

**MILLIKEN CLEAN COAL TECHNOLOGY  
DEMONSTRATION PROJECT**

**DATA REPORT FOR THE DESIGN COAL TESTS OF THE  
S-H-U SCRUBBER AT MILLIKEN**

**DRAFT REPORT**

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## DATA REPORT: DESIGN COAL TESTS OF THE S-H-U SCRUBBER AT THE NYSEG MILLIKEN STATION

### ABSTRACT

Tests of the Saarberg-Hölter Umwelttechnik GmbH (S-H-U) flue gas desulfurization (FGD) process were performed November 12-20, 1998, while burning the design coal at the NYSEG Milliken Station Unit No. 1. The objectives of the test program using the design coal were to demonstrate the effect of cocurrent and countercurrent liquid-to-gas ratio on SO<sub>2</sub> removal and scrubber operability. Measurements included SO<sub>2</sub> removal and scrubber pressure drop. SO<sub>2</sub> removal ranged from 85.6% using only five spray headers to 95.1% using all seven spray headers with formic acid (nominally 800 ppm). All but one of the tests were performed at a pH of 4.1 ±0.1. During one test, the pH was 3.9. Less SO<sub>2</sub> was removed during this test (85.4% at pH 3.9) compared to a duplicate test using the same spray header configuration (91.5% at pH 4.1). *Mass transfer increased with increasing liquid-to-gas ratio (L/G); in tests at similar L/G, mass transfer was dependent on the choice of the operating spray configuration.* Pressure drop through the scrubber was substantially influenced by changes in the countercurrent L/G, whereas cocurrent L/G did not have a significant effect on the scrubber pressure drop. Earlier tests were performed on Unit 2 from October 11 to November 21, 1995, while the unit was firing a 1.6% sulfur coal and on Unit 1 from April 21 to May 1, 1998, while the unit was firing a 4% sulfur coal.

## TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
CONCLUSIONS	2
EXPERIMENTAL METHODS	2
RESULTS AND DISCUSSION	3
SO <sub>2</sub> Removal	3
Pressure Drop	4
Mass Transfer	4
Other Considerations	6
DATA ACCURACY AND PRECISION	6
REFERENCES	7

## LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Test Conditions and Results	8
2	Laboratory Analyses of Gypsum Samples	11
3	Reproducibility of Measured Process Performance for Repeat Tests	12
4	Reproducibility of Uncontrolled Process Parameters for Repeat Tests	12

## LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	S-H-U Scrubber Schematic Showing Header Designation	13
2	Effect of L/G on SO <sub>2</sub> Removal	14
3	Four Cocurrent Sprays Operating	15
4	Three Countercurrent Sprays Operating	16
5	Effect of L/G on Pressure Drop - Countercurrent Sprays	17
6	Effect of L/G on Pressure Drop - Cocurrent Sprays	18
7	Effect of L/G on Mass Transfer	19
8	Four Cocurrent Sprays Operating	20
9	Three Countercurrent Sprays Operating	21

## APPENDICES

<u>Appendix</u>		<u>Page</u>
A	Statistical F-Ratio Test of Cocurrent and Countercurrent Headers vs. Scrubber Pressure Drop	22
B	Analyses of Coal Samples Collected During the FGD Tests (to be supplied by NYSEG)	26

## INTRODUCTION

The Saarberg-Hölter Umwelttechnik GmbH (S-H-U) flue gas desulfurization (FGD) process began operating at Milliken Station Unit 2 in January 1995 and at Unit 1 in June 1995. Tests of the S-H-U process while the unit was burning a 1.6% sulfur coal were performed from October 11 to November 21, 1995 (Reference 1). Tests using the design coal (3% S by weight) began on November 12, 1998. Details of the design coal test plan are given in Reference 2.

The objectives of the design coal test program were:

- To determine the SO<sub>2</sub> removal as a function of the limestone slurry spray liquid-to-gas ratio.
- To determine the mass transfer coefficients for the cocurrent and countercurrent sections of the scrubber for the design sulfur coal.

## CONCLUSIONS

The following are the major conclusions of the design coal test program:

### A. SO<sub>2</sub> Removal

- SO<sub>2</sub> removal ranged from 85.6% using only five spray headers to 95.1% using all seven spray headers, with formic acid concentration nominally 800 ppm.
- All but one of the tests were performed at a pH of 4.1 ±0.1. During one test the pH was out of the control range because of low limestone slurry flow. Less SO<sub>2</sub> was removed during this test (85.4% at pH 3.9) compared to a duplicate test using the same spray header configuration (91.5% at pH 4.1).

### B. Pressure Drop

- Pressure drop through the scrubber was substantially influenced by changes in the countercurrent slurry liquid-to-gas ratio (L/G), whereas cocurrent L/G did not have a significant effect on the scrubber pressure drop.

### C. Mass Transfer

- Mass transfer increased with increasing L/G; in tests at similar L/G, mass transfer was dependent on the choice of the operating spray configuration.

## EXPERIMENTAL METHODS

There are four cocurrent spray headers (Headers "A" through "D") and three countercurrent spray headers (Headers "E" through "G") in each S-H-U module (Figure 1). The combinations of operating spray headers used in this study were:

<u>Cocurrent</u>	<u>Countercurrent</u>	<u>Headers Off</u>
4	3	(none)
4	2	E
4	2	F
4	2	G
4	1	G & F
3	3	A
3	3	B
3	3	C
3	3	D
3	2	D & G
2	3	B & D
2	3	C & D

In this report, the header configurations are represented as a pair of numbers designating the number of cocurrent and countercurrent headers in operation; for example, (4,3) means four cocurrent and three countercurrent spray headers in operation. The 4,3 test was performed in triplicate, all of the 4,2 and 3,3 tests were performed in duplicate, and the remaining tests were performed once each.

These tests were performed on Unit 1 to define the performance of the S-H-U FGD system using several different header configurations. The same coal was fed to both boilers. Load was not a variable in these tests; the test plan was designed for full load on Unit 1 in all tests. Load changes during the S-H-U test period were handled by Unit 2, as much as possible to keep Unit 1 at full load. The scrubber slurry chloride content was not a test variable; at the design bleed rate (30,000 gal/hr per module) the steady-state chloride level should be about 40,000 ppm Cl<sup>-</sup> by wt; during the design coal tests it varied between 34,000 and 42,000 ppm.

The process is designed to achieve limestone utilization of 95% to 98% and to produce saleable gypsum by-product. The normal control scheme is to adjust the fresh limestone slurry feed rate based on the scrubber inlet gas SO<sub>2</sub> concentration and the inlet gas flow rate; trim control is based on scrubber slurry pH, which prevents excursions during major process changes such as load swings. The pH control loop maintained a constant scrubber chemistry during the design coal tests despite widely changing SO<sub>2</sub> removals that occurred when test conditions were changed. The pH was within ±0.1 of the set point (4.1 pH) for all tests except one: a 3,3 test with the D spray header off (Test S-D-1-10) in which the pH dropped to 3.9 because of a limestone slurry feed problem. The results of test S-D-1-10 are not included in the discussion of the variable effects on SO<sub>2</sub> removal or mass transfer.

The test plan was designed to study the effect of recycle slurry liquid-to-gas ratio (L/G) and mass transfer on scrubber performance. In the original design coal test plan, the formic acid concentration, the limestone grind size, and the gas velocity in the scrubber were included as test variables. However, the design coal test program was delayed because considerable time was spent solving spray header nozzle problems (described in detail in Reference 3). To complete the scrubber tests in 1998, the test program was shortened by eliminating test variables. Therefore, the design formic acid concentration (800 ppm), the design limestone grind size (90% -170 mesh limestone when formic acid is used) and the design gas velocity (20 ft/sec in the cocurrent section) were used during all of the design coal tests.

Liquid-to-gas ratio variation was achieved by varying the number of spray header pumps in operation. The spray header pumps operate in an on/off mode, i.e., there is no flow control on the headers. The pump design flow rates were used to calculate the L/G ratios in this report. Mass transfer was calculated for the cocurrent and countercurrent sections using the design flow values.

Each test was performed for a minimum of eight hours; the scrubber data (SO<sub>2</sub> removal, pressure drop, pH, etc.) usually lined out within one to six hours. Scrubber data were averaged for the time periods when SO<sub>2</sub> removal, pressure drop, pH, and gas flow were stable (<±3% relative) after line out. Data were collected using the plant's data logging system.

