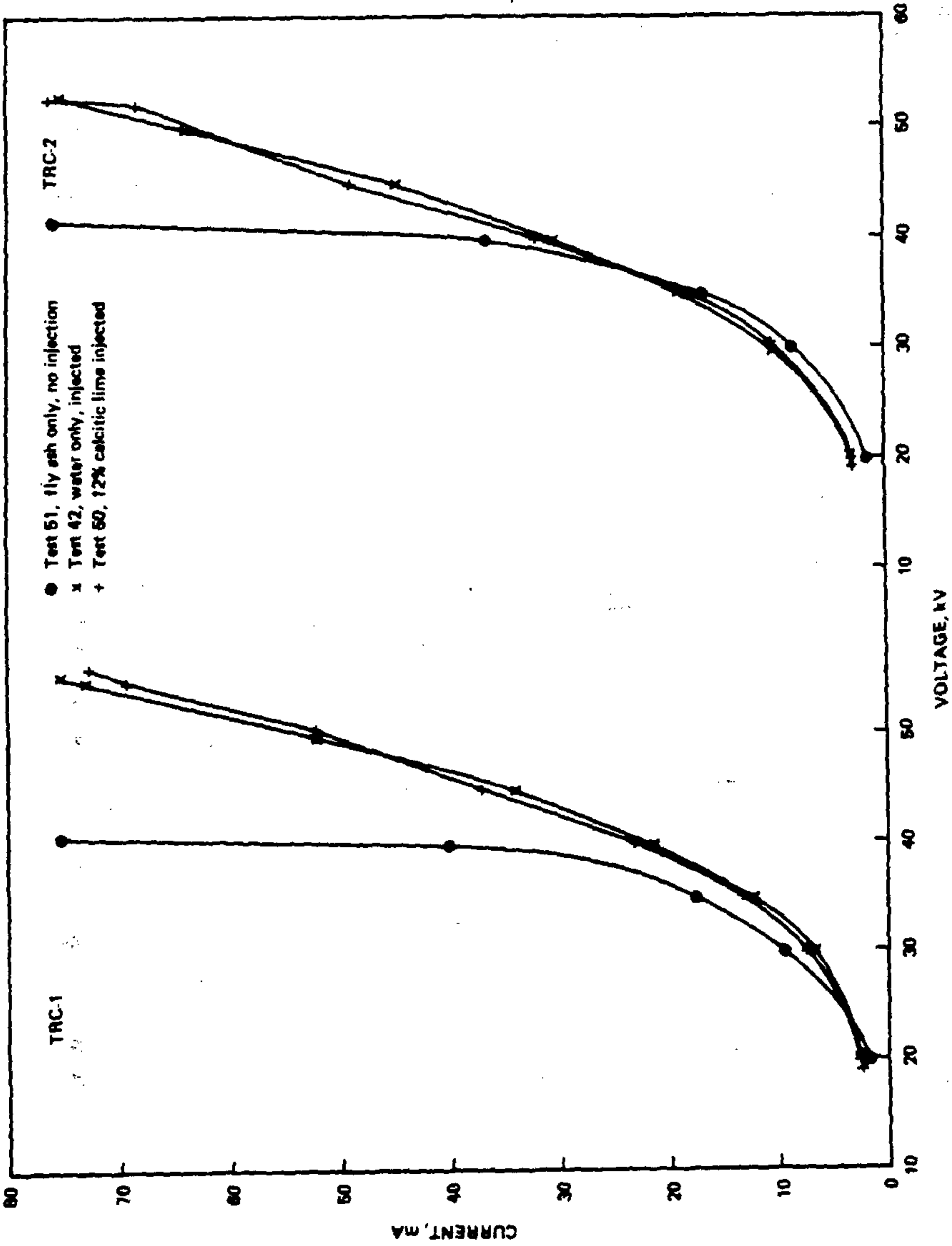


Figure 7-14 Typical VI Curves (Post Test)

Figure 7-15 correlates the plate current with applied voltage for the tests with lime injection. The points in Figure 7-15 are for the first field, TRC-1, and only data from tests at maximum power were plotted. Note that in most of the tests with dolomitic lime, it appears that less voltage was required to generate the plate current. The wide variation in the points suggests variable buildup of solids on the wires or plates, or significant current leakage.

7.3.6 Resistivity Measurements

In an effort to find a reason for the big difference in ESP performance with and without lime injection, the resistivity of the particulate matter was measured. Southern Research Institute made the measurements using an in situ technique it has developed. This technique has been used extensively on typical flue gases and it provided reproducible results. However, its application on flue gas downstream from in-duct injection is relatively new and the results are subject to confirmation.

Table 7-13 tabulates the values of measured resistivity. The results, summarized in order of increasing resistivity, are:

- Fly ash alone, no injection, 270°F — 1.1 - 2.7 E9 ohm-cm
- Injection of calcitic lime, 160°F — 3.4 - 4.3 E10 ohm-cm
- Injection of water, 160°F — 3.6 - 4.8 E10 ohm-cm
- Injection of dolomitic lime, 160°F — 4.5 - 4.8 E11 ohm-cm

The lower resistivity for fly ash alone without injection is reasonable, but for the three other cases the resistivity values bear no relationship to the ESP performance.

The variations of resistivity with temperature are also anomalous: with dolomitic lime, resistivity is lower at lower temperature (as expected), but with water only, it is higher at lower temperature (not as expected).

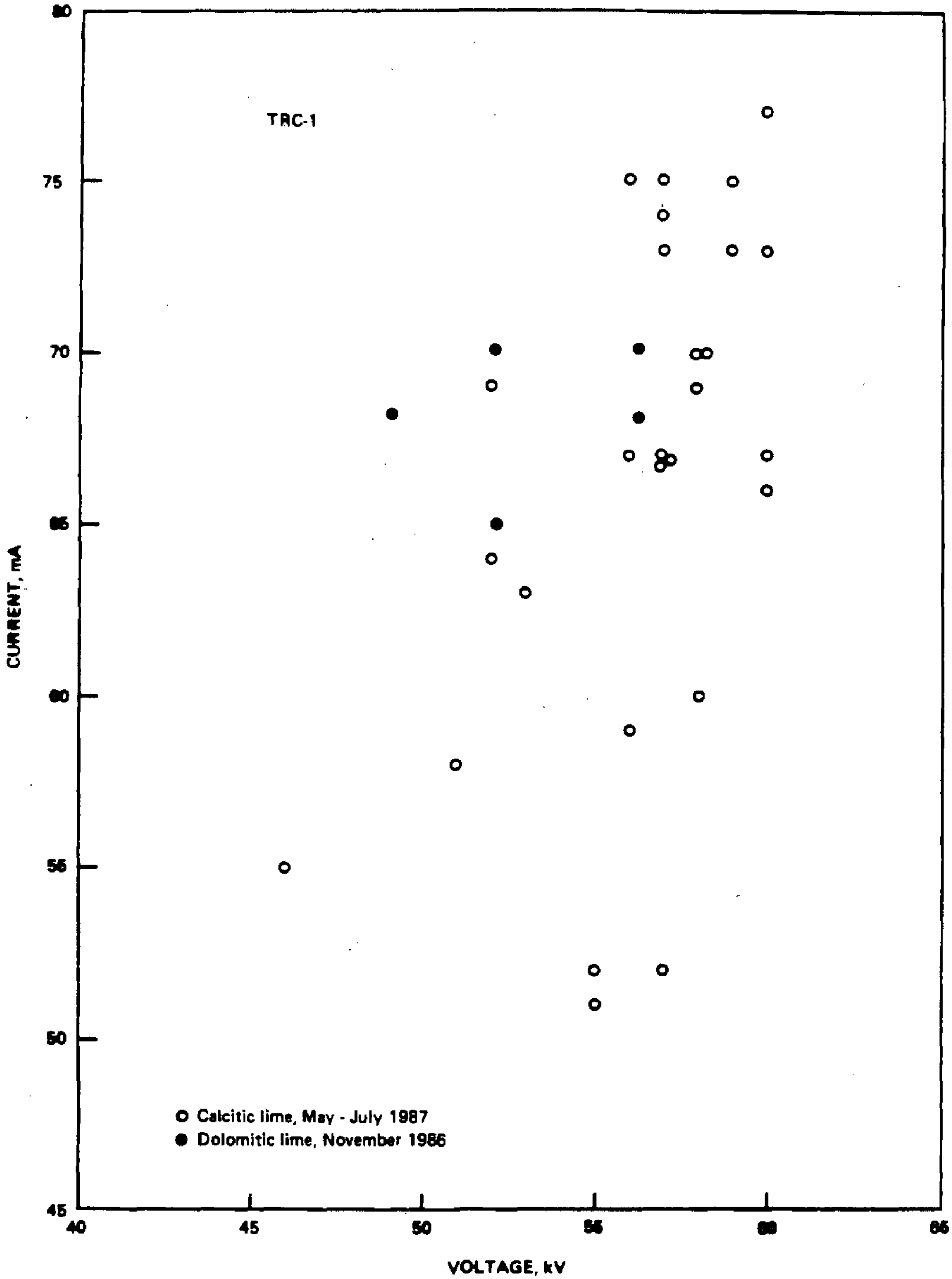


Figure 7-15 Variation of Operating Current with Voltage

Table 7-13

RESISTIVITY OF PARTICULATE MATTER

Date and Test No.	Time	Reagent Injected	Gas Temp. (°F)	Probe Temp. (°F)	Resistivity (ohm-cm)	Remarks
7/24 - 1	0930	Ambient			-	Check out apparatus; OK
7/24 - 2	1100 - 1140	Calcitic lime	152	151-153	-	Invalid; gas velocity too high
7/24 - 3	1403 - 1437	Calcitic lime	150	149-151	1.55 E11	Test invalid; slurry conc. uncertain
7/24 - 4	2321 - 2355	Water only	190	164	3.64 E10	Valid test
7/25 - 1	0045 - 0121	Water only	190	163-167	4.75 E10	Valid test
7/25 - 2	0216 - 0256	Water only	160	140-141	7.83 E10	Valid test
7/25 - 3	0340 - 0414	Water only	160	140-141	7.96 E10	Valid test
7/25 - 4	1308 - 1343	Calcitic lime	160	142-150	3.37 E10	Valid test
7/25 - 5	1412 - 1448	Calcitic lime	160	144-146	4.34 E10	Valid test
7/25 - 6	2341 - 0015	No injection	275	234-245	2.65 E9	Valid test
7/26 - 1	0127 - 0202	No injection	275	237-247	1.09 E9	Valid test
7/26 - 2	0310 - 0357	No injection	265	231-247	1.58 E9	Valid test
7/26 - 3	2319 - 2356	Dolomitic lime	190	162-167	1.42 E11	Invalid; may have compressed sample
7/27 - 1	0032 - 0107	Dolomitic lime	190	161-168	2.55 E12	Valid test
7/27 - 2	0200 - 0236	Dolomitic lime	190	165-167	1.93 E12	Valid test
7/27 - 3	0309 - 0345	Dolomitic lime	161	143-145	4.81 E11	Valid test
7/27 - 4	0430 - 0507	Dolomitic lime	164	143-146	4.53 E11	Valid test

NOTE: In-situ measurements by Southern Research Institute

The measured values of fly ash resistivity (1.1 to 2.7 E9 ohm-cm) without injection of water are typical when coal of 2 to 2.5 percent sulfur is burned, and they agree with resistivity calculated from the ash composition (Reference 7-4). However, the high resistivity of the fly ash with water injection is difficult to explain. It was postulated that alkali in the injected water could react with the sulfur trioxide (SO_3) in the flue gas. This could increase ash resistivity. However, reaction of all SO_3 with alkali in the water seems unlikely. Measurement showed an acid dew point (ADT) of 250°F for the flue gas - equivalent to 2 ppm of SO_3. Even if the water injected contained 100 ppm of bicarbonate alkalinity, it would be insufficient to neutralize all this SO_3 to bisulfate.

7.4 DISCUSSION OF ESP TESTS

Why the ESP performance deteriorated in these tests when lime was injected is the major question to be answered. Other corollary questions are:

- o Why did the ESP collect solids from lime injection so efficiently in the early tests, November 1986?
- o Is the low ESP efficiency with lime injection in the second series of tests a general effect or was it caused by some circumstance peculiar to these tests?

Unfortunately, the data do not provide conclusive answers.

The following discussion considers several possible causes of the poorer performance with lime. Some of these possibilities can be eliminated, while others are more likely and lead to tentative answers to the questions.

7.4.1 Resistivity

The higher resistivity of the particulate matter, when either the dolomitic or the calcitic lime was injected into the duct, compared to that of fly ash alone (with no injection) could explain why lime injection degraded the performance of the ESP. As shown in Table 7-13, resistivity with calcitic lime was about 4 E10 ohm-cm, and with dolomitic lime it was ten times higher, about 4.6 E11 ohm-cm. When there was no injection, the value was less than one-tenth these values, 1.6 to 2.6 E9 ohm-cm. However, when only water was injected, the resistivity was just as high as with calcitic lime, 3.6 to 4.8 E10 ohm-cm, and the best removal was achieved. Therefore, it is hard to see how the high resistivity from either type of lime can be the cause of the poor collection efficiency.

Figure 7-16 shows ash resistivity calculated by the well-accepted method (Reference 7-4) developed for the EPA. The resistivity is highly sensitive to flue gas temperature and flue gas SO_3 content. Calculations indicate that resistivity is not very sensitive to flue gas moisture and ash calcium content over the ranges used for these tests.

The measured ash resistivity at a probe temperature of 231°F to 247°F was 1.09 - 2.65 E9. Figure 7-16 indicates that this corresponds to a gas SO_3 content of about 3 to 7 ppm.

Since calculations indicate that neither injection of water or lime would raise resistivity to the levels measured, it is postulated that the water and lime injection altered the availability of the SO_3 for resistivity reduction. The measured resistivities correspond to an extrapolation of the curve representing a gas content of zero SO_3 to the temperatures where resistivity was measured.

As discussed above, the effect of water on reduction of SO_3 and increase of resistivity is not likely to be as significant as measured. However, the effect of the lime on increasing resistivity by reaction with SO_3 is more probable. This possibility requires further investigation.

7.4.2 Particle Size

As shown in the photomicrographs in Appendix C, the fly ash was coarser than either the dolomitic or the calcitic lime, unless possibly agglomeration raised the effective particle size of the lime. Therefore, if a big proportion of the unreacted lime and reaction products was dispersed when it dried, the concentration of very fine particles (i.e., less than 1 micron) entering the ESP was much higher when lime was injected.

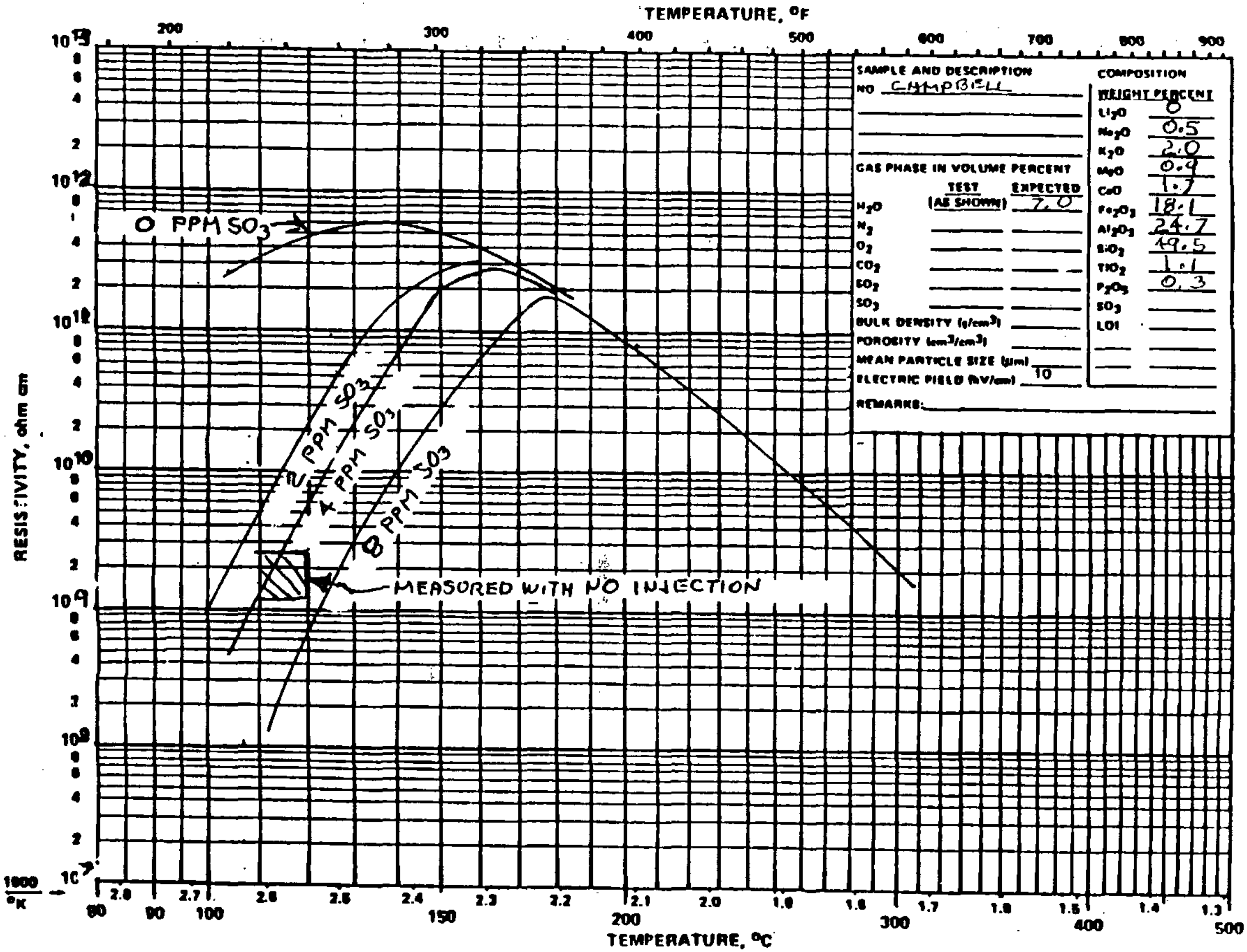


Figure 7-16 Ash Resistivity Calculation

This possibility is supported by the observation that the particulate matter collected on the filter of the inlet sampling probe during ESP tests was white and appeared to be mostly lime and reaction products. Solids that deposited in the duct, on the other hand, were dark and appeared to contain a higher percentage of fly ash.

Furthermore, when lime was injected, the solids collected on the filter of the inlet sampling probe were loose and free flowing. By contrast, the samples of fly ash, either with or without water injection, formed a coherent cake on the filter. Thus, the fly ash alone appeared to have a greater tendency to agglomerate than the solids from lime injection did.

The above observations suggest that with lime injection the particulate matter is finer and more dispersed and, thus, is intrinsically harder to collect. A lower agglomeration tendency would also increase reentrainment in the precipitator. If this caused the poor ESP performance, then the high collection efficiencies with lime injection observed in the tests in November 1986 may have been due to the cleanliness of the new ESP. The performance of many newly installed ESPs degrades for a period of a few days to a few weeks before reaching steady state. However, improved ESP performance was observed by others with spray dry FGD systems operating upstream of ESPs. This observed improvement argues against a conclusion that lime injection necessarily impairs ESP performance.

The benefit of the CZD system on precipitator performance will depend on the fly ash and flue gas properties. For relatively low-sulfur coals, higher resistivity ash will be produced which hinders precipitator performance. Injection of water and lime will increase the collection efficiency of the precipitator. This is due to the lower flue gas temperature reducing ash resistivity and allowing more electrical power input without detrimental sparking.

For a high-sulfur coal application, the ash resistivity is already sufficiently low to allow optimum precipitator performance. Reduction of the flue gas temperature does not improve precipitator performance. However, the possibility of the injected water and lime interfering with the resistivity reducing action of the SO_3, as discussed above, suggests that lower flue gas temperatures may compensate for lost SO_3, reduce ash resistivity, and improve precipitator performance.

7.4.3 Electrical Leakage

Another possible explanation for the lower removals with lime injection is that incompletely dried solids collected on insulators or built up on the wires or plates and allowed power to leak away. Figure 7-11 shows that migration velocity increased significantly with power input in tests with no injection, while with lime injection, migration velocity was much lower and increased very little with power. Also, although collection efficiency in Figure 7-8 increases with power when lime is injected, the points are quite scattered, suggesting the influence of some random effect like buildup and leakage. By contrast, the points for collection efficiency without injection in Figure 7-9 lie close to a smooth curve with little scatter. (Note that the scales in Figure 7-9 are expanded compared with those in Figure 7-8 which makes the points in Figure 7-9 appear more scattered than they are.)

Water alone injected into flue gas can be expected to evaporate more rapidly than the water in lime slurry. This condition will occur because the drying rate decreases with slurry droplets once the free moisture on the outside of the particles evaporates. In addition, with water injection, the loading of solids to the ESP was lower and the solids were coarser than with lime injection. Furthermore, the solids were not likely to be completely wetted with water-only injection, so that drying was more likely to be complete before the particulates reached the ESP.

On one occasion late in the test program, the ESP was energized while the manhole at the inlet was open and air was pulled through the ESP. Sparking could be heard in the vicinity of one of the insulators suspending the emitting electrodes in the first field. An attempt was made to clean these insulators with an air lance, but they were not accessible enough to clean them thoroughly. The above observation supports the possibility that electrical leakage at least contributed to the poor ESP performance with lime injection.

The solids discharged from the ESP hoppers always appeared dry and free-flowing, thus tending to refute the argument that incompletely dried solids caused sparking and power leaks when lime was injected. When the hoppers were emptied, there were few stoppages, and these were always easy to break loose. Furthermore, the collector plates and discharge electrodes did not accumulate deposits that were more than about 1/8-inch thick. These deposits were loose and easily brushed off; there was no evidence that wet solids had been collected.

The improved ESP performance when lime was injected at very low gas velocities can be explained by the longer time available for drying and finer atomization. Consequently, faster drying was achieved at the lower injection rates.

Similarly, the higher downstream gas temperatures used in the November 1986 tests (180°F and higher in four of six tests) may have dried the solids more thoroughly.

Also, the test with maximum power and gas flowing at 50 ft/sec (test 18 on May 28) that gave the highest efficiency with lime injection at this gas flow was at 170°F compared with 160°F for the other tests.

Thus, the evidence is strong, though not conclusive, that incompletely dried solids caused excessive electrical leakage when lime was injected to bring the gas temperature down to 160°F in the second series of tests. If this is the reason why lime injection caused the ESP performance to fall off, it can be corrected by better protection of the insulators and by improved atomization of the slurry.

7.4.4 Uneven Gas Distribution

When the test program was nearly over, it was found that the flow of solids in the test duct could be observed visually through the 4-inch sampling nozzle on the top of the duct 80 feet from point 3, where the downstream spray nozzles were located (see Figure 7-3). The entrained particulate matter was dilute enough to allow the bottom of the duct to be seen with a spotlight directed through a glass plate on the nozzle. This showed a concentrated stream of solids in the bottom 1 to 2 inches of the duct moving along more slowly than the gas. Obviously, most of the particles in this stream on the bottom of the duct were too coarse to stay suspended in the main stream of the gas, and these may have been incompletely dried.

About 30 feet beyond the sampling port, the duct turned upward 180° and connected to the ESP. Diverging vanes in the transition piece at the entrance to the ESP slowed the gas down and distributed it over the cross section of the ESP. An array of vertical 4-inch pipes serving as baffles just ahead of the collector plates also helped to distribute the gas flow evenly. However, it may be that the U-bend just ahead of the ESP concentrated a jet of solids and high-velocity gas, part of which was deflected upward by the top diverging vanes and found its way through the baffles with enough momentum to impinge on the insulators in the first field. This possibility is consistent with the particularly poor ESP performance in tests 34, 35, and 47 which had the highest gas flow in the duct, 60 ft/sec.

From the evidence available, it appears that electrical leakage is a likely cause of the poor ESP performance observed with lime injection. Segregation of the largest, slowest drying particles, combined with an ESP inlet geometry that directed them to the vicinity of the insulators supporting the emitting electrodes, may have been a significant factor in causing the leakage.

Another possibility is that localized high velocity areas in the precipitator caused reentrainment of collected particulate either from the collection plates or hoppers. There was no shape model testing of the precipitator and ducting. There were no field tests of velocity uniformity at the precipitator inlet and outlet. Reentrainment is suspected because performance improved much more at reduced velocities than would be predicted by the Deutsch equation with a k factor equal to 0.5. This phenomenon was observed both with and without lime injection. In addition, if the lime formed a fluffy nonagglomerating material, it would be subject to reentrainment due to localized high velocities.

REFERENCES

7-1. Robards, R. F., Deguzman, J. S., Runyen, R. A., Flora, H. B., "Spray Dryer/ESP Testing for Utility Retrofit Applications on High-Sulfur Coal," Energy Demonstrations and Technology, TVA, (1986) (3).

7-2. Chen, Y., et al, "Electrostatic Precipitators in Dry FGD Applications," Second International Conference on Electrostatic Precipitation, Kyoto, Japan, November 1984.

7-3. Graves, N. G., et al, "The Effect of Corona Power on Electrostatic Precipitator Performance," ASME/IEEE Joint Power Generation Conference, Denver, October 1982.

7-4. Bickelhaupt, R., A Technique for Predicting Fly Ash Resistivity, EPA - 600/7-79-204, 1979.

PART 3

Seward Station Tests

CONTENTS

Preceding Page Blank

ILLUSTRATIONS

TABLES

ABBREVIATIONS, ACRONYMS, AND DEFINITIONS

acfm	actual cubic feet per minute
ADT	acid dew point
AST	approach to saturation temperature
AVC	automatic voltage control
bhp	brake horsepower
CEM	continuous emissions monitor, term used to designate SO_2-O_2 monitor
CL	calcitic lime
conc	concentration
CPC	Consumers Power Company
CZD	confined zone dispersion
DOE	U.S. Department of Energy
d/s	downstream
EMV	effective migration velocity
ESP	electrostatic precipitator
Eff	efficiency
FGD	flue gas desulfurization
gpm	gallons per minute
HHV	higher heating value
ID	induced draft
Injection	spraying lime slurry or water into flue gas flowing in a duct
kscfm	thousand standard cubic feet per minute
L	lime
LFR	lime feed ratio, moles of lime (both Ca and Mg) fed per mole of SO_2 entering
MWe	megawatts, electric equivalent
NO_x	nitrogen oxides
NWIR	normalized water injection rate
O_2	oxygen
OH	hydroxide concentration
O&M	operating and maintenance
PEDA	Pennsylvania Energy Development Authority
PENELEC	Pennsylvania Electric Company
PETC	Pittsburgh Energy Technology Center
PHDL	pressure hydrated dolomitic lime (also called Type S lime)
PRDA	Program Research and Development Announcement
P&ID	piping and instrumentation diagram
P&ID	process and instrumentation diagram
SCA	specific collection area
scf	standard cubic feet
scfm	standard cubic feet per minute
SO_2	sulfur dioxide
SO_3	sulfur trioxide
SSCo	Spraying Systems Company
T/R	transformer/rectifier
u/s	upstream
VI	voltage current
W	water
WC	water column, the head difference in a water manometer

All temperatures are in degrees F, unless specified otherwise.

Section 1

INTRODUCTION

1.1 BACKGROUND

Pennsylvania Electric Co. (PENELEC) supplies about 40 percent of the electricity consumed in western Pennsylvania. Nearly all of it is generated by burning local coal. Proposed acid rain abatement regulations stimulated PENELEC into evaluating various methods available for compliance with the proposed regulations.

Bechtel's Confined Zone Dispersion (CZD) process for flue gas desulfurization (FGD) was one method selected for evaluation by PENELEC. The CZD process involves injecting a finely atomized slurry of hydrated lime into a straight run of duct between a boiler's air heater and its precipitator. Small-scale experiments had shown that an air atomizer can make fine sprays that will dry rapidly enough to avoid deposits on duct walls. A highly reactive lime was used that captured a significant proportion of the SO_2 during this short drying period. The CZD process is proprietary, covered by U.S. Patent No. 4,623,523.

A cooperative test program to study the effects of the CZD process retrofitted onto one of two parallel flue gas ducts on the 140 MWe Unit 15 boiler at Seward Station was entered into by PENELEC, Bechtel, and the Pennsylvania Energy Development Authority (PEDA) in November 1986. Proof-of-concept testing at a pilot-scale level of 5 MWe, supported by the U.S. Department of Energy (DOE), was under way having entered a 3-month shakedown phase in October 1986. Knowledge gained in this pilot-scale testing would be utilized in the Seward testing. Additional support to extend the Seward testing was provided by the DOE and New England Power Service in the summer of 1987.

1.2 OBJECTIVES

The objectives of the Seward Station test program were to:

- Establish the level of SO_2 removal effectiveness of the CZD technology under full-scale operating conditions
- Measure the impact, if any, of the CZD system on plant operation, such as corrosion in the duct, erosion, fouling, and particulate emissions from the stack
- Make a 4-week continuous run matching variations in boiler load, flue gas velocity, inlet temperature and inlet SO_2 concentration to maintain an adequate outlet flue gas temperature, and SO_2 removal without affecting the normal power plant operation
- Measure the particulate removal efficiency of the electrostatic precipitator (ESP) with and without lime slurry injection to determine the capability of the ESP to handle the additional grain loading when lime is injected into the system
- Test the effect of both pressure hydrated dolomitic lime (PHDL) and calcitic lime (CL) on SO_2 removal, lime utilization, and ESP performance
- Determine if the DOE proof-of-concept goals of 50 percent SO_2 removal and a levelized removal cost less than \$500/ton of SO_2 are obtainable

A 5-month test program that began in June 1987 consisted of 2 months of shakedown testing, 2 months of parametric testing with lime slurry, and 1 month of testing during continuous operation at 24 hours/day, 7 days/week. The tests were predominately conducted with PHDL, but a limited number of tests with hydrated and freshly slaked CL were also run.

Section 2

SUMMARY

The large-scale test program at the Seward Station of the Pennsylvania Electric Company (PENELEC) included the design, installation, and operation of the Confined Zone Dispersion (CZD) test system. The CZD system was retrofitted onto one of two parallel flue gas ducts on the 140 MW Unit 15. After shakedown of the system, the activity consisted of 2 months of parametric lime injection tests and 1 month of continuous lime injection tests. Electrostatic precipitator (ESP) performance was evaluated during this latter period.

2.1 TEST FACILITY

The flue gas was treated in approximately 35 feet of a straight ductwork section (8 feet wide x 11 feet high) situated between two sets of turning vanes. The ductwork section and turning vanes were located between two existing ESPs. At a nominal flue gas velocity of 64 ft/sec, the duct section had only 0.5 second of residence time. After slurry injection, the dried reaction products and fly ash were collected in the second existing ESP.

Pressure hydrated dolomitic lime (PHDL) and dry calcitic lime (CL) were received in self-unloading trucks and pneumatically transferred to a lime silo. The dry lime was slurried with water in a 2,500-gallon lime sump equipped with an agitator. The slurry was pumped from the sump to a vibrating screen to remove fine grit and then stored in either of two 10,000-gallon agitated lime feed tanks.

Two centrifugal feed pumps, operating in series, pumped lime from the feed tanks through a pump-around loop that passed close to a valved manifold which distributed lime to the atomizing nozzles. A separate valved manifold distributed atomizing air to the nozzles.

