

EPA-600/2-77-242  
December 1977

Environmental Protection Technology Series

# FLY ASH CONDITIONING WITH SULFUR TRIOXIDE



Industrial Environmental Research Laboratory  
Office of Research and Development  
U.S. Environmental Protection Agency  
Research Triangle Park, North Carolina 27711

## **RESEARCH REPORTING SERIES**

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into nine series. These nine broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The nine series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies
6. Scientific and Technical Assessment Reports (STAR)
7. Interagency Energy-Environment Research and Development
8. "Special" Reports
9. Miscellaneous Reports

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment, and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

## **REVIEW NOTICE**

This report has been reviewed by the participating Federal Agencies, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

# **FLY ASH CONDITIONING WITH SULFUR TRIOXIDE**

by

**Edward B. Dismukes and John P. Gooch**

**Southern Research Institute  
2000 Ninth Avenue, South  
Birmingham, Alabama 35205**

**Contract No. 68-02-2114  
Task No. 1  
ROAP No. 21ADL-027  
Program Element No. 1AB012**

**EPA Task Officer: Leslie E. Sparks**

**Industrial Environmental Research Laboratory  
Office of Energy, Minerals, and Industry  
Research Triangle Park, N.C. 27711**

**Prepared for**

**U.S. ENVIRONMENTAL PROTECTION AGENCY  
Office of Research and Development  
Washington, D.C. 20460**

## Table of Contents

<u>Section</u>		<u>Page</u>
I	Introduction and Summary.....	1
II	Background.....	5
III	Results from Test Program.....	7
IV	Mass Balance Considerations.....	50
V	Computer Model Projections of Precipitator Performance.....	59
	Acknowledgements.....	63
	References.....	64

## List of Tables

<u>Table No.</u>		<u>Page</u>
1	Mass Train Results Reported by Research Cottrell.....	16
2	Mass Train Results Reported by Kin Associates.....	18
3	<u>In situ</u> Resistivity from George Neal Plant, Unit 2.....	20
4	George Neal-Unit 2, Average voltages and currents for 3/27/76.....	31
5	Average voltages and currents for 5/17/76.....	32
6	Ultimate Analyses of Coal Samples.....	34
7	Analyses of Flue Gas.....	35
8	Analyses of Hopper Ash.....	40
9	pH Values and Soluble $\text{SO}_4^{-2}$ Concentrations of Hopper Ash.....	42
10	pH Values and Soluble Sulfate Concentrations of Cyclone Samples of Ash.....	46
11	pH Values and Soluble $\text{SO}_4^{-2}$ Concentrations of Filter Samples of Ash.....	48
12	Injected $\text{SO}_3$ Found in Outlet Cyclone Samples of Ash.....	57
13	Injected $\text{SO}_3$ Found in Outlet Filter Samples of Ash.....	58

## List of Figures

Figure No.		Page
1	Inlet Size Distribution (Cumulative Percent) for March 27, 1976 with 90% Confidence Intervals.....	8
2	Inlet Size Distribution (Cumulative Mass) for March 27, 1976 with 90% Confidence Intervals.....	9
3	Average Inlet Size Distribution (Cumulative Percent) for May 18-21, 1976 with 90% Confidence Intervals.....	10
4	Average Inlet Size Distribution (Cumulative Mass) for May 18-21, 1976 with 90% Confidence Intervals.....	11
5	Outlet Size Distribution (Cumulative Percent) for May 19, 1976.....	13
6	Outlet Size Distribution (Cumulative Mass) for May 19, 1976.....	14
7	Fractional Efficiency for May 19, 1976 (Based on single outlet sampling point)....	15
8	Resistivity Probe Voltage-Current Characteristics without SO <sub>3</sub> Injection.....	21
9	Resistivity Probe Voltage-Current Characteristics with SO <sub>3</sub> Injection.....	23
10	Arrangement of Transformer Rectifier Sets for George Neal Unit 2.....	24
11	V-I Characteristics for TR Set 3 on March 27, 1976.....	25
12	V-I Characteristics for TR Set 4 on March 27, 1976.....	26
13	V-I Characteristics for TR Set 7 on March 27, 1976.....	27
14	V-I Characteristics for TR Set 8 on March 27, 1976.....	28

List of Figures  
(Continued)

Figure No.		Page
15	V-I Characteristics for TR Set 3 on May 21, 1976.....	29
16	V-I Characteristics for TR Set 8 on May 21, 1976.....	30
17	Comparison of Predicted Gas Concentrations (Functions of Excess Air) with Observed Concentrations (Displayed by Dashed Horizontal Lines).....	36
18	Hopper Configuration for the Precipitator..	38
19	Soluble $\text{SO}_4^{-2}$ in Hopper Ash as a Function of Hopper Location or Gas Temperature.....	43
20	Locations for Sampling with Series Cyclones.....	45
21	Comparison of $\text{H}_2\text{SO}_4$ Concentrations at the Dew Point with Experimental Results.....	53
22	Relationship between Flue-Gas Temperature and Experimental $\text{H}_2\text{SO}_4$ Concentrations.....	54
23	Computer Model Projections of Collection- Efficiency without $\text{SO}_3$ .....	60
24	Computer Model Projections of Collection- Efficiency with $\text{SO}_3$ .....	62

## I. INTRODUCTION AND SUMMARY

This report describes a study conducted by Southern Research Institute for the purpose of evaluating an SO<sub>3</sub> injection system for the George Neal Unit 2 Boiler of Iowa Public Service Company in Sioux City, Iowa. The SO<sub>3</sub> injection system was supplied by Research Cottrell for the purpose of increasing the collection efficiency of the electrostatic precipitator installed on the subject boiler. The study was sponsored jointly by Iowa Public Service Company and the Industrial Environmental Research Laboratory of the Environmental Protection Agency. Mass loading determinations were conducted by Research Cottrell and Kin Associates. EPA's portion of the study was concerned primarily with accounting for the fate of the injected conditioning agent with emphasis on stack losses of SO<sub>3</sub>, whereas IPS's objective was to determine whether the injection system would provide a means of reliably increasing the precipitator collection efficiency to 99% at full load with normal plant operating conditions. A second objective of IPS was to obtain an estimate of the specific collecting area which would be required to achieve 99.0% collection efficiency without conditioning when the precipitator is collecting fly ash produced from the low sulfur, low sodium western coal which is used for fuel at this installation.

The study consisted of a two-phase test program that was followed by appropriate laboratory measurements and analyses. The two phases of the test program were: (1) An evaluation of precipitator performance at full load without SO<sub>3</sub> injection. These tests were conducted on March 27, 1976. (2) An evaluation of precipitator performance at full load with SO<sub>3</sub> injection. These tests were conducted during the week of May 17, 1976.

Results from the baseline tests on March 27 indicated that, as expected, precipitator performance was limited by the high electrical resistivity of the collected dust. The average collection efficiency reported by Research Cottrell was 91.3% at a plant load of



299 megawatts. Measurements with a point-plane probe indicated a dust resistivity value of approximately  $6 \times 10^{12}$  ohm-cm at 118°C (245°F). Voltage-current relationships obtained from the TR sets also exhibited behavior typical of precipitators collecting high resistivity dust. These voltage-current relationships were used to estimate the allowable electrical operating conditions which could be maintained without back corona or excessive sparking in the absence of SO<sub>3</sub> conditioning. The estimated electrical operating conditions, the precipitator geometry, and the measured particle size distributions at the precipitator inlet were used as input data to a computer program which simulates the operation of the precipitator. The computer program was then used to estimate the specific collecting area that would be required to achieve 99.0% collecting efficiency. If it is assumed that the enlarged precipitator should include a sufficient safety margin to allow about 12% of the collecting area to be de-energized without decreasing performance below 99% collection efficiency, the program output indicates that a specific collecting area of 108 m<sup>2</sup>/(m<sup>3</sup>/sec) (550 ft<sup>2</sup>/1000 ACFM) would suffice.

The test program with SO<sub>3</sub> injection was not conducted in accordance with our original test plan because of difficulties with the SO<sub>3</sub> injection system and the precipitator TR sets "tripping out". It is our understanding that the cause of the difficulty with the TR sets was ash build-up in the hoppers. As a result of these problems, only one efficiency test at a load of 300 MW was obtained with the SO<sub>3</sub> injection system operating continually and without transformer-rectifier failures. The results obtained were as follows:

Test at Stack	Outlet Dust Concentration, gm/m <sup>3</sup> (gr/ACF)	Precipitator Efficiency %
ASME	0.0508(.0222)	99.27
EPA	0.0703(.0307)	98.96
EPA with residue from first impinger	0.0828(.0362)	98.78

These results were obtained from the Kin Associates report concerning the subject test program, and the precipitator efficiencies are based on an inlet dust concentration of  $10.38 \text{ gm/DNm}^3$  at  $21^\circ\text{C}$  ( $70^\circ\text{F}$ ) ( $4.536 \text{ gr/DSCF}$ ). Although the above data indicate the performance of the precipitator was approaching the desired value of 99%, additional test data taken after the injection system and precipitator have operated under reasonably steady-state conditions for several days would be required to determine if 99% collection efficiency can be consistently maintained. This will require a solution to the ash build-up problem and also a turn-down capability for the  $\text{SO}_3$  system. The reported rate of  $\text{SO}_3$  injection during the test period was about 25 ppm by volume.

Our conclusions with regard to the effect of  $\text{SO}_3$  injection at this rate on the flue gas and fly ash properties, and the precipitator performance, may be summarized as follows:

(1) Dust resistivity values measured with the point-plane probe indicated that resistivity decreased to approximately  $4 \times 10^{10} \text{ ohm-cm}$  at  $143^\circ\text{C}$  ( $290^\circ\text{F}$ ).

(2) Voltage-current curves obtained from the precipitator power supplies indicated that the dust resistivity was not limiting the electrical operating conditions. The electrical operating conditions with  $\text{SO}_3$  conditioning, the precipitator geometry, and the measured inlet size distribution were used as input data to the mathematical model. The results indicated that a collection efficiency of greater than 99% is theoretically possible with a specific collecting area of  $39.37 \text{ m}^2/(\text{m}^3/\text{sec})$  ( $200 \text{ ft}^2/1000 \text{ ACFM}$ ) and with the improved voltages and currents.

(3) At the inlet of the precipitator, where the gas temperature averaged  $128^\circ\text{C}$  ( $262^\circ\text{F}$ ), about 2 ppm of the added  $\text{SO}_3$  was found in the gas phase, and about 23 ppm was found on the suspended fly ash. Ash samples were collected and fractionated by size in a series of cyclones; variations in the sulfate content of different samples may have been caused by fluctuations in either boiler load (total gas flow) or  $\text{SO}_3$  injection rate. Ash of smaller particle size contained

higher weight-percentage of sulfate than ash of larger size, as expected.

(4) In the precipitator hoppers adjacent to the center line through the precipitator, about 15 ppm of the injected  $\text{SO}_3$  was found as sulfate on the ash. This quantity of  $\text{SO}_3$  was lower than expected from other data ( $\text{SO}_3$  injection rate and  $\text{SO}_3$  found as sulfate on ash at the inlet and outlet). The discrepancy presumably was caused by a lower-than-average rate of  $\text{SO}_3$  injection in nozzles directly upstream from the hoppers in question.

(5) At the outlet of the precipitator, where the gas temperature averaged  $118^\circ\text{C}$  ( $244^\circ\text{F}$ ), less than 1 ppm of  $\text{H}_2\text{SO}_4$  vapor was found in the gas stream, and only about 2 to 3 ppm of  $\text{SO}_3$  was found as sulfate on the ash. The  $\text{H}_2\text{SO}_4$  vapor concentration was too low to be distinguished from that occurring without conditioning. The total sulfate on the outlet ash was only about 50% of the value found without conditioning. Even though the weight fraction of sulfate on the ash was increased by conditioning, the product of (1) sulfate fraction and (2) total ash concentration was lower with conditioning than without, because of the marked increase in precipitation efficiency. In other words, the decrease in factor (2) as the result of conditioning was more important than the increase in factor (1).

In summary, the data indicate that an adequate accounting was made for the fate of the injected  $\text{SO}_3$  and that the overall rate of  $\text{SO}_3$  emission from the stack (counting both  $\text{H}_2\text{SO}_4$  vapor and sulfate on the ash) was lower with conditioning than without. Additional testing will be required to determine whether the injection system can enable 99% collection efficiency of fly ash in the precipitator to be reliably achieved.

## II. BACKGROUND

Collection efficiency measurements on the electrostatic precipitator installed on Unit 2 of the George Neal Station have indicated that the precipitator performance is appreciably below the design value of 99% at full load conditions. Although the precipitator performance has in the past reportedly been limited by factors other than dust resistivity (specifically, a poor gas velocity distribution and hopper sweepage), both the electrical readings of transformer-rectifier sets and in situ resistivity measurements have shown that the electrical operating characteristics are severely limited by dust resistivity.

In order to achieve the design value for collection efficiency at this installation, two options are feasible: (a) increase the plate area of the precipitator, and (b) lower the dust resistivity to the extent that it does not limit the performance of the unit. Option (a) involves a large capital expenditure since it is estimated that the total plate area would have to be increased by a factor of about 3 in order to achieve 99% collection efficiency. The precipitator currently is designed for a gas flow of 512.48 m<sup>3</sup>/sec at 129°C (1,086,000 ACFM at 263°F), and the existing plate area is 19,906 m<sup>2</sup> (214,272 ft<sup>2</sup>). This gives a design specific collecting area of 38.84 m<sup>2</sup>/(m<sup>3</sup>/sec) or 197 ft<sup>2</sup>/1000 ACFM. In view of the expense required to enlarge the existing unit the required amount, Iowa Public Service decided to evaluate the use of an SO<sub>3</sub> injection system for the purpose of lowering ash resistivity and increasing the precipitator performance.

The SO<sub>3</sub> injection system was supplied and operated by Research Cottrell. The system burns molten sulfur to produce SO<sub>2</sub> which is subsequently oxidized to SO<sub>3</sub> in a catalytic reactor. The gas leaving the converter is transported to the precipitator inlet duct through an insulated line, and injection into the flue gas is accomplished with an insulated manifold. The system is designed with the objective of maintaining the temperature in the transport line and

in the manifold above the  $\text{H}_2\text{SO}_4$  dewpoint. The design details of the  $\text{SO}_3$  system are not provided in this report as a result of a confidentiality agreement with Research Cottrell.

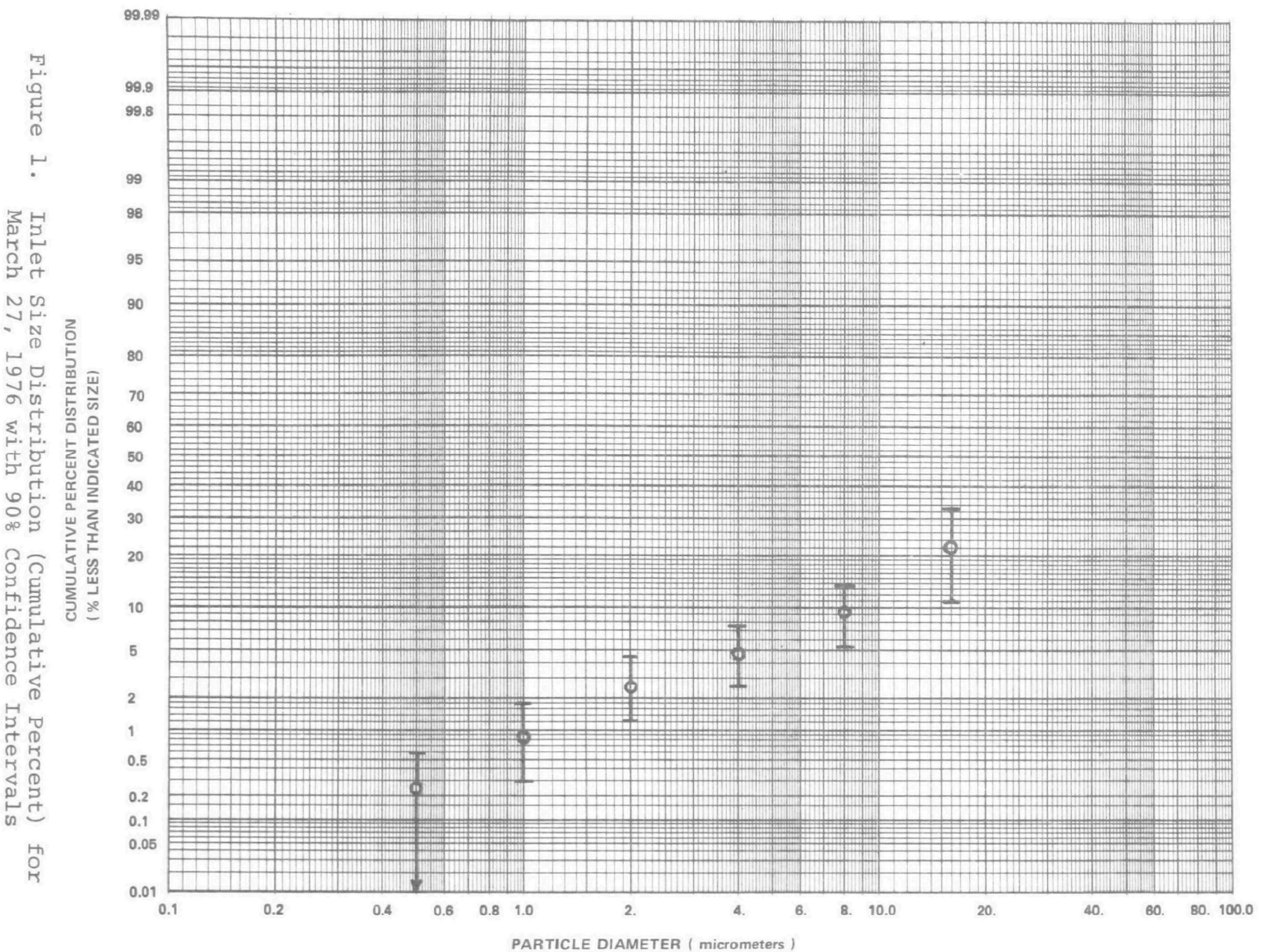
### III. RESULTS FROM TEST PROGRAM

#### A. Particle Size Measurements

Particle size measurements were conducted during both the baseline and SO<sub>2</sub> injection tests with cascade impactors and cyclones. The purpose of the cascade impactor measurements was to provide size distribution data for subsequent use in a mathematical model which was employed to simulate the operation of the precipitator during the test program. Multistage cyclones were used primarily to obtain size fractionated samples for chemical analysis, and results from these measurements will be presented in the section on chemical analyses.

During the baseline test series (March 27), a total of eight Brink cascade impactor runs were performed at the precipitator inlet, and two Andersen impactor runs were performed at the outlet. Useful data were not obtained from the outlet runs because of substrate sticking and stage overloading. Inlet impactor runs were made with four-point traverses in which two points were approximately 0.3 meter (1 ft) apart at the top of the duct and the other two points were the same distance apart at the center of the duct. The traverses were conducted in port Nos. 2, 4, 5, and 7 (See Figure 20). Figure 1 gives the data obtained from the March 27 inlet series on log probability co-ordinates, and Figure 2 presents the distribution in terms of cumulative mass loadings as a function of particle diameter.