## RESULTS AND DISCUSSION

The test conditions and results are listed in Table 1. The maximum SO<sub>2</sub> removal was achieved using the (4,3) header configuration; the removals were 96.3%, 95.1%, and 94.0%, giving an average of 95.1 ±2.9% (95% confidence). The following is a discussion of the variable effects on SO<sub>2</sub> removal, pressure drop, and mass transfer.

### A. SO<sub>2</sub> Removal

1. The effect of liquid to gas ratio (L/G). In wet scrubbers, an increase in the liquid-to-gas ratio represents an increase in the reactive slurry flow rate and an increase in the droplet surface area for mass transfer to take place; as a result, more SO<sub>2</sub> is removed. This is illustrated in Figure 2, which shows SO<sub>2</sub> removal as a function of total L/G based on the slurry pump design flow rates to the headers. The average removal ranged from a low of 86.2% at 116 gal/kacf to a high of 95.1% at 162 gal/kacf. SO<sub>2</sub> removal was dependent upon the spray header configuration, as shown by the wide range of SO<sub>2</sub> removals for the six-header tests at 135-140 gal/kacf in Figure 2. For example, SO<sub>2</sub> removal was about 87% with the A or E header off, but over 90% with any other single header off.

The SO<sub>2</sub> removals for the tests in which all four cocurrent spray header pumps were operating are compared in Figure 3. The SO<sub>2</sub> removal varied depending upon which countercurrent spray headers were in use. For example, the average SO<sub>2</sub> removals were 87.3%, 90.2%, and 91.7%, respectively, when the E, F, or G header pump was shut off in the (4,2) tests.

The SO<sub>2</sub> removals for the tests in which all three countercurrent spray header pumps were operating are compared in Figure 4. Again, the SO<sub>2</sub> removal varied depending upon which cocurrent spray headers were in use. The average removals were 86.7%, 93.4%, 90.7, and 91.5%, respectively, when the A, B, C, or D header pump was shut off in the (3,3) tests.

Based on the results shown in Figures 3 and 4, turning off the uppermost headers (A and E) affected the SO<sub>2</sub> removal more than if any other header was turned off.

2. Effect of pH. The pH was not a variable in the design coal test plan. However, as mentioned earlier, the pH was 3.9 in one of the tests (Test S-D-1-10) because of a limestone slurry feed problem. SO<sub>2</sub> removal during this test was 85.4%; in a duplicate test using the same spray header configuration (Test S-D-1-2) the removal was 91.5% at 4.1 pH. Although this was not a rigorous test of pH, it illustrates the sensitivity of the process to pH changes.

## B. Pressure Drop

The pressure drop across the scrubber was a function of the number of countercurrent spray headers operating. Figure 5 shows the relationship between the pressure drop and the number of countercurrent header pumps operating. The average effect of each countercurrent header was to increase the pressure drop by 0.41 inches.

The effect of cocurrent spray headers on the pressure drop was not statistically significant. Figure 6 shows the relationship between the pressure drop and the number of cocurrent headers. A statistical F-ratio test (Appendix A) confirms the significance of the countercurrent headers and the lack of significance of the cocurrent headers on the scrubber pressure drop. These results are similar to the results obtained in Unit 2 during the 1.6% sulfur tests<sup>1</sup>.

## C. Mass Transfer

Mass transfer is discussed in terms of the number of transfer units (NTU), which is derived from the two-film theory of mass transfer. This theory assumes that the bulk gas-phase and bulk liquid-phase are well mixed and that the concentration of SO<sub>2</sub> is constant throughout both bulk phases. All mass transfer is assumed to occur in a gas-phase and liquid-phase boundary layer. The equation derived from theory is:

$$NTU = \ln \left( \frac{SO_2 \text{ in}}{SO_2 \text{ out}} \right) = \frac{K_g \cdot A \cdot P \cdot V}{G}$$

where: NTU = number of transfer units (dimensionless)  
SO<sub>2</sub> in = concentration of SO<sub>2</sub> at the scrubber inlet (ppmv)  
SO<sub>2</sub> out = concentration of SO<sub>2</sub> at the scrubber exit (ppmv)  
K<sub>g</sub> = global mass transfer coefficient (mol/cm<sup>2</sup>-sec-atm)  
A = interfacial mass transfer area per unit volume (cm<sup>2</sup>/m<sup>3</sup>)  
P = absolute scrubber pressure (atm)  
V = scrubber volume (m<sup>3</sup>)  
G = molar gas flow rate (mol/sec)

The pressure and scrubber volume are constant. The SO<sub>2</sub> removal is affected by the global mass transfer coefficient, the mass transfer area, and the gas flow rate. The global mass transfer coefficient is a combination of the gas-phase and liquid-phase mass transfer coefficients, generally written as:

$$K_g = \left( \frac{1}{k_g} + \frac{H}{e \cdot k_l} \right)^{-1}$$



where:  $k_g$  = gas phase mass transfer coefficient (mol/cm<sup>2</sup>-sec-atm)  
 $k_l$  = liquid phase mass transfer coefficient (cm/sec)  
H = Henry's Law constant for SO<sub>2</sub> in the scrubber liquid (atm/mol/l)  
e = an enhancement factor to account for diffusion of SO<sub>2</sub> through the liquid as bisulfite or sulfite (dimensionless)

The global mass transfer coefficient is affected by any process variable that affects the physical or chemical properties of the two boundary layers. For example, additives such as formic acid increase the buffer capacity of the liquid, which decreases H; the enhancement factor, e, decreases with increasing SO<sub>2</sub> concentration; the gas distribution and scrubber geometry affect  $k_l$ ; all of these affect the liquid phase mass transfer resistance, H/(ek<sub>l</sub>).  $k_g$  is affected by the scrubber geometry; countercurrent water/gas flow tends to have higher  $k_g$  than cocurrent water/gas flow because the gas phase boundary layer is thinner in countercurrent flow. Increasing the liquid flow rate increases the number of droplets which increases the interfacial mass transfer area, A. Increasing the gas flow rate, G, decreases the residence time in the scrubber, but can also increase the gas phase mass transfer coefficient by decreasing the gas phase boundary layer thickness.

Thus, determining the effect of process variables on mass transfer is complicated for the reasons just described. Common industry practice has been to plot NTU as a function of L/G, which is often (but not necessarily always) a linear function when everything else is held constant. It is assumed that the fresh water quench at the scrubber inlet and the fresh water mist eliminator wash at the scrubber exit do not contribute significantly to the SO<sub>2</sub> removal or overall mass transfer; combined they contribute 100 to 200 gpm, which is a total L/G of 0.2 to 0.4 gal/kacf.

Figure 7 is a graph of NTU vs total L/G for the design coal tests with a least-squares line drawn through the data points. Mass transfer was dependent upon which spray headers were in use, as shown by the scatter of points for the six-header tests at 135-145 gal/kacf in Figure 7.

The NTU are shown in Figure 8 for the tests in which all four cocurrent spray header pumps were operating and in Figure 9 for the tests in which all three countercurrent spray header pumps are operating. Based on the results shown in these two figures, turning off the uppermost headers (A and E) reduced mass transfer more than if any other header was turned off.

In the 1.6% sulfur coal tests,<sup>1</sup> NTU was calculated for each cocurrent spray header from the slope of NTU vs L/G for tests without countercurrent sprays. A least squares fit, forced through the origin, was used to obtain the slope. The NTU for each countercurrent spray was determined by subtracting the cocurrent NTU from the total scrubber NTU. However, to limit SO<sub>2</sub> emissions, no design coal tests were performed without countercurrent sprays. Therefore, the method used in the 1.6% sulfur coal tests for determining each header's mass transfer cannot be applied to the design coal test data. Instead, each header's mass transfer was estimated by subtracting the NTU measured in the six-header (4,2 and 3,3) tests from the NTU measured in the seven-header (4,3) test. The estimated mass transfers calculated in this manner are listed in the following table. The mass transfers from the 1.6% sulfur coal tests using 800 ppm formic acid in Unit 2 are given for comparison.

	design coal test NTU	1.6% sulfur coal test NTU (800 ppm formic acid)
Header A	1.018	0.412
Header B	0.314	0.412
Header C	0.654	0.412
Header D	0.566	0.000
Header E	0.920	1.544
Header F	0.706	0.692
Header G	0.524	0.504
Sum of individual NTU's	4.702	3.976
Average NTU measured for 4,3 tests	3.036	3.862

For the design coal tests, the sum of the individual NTU's was substantially higher than the measured total NTU in the 4,3 configuration; this indicates that the estimation method is not as precise as the calculation used for the 1.6% sulfur coal test data.