On-line measurements included the following:

- Gas velocity and temperature upstream of lime injection
- Gas temperature before and after the downstream ESP
- SO_2, NO_x, and O_2 concentrations upstream of the spray nozzles and downstream of the ESP and the ID fan
- Flow of lime slurry and atomizing air
- Temperature profiles in the duct cross section at several distances downstream of the injection point

2.2 SHAKEDOWN TESTS

The shakedown tests began in June of 1987 and continued into August of 1987. During this period, the system was checked out and made operable, and the operating team was mobilized and trained. Water atomization tests were performed to determine the pressure and flow characteristics of the atomizing nozzles and the orientation constraints of the multiple atomizer array.

Prior to the Seward testing, several nozzle atomizers were tested at the University of California, Davis, to calibrate the nozzles and to determine the effects of air and water rates on fineness of atomization. Nozzle performance results were also available from the pilot-scale CZD testing at the Campbell Station of Consumers Power Company (CPC). These two test programs identified the Spraying Systems Company's (SSCo) Casterjet nozzle as an acceptable atomizer for the Seward tests.

The next step involved testing the calibrated nozzles in the flue gas duct to determine the best configuration and the minimum ratio of atomizing air to water required to avoid wetting the duct and turning vanes. The testing started with a single nozzle and evolved to a nine-nozzle array.

Because of the short duct and limited residence time, a much higher air-to-water ratio than expected was required to provide the fine atomization necessary for rapid evaporation. The air and discharge orifices of the nozzle were enlarged to provide this higher ratio.

2.3 LIME INJECTION TESTS

Two months of parametric lime injection tests began in August 1987 and were followed by a month of continuous lime injection tests in October.

The parametric tests, which normally lasted several hours, investigated the effects of lime concentration on the extent of flue gas desulfurization, lime utilization, and lime injection rate. The continuous lime injection tests investigated the long-term effects of lime injection on the atomizers, duct deposits, and ESP performance.

The lime injection tests confirmed that fine atomization and restricted lime feed rates were necessary to dry the atomized droplets sufficiently to avoid deposition on the turning vanes located about 35 feet downstream of the nozzles. These restricted feed rates limited the maximum SO_2 removal. The following results were obtained.

2.3.1 Duct Temperature Profiles

Temperature profiles taken in the duct cross section at several distances from the injection point confirmed that a true confined zone, a moist interior surrounded by hot gas, could be obtained.

2.3.2 PHDL Injection

With PHDL injection, SO_2 removal ranged from 6 to 30 percent, depending on the slurry flow rate and slurry concentration. The LFR ranged from 0.11 to 1.34. NO_x removal ranged from 8 to 21 percent and increased with increasing slurry concentration. Lime utilization, based on combined SO_2 and NO_x removal, ranged from 23 to 90 percent.

2.3.3 Slurry Concentration

Sulfur dioxide removal increased and lime utilization decreased with increasing slurry concentration.

2.3.4 Calcitic Lime

With CL, either freshly slaked or a slurry prepared from dry hydrate, SO_2 removal, NO_x removal, and lime utilization were significantly lower than corresponding values for the PHDL. The unexpected lower performance for the freshly slaked lime may have been caused by eroded nozzle tips. Time was not available to repeat the freshly slaked CL tests with erosion resistant tips.

2.3.5 Duct Deposits

It appeared that duct deposits could be prevented by limiting injection rates to the point where the atomized droplets dried before they reached the first interior duct surface, the turning vanes. However, since this was a manually controlled operation, it was not possible to follow load closely, particularly at night. Consequently, there were times when the injection rate was excessive, resulting in low downstream temperatures with some deposition on the vanes and surrounding areas. Poor atomization resulting from eroded atomizers also caused some deposits.

2.4 ANALYSIS OF SO_2/NO_x DATA

The test data for PHDL were arranged into groups according to weight percent slurry concentration. A plot of SO_2 removal versus gallons per minute of slurry injected was made identifying each group with a unique symbol. It was found that a straight line could be drawn from the origin through the data points for each group.

These plots show that the Seward test data exhibit a positive linear relationship of SO_2 removal versus slurry injection rate. The plots also showed that, at a given injection rate, SO_2 removal increases with slurry concentration.

Lime utilization data were plotted to determine how lime utilization is related to lime type and lime concentration for SO_2 and NO_x removal. From these plots, the Seward test data show the following relationships:

- Both CL and PHDL utilization decrease with increasing lime concentration for both SO_2 and NO_x removal.

- PHDL utilization is higher compared with CL for either SO_2 or NO_x removal at a given lime concentration.

As noted earlier, the short residence time available in the test duct at Seward limited the lime injection rate to a point where a maximum of only 30 percent SO_2 removal could be obtained. A full-scale commercial system with a longer straight run of duct would not be limited in this way. Furthermore, the ductwork configuration at Seward is suitable for installation of a second set of atomizers upstream of the set used, which would approximately double the residence time. This would allow more slurry to be injected and result in higher SO_2 removal.

The plots described above were extrapolated to project the slurry injection rate and concentration required for 50 percent SO_2 removal. By this extrapolation, the injection of about 55 gpm of 7.5 percent PHDL would remove 50 percent of the SO_2 at Seward.

This extrapolation is probably conservative. Using two-stage injection and increasing residence time would permit more injection points, better gas/spray dispersion, a larger and more uniform confined zone, and a closer approach to saturation temperature for the treated gas. These factors should provide better lime utilization thereby obtaining 50 percent SO_2 removal at an injection rate lower than 55 gpm.

Two-stage injection is expected to provide much higher NO_x removals compared with that obtained in the single-stage injection tests during the Seward test program.

2.5 ESP TESTS

Particulate removal efficiency testing of the downstream ESP with and without lime slurry injection was conducted to determine the capability of the ESP to handle the additional grain loading when lime was injected into the system. An existing online opacity monitor mounted in the stack was also used to indicate ESP performance during the testing.

During the short-term parametric tests, the opacity decreased and remained lower during lime injection and then increased when injection was stopped. During the long-term continuous injection tests, the opacity decreased at the start of injection and remained low initially, but then rose after 5 to 10 hours' operation to a level exceeding the original opacity prior to the start of injection. Off-power rapping was successful in restoring opacity to acceptable levels, but was required intermittently.

Particulate removal efficiency tests were performed for fly ash alone (no injection), during injection of PHDL and during CL injection. Only one slurry injection rate per test was evaluated. The average particulate removal efficiency was slightly higher during the CL injection and slightly lower during the PHDL injection compared with fly ash alone. The average emissions were the same during CL injection but higher during PHDL injection compared with fly ash alone.

The CZD testing was conducted with the ESP in an as-found condition. No attempt was made to optimize the mechanical/electrical condition prior to testing. Analysis of the ESP operating characteristics during the testing suggests that the precipitator had some deficiencies with the automatic voltage controllers and rapping systems.

The capability of off-power rapping to reduce opacity levels suggests that a well-tuned ESP, with automatic controls for voltage and rapping, and with discharge electrode rapping, may be capable of maintaining acceptable opacity levels during lime injection. As with the tests at Campbell Station, it is felt that further ESP testing is needed.

Section 3

FACILITY AND PROCESS DESCRIPTIONS

3.1 HOST UNIT

The large-scale tests were carried out at the Seward Station of PENELEC. The Confined Zone Dispersion (CZD) system was retrofitted onto one of two parallel flue gas ducts on the 140 MW Unit 15. During the test period, the unit burned 1.2 percent sulfur coal. Load typically varied from 135 to 145 MW, gas inlet temperature typically varied from 280 to 300°F, inlet SO_2 concentration varied from 730 to 870 ppmv, and gas flow rate was about 230,000 scfm.

The flue gas was treated in approximately 35 feet length of an 8 feet wide x 11 feet high section of straight ductwork between two sets of turning vanes. The ductwork section and turning vanes were located between two existing ESPs. At a nominal flue gas velocity of 64 ft/sec, the duct section has only about a half second residence time. After slurry injection the dried reaction products and fly ash were collected in the second existing ESP.

3.2 PROCESS DESCRIPTION

Figure 3-1 is the process and instrumentation diagram of the CZD demonstration unit. It shows:

- The arrangement of the CZD system equipment, interconnecting piping, and instrumentation
- Flue gas flow, corresponding usages of dolomitic lime, water, compressed air, and quantities of desulfurization products generated by the system
- Stream flows
- Equipment sizes, capacities, and units of motor brake horsepower (bhp)

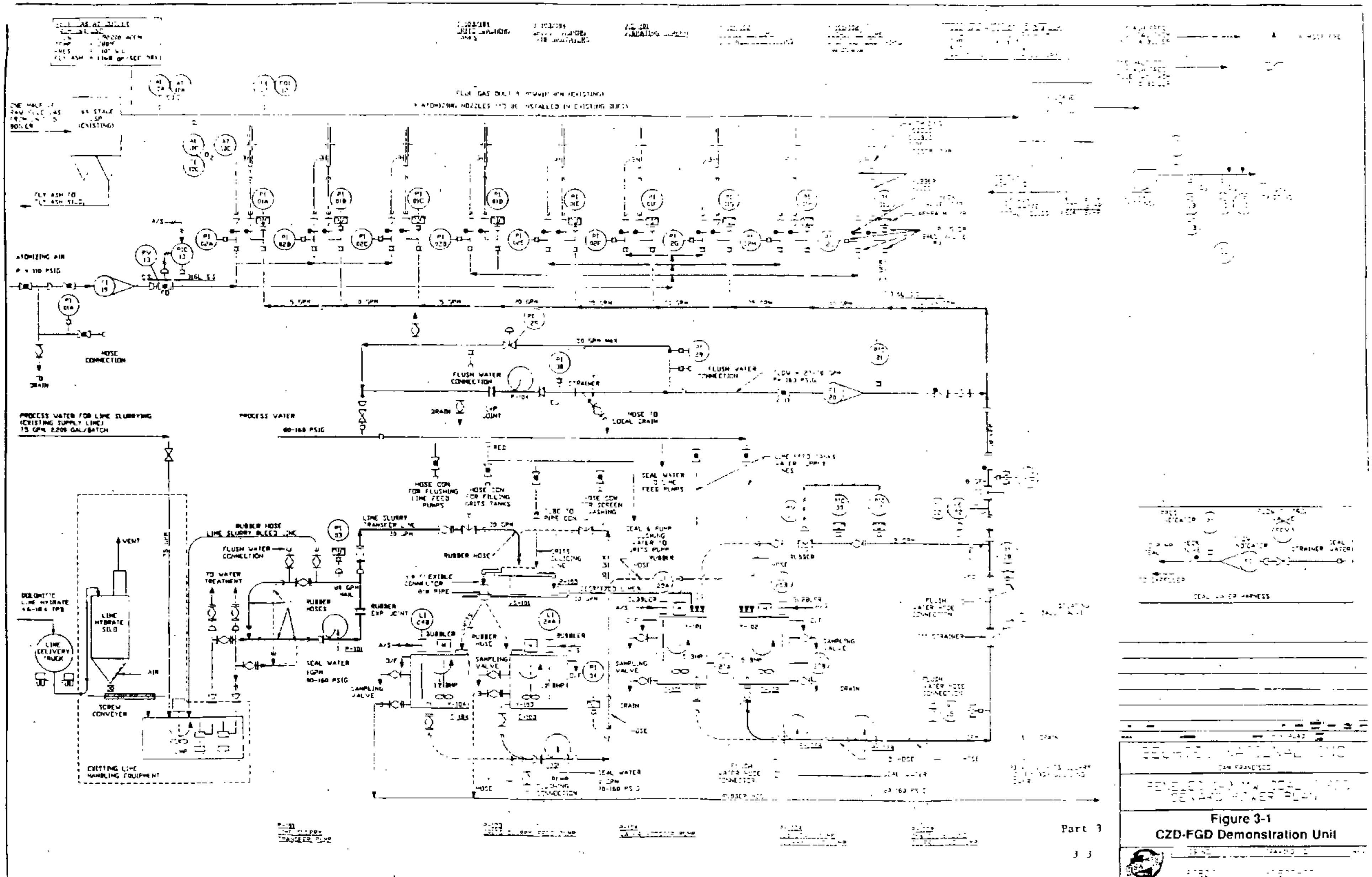
Pressure hydrated dolomitic lime (PHDL) was predominantly used for the tests. It was delivered by self-unloading trucks into the lime silo. This silo was equipped with a vent filter, air slides, an air blower, a slide valve, a rotary air lock valve, and a screw conveyor connecting it to the lime sump. The PHDL was slurried with water in the lime sump, which was equipped with an agitator and two sump pumps (one working, one standby). The lime silo and the lime sump were instrumented for either automatic or manual operation. They were the existing components of the power station, which, in addition to supplying lime slurry for treating the station's wastewater, were used for preparing lime slurry for the operation of the CZD system. During the demonstration program, the lime silo and sump were operated manually.

The CZD system was designed to operate using 20 wt% lime slurry. The lime sump was designed for batchwise operation. It had a net operating capacity of about 2,500 gallons. A batch of 2,430 gallons of slurry was sufficient for 3 hours of CZD system operation at its full design capacity. The procedure was to prepare 2,430-gallon batches of the lime slurry in the lime sump. From the lime sump, the lime slurry was pumped to the degritting equipment in the CZD equipment enclosure under the desulfurization duct 400 feet away. A new lime slurry transfer pump was provided for this purpose. This pump was connected to operate in series with either of the two existing sump pumps. During the CZD program, one of the sump pumps served as the first-stage transfer pump, and the other supplied lime to the station's water treatment plant.

Two forms of calcitic lime (CL) were also used during the test program: dry hydrate and a freshly slaked slurry of CL. The hydrate was delivered to the lime silo and processed in an identical manner to the PHDL. The slurry was pumped from self-unloading trucks to the degritting screens with the subsequent processing steps the same as for the other two limes.

Freshly slurried lime contains abrasive grit that is unreactive towards SO_2 and can plug the atomizing nozzles. This grit was removed from the slurry by the degritting equipment.

The degritting equipment consisted of a vibrating screen to separate grit from the lime slurry, two agitated grit slurry tanks, and one grit slurry pump.



Part 3

3-3

Figure 3-1
CZD-FGD Demonstration Unit

The degritted lime drained from the vibrating screen to one of two lime slurry feed/storage tanks. The grit separated from the lime slurry dropped from the vibrating screen into the trough that surrounded the screen and was sluiced from it into the grit washing tank. In the tank, the grit was washed with water for the recovery of lime entrained by it from the lime slurry. The entrained lime was recovered by reslurrying grit with water and filtering the grit slurry through the degritting screen. The degritting screen operated in a cyclic fashion: first, it was used to remove the grit from the lime slurry; then, it was used to recover the lime entrained by the grit.

The reslurried grit was pumped to the degritting screen with the grit pump, and the filtered-off grit was then collected in the washed grit tank (the second of the two grit tanks). The filtrate containing the recovered lime was drained from the screen into the lime feed tank. The recovery of lime from grit resulted in diluting the degritted lime slurry in the lime feed tanks from 20 to 13 percent.

For supplying the lime slurry to the atomizing nozzles, the CZD system had two agitated lime feed tanks, two lime feed pumps operating in series, and a lime slurry loop main interconnecting the feed pumps to the atomizing nozzles.

The lime slurry feed tanks operated batchwise. One was used for pumping the lime slurry to the atomizing nozzles while the other received freshly degritted and recovered lime. Each feed tank had sufficient capacity to hold enough lime slurry for a 6-hour operation of the plant. The batchwise operation of these tanks permitted accurate measurement of the actual lime usage (by measuring the concentration and volume of the lime slurry used during any period of plant operation). The loop main provided for feeding the lime slurry to the atomizing nozzles enabled the plant operators to vary the actual lime feed rate without the danger of plugging the feed piping with sedimenting solids. The lime slurry feed loop main was connected to the atomizing nozzles by a short header.

The lime slurry atomization system had nine air-atomizing nozzles mounted in the flue gas duct. The atomizing air, lime slurry, and water were distributed to the atomizing nozzles via separate valve manifolds connected to the atomizing nozzles by hoses.

The atomizing air and liquid headers were equipped with rotameter-type flow indicators. All headers had pressure gauges and manual valves for controlling their flows. The inlet and outlet SO_2 and O_2 analyzer/recorder and flue gas temperature recorders were provided to help the operators determine the proper flows of lime and water to the atomizing nozzles.

3.3 SECTION OF TEST DUCT

Figure 3-2 is a plan view of the test duct section. It shows the location of the atomizing nozzle ports, the temperature probe ports, the turning vanes upstream and downstream of the atomizers, and the downstream ESP.

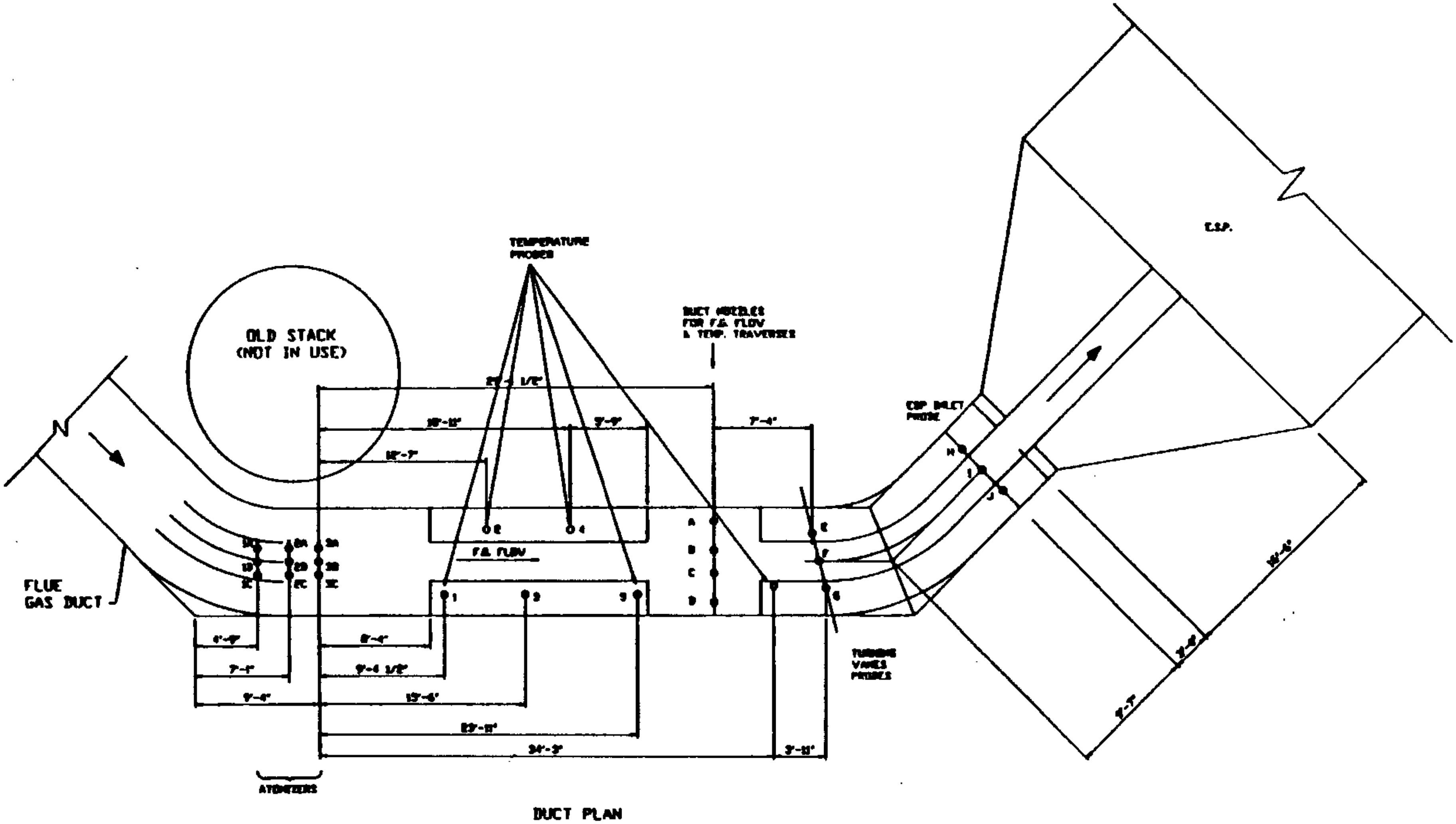


Figure 3-2 Arrangement of Atomizers and Test Nozzles

Section 4

DRYING AND SO_2/NO_x REMOVAL

With the Confined Zone Dispersion (CZD) process, even more than with other lime spray dry FGD systems, drying must take place rapidly before wet droplets can impact on the duct surfaces and build up deposits. At the same time, the spray droplets must remain wet long enough for the lime to react and capture sufficient SO_2. The reaction with SO_2 is fast as long as the lime particles are wet.

The short residence time in the Seward test duct accentuated the demand for rapid drying and reaction. Therefore, the test program emphasized fine atomization, intimate flue gas/spray dispersion, and attainment of a confined zone - factors which promoted both drying and SO_2 removal.

4.1 NOZZLE ATOMIZATION TESTS

4.1.1 Wind Tunnel Testing

Initially, several Spraying Systems Casterjet two-fluid nozzle atomizers were tested in a wind tunnel at the University of California, Davis, where the effects of air and water rates on the fineness of atomization were measured. Nozzles with standard 25,150 and 25,200 tips produced coarser droplets than did nozzles with special tips. The special tips were specified for the Seward CZD system.

Wind tunnel testing of the atomizers with the special tips showed that at a constant air flow rate, the surface area of the atomized droplets is constant and independent of the water rate over the conditions tested. This implies that a reduction in liquid feed rate at a constant air flow rate would result in finer droplets with a reduced evaporation/drying time.

Wind tunnel testing of atomizers was also conducted with lime slurry. In general, the tests showed that:

- o Droplet size varied inversely with air pressure

- Droplet size varied inversely with air flow rate
- Droplet size varied directly with liquid rate
- Droplet size was finer for pressure hydrated dolomitic lime (PHDL) slurries than for water at comparable operating conditions. This phenomenon is attributed to the lower surface tension of the slurry.

The atomizers selected for CZD testing were calibrated at U.C. Davis to determine their pressure/flow characteristics.

4.1.2 Parametric Water Injection Tests

The next step in the program involved testing the calibrated atomizers in the flue gas duct to determine their best configuration and the minimum ratio of atomizing air to water required to avoid wetting the duct and turning vanes. The dimensions of the plume resulting from injection were determined by manually taking multipoint temperature traverses of the duct cross section at several distances downstream of the injection point.

Initially, a single atomizer, attached to a lance which contained the air and liquid feed pipes, was installed through a nozzle port on top of the ductwork to position it in the center of the duct cross section. The first few tests with this atomizer showed that the downstream turning vanes were being wetted at very low liquid flow rates because of incomplete evaporation in the short residence time. These tests established that a much higher air-to-water ratio than expected was required. This correction was accomplished by enlarging the air inlet orifice and discharge tip of the atomizer. This change improved the evaporation rate and allowed a higher liquid feed rate.

Subsequent testing with additional atomizers led to the final array of nine single atomizers arranged in one vertical plane of the duct cross section. These atomizers were arranged three to a lance and installed through three nozzle ports on top of the ductwork.

Isotherm plots of the duct cross section at three distances downstream of the atomizers during water injection are shown in Figure 4-1. During the test the total water flow rate was 17.2 gpm. These isotherms define the shape of the confined zone plume of atomized water in the duct. Note that at all three duct cross sections, the duct surfaces are at or above 200°F and therefore are bound to be dry.

The water injection tests also showed that:

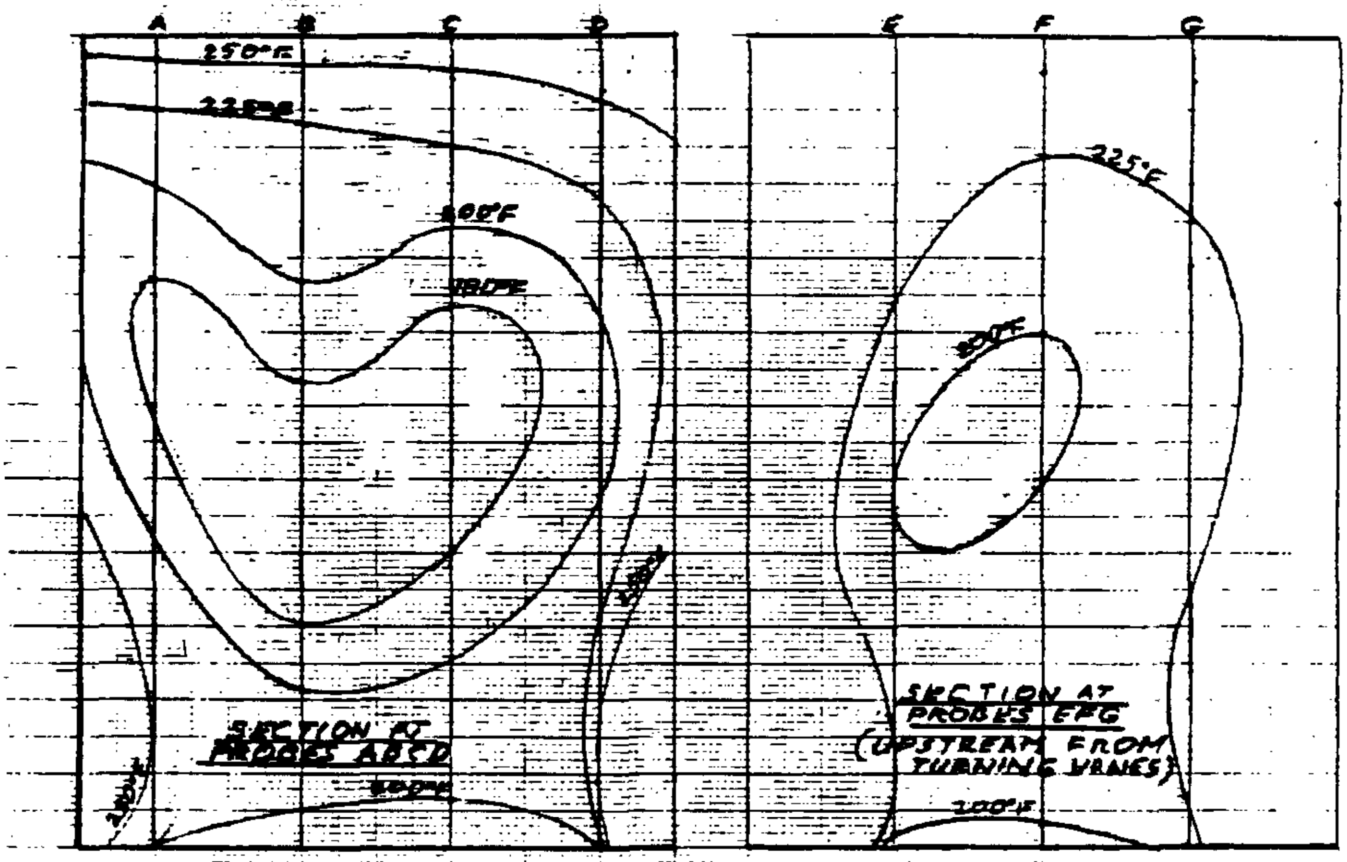
- o At least 30 scf of atomizing air are required per gallon of water to provide fine enough droplets for complete evaporation in the 1/2 second residence time.
- o The plume of atomized water droplets in the flue gas tends to gravitate towards the bottom of the duct if the droplets are not fine enough.

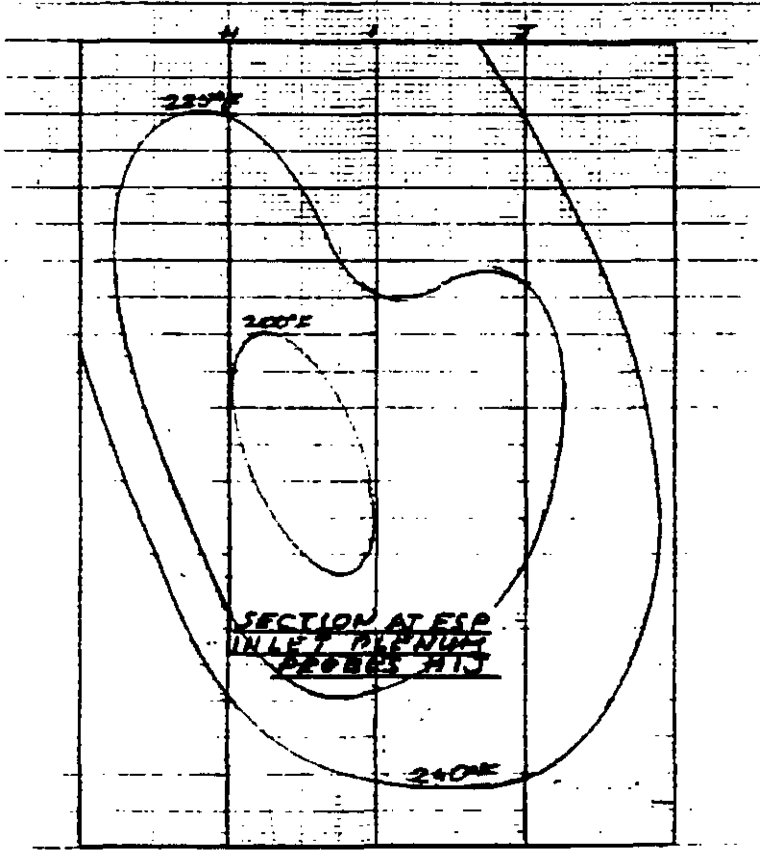
4.1.3 <u>Parametric PHDL Injection Tests</u>

PHDL injection tests were conducted using the nine-atomizer array. Compared with the results of the water injection tests, slurry injection resulted in higher injection rates, lower atomizing air-to-liquid ratios, and lower exit gas temperatures. Duct cross section isotherms measured during injection of 21 gpm of 7.8 percent PHDL slurry are shown in Figure 4-2.