The second series of particle size measurements was conducted the week of May 17, 1976. A total of sixteen Brink impactor runs were conducted on May 18, 19, 20, and 21 using the same traversing procedure described above. Outlet Andersen impactor runs were also conducted on May 19, 20, and 21, but only the data obtained on May 19 are of interest because of problems encountered with the precipitator or the injection system on the other test days. Figures 3 and 4 give the average inlet size distribution on log probability



ERROR BARS INDICATE 90 % CONFIDENCE INTERVAL

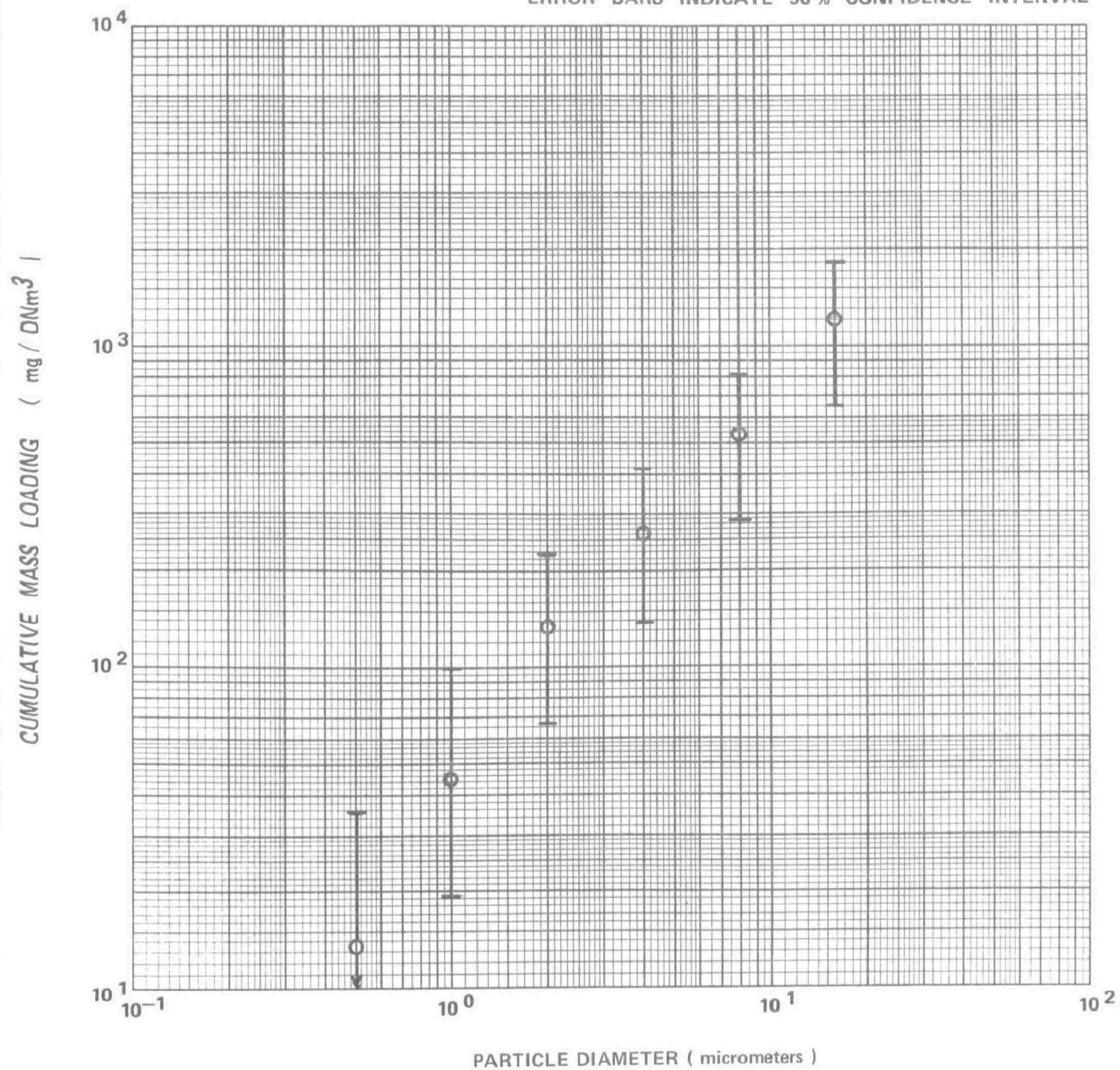


Figure 2. Inlet Size Distribution (Cumulative Mass) for March 27, 1976 with 90% Confidence Intervals



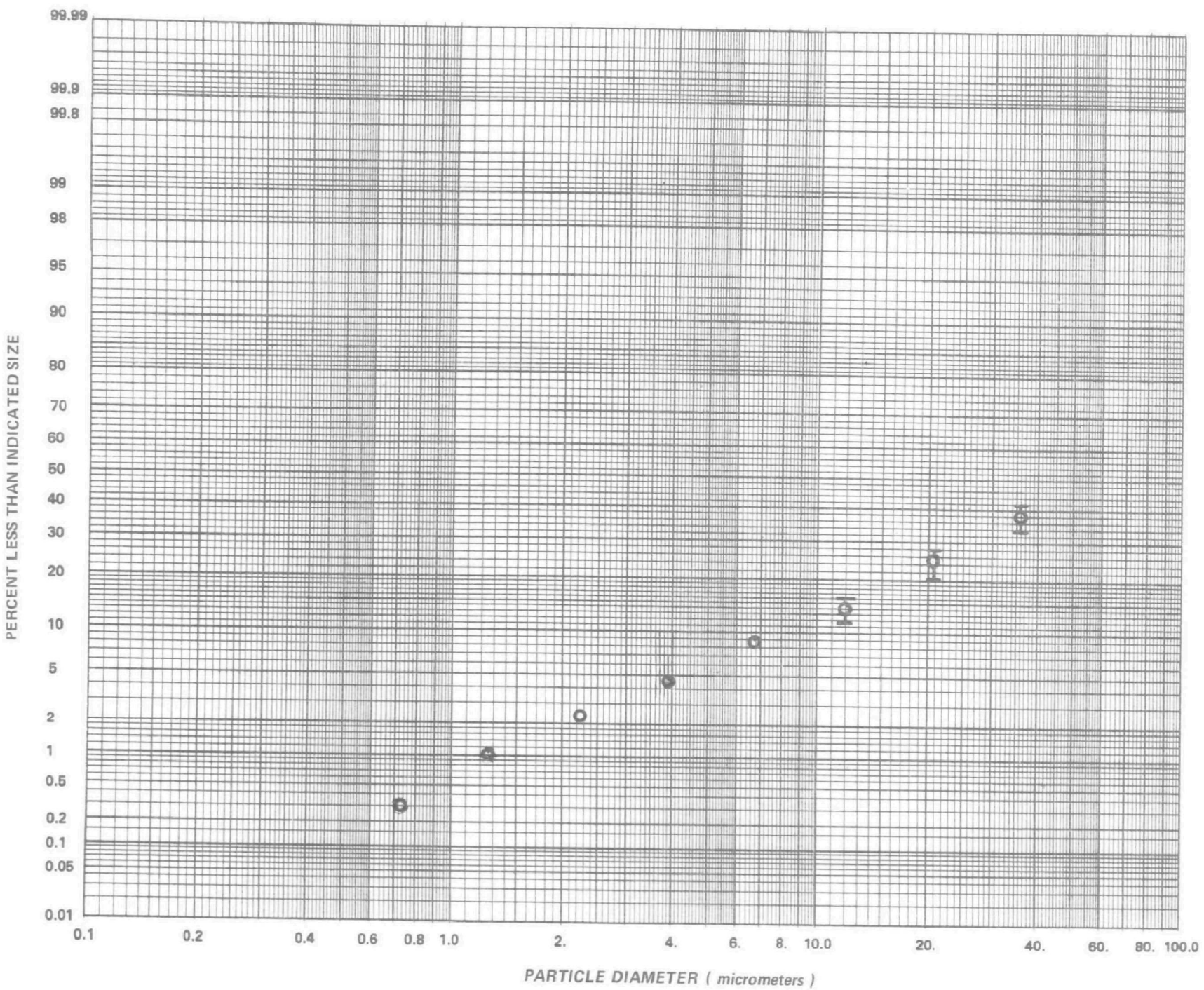


Figure 3. Average Inlet Size Distribution (Cumulative Percent) for May 18-21, 1976 with 90% Confidence Intervals

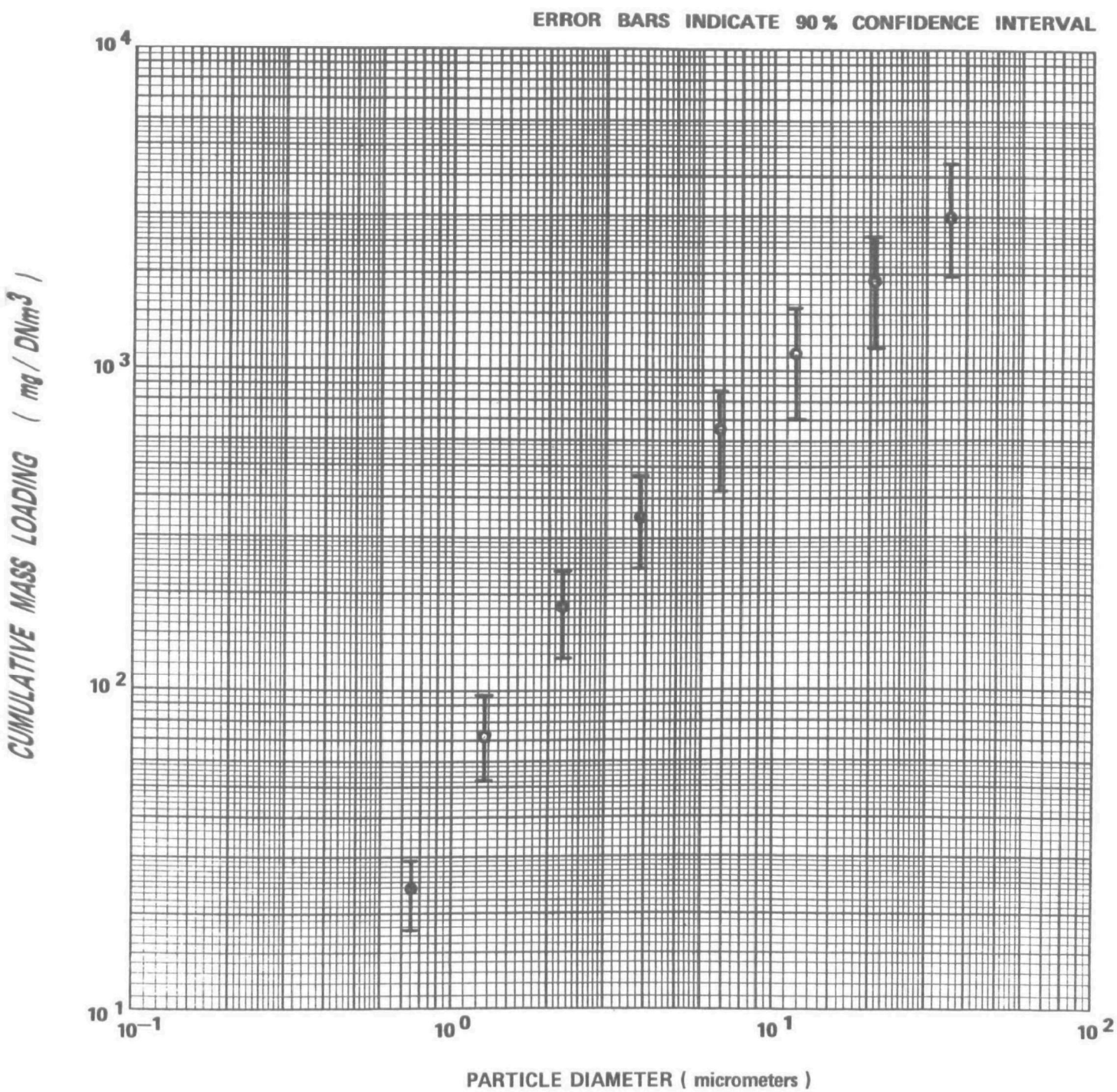


Figure 4. Average Inlet Size Distribution (Cumulative Mass)  
for May 18-21, 1976 with 90% Confidence Intervals

co-ordinates and in terms of cumulative mass loading for the time period May 18-21. Figures 5 and 6 are similar presentations of the size distribution obtained on May 19 at the outlet of the precipitator. The cumulative percent distribution is based on the total outlet mass loading obtained with the impactor ( $35.45 \text{ mg/DNm}^3$ ). Because of the almost 10 meter (32.8 feet) depth of the outlet duct work, full traverses were impractical. Therefore, single point sampling was performed at a depth of 2.4 meters (7.8 feet). This single point outlet size distribution, together with the average of the size distributions obtained on May 18-21, were used to compute the fractional collection efficiencies shown in Figure 7. Note that a comparison of Figure 1 and 3 shows that essentially the same inlet size distribution was obtained for the March and May test series. The data from Figure 4 were used in the computer model projections, which will be discussed in a subsequent section.

#### B. Mass Train Results

Inlet and outlet mass loadings for the baseline test were determined by Research Cottrell using the ASME Power Test Code 27 method on March 27 and March 28. The inlet sampling location was upstream of the injection manifold (Figure 20), and outlet data were obtained in the stack. These data are given in Table 1.

Mass train data during the  $\text{SO}_3$  injection tests in May were obtained by Kin Associates, Inc. using the following methods:

(1) A modified ASME sampling train at the inlet location with an in-stack filter.

(2) A modified ASME sampling train at the stack location with an in-stack Gelman type AE glass fiber filter.

(3) An EPA Method 5 sampling train at the stack. Four tests were conducted with this equipment, but only one data set was considered useful due to problems with the precipitator or the  $\text{SO}_3$  injection system. The tests were designated as follows:

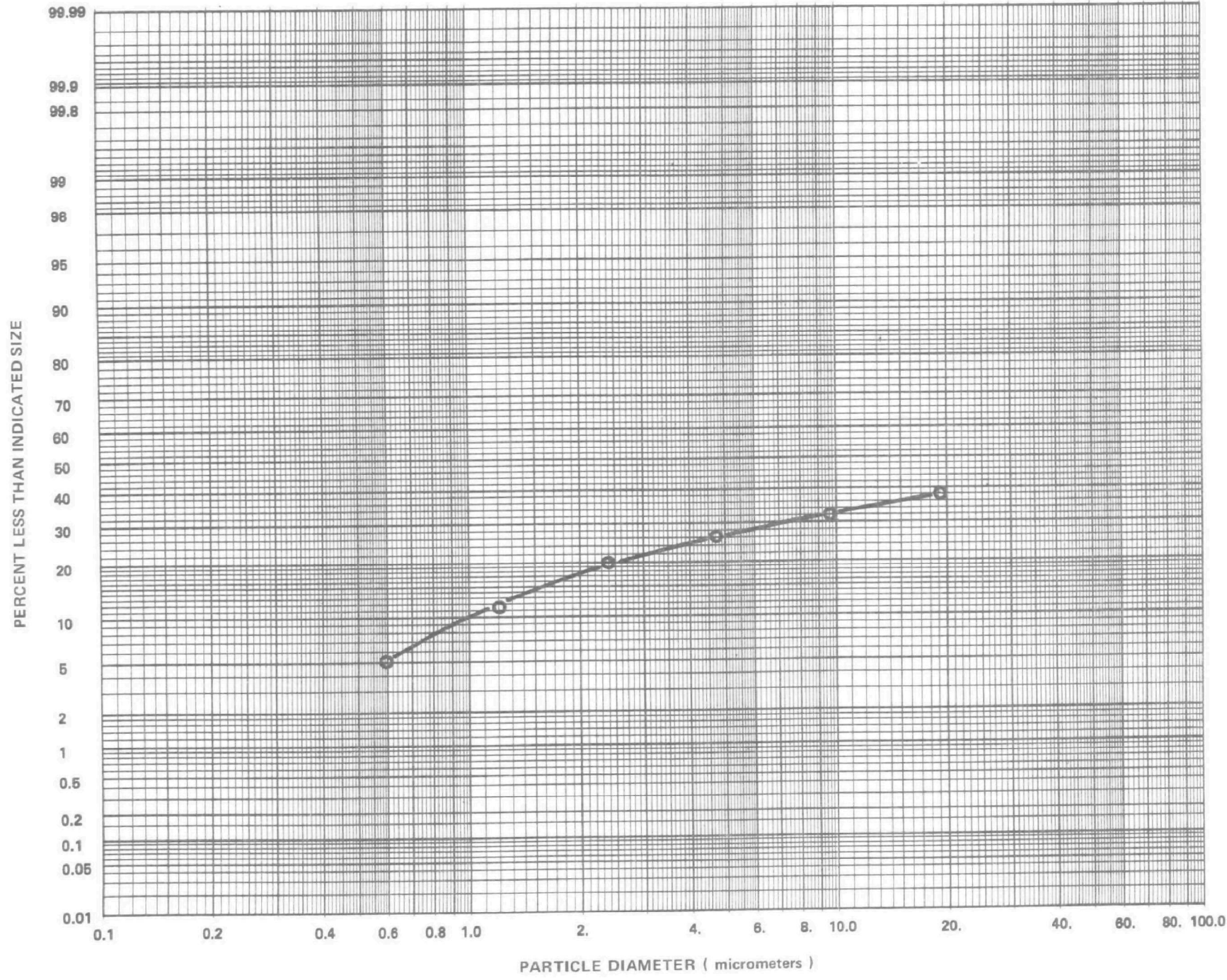


Figure 5. Outlet Size Distribution (Cumulative Percent) for May 19, 1976



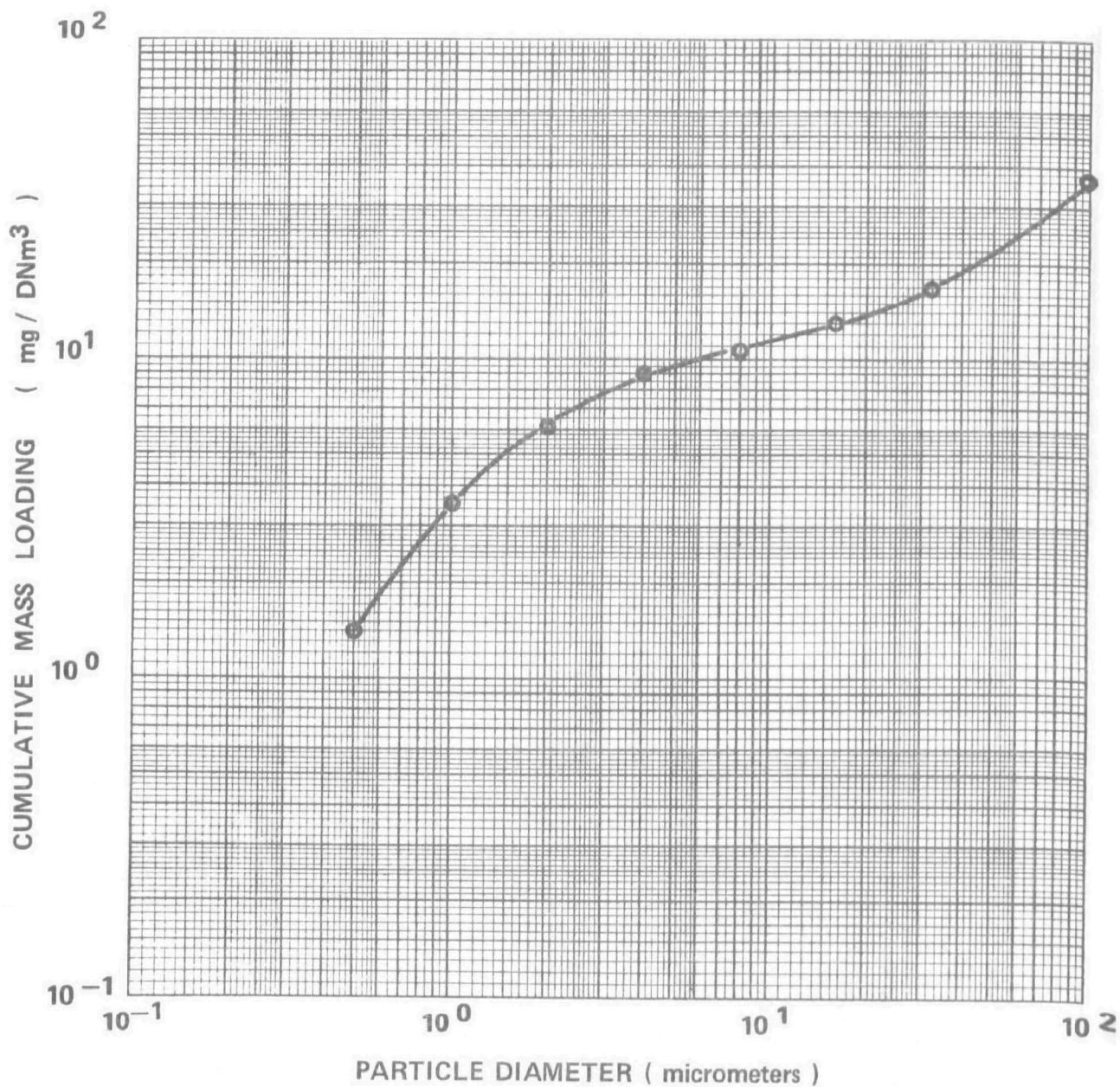


Figure 6. Outlet Size Distribution (Cumulative Mass) for May 19, 1976

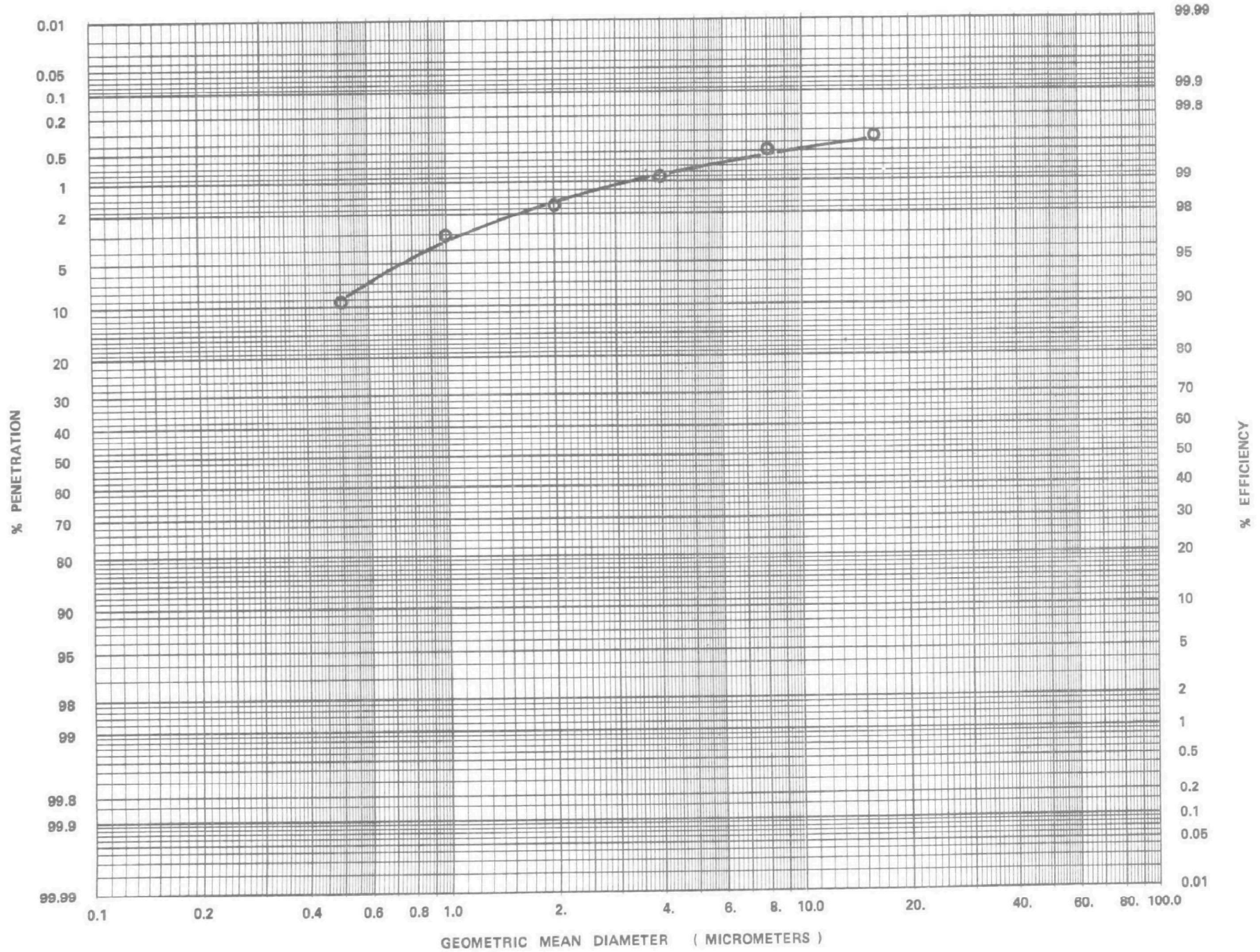


Figure 7. Fractional Efficiency for May 19, 1976  
(Based on single outlet sampling point)

Table 1. Mass Train Results Reported by Research Cottrell

Date	Boiler Load MW	Temperature, °C (°F)		Gas Volume, m <sup>3</sup> /sec (ACFM)		Dust Concentration gm/m <sup>3</sup> (gr/ACF)		Efficiency %	Specific Collecting <sup>1</sup> Area m <sup>2</sup> /(m <sup>3</sup> /sec) (ft <sup>2</sup> /1000 ACFM)
		In	Out	In	Out	In	Out		
3-27	299	107 (224)	96 (204)	417 (833,000)	585 (1,240,000)	6.32 (2.76)	0.482 (0.21)	92.4	34.02 (173)
3-28 <sup>2</sup>	299	111 (231)	93 (199)	349 (740,000)	386 (819,000)	6.04 (2.64)	0.593 (0.259)	90.2	51.6 (262)

---

1. Based on outlet flow rates

2. Gas flow appears inconsistent with boiler load.

<u>Date</u>	<u>Test No.</u>	<u>Description</u>
5/19/76	2-1	SO <sub>2</sub> converter temperature fell; SO <sub>3</sub> injection rate uncertain
5/19/76	2-2	Normal test
5/20/76	2-3	Interrupted due to TR set failure
5/21/76	2-4	Interrupted due to TR set failure

Table 2 summarizes the data obtained by Kin Associates on May 19. The dissolved solids in the first impinger were obtained to determine whether any SO<sub>3</sub> remaining in the gas phase at the stack would appear in the residue after evaporation of the liquid. The results in Table 2 indicate that the outlet mass loading is increased about 18% if the impinger solids are included. Chemical analyses of the impinger wash were also conducted, and these results are discussed in a subsequent section.

It is of interest to compare the mass loadings obtained with the mass trains in the stack with that obtained from the single point measurement with the Andersen impactor at the precipitator outlet. The Andersen impactor obtained a mass loading of 0.0227 gm/m<sup>3</sup> (.00992 gr/ACF) which is only 32% of the results indicated by the EPA train without inclusion of the impinger. Thus, the fractional efficiencies plotted in Figure 7 are not representative of the overall precipitator performance. It is probable that most of the relatively large particles resulting from rapping reentrainment are concentrated near the bottom of the duct and were, therefore, not captured by the impactor. The data in Figure 7 should, however, provide a reasonably accurate representation of sub-two micron collection efficiencies. Similarly, the total mass loadings obtained with the limited impactor traverses at the inlet will show significant disagreement with the mass train results, but the smaller size fractions should be represented with sufficient accuracy for use as input data to the precipitator computer model.

A comparison of the ASME-derived mass loadings and precipitator efficiencies in Tables 1 and 2 shows that, for the brief period when



Table 2. Mass Train Results Reported by Kin Associates

Date	Boiler load MW	Temperature, °C (°F)		Gas Volume m <sup>3</sup> /sec (ACFM)		Dust Concentration gm/m <sup>3</sup> (gr/ACF)				Efficiency, %	Specific Collecting Area m <sup>2</sup> /(m <sup>3</sup> /sec) (ft <sup>2</sup> /1000 ACFM)	Test No.	
		In	Out	In	Out	In	Out						
							ASME	EPA	EPA & First Impinger				
5-19	303	129 (264)	122 (252)	557 (1,180,000)	476 (1,009,000)	6.85 (2.99)	0.0508 (0.0222)	0.0703 (0.0307)	0.0828 (0.0362)	99.27	98.96	41.82 (212)	2-2

normal precipitator operation was possible, the precipitator performance was increased to the extent that outlet mass concentrations decreased by about a factor of ten as a result of the SO<sub>3</sub> injection. This increase in efficiency is consistent with the improvement in power supply performance and the decrease in dust resistivity, as discussed below.

### C. Resistivity Measurements

In situ resistivity data were obtained with a point-plane probe<sup>1</sup> during both the baseline and SO<sub>3</sub> injection test series. These data are given in Table 3, and it is apparent that dust resistivity during the SO<sub>3</sub> injection tests is about two decades lower than it was during the baseline series. The data in Table 3 are obtained with parallel plate cell geometry with an applied electric field slightly lower than the value which is sufficient to cause spark-over. It is also possible to obtain resistivity data from the voltage-current characteristics of the apparatus with and without dust on the collecting electrode as illustrated in Figure 8. The collecting area of the measurement cell is 5 cm<sup>2</sup>, and resistivity may be calculated from the dust layer thickness 0.09 cm, the voltage difference between the "clean" and "dirty" voltage-current curves (5600 volts), a selected current (0.5 x 10<sup>-6</sup>A), and the cell area. Thus,

$$\rho = \frac{(5600V)(5\text{cm}^2)}{(0.5 \times 10^{-6}\text{A})0.09 \text{ cm}} = 6.2 \times 10^{11} \text{ ohm-cm}$$

at an applied field strength of 62.2 kV/cm with a current density of 100 nA/cm<sup>2</sup>. In contrast, the parallel plate data were obtained with an applied field of 16.6 kV/cm at a current density of 2 nA/cm<sup>2</sup> and the resistivity obtained under these conditions was 8.3x10<sup>12</sup> ohm-cm. The resistivity value derived from the voltage-current curves is expected to be lower than the parallel plate data under these conditions as a result of electrical breakdown (back corona) in the deposited dust layer.

Table 3. In situ Resistivity from George Neal Plant, Unit 2

Baseline Test Series (3/27/76)		SO <sub>3</sub> Injection Test Series		
Temperature °C(°F)	Resistivity ohm-cm	Temperature °C(°F)	Date	Resistivity, ohm-cm
110(230)	$8.3 \times 10^{12}$	127(261)	5/17/76	$4.4 \times 10^{10}$
118(244)	$5.7 \times 10^{12}$	132(270)	5/19/76	$3.1 \times 10^{10}$
118(244)	$5.9 \times 10^{12}$	138(280)	5/19/76	$1.0 \times 10^{11}$
121(250)	$6.8 \times 10^{12}$	142(288)	5/19/76	$4.1 \times 10^{10}$
		143(289)	5/20/76	$3.5 \times 10^{10}$
		143(289)	5/20/76	$4.1 \times 10^{10}$

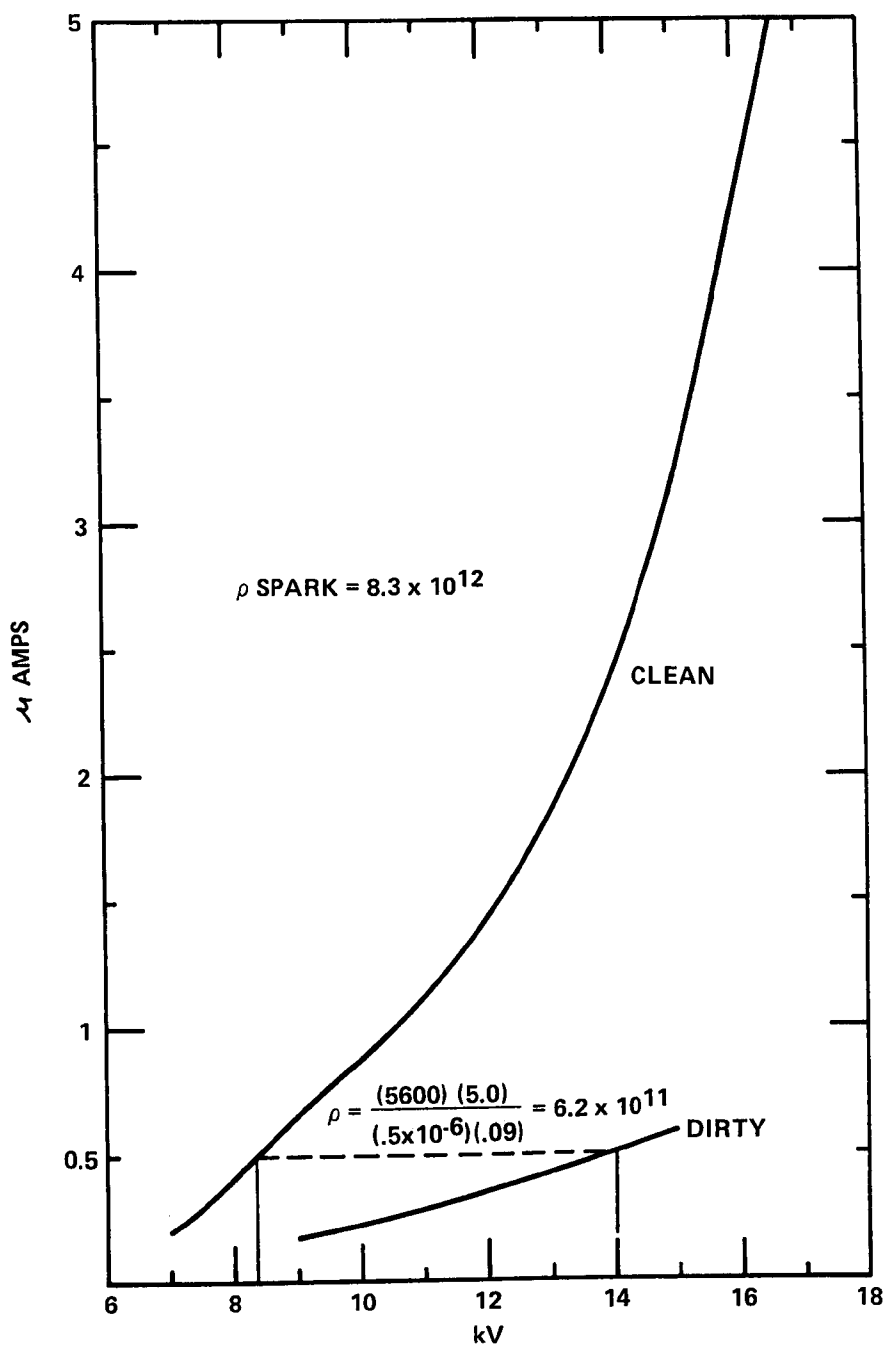


Figure 8. Resistivity Probe Voltage-Current Characteristics without  $\text{SO}_3$  Injection

Figure 9 shows the resistivity probe voltage-current relationships with  $\text{SO}_3$  injection. Note that the resistivity derived from the voltage-current curve at  $100 \text{ nA/cm}^2$  is higher than the parallel plate data because, with the relatively low dust resistivity, electrical breakdown is not occurring in the deposited dust layer at this current density. In general, the parallel plate data are considered more reliable than that derived from the voltage-current curves.

#### D. Voltage-Current Characteristics of the Precipitator

Figure 10 illustrates the arrangement of the transformer-rectifier sets on the precipitator. The power supplies are not equipped with secondary voltage meters, and therefore voltage divider resistors were attached to selected TR sets for the purpose of obtaining secondary voltage readings. Figures 11 through 14 present the secondary voltage-current relationships for the indicated TR sets obtained during the baseline test on March 27. These curves indicate that back corona and/or severe sparking occur at low values of current density, which is indicative of high dust resistivity. Note that the automatic operating point location is such that much of the power input is not useful power for the precipitation process. Figures 15 and 16 show the secondary voltage-current relationships for TR sets 3 and 8 with  $\text{SO}_3$  injection on May 21. The shape of these curves, in contrast to Figures 11, 12, 13, and 14, indicates that dust resistivity is not limiting the electrical operating conditions. This conclusion is consistent with the in situ resistivity measurements. However, as stated previously, TR sets were tripping out during this test series due to dust removal problems. Average electrical readings from the panel meters for March 27 and for May 19 are given in Tables 4 and 5, respectively.