#### D. Other Considerations

1. Lab analyses. Laboratory analyses were performed on 5 gypsum samples. The results are shown in Table 2. They indicate that the gypsum purity was 92.7% to 95.3% and the calcium carbonate content was 0.6% to 3%.
2. Process operability. In general, no significant scrubber operability problems occurred during the test period. No measurable pressure drop increase with time was observed, indicating that the mist eliminators experienced no plugging problems; the mist eliminators kept the opacity within acceptable limits. The power requirement of the slurry recycle pumps was constant during the test period, which indicates that the spray headers did not plug.

### DATA ACCURACY AND PRECISION

The seven-header tests were performed in triplicate and the six-header tests were performed in duplicate. The statistical analysis of replicate sampling runs using a pooled standard deviation is a method for measuring the process reproducibility. Reproducibility refers to the agreement among replicate tests. Reproducibility as determined by the pooled standard deviation method is affected by all process uncertainties, including process measurement uncertainty, process control variation, process performance variation, the effect of uncontrolled variables (inlet temperature and flow rate, inlet SO<sub>2</sub> concentration, chlorides), and data accuracy. That is, the reproducibility includes uncertainty in the measured SO<sub>2</sub> removal as well as variability in the independent variables which determine the removal (e.g., L/G, gas flow, slurry pH, etc.).

The pooled standard deviation is calculated using the following formula:

$$S_{pooled} = \sqrt{\frac{(n_1-1) s_1^2 + (n_2-1) s_2^2 + \dots + (n_k-1) s_k^2}{(n_1-1) + (n_2-1) + \dots + (n_k-1)}}$$

where:  $n_j$  = the number of repeat measurements for the  $j^{\text{th}}$  test,  $j = 1, \dots, k$

$s_j$  = the standard deviation of the  $j^{\text{th}}$  test

$k$  = total number of tests, not including replicates

Tables 3 and 4 show the pooled standard deviation of measured process performance and uncontrolled process parameters for the repeated tests. The reproducibility confidence band is calculated by multiplying Student's t-statistic ( $t_{95\%}$  for the corresponding degrees of freedom at a 95% confidence level) by the pooled standard deviation. There were seven degrees of freedom for each parameter. The confidence band divided by the average measured value *within the range* gives the confidence band as a percentage of the measured value. For example, the average NTU of the six- and seven-header tests was 2.48; at 95% confidence limits, the reproducibility of the NTU for these tests was  $\pm 0.39$ . Thus, when a test is performed in which an NTU of 2.48 is measured, a repeat test should give  $2.48 \pm 0.39$  (or between 2.09 and 2.87) 95% of the time.

The reproducibilities of the  $\text{SO}_2$  removal, pressure drop and NTU are given in Table 3. These reproducibilities are less than  $\pm 16\%$  of the average values. A  $\pm 15\%$  reproducibility on a full-scale unit, with variations in the flue gas flow, temperature, scrubber slurry pH, chlorides, or other process conditions or fluctuations, is generally considered to be good.

The reproducibility for pH, gross boiler load, scrubber inlet gas flow, scrubber inlet gas temperature, and scrubber inlet gas  $\text{SO}_2$  concentration were all within  $\pm 9.1\%$  (relative) or less as shown in Table 4. The relative stability of these parameters contributed to the good reproducibility of the  $\text{SO}_2$  removal, NTU, and pressure drop.

## REFERENCES

1. Letter to W. Savichky from J. A. Withum, Re: Data Report for 1.6% Sulfur Coal Test of the S-H-U Scrubber at Milliken - Final Version (CO/NYSEG FGD 410), May 12, 1998.
2. Letter to W. Savichky from J. A. Withum, Re: Final Detailed Test Plan for the Design Sulfur Coal Test of the S-H-U Scrubber at the NYSEG Milliken Station (CO/NYSEG FGD 342), May 10, 1996.
3. Letter to J. Harvilla from J. A. Withum, Re: Milliken Clean Coal Demonstration Project - Materials of Construction (CO/NYSEG FGD 430), December 16, 1998.

Table 1. Test Conditions and Results

Date	Data Start Time	Data End Time	Test No.	SO <sub>2</sub> Removal %	Mass Transfer Units NTU	L/G		Number of Headers Operating		Inlet/Outlet Δp in W.C.	Avg pH	Inlet		Coal S <sub>1</sub> % Based on Gas Analyzers	Stack Gas		SO <sub>2</sub> Emissions lb/MM Btu	
						inlet flow	exit flow	Co-Current	Counter-Current			Gas Flow KACFM	Temperature °F		SO <sub>2</sub> Conc. ppm	Measured Flow KACFM		Calculated Flow KACFM
12 Nov. 1998	12:00 pm	5:00 pm	S-D-1-01	98.3%	3,291	135	167	4	3	2.15	4.17	546	283	2.20	441	462	42	0.12
12 Nov. 1998	8:00 pm	12:00 am	S-D-1-02	91.5%	2,470	111	138	3	3	2.22	4.14	570	286	2.23	456	479	98	0.29
13 Nov. 1998	5:00 am	8:00 am	S-D-1-03	90.3%	2,355	111	138	4	2	1.73	4.17	567	286	2.19	455	477	111	0.32
13 Nov. 1998	10:00 am	11:00 am	S-D-1-04	89.8%	2,281	112	140	3	3	2.15	4.14	565	286	2.28	450	475	119	0.35
13 Nov. 1998	9:00 pm	12:00 am	S-D-1-05	90.2%	2,328	110	138	4	2	2.03	4.16	571	284	2.20	457	482	114	0.33
12 Nov. 1998	7:00 am	8:00 am	S-D-1-06	93.7%	2,757	114	141	3	3	2.05	4.13	551	284	2.12	445	465	69	0.20
16 Nov. 1998	6:00 am	8:00 am	S-D-1-07	83.5%	1,800	109	138	4	2	1.78	4.13	579	287	2.17	457	486	191	0.55
16 Nov. 1998	1:00 pm	4:00 pm	S-D-1-08	88.8%	2,028	109	137	3	3	2.41	4.04	577	286	2.17	460	485	150	0.43
16 Nov. 1998	8:00 pm	12:00 am	S-D-1-09	94.0%	2,807	123	156	4	3	2.49	4.13	598	284	2.13	471	503	67	0.20
17 Nov. 1998	5:00 am	8:00 am	S-D-1-10	85.4%	1,931	107	135	3	3	2.41	3.88	591	284	2.28	485	497	176	0.51
17 Nov. 1998	2:00 pm	3:00 pm	S-D-1-11	93.1%	2,668	112	140	4	2	1.94	4.04	565	279	2.08	450	478	76	0.22
17 Nov. 1998	8:00 pm	11:00 pm	S-D-1-12	91.6%	2,483	108	131	3	3	2.41	4.06	595	280	2.15	480	504	93	0.27
18 Nov. 1998	5:00 am	8:00 am	S-D-1-13	90.2%	2,333	109	134	4	2	2.06	4.18	575	280	2.29	470	488	118	0.33
18 Nov. 1998	1:00 pm	4:00 pm	S-D-1-14	93.2%	2,688	113	139	3	3	2.10	4.08	558	279	2.38	454	472	84	0.24
18 Nov. 1998	9:00 pm	11:00 pm	S-D-1-15	81.2%	2,432	115	141	4	2	1.65	4.16	549	278	2.34	446	467	107	0.31
19 Nov. 1998	4:00 am	7:00 am	S-D-1-16	88.6%	2,010	110	136	3	3	2.33	4.12	572	280	2.26	482	484	156	0.46
19 Nov. 1998	1:00 pm	4:00 pm	S-D-1-17	85.6%	1,936	90	114	3	2	1.80	4.18	582	281	2.21	482	491	161	0.49
19 Nov. 1998	8:00 pm	12:00 am	S-D-1-18	85.7%	1,943	94	118	2	3	2.04	4.16	558	282	2.30	444	471	172	0.50
20 Nov. 1998	4:00 am	8:00 am	S-D-1-19	85.7%	1,948	92	115	4	1	1.42	4.15	574	284	2.32	455	483	173	0.51
20 Nov. 1998	1:00 pm	3:00 pm	S-D-1-20	87.7%	2,088	107	134	3	3	2.22	4.12	589	283	2.29	489	497	139	0.43
20 Nov. 1998	10:00 pm	11:00 pm	S-D-1-21	95.1%	3,008	131	163	4	3	2.25	4.16	580	288	2.35	450	472	60	0.17

Table 1. Test Conditions and Results (Continued)