The downstream temperature required to dry the atomized slurries was investigated by inserting pipe probes containing multiple thermocouples through test ports located on top of the duct. Typically, the probes remained in the duct for 30 minutes while the plume temperature along the probe length was measured. (Note that the temperature measured was usually lower than the true gas temperature because undried particles contacting the thermocouple would lower its temperature below the gas temperature by evaporative cooling.) When the probes were removed they were inspected to determine the extent and nature of any deposits. The following temperature/deposit relationships were observed:

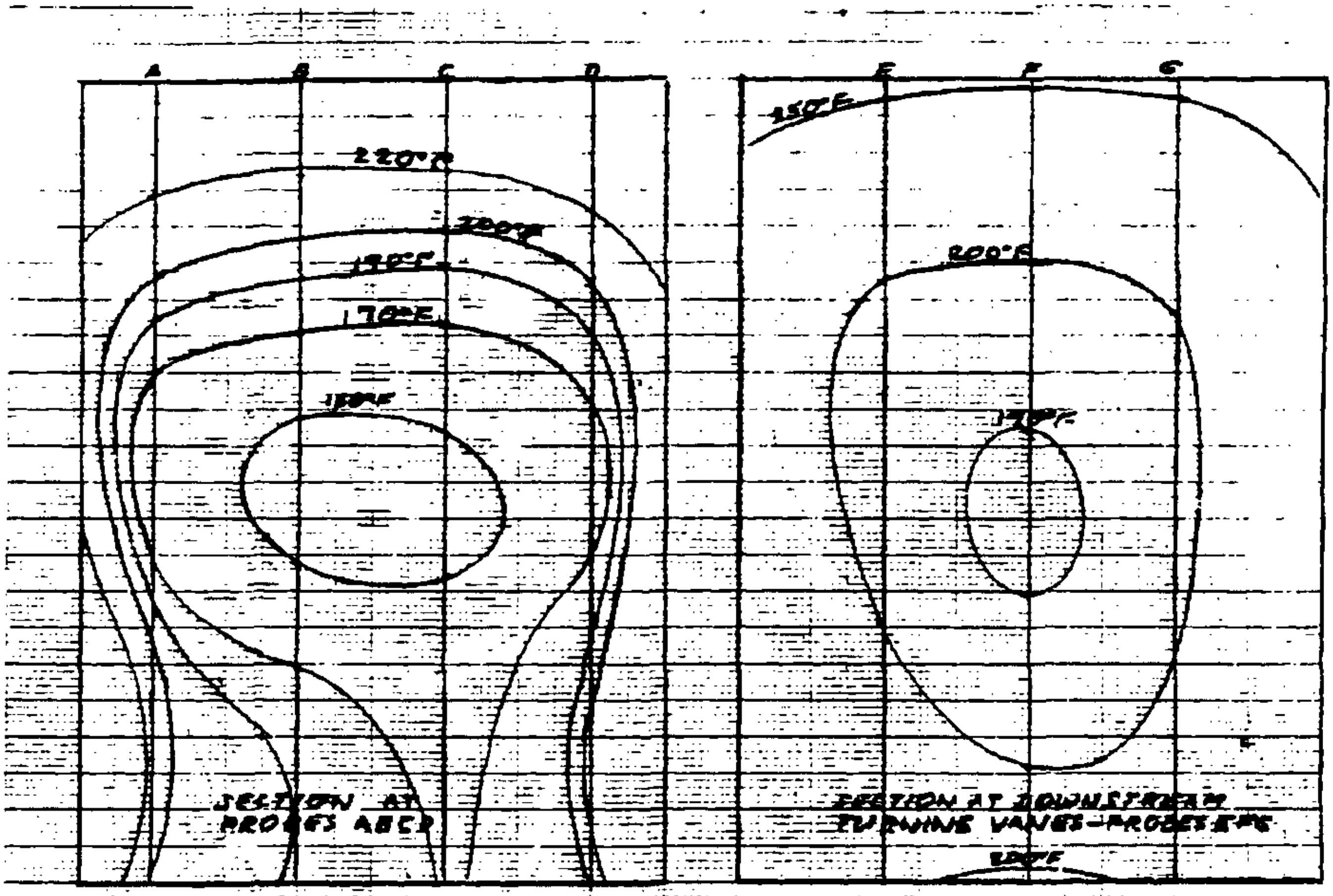
- o Very wet deposits formed below 140°F
- o Damp deposits formed between 140 to 155°F

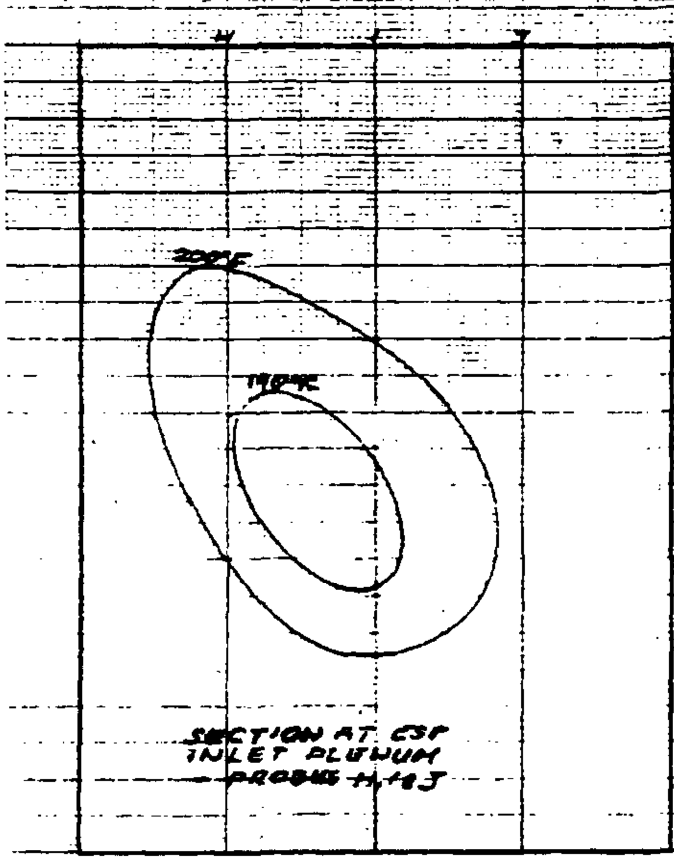




Note: See Figure 3-2 of Part 3 for location of planes ABCD, EFG, and HIJ

Figure 4-1 Duct Cross Section Isotherms Water Injection Test No. 1 9/14/87





Note: See Figure 3-2 of Part 3 for location of planes ABCD, EFG, and HIJ

Figure 4-2 **Duct Cross Section Isotherms Lime Injection Test No. 1 9/15/87**

- Dry deposits formed between 155 to 170°F
- No deposits formed above 170°F

From these observations it was concluded that the buildup on the turning vanes could be prevented by limiting the injection rate of slurry to an amount that would keep the temperature in front of the turning vanes at or above 170°F. Limiting the injection rate in this manner also limited SO_2 removal.

The parametric lime injection tests also showed that the atomizers must be arranged to:

- Avoid impingement of one spray on another
- Provide minimum clearances of 2 feet from the ceiling and 2-1/2 feet from walls

4.1.4 Continuous Lime Slurry Injection

The system was operated continuously to determine the long-term effects of lime injection on system performance. During this period, the system control philosophy was to keep the gas temperature above 170°F at the vertical plane in front of the turning vanes downstream of the injection point. This temperature was determined by manually taking an 18-point temperature traverse. The temperature at any point in the traverse was regulated by manually adjusting the lime slurry rate to one or more of the nine injection atomizers.

This procedure was usually adequate for control during the daytime when the boiler load was fairly constant. However, during periods of sudden boiler load changes, particularly at night, this manual control technique was not sufficiently responsive. This situation resulted in momentary excessive injection rates, low profile temperatures, and consequently, some deposits on the surrounding areas.

Calcitic lime (CL), both freshly slaked and as a slurry prepared from dry hydrate, was tested during the continuous run. Significant and rapid erosion of the nozzle discharge tips was experienced with both CL types.

4.2 DEPOSITS

Although the test system operating philosophy was to avoid deposit formation, some did occur. As mentioned earlier, deposits formed as a result of erosion of the atomizer tips and from the inability to closely follow plant load. Most of the deposits were friable and easily dislodged with a light blow. Others, apparently formed from wet droplets or incompletely atomized sprays, were very hard and difficult to breakup or to dislodge.

Several unit outages provided the opportunity to enter and inspect the deposits inside the system. While the extent of the deposits varied, and they were never severe enough to interfere with the plant operation, the deposit pattern had the following typical characteristics:

- Floor deposits in an area just downstream of the atomizers to the downstream turning vanes
- Slight deposits on the duct walls
- Deposits on the concave (impact) sides of the downstream turning vanes and spalled off deposits on the floor under the vanes
- Negligible deposits on the convex (nonimpact) sides of the turning vanes and the top of the duct
- Some deposits on the perforated baffle at the inlet to the electrostatic precipitator (ESP)
- Deposits on the ESP discharge wires

While deposits did form in the test system during the test program, the factors responsible for their formation are known and countermeasures can be taken to eliminate or minimize them. These measures include:

- Improved configuration of the atomizers to eliminate droplet impaction on adjacent sprays
- Use of nozzles with erosion resistant tips to reduce nozzle wear and eliminate nonuniform spray patterns
- More sophisticated instrumentation to provide better process control and load-following capability
- If necessary, installation of mechanical devices to dislodge and remove deposits

4.3 SO_2 AND NO_x REMOVAL

As noted previously, the need for slurry to dry before contacting the turning vanes only 35 feet downstream of the nozzles limited the slurry injection rate. This situation resulted in limited SO_2 removal below the DOE goal of 50 percent and, also, limited NO_x removal. Considering the injection rates that were possible, the SO_2 and NO_x removals were impressive and also provided high lime utilization. Lime utilization is defined as the percent of lime fed that reacts. (See Appendix J for a discussion on the calculation of lime utilization). The following typical results were obtained:

- With PHDL injection, SO_2 removal ranged from 6 to 30 percent depending on the slurry flow rate and concentration. NO_x removal ranged from 8 to 21 percent and increased with increasing slurry concentration. Lime utilization, based on combined SO_2 and NO_x removal, ranged from 23 to 90 percent.

- With freshly slaked CL, and for the conditions tested, SO_2 removal ranged from 10 to 22 percent, NO_x removal ranged from 8 to 18 percent, and lime utilization, based on combined SO_2 and NO_x removal, ranged from 23 to 33 percent. Two particular factors may have been responsible for these results.

    - The tests with the freshly slaked CL were conducted with severely worn nozzle tips; new tips were not available at the time, and the test schedule did not permit repeat testing with new tips. The unexpected lower performance obtained can be explained in part by deteriorated atomization resulting from eroded nozzle tips.

    - The short residence time in the spray zone may have also reduced the performance of the CL.

- With a slurry prepared from dry hydrated CL, and for the conditions tested, SO_2 removal ranged from 7 to 12 percent, NO_x removal ranged from 7 to 12 percent, and lime utilization, based on combined SO_2 and NO_x removal, ranged from 29 to 44 percent. Some of these results may have been influenced by testing with worn nozzle tips.

For all three limes tested, both SO_2 and NO_x removal increased with increasing lime concentration, while lime utilization decreased with increasing lime concentration.

Table 4-1 is a summary of SO_2 and NO_x removal and lime utilization results obtained during the testing.

Section 5

ESP PERFORMANCE

The Confined Zone Dispersion (CZD) injection point was located in a ductwork section between two electrostatic precipitators (ESPs). The ESP upstream of the injection point had a particulate removal efficiency of 75 percent. The downstream, or test ESP, was a plate and weighted wire design manufactured by the Buell Emission Control Division of Envirotech Corporation. (Refer to Appendix L for the test ESP characteristics.)

The performance of the ESP was monitored by an online opacity monitor in the stack. Although this stack also exhausted the gas from the other duct of Unit 15, the opacity monitor readings were felt to be a good indication of the performance of the test ESP. Specific measurements of the particulate removal efficiency of the test ESP, with and without lime injection, were also taken to determine its capability to handle the additional grain loading during lime injection.

In addition to the discussion below, information pertaining to the ESP performance is included in the following appendices:

- Appendix L: Characteristics of Seward ESP
- Appendix M: Report on Particulate Emissions by Clean Air Engineering, Inc.
- Appendix N: Review of Seward ESP Performance Data by W. R. Lane, Bechtel
- Appendix O: Seward #15 Precipitator Performance Evaluation by D. L. Strein, PENELEC

5.1 STACK OPACITY

5.1.1 <u>Parametric Lime Injection Tests</u>

During the short-term parametric lime injection tests, the opacity decreased, remained lower during injection, and then increased when injection stopped. Figure 5-1, the August 14, 1987, recording of the stack opacity, shows this effect.

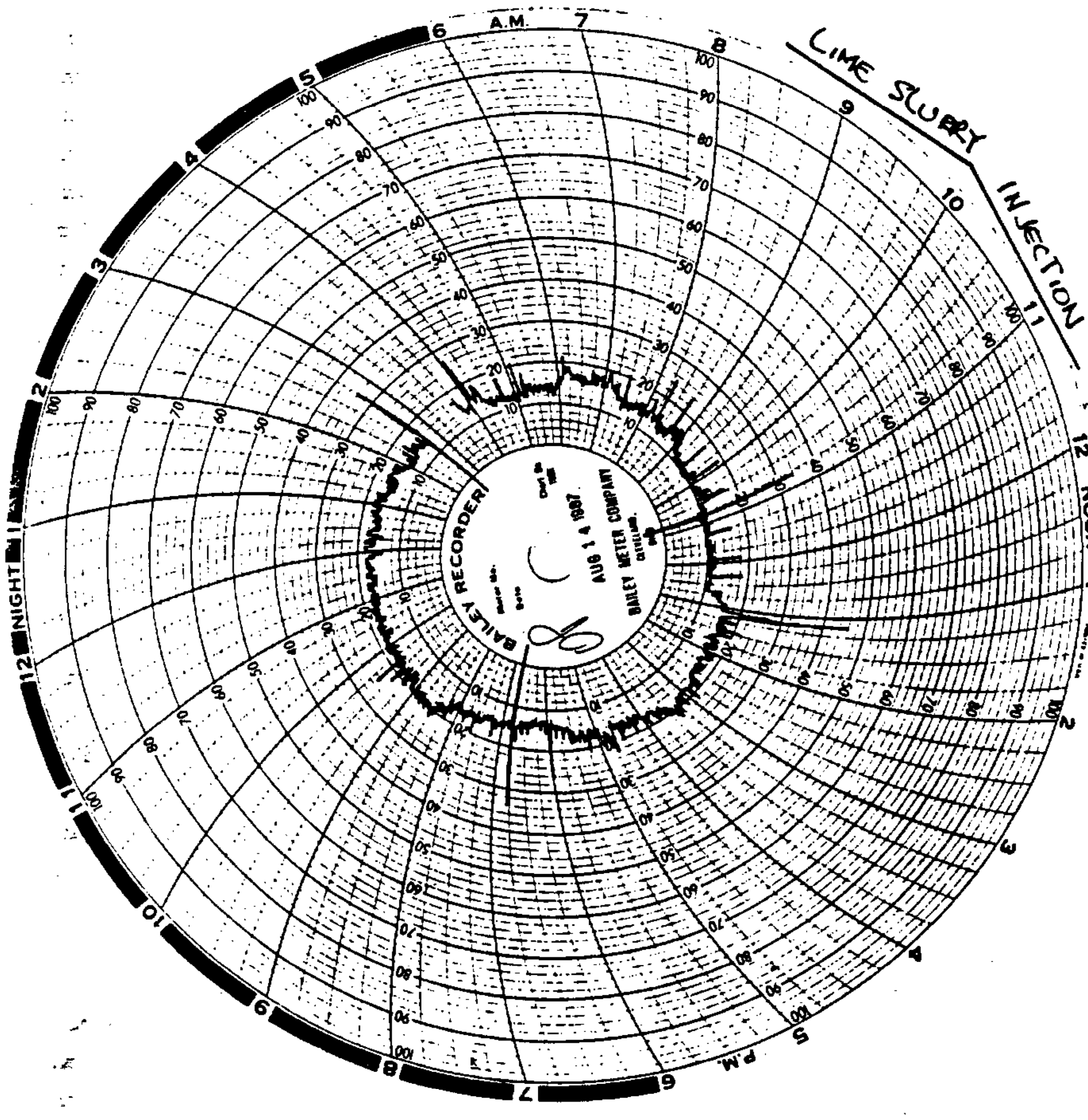


Figure 5-1 Recording of the Stack Opacity – 8/14/87

5.1.2 Continuous Lime Injection Tests

During the long-term, continuous lime injection tests, the opacity decreased at the start of injection and remained low. However, after 5 to 10 hours of operation, the opacity rose to a level exceeding the original one (baseline level) prior to the start of injection. The opacity was restored to the baseline level by using off-power rapping. Off-power rapping refers to sequentially deenergizing each of the four ESP fields for a few minutes (while three fields remain energized, the fourth field is rapped while it is deenergized). During the off-power rapping period, there were excursions in the stack opacity. Off-power rapping has to be repeated approximately every 8 hours during continuous injection.

Figure 5-2, the October 23, 1987, recording of the stack opacity, shows the reduction in opacity level after off-power rapping at approximately 3 am, 9 am, and 6 pm.

5.2 ESP TESTS

5.2.1 Particulate Removal Efficiency Measurements

Clean Air Engineering, Inc., Palatine, IL was contracted to determine the particulate removal efficiency of the test ESP. Measurements were made during PHDL injection (10/15/87), during CL injection (10/23/87), and for fly ash alone, i.e., no injection (11/10/87). Three sets of simultaneous particulate concentration measurements were taken at the inlet and outlet at the ESP on each day. The slurry injection rate was similar during each measurement.

The results are summarized in Table 5-1. From the table, it can be seen that the average particulate removal efficiency was slightly higher during CL injection (98.04%) and slightly lower during PHDL injection (95.48%) compared with fly ash alone (96.56%). The average emissions were approximately the same during the CL injection (0.0685 lb/MBtu), but higher during PHDL injection (0.1214 lb/MBtu) compared with the fly ash alone (0.0707 lb/MBtu).

The inlet loading during CL injection was 80 percent higher than with no injection. The capability of the ESP to maintain emission levels during CL injection to that with no injection is very encouraging. This supports the

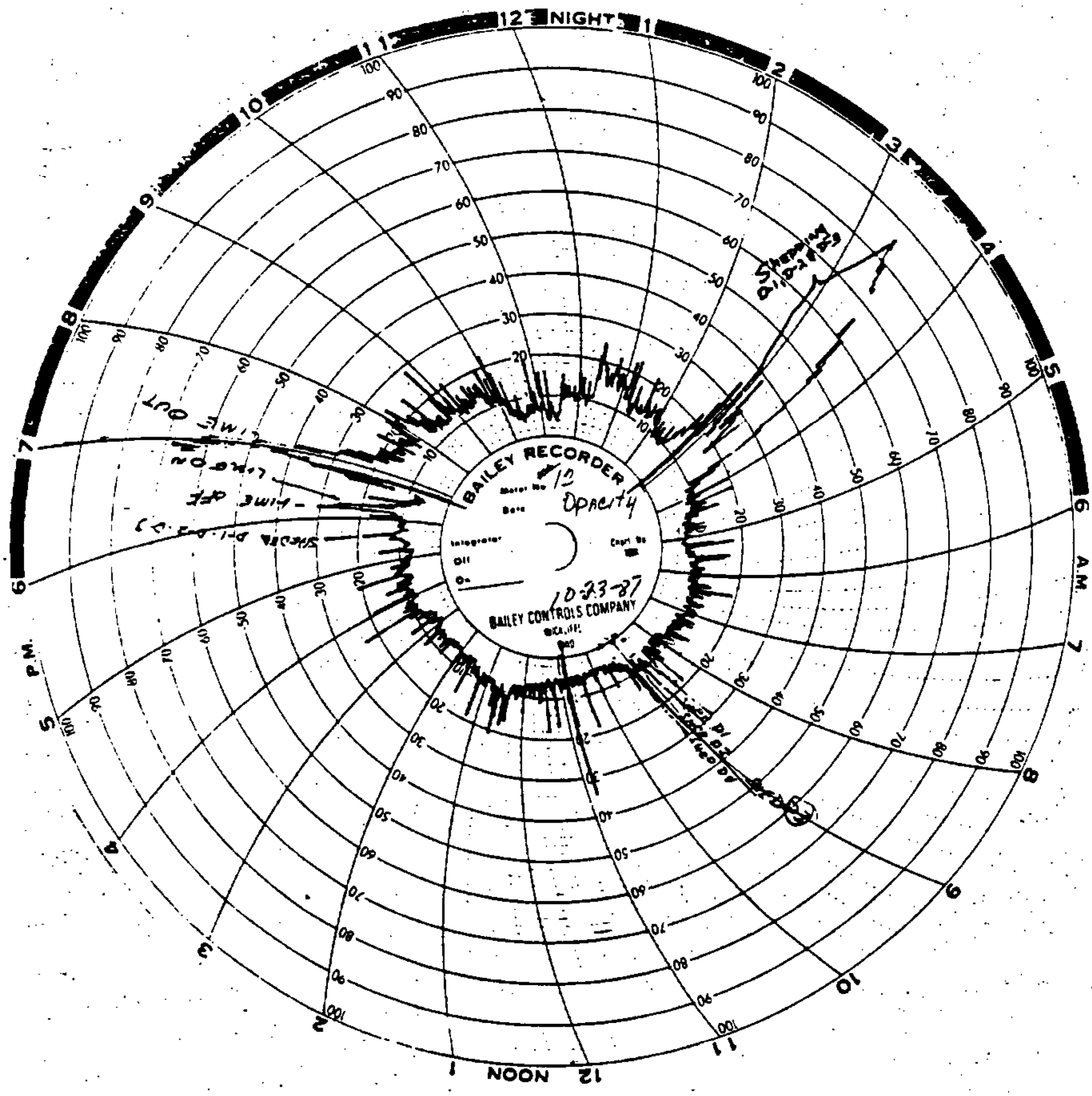


Figure 5-2 Recording of the Stack Opacity – 10/23/87

Table 5-1

PARTICULATE EMISSIONS (PE)

	PE Without Lime Slurry Injection (11/10/87)	PE With Lime Slurry and with Type S Lime (10/15/87)	Emissions and with Hydrated Lime (10/23/87)
	Average of Three Tests		
INLET			
Gas Conditions			
Temperature, °F	244	191	194
Moisture, % vol.	5.2	7.3	7.2
O_2, % dry vol.	9.6	9.3	8.5
CO_2, % dry vol.	9.7	10.3	10.7
Volumetric Flow Rate			
acfm	290,133	249,533	309,133
dscfm	197,833	176,700	218,433
Particulate Conc.			
Grains/dscf	0.7845	1.1034	1.4056
OUTLET			
Gas Conditions			
Temperature, °F	262	225	226
Moisture, % vol.	4.0	7.1	6.9
O_2, % dry vol.	10.2	9.3	9.2
CO_2, % dry vol.	9.3	10.5	10.3
Volumetric Flow Rate			
acfm	319,033	324,233	317,300
dscfm	221,200	225,466	218,733
Particulate Conc.			
Grains/dscfm	0.0275	0.0499	0.0273
Lb/hr	52.13	96.37	50.87
Lb/MBtu*	0.0707	0.1214	0.0685
PARTICULATE REMOVAL EFFICIENCY %	96.56	95.48	98.04

*As calculated with an FD factor of 9.277 / 9.440 / 9.864

possibility that lime injection, while increasing the ESP inlet loading, may not increase emissions. The reason for this is that the reduced flue gas temperature reduces the particulate resistivity and promotes collection. This phenomenon is especially true at plants such as Seward that burn low-sulfur coal.

The PHDL data indicated higher emissions with a higher inlet loading.

5.2.2 ESP Operations

Table 5-2 is a summary of ESP test data with and without lime injection including the average power to each ESP field. The use of these data in analyzing the ESP performance is discussed below.

Gas Temperature Effects. The decrease of flue gas temperature with lime slurry injection allowed increased power input to the precipitator by the automatic voltage control system. The average power with no lime injection was about 92,000 kW. This amount was increased by 25 percent to 114,000 kW with lime injection.

With an assumed average gas rate of 300,000 acfm, the power consumption in terms of watts per 1000 acfm was about 306 with no injection and 380 with injection. The 25 percent increase in power input would be expected to improve collection efficiency.

Field Input Power Variation. The data in Table 5-2 show considerable variation of power input from field to field. Generally, the power consumption is expected to increase from field to field through the precipitator. This is due to less particulate in the gas stream as it reaches successive fields. The data indicate low power input to the second and the fourth field during slurry injection, compared with the power input to the other two fields.

The variation of power input in this unexpected way is symptomatic of other problems with the precipitator.

Table 5-2

ELECTROSTATIC PRECIPITATOR TEST DATA
WITH AND WITHOUT LIME SLURRY INJECTION

Seward Station, Pennsylvania Electric Company, 1987

Date	07/21	07/23	08/05	10/15	10/23	11/10
Time	8:30-10:00	8:30-10:00	8:30-10:00	8:30-3:00	9:30-3:00	8:30-5:00
Lime injection	NO	NO	NO	YES	YES	NO
Plant load, MW	142	141	141	140	142	Unknown
Emission opacity	12	12	16	10	11	Unknown
Gas temperature	299	298	290	191	194	244
ESP D power, kW						Unknown
Field 1	28,475	26,988	22,625	32,680	33,000	Unknown
Field 2	17,170	10,627	11,275	21,583	19,500	Unknown
Field 3	22,312	24,255	16,425	43,833	39,100	Unknown
Field 4	31,607	33,300	30,837	22,770	15,000	Unknown
Total	99,564	95,170	81,162	120,866	106,600	Unknown
ESP Inlet				Note 1	Note 1	Note 1
acfm				249,600	309,100	290,100
Grains/dscf				1.1034	1.406	0.785
ESP Outlet						
acfm				324,200	317,300	319,000
Grains/dscf				0.0499	0.0273	0.0275
Percent Collection				95.48	98.06	96.49
				Note 1	Note 1	Note 1

Notes:
1. Test data are average of three tests on each day.

These problems include poorly performing automatic voltage controllers, inadequate rapping, and, possibly, collection plate rappers to discharge electrode alignment problems. It is suggested that with modifications, this precipitator could perform better. Installation of modern automatic voltage controllers and better rapping systems at other plants have reduced emissions by over 50 percent in many cases.

<u>ESP Collection Efficiency Variation</u>. The average collection efficiency during lime injection of 95.48 percent on October 15th is considerably different from the 98.06 percent obtained on October 23rd. There is no obvious explanation for this variation. However, it is expected that nonuniform rapper and voltage controller operation may have played a part.

It is also of interest that, of the 2 days with slurry injection, the day with the lowest power input had the highest collection efficiency. In fact, the power input on the high collection day was lower in three of the four fields. This is not compatible with precipitator technology.

<u>Rapping System Comments</u>. This precipitator utilizes vibrators to clean the discharge electrodes and electromagnetic impact rappers to clean the collection plates. Vibrators have performed well at many plants but have also been inadequate at many others. The condition of the collection plate rappers is not known and deserves some attention. Rappers deteriorate with time. This includes deterioration of the coils, linings, power suppliers, and controllers. It is possible that the rappers for the second field are not rapping as hard as the other rappers or that the rapper shaft to support beam connections are loose.

It is noteworthy that with slurry injection the power input increased to each field except the fourth. The plant utilized off-power rapping to clean the collection plates at times during the injection period. This practice did not occur during the actual emission testing and was not utilized for the fourth field.

Off-power rapping refers to shutting off the transformer power supply to a field while it is being rapped. The lack of corona current flow reduces the amount of electrical charge holding the ash to the collection plate, thus making rapping more effective in removing the ash.

The plant is considering the installation of a new rapping control system. This will probably improve performance.

Waste Products. The waste products collected by the test ESP were a mixture of fine coal ash, reaction products consisting of sulfates and sulfites of calcium and magnesium, and unreacted lime. The waste was a fine, dry, free-flowing powder. No problems were encountered in discharging the material from the ESP hoppers.

5.2.3 Evaluation of the Effect of Lime Slurry Injection on ESP Performance by D. L. Strein

Mr. D. L. Strein of PENELEC, the ESP Specialist, analyzing the electrostatic precipitator behavior during the lime slurry injection test, made the following observations (see Appendix O for the complete report):

". . . Upon initial injection of the lime slurry, the stack opacity decreased and the precipitator current density increased. This is likely caused by flyash agglomeration and a possible decrease in ash resistivity due to the presence of moisture and a decrease in gas temperature. As time went on, the opacity and precipitator power would deteriorate to the point where the opacity was near the 20% regulatory limit. Power-off rapping was then necessary to bring the stack opacity back down to where it was initially before the lime slurry injection was started. The cause of the precipitator performance deterioration is likely due to the plate and wire build-up which accumulated over a long period of time. When the lime slurry system was shut down, the opacity would initially increase to values well above 20%. After a short period of time it would then recover to a value under 20%. I suspect this phenomenon was caused by the precipitator shedding its accumulated layer of the ash/lime combination.

It is quite normal for a precipitator to experience a transient condition upon a sudden change in flue gas composition. I suspect in this case the shedding was due to a sudden increase in gas temperature when the slurry system was shut down.

"It is impossible to predict whether or not improvements in the lime slurry injection system could be made which would eliminate a capacity problem on a long term basis. However, the main concern at this point appears to be deposition of the lime in the precipitator inlet duct, the precipitator inlet perforated plate, and the internal collecting plates and emitting wires. The deposition problem could very well be caused by insufficient drying time. If this deposition problem can be resolved, I believe the opacity problem can be reduced. However, if further experimentation with this system indicates the deposition problem has been resolved and an opacity problem is still created, there are no quick and easy solutions. Probably the only solution that would deal with this type of problem is a larger precipitator."

Section 6

ANALYSIS OF SO_2/NO_X REMOVAL DATA

6.1 SO_2 REMOVAL

The test results presented in Section 4 indicated that lime slurry concentration had an effect on SO_2 removal. To further investigate this effect, the test data for PHDL presented in Table 4-1 were rearranged into four groups according to weight percent slurry concentration. The four concentration groups are:

- o Very low (1.6 to 3.7 percent)
- o Low (4.7 to 6.5 percent)
- o Medium (7.0 to 7.8 percent)
- o High (8.3 to 13 percent)

The groupings are shown in Table 6-1.

A plot of percent SO_2 removal versus gallons per minute of slurry injected was made identifying each group with a unique symbol. A line was then drawn from the origin through the data points for each group.

The plot is shown in Figure 6-1.

Figure 6-1 shows that the Seward test data exhibit a positive linear relationship of SO_2 removal versus slurry injection rate. The data also show that, at a given injection rate, SO_2 removal increases with slurry concentration.

6.2 LIME UTILIZATION

The utilization data in Table 4-1 were plotted to determine how lime utilization is related to lime type and lime concentration for SO_2 and NO_x removal. Lime utilization is defined as the percent of lime fed that reacts (see Appendix J).