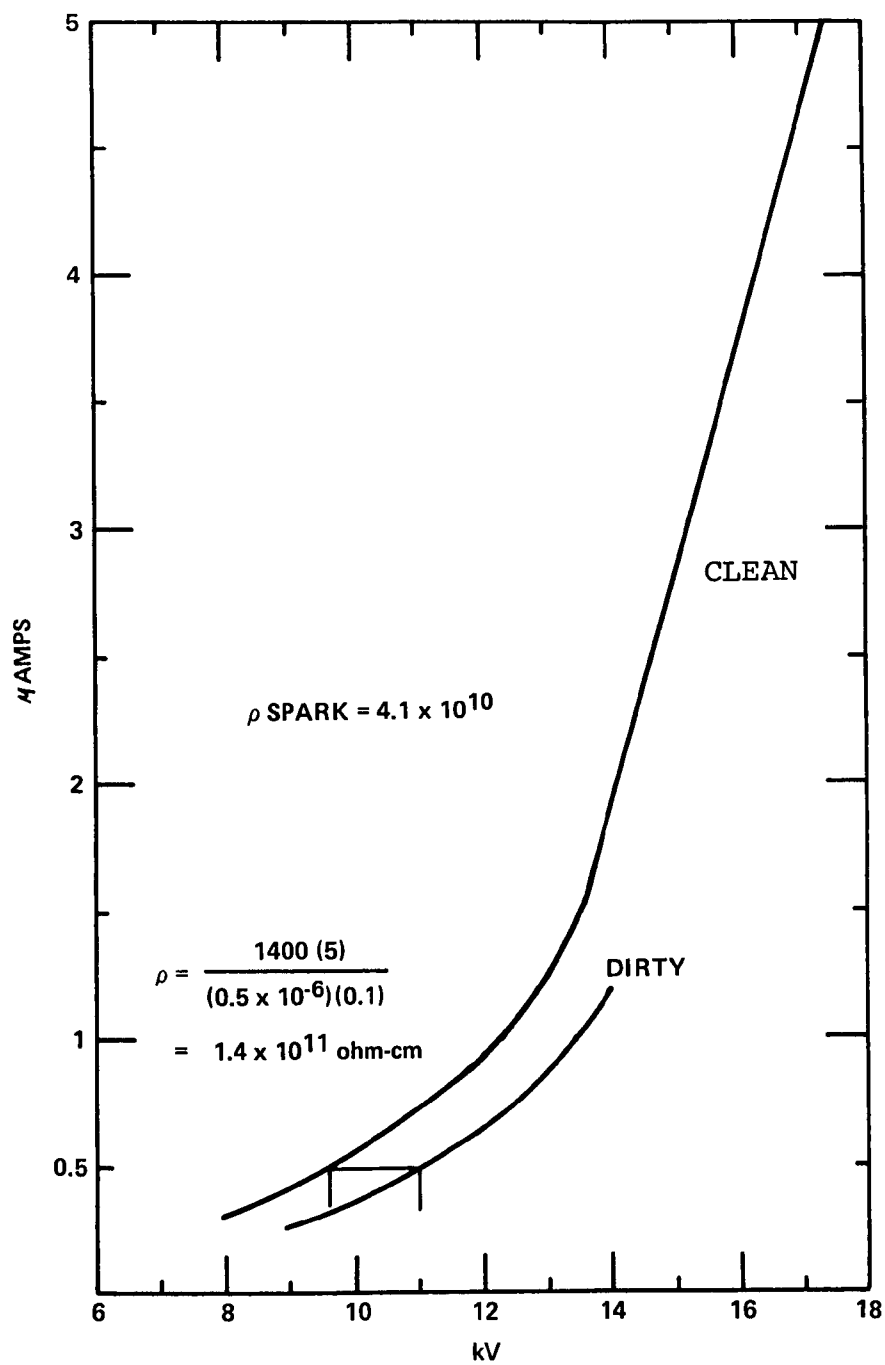


Figure 9. Resistivity Probe Voltage-Current Characteristics with  $\text{SO}_3$  Injection