Date	Data Start Time	Data End Time	Test No.	Limestone Slurry Density, %	Average Coal Flow ton/hr	Average Gross Load MW	Average Net Load MW	Average Opacity %	Average NOx Emissions lb/MM Btu	Average O <sub>2</sub> %
12-Nov-98	12:00 pm	5:00 pm	S-D-1-01	41.53	51.11	151	140	3.93	0.355	3.30
12-Nov-98	8:00 pm	12:00 am	S-D-1-02	41.53	52.92	156	146	4.12	0.369	3.30
13-Nov-98	5:00 am	8:00 am	S-D-1-03	42.05	53.40	158	147	4.00	0.354	3.31
13-Nov-98	10:00 am	11:00 am	S-D-1-04	42.05	51.76	154	143	4.11	0.366	3.51
13-Nov-98	9:00 pm	12:00 am	S-D-1-05	41.12	54.40	157	147	4.28	0.310	3.30
12-Nov-98	7:00 am	8:00 am	S-D-1-06	41.53	51.20	151	140	4.07	0.305	3.30
16-Nov-98	6:00 am	8:00 am	S-D-1-07	42.14	54.61	158	146	3.78	0.351	3.29
16-Nov-98	1:00 pm	4:00 pm	S-D-1-08	42.14	63.82	156	146	3.52	0.284	3.17
16-Nov-98	8:00 pm	12:00 am	S-D-1-09	42.15	55.13	158	147	4.17	0.324	3.31
17-Nov-98	5:00 am	8:00 am	S-D-1-10	41.53	55.23	158	147	3.61	0.321	3.31
17-Nov-98	2:00 pm	3:00 pm	S-D-1-11	41.53	52.87	150	140	3.78	0.328	3.42
17-Nov-98	8:00 pm	11:00 pm	S-D-1-12	41.53	55.38	158	147	4.10	0.322	3.30
18-Nov-98	5:00 am	8:00 am	S-D-1-13	40.75	55.43	158	146	3.79	0.308	3.29
18-Nov-98	1:00 pm	4:00 pm	S-D-1-14	40.01	52.82	151	140	3.35	0.345	3.29
18-Nov-98	9:00 pm	11:00 pm	S-D-1-15	39.06	52.18	151	140	4.23	0.342	3.29
19-Nov-98	4:00 am	7:00 am	S-D-1-16	38.28	53.16	154	143	4.35	0.349	3.30
19-Nov-98	1:00 pm	4:00 pm	S-D-1-17	39.99	62.22	151	141	4.00	0.361	3.67
19-Nov-98	6:00 pm	12:00 am	S-D-1-18	40.39	51.96	152	142	4.12	0.359	3.30
20-Nov-98	4:00 am	8:00 am	S-D-1-19	42.05	52.95	155	144	4.12	0.371	3.36
20-Nov-98	1:00 pm	3:00 pm	S-D-1-20	42.05	52.09	155	145	4.64	0.369	3.67
20-Nov-98	10:00 pm	11:00 pm	S-D-1-21	42.05	51.98	155	144	4.47	0.334	3.04

Table 1. Test Conditions and Results (Continued)

Date	Data Start Time	Data End Time	Test No.	Spray Header Amps										Formic Acid Pump Settings			Scrubber Solution Analyses		Gypsum Sample Analyses			Limestone Slurry Wet Sieve Analysis		
				Cocurrent					Countercurrent					AMP- 101	AMP- 201	AMP- 301	Formic Acid ppm wt	Chloride ppm wt	carbonate wt %	sulfite wt %	% -100 mesh	% -170 mesh	% -200 mesh	% -325 mesh
				A	B	C	D	E	F	G														
12-Nov-98	12:00 pm	17:00 pm	S-D-1-01	53	43	43	37	48	40	40	40	40	10	0	20	714	34,000	0.599	0.016	90.10				
12-Nov-98	20:00 pm	24:00 pm	S-D-1-02	54	43	43	0	48	40	40	40	10	0	20										
13-Nov-98	05:00 am	08:00 am	S-D-1-03	53	43	42	36	46	39	0	20	10	0	20										
13-Nov-98	10:00 am	11:00 am	S-D-1-04	53	43	0	37	47	39	39	25	25	0	20		657	38,000							
13-Nov-98	21:00 pm	24:00 pm	S-D-1-05	54	43	43	36	47	0	37	25	25	0	20										
12-Nov-98	07:00 am	08:00 am	S-D-1-06	53	0	43	37	46	40	40	30	0	20	20										
16-Nov-98	06:00 am	08:00 am	S-D-1-07	54	43	43	37	0	40	40	20	20	0	20										
16-Nov-98	13:00 pm	16:00 pm	S-D-1-08	0	43	43	36	46	40	39	20	20	0	20		578	40,000	0.718	0.024	90.55				
16-Nov-98	20:00 pm	24:00 pm	S-D-1-09	54	44	44	37	49	41	39	25	25	0	20										
17-Nov-98	05:00 am	08:00 am	S-D-1-10	54	45	44	0	49	40	40	25	25	0	20										
17-Nov-98	14:00 pm	15:00 pm	S-D-1-11	52	43	43	37	47	40	0	0	20	20	20		599	37,000							
17-Nov-98	20:00 pm	23:00 pm	S-D-1-12	54	45	0	36	48	40	40	25	25	0	20										
18-Nov-98	05:00 am	08:00 am	S-D-1-13	54	45	43	36	48	0	40	25	25	0	20										
18-Nov-98	13:00 pm	16:00 pm	S-D-1-14	54	0	43	36	47	40	40	25	25	0	20		785	42,000	2.500	0.024	89.29				
18-Nov-98	21:00 pm	23:00 pm	S-D-1-15	55	44	43	38	0	41	40	0	10	30	30										
18-Nov-98	04:00 am	07:00 am	S-D-1-16	0	45	44	39	49	41	40	0	0	30	30										
18-Nov-98	13:00 pm	16:00 pm	S-D-1-17	53	44	43	0	48	40	0	0	30	30	30		495	41,000							
18-Nov-98	20:00 pm	24:00 pm	S-D-1-18	52	43	0	0	47	40	39	0	0	30	30										
18-Nov-98	04:00 am	08:00 am	S-D-1-19	54	44	43	48	48	0	0	0	30	30	30										
20-Nov-98	13:00 pm	15:00 pm	S-D-1-20	54	0	43	0	48	40	40	0	0	30	30		534	37,000	1.435	0.016	89.89				
20-Nov-98	22:00 pm	23:00 pm	S-D-1-21	53	44	43	37	48	39	39	0	0	30	30										

Table 2. Laboratory Analyses of Gypsum Samples

Test Number	wt % Free Moisture		wt % Combined Water		Soluble Chloride	Major Ash Analyses. Wt% As Determined								wt % Gypsum, Dry Basis (Based on Combined Water)	wt % CaCO <sub>3</sub> , Dry Basis (Based on CO <sub>3</sub> Analysis)
	As Deter.	As Deter.	As Deter.	Corrected to 0% Moisture		wt % As Deter.	CO <sub>3</sub>	CaO	SO <sub>3</sub>	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO		
S-D-1-01	1.92	19.52	19.90	<0.003		0.53	33.30	52.54	0.60	0.14	0.19	0.15	0.04	95.1	0.90
S-D-1-04	5.18	18.92	19.95	<0.003		0.41	33.38	52.27	0.35	0.07	0.11	0.13	0.01	95.3	0.72
S-D-1-08	5.36	18.86	19.93	<0.003		0.34	32.80	50.96	0.29	0.08	0.11	0.16	0.03	95.2	0.60
S-D-1-14	6.18	18.20	19.40	<0.003		1.68	33.69	50.20	0.29	0.07	0.11	0.18	<0.01	92.7	2.99
S-D-1-20	6.58	18.56	19.87	<0.003		0.63	32.93	50.16	0.47	0.06	0.15	0.18	0.03	94.9	1.12
Minimum	1.92	18.20	19.40			0.34	32.80	50.16	0.29	0.06	0.11	0.13	<0.01	92.7	0.60
Maximum	6.58	19.52	19.95			1.68	33.69	52.54	0.60	0.14	0.19	0.18	0.04	95.3	2.99
Average	5.04	18.81	19.81			0.72	33.22	51.23	0.40	0.08	0.13	0.16	0.02	94.7	1.27
Std. Dev.	1.84	0.49	0.23			0.55	0.36	1.13	0.13	0.03	0.04	0.02	0.01	1.1	0.98

Table 3. Reproducibility of Measured Process Performance for Repeat Tests.