Table 6-1

SEWARD DOLOMITIC LIME DATA
GROUPED BY SLURRY CONCENTRATION

Run Date	Note	SO_2 Removal (%)	Slurry Feed Rate (gpm)	Slurry Concentration (Wt %)
		Slurry concentration range: 1.65% to 3.74%		
8/12		6.32	22.5	1.65
8/13		12.4	30.0	3.13
8/6		7.7	19.0	3.74
		Slurry concentration range: 4.7% to 6.5%		
9/17		12.0	17.5	4.7
8/20		17.2	30.0	4.9
9/18		12.0	18.5	5.0
9/21		13.0	17.5	5.8
9/23		16.8	22.2	5.9
9/15	Test II	12.4	18.4	6.0
8/14		20.1	27.5	6.1
10/15	0000-0300	8.9	14.1	6.5
		Slurry concentration range: 7.0% - 7.8%		
10/15	0600-0700	12.1	13.8	7.1
10/15	1400-1500	16.8	19.7	7.3
10/12	2nd shift	15.4	18.6	7.4
10/13	2nd shift	15.3	17.3	7.5
9/24		18.5	20.0	7.7
9/15	Test I	15.2	17.6	7.8
10/13	1700	18.7	21.1	7.8
10/13	3rd shift	14.5	16.6	7.8
		Slurry concentration range: 8.3% - 13.0%		
8/17		23.4	35.0	8.3
8/18		29.4	33.0	12.4
8/19		22.2	27.5	13.0

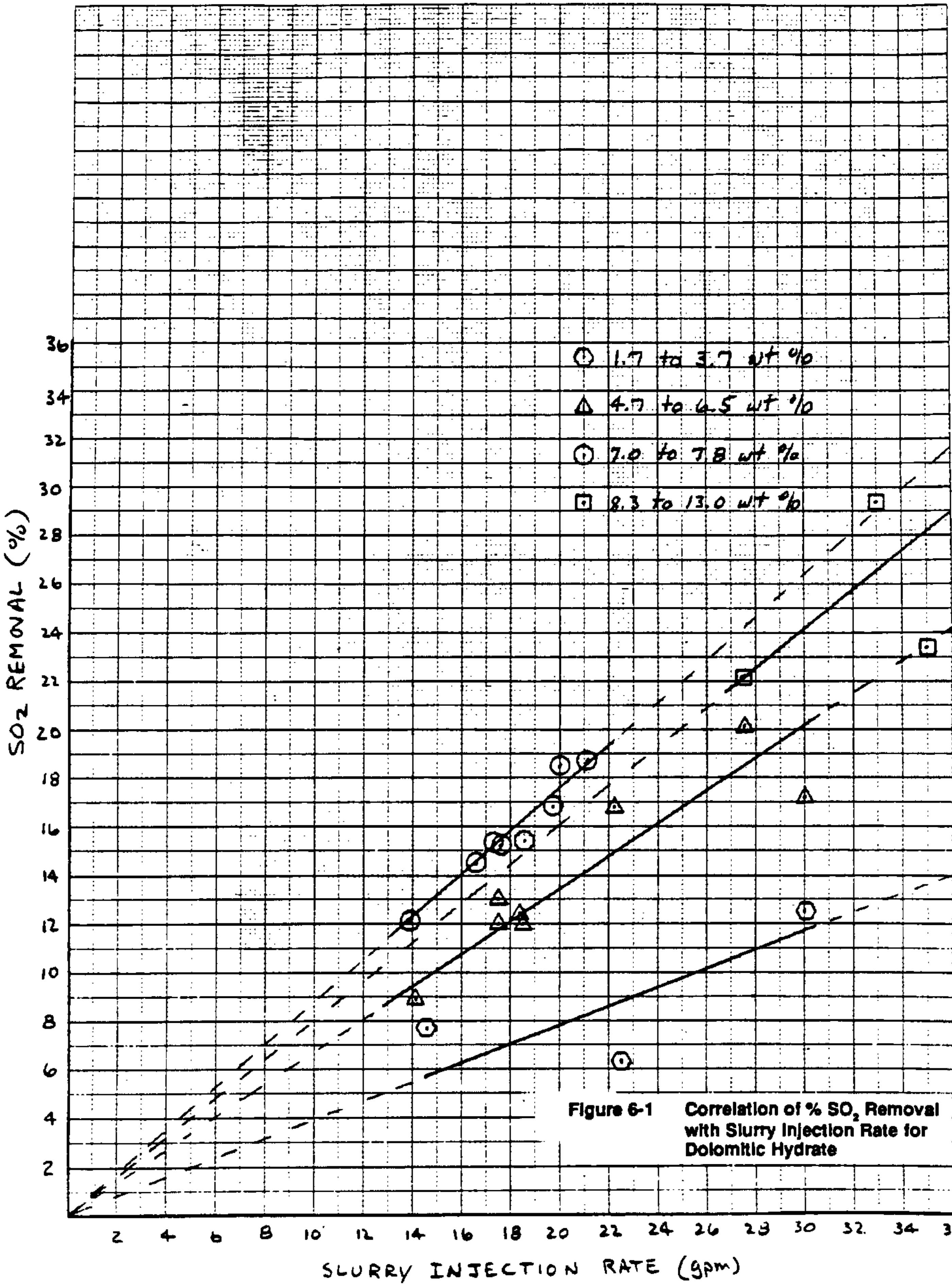


Figure 6-1 Correlation of % SO_2 Removal with Slurry Injection Rate for Dolomitic Hydrate

Figure 6-2 is a composite plot showing the effect of calcitic lime utilization versus lime slurry concentration for SO_2 removal, NO_x removal, and combined SO_2/NO_x removal. Figure 6-3 is a similar plot for PHDL. The lines in Figures 6-2 and 6-3 are empirically fitted to the data.

From these plots, the Seward test data show the following relationships:

- Both CL and PHDL utilization decrease with increasing lime concentration for both SO_2 and NO_x removal.
- PHDL utilization is higher compared with CL for either NO_x or SO_2 removal at a given lime concentration.

6.3 PROJECTIONS FOR 50 PERCENT SO_2 REMOVAL

As noted earlier, the short residence time available in the test duct at Seward limited the lime injection rate to a point where a maximum of only 30 percent SO_2 removal could be obtained. A full-scale commercial system with a longer straight run of duct would not be limited in this way. Furthermore, the ductwork configuration at Seward is suitable for installation of a second set of atomizers upstream of the set used, which would approximately double the residence time. This would allow more slurry to be injected and result in higher SO_2 removal.

The relationship shown in Figure 6-1 can be used to project the slurry injection rate and concentration required for 50 percent SO_2 removal. The relationship for medium lime concentration (7.0 to 7.8 percent) has been reproduced and extrapolated in Figure 6-4. By this extrapolation, the injection of about 55 gpm of 7.5 percent PHDL would remove 50 percent of the SO_2 at Seward.

This extrapolation is probably conservative. The testing at Seward had a relatively small confined zone which allowed a large fraction of the gas to bypass the CZD treatment. Using two-stage injection and increasing residence time would permit more injection points, better gas/spray dispersion, a larger and more uniform confined zone, and a closer approach to saturation temperature for the treated gas. These factors should provide better lime utilization thereby obtaining 50 percent SO_2 removal at an injection rate lower than 55 gpm.

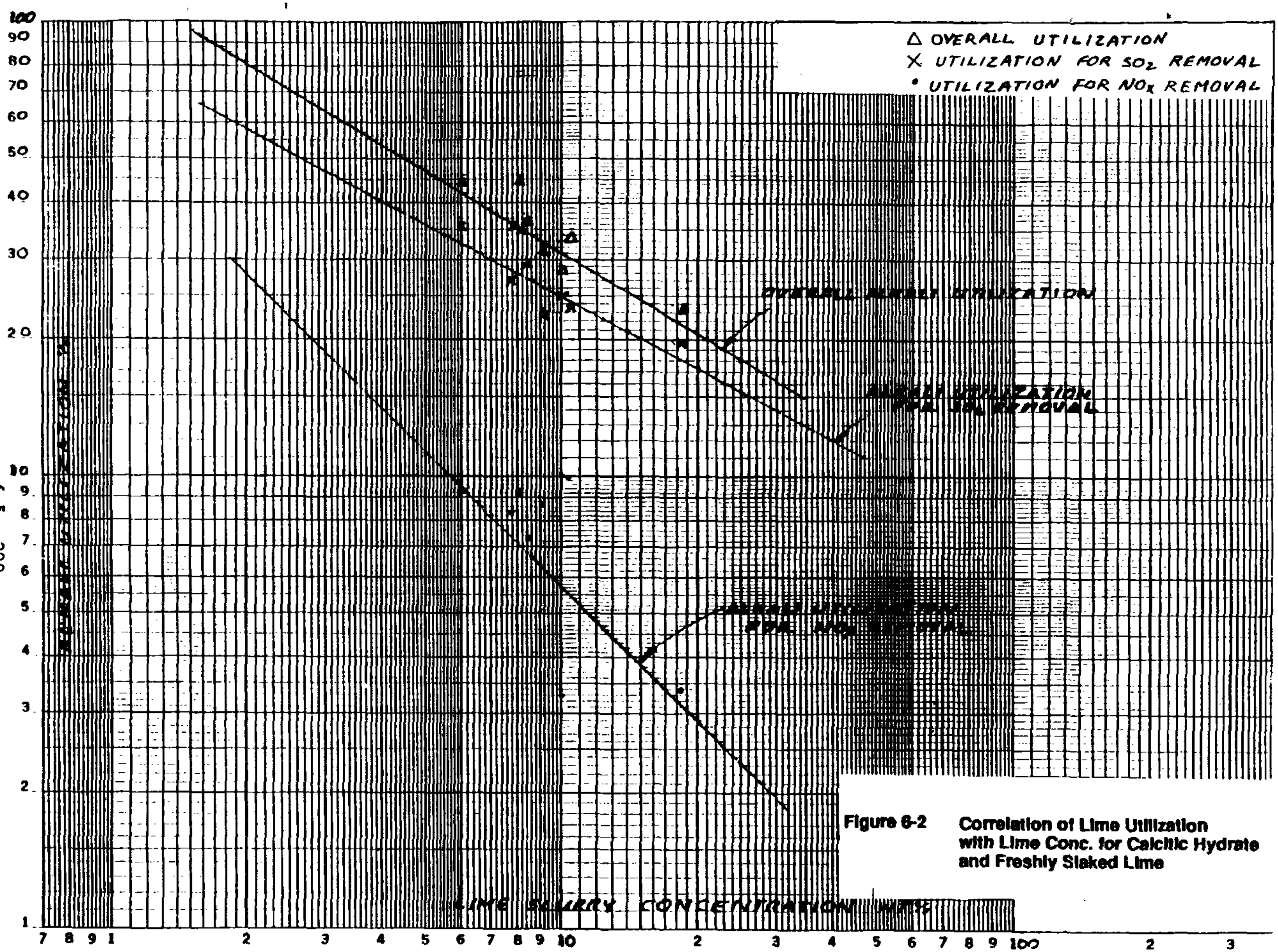


Figure 6-2 Correlation of Lime Utilization with Lime Conc. for Calcitic Hydrate and Freshly Slaked Lime

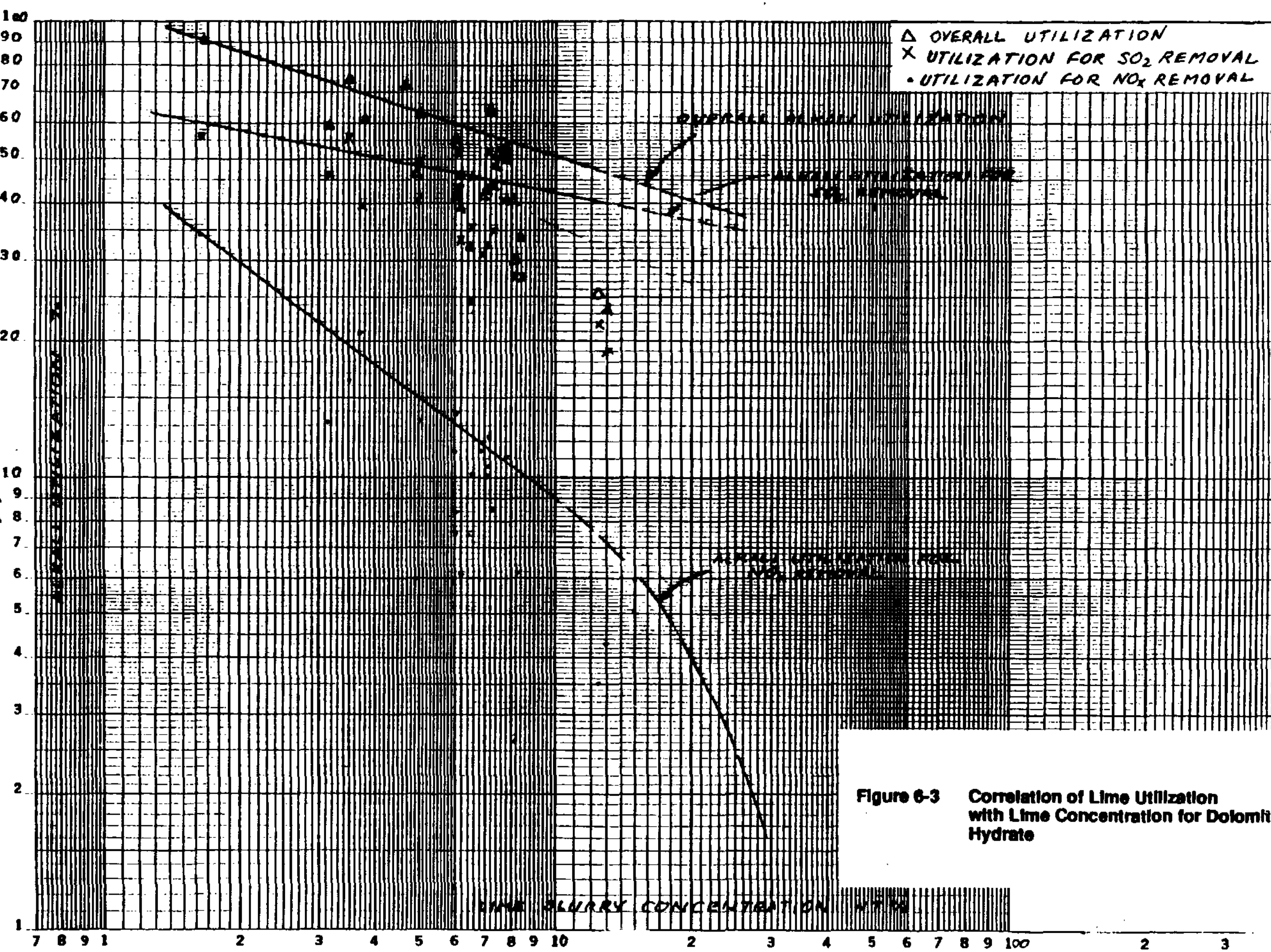


Figure 6-3 Correlation of Lime Utilization with Lime Concentration for Dolomitic Hydrate

CZD TESTING AT PENELEC SEWARD STATION

PLOT OF AVERAGE TEST DATA WITH 7.5% LIME SLURRY CONC.

AND EXTRAPOLATION TO 50% SO_2 REMOVAL

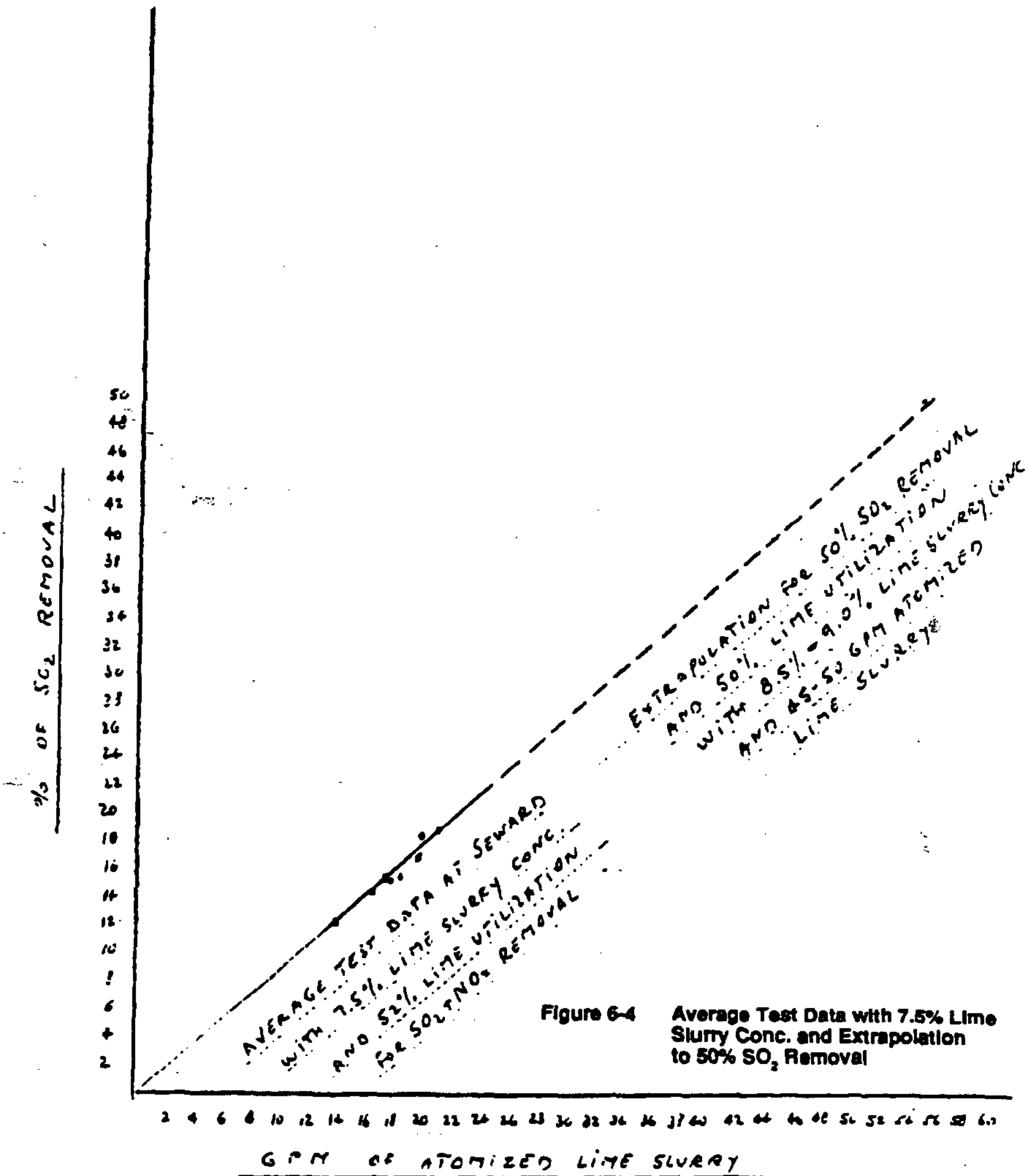


Figure 6-4 Average Test Data with 7.5% Lime Slurry Conc. and Extrapolation to 50% SO_2 Removal

Two-stage lime injection is expected to provide much higher NO_x removals compared with that obtained in the single-stage injection tests during the Seward test program.

At any given SO_2 removal, the injection rate could also be lowered by increasing lime feed solids. However, utilization would be reduced. For economic reasons, it is better to operate at conditions that produce the highest utilization which implies operating at the lowest feed solids possible.

PART 4

Combined Analyses and Projections

CONTENTS

ILLUSTRATIONS

TABLES

Preceding Page Blank

Table		Page
2-15	Case 2 - CZD Process Retrofit - Projected Capital Requirements	2-51
2-16	Case 2 - CZD Process Retrofit - Projected First Year Operating Cost	2-52
2-17	Case 2 - CZD Process Retrofit - 30-Year Levelized Busbar Cost	2-53
2-18	Case 2 - Estimated Cost of SO_2 Removal	2-53

ABBREVIATIONS, ACRONYMS, AND DEFINITIONS

acfm	actual cubic feet per minute
ADT	acid dew point
AST	approach to saturation temperature
AVC	automatic voltage control
bhp	brake horsepower
CEM	continuous emissions monitor, term used to designate SO_2-O_2 monitor
CL	calcitic lime
conc	concentration
CPC	Consumers Power Company
CZD	confined zone dispersion
DOE	U.S. Department of Energy
d/s	downstream
EMV	effective migration velocity
ESP	electrostatic precipitator
Eff	efficiency
FGD	flue gas desulfurization
gpm	gallons per minute
HHV	higher heating value
ID	induced draft
Injection	spraying lime slurry or water into flue gas flowing in a duct
kscfm	thousand standard cubic feet per minute
L	lime
LFR	lime feed ratio, moles of lime (both Ca and Mg) fed per mole of SO_2 entering
MWe	megawatts, electric equivalent
NO_x	nitrogen oxides
NWIR	normalized water injection rate
O_2	oxygen
OH	hydroxide concentration
O&M	operating and maintenance
PEDA	Pennsylvania Energy Development Authority
PENELEC	Pennsylvania Electric Company
PETC	Pittsburgh Energy Technology Center
PHDL	pressure hydrated dolomitic lime (also called Type S lime)
PRDA	Program Research and Development Announcement
P&ID	piping and instrumentation diagram
P&ID	process and instrumentation diagram
SCA	specific collection area
scf	standard cubic feet
scfm	standard cubic feet per minute
SO_2	sulfur dioxide
SO_3	sulfur trioxide
SSCo	Spraying Systems Company
T/R	transformer/rectifier
u/s	upstream
VI	voltage current
W	water
WC	water column, the head difference in a water manometer

All temperatures are in degrees F, unless specified otherwise.

Section 1

COMBINED DATA ANALYSES

As discussed in Parts 2 and 3, the data sets obtained from the Campbell site and the Seward site were separately correlated using several approaches. These approaches provided good correlations for the data from either site. However, the widely different test conditions at Campbell and Seward made it difficult to analyze the data on a common basis. Compared with Campbell, Seward had these principal differences:

- Extremely short residence time
- Much larger duct cross section
- Higher gas velocity and gas flow rate
- Finer and more uniform atomization
- Higher total injection rates
- Lower inlet SO_2 concentration
- Lower SO_2 removals
- High approach to saturation temperatures
- Capability to establish a confined zone
- Minimal duct deposits

An attempt was made to use the rational and empirical correlation approaches described in Part 2 to correlate the combined SO_2 removal data set from both sites, but no useful correlations were obtained. A new approach was developed, suggested by the correlation for the Seward data of SO_2 removal versus lime slurry injection rate shown in Part 3, Figure 6-1. This approach, described below, successfully correlated the combined data set and appears to provide reasonable extrapolations for the full-scale projections.

1.1 CORRELATION APPROACH

Figure 6-1 of Part 3 shows that the percentage of SO_2 removal increases with an increase in either slurry injection rate or lime concentration. This is expected because either action increases the amount of lime available in the system to react with SO_2.

Furthermore, the increase in percentage SO_2 removal is shown to be proportional to the increase in slurry feed rate. At Seward, the flow rate, temperature, and SO_2 concentration of the untreated gas were quite stable, and the short residence time limited the injection rate. As a result, the temperature and SO_2 concentration of the treated gas were held to relatively narrow ranges, and the SO_2 removals were held to a small range of low to moderate values. Under these conditions of relatively constant flue gas properties and low SO_2 removals, a proportional relationship between percentage SO_2 removal and injection rate is reasonable. For a broader range of operating conditions, a direct relationship would also be expected, but it would not be expected to be proportional.

Percentage SO_2 removal does not increase proportionally with lime concentration. Although there is scatter in the data, Figure 6-1 of Part 3 shows that, at a given injection rate, an increase in lime concentration yields a lesser increase in SO_2 removal. This effect is also supported by the decrease in lime utilization with increasing lime concentration for both the Campbell and Seward data as shown, respectively, in Figures 6-14 and 6-15 of Part 2, and Figures 6-2 and 6-3 of Part 3.

It was also known from the analysis of the Campbell data, and from reports on spray dry flue gas desulfurization (FGD), that there is a strong inverse relationship between percentage SO_2 removal and AST.

Furthermore, logical analysis indicates that percentage SO_2 removal is inversely related to SO_2 concentration. This can be shown by examining a hypothetical situation where a CZD process is operating at constant conditions and there is a sudden increase in the inlet SO_2 concentration while everything else remains constant. The percentage SO_2 removal can be expected to drop somewhat. If the absolute SO_2 removal was unaffected by SO_2 concentration then, the percentage SO_2 removal would be reduced in proportion to the change in SO_2 concentration. However, because a higher SO_2 concentration provides a higher driving force for SO_2 dissolution and reaction, the percentage SO_2 removal may be reduced less than in proportion to the SO_2 concentration change.

To directly compare the data from the full-scale test site and the pilot-scale test site, it was necessary to normalize the slurry injection rates. Furthermore, because the slurry concentrations at the two test sites were typically different, it was felt that a normalization based on water injection would be more representative than slurry injection. Therefore, the injection rate was normalized by dividing the water portion of the slurry feed rate in gallons per minute (gpm) by the gas flow rate in thousand cubic feet per minute (kscfm). The quantity was called the normalized water injection rate (NWIR).

This analysis suggested a correlation equation of the following form:

$$\text{Fraction } SO_2 \text{ removal} = K\,(NWIR)^a\,(Wt\ \%)^b\,(Avg\ SO_2)^c\,(AST)^d$$

where:

K	= a coefficient to account for the effect of unmeasured variables, system differences, and lime type
NWIR	= normalized water injection rate, gal/kscf
Wt %	= feed solids, wt %
Avg SO_2	= average SO_2 concentration, ppmv, wet basis
AST	= approach to saturation temperature, °F

The analysis also suggested that exponents a and b would be positive while exponents c and d would be negative. Average SO_2 concentration (the arithmetic average of the inlet and outlet SO_2 concentrations in ppmv on a wet basis) was used instead of inlet SO_2 concentration because it provided the better correlation.

The SO_2 removal data were grouped into three data sets: Seward pressure hydrated dolomitic lime (PHDL), Campbell PHDL injected through two nozzles, and Campbell calcitic lime (CL), shown respectively in Tables 1-1, 1-2, and 1-3. The data for Campbell PHDL injected through one nozzle were not used

Table 1-1
SEWARD AVERAGED RUN DATA
DOLOMITIC LIME WITH NO WATER INJECTION

RUN DATE	NOTE	SO2 RMVL	LIME UTIL FOR SO2 RMVL %	LFR	TOTAL LIME FEED RATE gpm	LIME CONC wt%	INLET TEMP deg F	OUTLET TEMP, F =(TIN-15 -2*FEED)	MEASURED GAS SO2 CONC INLET ppmv wet	MEASURED GAS SO2 CONC OUTLET ppmv wet	FLUE GAS FLOW RATE 1000 SCFM	SpGr	WATER INJ RATE gpm
08/06		7.7%	39.40	0.195	19.00	3.74	286	233	802	688	218.5	1.018	18.6
08/12		6.3%	56.30	0.112	22.50	1.65	279	219	727	619	207.8	1.008	22.3
08/13		12.5%	45.70	0.272	30.00	3.13	288	213	745	602	211.1	1.015	29.5
08/14		20.1%	43.20	0.466	27.50	6.06	279	209	783	571	213.1	1.031	26.6
08/17		23.4%	27.50	0.851	35.00	8.28	298	213	740	519	218.5	1.044	33.5
08/18		29.4%	22.00	1.336	33.00	12.40	295	214	730	470	209.9	1.069	30.9
08/19		22.2%	19.00	1.168	27.50	13.00	299	229	734	527	213.5	1.073	25.7
08/20		17.2%	40.50	0.425	30.00	4.90	293	218	746	566	217.6	1.025	29.2
09/15	TEST I	15.2%	40.90	0.372	17.60	7.75	281	231	783	630	220.0	1.041	16.9
09/15	TEST II	12.4%	42.10	0.295	18.35	6.00	290	238	768	642	226.0	1.031	17.8
09/17		12.0%	50.00	0.240	17.50	4.71	294	244	735	597	215.0	1.024	17.1
09/18		12.0%	57.00	0.211	18.50	5.00	280	228	749	614	211.0	1.025	18.0
09/21		13.0%	41.10	0.316	17.50	5.80	288	238	760	605	214.0	1.030	17.0
09/23		16.8%	39.80	0.421	22.20	5.87	286	227	753	576	212.1	1.030	21.5
09/24		18.5%	35.60	0.520	20.00	7.70	288	233	734	570	212.7	1.040	19.2
10/12	2nd SHFT	15.1%	38.60	0.392	18.60	7.40	288	236	783	625	210.0	1.039	17.9
10/13	1700	18.7%	42.60	0.439	21.10	7.80	294	237	811	634	214.0	1.041	20.3
10/13	3rd SHFT	14.5%	40.60	0.357	16.60	7.80	292	244	814	668	210.0	1.041	15.9
10/13	2nd SHFT	15.3%	43.30	0.353	17.28	7.50	294	244	785	636	220.0	1.039	16.6
10/15	0000-0300	8.9%	35.40	0.251	14.10	6.50	281	238	835	695	205.4	1.034	13.6
10/15	0600-0700	12.1%	47.50	0.255	13.85	7.10	283	240	843	681	216.5	1.037	13.3
10/15	1400-1500	16.8%	44.70	0.376	19.70	7.30	292	238	870	683	210.1	1.038	19.0
MINIMUM :		6.3%	19.00	0.112	13.85	1.65	279	209	727	470	205.4	1.008	13.3
MAXIMUM :		29.4%	57.00	1.336	35.00	13.00	299	244	870	695	226.0	1.073	33.5
AVERAGE :		15.5%	40.58	0.437	21.70	6.70	289	230	774	610	213.9	1.035	20.9