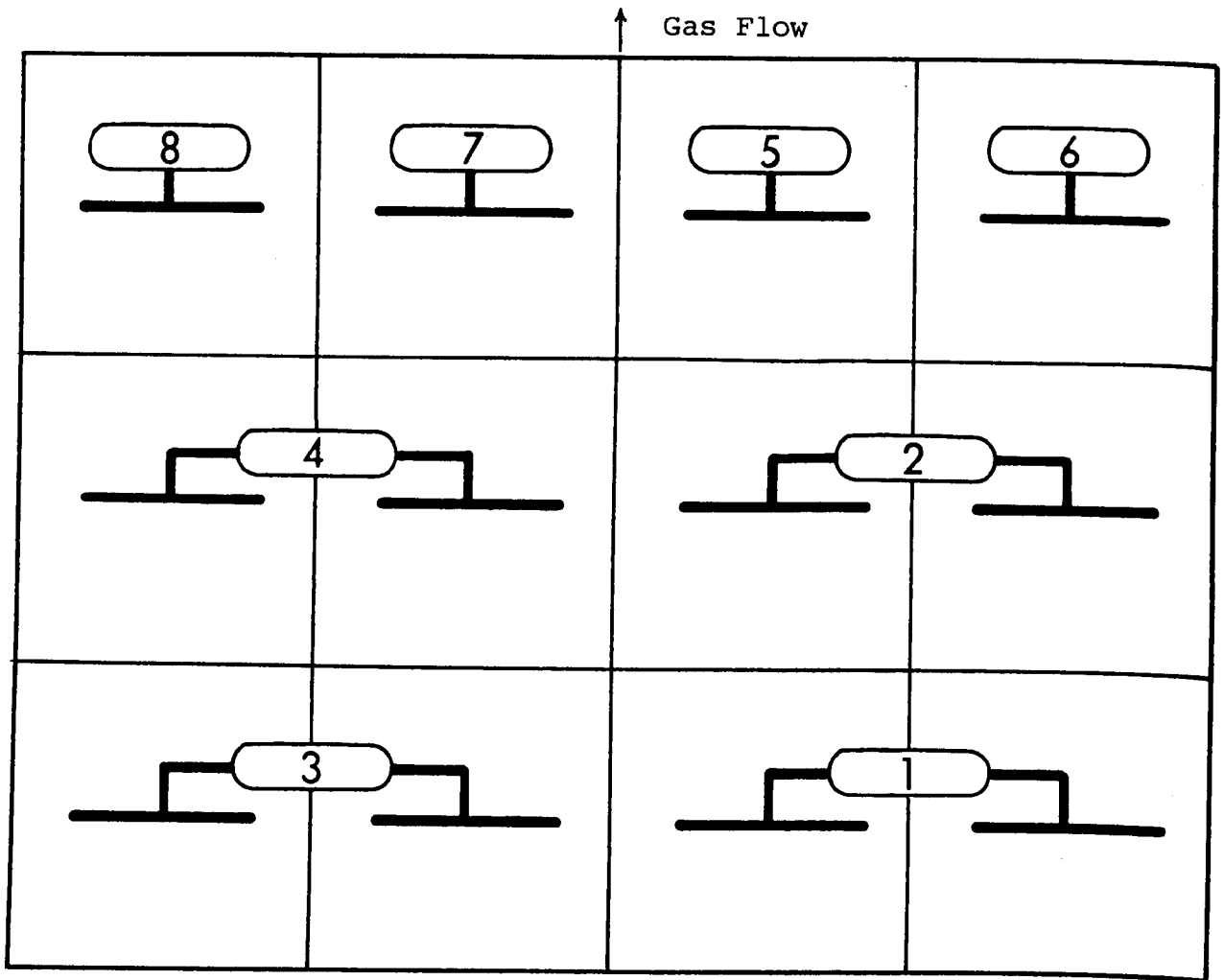


Figure 10. Arrangement of Transformer Rectifier Sets for George Neal Unit 2

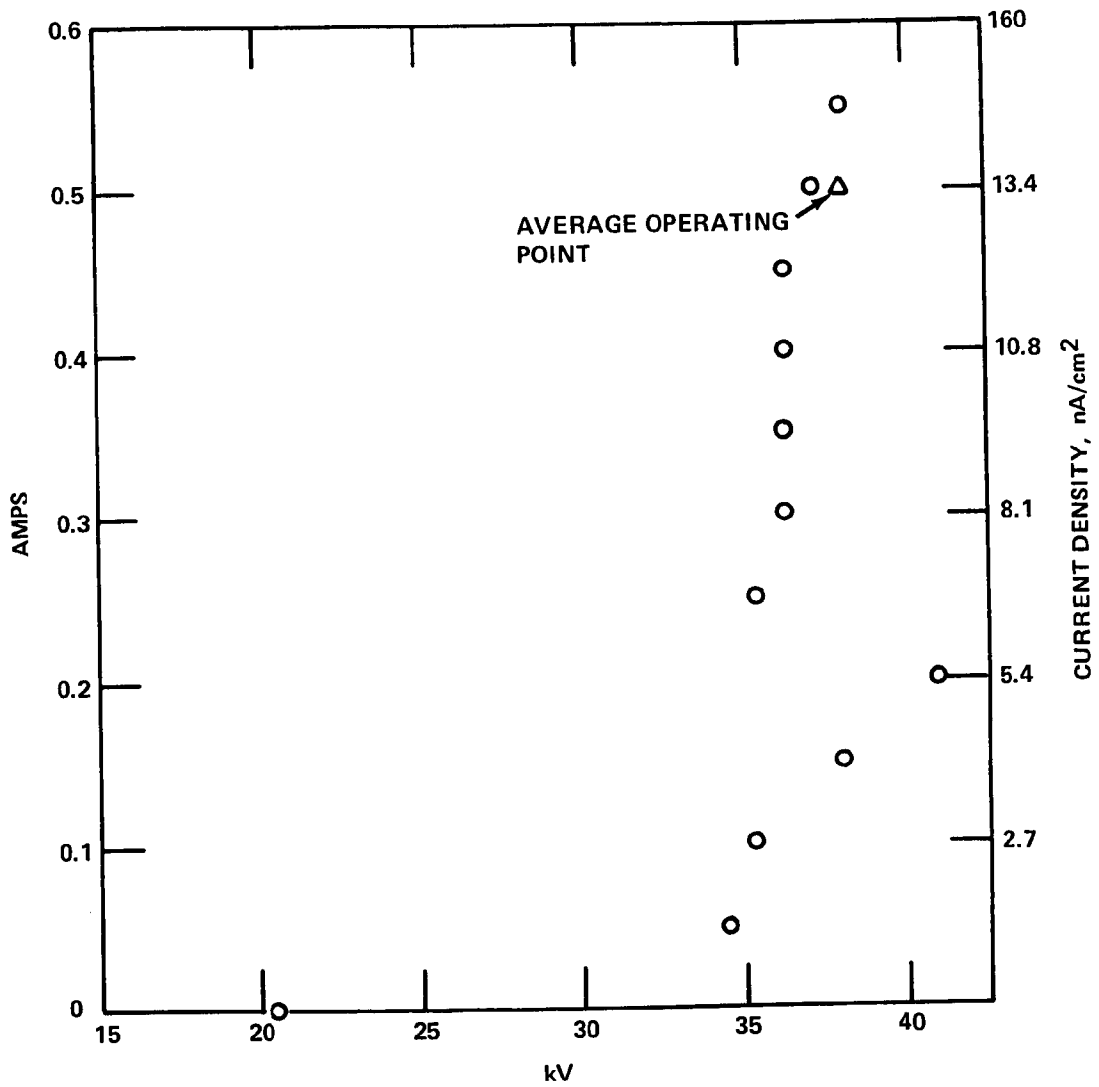


Figure 11. V-I Characteristics for TR Set 3 on March 27, 1976



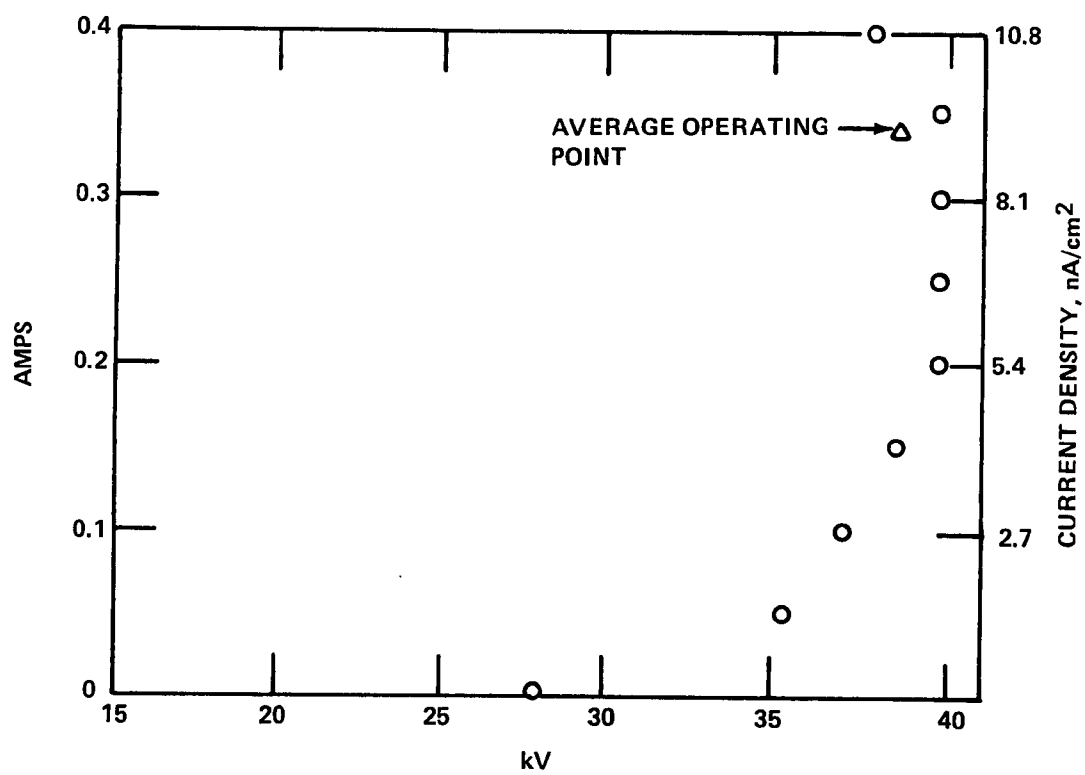


Figure 12. V-I Characteristics for TR Set 4 on March 27, 1976

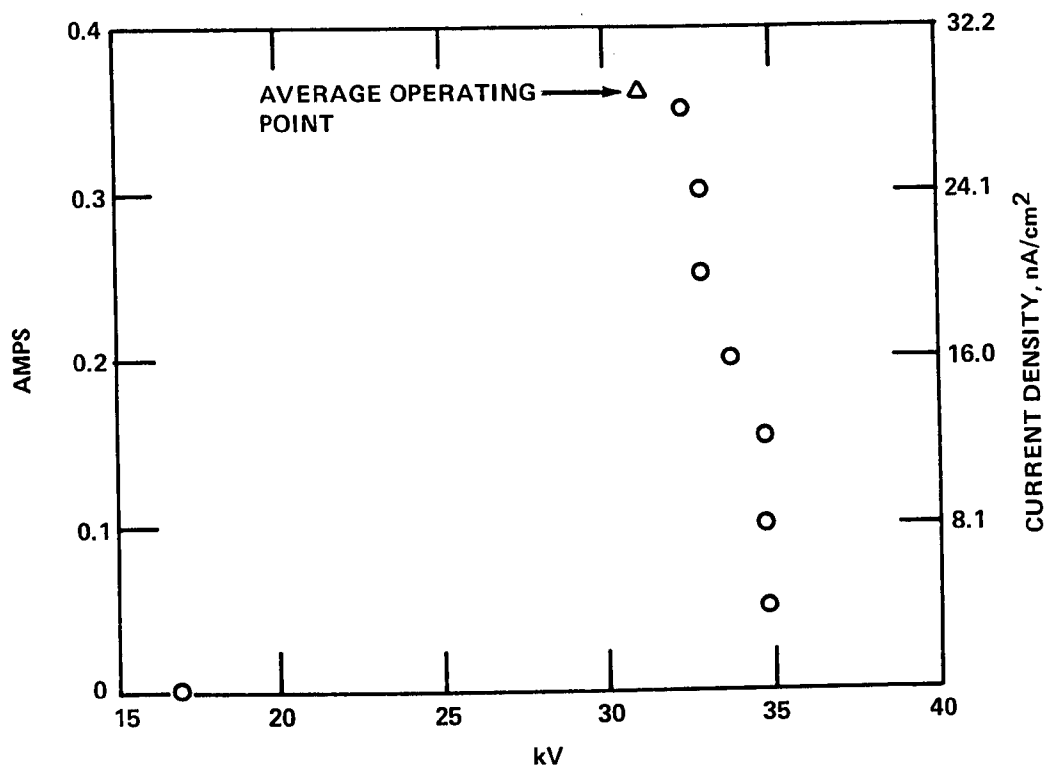


Figure 13. V-I Characteristics for TR Set 7 on March 27, 1976

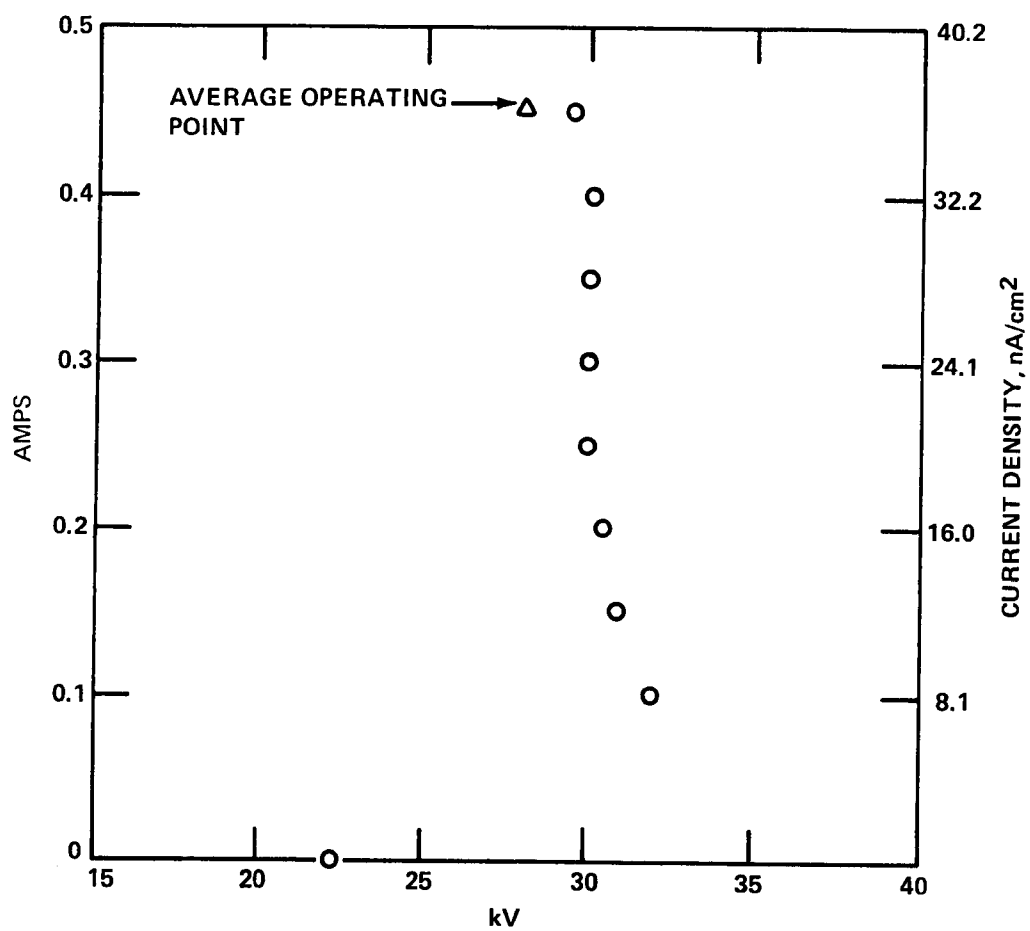


Figure 14. V-I Characteristics for TR Set 8 on March 27, 1976

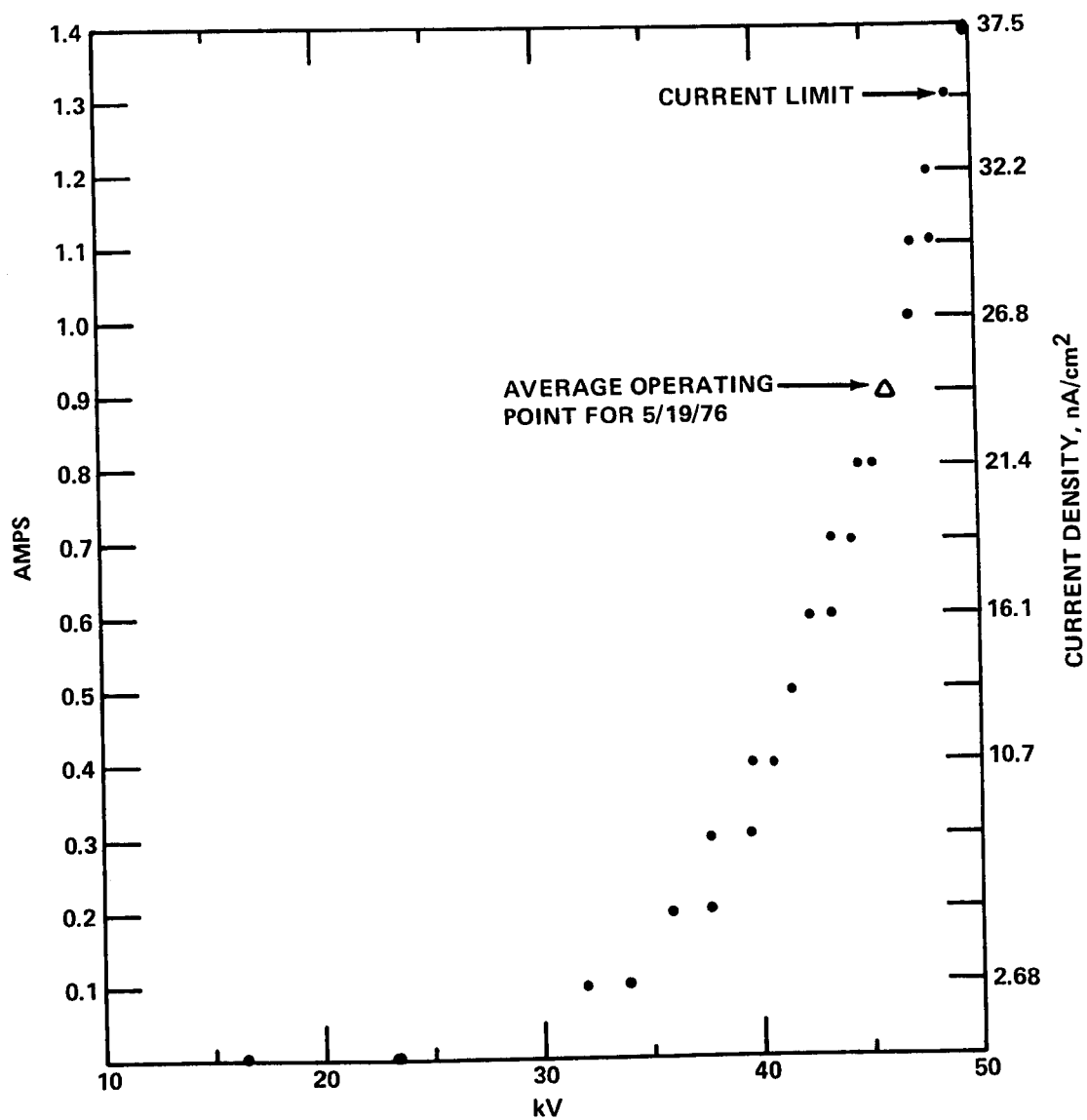


Figure 15. V-I Characteristics for TR Set 3 on May 21, 1976

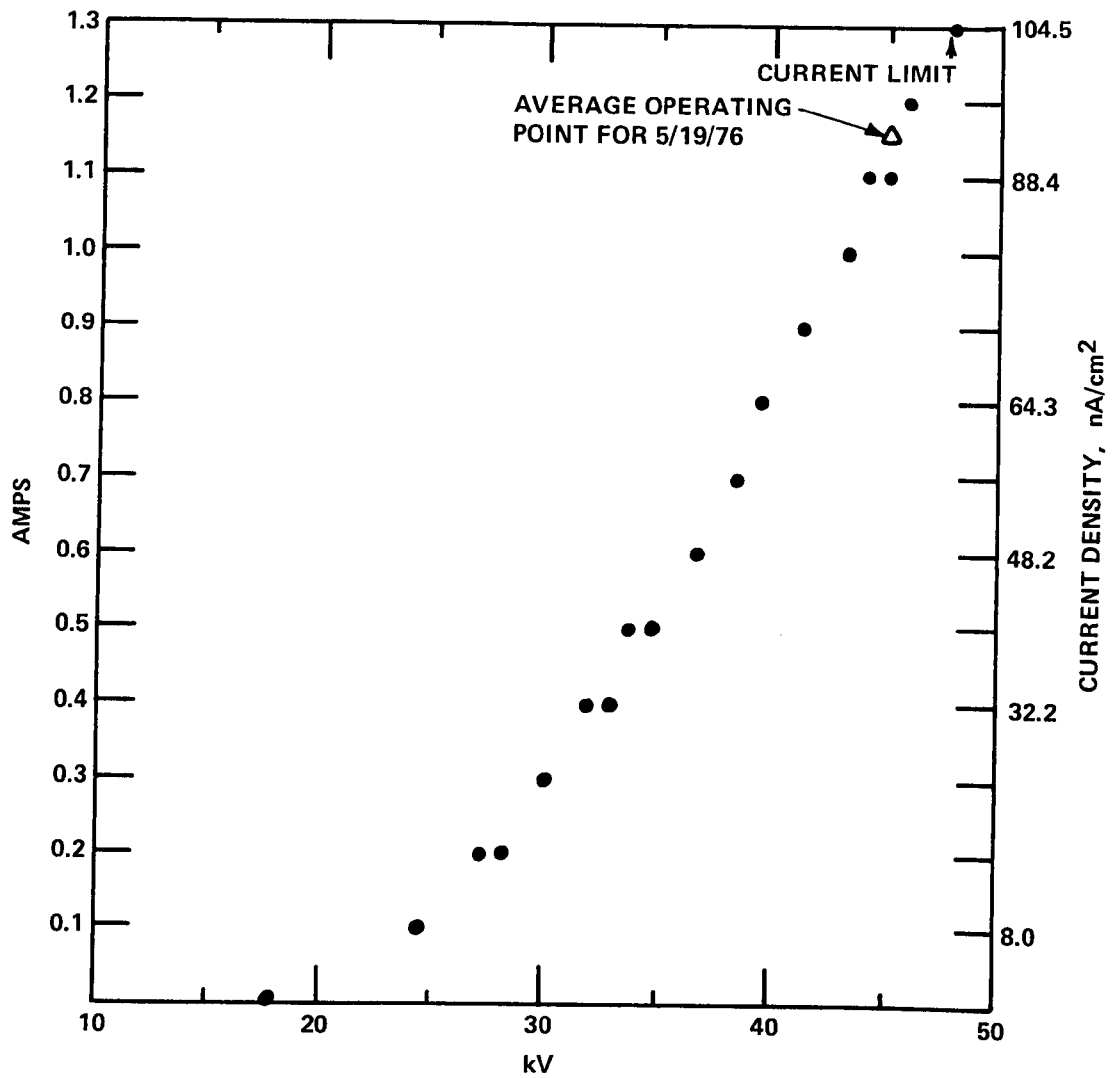


Figure 16. V-I Characteristics for TR Set 8 on May 21, 1976

Table 4. George Neal - Unit 2  
Average voltages and currents for 3/27/76

<u>TR#<sup>1</sup></u>	<u>Primary amps</u>	<u>Primary volts</u>	<u>Secondary amps</u>	<u>Current Density nA/cm<sup>2</sup></u>
7	76	213	0.36	29.0
8	93	230	0.45	36.2
4	80	205	0.34	9.2
3	105	220	0.5	13.4
1	40	170	0.07	1.8
2	30 to 40	150 to 200	0.06 to 0.14	(sparking, meters swinging)
5	140	280	0.8	64.3
6	145	275	0.82	65.9 no sparking
6 <sup>2</sup>	110	225	0.43	34.6 sparking

---

1. TRs 1, 2, 3, and 4 each have 40,176 ft<sup>2</sup> collecting surface.  
TRs 5, 6, 7, and 8 each have 13, 392 ft<sup>2</sup> collecting surface,  
for 214,272 ft<sup>2</sup> total.

2. Average readings during sparking.

Table 5. Average voltages and currents for 5/17/76

<u>TR No.</u>	<u>Primary Amps</u>	<u>Primary volts</u>	<u>Secondary amps</u>	<u>Current Density nA/cm<sup>2</sup></u>
7 <sup>1</sup>	86.1	215	.474	38.1
8	191	346	1.156	92.9
4	199	295	1.137	30.5
3	164	328	.917	24.6
1	137	306	.728	19.5
2	220	312	1.397	37.4
5	195	353	1.234	99.2
6	193	349	1.248	100.0

---

1. Declined from 1.18 amps to 0.15 amps at end of day.

## E. Chemical Analyses

### 1. Coal

Ultimate analyses of four coal samples (one collected during the baseline test and three during the conditioning tests) are given for the "as received" condition in Table 6. The data show a reasonable degree of uniformity, as desired. The aspect of the coal composition that is of primary interest is the sulfur concentration, which is around 0.6% by weight.

### 2. Flue gases

The vapors of  $\text{SO}_2$  and  $\text{H}_2\text{SO}_4$  were determined with a sampling train in which the  $\text{H}_2\text{SO}_4$  was first condensed around  $70^\circ\text{C}$  ( $160^\circ\text{F}$ ) and the  $\text{SO}_2$  was absorbed in a bubbler filled with aqueous  $\text{H}_2\text{O}_2$ . Each sample was titrated as dilute  $\text{H}_2\text{SO}_4$  with  $\text{Ba}(\text{ClO}_4)_2$  and Thorin as the endpoint indicator.<sup>2</sup> The concentration of  $\text{H}_2\text{O}$  vapor was determined by condensing part as the liquid and absorbing the remainder with silica gel. Concentrations of  $\text{CO}_2$  and  $\text{O}_2$  were determined by Orsat analysis.

Theoretical concentrations of  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{O}_2$ , and  $\text{SO}_2$  were computed by using the coal analysis in Table 6 and assuming the combustion air contained 2% of  $\text{H}_2\text{O}$  vapor. The percentage of excess air was not known; hence, predicted concentrations of the flue gases were displayed in a graph as functions of excess air to permit a comparison with the experimental results.

Table 7 gives the results of the experimental determinations, and Figure 17 compares these results (except for  $\text{H}_2\text{SO}_4$ ) with the computed curves for varying percentages of excess air. The data in the table indicate that during the conditioning tests the concentrations averaged 11.9%  $\text{CO}_2$ , 7.2%  $\text{H}_2\text{O}$ , 5.6%  $\text{O}_2$ , and 431 ppm  $\text{SO}_2$ . No reliable data were obtained for the first three of these gases during the baseline test; however, the somewhat higher result for  $\text{SO}_2$  during the baseline test indicates that a lower excess air level was used during this test. The data for  $\text{H}_2\text{SO}_4$  were higher



Table 6. Ultimate Analyses of Coal Samples

	<u>Baseline Test</u>	<u>Conditioning Tests</u>			
	<u>3/27</u>	<u>5/19N</u>	<u>5/19PM</u>	<u>5/21N</u>	<u>Average</u>
Moisture <sup>1</sup>	6.86	6.28	5.91	5.89	6.03
Carbon	60.83	62.24	59.72	60.89	60.96
Hydrogen <sup>2</sup>	4.88	5.56	4.60	4.37	4.84
Nitrogen	1.26	0.65	0.88	1.26	0.93
Sulfur	0.66	0.57	0.61	0.57	0.57
Ash	10.45	10.66	13.84	11.52	12.00
Oxygen <sup>2</sup>	15.06	14.05	14.44	15.50	14.67
Btu/lb	10,949	11,047	10,579	11,008	10,878

---

<sup>1</sup>Determined by air drying.

<sup>2</sup>Elements assumed to be present as chemically-bound water (all of the oxygen and an equivalent amount of the hydrogen - less than the total of hydrogen, of course).

Table 7. Analyses of Flue Gas

Sampling Conditions	Baseline Test	Conditioning Tests					
Date	3/27	5/19	5/19	5/20	5/20	5/21	5/21
Location	Inlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
Temperature, °F	250	265	250	285	250	285	250
°C	121	129	121	141	121	141	121
Flue-gas Concentration							
CO <sub>2</sub> , %	---	11.7	11.6	11.2	11.0	12.9	12.9
O <sub>2</sub> , %	---	6.0	6.0	6.3	6.2	4.6	4.5
H <sub>2</sub> O, %	---	6.6	7.6	6.7	8.1	7.1	7.3
SO <sub>2</sub> , ppm	521	473	419	446	391	428	----
H <sub>2</sub> SO <sub>4</sub> , ppm	0.4	1.2	0.9	10.6	0.6	8.0	----

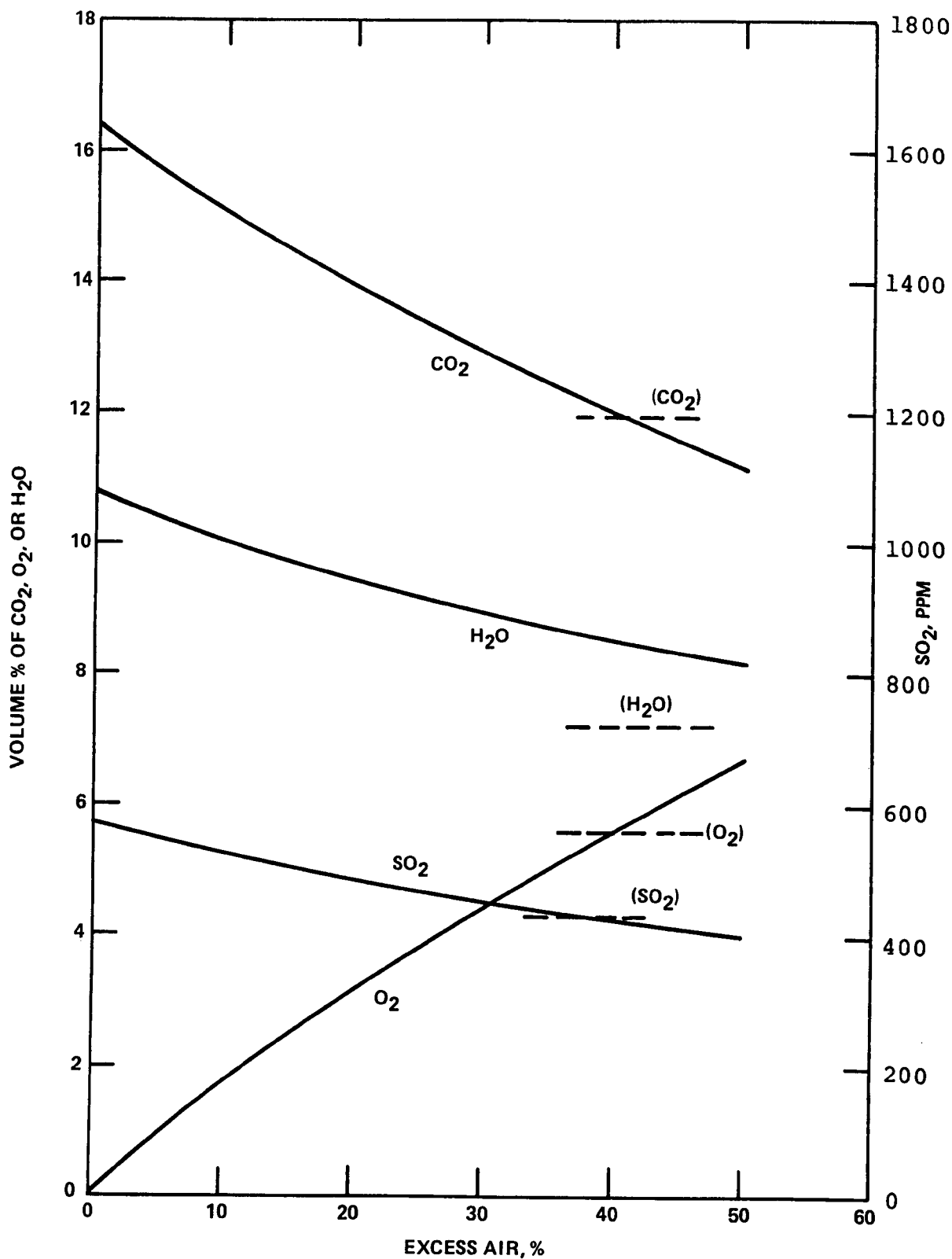


Figure 17. Comparison of Predicted Gas Concentrations (Functions of Excess Air) with Observed Concentrations (Displayed by Dashed Horizontal Lines)

during conditioning as expected; no average of these data is meaningful, however, because of the variation in the sampling temperature (a point later discussed in greater detail).

The comparison of observed and predicted concentrations in Figure 17 shows the experimental results lying on the predicted curves at excess air levels as follows:  $O_2$ , 40% excess air;  $H_2O$ , >50% excess;  $CO_2$ , 42% excess; and  $SO_2$ , 38% excess. These comparisons lead to two observations: (1) the experimental concentrations of  $CO_2$ ,  $O_2$ , and  $SO_2$  are consistent with the same excess air level (about 40%) but (2) the concentration of  $H_2O$  indicates a considerably higher air level and is thus probably lower than the true value (the estimated true concentration of  $H_2O$  is about 8.5%).

### 3. Fly ash

#### a. Overall oxide composition

Samples of fly ash were collected from selected hopper locations under the precipitator to be analyzed for overall composition as expressed by oxide concentrations. The configuration of the hopper system is shown in Figure 18. The hoppers used in sampling during the baseline test were Nos. 16 (inlet row) and 8 (outlet row); those used in the conditioning tests were Nos. 17 (inlet) and 9 (outlet). All of the samples were thus taken from hoppers adjacent to the midline of the precipitator.

For each inlet and outlet sample taken at a given time, a composite was prepared to represent the appropriate amounts from each source. The ratio of inlet sample to outlet sample in the composite was 3.6:1.0 for the baseline test or 10.0:1.0 for the conditioning tests.