	Avg. Value	S <sub>pooled</sub>	95% conf. band
SO <sub>2</sub> Removal, %	91.0	1.56	±3.70
Scrubber Pressure Drop, " H <sub>2</sub> O	2.09	0.090	±0.214
NTU	2.48	0.164	±0.388

Table 4. Reproducibility of Uncontrolled Process Parameters for Repeat Tests.

	Avg. Value	S <sub>pooled</sub>	95% conf. band
pH	4.12	0.03	±0.08
Gross Load, MW	155	2.4	±5.8
Inlet Gas Flow, k acfm	568	13.3	±31.5
Inlet Gas Temperature, °F	283	3.1	±7.2
Inlet Gas SO <sub>2</sub> , ppm	1175	45	±107



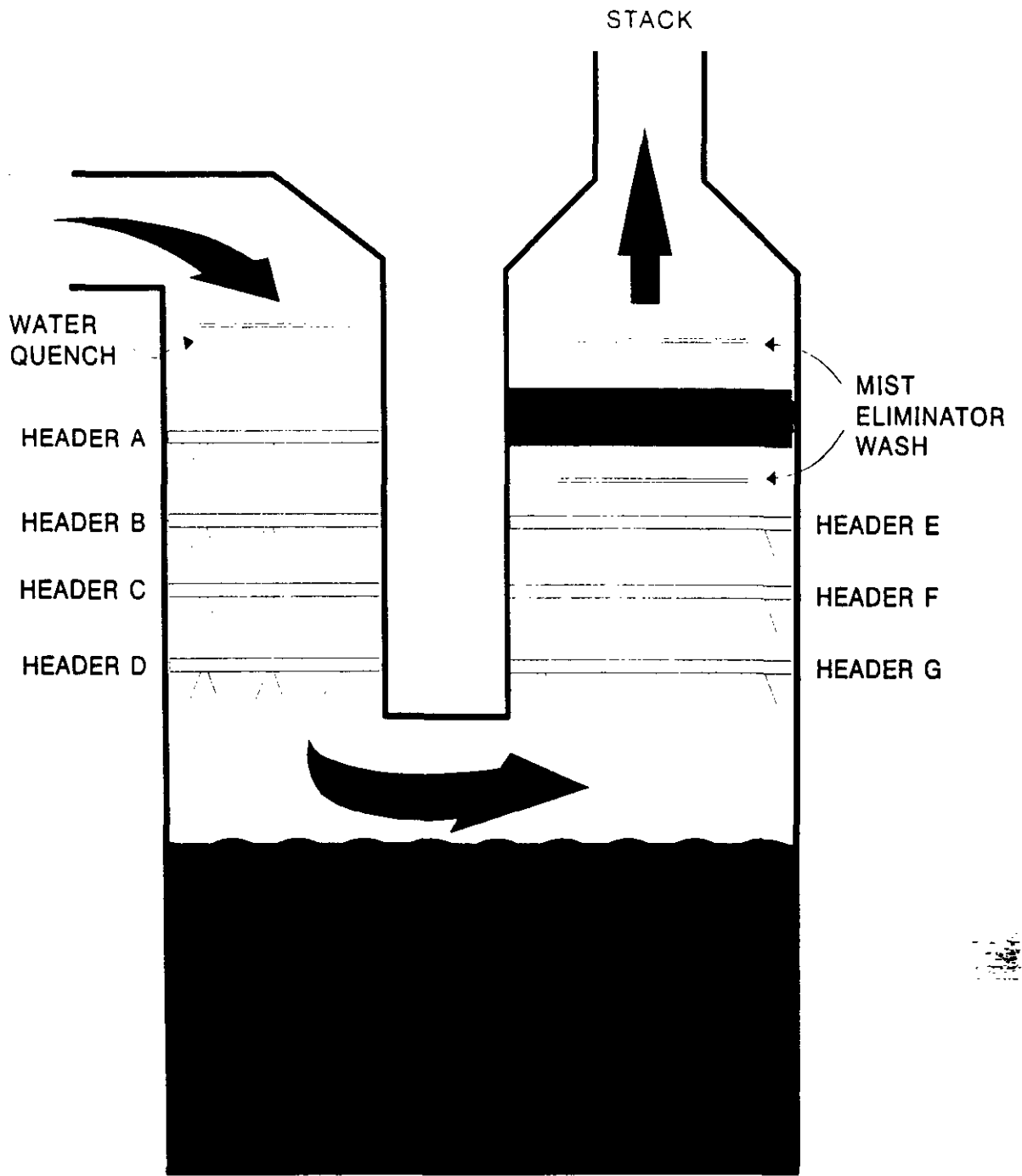


Figure 1. S-H-U Scrubber Schematic Showing Header Designation.

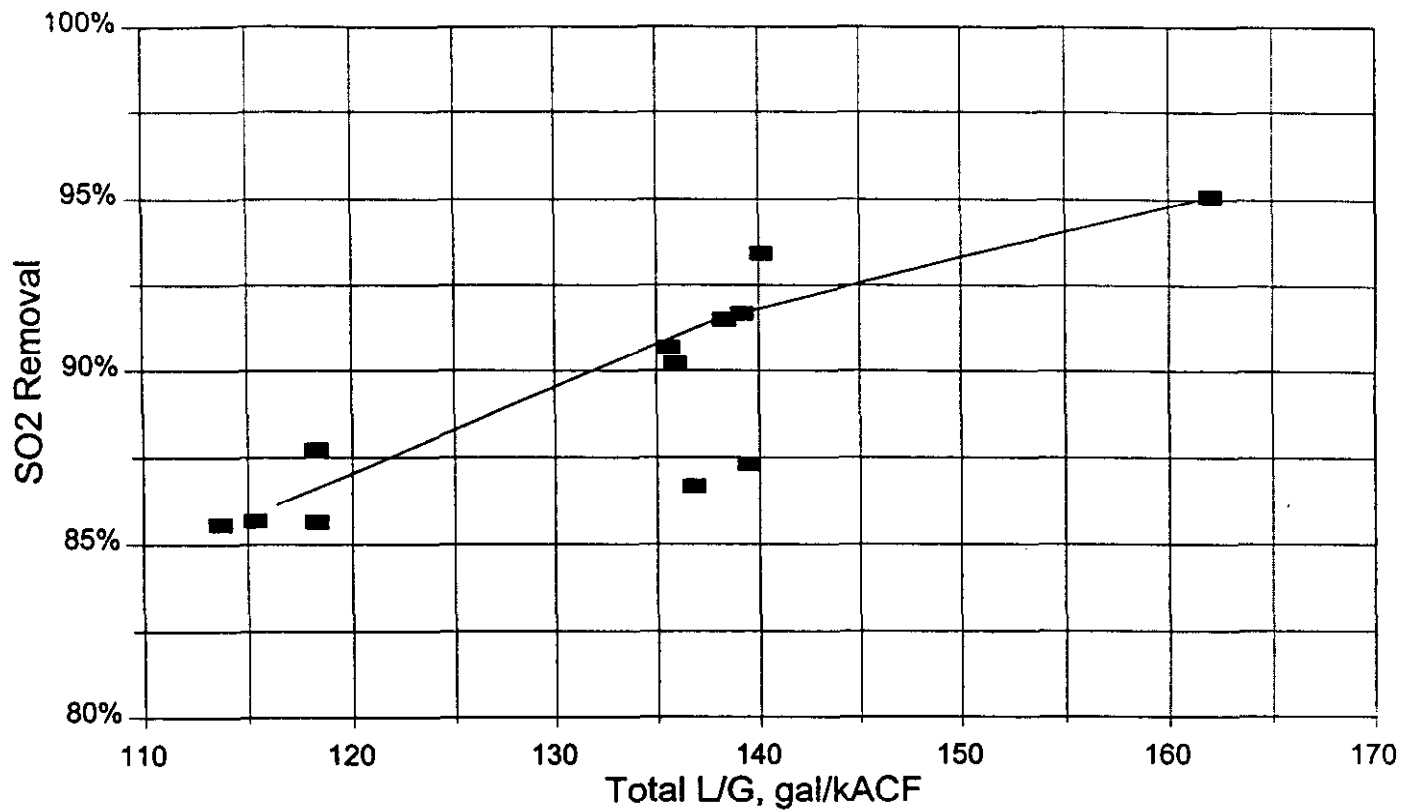


Figure 2. Effect of L/G on SO<sub>2</sub> Removal.