Table 1-2
CAMPBELL AVERAGED RUN DATA
DOLOMITIC LIME WITH NO WATER INJECTION

25-Mar-88

RUN DATE	RUN END TIME	SO2 RMVL	LIME UTIL	LFR	TOTAL LIME FEED RATE gpm	LIME CONC Meq/gal	INLET TEMP deg F	OUTLET TEMP deg F	MEASURED GAS SO2 CONC INLET ppmv dry	MEASURED GAS SO2 CONC OUTLET ppmv dry	GAS FLOW %	SpGr	SLURRY CONC wt%	WATER INJ RATE gpm	FLUE GAS FLOW RATE 1000 SCFM	WIR gpm/ 1000 SCFM	CALCULATED GAS SO2 CONCENTRATION INLET ppmv wet	CALCULATED OUTLET ppmv wet	CALCULATED AVERAGE ppmv wet
02/05	14:45	35.4%	21.2%	1.675	2.23	0.0450	290	165	1540	805	54	1.092	15.9	2.05	7.84	0.261	1448	795	1122
02/05	15:43	46.5%	20.3%	2.295	2.54	0.0450	291	156	1302	718	54	1.092	15.9	2.33	7.84	0.298	1412	641	1027
02/05	16:20	49.5%	26.2%	2.150	1.89	0.0450	294	155	1478	670	48	1.092	15.9	1.73	6.97	0.249	1389	603	996
02/06	13:00	43.5%	25.4%	1.717	2.59	0.0450	302	163	1673	843	54	1.092	15.9	2.38	7.84	0.303	1572	752	1162
02/06	15:34	47.3%	23.6%	2.001	2.51	0.0450	306	160	1680	795	48	1.092	15.9	2.31	6.97	0.331	1579	706	1143
02/10	13:04	27.3%	16.9%	1.615	2.13	0.0450	290	180	1527	955	54	1.092	15.9	1.96	7.84	0.250	1435	860	1148
02/10	13:34	43.0%	25.7%	1.674	2.40	0.0450	290	160	1473	740	54	1.092	15.9	2.20	7.84	0.281	1385	663	1024
02/10	14:32	47.4%	25.2%	1.883	2.04	0.0477	290	160	1497	698	48	1.098	16.7	1.87	6.97	0.268	1407	626	1017
02/11	13:21	52.2%	31.3%	1.671	4.06	0.0450	280	156	1583	722	90	1.092	15.9	3.73	13.07	0.285	1488	646	1067
02/12	14:18	39.9%	45.4%	0.879	4.39	0.0220	303	157	1622	912	90	1.039	7.5	4.22	13.07	0.323	1525	811	1168
02/18	14:15	29.5%	36.4%	0.812	2.18	0.0226	286	160	1566	956	54	1.041	7.8	2.09	7.84	0.267	1472	850	1165
02/19	16:10	42.2%	23.1%	1.825	2.48	0.0433	300	160	1497	750	54	1.088	15.3	2.29	7.84	0.291	1407	671	1039
02/20	15:35	49.5%	29.4%	1.680	1.18	0.0433	303	160	1569	686	26	1.088	15.3	1.09	3.78	0.288	1475	614	1044
02/25	15:40	46.3%	25.2%	1.852	2.55	0.0433	298	160	1537	711	54	1.088	15.3	2.35	7.84	0.300	1444	635	1040
02/26	12:30	45.5%	23.0%	1.987	2.55	0.0433	295	160	1434	676	54	1.088	15.3	2.35	7.84	0.300	1348	604	976
03/03	14:10	46.1%	17.0%	2.506	2.38	0.0593	297	160	1406	657	54	1.125	20.1	2.14	7.84	0.273	1321	589	`55
03/07	12:45	45.0%	14.7%	3.067	2.82	0.0593	298	160	1403	744	54	1.125	20.1	2.53	7.84	0.323	1319	662	990
03/07	13:45	48.1%	15.3%	3.151	2.34	0.0593	302	160	1331	661	54	1.125	20.1	2.28	7.84	0.291	1251	591	921
03/10	16:45	50.1%	18.0%	2.789	2.55	0.0593	298	162	1403	648	54	1.125	20.1	2.29	7.84	0.292	1319	580	949
03/21	13:10	61.8%	17.4%	3.544	3.17	0.0614	324	160	1414	494	54	1.130	20.7	2.84	7.84	0.362	1329	437	883
03/23	15:00	59.6%	18.6%	3.246	3.02	0.0614	315	160	1471	535	54	1.130	20.7	2.71	7.84	0.345	1383	474	928
03/24	14:40	57.3%	18.0%	3.073	3.04	0.0614	315	160	1566	632	54	1.130	20.7	2.72	7.84	0.347	1472	560	1016
03/28	14:10	47.7%	15.8%	3.025	2.97	0.0580	297	160	1467	679	54	1.122	19.8	2.67	7.84	0.341	1379	602	991
04/01	15:20	35.0%	13.7%	2.203	0.88	0.0580	267	160	1331	769	24	1.122	19.8	0.79	3.51	0.225	1251	695	973
04/10	16:15	39.3%	22.3%	1.761	3.22	0.0416	293	160	1468	797	72	1.084	14.0	2.90	10.45	0.285	1380	714	1047
04/14	17:33	38.0%	37.0%	1.006	2.60	0.0226	307	160	1503	817	54	1.041	7.8	2.50	7.84	0.318	1413	728	1070
04/15	16:10	42.5%	21.1%	2.010	1.72	0.0440	311	160	1447	722	36	1.090	15.5	1.58	5.23	0.303	1360	644	1002
05/07	23:30	41.3%	22.3%	1.851	1.59	0.0436	301	160	1358	683	36	1.089	15.4	1.46	5.23	0.280	1276	612	944
05/08	06:00	51.5%	27.3%	1.880	1.63	0.0436	327	160	1365	555	36	1.089	15.4	1.50	5.23	0.287	1283	497	890
05/08	22:30	46.9%	17.4%	2.700	1.67	0.0574	309	160	1387	639	36	1.120	19.6	1.50	5.23	0.288	1304	572	938
05/09	08:00	45.5%	17.2%	2.661	1.59	0.0574	291	160	1327	650	36	1.120	19.6	1.43	5.23	0.274	1247	583	915
05/10	00:10	46.8%	18.3%	2.568	1.52	0.0574	298	160	1360	644	36	1.120	19.6	1.37	5.23	0.262	1278	579	929
05/10	07:40	60.1%	19.1%	3.194	1.95	0.0574	331	160	1363	476	36	1.120	19.6	1.76	5.23	0.336	1282	423	852
05/10	12:15	50.0%	18.3%	2.739	1.69	0.0574	315	170	1360	618	36	1.120	19.6	1.52	5.23	0.291	1278	552	915
05/10	17:45	43.5%	19.7%	2.214	1.37	0.0574	292	170	1374	705	36	1.120	19.6	1.23	5.23	0.236	1291	637	964
05/11	00:55	64.0%	24.3%	2.637	1.63	0.0574	290	150	1366	431	36	1.120	19.6	1.47	5.23	0.281	1284	386	835
05/12	13:05	40.6%	29.1%	1.395	1.50	0.0330	301	160	1371	700	36	1.065	11.7	1.41	5.23	0.270	1289	620	958
07/27	00:20	17.0%	12.2%	1.402	1.23	0.0432	280	180	1455	1023	36	1.088	15.3	1.13	5.23	0.217	1368	926	1147
07/27	02:50	25.8%	22.3%	1.159	1.11	0.0432	280	180	1560	1034	36	1.088	15.3	1.02	5.23	0.196	1466	940	1203
07/27	06:20	47.0%	29.2%	1.612	1.61	0.0432	284	160	1626	761	36	1.088	15.3	1.48	5.23	0.284	1528	682	1105
07/27	09:55	56.4%	27.1%	2.084	2.96	0.0432	300	160	1543	580	54	1.088	15.3	2.73	7.84	0.348	1451	514	982
07/27	12:00	55.5%	27.7%	2.006	4.60	0.0432	304	160	1528	615	88	1.088	15.3	4.24	12.78	0.332	1436	546	991
MINIMUM :		17.0%	12.2%	0.812	0.88	0.0220	267	150	1327	431	24	1.039	7.5	0.79	3.51	0.196	1247	386	835
MAXIMUM :		64.0%	45.4%	3.544	4.60	0.0614	331	180	1680	1034	90	1.130	20.7	4.24	13.07	0.362	1579	940	1203
AVERAGE :		45.4%	22.9%	2.126	2.29	0.0478	299	162	1470	714	49	1.099	16.6	2.10	7.14	0.290	1382	639	1010

Table 1-3
CAMPBELL AVERAGED RUN DATA
CALCITIC LIME WITH NO WATER INJECTION

25-Mar-88

RUN DATE	RUN END TIME	SO2 RMVL	LIME UTIL	LFR	TOTAL LIME FEED RATE gpm	LIME CONC #eq/gal	INLET TEMP deg F	OUTLET TEMP deg F	MEASURED GAS SO2 CONC INLET ppmv dry	MEASURED GAS SO2 CONC OUTLET ppmv dry	GAS FLOW %	SpGr	SLURRY CONC wt%	WATER INJ RATE gpm	FLUE GAS FLOW RATE 1000 SCFM	MWIR gpm/ 1000 SCFM	CALCULATED GAS SO2 CONCENTRATION INLET ppmv wet	CALCULATED GAS SO2 CONCENTRATION OUTLET ppmv wet	CALCULATED GAS SO2 CONCENTRATION AVERAGE ppmv wet
04/18	12:46	42.7%	45.0%	0.920	2.64	0.0197	310	160	1420	712	54	1.044	8.4	2.53	7.04	0.322	1335	634	984
04/21	15:10	47.0%	32.7%	2.046	3.00	0.0358	319	162	1350	382	54	1.081	14.3	2.78	7.04	0.355	1269	338	803
05/13	10:10	42.7%	41.7%	1.036	1.49	0.0271	290	160	1412	714	36	1.062	11.3	1.40	5.23	0.268	1327	641	984
05/13	12:40	43.7%	36.8%	1.108	1.59	0.0271	304	160	1402	686	36	1.062	11.3	1.50	5.23	0.286	1318	614	966
05/13	23:45	51.1%	38.5%	1.326	1.76	0.0276	310	160	1415	616	36	1.063	11.5	1.66	5.23	0.317	1330	548	939
05/14	13:15	52.4%	41.9%	1.253	1.55	0.0276	301	160	1320	552	36	1.063	11.5	1.44	5.23	0.279	1241	495	868
05/15	10:45	53.3%	41.6%	1.282	1.65	0.0276	305	160	1373	559	36	1.063	11.5	1.55	5.23	0.297	1290	499	895
05/16	09:40	46.2%	42.5%	1.087	1.50	0.0276	289	160	1381	662	36	1.063	11.5	1.41	5.23	0.270	1299	594	946
05/17	07:45	35.6%	31.0%	1.149	1.45	0.0276	295	170	1346	786	36	1.063	11.5	1.36	5.23	0.261	1265	706	985
05/18	08:00	47.9%	42.4%	1.138	2.18	0.0311	282	160	1359	644	54	1.071	12.7	2.04	7.04	0.260	1277	579	928
05/18	16:45	41.5%	38.6%	1.077	1.43	0.0281	288	160	1440	765	36	1.064	11.7	1.34	5.23	0.257	1354	688	1021
05/18	23:45	36.0%	33.7%	1.077	1.35	0.0281	280	160	1367	804	36	1.064	11.7	1.27	5.23	0.243	1285	725	1005
05/19	10:30	44.8%	39.9%	1.123	1.45	0.0281	275	150	1404	703	36	1.064	11.7	1.36	5.23	0.261	1320	632	976
05/20	01:30	42.1%	33.0%	1.276	1.50	0.0286	299	160	1299	670	36	1.065	11.9	1.41	5.23	0.269	1221	601	911
05/20	10:30	46.4%	32.0%	1.449	1.66	0.0286	301	160	1264	619	36	1.065	11.9	1.56	5.23	0.298	1190	553	871
05/20	13:40	48.5%	39.7%	1.225	1.51	0.0286	296	160	1370	632	36	1.065	11.9	1.42	5.20	0.273	1288	567	927
05/21	05:10	48.4%	40.5%	1.195	1.58	0.0286	301	160	1461	664	36	1.065	11.9	1.48	5.23	0.284	1373	595	984
05/21	08:10	48.0%	38.4%	1.248	1.68	0.0286	294	160	1470	657	36	1.065	11.9	1.58	5.23	0.302	1382	586	984
05/21	12:00	60.9%	43.9%	1.390	3.60	0.0286	308	160	1419	488	72	1.065	11.9	3.38	10.43	0.324	1333	427	880
05/22	02:35	60.5%	44.0%	1.380	2.78	0.0275	311	160	1429	492	54	1.063	11.5	2.62	7.04	0.334	1343	437	890
05/22	07:35	56.9%	43.9%	1.295	2.58	0.0275	302	160	1412	515	54	1.063	11.5	2.43	7.04	0.310	1327	459	893
05/22	12:30	50.6%	43.1%	1.339	4.44	0.0275	302	160	1422	524	88	1.063	11.5	4.18	12.70	0.327	1337	466	901
05/23	07:00	40.3%	40.3%	1.200	1.60	0.0275	298	160	1417	626	36	1.063	11.5	1.51	5.23	0.288	1332	568	946
05/23	11:25	63.3%	44.7%	1.415	2.84	0.0275	322	160	1427	437	54	1.063	11.5	2.67	7.04	0.341	1341	388	865
05/24	12:04	35.7%	30.2%	1.182	1.52	0.0292	295	160	1362	801	36	1.067	12.1	1.43	5.23	0.273	1280	719	999
05/25	03:35	34.8%	26.5%	1.334	1.56	0.0287	288	160	1303	766	36	1.065	11.9	1.46	5.23	0.280	1225	686	956
05/25	08:50	32.8%	28.4%	1.155	1.36	0.0287	282	160	1386	801	36	1.065	11.9	1.28	5.23	0.244	1228	722	975
05/26	02:20	42.0%	42.5%	0.988	1.49	0.0286	287	160	1564	797	36	1.065	11.9	1.40	5.23	0.268	1470	715	1093
05/26	07:20	36.5%	43.7%	0.837	0.98	0.0286	270	160	1617	879	29	1.065	11.9	0.92	4.18	0.220	1520	795	1158
05/26	09:10	40.8%	43.7%	0.932	1.30	0.0286	274	160	1540	773	36	1.065	11.9	1.22	5.23	0.234	1448	698	1073
05/26	11:05	46.0%	44.4%	1.057	3.65	0.0286	288	160	1560	750	88	1.065	11.9	3.43	12.70	0.268	1466	673	1070
05/26	12:40	50.7%	46.3%	1.094	3.65	0.0286	285	160	1507	687	88	1.065	11.9	3.43	12.70	0.268	1416	616	1016
05/26	22:45	44.4%	43.0%	1.016	1.51	0.0272	294	160	1562	741	36	1.062	11.4	1.42	5.23	0.272	1468	665	1066
05/27	07:15	61.0%	52.0%	1.173	1.80	0.0272	303	150	1611	522	36	1.062	11.4	1.69	5.23	0.324	1514	465	989
05/27	12:30	59.3%	49.6%	1.197	4.42	0.0272	306	150	1587	567	88	1.062	11.4	4.16	12.78	0.326	1491	504	998
05/27	22:55	38.5%	33.6%	1.147	1.61	0.0281	310	170	1523	814	36	1.064	11.7	1.51	5.23	0.289	1431	728	1080
05/28	06:55	39.0%	36.8%	1.068	1.53	0.0281	309	170	1566	818	36	1.064	11.7	1.44	5.23	0.275	1472	733	1103
05/28	10:10	42.6%	37.5%	1.297	3.78	0.0281	299	170	1605	808	79	1.064	11.7	3.55	11.52	0.388	1509	749	1129
05/28	11:20	44.1%	41.1%	1.071	3.78	0.0281	305	170	1565	810	88	1.064	11.7	3.55	12.70	0.270	1471	726	1099
05/28	12:55	60.8%	47.1%	1.291	4.70	0.0281	307	150	1517	533	88	1.064	11.7	4.42	12.70	0.346	1426	473	949
05/29	12:05	46.8%	36.6%	1.278	4.37	0.0271	301	160	1480	673	88	1.062	11.3	4.12	12.70	0.322	1391	598	995
05/29	21:25	50.6%	42.4%	1.191	1.79	0.0279	313	160	1619	703	36	1.064	11.6	1.68	5.23	0.322	1522	625	1073
05/30	07:25	48.8%	43.2%	1.130	1.65	0.0279	303	160	1572	716	36	1.064	11.6	1.55	5.23	0.297	1478	640	1059
06/02	19:45	63.9%	31.8%	2.013	1.85	0.0424	308	160	1505	483	36	1.096	16.4	1.69	5.23	0.324	1415	429	922
06/02	23:45	64.9%	35.1%	1.851	1.75	0.0424	299	160	1550	479	36	1.096	16.4	1.60	5.23	0.307	1457	427	942
06/03	04:45	60.4%	32.6%	1.855	1.60	0.0424	289	160	1491	526	36	1.096	16.4	1.47	5.23	0.288	1402	471	936
06/03	06:15	54.2%	34.7%	1.537	1.50	0.0424	281	160	1540	640	36	1.096	16.4	1.37	5.23	0.263	1448	575	1011
06/03	07:15	60.6%	36.2%	1.674	1.65	0.0424	295	160	1555	550	36	1.096	16.4	1.51	5.23	0.289	1462	492	977

Table 1-3 (Cont'd)

25-Mar-88

RUN DATE	RUN END TIME	SO2 RMVL	LIME UTIL	LFR	TOTAL LIME FEED RATE gpm	LIME CONC Beq/gal	INLET TEMP deg F	OUTLET TEMP deg F	MEASURED GAS SO2 CONC INLET ppmv dry	MEASURED GAS SO2 CONC OUTLET ppmv dry	GAS FLOW %	SpGr	SLURRY CONC wt%	WATER INJ RATE gpm	FLUE GAS FLOW RATE 1000 SCFM	W/G gpm/ 1000 SCFM	CALCULATED GAS SO2 CONCENTRATION INLET ppmv wet	CALCULATED GAS SO2 CONCENTRATION OUTLET ppmv wet	CALCULATED GAS SO2 CONCENTRATION AVERAGE ppmv wet
06/03	10:30	70.4%	37.1%	1.896	2.77	0.0399	296	160	1500	407	54	1.090	15.6	2.55	7.84	0.325	1410	362	886
06/03	11:45	64.8%	35.8%	1.811	2.77	0.0399	297	160	1570	500	54	1.090	15.6	2.55	7.84	0.325	1476	445	960
06/05	23:30	64.9%	49.5%	1.315	1.73	0.0326	302	160	1658	518	36	1.074	13.2	1.61	5.23	0.308	1558	461	1010
06/06	07:30	62.3%	52.5%	1.186	1.63	0.0326	297	160	1624	548	36	1.074	13.2	1.52	5.23	0.291	1527	490	1008
06/10	22:00	67.9%	38.0%	1.793	1.80	0.0418	298	160	1623	460	36	1.094	16.2	1.65	5.23	0.316	1526	410	968
06/11	06:00	66.7%	42.1%	1.585	1.67	0.0418	294	160	1646	481	36	1.094	16.2	1.53	5.23	0.293	1547	430	989
06/11	07:30	62.5%	39.3%	1.596	1.60	0.0418	288	160	1553	513	36	1.094	16.2	1.47	5.23	0.281	1460	460	960
06/12	01:45	54.5%	48.9%	1.116	1.66	0.0274	294	160	1579	642	36	1.063	11.4	1.56	5.23	0.299	1484	574	1029
06/12	08:00	50.0%	55.8%	0.896	1.36	0.0274	282	160	1601	701	36	1.063	11.4	1.28	5.23	0.245	1505	632	1068
06/12	10:05	52.7%	47.7%	1.106	3.90	0.0274	288	160	1520	685	88	1.063	11.4	3.67	12.78	0.287	1429	613	1021
06/12	12:30	52.3%	45.9%	1.140	4.57	0.0274	292	160	1520	685	100	1.063	11.4	4.30	14.52	0.296	1429	612	1020
06/12	21:50	58.0%	55.0%	1.055	1.70	0.0264	302	160	1542	570	36	1.060	11.1	1.60	5.23	0.307	1450	508	979
06/13	01:50	58.0%	52.8%	1.099	1.70	0.0264	301	160	1481	551	36	1.060	11.1	1.60	5.23	0.307	1392	492	942
06/13	05:35	60.6%	55.9%	1.088	2.60	0.0264	297	160	1525	555	54	1.060	11.1	2.45	7.84	0.313	1434	495	964
06/13	07:05	64.3%	52.4%	1.227	2.87	0.0264	303	160	1493	490	54	1.060	11.1	2.71	7.84	0.345	1404	434	919
06/13	09:00	54.2%	45.2%	1.199	4.25	0.0264	300	160	1483	650	88	1.060	11.1	4.01	12.78	0.314	1394	579	987
06/13	12:30	56.8%	45.8%	1.242	4.75	0.0264	312	160	1600	652	88	1.060	11.1	4.48	12.78	0.351	1504	577	1041
07/24	07:35	51.0%	46.5%	1.097	1.69	0.0280	304	160	1658	678	36	1.064	11.6	1.59	5.23	0.304	1558	605	1082
07/24	09:00	52.7%	41.9%	1.257	4.23	0.0280	298	160	1480	645	88	1.064	11.6	3.98	12.78	0.311	1391	575	983
07/24	10:00	49.3%	42.1%	1.170	3.91	0.0280	288	160	1470	670	88	1.064	11.6	3.68	12.78	0.288	1382	600	991
07/24	12:15	59.0%	43.4%	1.361	4.46	0.0280	307	160	1443	515	88	1.064	11.6	4.19	12.78	0.328	1356	458	907
07/24	13:45	63.8%	48.1%	1.328	4.54	0.0280	310	160	1507	470	88	1.064	11.6	4.27	12.78	0.334	1416	417	917
07/24	14:25	65.6%	59.6%	1.101	2.48	0.0280	311	164	1615	445	54	1.064	11.6	2.33	7.84	0.297	1518	398	958
MINIMUM :		32.8%	26.5%	0.837	0.98	0.0192	274	150	1266	382	29	1.044	8.4	0.92	4.18	0.220	1190	338	803
MAXIMUM :		70.4%	59.6%	2.046	4.75	0.0424	322	170	1658	879	100	1.096	16.4	4.48	14.52	0.355	1558	795	1158
AVERAGE :		52.2%	41.9%	1.270	2.37	0.0299	297	160	1408	628	51	1.068	12.3	2.22	7.40	0.295	1399	562	980

because they had shown poorer performance as discussed in Part 2. Each data set was regressed separately using a personal computer-based regression program to obtain the values of the exponents and the coefficient, K, that provided the best fit. Fit was measured by the square of the correlation coefficient, R^2, provided by the regression program. An R^2 value of 1 is a perfect fit; 0 is completely random.

Using the initial regressions as a guide, additional regressions for each data set were made using fixed values for the exponents. The objective was to find single values for each exponent that, when used to correlate each set, did not significantly affect the data fit. The final result was the correlation of each data set to the equation where the measured variables had the same exponents and the only difference was the value of the coefficient, K. The value of K, obtained this way, was a measure of the difference in performance between the test systems.

The fully regressed correlation (where the exponents were determined by the regression program) for the separate data sets gave the values shown in Table 1-4 for the exponents, k, and R^2.

Table 1-4

FULL REGRESSION VALUES

Data Set	a	b	c	d	K	R^2
Seward PHDL	0.707	0.620	-0.208	+0.144	0.49	0.906
Campbell PHDL	0.806	0.278	-0.580	-0.675	346	0.830
Campbell CL	1.196	0.639	-0.210	-0.306	5.7	0.713

These results show a good fit for the Seward PHDL data, and somewhat poorer fits for the Campbell data. The values for the exponents and the coefficient are so widely different for the different data sets that a comparison of these values is not useful.

A comparison of calculated versus actual SO_2 removal for the Seward and Campbell PHDL fully regressed correlations is shown in Figure 1-1.

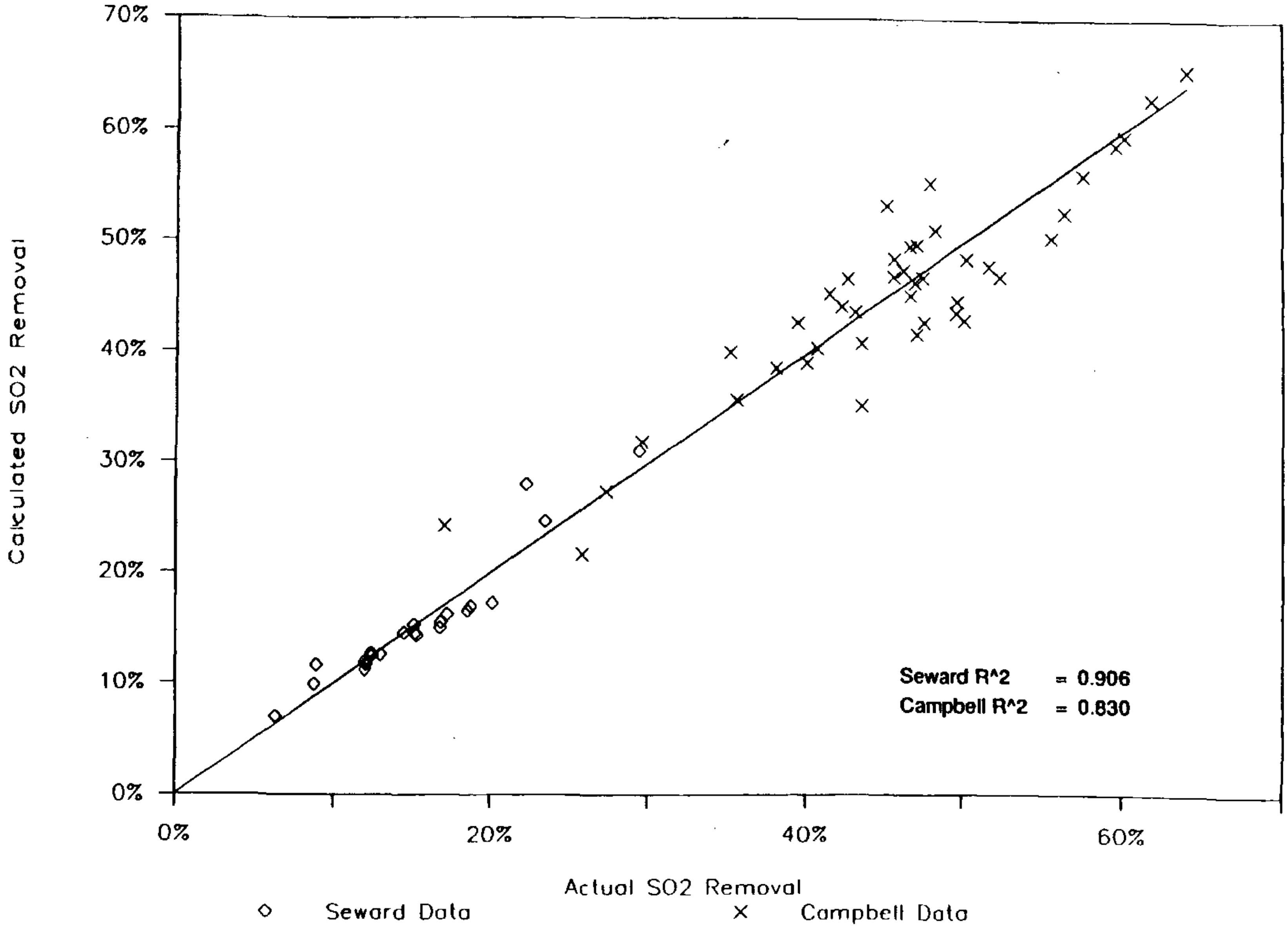


Figure 1-1 **Calculated vs Actual SO_2 Removal for Full Regression Case**

By examining the sensitivity of the fit to exponent values, fixed values of the exponents that had the least effect on the fit were selected. A final regression using the fixed values for the exponents (Table 1-5) produced the following results:

Table 1-5

FIXED EXPONENT REGRESSION VALUES

Data Set	a	b	c	d	K	R^2
Seward PHDL	0.65	0.45	-0.4	-0.4	27.3	0.877
Campbell PHDL	0.65	0.45	-0.4	-0.4	19.1	0.774
Campbell CL	0.65	0.45	-0.4	-0.4	24.4	0.654

Here, the exponent values are the same for each data set and the fit of each set, as measured by R^2, is only slightly worse than it was for the fully regressed results above.

A comparison of calculated versus actual removal for this Seward and Campbell PHDL correlations with the same exponent values is shown in Figure 1-2. Note that this plot is very similar to the one in Figure 1-1.

Table 1-6 shows the range of the variables used in the correlation.

Table 1-6

RANGE OF VARIABLES

Variables	Seward	Campbell
NWIR, gal/kscf	0.06 - 0.15	0.2 - 0.36
Wt%	1.6 - 16	7.5 - 21
Avg SO_2, ppmv, wet	600 - 780	800 - 1200
AST, °F	95 - 130	25 - 55
SO_2 removal, %	6 - 29	17 - 70

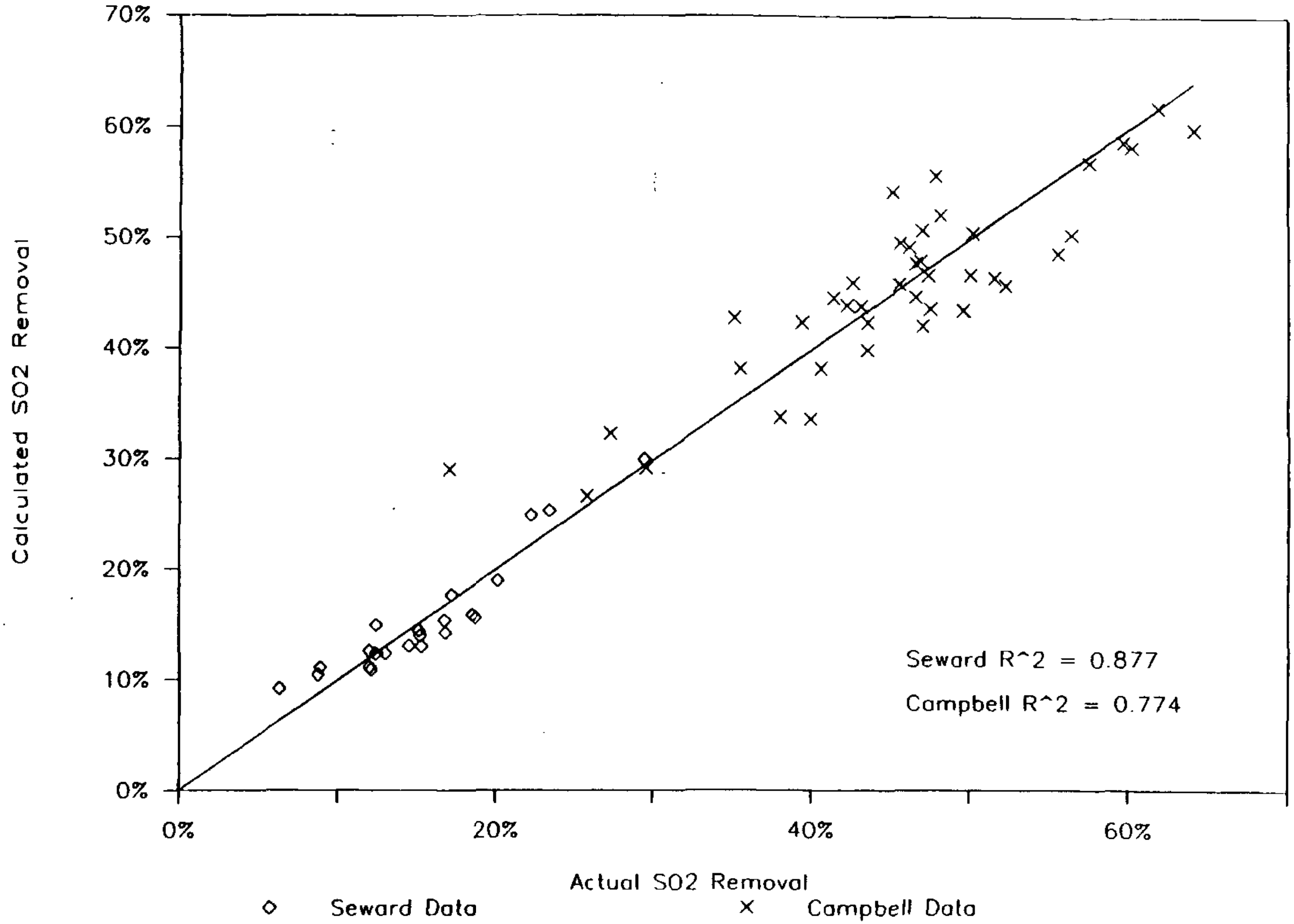


Figure 1-2 Calculated vs Actual SO_2 Removal for Fixed Exponent Case

1.2 SO_2 REMOVAL PREDICTIONS

The correlation provides reasonably accurate predictions of SO_2 removal when the variables are within these ranges. The accuracy of extrapolations outside these ranges is unknown and should be done with caution. For the generic 500 MWe case, where only the SO_2 concentration is significantly outside this range, the correlation should be suitable for preliminary design values.

The difference in performance for the Seward and Campbell test systems can be measured by examining the values of K obtained for the PHDL data sets. The value of K for the Seward PHDL data set is approximately 43 percent higher than that for the Campbell PHDL data set. This means that system differences provided a 43 percent higher performance at Seward compared with Campbell. This implies that operation of a large-scale system similar to Seward at the same test conditions used at Campbell would produce SO_2 removal results approximately 43 percent better than those obtained during the actual Campbell tests.

Comparing the value of K for the Campbell PHDL and CL data sets shows that the SO_2 removal performance for calcitic lime was about 28 percent higher than that for PHDL, at the conditions tested. No useful large-scale system data was collected for CL, and we therefore have no evidence that the improved performance of CL over PHDL will also be observed in large-scale installations. Further testing is needed to confirm if calcitic lime will produce significantly better SO_2 removal in a full-scale system.

For the full-scale projections, the correlation should be used with the value of K obtained for the Seward PHDL data. This takes into account the better SO_2 removal performance of the full-scale system produced by the ability to establish a true confined zone. The lime type should be PHDL because this is the only type for which data are available from both test sites.

Section 2

FULL-SCALE PROJECTIONS

Conceptual designs for two full-scale retrofit installations, a generic 500 MWe unit and J. H. Campbell Unit 1 of the Consumers Power Company are presented in this section. The 500 MWe unit is referenced in PRDA RA-22-85PC81001 (Reference 2-1).

2.1 USE OF TEST RESULTS IN PROJECTIONS

The initial proof-of-concept testing of the Confined Zone Dispersion (CZD) process was conducted at Campbell Station on a pilot-scale level. The results of the Campbell testing were to be used in making the two full-scale projections stated above. Department of Energy (DOE) support was provided for further testing at Seward Station on a full-scale level to obtain supplemental, and, it was hoped, more realistic data for the projections.

The extent and nature of the test data obtained at both sites were limited by physical constraints of the test systems. At Campbell, the small size of the test duct promoted deposition and limited gas flow and slurry injection rates. At Seward, the short residence time limited injection rates and SO_2 removal. (For additional details, see appropriate report sections in Parts 2 and 3, respectively, for Campbell and Seward Stations).

Despite the limitations, information obtained at the test sites is useful in providing preliminary design information for the full-scale projections. This design information concerns SO_2 removal, gas outlet temperature, lime type, lime concentration, NO_x removal, deposition, and ESP performance/upgrading. The full-scale projections should be reviewed and modified as additional CZD test data become available.