The appropriate ratios were computed by assuming that for each test mode (with conditioning or without) the effective migration velocity  $w$  in the Deutsch equation was constant through the precipitator from inlet to outlet. In view of the fact that the electrode area over the inlet hoppers is one-half of the total, equations involving the total precipitation efficiency  $E_t$  and the inlet

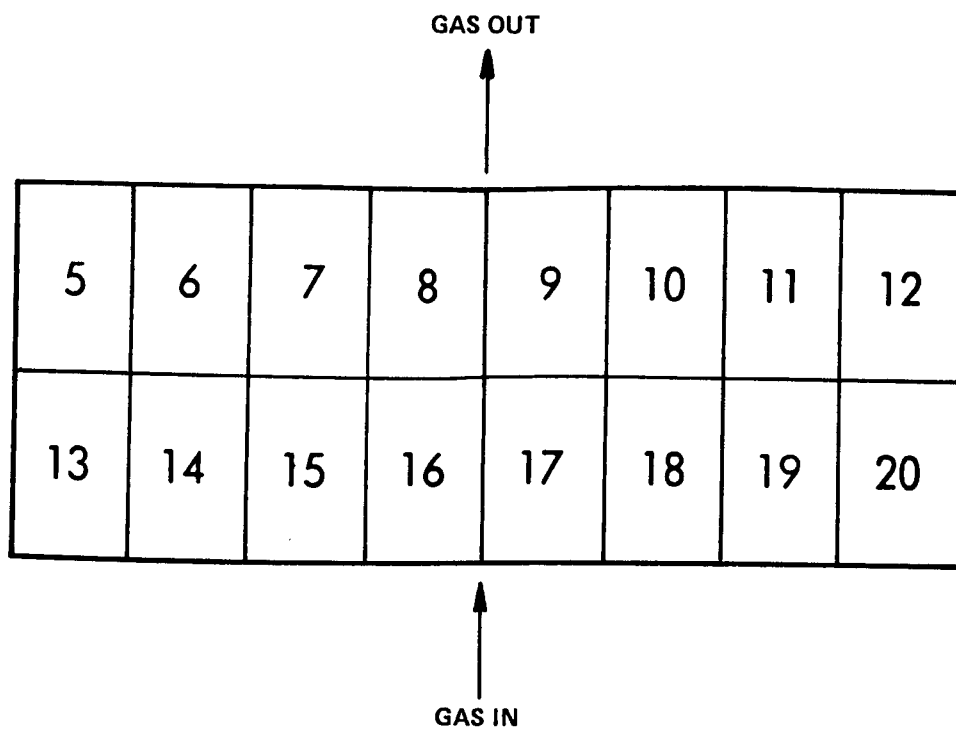


Figure 18. Hopper Configuration for the Precipitator

precipitation efficiency  $E_i$  can be written in terms of the respective electrode areas  $A_t$  and  $A_i$  as follows:

$$\begin{aligned}\ln(1 - E_t) &= -A_t w/V \\ \ln(1 - E_i) &= -A_i w/V \\ &= -0.5 A_t w/V \\ &= 0.5 \ln(1 - E_t)\end{aligned}$$

Therefore,

$$\begin{aligned}1 - E_i &= (1 - E_t)^{0.5} \\ E_i &= 1 - (1 - E_t)^{0.5}\end{aligned}$$

The fractions of ash received by the inlet and outlet hoppers, respectively, are  $E_i$  and  $(E_t - E_i)$ . Hence, the ratio of masses is given by

$$\frac{\text{Inlet mass}}{\text{Outlet mass}} = \frac{E_i}{E_t - E_i} = \frac{1 - (1 - E_t)^{0.5}}{E_t - 1 + (1 - E_t)^{0.5}}$$

With  $E_t$  taken as 0.924 for the baseline test, the computed mass ratio is 3.6. Similarly, with  $E_t$  taken as 0.990 for the conditioning tests, the result is 10.0.

A portion of each composite sample was ignited to determine the weight loss during ignition and then it was divided into three final fractions that were separately dissolved in (a) a mixture of HF and  $H_2SO_4$ , (b) fused NaOH, and (c) fused  $Na_2CO_3$ . The fraction dissolved by acid was analyzed for Li, Na, K, Mg, Ca, Fe, and Ti by atomic absorption spectroscopy and for P by a colorimetric procedure. The fraction dissolved in fused NaOH was analyzed colorimetrically for Al and Si, and the fraction dissolved in fused carbonate was used for turbidimetric determination of S as  $SO_3$ .

The results of the analyses expressed as oxide weight percentages are given in Table 8. These data indicate that the major difference (on a relative basis) in the samples from the baseline and conditioning tests was in %  $SO_3$ ; the difference was a gain of about 0.67% as the result of  $SO_3$  injection during the conditioning tests.

Table 8. Analyses of Hopper Ash

Component	Weight %, Baseline Test				Weight %, Conditioning Tests				
	3/27AM	3/27AM	3/27PM	Avg.	5/19AM	5/19PM	5/20	5/20	Avg.
Li <sub>2</sub> O	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Na <sub>2</sub> O	0.39	0.34	0.34	0.36	0.45	0.45	0.39	0.46	0.44
K <sub>2</sub> O	1.9	1.9	2.0	1.9	1.9	2.0	1.8	1.7	1.9
MgO	2.6	3.0	2.3	2.7	2.9	2.9	2.4	3.0	2.8
CaO	13.6	15.0	14.4	14.3	15.0	13.1	13.2	14.6	14.0
Fe <sub>2</sub> O <sub>3</sub>	6.7	6.5	6.4	6.5	5.7	5.9	5.9	6.0	5.9
Al <sub>2</sub> O <sub>3</sub>	17.9	19.6	19.5	19.0	17.9	17.9	17.2	18.3	17.8
SiO <sub>2</sub>	53.0	48.7	51.9	51.1	50.3	51.7	53.0	53.4	52.1
TiO <sub>2</sub>	1.3	1.0	0.9	1.1	0.9	0.9	0.8	1.1	0.9
P <sub>2</sub> O <sub>5</sub>	0.2	1.1	0.9	0.7	0.7	0.7	0.6	0.7	0.7
SO <sub>3</sub>	0.78	0.75	0.75	0.76	1.38	1.66	1.26	1.42	1.43
LOI	0.39	0.18	0.21	0.33	0.51	0.58	0.50	0.44	0.51

b. pH and soluble sulfate concentration

Determinations of the pH values of fly-ash slurries in distilled water and the concentrations of  $\text{SO}_4^{-2}$  dissolved in the slurries were made for ash samples from several sources: (1) precipitator hoppers, (2) cyclones used for sampling from the flue-gas ducts, and (3) filters used for sampling from the stack. For the determination of pH and soluble  $\text{SO}_4^{-2}$  values, 0.1 g of ash was mixed with 30 ml of distilled water and stirred until the pH reached a stable value. This pH value was then recorded; the liquid phase was separated from the suspended solids and analyzed for  $\text{SO}_4^{-2}$ .

(1) Hopper samples. The data for hopper samples are given in Table 9. The pH values listed are in the highly alkaline range; all are above pH 11 and show no significant variation with hopper source or with sampling conditions (with or without  $\text{SO}_3$  injection). Within the first minute or so after addition of fly ash to water, however, the samples taken during  $\text{SO}_3$  injection showed evidence of free  $\text{H}_2\text{SO}_4$  on the ash surfaces. Minima in the range pH 4-5 occurred with the conditioned samples, but such pronounced minima with unconditioned samples were not usually observed. The eventual rise in pH to values above 11 is attributed to the excess of soluble base toward the interior of the ash particles.

The data for  $\text{SO}_4^{-2}$  in ash samples taken across the inlet to the precipitator are plotted in Figure 19. Across the bottom of the horizontal axis, hopper numbers are shown to identify the locations within the precipitator where the samples originated; across the top, temperatures measured in the inlet duct upstream from the hoppers are given to show the temperature gradient resulting from the Ljungstrom air preheater. The data for two complete sets of hopper samples taken during  $\text{SO}_3$  injection are plotted and connected by line segments; averages of results for individual hopper samples taken with and without injection are also plotted.



Table 9. pH Values and Soluble  $\text{SO}_4^{-2}$  Concentrations<sup>1</sup> of Hopper Ash

Hopper No.		Baseline Test				Conditioning Tests							
		3/27 AM		3/27 PM		5/19 N		5/19 PM		5/20		5/21	
Inlet	Outlet	pH	$\text{SO}_4^{-2}$	pH	$\text{SO}_4^{-2}$	pH	$\text{SO}_4^{-2}$	pH	$\text{SO}_4^{-2}$	pH	$\text{SO}_4^{-2}$	pH	$\text{SO}_4^{-2}$
13										11.7	0.7		
	5											11.3	2.0
14										11.5	1.6		
	6											11.3	1.6
15										11.5	1.3		
	7											11.4	1.7
16		11.6	0.7	11.5	0.3					11.7	0.7		
	8	11.7	0.5	11.7	0.5							11.4	1.4
17						11.6	1.1	11.5	1.2	11.7	0.4		
	9					11.6	1.3	11.5	1.3			11.5	1.0
18										11.6	1.3		
	10											11.6	0.7
19										11.6	1.1		
	11											11.6	0.7
20										11.6	0.7		
	12											11.6	0.7

<sup>1</sup>Weight percentage

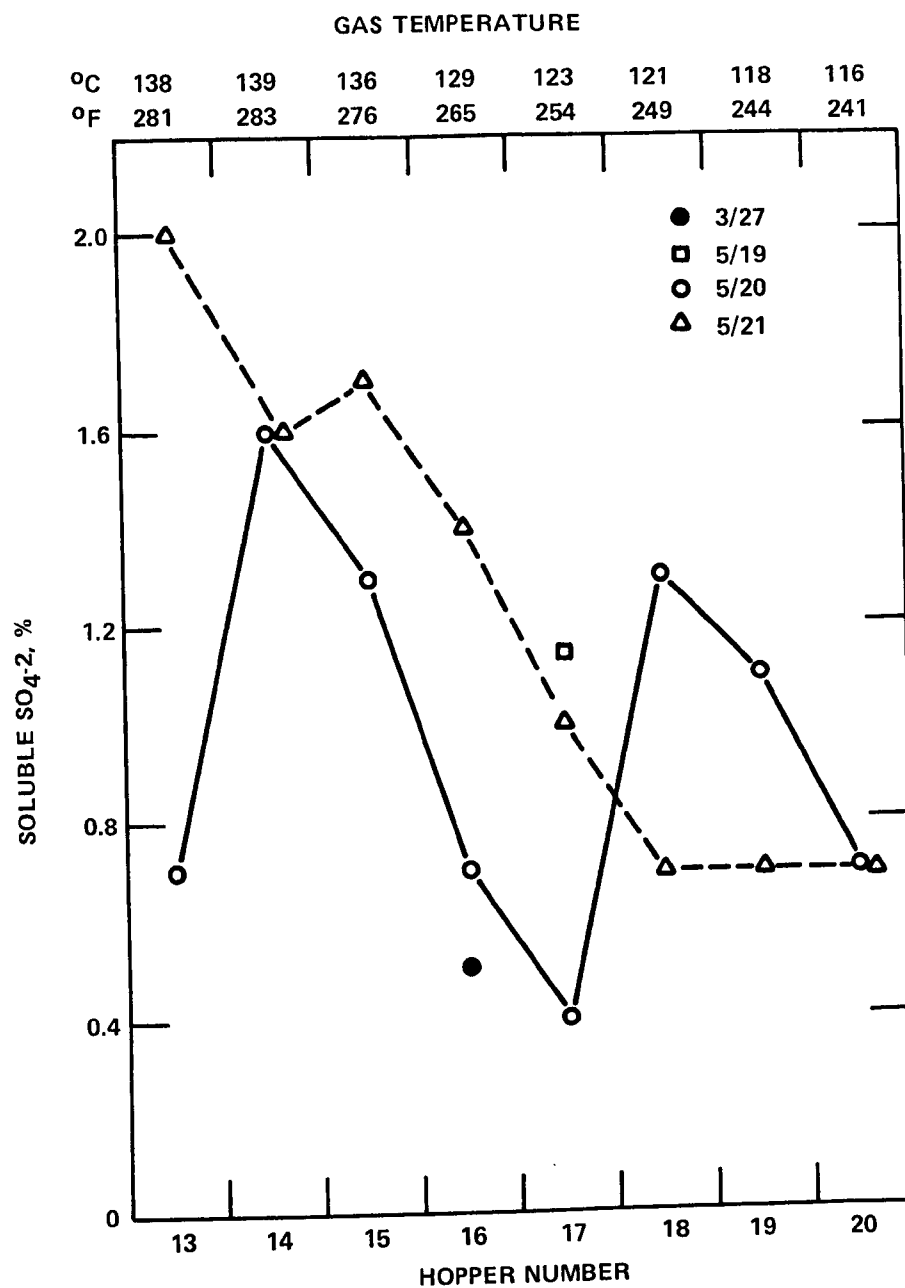


Figure 19. Soluble  $\text{SO}_4^{2-}$  in Hopper Ash as a Function of Hopper Location or Gas Temperature

The variation in  $\text{SO}_4^{-2}$  across the precipitator inlet shows an essentially continuous, downward trend with decreasing gas temperature during  $\text{SO}_3$  injection on May 21, but show no consistent trend during injection on May 20. A possible explanation of either variation is a lack of uniformity in the rate of flow of  $\text{SO}_3$  into the inlet gas duct. Another possible explanation for the more or less regular trend on May 21 is the effect of temperature. However, the observed direction of the trend (simultaneous decreases in both  $\text{SO}_4^{-2}$  and temperature) is opposite to that expected from previous data in another study of  $\text{SO}_3$  conditioning<sup>3</sup> or expected from the observed  $\text{H}_2\text{SO}_4$  concentrations in the gas phase at different temperatures (Table 7).

(2) Cyclone samples. Locations in the gas ducts where the series cyclones were used for sampling fly ash during conditioning tests are indicated in Figure 20. The numbers circled in this diagram are subsequently used to identify the different samples. It may be seen from the diagram that two samples were taken upstream from the line of  $\text{SO}_3$  injection nozzles on opposite sides of the duct at estimated temperatures of  $138^\circ\text{C}$  ( $280^\circ\text{F}$ ) and  $115^\circ\text{C}$  ( $240^\circ\text{F}$ ), another three samples were taken between the nozzles and the precipitator (again at different temperature extremes), and a final set of three samples were taken at one location in the outlet duct near the stack.

The results of determinations of pH and soluble  $\text{SO}_4^{-2}$  are given in Table 10. Data are given for each size fraction and for weighted composites of the inlet samples, but only for composites of the outlet samples (which were of such limited quantity to prevent study of each fraction).

The pH data, in general, show increasing acidity with decreasing particle size or with increasing available  $\text{SO}_3$  as the result of injection. The  $\text{SO}_4^{-2}$  data show the same effects.

The only location in the flue-gas train where cyclone samples were collected during the baseline test was at the outlet of the precipitator. A composite of different size ranges of this sample gave these results:  $\text{pH} = 10.8$ ;  $\% \text{SO}_4^{-2} = 2.6$ .

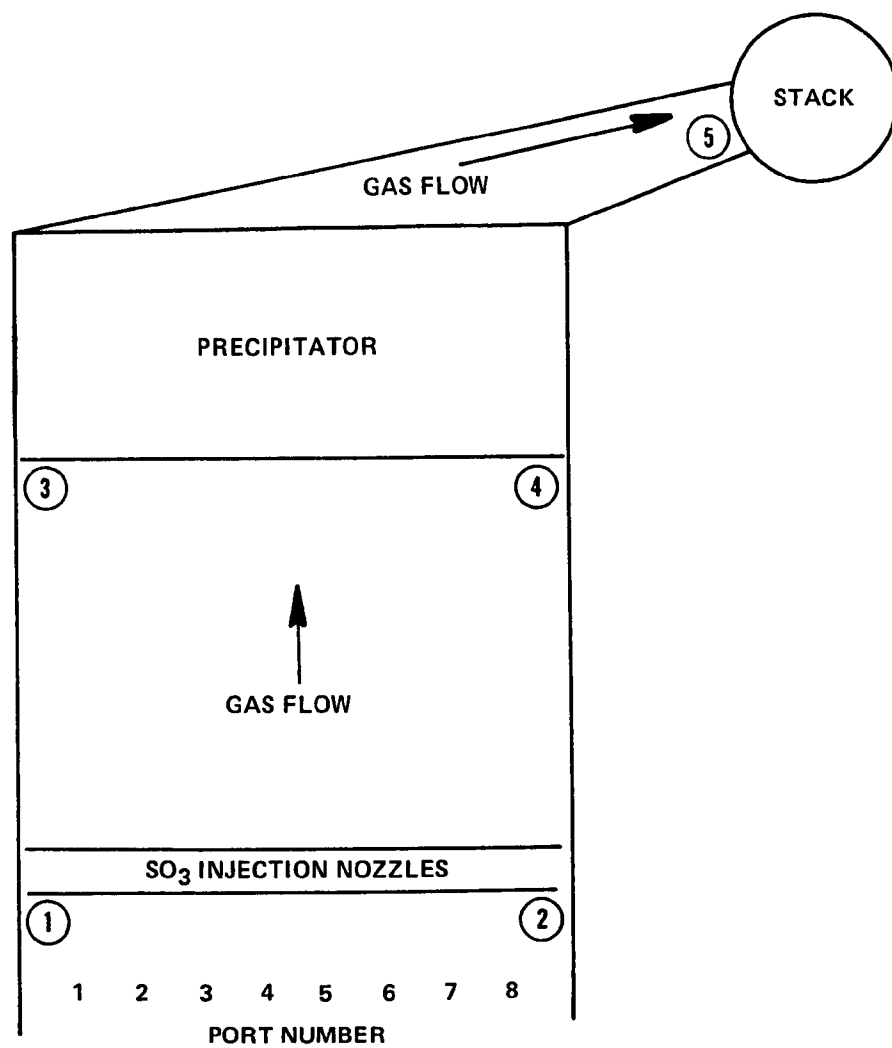


Figure 20. Locations for Sampling with Series Cyclones

Table 10. pH Values and Soluble Sulfate Concentrations of Cyclone Samples of Ash

Sample	Source	Relative Temperature <sup>1</sup>	Size Fraction <sup>2</sup> , $\mu\text{m}$	pH	Soluble $\text{SO}_4^{2-}$ , %
1	Inlet before injection	High	C	11.2	0.27
			M	9.8	0.92
			F	8.7	1.5
			Comp.		0.30
2	Inlet before injection	Low	C	11.2	0.34
			M	9.6	0.84
			F	8.7	1.6
			Comp.		0.37
3a	Inlet after injection	High	C	11.1	1.2
			M	11.1	2.0
			F	10.9	3.7
			Comp.		1.6
3b	Inlet after injection	High	C	11.3	0.82
			M	9.5	3.4
			F	6.7	6.6
			Comp.		1.1
4	Inlet after injection	Low	C	11.1	1.2
			M	11.2	1.4
			F	10.8	2.8
			Comp.		1.4
5a	Outlet		Comp.	7.8	6.4
5b	Outlet		Comp.	8.2	6.3
5c	Outlet		Comp.	8.7	7.6

<sup>1</sup>High temperature, ca 138°C (280°F), Low Temperature, ca 115°C (240°F).