### Four Cocurrent Sprays Operating 4,1 and 4,2 Test Series

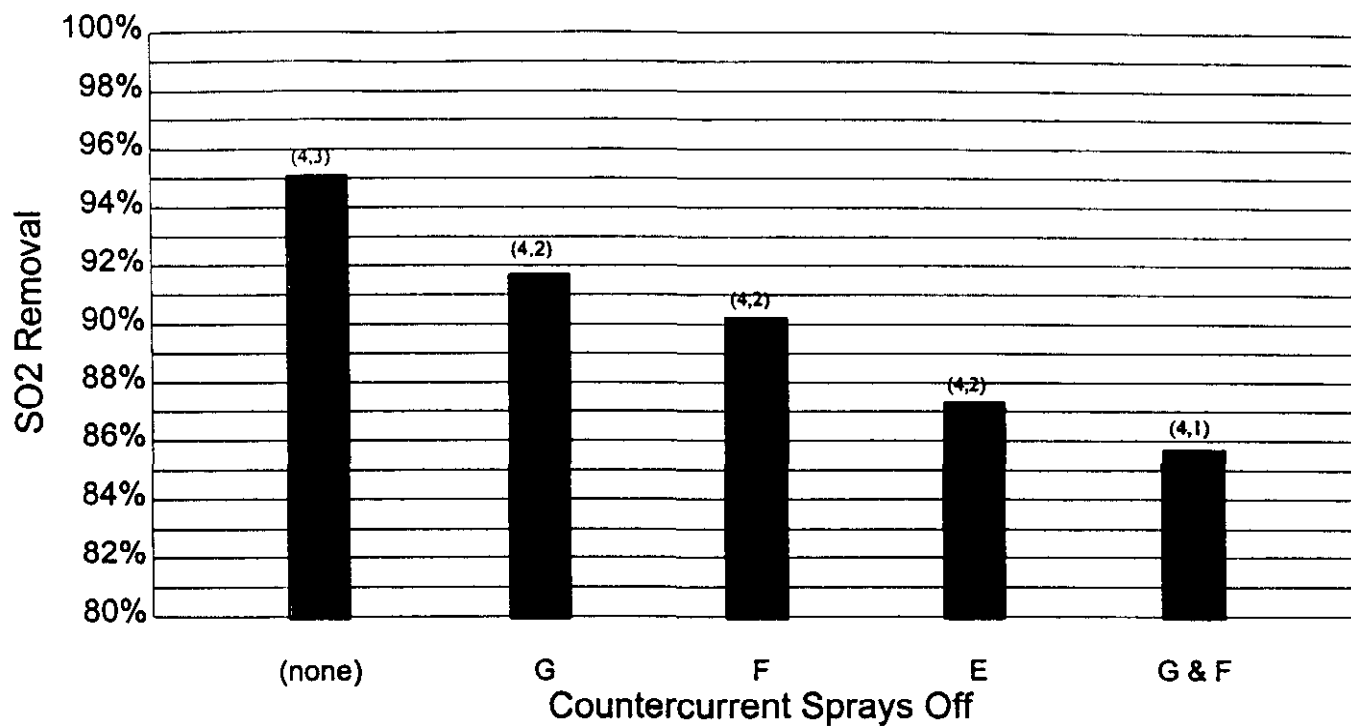


Figure 3. Four Cocurrent Sprays Operating.

Three Countercurrent Sprays Operating  
4,3; 3,3 and 2,3 Test Series

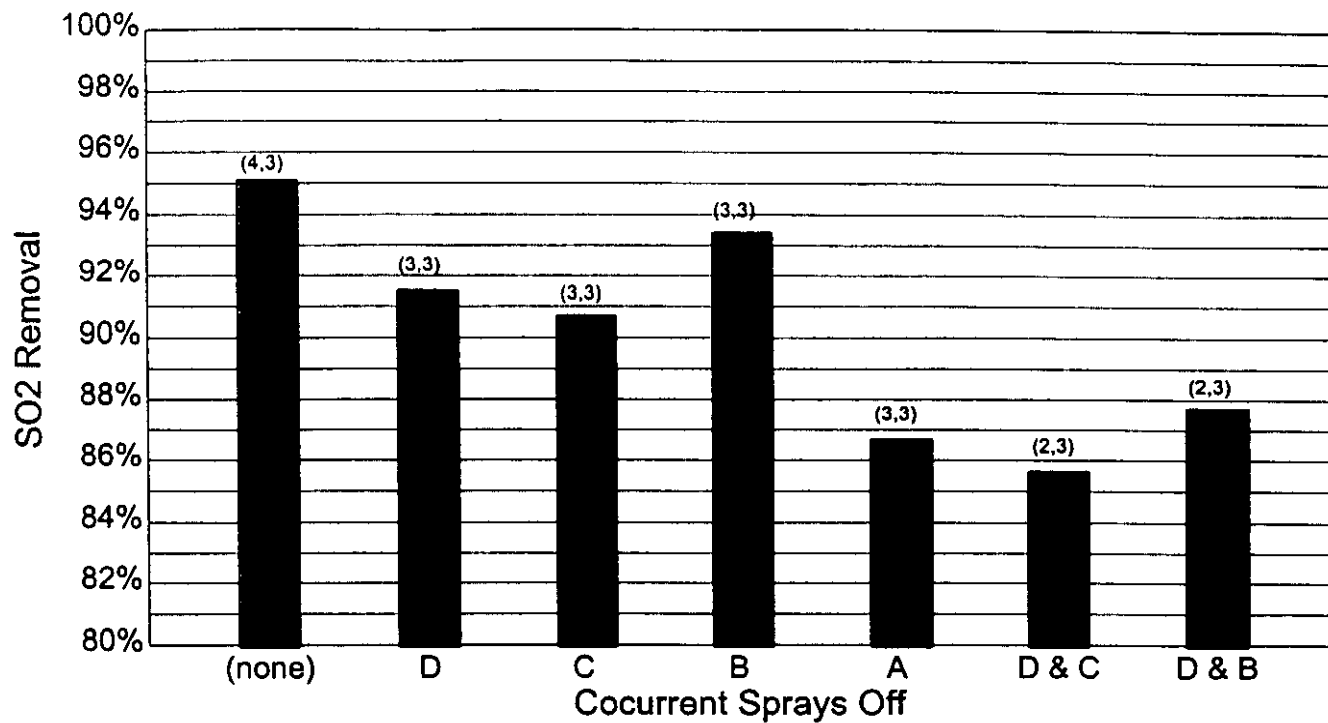


Figure 4. Three Countercurrent Sprays Operating.

### Effect of L/G on Pressure Drop

(error bars = two standard deviations)

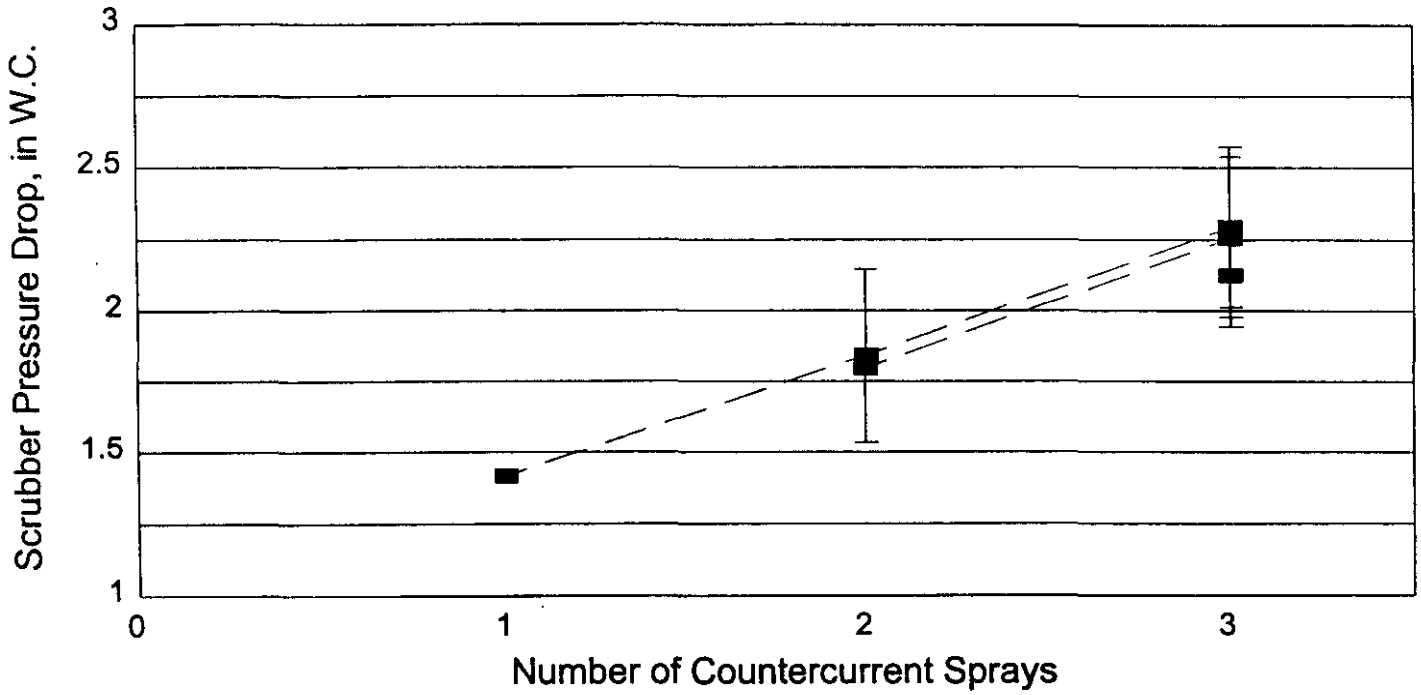


Figure 5. Effect of L/G on Pressure Drop.