The correlation developed in Part 4, Section 1, for the combined Campbell and Seward SO_2 removal data will be used to predict lime concentrations for the full-scale projections. The value of K (27.3) obtained for the Seward pressure hydrated dolomitic lime (PHDL) data will be used. This value takes into account the better SO_2 removal performance of the full-scale system produced by the ability to establish a true confined zone. The lime type to be used is PHDL because this is the only type for which data are available from both test sites. Sensivity analyses for calcitic lime (CL), using the same K factor, and for the use of another K factor will also be conducted for comparison.

The level of SO_2 removal for the full-scale projections is specified at 50 percent. The levels of the independent variables in the correlation equation will be determined as follows:

- AST – The outlet temperature chosen for the projections is 170°F, the temperature required to keep the turning vanes deposit-free at Seward. At an assumed saturation temperature of 125°F, this provides an AST of 45°F. For an ideal confined zone at 125°F, this would allow an envelope of inlet flue gas at 280°F of approximately 29 percent of the inlet gas flow.

- NWIR – The value of this variable will be calculated from a heat balance based on the flue gas characteristics. For a given flue gas, once the outlet temperature is specified, NWIR varies directly with the gas inlet temperature.

- Avg SO_2 – The average concentration of SO_2 in the gas will be calculated from a material balance.

- Wt% – The correlation equation will be solved for Wt% using the values of the other variables as specified above.

2.1.1 NO_x Removal

At the Campbell test site, NO_x removal tests were inconclusive. At the Seward test site, NO_x removal reached 17 percent and this could improve with additional testing. The specified NO_x reduction for the full-scale projections is 50 percent. The DOE guidelines require that a penalty be assessed for processes which do not inherently reduce NO_x emissions by a minimum of 50 percent. Because 50 percent NO_x removal was not demonstrated, this penalty will be assessed and no credit will be taken for CZD NO_x removal.

2.1.2 Deposits

During the full-scale tests, it appeared that deposits could be prevented if the atomized droplets dried before they impinged on the interior duct surfaces. Fine-spray nozzles with erosion resistant tips and suitable instrumentation for the required process control will be included in the projections to provide for adequate droplet drying. No special mechanical devices to dislodge or remove deposits will be included. If additional CZD testing shows a need for mechanical devices, the projections should be modified accordingly.

2.1.3 ESP Performance/Upgrading

The capability of an existing electrostatic precipitator (ESP) to handle the additional loading resulting from lime injection was not conclusively determined during the CZD testing. Some tests indicated ESP emissions were no greater during lime injection than without; others indicated emissions increased during lime injection. The reasons for the increased emissions could not be conclusively identified, so it is not possible to specify corrective measures.

No ESP modifications to upgrade performance have been included in the full-scale projections. However, new ESP conveyors and waste solids storage silos have been included to handle the increased quantities of waste solids.

2.1.4 Atomizing Air Pressure and Flow Rate

The testing at both sites showed that high atomizing air pressure provided fine atomization which increased the evaporation rate and improved drying. This, in turn, allows a higher slurry feed rate and a closer approach to saturation which should increase SO_2 removal. A practical limit of 90 psig was established at both sites and will be used for the projections. A minimum of 30 scf atomizing air per gallon of slurry was required in the Seward testing to maintain good temperature profiles and dry downstream turning vanes. A design value of 30 scf/gallon of feed will be used for the projections.

2.2 CASE 1: GENERIC 500 MWe REFERENCE PLANT

The reference power plant specified for this retrofit study is a pulverized coal-fired plant consisting of two 500 MWe boiler units (i.e., Unit 1 and Unit 2). The plant is assumed to be located near Milwaukee, Wisconsin. For the purpose of this evaluation, only Unit 1 is to be retrofitted for a 50 percent reduction of SO_2 using the CZD process.

2.2.1 Power Plant Design Information

Tables 2-1 and 2-2 list additional power plant design information provided by the DOE guidelines (Reference 2-1).

Table 2-1

CASE 1
KEY BOILER DESIGN DATA AND FLUE GAS CHARACTERISTICS

Characteristics	Specifications
Plant rating, MW net	500
Estimated remaining life, yr	30
Net plant heat rate, Btu/kWh	10,000
Capacity factor, %	65
Sulfur content of coal, % (Detailed specification of Illinois No. 6 bituminous coal is given in Table 2-2)	4
Average heating value of coal, Btu/lb	10,100
Gas flow rate, acfm/MW	4,000
Gas temperature, °F	280
Boiler efficiency, %	88
Average coal burn rate, tph	247
SO_2 emission, tph	18.77
NO_x emission, tph	2.22

Table 2-2

CASE 1
REPRESENTATIVE EAST-CENTRAL COAL: ILLINOIS NO. 6 BITUMINOUS*

Proximate Analysis	Average (Wt%)	Range (Wt%)
Moisture	12.0	10 to 14
Volatile matter	33.0	31 to 35
Fixed carbon	39.0	37 to 41
Ash	16.0	13 to 19
Gross heating value, Btu/lb	10,100	9,800 to 10,400
Grindability, hardgrove	56.0	
Total sulfur, Wt%	4.0	3.4 to 4.6
Ultimate Analysis, Wt%		
Moisture	12.0	10 to 14
Carbon	57.5	
Hydrogen	3.7	
Nitrogen	0.9	
Chlorine	0.1	
Sulfur	4.0	
Oxygen	5.8	
Ash	16.0	13 to 19
	100.0	
Sulfur Forms, Wt%		
Pyritic	2.0	
Organic	1.9	
Sulfate	0.1	
	4.0	
Ash Fusion, °F	Reducing	Oxidizing
Initial deformation	1,950	2,250
Softening (H=W)	2,030	2,300
Hemispherical (H=1/2W)	-	-
Fluid	2,150	2,450
Ash Analysis, Wt%	Average	Range
Silica, SiO_2	45.0	
Ferric oxide, Fe_2O_3	20.0	
Alumina, Al_2O_3	18.0	
Titanic oxide, TiO_2	1.0	
Calcium oxide, CaO	7.0	
Magnesia, MgO	1.0	
Sulfur trioxide, SO_3	3.5	
Potassium oxide, K_2O	1.9	
Sodium oxide, Na_2O	0.6	0.4 to 1.5
Phosphorous pentoxide, P_2O_5	0.2	
Undetermined	1.8	
Total	100.0	

*Reference 2-2

Particulate Removal and Disposal. To meet environmental air emission standards, the plant is equipped with ESPs, which remove flue gas particulates to NSPS (New Source Performance Standards) limits. A pneumatic conveying system transports fly ash from each ESP to ash bins. Dry fly ash is then transported to a lined landfill located 10 miles away.

Seismic Zone and Soil. The plant site is located in Seismic Zone 1 on good soil having bearing capacity of 4 ksf (1,000 pounds per square foot) or more.

Overall Retrofit Factors. For the purpose of this evaluation, only three retrofit characterizations, as shown in Table 2-3, are to be considered. Each characterization takes into account factors such as site accessibility and congestion, underground obstructions, soil conditions, and the location of the flue gas cleanup system on the power plant site. On the basis of these individual factors, an overall retrofit factor for each DOE established retrofit zone was computed as shown in Table 2-3 and Figure 2-1.

Duct Work and Stack. The layout of duct work from the plant air preheater outlet to the chimney, including the ESP manifold and ID fans, is shown in Figure 2-2. Ducts are sized for a gas velocity of 3,600 fpm. A straight run of approximately 100 feet of duct appears to be available for the injection of lime slurry. Therefore, no major modifications to the existing duct work will be necessary. The reference plant's stack design is 718 feet in height and consists of a concrete chimney with an acid brick liner. It is assumed that no modifications to the chimney will be required.

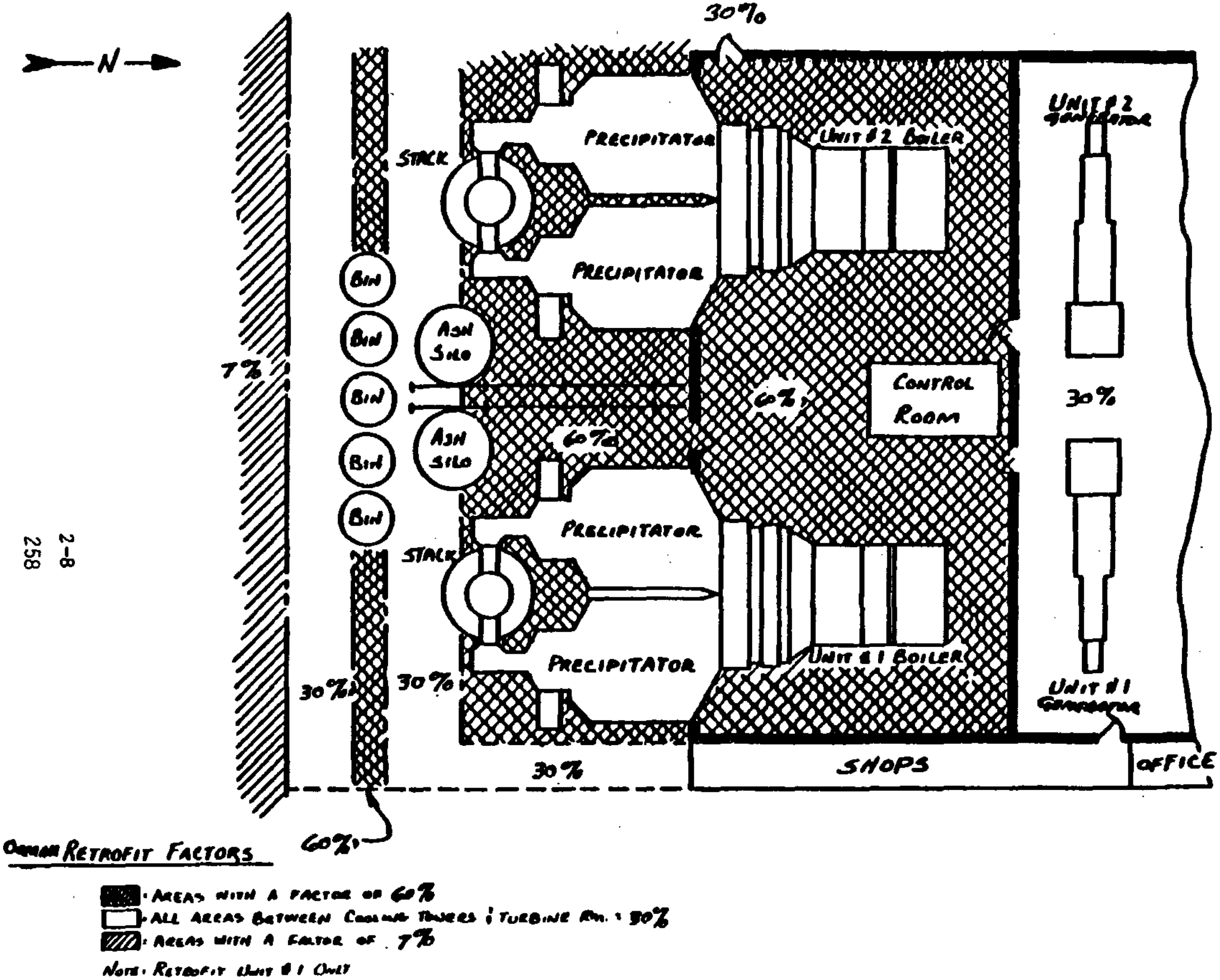
Site Arrangement and Layout. A plan view of the ESP manifold and duct to chimney is shown in Figure 2-1. Figure 2-2, an elevation view, depicts the height restriction of work space and accessibility around in the proximity of the boiler and stack. Figure 2-3 shows a plan view of the reference plant site plot plan. Figures 2-1 and 2-3 also show overall retrofit factors as they apply to the plant site.

Table 2-3

CASE 1
OVERALL RETROFIT FACTORS[a]

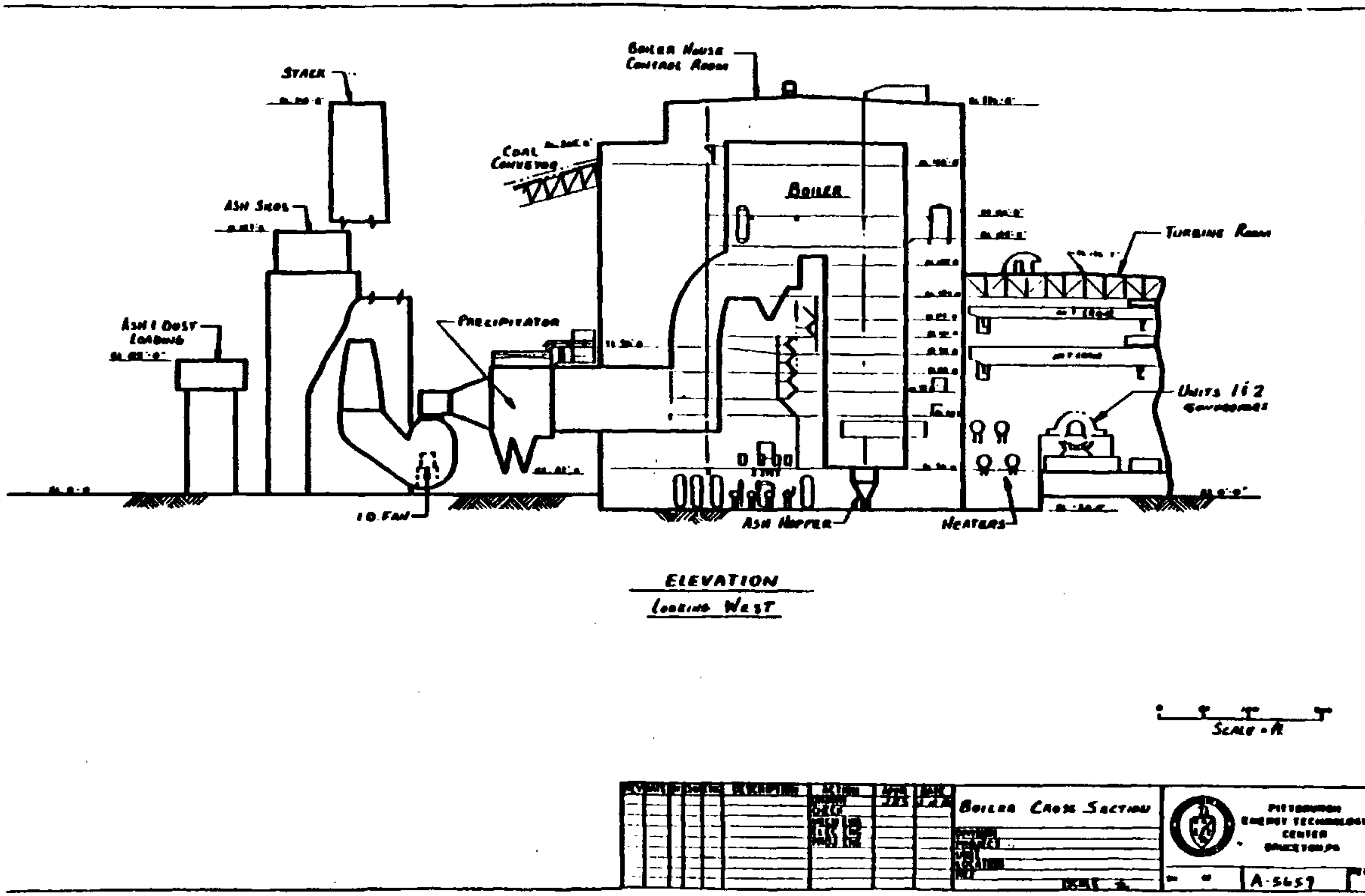
Retrofit Characterization	Site Accessibility and Congestion (A)	Underground Obstruction (B)	Soil[b] Factor (C)	Ductwork Length (D)	Overall[c] Retrofit Factor
Low	Some aboveground interferences and work space limited. Factor = 1.08	One of the following major obstacles such as ductwork, water lines, or pipe exists. Factor = 1.01	Good soil with bearing capacity of 4 ksf or more. Factor = 0.96	Flue gas cleaning system can be located close-in. Factor = 1.02	1.07
Medium	Limited space interferences with existing structure which cannot be relocated. Special designs are necessary. Factor = 1.25	More than one major obstacle exists. Factor = 1.02	Good soil with bearing capacity of 4 ksf or more. Factor = 0.96	Flue gas cleaning system exit can be located close-in. Factor = 1.06	1.30
High	Severely limited space and access. Crowded working space. Factor = 1.42	15 or more minor piping or electrical obstructions. Factor = 1.05	Good soil with bearing capacity of 4 ksf or more. Factor = 0.96	Flue gas cleaning system can be located remotely. Factor = 1.12	1.60

(a) The information presented in this table was developed from EPRI Report CS-3696 (Ref. 2-5)
(b) Includes site-specific adjustments for the plant being located in Seismic Zone 1
(c) Overall Retrofit Factor is defined as (A) x (B) x (C) x (D)



Part 4

Figure 2-1 Retrofit Factors for Reference Site



Part 4

Figure 2-2 Reference Plant Cross Section

SO_2 and NO_x Emission Control Requirements. The base case utility boiler (i.e., Unit 1) to be retrofitted is uncontrolled with regard to acid rain precursors (i.e., SO_2 and NO_x) emission. Total emissions of SO_2 and NO_x from the uncontrolled boiler before the retrofit are 18.77 and 2.22 tons per hour, respectively. Retrofit of any control process to the boiler is required to reduce 50 percent of the SO_2 and NO_x emissions as a minimum. For those control processes which do not inherently reduce NO_x emission to the required 50 percent minimum, a $4.80/kW (in 1982 base year dollars) total retrofit capital requirement and $1.14/kW-yr first-year operating cost will be assessed by DOE to account for NO_x removal to a 50 percent control minimum by combustion modification technology.

2.2.2 Conceptual CZD Process Design Criteria

The design criteria for the CZD process to be retrofitted to Unit 1 of the reference plant are described as follows:

1. The CZD process is designed for 50 percent SO_2 removal. Although some NO_x removal was detected in the tests, the results were inconsistent. Because NO_x of 50 percent were not demonstrated during testing, no credit for NO_x reduction will be taken in this study and penalties stated above for not having 50 percent NO_x reduction will be assessed.

2. As stated in Section 2.1, PHDL is chosen as the reagent because of its better performance during full-scale testing compared with CL.

3. On the basis of the test results at PENELEC, it appears possible to confine the reaction zone in a large duct at temperatures approaching the saturation temperature for good SO_2 removal and intermix with the hot gas in the outer zone to achieve high overall gas outlet temperature. For this application, the gas outlet temperature after mixing is set at 170°F.

4. Once the gas outlet temperature is established, the quantity of water that can be evaporated in the system is determined by heat balance. The average concentration of SO_2 in the gas is calculated by a material balance. The lime feed slurry concentration is calculated by the correlation equation described in Section 2.1. The lime utilization and LFR can also be calculated (although they are not needed for any process calculations, they are useful performance indices).

5. From Figure 2-2, a straight duct section of over 100 feet, ahead of the ESP, appears to be available for the lime injection. At a design gas velocity of 60 fps, this will give a contact time of approximately 1.6 seconds, which should be sufficient for the reaction and drying to take place.

6. The reaction products from this process, nonhazardous waste solids of calcium and magnesium sulfite/sulfate and unreacted lime, will be collected with the fly ash in the existing ESP and disposed of together. The existing ash conveyor and silo capacity may be sufficient but would require more frequent emptying. To be conservative, a larger ash conveyor and one additional silo is provided for handling and storage of the waste solids/fly ash mix.

7. Powdered PHDL will be delivered in open-bottom railcars. Lime storage silos are designed for 30 days' supply.

The process design parameters, raw material and utility requirements, and process effluents are summarized in the Table 2-4.

Table 2-4

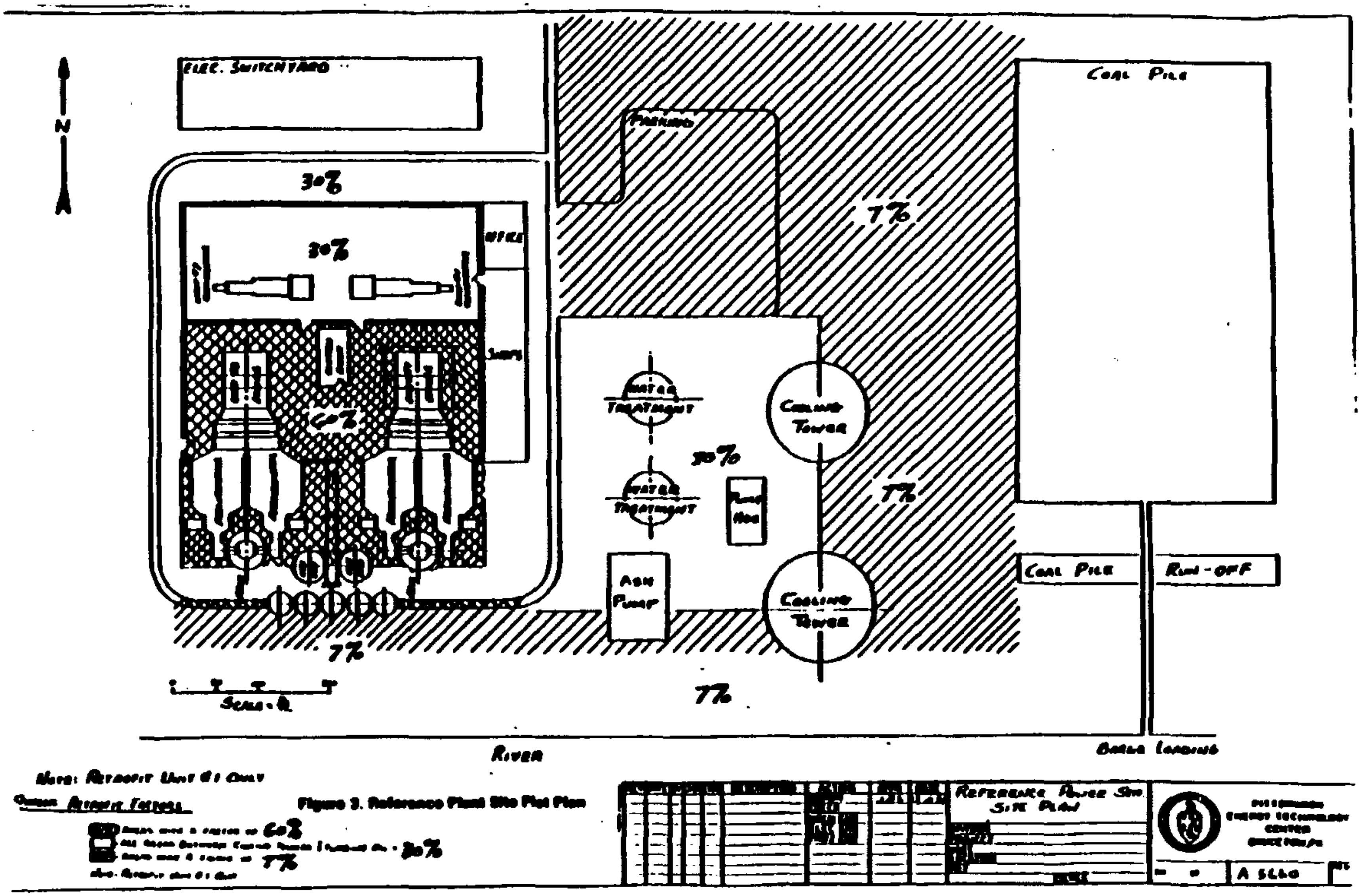
CASE 1
PROCESS DESIGN CHARACTERISTICS

Process Design Parameters	Specifications
SO_2 removal, %	50
Spray down temperature, °F	170
Approach to saturation temperature, °F	45
Normalizer water injection rate, gal./kscf gas	0.265
Average SO_2 concentration, ppmv, wet basis	2049
Lime feed ratio, 1/2 [moles $Ca(OH)_2 \cdot Mg(OH)_2$]/mole SO_2 entering	1.46
Lime utilization, %	34.3
Lime purity, %	95.5
Lime slurry concentration, Wt%	24.3
Atomizing air pressure, psig	90
Atomizing air flow, scfm/gpm slurry	30
Raw Material and Utility Requirements	
PHDL, 95.5% $Ca(OH)_2 \cdot Mg(OH)_2$, tph	29.6
Process water, gpm	354
Electricity, kW	4000
Process Effluents	
SO_2, tph	9.4
NO_x, tph	1.1
Fly ash, tph	31.6
Reaction products, tph	36.4
Grit, tph, wet	1.66
Wastewater, gpm	none

2.2.3 Process Description

Figure 2-4 is a process flow diagram showing the major equipment and overall material balances.

The PHDL is delivered by railcars and is discharged into a below-grade hopper in a closed unloading station equipped with a baghouse. Blowers transfer the lime from the unloading station to storage silos. The lime is then conveyed pneumatically to the day bin located above the slurry makeup tank. Lime is gravimetrically fed from the day bin to the slurry makeup tank until the desired concentration is obtained. Then it is pumped to a vibrating screen for degritting. The degritted lime slurry falls into the storage tank while



Part 4

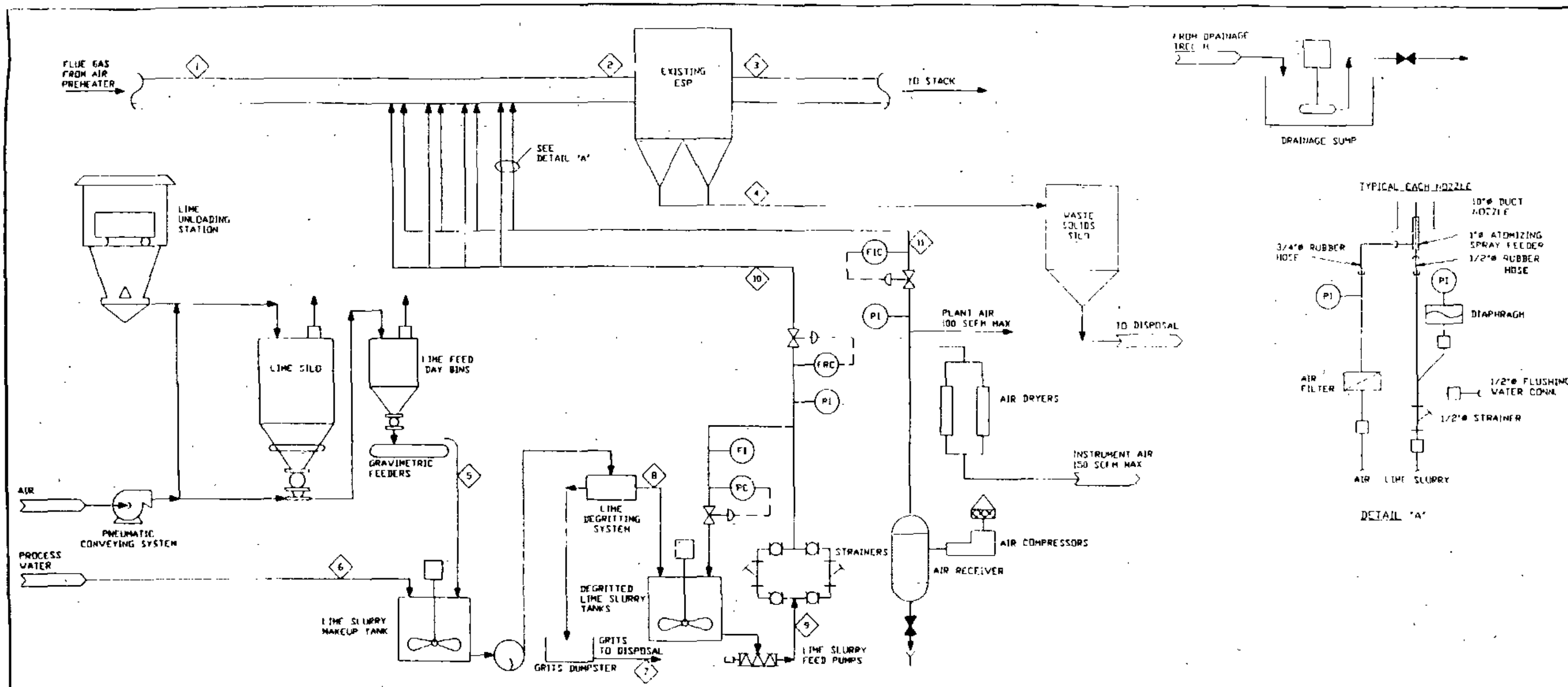
Figure 2-3 Reference Plant Site Plot Plan the wet grit fall into a dumpster for disposal with the reaction waste solids. The degritted lime slurry is transferred to the feed tank from which it is pumped through a strainer to the spray station. The lime slurry feed is controlled by pressure and flow controllers through a recycle loop.

The degritted lime slurry is atomized with compressed air at 90 psig and is sprayed into the center core of the duct through 80 nozzles, 5 gpm lime slurry and 150 scfm air to each nozzle. Sulfur dioxide (SO_2) in the flue gas exiting the air preheater reacts with the lime ($Ca(OH)_2.Mg(OH)_2$) in the spray droplets to form mostly calcium/magnesium sulfite ($CaSO_3.MgSO_3.H_2O$). The reaction products and the unreacted lime dry as the water evaporates. The temperature at the center core of the duct is close to the adiabatic saturation temperature of the flue gas while the surrounding gas remains hot. As the gas travels toward the ESP, it intermixes to reach a temperature of approximately 170°F.

The dry reaction products, the unreacted lime, and the fly ash (80 percent of the coal ash) are collected together in the existing ESP. From the ESP hoppers, these waste solids are conveyed to the existing ash silos. These waste solids are then transported to a lined landfill located 10 miles away.

2.2.4 Major Equipment

A general layout of the major equipment is shown in Figure 2-5. The lime silos are located across the road from the ash bins. The lime slurry preparation equipment, including the makeup tank, degritting screens, and slurry storage tanks, is located next to the lime silos. The air compressors are also located in this area to take advantage of the low retrofit factor. The degritted lime slurry feed tank is located close to the ESPs in order to get a short run of slurry line to the injection nozzles. A short slurry line minimizes potential operating problems, such as lime freezing and line plugging. A description of the major equipment is given in Table 2-5.