<sup>2</sup>C, M, and F correspond to  $D_{50}$  values of 2.2, 0.8, and 0.5  $\mu\text{m}$ , respectively. Comp. indicates a composite of all size ranges.

(3) Filter samples. Samples of the fly ash collected on the filters that were used at the precipitator outlet (in the stack) during the efficiency tests were analyzed. These samples were from both the ASME and EPA sampling trains. The results are given in Table 11.

#### 4. Gases absorbed in the EPA mass-sampling train

Analyses were conducted to determine whether nonvolatile material was collected in the impingers of the EPA mass-sampling train at the outlet of the precipitator. Weights of solid material in the first impinger catches were taken into account in calculating the mass concentrations. These weights were determined by drying aliquots of the material caught by use of a temperature high enough to evaporate water rapidly. However, a less vigorous drying procedure could leave a residue of absorbed gases—specifically including  $\text{H}_2\text{SO}_4$  absorbed from the filtered flue gas or  $\text{H}_2\text{SO}_4$  produced by absorption of  $\text{SO}_2$  from the flue gas and oxidation of the  $\text{SO}_2$  in the absorption medium.

In view of this possibility, we performed analyses for absorbed gases in aliquots of the first impinger catches and in composites of the second and third impinger catches. One analytical method employed with a few samples was to titrate absorbed acid with  $\text{NaOH}$ ; the results indicate that comparable amounts of two acids were present:  $\text{H}_2\text{SO}_4$  and  $\text{H}_2\text{SO}_3$  (sulfurous acid, or absorbed but unoxidized  $\text{SO}_2$ ). Reasoning that the  $\text{H}_2\text{SO}_3$  would be lost during any drying procedure, we then removed the  $\text{H}_2\text{SO}_3$  and determined the remaining quantity of  $\text{SO}_4^{-2}$  (not only the  $\text{H}_2\text{SO}_4$  evidently present but also any  $\text{SO}_4^{-2}$  leached from solid material).

The results of the  $\text{SO}_4^{-2}$  determinations indicated that virtually equal quantities appeared in the first impinger catch and in the composite of the second and third impinger catches. The total amount of  $\text{SO}_4^{-2}$  found was equivalent to about 5 ppm of  $\text{H}_2\text{SO}_4$  vapor, which could give a particulate concentration of about  $.02 \text{ gm/m}^3$  ( $0.01 \text{ gr/CF}$ )\* as  $\text{H}_2\text{SO}_4$  mist in the plume. As such, the

---

\* Concentration at  $21^\circ\text{C}$  and 1 atm.

Table 11. pH Values and Soluble  $\text{SO}_4^{-2}$   
Concentrations of Filter Samples of Ash

<u>Test</u>	<u>Sampling Train</u>	<u>pH</u>	<u>Soluble <math>\text{SO}_4^{-2}</math>, %</u>
2-1	ASME	10.4	5.1
	EPA	10.4	4.9
2-2	ASME	9.9	5.6
	EPA	9.6	3.4
2-3	ASME	10.5	4.2
	EPA	--- <sup>1</sup>	--- <sup>1</sup>
2-4	ASME	9.5	6.2
	EPA	--- <sup>1</sup>	--- <sup>1</sup>

---

<sup>1</sup>Filter sample not available for analyses.

$\text{SO}_4^{-2}$  found would be significant. However, the finding of  $\text{SO}_4^{-2}$  concentrations in the second and third impingers that were nearly equivalent to those in the first impinger suggests that much of the  $\text{SO}_4^{-2}$  found was from absorbed and oxidized  $\text{SO}_2$ , and not from  $\text{H}_2\text{SO}_4$  vapor. As  $\text{SO}_2$  in the flue gas, the material found would not be logically included in the particulate emission.



#### IV. MASS BALANCE CONSIDERATIONS

##### A. Sulfur Excluding Injected SO<sub>3</sub> (Conditioning Test)

It is possible to use the analytical data given in Section III.E to compare the rate of combustion of sulfur in the coal with the rates of production of sulfur compounds in the flue gas and in the fly ash. We made this comparison by using the data from the conditioning tests with carbon as a basis for comparison. In other words, we assumed that all of the carbon in the coal appeared as CO<sub>2</sub> in the flue gas and then compared the mole ratio to sulfur to carbon in the fuel against the mole ratio in the combination of flue gas and fly ash.

For the fuel, the average weight ratio of sulfur to carbon is 0.57/60.96 (Table 6), which corresponds to a mole ratio of:

$$\frac{0.57/32.07}{60.96/12.01} = 3.5 \times 10^{-3}$$

For the flue gas, the average concentrations of SO<sub>2</sub> and CO<sub>2</sub> are approximately 430 ppm and 12% by volume, respectively (Table 7). The concentration of SO<sub>3</sub> in the gas phase prior to injection of this compound is negligible (less than 1 ppm). However, the concentration of SO<sub>3</sub> in the fly ash is not small enough to be ignored. If the weight percentage of SO<sub>3</sub> in the ash prior to treatment with this gas from the conditioning system is taken as 0.76% (Table 8) and the fly ash concentration entering the precipitator is computed on an absolute basis (that is, for moist flue gas) as 9.00 mg/m<sup>3</sup>,\* then the SO<sub>3</sub> in the ash corresponds to a gas-phase composition of:

$$\frac{0.0076 \times 9.00 \text{ gm/m}^3}{80 \text{ gm/mol}} = 0.85 \times 10^{-3} \text{ mol/m}^3$$

This concentration is added to the concentration of SO<sub>2</sub>, which is:

$$\frac{430 \times 10^{-6} \text{ m}^3/\text{m}^3}{24.1 \times 10^{-3} \text{ m}^3/\text{mol}} = 17.8 \times 10^{-3} \text{ mol/m}^3$$

---

\* This concentration represents the average of several inlet determinations, expressed for a temperature of 21°C at a pressure of 1 atm with water vapor present.

The concentration of CO<sub>2</sub> is:

$$\frac{0.12 \text{ m}^3/\text{m}^3}{24.1 \times 10^{-3} \text{ m}^3/\text{mol}} = 5.0 \text{ mol/m}^3$$

Thus, the mole ratio of sulfur to carbon in the combination of flue gas and fly ash is given by:

$$\frac{(17.8 + 0.85) \times 10^{-3}}{5.0} = 3.7 \times 10^{-3}$$

Three conclusions are now evident. First, the sulfur/carbon ratio in the combustion products ( $3.7 \times 10^{-3}$ ) agrees remarkably well with the ratio in the fuel ( $3.5 \times 10^{-3}$ ). Second, there is evidently little of the sulfur in the fuel that is discharged from the boiler as bottom ash. Third, if it is assumed that all of the sulfur in the fuel is initially oxidized to SO<sub>2</sub> but that subsequent partial oxidation of SO<sub>2</sub> to SO<sub>3</sub> occurs in the flue-gas train as the temperature is lowered, then the conversion factor of SO<sub>2</sub> to SO<sub>3</sub> is best represented by the concentration of SO<sub>3</sub> in the fly ash (not in the flue gas). The computed conversion factor is:

$$\frac{0.85 \times 10^{-3}}{(17.8 + 0.85) \times 10^{-3}} \times 100 = 4.4\%$$

B. Injected SO<sub>3</sub>: Quantity Accounted for at the Inlet of the Precipitator

1. SO<sub>3</sub> present as H<sub>2</sub>SO<sub>4</sub> vapor in the gas phase

Data on inlet concentrations of H<sub>2</sub>SO<sub>4</sub> vapor are necessarily limited to the results that could be obtained at the only two sampling ports available between the injection nozzles and the precipitator. The data (given previously in Table 7) were for different temperatures, around 130°C (265°F) toward one side of the duct and around 143°C (290°F) on the other side. They show higher concentrations of H<sub>2</sub>SO<sub>4</sub> at the higher gas temperature, as expected.

To obtain a reasonable approximation of the average H<sub>2</sub>SO<sub>4</sub> concentration at the precipitator inlet, the following approach was

taken: First, Figure 21 was prepared to compare the  $\text{H}_2\text{SO}_4$  concentrations found at different sampling temperatures with the concentrations predicted from the data of Banchero and Verhoff<sup>4</sup> at the dew point (theoretically, the maximum vapor concentrations attainable). As expected, the experimental results are portrayed by a curve falling substantially below the dew point curve. Next, Figure 22 was prepared to show average gas temperatures at different distances across the inlet duct (these temperatures were computed from the data of Kin Associates that were obtained in pitot traverses). Also plotted in Figure 22 were  $\text{H}_2\text{SO}_4$  concentrations at these temperatures as obtained by interpolation of the previous curve (Figure 21) for the experimental values. Finally, the average  $\text{H}_2\text{SO}_4$  concentration across the duct was computed from the relationship between apparent experimental concentration and location in the duct.

The value of the average thus obtained is 1.8 ppm. It represents the approximate increase in the  $\text{H}_2\text{SO}_4$  vapor concentration as the result of  $\text{SO}_3$  injection (the concentration during the baseline test has been reported as 0.4 ppm but is not large enough to be clearly distinguished from zero).

## 2. $\text{SO}_3$ present as $\text{SO}_4^{-2}$ in the fly ash

Data based on hopper samples. Average values for the total percentage of  $\text{SO}_3$  in fly ash collected in hoppers adjacent to the midline of the precipitator are 0.76% without conditioning and 1.43% with conditioning (Table 8). Using the difference of 0.67% as a measure of the effect of  $\text{SO}_3$  injection and taking the value of  $9.00 \text{ gm/m}^3$  as representative of the fly-ash concentration at the inlet of the precipitator,\* one calculates as follows to obtain the concentration of injected  $\text{SO}_3$  thus accounted for:

---

\* This concentration represents the average of several inlet determinations, expressed for a temperature of  $21^\circ\text{C}$  at a pressure of 1 atm with water vapor.

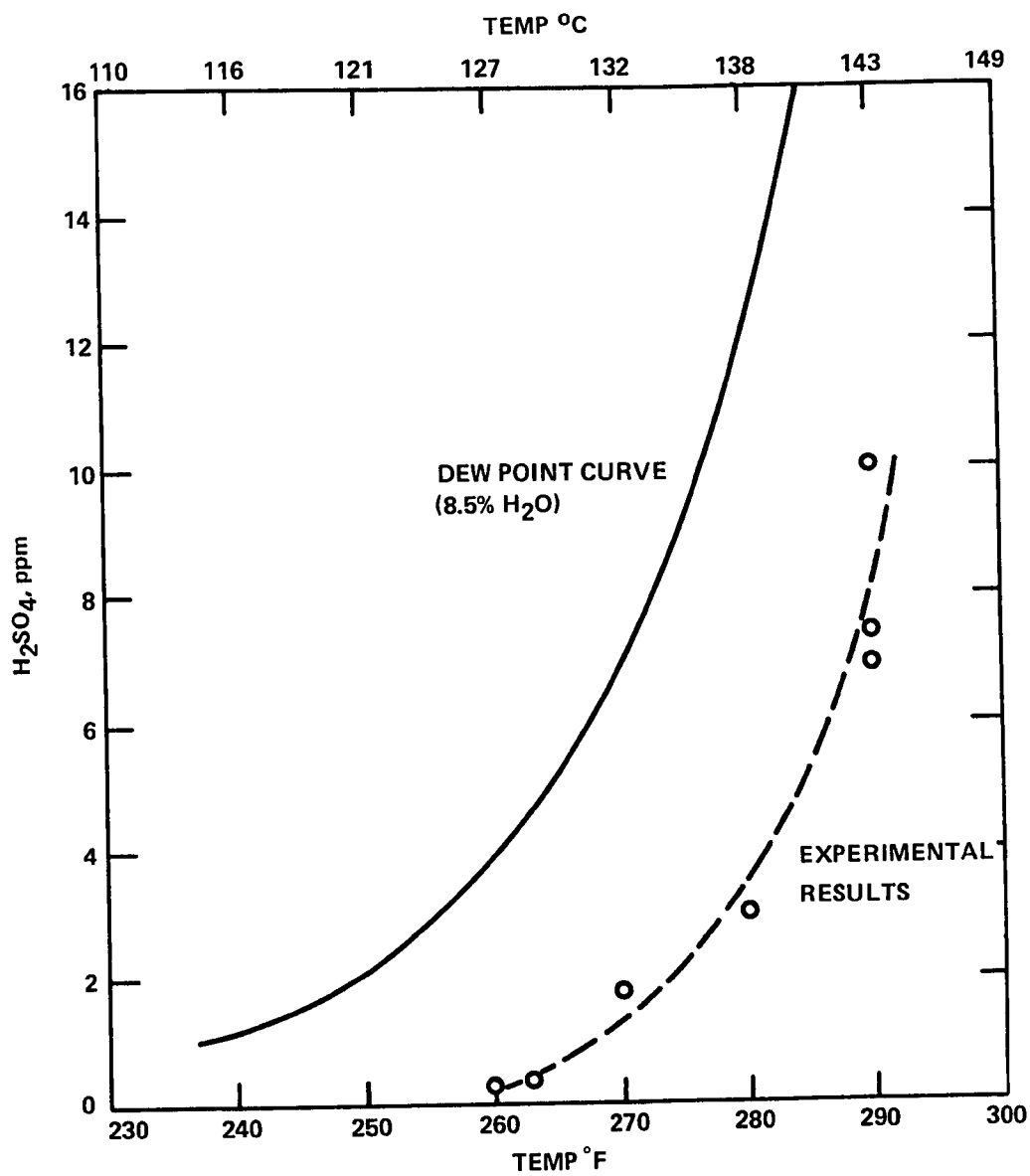


Figure 21. Comparison of H<sub>2</sub>SO<sub>4</sub> Concentrations at the Dew Point with Experimental Results

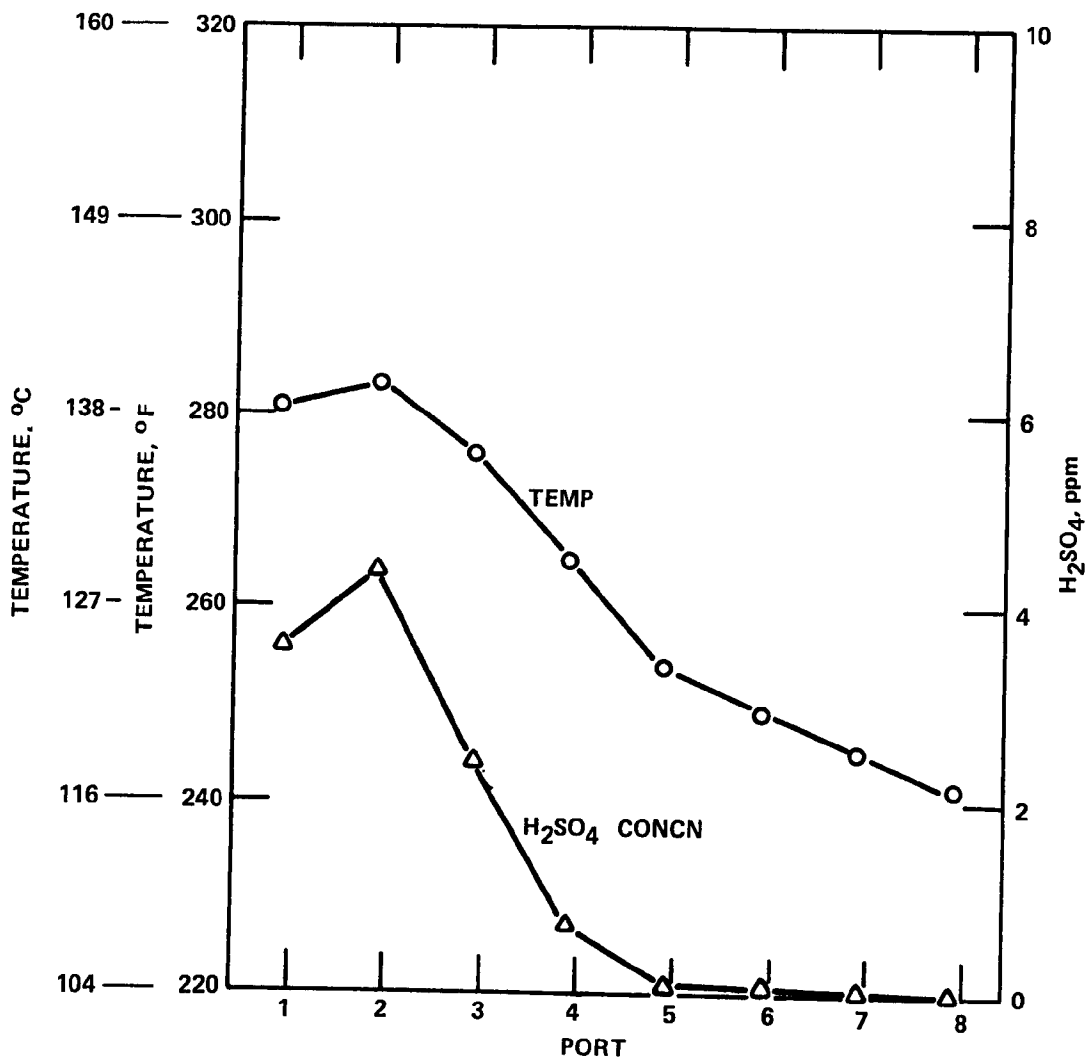


Figure 22. Relationship between Flue-Gas Temperature and Experimental H<sub>2</sub>SO<sub>4</sub> Concentrations

$$\frac{0.0067 \times 9.00 \text{ gm/m}^3}{80 \text{ gm/mol}} = 0.75 \times 10^{-3} \text{ mol/m}^3$$

$$0.75 \times 10^{-3} \text{ mol/m}^3 \times 24.1 \times 10^{-3} \text{ m}^3/\text{mol} = 18.0 \times 10^{-6} \text{ m}^3/\text{m}^3$$

In other words, 18 ppm or about 75% of the 25 ppm of injected  $\text{SO}_3$  is accounted for. In connection with this result, it is necessary to point out that the composition of fly ash collected near the middle of the precipitator may not be representative of the total collected, particularly in view of the erratic nature of results for soluble  $\text{SO}_4^{-2}$  in ash across the entire inlet of the precipitator (Figure 19).

Data based on cyclone samples. Results of determinations of soluble  $\text{SO}_4^{-2}$  in fly ash collected in cyclones during  $\text{SO}_3$  injection give another basis for calculating the fraction of the conditioning agent found in the fly ash. Two composite samples taken upstream from the injection nozzles were found to contain an average of about 0.34% soluble  $\text{SO}_4^{-2}$  (Table 10). Corresponding samples taken between the nozzles and the precipitator contained individually 1.6, 1.1, and 1.4% soluble  $\text{SO}_4^{-2}$  or averaged 1.37%. The difference in the averages, 1.03%, upstream and downstream of the nozzles corresponds to the following concentration of injected  $\text{SO}_3$ :

$$\frac{0.0103 \times 9.00 \text{ gm/m}^3}{96 \text{ gm/mol}} \times 24.1 \times 10^{-3} \text{ m}^3/\text{mol} = 23 \times 10^{-6} \text{ m}^3/\text{m}^3$$

The result, 23 ppm, is very close to the nominal value of the injected concentration.