### Effect of L/G on Pressure Drop

(error bars = two standard deviations)

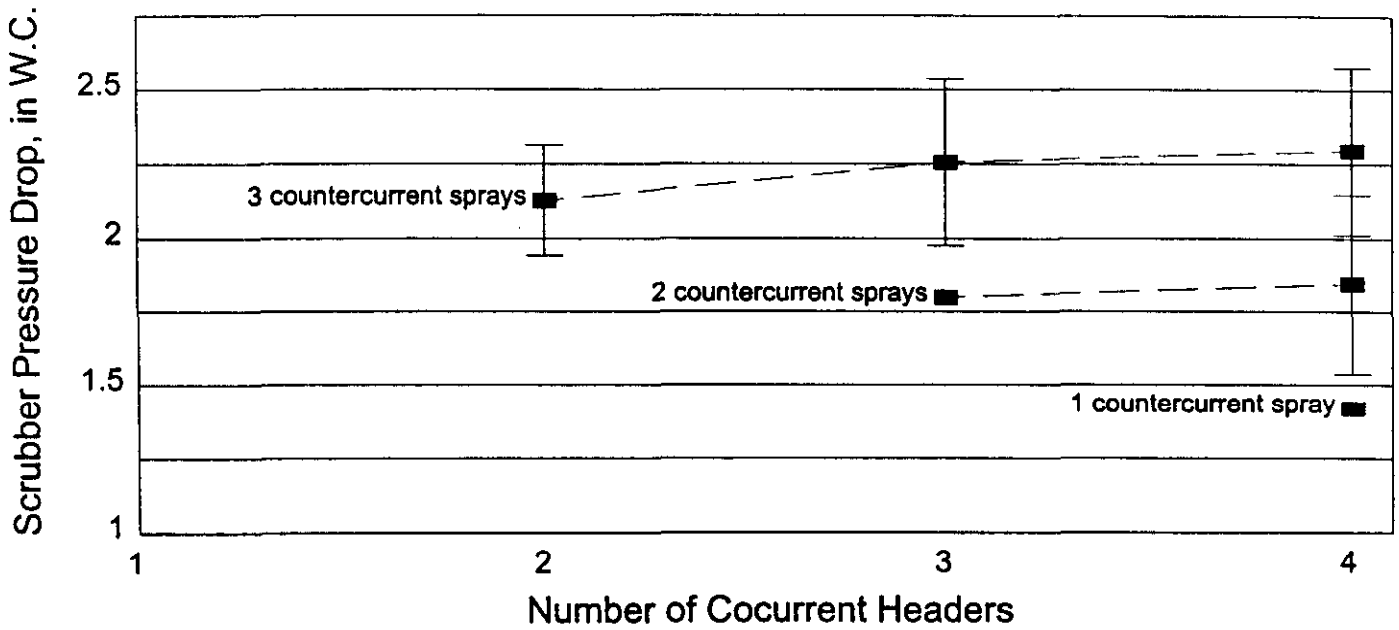


Figure 6. Effect of L/G on Pressure Drop.