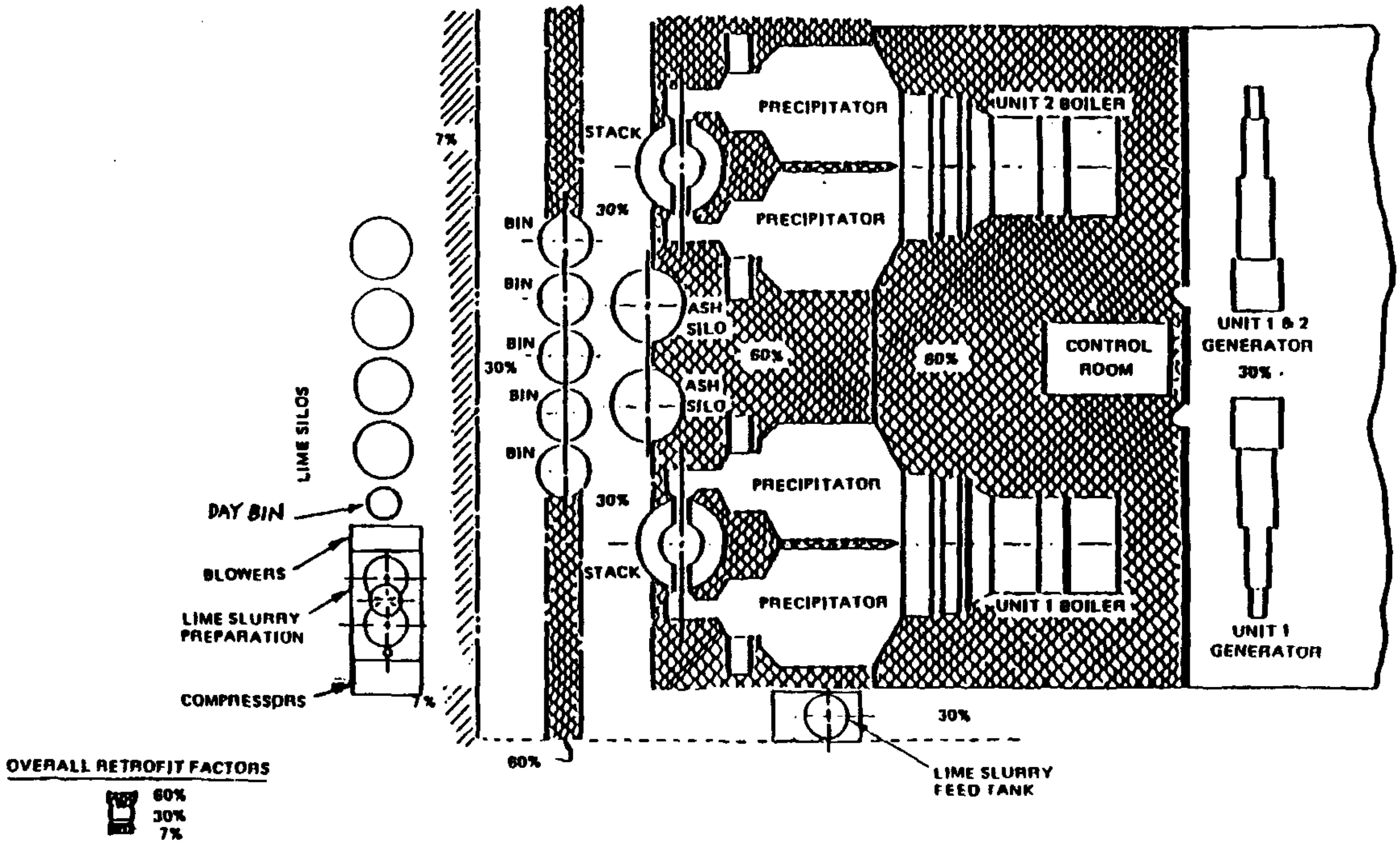
STREAM No		1	2	3	4	5	6	7	8	9	10	11
COMPONENT		FLUE GAS @ AIR HEATER OUTLET	FLUE GAS AT ESP INLET	FLUE GAS TO STACK	DRY WASTE SOLIDS	LIME TO MAKEUP TANK	PROCESS WATER	GRIT TO DISPOSAL	DEGRITTED LIME SLURRY TO STORAGE	LIME SLURRY FROM FEED PUMP	LIME SLURRY TO SPRAY NOZZLES	ATOMIZING AIR
FLUE GAS	lb/hr	6,212,000	6,497,000	6,361,000								
	acfm	2,000,000	1,796,000	1,796,000								
TEMPERATURE	°F	280	170	170								
SO_2	lb/hr	37,540	18,770	18,770								
	ppmv wet	2,780	1,318	1,318								
FLY ASH	lb/hr	63,200										
	gr/acf	3.7										
WASTE SOLIDS	lb/hr		136,000	150	135,850							
	gr/acf		8.8	0.6								
RAW DOLOMITIC LIME	lb/hr					59,260						
GRIT IN LIME	lb/hr					2,670		2,630				
GRIT FREE LIME	lb/hr					56,590			56,590		56,590	
WATER	lb/hr						176,960	660	176,300		176,300	
	gpm						354	1.3	353		353	
LIME SLURRY	gpm								401	520	401	
	wt%								24.1	24.3	24.3	
COMPRESSED AIR	scfm											12,000
	psia											100

BECHTEL NATIONAL, INC.
SAN FRANCISCO

500 MW CONCEPTUAL DESIGN
CASE 1

CZD PROCESS FLOW DIAGRAM

JOB NO. 17939 DRAWING NO. FIGURE 2-4



Part 4

Figure 2-5 Retrofit Equipment Location Plan

Table 2-5

CASE 1
MAJOR EQUIPMENT ITEMS

Item		Quantity
Railspur		1
Service:	Provide access for lime delivery	
Length:	1000 ft	
Lime Unloading Station		1
Service:	Lime unloading from railcar	
Includes:	1-two railcar covered area 2-6000 acfm baghouse, 2400 ft^2 cloth each. 20 hp total	
Lime Storage Silos		
Dimensions:	70' dia. x 100' straight side 60° conical bottom	4 op.
Capacity:	5,330 tons each Total 30 days' supply	
Material:	Steel-reinforced concrete	
Accessories:	Baghouse, 700 ft^2 each cloth area	
Reagent Pneumatic Conveyor System		2 op., 1 spare blower
Type:	Pneumatic	
Service:	PHDL	
Flow rate:	8,000 acfm	
Transfer line:	14" dia. x 300' L	
Blower motor rating:	600 hp	
Lime Feed Day Bins		2 op.
Dimensions:	28' dia. x 40' straight side 60° conical bottom	
Capacity:	440 tons each	
Material:	Carbon steel	
Accessories:	Rotary valve discharge, vibrators	
Lime Gravimetric Feeders		2 op., 2 spare
Dimensions:	36" W x 10' L	
Solids rate:	30,000 lb/hr	
Service:	PHDL	
Motor rating:	20 hp	
Lime Slurry Storage Tanks		3 (1 makeup tank, 2 degritted lime slurry tanks)
Dimensions:	40' dia. x 40' high	
Service:	24.3 Wt% slurry	
Capacity:	300,000 gal. each	
Material:	Carbon steel, closed top, four baffles	
Accessories:	Agitator with 90-hp motor	

Table 2-5 (Cont'd)

Item		Quantity
Lime Degritting System		1 op., 1 spare
Type:	Vibrating screen	
Service:	Separating grit from lime slurry	
Feed rate:	500 gpm	
Material:	316 stainless steel	
Motor:	5 hp	
Lime Degritting Feed Pumps		1 op., 1 spare
Type:	Horizontal centrifugal	
Material:	Rubber-lined, carbon steel	
Flow:	500 gpm	
Head:	25 psi	
Motor:	15 hp	
Lime Slurry Feed Pumps		1 op., 1 spare
Type:	Positive displacement	
Material:	Rubber-lined, carbon steel	
Flow:	600 gpm	
Head:	100 psi	
Motor:	60 hp	
Grit Dumpsters		3
Capacity:	640 ft^3	
Material:	Carbon steel	
Dual-Fluid Atomizing Nozzles		80 op.,
Type:	Spraying Systems Co. CJ nozzles or equivalent	100 installed
Capacity:	5 gpm each max.	
Material:	316 stainless steel body, carbide target bolt	
Air Compressors		1 op., 1 spare
Type:	4-stage, centrifugal compressor with intercooling	
Capacity:	12,000 acfm	
Pressure:	120 psia	
Material:	Carbon steel	
Motor:	3,600 hp	
Accessories:	Prefilter, silencer, intercoolers, after cooler, control unit, air receiver, air dryer for 150 scfm	

Table 2-5 (Cont'd)

Item		Quantity
Drainage Sump		1
Capacity:	5,000 gallon	
Material:	Concrete	
Accessories:	Agitator with 3-hp motor; two sump pumps, 100 gpm each	
Waste Pneumatic Conveyor system		1
Type:	Pneumatic	
Service:	Waste solids	
Flow rate:	3000 cfm	
Transfer line:	8" dia. x 400' L	
Blower motor rating:	250 hp	
Waste Solids Silo		1
Dimensions:	28' dia. x 50' straight side	
Capacity:	800 tons	
Material:	Carbon steel	
Accessories:	Baghouse, airlock, conveyor	

2.2.5 Economics and Cost Estimates

Estimating Methodology. A cost estimating methodology developed by DOE follows. This method:

- Levelizes total retrofit capital requirements using standardized assumptions and economic factors developed by EPRI (Refs. 2-1, 2-3, and 2-5) as well as simplifications determined to be suitable by DOE
- Levelizes all costs to 1982 base-year dollars
- Levelizes capital costs for dissimilar acid rain precursor (i.e., SO_2 and NO_x) control approaches at different stages of technical maturity
- Calculates the total retrofit capital requirement and first-year operating and maintenance (O&M) costs, from which a total levelized retrofit cost can be calculated

Information required to generate the estimates was obtained from equipment vendors, published cost data, and Bechtel inhouse cost files. Capital costs were estimated by the modular factor cost estimating approach developed by Guthrie (Reference 2-7). Process equipment sizing and cost were developed by Bechtel. Operating costs were calculated based on estimated reagent and utility consumption, and the DOE-specified operating cost criteria in Table 2-6.

Economic Parameters. Key economic parameters are specified by DOE (Reference 2-1) and given in Table 2-7.

Major Process Area Capital Estimates. There are five major process areas required for the conceptual 500 MWe CZD process retrofit:

Area	Description
10	Reagent feed system
20	SO_2 removal system
30	Flue gas system
60	Waste handling system
70	General support area

Table 2-6

CASE 1
OPERATING COST CRITERIA

Fixed Operating Cost	Unit	Rate
Operating labor (2 men/shift)	Manhour	$18.30/hr (Dec. 1982)
Administration and support labor	$/yr	30% of O&M labor
Maintenance factor	Percent	4% of process capital

Variable Operating Cost	Unit	Dec. 1982, $/unit[(a)]	Level. Factor	30-Year Levelized Cost, $/unit
Process water	1,000 gal	0.60	2.31	1.39
Power	kWh	0.045	2.44	0.110
PHDL[(b)]	t	65.00	2.31	150.15
Dry solids disposal (lined)	t	6.17	2.31	14.25
Fly ash disposal (unlined)	t	4.67	2.31	10.79

(a) The cost of freight is included.
(b) The price for the PHDL used in this study is not cited in Reference 2-1. The 1982 delivered price is $65/t.

Table 2-7

CASE 1
KEY ECONOMIC PARAMETERS

Base year for cost levelization	1982[a]
Engineering and home office fees[b]	10%
Project contingency[c]	22.5%
Process contingency (depending on commercial status of equipment or system)[d]	5 to 20%
Royalty allowance	0.5% of process capital
Preproduction costs	2% of total plant investment
Capital fixed charge rate (FCR) for 30 years of plant life and assumed costs of capital at 12.5%	15.3%
Salvage value of process equipment at the end of the 30-year term	Zero
Levelization factor for 30-year term assuming 8.5% inflation	2.31
Sales tax (Wisconsin)	5%

(a) Cost data in other year can be calculated by:

$$\text{(Cost Data in 1982 Base Year)} \times \frac{\text{Chem. Eng. Plant Cost Index for That Year}}{314.0}$$

(b) Additional engineering and home office fee to account for site access and underground obstruction factors are included in the overall retrofit factors specified in Table 2-3.

(c) This represents an average project contingency factor based on EPRI's Class II Preliminary Design/Estimate Project Contingency range (Ref. 2-2).

(d) Selected by Bechtel: 20 percent for the SO_2 removal system; 5 percent for all other systems

Area 10 includes facilities for receiving, unloading, transporting, preparing, storing, and feeding lime. Dry PHDL is chosen to be the reagent used, and it is slurried on site.

Area 20 includes equipment required for SO_2 removal, such as the degritted lime slurry feed tank, air compressors, lime slurry injection system, control instruments, and SO_2/O_2 monitors.

In area 30, no modifications or new equipment are provided to upgrade precipitator performance. This area is included because additional CZD testing may show a need to upgrade the precipitator.

Area 60 includes a conveyor and a storage silo to increase handling and storage capacity for the additional waste solids (reaction products) generated, although the existing conveyors and ash silos may be adequate.

Area 70 includes makeup water pumps, drainage sump, and fire protection and safety equipment.

Capital costs of these areas include the initial investment costs necessary to design, procure, install, and commission each process equipment item or system. Capital costs consist of the direct and indirect costs incurred before the operation of the total control system commences (Reference 2-6). Detailed process area capital estimates are given as Worksheet 1. (All worksheets referenced appear at the end of this subsection.) For these estimates, the modular factor cost estimating approach developed by Guthrie (Reference 2-7) was followed.

Total Retrofit Capital Requirement Estimate Summary. Table 2-8 is a summary of the total retrofit capital requirement estimates.

First Year Operating Costs. The estimated first year operating costs are given in Table 2-9.

Table 2-8

CASE 1
TOTAL RETROFIT CAPITAL REQUIREMENT ESTIMATE SUMMARY

	Item	$/kW[a]
(A)	Total process area capital (from Worksheet 2)	23.85
(B)	Total plant scope adjustment capital (from Worksheet 3)	0.80
(C)	Total process capital, (A) + (B)	24.65
(D)	General facilities, 10% of (C)	2.46
(E)	Project contingency, 22.5% of (C)	5.55
(F)	Engineering and home office fees, 10% of (C)[b]	2.46
(G)	Total plant retrofit cost, (C) + (D) + (E) + (F)	35.12
(H)	Allowance for funds during construction 2 years = 0.018 of (G)	0.63
(I)	Total plant retrofit investment, (G) + (H)	35.75
(J)	Royalty allowance, 0.5% of (C)	0.12
(K)	Preproduction costs, 2% of (I)	0.71
(L)	Inventory capital (60 day of raw material and consumables)	5.63
(M)	Total capital retrofit requirement, (I) + (J) + (K) + (L)	42.21
(N)	NO_x removal penalty assessment[c]	4.80
	TOTAL	47.01

(a) $$\$/kW = \frac{Cost}{(500{,}000\ kW - Process\ Power)} = \frac{Cost}{(500{,}000\ kW - 4{,}000\ kW)}$$

(b) Additional engineering and home office fees to account for underground obstruction factor are included in the overall retrofit factor calculation.

(c) Specified by DOE guidelines.

Table 2-9

CASE 1
ESTIMATED FIRST YEAR OPERATING COST

PART I

Fixed Operating and Maintenance Costs						$/kW-yr
(A) Operating labor[a]						0.64
(B) Maintenance labor[b]						
	Process Area Capital Cost[c]		Maintenance Factor[d]			
- Process area 10	(14.50)	X	(0.04)	X 0.4		0.23
- Process area 20	(8.00)	X	(0.04)	X 0.4		0.13
- Process area 60	(1.20)	X	(0.04)	X 0.4		0.02
- Process area 70	(0.15)	X	(0.04)	X 0.4		0.0
- Plant scope adjustment[e]						
	(0.8)	X	(0.2)			0.16
(C) Maintenance material, 150% of (B)						0.81
(D) Administrative and support labor @ 30% of (A + B)						0.35
Subtotal Part I - Fixed Cost						(2.34)

(a) Operating labor cost, $/kW-yr =

$$\frac{(8.4\ \text{man wks/wk})\ (\$18.30/\text{hr})\ (2080\ \text{hr/yr})}{(500{,}000\ \text{kW} - 4{,}000\ \text{kW})}$$

(b) Maintenance Labor = (40%) X (Process Capital Cost by Process Area) X (Maintenance Factor).

(c) Process capital costs are to be taken from Worksheet 2 for each respective process area.

(d) Maintenance factors for each process area are taken from Table 2-6.

(e) Plant Scope Adjustment = (Total Plant Scope Adjustment Capital Cost from Worksheet 3) X (Maintenance Factor of 0.2)

Table 2-9 (Cont'd)

PART II

Variable Operating Costs[a]		$/kW-yr
(A)	Reagents and chemicals (lime @ $65/t)	22.11
(B)	Process water @ $0.60/1000 gal	0.15
(C)	Power @ $0.045/kWh	2.48
(D)	Waste disposal[b]	3.12
	Subtotal Part II - Variable Operating Costs	27.86
	NO_x removal penalty assessment (specified by DOE)	1.14
	Total Generalized First Year Operating Costs (Subtotal Part I and Subtotal Part II)	31.34

(a) Variable Operating Costs, $/kW-yr =

$$\frac{(\$\ \text{Cost per Hour}) \times (8760\ \text{hr/yr}) \times (\text{Capacity Factor})}{(500{,}000\ \text{kW} - \text{Process Power})}$$

Use a capacity factor of = 0.78 for power cost and a capacity factor of 0.65 for all other variable operating costs.

(b) Waste disposal costs are calculated as follows:

Total fly ash (16% coal ash, 80% overhead)	31.6 tph
Total reaction products (including excess lime)	36.4 tph
Total	68.0 tph

Disposal Charges (from Table 2-6)
Waste solids, lined landfill, @ $6.17/t
Fly ash, unlined landfill, @ $4.67/t

First year disposal cost = Total waste solids less credit for fly ash
= (68.0)(6.17) - (31.6)(4.67) = $271.99/hr
= $3.12/kW-yr

This calculation assumes the plant was disposing of fly ash at $4.67/t before the retrofit. A credit is taken for this because after the retrofit the fly ash is disposed of with the solid waste at the higher rate of $6.17/t.

Summary of Cost Estimates. A summary of the cost estimates is given in Table 2-10. This table indicates the total retrofit capital requirement of \$47.01/kW, including NO_x nonremoval penalty. The estimated first year operations and maintenance costs are \$31.34/kW-yr. The calculated SO_2 removal cost is \$357/ton SO_2. In terms of 30-year levelized busbar electricity cost, it becomes 14.0 mills/kWh.

2.2.6 Sensitivity Analysis

This section contains an assessment of the impact of using type CL lime, and that of a 25 percent greater value of the correlation factor, K, on the 500 MWe projection.

Use of Type CL Lime. The CZD system design, performance, and costs will be influenced by the type of lime that is selected as reagent for a given retrofit. Although no useful large-scale system data were collected for CL, its performance was superior to PHDL in the pilot-scale tests, and further testing is expected to more clearly define its SO_2 removal performance capability. For this analysis, its performance will be assumed equal to that of PHDL by using the same value of correlation factor, K.

Use of the same correlation factor means that the weight consumption for the two lime types is the same on a hydrated basis because the correlation is based on weight percent of hydrated lime. Use of the same weight consumption implies that the CL utilization will be slightly higher and its LFR will be slightly lower than those for PHDL because these factors are determined on a molar basis, and CL has a higher molecular weight than PHDL (74.1 versus 66.2).

A major impact on the conceptual design brought about by the substitution of CL for PHDL is the reduction in the storage volume required for the dry lime. This reduction is brought about by two factors:

- The CL will be delivered to the plant site in the unhydrated or quicklime form. Since the water of hydration does not have to be stored, the weight of lime to be stored is reduced by approximately 18 percent.

Table 2-10

CASE 1
ESTIMATED COST OF SO_2 REMOVAL
(in 1982 dollars)

Item	\$/kW	\$/kW-yr	\$/ton SO_2	Levelized mills/kWh
Total capital requirement	47.01		66.65[a]	1.3
First year operating cost				
Fixed		2.34		0.9
Variable		27.86		11.3
NO_x penalty		1.14		0.5
Total		31.34	290.43[b]	
Total cost per ton of SO_2			357.08	—
30-year levelized busbar cost @ 65% capacity factor				14.0

(a) $\frac{(\$47.01/kW) \times (496{,}000\ kW) \times (0.153\ FCR/yr)}{(9.4\ tph\ SO_2\ removed) \times (8760\ hr/yr) \times (0.65)} = \$66.65/ton\ SO_2$

(b) $\frac{(\$31.34/kW\text{-}yr) \times (496{,}000\ kW)}{(9.4\ tph\ SO_2\ removed) \times (8{,}760\ hr/yr) \times (0.65)} = \$290.43/ton\ SO_2$

CASE 1 – WORKSHEET 1
MAJOR PROCESS AREA CAPITAL ESTIMATE

Process Area: 10 – Reagent Feed System

Major Process Equipment	No.[a]	Factory Material, $1000s	Field Material, $1000s	Field Labor, $1000s	Indirect Field Cost, $1000s	Sales[b] Tax, $1000s	Sub-Total, $1000s	Retrofit[c] Factor	Process Cost, $1000s
Enclosure (100'x50'x60'H)	1	120	42	36	30	8	236	1.07	253
Railspur	1								150
Lime unloading station	1								690
Lime silo	4	1,890	663	568	474	127	3,722	1.07	3,982
Pneumatic conveyor system	2	249	87	75	62	17	490	1.07	524
Lime feed day bin	2	254	89	76	64	17	500	1.07	535
Lime grav. feeder	2	39	14	12	9	2	76	1.07	81
Lime slurry tank	2	245	86	74	61	17	483	1.07	517
Miscellaneous (vib. screens, grit dumpsters, pumps, etc.)		57	20	17	14	3	111	1.07	119
						Process Cost			6,851
						Process Contingency, 5%[d]			343
						Total Process Cost			7,194

Note: All cost estimate breakdowns follow Guthrie's "Process Plant Estimation Evaluation and Control" (Reference 2-7).
(a) Total number of equipment items are specified to achieve 30 years of reliable operation. For purposes of this cost estimate, it is assumed no salvage value exists for process equipment at end of useful life.
(b) Assume 5% of total material costs.
(c) See Table 2-3 and Figure 2-1 to determine retrofit factors for each major process equipment item.
(d) Refer to Table 2-7

RR:8308r
Part 4

CASE 1 - WORKSHEET 1 (Cont'd)

Process Area: 20 - SO_2 Removal System

Major Process Equipment	No.[a]	Factory Material, $1000s	Field Material, $1000s	Field Labor, $1000s	Indirect Field Cost, $1000s	Sales[b] Tax, $1000s	Sub-Total, $1000s	Retrofit[c] Factor	Process Cost, $1000s
Degritted lime feed tank	1	123	43	37	31	9	243	1.30	316
Lime slurry feed pump	2	22	8	7	5	1	43	1.30	56
Air compressor	2	735	257	221	184	49	1,446	1.07	1,547
Spray system including 81 spray nozzles, control instrument and monitor		691	70	200	144	38	1143	1.07	1,223
Enclosure (65'x50'x50'H)	1	65	23	20	16	4	128	1.30	166

Process Cost	3,308
Process Contingency, 20%[d]	662
Total Process Cost	3,970

Note: All cost estimate breakdowns follow Guthrie's "Process Plant Estimation Evaluation and Control" (Reference 2-7).
(a) Total number of equipment items are specified to achieve 30 years of reliable operation. For purposes of this cost estimate, it is assumed no salvage value exists for process equipment at end of useful life.
(b) Assume 5% of total material costs.
(c) See Table 2-3 and Figure 2-1 to determine retrofit factors for each major process equipment item.
(d) Refer to Table 2-7

RR:8308r
Part 4

CASE 1 - WORKSHEET 1 (Cont'd)

Process Area: 60 - Waste Handling System

Major Process Equipment	No.[a]	Factory Material, $1000s	Field Material, $1000s	Field Labor, $1000s	Indirect Field Cost, $1000s	Sales[b] Tax, $1000s	Sub-Total, $1000s	Retrofit[c] Factor	Process Cost, $1000s
Waste solids conveyor	1	51	18	16	13	3	101	1.3	131
Waste solids silo	1	170	60	51	43	11	335	1.3	436

Process Cost	567
Process Contingency, 5%[d]	28
Total Process Cost	595

Note: All cost estimate breakdowns follow Guthrie's "Process Plant Estimation Evaluation and Control" (Reference 2-7).
(a) Total number of equipment items are specified to achieve 30 years of reliable operation. For purposes of this cost estimate, it is assumed no salvage value exists for process equipment at end of useful life.
(b) Assume 5% of total material costs.
(c) See Table 2-3 and Figure 2-1 to determine retrofit factors for each major process equipment item.
(d) Refer to Table 2-7

RR:8308r
Part 4

CASE 1 - WORKSHEET 1 (Cont'd)

Process Area: 70 - General Support Area

Major Process Equipment	No.[a]	Factory Material, $1000s	Field Material, $1000s	Field Labor, $1000s	Indirect Field Cost, $1000s	Sales[b] Tax, $1000s	Sub-Total, $1000s	Retrofit[c] Factor	Process Cost, $1000s
Drainage sump, including agitator, pumps, and trench	1	20	7	6	5	1	39	1.07	42
Makeup water pump	2	9	3	3	2	1	18	1.07	19
Fire protection and safety equipment		5	1	2	1		9	1.07	10

Process Cost	71
Process Contingency, 5%[d]	4
Total Process Cost	75

Note: All cost estimate breakdowns follow Guthrie's "Process Plant Estimation Evaluation and Control" (Reference 2-7).
(a) Total number of equipment items are specified to achieve 30 years of reliable operation. For purposes of this cost estimate, it is assumed no salvage value exists for process equipment at end of useful life.
(b) Assume 5% of total material costs.
(c) See Table 2-3 and Figure 2-1 to determine retrofit factors for each major process equipment item.
(d) Refer to Table 2-7

RR:8308r
Part 4

CASE 1 - WORKSHEET 2

TOTAL PROCESS CAPITAL COST ESTIMATE SUMMARY

Area	Description	$/kW*
10	Reagent feed system	14.50
20	SO_2 removal system	8.00
60	Waste handling system	1.20
70	General support area	0.15
	Process Capital Subtotal	23.85

$$* \ \$/kW = \frac{\text{(Total Process Area Cost)}}{\text{(500,000 kW - Process Power)}}$$

CASE 1 – WORKSHEET 3
EXISTING PLANT SCOPE ADJUSTMENT CAPITAL COST*

	Item	$/kW
(1)	New chimney (if a new chimney is needed, add $7/kW	0
(2)	Coating existing chimney	0
(3)	Boiler reinforcement (if absolutely needed, add $4.5/kW)	0
(4)	Draft controls (instead of boiler reinforcement, if implosion controls will work, add $1.3/kW)	0
(5)	Demolition and relocation of existing equipment and buildings**	
	– Low number of existing interferences to move, add $0.3/kW	
	– Medium number of existing interferences to move, add $0.8/kW	0.8
	– High number of existing interferences to move, add $1.5/kW	
	TOTAL	0.8

* Other scope adjustment capitals needed for by-product system, cooling tower, and particulate collector should be included in major process cost estimates (Worksheet 1).

** Depending upon the location of major process equipment, see Figure 2-5 for reference retrofit zones.

RR:8309r
Part 4

- The CL quicklime is more dense than the PHDL (55 lb/ft^3 versus 30 lb/ft^3). This reduces the required storage capacity by an additional 45 percent.

The impact of the reduced storage volume for the CL is partially offset by the requirement for onsite equipment (slakers) to hydrate it.

The CL is also less expensive than the PHDL - $60/ton for the CL quicklime versus $65/ton for the PHDL. This cost difference is magnified by the fact that the weight of the quicklime required is approximately 80 percent of the weight of PHDL.

From the point in the process where the quicklime is hydrated, the equipment requirements - storage and feed tanks, degritting equipment, transfer and feed pumps, atomization system, air compressors, and instrumentation and controls - are nearly identical for both CL and PHDL.

The net effect of changes reduces the capital and operating costs for the design for CL compared with the design for PHDL. The estimated total retrofit capital requirement reduces to $42.13/kW, including NO_x nonremoval penalty. The estimated first year O&M costs reduce to $25.07/kW-yr. The calculated SO_2 removal cost is $292/ton SO_2 and the 30-year levelized busbar electricity cost becomes 11.30 mills/kWh.

Use of a 25 Percent Greater K Value. Additional full-scale testing is expected to show an improvement in SO_2 removal performance which will increase the value of the correlation factor, K. The amount of the expected improvement cannot be predicted at this time. A 25 percent improvement is used to illustrate how an improvement will affect the conceptual design.

The increase in the value of K produces more than a proportionate reduction in the lime requirements because the lime utilization also increases. The reduction in lime requirements proportionately reduces the requirements for dry lime storage and handling equipment. The lime slurry handling equipment, including the atomization system, is not significantly affected because the size of these items is dictated by the evaporation requirements which do not change.

A 25 percent increase in K for the 500 MWe conceptual design using PHDL reduces the estimated total retrofit capital requirements to \$38.46/kW, including NO_x nonremoval penalty. The estimated first-year O&M costs become \$19.57/kW-yr. The calculated SO_2 removal cost is \$236/ton SO_2, and the 30-year busbar electricity cost becomes 8.9 mills/kWh.

2.3 CASE 2: CAMPBELL UNIT 1, CONSUMERS POWER COMPANY

Campbell Unit 1 of Consumers Power Company is a base-loaded pulverized coal-fired boiler, located in West Olive, Michigan. It burns medium sulfur coal, and the SO_2 emissions are uncontrolled. Fly ash is removed by two electrostatic precipitators in series - 1E and 1W. The collected fly ash is currently sold. Other key boiler design data and flue gas characteristics are as follows:

Table 2-11

CASE 2
KEY BOILER DESIGN DATA AND FLUE GAS CHARACTERISTICS

Characteristics	Specifications
Unit rating, MW net	260
Estimated remaining life, yr	30
Net plant heat rate, Btu/kWh	9,520
Capacity factor, %	80
Coal as fired	
Moisture, %	11.3
Ash, %	10.7
Sulfur, %	2.2
High heating value (HHV), Btu/lb	11,178
Flue gas temperature, °F	280-330
Flue gas flow, acfm @ 300°F	863,700
Flue gas SO_2 concentration, ppmv, wet basis	1,617
Particulate emissions control device	2-stage ESP 1st stage 95% 2nd stage 97%

2.3.1 <u>Conceptual CZD Process Design Criteria</u>

The design criteria for the CZD process to be retrofitted to Campbell Unit 1 are described as follows:

1. Campbell Unit 1 has two precipitators (east and west) arranged in series and connected by two ducts, each 12 ft 8 in. by 12 ft 8 in. The straight sections of these ducts are approximately 69 feet long. The lime injection points will be located at the east ESP exit end of the straight ducts as shown in Figure 2-6. This will give a gas-reactant contact time of approximately 1.5 seconds at a calculated gas velocity of 44 fps.

2. The reaction products from this process, nonhazardous solids of calcium and magnesium sulfite/sulfate, and unreacted PHDL, will be collected together with the fly ash in the west ESP and conveyed to the ash silo. (Note: Most of the fly ash (95 percent) is collected in the east ESP.) A new conveyor system and additional storage capacity are provided to handle the increased quantity. (Note: The fly ash collected in the west ESP can no longer be sold unless a new application can be found for the mix.) It is assumed that the fly ash/reaction products mix will be disposed of together in a lined landfill located offsite at a cost of $6.50/ton.

3. The flue gas temperature at the lime slurry injection point is taken as 300°F. This was the average flue gas temperature at the first injection point during the Campbell CZD tests.

4. It is assumed that no modifications to the existing chimney will be required.

5. The CZD process is designed to remove 50 percent of the uncontrolled SO_2 emissions using PHDL as the reagent. PHDL will be supplied as a dry powder and mixed with water on site to form a slurry.