### C. Injected $\text{SO}_3$ : Quantity Accounted for in Stack Emissions

#### 1. Emission as $\text{H}_2\text{SO}_4$ vapor

Concentrations of  $\text{H}_2\text{SO}_4$  found in the outlet duct during conditioning tests were all less than 1 ppm. Such low values are to be expected as a result of the low gas temperature recorded at the sampling point  $120^\circ\text{C}$  (about  $250^\circ\text{F}$ ), if one consults the dew point concentrations predicted by Banchemo and Verhoff<sup>4</sup> (Figure 21). It is therefore evident that if  $\text{SO}_3$  injection significantly increases

$\text{SO}_4^{-2}$  emissions, the increase must be found in the composition of emitted particulates.

## 2. Emission of $\text{SO}_4^{-2}$ in particulates

Data from cyclone samples. The soluble  $\text{SO}_4^{-2}$  concentrations in particulate collected in cyclones at the outlet duct during conditioning tests were individually 6.4, 6.3, and 7.6% or the average was 6.8% (Table 10). The average value was used with outlet particulate concentrations calculated from efficiency tests to compute equivalent concentrations of  $\text{SO}_3$  lost to the stack in the solid phase as summarized in Table 12.

The soluble  $\text{SO}_4^{-2}$  content of outlet ash during the baseline test was 2.6%. The particulate concentration at this time was about 0.63 mg/l.\* Thus, the corresponding  $\text{SO}_3$  concentration without conditioning was 4.4 ppm, a value that exceeded each emission level given in Table 12 except those for Test 2-3, which is known to have given a faulty indication of the precipitator performance during conditioning. It is evident, therefore, that the total amount of  $\text{SO}_3$  emitted in particulates was lower with conditioning than without as a result of the marked reduction in the mass concentration of particulates.

Data from filter samples. Computations of stack losses of  $\text{SO}_3$  as particulate  $\text{SO}_4^{-2}$  found on the filters used in the efficiency tests gave the results summarized in Table 13. These results confirm the conclusion just given: an insignificant fraction of the injected  $\text{SO}_3$  escapes to the stack as  $\text{SO}_4^{-2}$  in particulates.

---

\* This concentration is the average of two outlet determinations, expressed for a temperature of 21°C at a pressure of 1 atm, with water vapor present.

Table 12. Injected SO<sub>3</sub> Found  
In Outlet Cyclone Samples of Ash

<u>Test</u>	<u>Sampling Train<sup>1</sup></u>	<u>Particulate Con- centration<sup>2</sup>, gm/m<sup>3</sup></u>	<u>Corresponding SO<sub>3</sub> Concentration, ppm</u>
2-1	ASME	0.092	1.6
	EPA	0.163	2.8
2-2	ASME	0.071	1.2
	EPA	0.098	1.7
2-3	ASME	0.318	5.4
	EPA	0.556	9.5
2-4	ASME	0.205	3.5
	EPA	0.210	3.6

- 
1. Used for determination of total particulate concentration given in next column.
  2. At 21°C and 1 atm. with water vapor present.



Table 13. Injected SO<sub>3</sub> Found  
In Outlet Filter Samples of Ash

<u>Test</u>	<u>Sampling Train</u>	<u>Particulate Con- centration<sup>1</sup>, gm/m<sup>3</sup></u>	<u>Corresponding SO<sub>3</sub> Concentration, ppm</u>
2-1	ASME	0.092	1.2
	EPA	0.163	2.0
2-2	ASME	0.071	1.0
	EPA	0.098	0.8
2-3	ASME	0.318	3.3
	EPA	0.556	--- <sup>2</sup>
2-4	ASME	0.205	3.3
	EPA	0.210	--- <sup>2</sup>

---

1. At 21°C and 1 atm. with H<sub>2</sub>O present.

2. Filter sample not available for analysis.

## V. COMPUTER MODEL PROJECTIONS OF PRECIPITATOR PERFORMANCE

The SRI-EPA mathematical model<sup>6</sup> was used to analyze the performance of the precipitator during the test program and to estimate the plate area required for 99% collection efficiency without the aid of conditioning agent. In order to use the model to simulate the precipitator operation with high dust resistivity, it is necessary to estimate a "useful" input power from the voltage-current relationships. This is required because the model is based on the assumption that the input values of current and voltage represent a unipolar particle charging process in which all of the charge transported to the collecting electrode from the corona wires is carried by either corona current or the charged dust particles. The average conditions used were estimated from the voltage-current relationships obtained on March 27. The averages of the values selected for the TR sets are: 35kV applied voltage, 3.5 nA/cm<sup>2</sup> current density. Figure 23 presents results from the computer program in terms of overall collection efficiency as a function of specific collecting area. The theoretical performance is clearly much greater than the measured performance obtained by Research Cottrell on March 27. However, if the overall collection efficiency is reduced by empirical relationships which are intended to estimate the effects of gas sneackage, particle reentrainment, and non-uniform gas velocity distribution, fair agreement can be obtained by assuming a gas velocity distribution with a normalized standard deviation of 25%, and by further assuming that reentrainment and gas sneackage losses amount to 20% of the mass collected in each stage over three effective stages. The computer projection based on these assumptions is labeled curve 2 on Figure 23. These assumptions indicate that a specific collecting area of 78.8 m<sup>2</sup>/(m<sup>3</sup>/sec) (400 ft<sup>2</sup>/1000 ACFM) would result in 99.0% overall collection efficiency. However, this projection does not contain a safety factor for TR set failures, nor does it consider the possibility that the

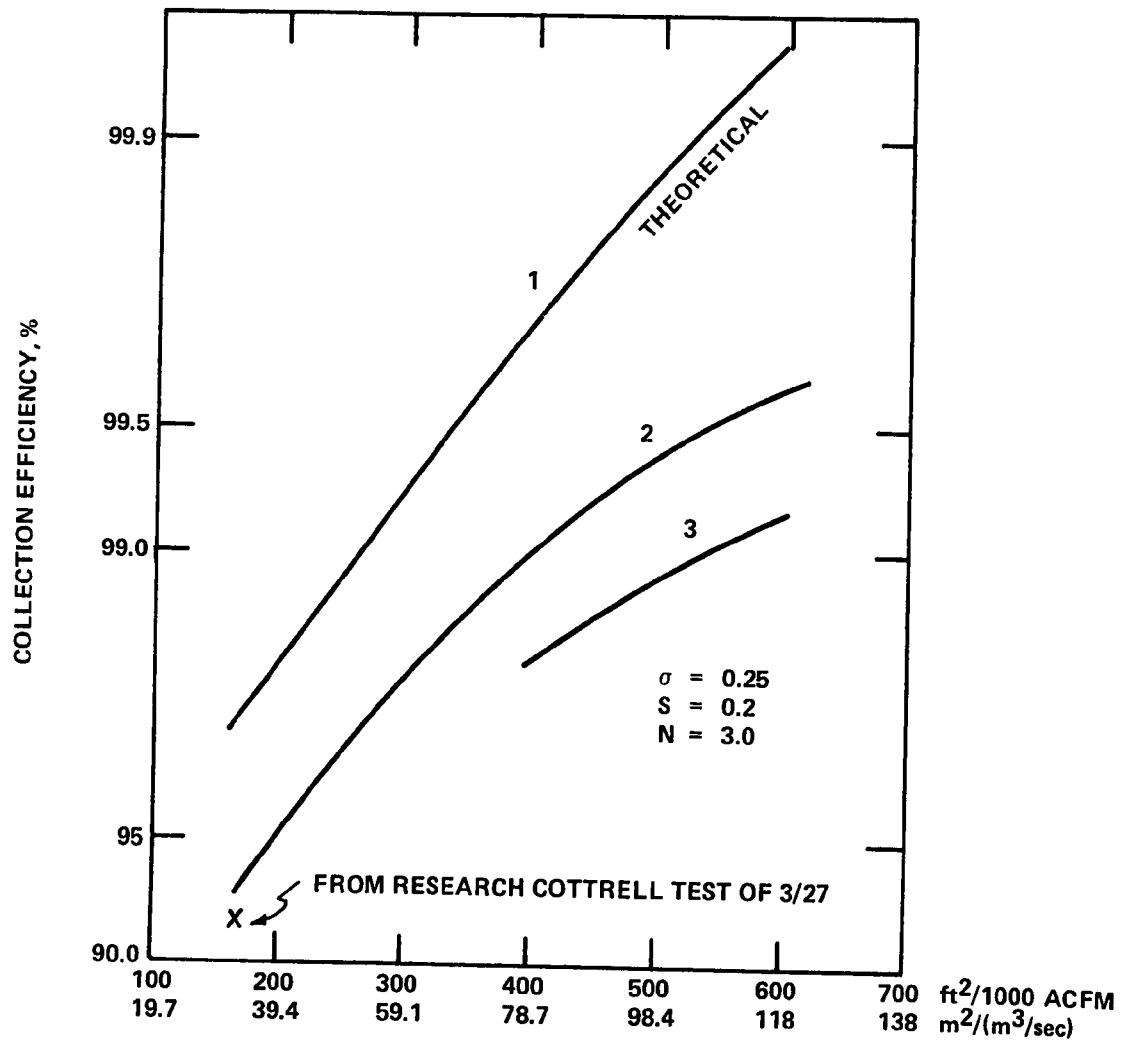


Figure 23. Computer Model Projections of Collection-Efficiency without SO<sub>3</sub>

assumed electrical operating conditions may be degraded if dust resistivity increases. The latter consideration constitutes a major uncertainty since the electrical operating characteristics of the precipitator will be critically influenced by dust resistivity changes.

In an effort to obtain an estimate of specific collecting area which includes a safety margin, the following procedure was employed to obtain curve 3 on Figure 23: (1) The model was used to calculate the overall efficiency if the SCA were effectively reduced from 78.8 to 59.0  $\text{m}^2/(\text{m}^3/\text{sec})$  (400 to 350  $\text{ft}^2/1000 \text{ ACFM}$ ) in 1/2 of the precipitator. (2) The model was used to calculate overall efficiency if the SCA were reduced from 118 to 88  $\text{m}^2/(\text{m}^3/\text{sec})$  (600 to 450  $\text{ft}^2/1000 \text{ ACFM}$ ) in 1/2 of the precipitator. (3) The results from (1) were plotted at 78.8  $\text{m}^2/(\text{m}^3/\text{sec})$  (400  $\text{ft}^2/1000 \text{ ACFM}$ ), and the results from (2) were plotted at 118  $\text{m}^2/(\text{m}^3/\text{sec})$  (600  $\text{ft}^2/1000 \text{ ACFM}$ ). This procedure results in an estimated requirement of 108  $\text{m}^2/(\text{m}^3/\text{sec})$ , or 550  $\text{ft}^2/1000 \text{ ACFM}$ , to achieve 99% collection efficiency with a safety margin for transformer-rectifier failures as specified above.

Figure 24 gives the theoretical model projections and the reduced projections (using the same parameters for gas velocity distribution and reentrainment and sneaking as were used in Figure 23) with the average electrical operating conditions achieved with  $\text{SO}_3$  conditioning. These results indicate that, with the measured size distribution and electrical operating parameters achieved during the  $\text{SO}_3$  injection test, 99% collection efficiency is theoretically possible at the existing SCA. However, as stated earlier, additional testing is required to determine whether the  $\text{SO}_3$  system will allow precipitator performance to remain at the 99% level for extended periods with a boiler load of 300 MW.

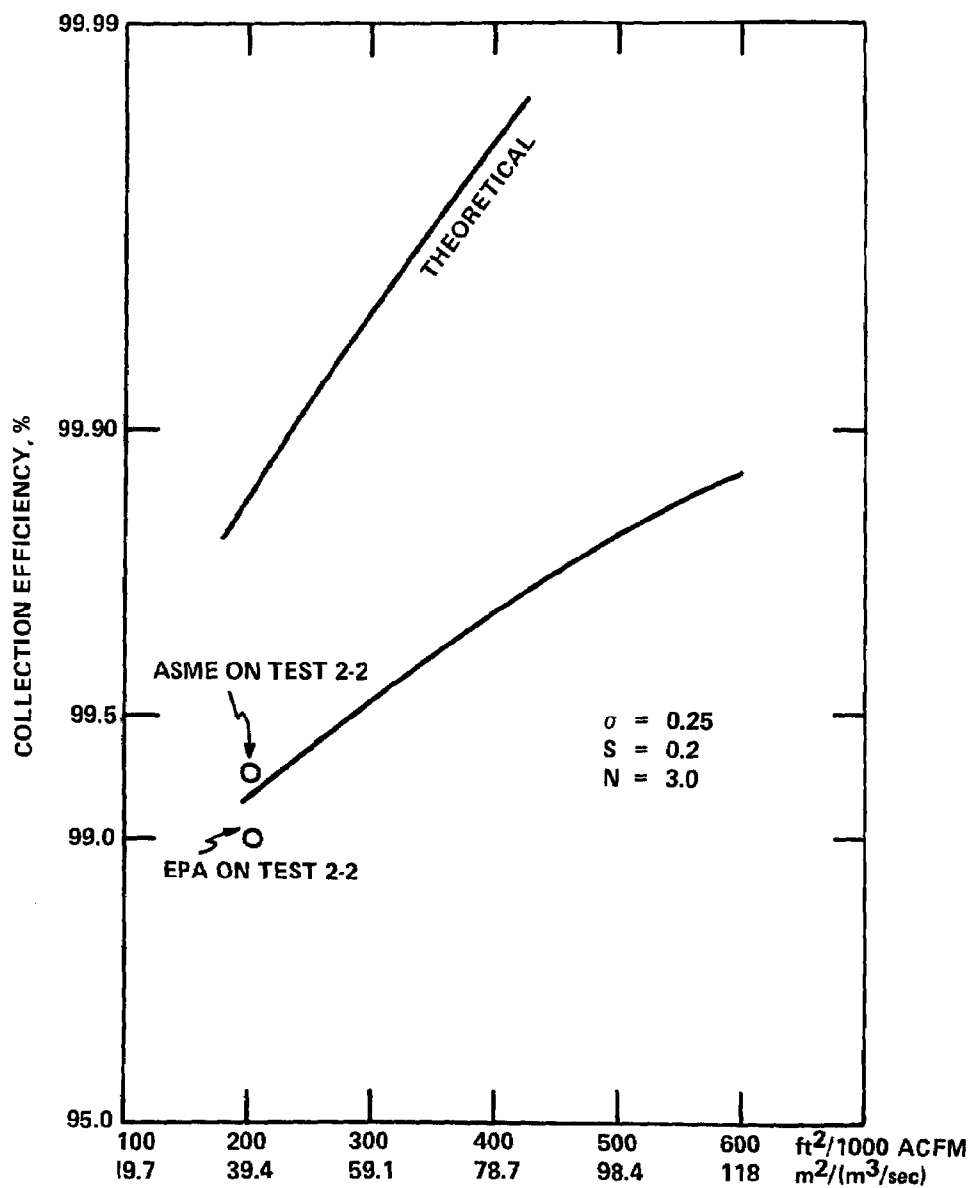


Figure 24. Computer Model Projections of Collection-Efficiency with  $\text{SO}_3$

## ACKNOWLEDGEMENTS

Appreciation is expressed to Research Cottrell and Kin Associates, for assistance in obtaining mass loading measurements, and to Iowa Public Service Company for financial and technical assistance. Mr. G. H. Marchant, Jr., supervised the Institute personnel in the field, who consisted of several members of the Physics Section and the Physical Chemistry Section.

Submitted by:

*Edward B. Dismukes*

Edward B. Dismukes,  
Senior Research Advisor

*John P. Gooch*

John P. Gooch, Head  
Control Device Research Division

## REFERENCES

1. Grady B. Nichols, "Techniques for Measuring Fly Ash Resistivity", EPA-650/2-74-079, August 1974.
2. J. S. Fritz and S. S. Yamamura, Anal. Chem. 27, 9 (1955).
3. E. B. Dismukes, "Conditioning of Fly Ash with Sulfur Trioxide and Ammonia", EPA-600/2-75-015, August 1975.
4. J. T. Banchemo and F. H. Verhoff, J. Inst. Fuel 48, 76 (1975).

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)			
1. REPORT NO. <b>EPA-600/2-77-242</b>		3. RECIPIENT'S ACCESSION NO.	
4. TITLE AND SUBTITLE <b>Fly Ash Conditioning with Sulfur Trioxide</b>		5. REPORT DATE <b>December 1977</b>	
7. AUTHOR(S) <b>Edward B. Dismukes and John P. Gooch</b>		6. PERFORMING ORGANIZATION CODE	
9. PERFORMING ORGANIZATION NAME AND ADDRESS <b>Southern Research Institute 2000 Ninth Avenue, South Birmingham, Alabama 35205</b>		8. PERFORMING ORGANIZATION REPORT NO.	
12. SPONSORING AGENCY NAME AND ADDRESS <b>EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711</b>		10. PROGRAM ELEMENT NO. <b>1AB012; ROAP 21ADL-027</b>	
		11. CONTRACT/GRANT NO. <b>68-02-2114, Task 6</b>	
		13. TYPE OF REPORT AND PERIOD COVERED <b>Task Final; 3-11/76</b>	
		14. SPONSORING AGENCY CODE <b>EPA/600/13</b>	
15. SUPPLEMENTARY NOTES <b>IERL-RTP project officer is Leslie E. Sparks, Mail Drop 61, 919/541-2925.</b>			
16. ABSTRACT <b>The report describes an evaluation of an SO<sub>3</sub> injection system for the George Neal Unit 2 boiler of the Iowa Public Service Co. in Sioux City, Iowa. Results of base line tests without conditioning indicate a dust resistivity of 6 x 10 to the 12th power ohm-cm at 118 C: the precipitator's average collection efficiency was 91.3% at a specific collecting area of 42.8 sq m/(cu m/sec). Because transformer-rectifier sets tripped out, apparently due to ash buildup in the hoppers, only one precipitator efficiency test was conducted with the SO<sub>3</sub> system operating continuously with all T-R sets operating. Results of this test were: (1) specific collecting area = 41.8 sq m/(cu m/sec); (2) collection efficiencies = 99.27% (ASME method), 98.96% (EPA method), and 98.78% (EPA method, including first impinger residue); and (3) 4 x 10 to the 10th power ohm-cm dust resistivity at 143 C. An adequate accounting was made for the fate of the injected SO<sub>3</sub>.</b>			
17. KEY WORDS AND DOCUMENT ANALYSIS			
a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
<b>Air Pollution</b> <b>Fly Ash</b> <b>Treatment</b> <b>Sulfur Trioxide</b> <b>Dust</b> <b>Electrostatic</b> <b>Precipitators</b>		<b>Air Pollution Control</b> <b>Stationary Sources</b>	<b>13B</b> <b>21B</b>  <b>07B</b> <b>11G</b>  <b>20C</b>
18. DISTRIBUTION STATEMENT		19. SECURITY CLASS (This Report)	21. NO. OF PAGES
<b>Unlimited</b>		<b>Unclassified</b>	<b>71</b>
		20. SECURITY CLASS (This page)	22. PRICE
		<b>Unclassified</b>	