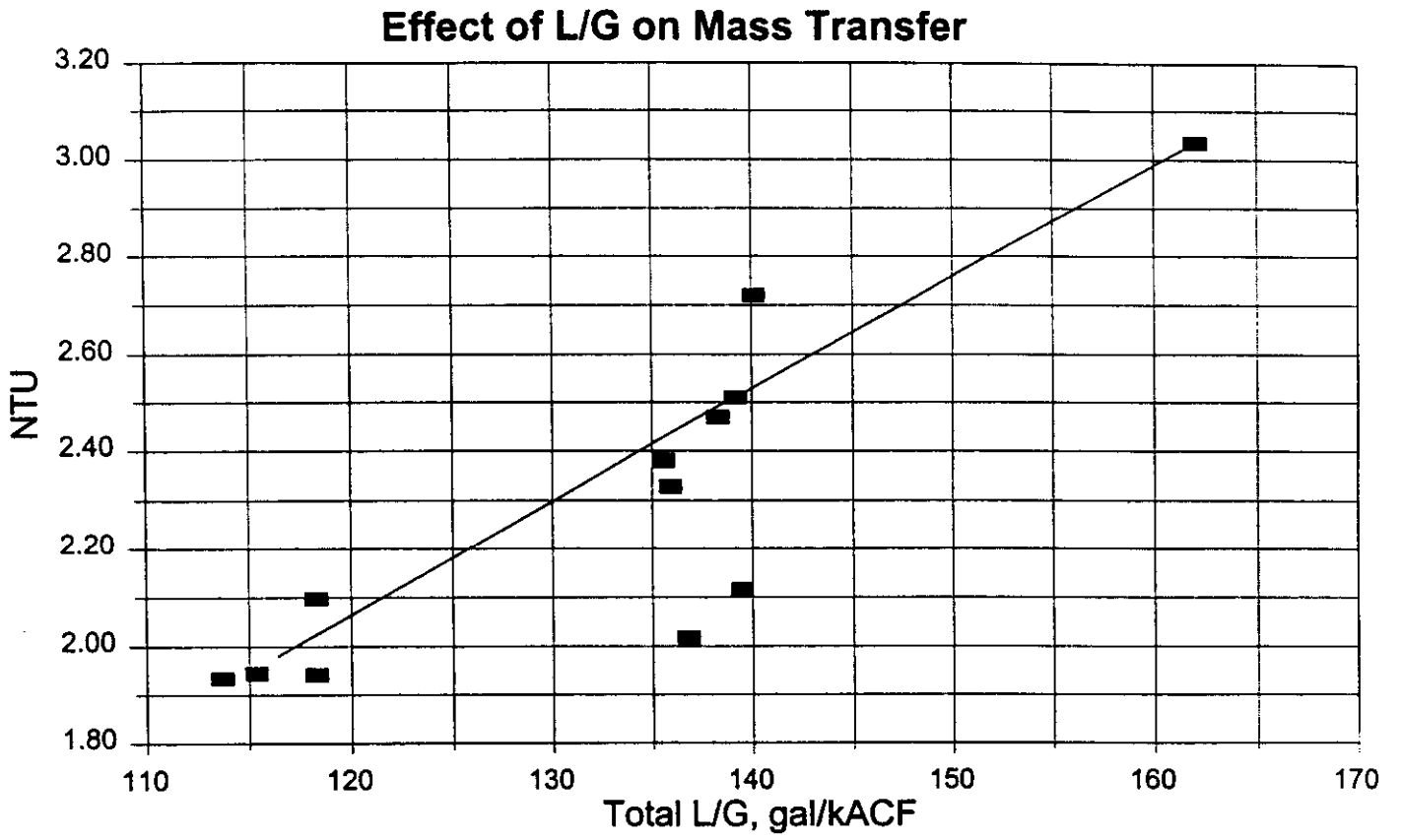


Figure 7. Effect of L/G on Mass Transfer

Four Cocurrent Sprays Operating  
4,3; 4,2 and 4,1 Test Series

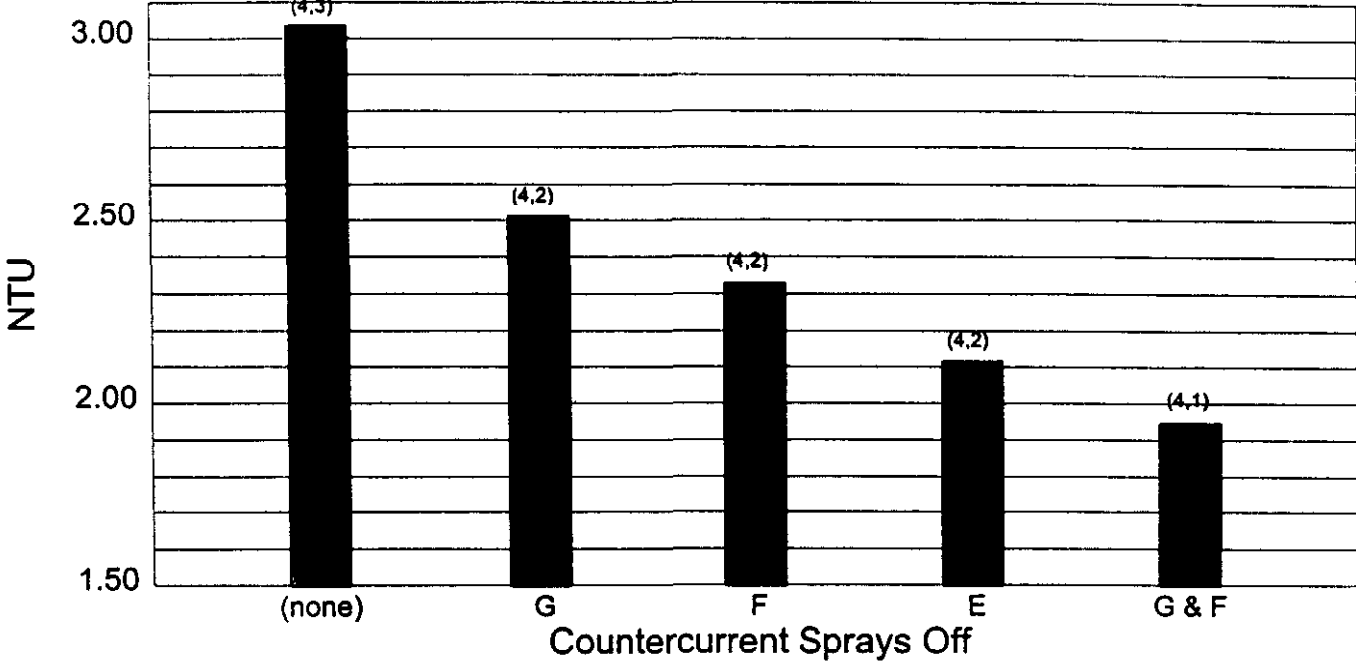


Figure 8. Four Cocurrent Sprays Operating.



Three Countercurrent Sprays Operating  
4,3; 3,3 and 2,3 Test Series

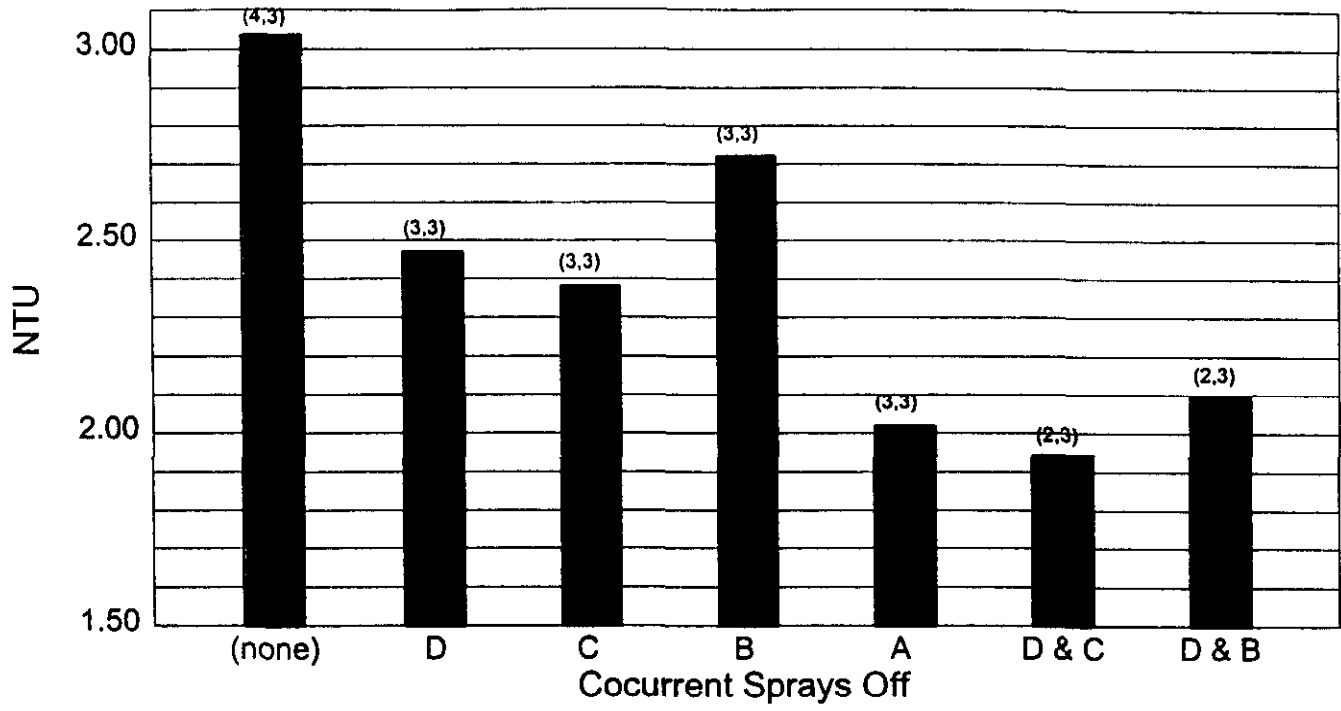


Figure 9. Three Countercurrent Sprays Operating.

**Appendix A**

**STATISTICAL F-RATIO TEST OF COCURRENT AND COUNTERCURRENT  
HEADERS vs SCRUBBER PRESSURE DROP**

## Analysis of Variance - Inlet/Outlet dp, "WC

### Analysis for All Cocurrent Headers

No. of countercurrent headers	3	2	1	Grand Total	Sum of Squares
Data	2.15	1.65	1.42		9.360
	2.25	1.73			8.054
	2.49	1.76			9.265
	2.05	1.84			7.586
	2.10	2.03			8.557
	2.15	2.06			8.862
	2.22	1.80			8.157
	2.33				5.436
	2.41				5.827
	2.41				5.829
	2.41				5.830
	2.04				4.146
	2.22				4.933
Totals	29.243	12.862	1.419	43.524	91.840
n	13	7	1	21	
Averages	2.249	1.837	1.419	2.073	

#### ANOVA Table

Source	Sum of Squares	Degrees of Freedom	Variance	F Ratio
Between Columns	1.2210	3	0.40699	16.719
Between Rows	0.4138	17	0.02434	
Totals	1.6348	20		

F-Table Lookup @ 1% for (3,17) d.f. = 5.185 \*\* SIGNIFICANT  
 F-Table Lookup @ 5% for (3,17) d.f. = 3.197 \*\* SIGNIFICANT  
 F-Table Lookup @ 10% for (3,17) d.f. = 2.437 \*\* SIGNIFICANT

## Analysis of Variance - Inlet/Outlet dp, "WC

### Analysis for 2 Countercurrent Headers

No. of cocurrent headers	4	3	Grand Total	Sum of Squares
Data	1.65	1.80		5.958
	1.73			2.991
	1.76			3.081
	1.84			3.374
	2.03			4.135
	2.06			4.235
Totals	11.063	1.799	12.862	23.774
n	6	1	7	
Averages	1.844	1.799	1.837	

#### ANOVA Table

Source	Sum of Squares	Degrees of Freedom	Variance	F Ratio
Between Columns	0.0017	2	0.00087	0.025
Between Rows	0.1404	4	0.03509	
	0.1421	6		

Totals

F-Table Lookup @ 1% for (2,4) d.f. = 18.000 \* NOT SIGNIFICANT  
 F-Table Lookup @ 5% for (2,4) d.f. = 6.944 \* NOT SIGNIFICANT  
 F-Table Lookup @ 10% for (2,4) d.f. = 4.325 \* NOT SIGNIFICANT

Appendix B

**ANALYSES OF COAL SAMPLES COLLECTED DURING THE FGD TESTS  
(TO BE SUPPLIED BY NYSEG)**