6. The lime storage silo is sized for 30 days' supply of lime.

7. An overall retrofit factor of 1.07 is used.

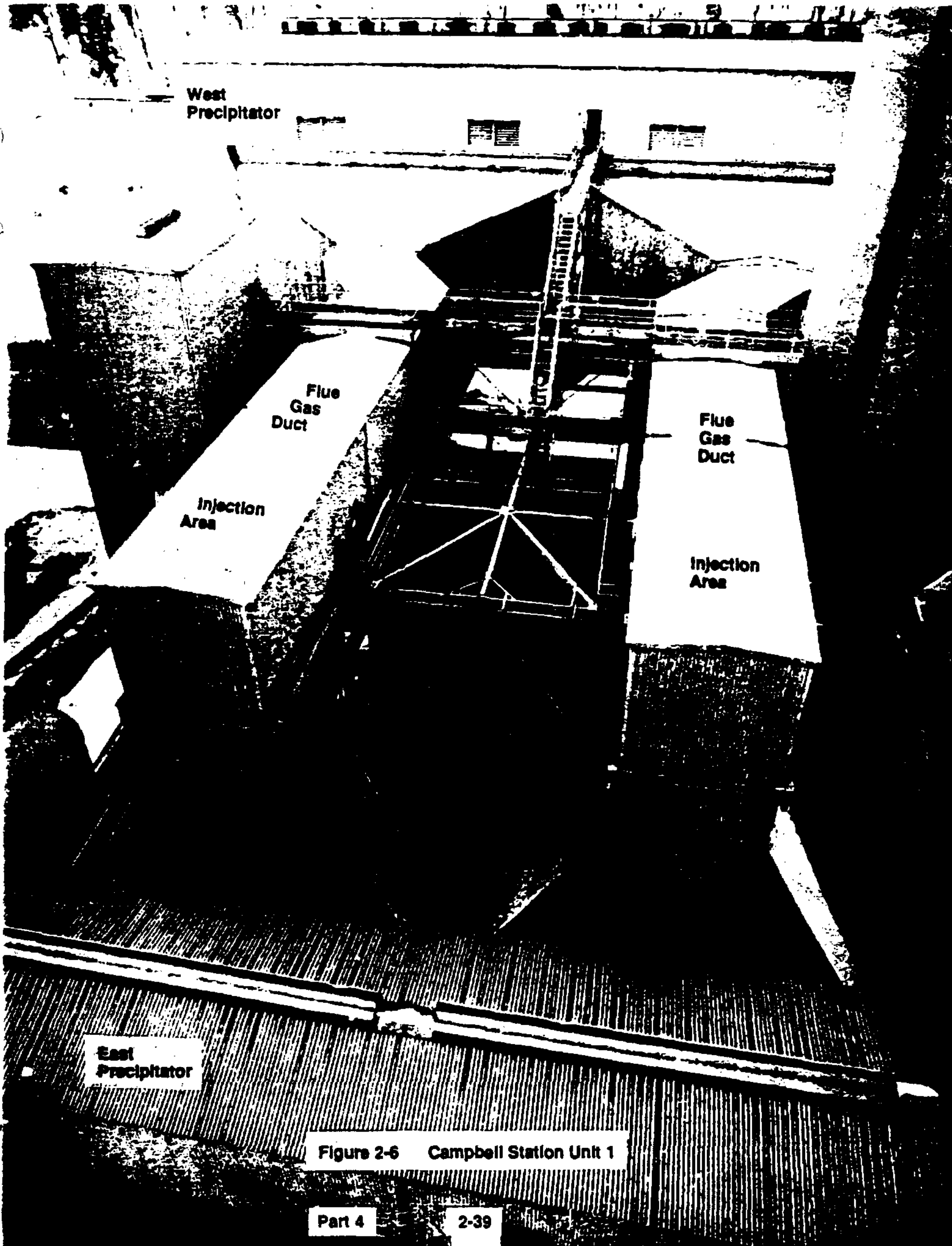


Figure 2-6 Campbell Station Unit 1

8. It is assumed that NO_x reduction is not required for this project. No credit will be taken for the potential NO_x reduction capability of the CZD process.

The process design parameters, raw material and utility requirements, and process effluents are summarized in Table 2-12.

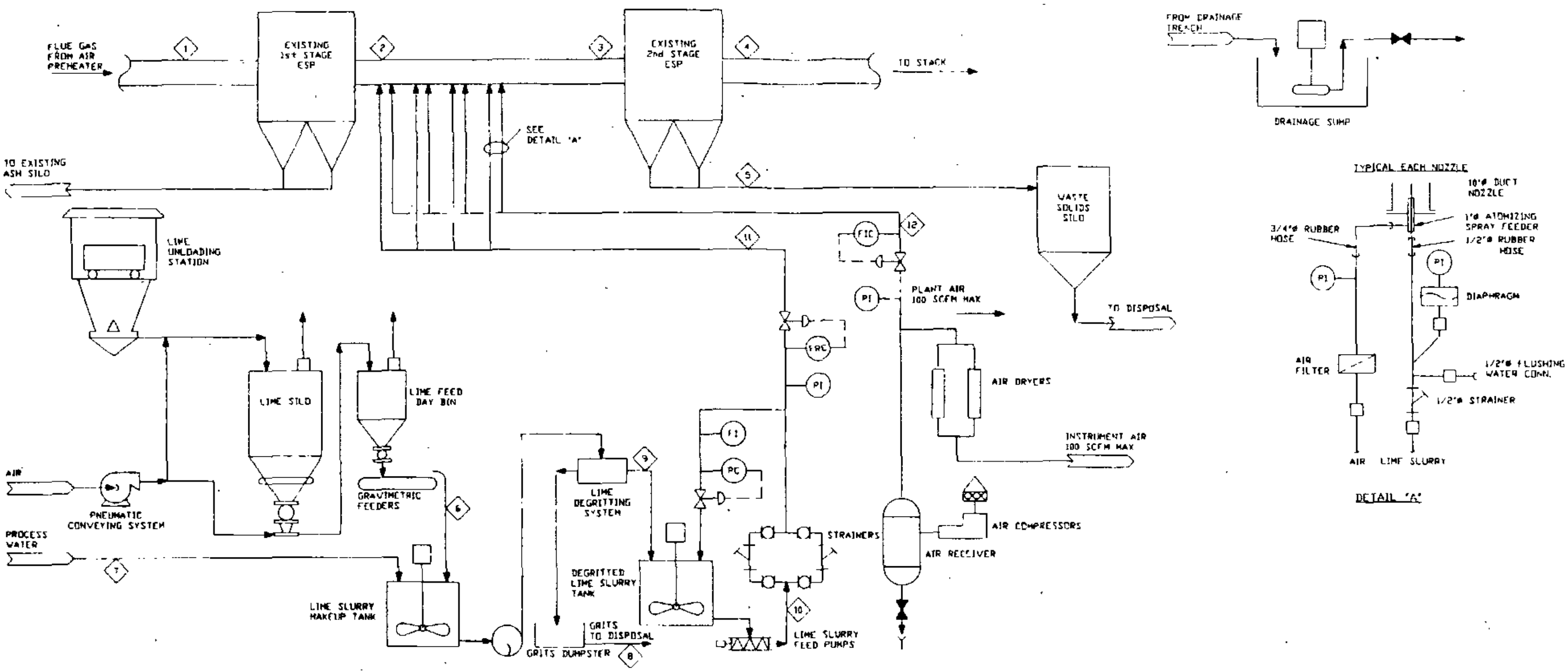
Table 2-12

CASE 2
PROCESS DESIGN CHARACTERISTICS

Process Design Parameters	Specifications
SO_2 removal, %	50
Flue gas temperature at injection point, °F	300
Spraydown temperature, °F	170
Approach to saturation temperature, °F	45
Normalized water injection rate, gal/kscf gas	0.284
Average SO_2 concentration, ppmv, wet basis	1189
Lime feed ratio, 1/2 [moles $Ca(OH)_2 \cdot Mg(OH)_2$]/mole SO_2 entering	1.32
Lime utilization, %	38
Lime purity, %	95.5
Lime slurry concentration, Wt%	13.6
Atomizing air pressure, psig	90
Atomizing air flow, scfm/gpm	30
Raw Material and Utility Requirements	
PHDL, 95.5% $Ca(OH)_2 \cdot Mg(OH)_2$, tph	6.58
Process water, gpm	160
Electricity, kW	1,600
Process Effluents	
SO_2, lb/hr	4,620
Fly ash, tph (ESP 1E)	9.00
Reaction products, tph (ESP 1W)	8.70
Grit, lb/hr, wet	740
Wastewater, gpm	none

2.3.2 Process Description

Figure 2-7 is a process flow diagram showing the major equipment and overall material balances.



STREAM No		1	2	3	4	5	6	7	8	9	10	11	12
COMPONENT		FLUE GAS FROM AIR PREHEATER	FLUE GAS 1st STAGE ESP OUTLET	FLUE GAS 2nd STAGE ESP INLET	FLUE GAS TO STACK	DRY WASTE SOLIDS	LIME TO MAKEUP TANK	PROCESS WATER	GRIT TO DISPOSAL	DEGRITTED LIME SLURRY TO STORAGE	LIME SLURRY FROM FEED PUMP	LIME SLURRY TO SPRAY NOZZLES	ATOMIZING AIR
FLUE GAS	lb/hr	2,647,000	2,629,000	2,744,000	2,727,000								
	acfm	863,700	863,700	758,200	758,200								
TEMPERATURE	°F	300	300	170	170								
SO_2	lb/hr	9,240	9,240	4,620	4,620								
	ppmv, wet	1,617	1,617	764	764								
FLY ASH	lb/hr	18,960	960										
	gr/acf	2.56	0.13										
WASTE SOLIDS	lb/hr			17,480	74	17,410							
	gr/acf			2.69	0.01								
RAW DOLOMITIC LIME	lb/hr						13,150						
GRIT IN LIME	lb/hr						600		600				
GRIT FREE LIME	lb/hr						12,560			12,560		12,560	
WATER	lb/hr							80,000	150	80,000		80,000	
	gpm							160	0.3	160		160	
LIME SLURRY	gpm									172	220	172	
	wt%									13.6	13.6	13.6	
COMPRESSED AIR	scfm												5100
	psig												120

BECHTEL NATIONAL, INC.
SAN FRANCISCO

260 MW CONCEPTUAL DESIGN
CASE 2

CZD PROCESS FLOW DIAGRAM

FIGURE 2-1

Part 4

2-41

PHDL is delivered by railcars and is discharged into a below grade hopper in a closed unloading station equipped with a baghouse. From the unloading station the lime is pneumatically conveyed to the storage silo, and from the silo to the day bin. The lime is gravimetrically fed from the day bin to the slurry makeup tank where it is mixed with process water to the desired concentration. The slurry from the makeup tank is pumped to a vibrating screen for degritting. The degritted lime slurry falls into the storage tank while the wet grit falls into a dumpster for disposal with the reaction waste solids. From the storage tank the degritted lime slurry is pumped through a strainer to the points of injection. The lime slurry feed is controlled by pressure and flow controllers through a recycle loop.

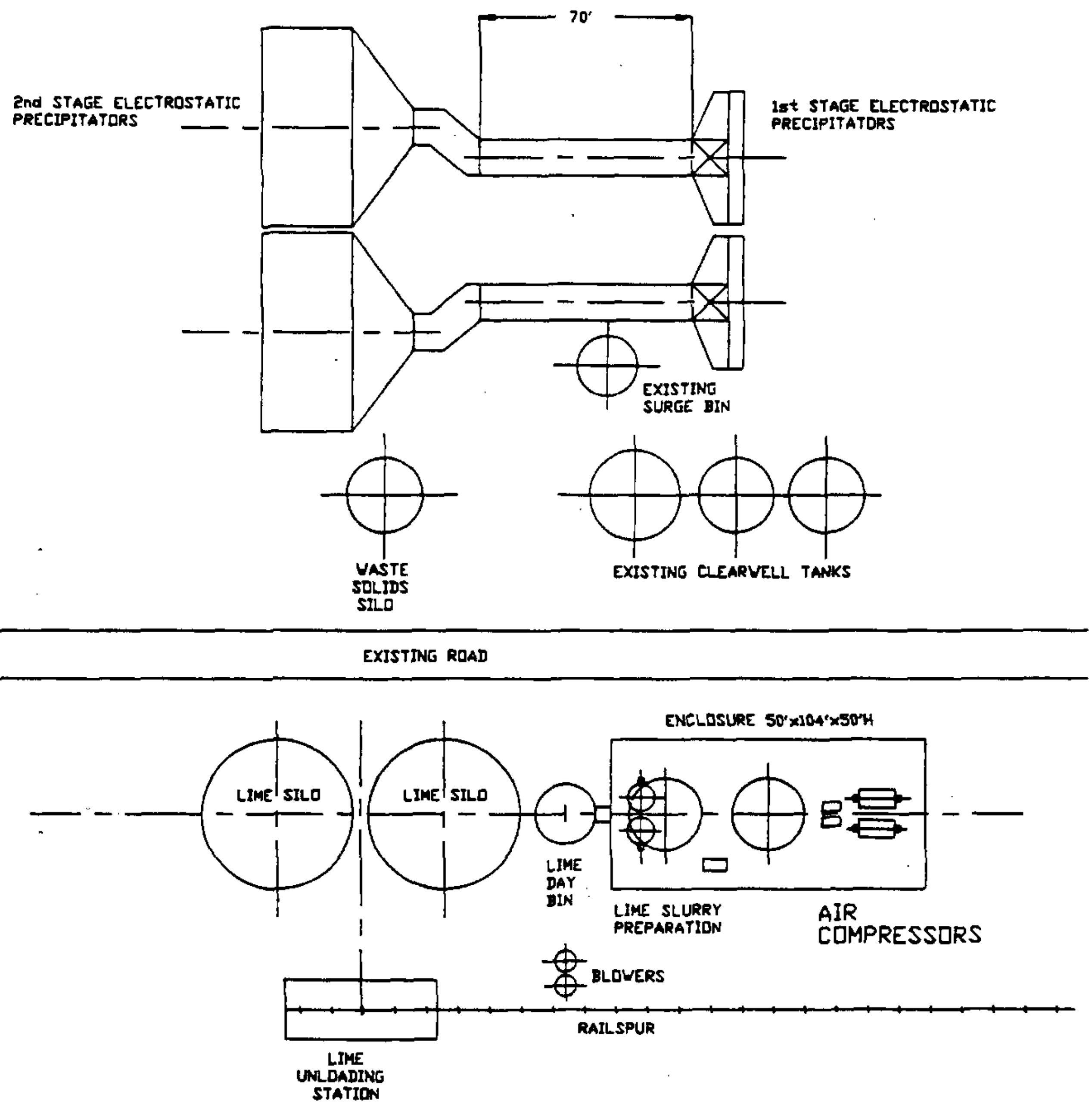
The degritted lime slurry is atomized with compressed air at 90 psig and is injected into the center core of the ducts through 36 spray nozzles, 18 installed at each duct. Sulfur dioxide (SO_2) in the flue gas exiting the east side precipitators reacts with the lime ($Ca(OH)_2 \cdot Mg(OH)_2$) in the spray droplets to form mostly calcium/magnesium sulfite ($CaSO_3 \cdot MgSO_3 \cdot H_2O$). The reaction products and the unreacted lime get dry as the water evaporates. The temperature at the center core of the ducts is close to the adiabatic saturation temperature of the flue gas while the surrounding gas remains hot. As the gas travels toward the west side precipitators, it intermixes to reach a temperature of approximately 170°F.

The dry reaction products, the unreacted lime, and the fly ash are collected together in the west side precipitators. From the precipitator hoppers these waste solids are conveyed to the ash silos. These waste solids are then transported to a lined landfill located off the site.

2.3.3 Major Equipment

A general layout of the major equipment is shown in Figure 2-8. The waste solids silo will be located next to the existing second-stage precipitators. The rest of the equipment will be located south of the existing clearwell tanks. A description of major equipment is given in Table 2-13.

Preceding Page Blank



NONE YS/ACAD

BECHTEL NATIONAL, INC.
SAN FRANCISCO

260 MW CONCEPTUAL DESIGN

CASE 2
MAJOR EQUIPMENT LAYOUT

JOB NO.	DRAWING NO.	REV.
17939	FIGURE 2-8	

Table 2-13

CASE 2
MAJOR EQUIPMENT ITEMS

Item		Quantity
Railspur		1
Service:	Provide access for lime delivery	
Length:	600 ft	
Lime Receiving System		1 lot
Service:	PHDL receiving and unloading area	
Includes:	1 - railcar covered area	
	1 - 3,000 acfm baghouse, 1200 ft^2 cloth, 7.5 hp	
Lime Storage Silos		2
Dimensions:	50' dia. x 88' straight side, 60° conical bottom	
Capacity:	30 days' supply, 4,740 tons	
Material:	Steel-reinforced concrete	
Accessories:	Baghouse, 360 ft^2 cloth area, each	
Reagent Pneumatic Conveyor System		1, 1 spare blower
Type:	Pneumatic	
Service:	PHDL	
Flow rate:	3,000 acfm	
Transfer line:	10" dia. x 200" L	
Blower motor rating:	200 hp	
Lime Feed Day Bin		1
Dimensions:	20' dia. x 36' straight side, 60° conical bottom	
Capacity:	24 hours' supply, 158 tons	
Material:	Carbon steel	
Accessories:	Rotary valve, bin vibrators, baghouse, 230 ft^2 cloth area	
Lime Gravimetric Feeders		1 op., 1 spare
Dimensions:	24" W x 10' L	
Solids rate:	15,000 lb/hr	
Service:	PHDL	
Motor rating:	7.5 hp	
Lime Slurry Storage Tanks		2 (1 makeup tank and 1 feed tank)
Dimensions:	24'-0" dia. x 40' high	
Capacity:	122,000 gal. each	
Service:	13.6% slurry	
Material:	Carbon steel, closed top, four baffles	
Accessories:	Agitator with 40 hp motor	

Table 2-13 (Cont'd)

Item		Quantity
Lime Degritting System Feed Pumps		1 op.,
Type:	Horizontal centrifugal	1 spare
Material:	Rubber-lined, carbon steel	
Flow:	200 gpm	
Head:	25 psi	
Motor:	5 hp	
Lime Degritting System		1 op.,
Type:	Vibrating screen	1 spare
Service:	Separating grit from lime slurry	
Feed rate:	200 gpm	
Material:	316 stainless steel	
Motor:	2 hp	
Lime Slurry Feed Pumps		1 op.,
Type:	Positive displacement	1 spare
Material:	Rubber-lined, carbon steel	
Flow:	250 gpm	
Head:	100 psig	
Motor:	25 hp	
Grit Dumpsters		2
Capacity:	270 ft^3 each	
Material:	Carbon steel	
Dual-Fluid Atomizing Nozzles		36 installed
Type:	Spraying Systems Co. CJ nozzles, or equivalent	
Capacity:	5 gpm each max.	
Material:	316 stainless steel body, carbide target bolt	
Air Compressors		
Type:	4-stage centrifugal compressor with intercooling	1 op.,
Capacity:	5,400 scfm	1 spare
Pressure:	120 psia	
Material:	Carbon steel	
Motor:	1,500 hp	
Accessories:	Prefilter, silencer, aftercooler, control unit, air receiver, and air dryer for 150 scfm	
Drainage Sump		1
Capacity:	3,000 gal.	
Material:	Concrete	
Accessories:	Agitator with 2 hp motor; two sump pumps, 50 gpm each	
Waste Solids Silo		1
Dimensions:	25' dia. x 46' straight side, 60° conical bottom	
Capacity:	630 tons (72 hours' production)	
Material:	Carbon steel	
Accessories:	Baghouse, airlock, conveyor	

2.3.4 Economics and Cost Estimates

Estimating Methodology. The cost estimating methodology used for this case follows the EPRI Technical Assessment Guide for a Class II level of analysis. For this method, the following design information is required and provided:

- General site conditions, geographic location, and plant layout
- Process flow diagram with material balances
- Major equipment specifications
- Preliminary instrumentation and line sizing

Major equipment costs are based upon Bechtel inhouse information, adjusted to current cost index, and vendors' telephone quotes. Other materials are by ratio to major equipment costs on plant parameters. Construction labors are from labor/material ratios for similar work, adjusted for site conditions and using expected average labor rates. Other economic parameters and assumed unit costs are given in Table 2-14. All costs are expressed in 1988 dollars.

Scope of Work. Design, furnish materials, fabricate, deliver, and erect duct injection flue gas desulfurization (FGD) system, complete with all necessary auxiliary and accessory equipment in accordance with the accompanying process flow diagram, major equipment list, and layout. Specifically, the items provided include:

- Duct injection FGD system complete with instruments, controls, and accessories, including continuous SO_2 monitors
- Complete SO_2 removal reagent unloading, storage, preparation, and handling system
- Complete access facilities to the reagent storage and preparation system, and the injection system including walkways, platforms, and stairs
- Thermal insulation and lagging for all required equipment and piping
- All process tanks and required agitation

Table 2-14

CASE 2
ECONOMIC PARAMETERS AND ASSUMED UNIT COSTS

Base year for cost estimates	1988
Engineering	10% of process capital
Home office, overhead, fees	10% of process capital
Project contingency	20% of process capital
Process contingency	
Lime injection system	20%
Balance of equipment	5%
Allowance for funds during construction	2% of plant cost
Royalty allowance	0.5% of process capital
Preproduction costs	2% of total plant investment
Inventory capital	30 days' raw materials and consumables
Capital fixed charge rate (FCR)	15.3%
Levelization factor for 30-year term	2.31
Sales tax (Michigan)	4%
Salvage value of process equipment	None
NO_x removal penalty assessment	None
PHDL, delivered	$65/ton
Process water	$0.60/1,000 gal
Power	$0.045/kWh
Waste solids disposal	$6.50/ton
Operating labor, 2 men/shift	$27.00/hr/man
Maintenance, total (labor 40%, materials 60%)	4% of process capital
Administration and support labor	30% of Operations and Maintenance labor

- All pumps, piping, supports, valves, and accessories
- All hoists, lift beams, monorails, and cranes
- Complete electrical power and control system, including:
  - Switchgear, transformers, load centers, and motor control centers
  - Power distribution/control panels for all equipment
  - Electric drives
  - Electrical conduit, wiring, cables, pull boxes, and fittings for complete system within interface limits
  - Control systems, instrumentation, and control panels for all equipment
- Support steel for all materials furnished, including platforms, stairs, and handrails
- Painting of exposed steel surfaces

The following are special exclusions:

- A solids recycle system (not used with this design)
- No special tools required for either operation or maintenance
- A gas distribution modeling test of the CZD equipment
- General facilities pro rata costs
- Owners' engineering and home office costs

The following items require work to be performed by others:

- All earthwork, site improvements, sewers, and drains
- All necessary roads and paving
- Single electric power supply of 13.8 kV
- Ground connections from ground pads on columns to owner's grounding system
- Waste disposal site construction (waste disposal cost including transportation, placement, and capital charges)
- Precipitator 1-W upgrading

Summary of Cost Estimates. A breakdown of the capital cost estimate is shown in Table 2-15. The projected first year operating cost is detailed in Table 2-16. The estimated 30-year levelized busbar electricity cost is given in Table 2-17. A summary of the cost estimates is given in Table 2-18. The detailed process area capital estimates are given in Worksheet 1 which follows Table 2-18.

As shown in Table 2-18, the total retrofit capital requirement is $29.49/kW; the first year operating cost is $18.07/kW-yr; the 30-year levelized busbar cost is 6.5 mills/kWh. The calculated SO_2 removal cost is $360.38 per ton of SO_2 removed, including both capital charge and O&M costs.

2.3.5 Sensitivity Analysis

A cost sensitivity analysis was not conducted for the Campbell Unit 1 conceptual design. However, as discussed for the 500 MWe conceptual design, additional full-scale testing is expected to show an improvement in SO_2 removal performance. This improvement would result in a reduction in the estimated costs for Campbell Unit 1 similar to those presented for the 500 MWe case.

Table 2-15

CASE 2
CZD PROCESS RETROFIT
PROJECTED CAPITAL REQUIREMENTS
(Base Year - 1988)

	$1,000	$/kW
Total process capital	5,003[a]	19.36[b]
Engineering, 10%	500	1.93
Home office overhead, fees, 10%	500	1.93
Project contingency, 20%	1,001	3.87
Total plant cost	7,004	27.09
Allowance for funds during construction	140	0.54
Total plant investment	7,144	27.63
Royalty allowance	25	0.10
Preproduction costs	143	0.55
Inventory capital	312	1.21
Total capital requirement	7,624	29.49

(a) Summation of the major process area capital estimates in Worksheet 1

(b) $\frac{\$5,003,000}{260,000\ kW - 1,600\ kW} = \$19.36/kW$

Table 2-16

CASE 2
CZD PROCESS RETROFIT
PROJECTED FIRST YEAR OPERATING COST

	$/yr	$/kW-yr
Operating labor	378,400	1.46
Maintenance labor	80,000	0.31
Maintenance materials	120,100	0.46
Administration and support labor	137,500	0.53
Total fixed O&M cost	716,000	2.76
Lime	2,997,000	11.60
Process water	40,400	0.16
Electricity	504,600	1.95
Waste disposal	414,500	1.60
Total variable O&M cost	3,956,500	15.31
Total projected first year operating cost	4,672,500	18.07

Table 2-17

CASE 2
CZD PROCESS RETROFIT
30-YEAR LEVELIZED BUSBAR COST

	Levelized Mills/kWh
Total capital	0.6
Fixed O&M	0.9
Variable O&M	5.0
Total levelized busbar cost	6.5

Table 2-18

CASE 2
ESTIMATED COST OF SO_2 REMOVAL
(in 1988 dollars)

Item	$/kW	$/kW-yr	$/ton SO_2	Mills/kWh
Total capital requirement	29.49		71.95	0.6
First year operating cost				
Fixed		2.76		0.9
Variable		15.31		5.0
Total		18.07	288.43	—
Total cost per ton of SO_2			360.38	
30-year levelized busbar cost @ 80% capacity factor				6.5

CASE 2 - WORKSHEET 1
MAJOR PROCESS AREA CAPITAL ESTIMATE

Process Area: 10 - Reagent Feed System

Major Process Equipment	No.[a]	Factory Material, $1000s	Field Material, $1000s	Field Labor, $1000s	Indirect Field Cost, $1000s	Sales[b] Tax, $1000s	Sub-Total, $1000s	Retrofit[c] Factor	Process Cost, $1000s
Enclosure (104'x50'x50'H)	1	110	39	33	28	6	216	1.07	231
Railspur	1								106
Lime unloading station	1								280
Lime silo	2	562	197	169	141	30	1,099	1.07	1,176
Pneumatic conveyor system	2	78	27	23	19	4	151	1.07	162
Lime feed day bin	1	80	28	24	20	4	156	1.07	167
Lime grav. feeder	1	15	5	5	4	1	30	1.07	32
Lime slurry tank	1	67	23	20	17	4	131	1.07	140
Miscellaneous (vib. screens, grit dumpsters, pumps, etc.)		35	12	11	9	2	69	1.07	74
Process Cost									2,368
Process Contingency, 5%[d]									118
Total Process Cost									2,486

Note: All cost estimate breakdowns follow Guthrie's "Process Plant Estimation Evaluation and Control" (Reference 2-7).

(a) Total number of equipment items are specified to achieve 30 years of reliable operation. For purposes of this cost estimate, it is assumed no salvage value exists for process equipment at end of useful life.

(b) Michigan sales tax at 4 percent on total material costs.

(c) A retrofit factor of 7 percent of direct costs was used for each major equipment item.

(d) Process contingencies are 20 percent for the SO_2 removal system and 5 percent for all other systems.

RR:8310r
Part 4

CASE 2 - WORKSHEET 1 (Cont'd)

Process Area: 20 - SO_2 Removal System

Major Process Equipment	No.[a]	Factory Material, $1000s	Field Material, $1000s	Field Labor, $1000s	Indirect Field Cost, $1000s	Sales Tax,[b] $1000s	Sub-Total, $1000s	Retrofit Factor[c]	Process Cost, $1000s
Degritted lime feed tank	1	67	23	20	17	4	131	1.07	140
Lime slurry feed pump	2	18	6	5	5	1	35	1.07	37
Air compressor	2	407	142	122	102	22	795	1.07	851
Spray system including 81 spray nozzles, control instrument and monitor		405	41	122	101	22	691	1.07	739

Process Cost	1,767
Process Contingency, 20%[d]	353
Total Process Cost	2,120

Note: All cost estimate breakdowns follow Guthrie's "Process Plant Estimation Evaluation and Control" (Reference 2-7).

(a) Total number of equipment items are specified to achieve 30 years of reliable operation. For purposes of this cost estimate, it is assumed no salvage value exists for process equipment at end of useful life.

(b) Michigan sales tax at 4 percent on total material costs.

(c) A retrofit factor of 7 percent of direct costs was used for each major equipment item.

(d) Process contingencies are 20 percent for the SO_2 removal system and 5 percent for all other systems.

RR:8310r r1:Rev.1
Part 4

CASE 2 - WORKSHEET 1 (Cont'd)

Process Area: 60 - Waste Handling System

Major Process Equipment	No.[a]	Factory Material, $1000s	Field Material, $1000s	Field Labor, $1000s	Indirect Field Cost, $1000s	Sales Tax,[b] $1000s	Sub-Total, $1000s	Retrofit Factor[c]	Process Cost, $1000s
Waste solids conveyor	1	12	4	4	3	1	24	1.07	26
Waste solids silo	1	144	50	43	36	8	281	1.07	301

Process Cost	327
Process Contingency, 5%[d]	26
Total Process Cost	343

Note: All cost estimate breakdowns follow Guthrie's "Process Plant Estimation Evaluation and Control" (Reference 2-7).

(a) Total number of equipment items are specified to achieve 30 years of reliable operation. For purposes of this cost estimate, it is assumed no salvage value exists for process equipment at end of useful life.

(b) Michigan sales tax at 4 percent on total material costs.

(c) A retrofit factor of 7 percent of direct costs was used for each major equipment item.

(d) Process contingencies are 20 percent for the SO_2 removal system and 5 percent for all other systems.

RR:8310r r1:Rev.1
Part 4

CASE 2 - WORKSHEET 1 (Cont'd)

Process Area: 70 - General Support Area

Major Process Equipment	(a) No.	Factory Material, $1000s	Field Material, $1000s	Field Labor, $1000s	Indirect Field Cost, $1000s	(b) Sales Tax, $1000s	Sub-Total, $1000s	(c) Retrofit Factor	Process Cost, $1000s
Drainage sump, including agitator, pumps, and trench	1	14	5	4	3	1	27	1.07	29
Makeup water pump	2	6	2	2	1	-	11	1.07	12
Fire protection and safety equipment		5	2	1	1		9	1.07	10

Process Cost	51
Process Contingency, 5%(d)	3
Total Process Cost	54

Note: All cost estimate breakdowns follow Guthrie's "Process Plant Estimation Evaluation and Control" (Reference 2-7).

(a) Total number of equipment items are specified to achieve 30 years of reliable operation. For purposes of this cost estimate, it is assumed no salvage value exists for process equipment at end of useful life.

(b) Michigan sales tax at 4 percent on total material costs.

(c) A retrofit factor of 7 percent of direct costs was used for each major equipment item.

(d) Process contingencies are 20 percent for the SO_2 removal system and 5 percent for all other systems.

RR:8310r r1:Rev.1
Part 4

REFERENCES

2-1 Acid Rain Precursor Control Technology Initiative in the Department of Energy's Flue Gas Cleanup Program, PRDA RA-22-85PC81001, February 2, 1985.

2-2 Technical Assessment Guide, EPRI Report P-2410-SR, May 1982, p. 2-10.

2-3 Economic Evaluation of FGD Systems, EPRI Report CS-3342, Volume 2, December 1983, p. 2-4.

2-4 Supplement No. 8 for Computation of Air Pollutant Emission Factors, Third Edition, USEPA Report AP.42, p. 1.1-3.

2-5 Retrofit FGD Cost-Estimating Guidelines, EPRI Report CS-3696, October 1984.

2-6 Acid Rain: Control Strategies for Coal-Fired Utility Boilers - Volume I, DOE Report on Contract DE-AC21-81MC16361, May 1982.

2-7 Guthrie, K. M., Process Plant Estimation Evaluation and Control, Craftman's Book Company, 1974.