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PARTICULATE COLLECTION EFFICIENCY MEASUREMENTS ON A WET ELECTROSTATIC PRECIPITATOR

U.S. Environmental Protection Agency
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PARTICULATE COLLECTION EFFICIENCY MEASUREMENTS ON A WET ELECTROSTATIC PRECIPITATOR

by

John P. Gooch and Joseph D. McCain

Southern Research Institute
2000 Ninth Avenue South
Birmingham, Alabama 35205

for

The M. W. Kellogg Co.
1300 Three Greenway Plaza
Houston, Texas 77046

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EPA Project Officer: Leslie E. Sparks

Control Systems Laboratory
National Environmental Research Center
Research Triangle Park, North Carolina 27711

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ABSTRACT

Fractional and overall particulate collection efficiency measurements were made on a plate-type wet electrostatic precipitator collecting fume from an aluminum pot line. Overall collection efficiency determinations, based on a mass train with an in-stack filter, ranged from 95.0 to 98.0%. The mass filter obtained much higher total outlet mass loadings than did the Andersen impactors, presumably because of large entrained liquor droplets which were captured by the mass traverse, but not by the single-point impactor measurements. The average minimum collection efficiency in the size range 0.2 to 1.0 μm diameter (based on the Andersen data) was 98.5%.

Comparisons between measured (with Andersen impactors) and predicted collection efficiencies obtained from a mathematical model of an electrostatic precipitator indicated fair agreement in the size range from 0.2 to about 1.3 μm. For larger particles, the collection efficiency-particle size relationship departed drastically from the expected pattern, possibly because of liquor carryover from the electrode irrigation system.

CONTENTS

		Page
Abstract		iii
List of Figures		v
List of Tables		vi
Conversion Factors		vii
Sections		
I	Summary and Conclusions	1
II	Introduction	3
III	Measurement Techniques	7
IV	Results	14
V	Discussion	36
VI	References	48
VII	Appendix	50

FIGURES

No.		Page
1	Schematic of scrubber-precipitator system and sampling locations	4
2	Schematic of primary emission control system at the test site	5
3	Comparison of sedimentation and equivalent optical diameters	9
4	Optical and diffusional sizing system	10
5	Inlet Andersen data	17
6	Outlet Andersen data	18
7	Andersen data on log probability co-ordinates	19
8	Comparison of Andersen and Brink average inlet data	20
9	Inlet differential size distribution	22
10	Outlet differential size distribution	23
11	Andersen fractional efficiency data	24
12	Relative concentration variation from condensation nuclei counter	26
13	Relative concentration variation from optical particle counter	27
14	Cumulative size distributions on a number basis for various industrial particulate sources as measured by optical and diffusional methods	28
15	Measured fractional efficiencies for a wet electrostatic precipitator with the operating parameters as indicated, installed downstream of a spray-type scrubber on an aluminum reduction pot line	29
16	Wet electrostatic precipitator	37
17	Schematic of electrode arrangement	38
18	Voltage current relationship and operating ranges	41

TABLES

No.		Page
1	Weight changes of Andersen substrate after sampling filtered effluent from wet ESP	12
2	Andersen inlet data	15
3	Andersen outlet data	16
4	Mass train test results	31
5	Results from tests conducted by a local pollution control agency	33
6	Summary of specifications for the wet electrostatic precipitators	40
7	Effect of dielectric constant on predicted efficiencies	43
8	Precipitation rate parameters	45
9	Qualitative comparison of mass measurements	45
10	Operating power estimated for wet electrostatic precipitator no. 553	47

CONVERSION FACTORS

To Convert From	To	Multiply By
lbs	Kg	0.454
grains/cf	grams/m^3	2.29
cfm	m^3/sec	0.000472
lbs/in^2	Kg/m^2	703
°F	°C	(°F - 32) x 5/9
ft^2/1000 cfm	m^2/(m^3/sec)	0.197
inches w.g.	mm Hg	1.868
gallon	liter	3.785
ft	m	0.3048
inches	m	0.0254

SECTION I

SUMMARY AND CONCLUSIONS

Fractional and overall particulate collection efficiency measurements were made on a plate-type wet electrostatic precipitator collecting fume from an aluminum pot line consisting of horizontal stud self-baking aluminum reduction cells. The average mass median diameter of the inlet particulate, as determined with Andersen impactors, was 0.60 μm, and the average minimum collection efficiency in the size range 0.2-1.0 μm diameter (again based on Andersen data) was 98.5%. Overall collection efficiency determinations, based on a mass train with an in-stack filter, ranged from 95.0 to 98.0%. The mass filter obtained much higher total outlet mass loadings than did the Andersen impactors (4.2 mg/am^3 vs 0.84 mg/am^3), presumably because of large entrained liquor droplets which were captured by the mass traverse, but not by the single-point impactor measurements. Agreement was obtained between total mass loadings from the Andersens and the mass filter at the inlet.

Diffusional measurements indicated an increasing collection efficiency in the size range from 0.1 to 0.07 μm, with an indicated collection efficiency of 99.6% for 0.07 μm diameter particles. Optically and inertially determined collection efficiencies showed fair agreement in the size range 0.3-1.0 μm, but the conversion of the optical number density to mass loadings showed that the optical instrument was detecting at least one order of magnitude less mass than were the Andersen impactors at equivalent particle sizes, at both the precipitator inlet and outlet. Possible reasons for the discrepancy are evaporation of volatile components in the optical system, loss of particle count due to systematic errors in the sampling system and particle counter, and the steep slope of the size distribution on a number basis.

The estimated operating power requirements for the wet precipitator totaled 114 kw, or 2.58 kw/(m^3/sec). This includes high voltage power requirements, pumping power, fan power, based on 1.27 cm (1/2") water column pressure drop, and power to heat the high voltage insulators. If electrical power costs are $0.01/kwh, the energy costs for operating the unit are estimated as $27.00/day.

Comparisons between measured (with Andersen impactors) and predicted collection efficiencies obtained from a mathematical model of an electrostatic precipitator indicated fair agreement in the size range from 0.2 to about 1.3 μm. For larger particles, the collection efficiency-particle size relationship departed drastically from the expected functional form, presumably because of liquor-carryover from the electrode irrigation system.

SECTION II
INTRODUCTION

This report presents the results obtained from a performance test conducted by Southern Research Institute on a wet electrostatic precipitator collecting fume from horizontal stud Soderburg aluminum reduction cells during the period August 19-23, 1974. The wet electrostatic precipitator was designated as ESP No. 553. The objectives of the test series were (1) to determine the fractional and overall particulate collection efficiency of the electrostatic precipitator, (2) to compare the measured performance of the precipitator with that projected from a mathematical model.

At the reduction plant, wet precipitators are installed both with and without a spray tower prior to the precipitator. Since the occurrence of condensation within the precipitator itself confuses interpretation of the data, it was decided to conduct the test series on a unit which is preceded by two spray towers, to minimize this effect. The spray towers treat exhaust gas from 28 pots with an alkaline solution which cools the gas from about 220°F to about 100°F. Figure 1 shows the arrangement of the wet precipitator, scrubbers, and sampling locations. Figure 2 is a schematic of the liquor flow through the system given by Bakke.[1]

Horizontal stud Soderburg cells are of the "self-baking" type, in that the carbon electrode is baked within the cell. The effluent from the cell therefore contains hydrocarbons volatilized from the binders used to make the anode. Other constituents include HF gas, which results from hydrolysis of fluoride salts, particulates of vaporized bath

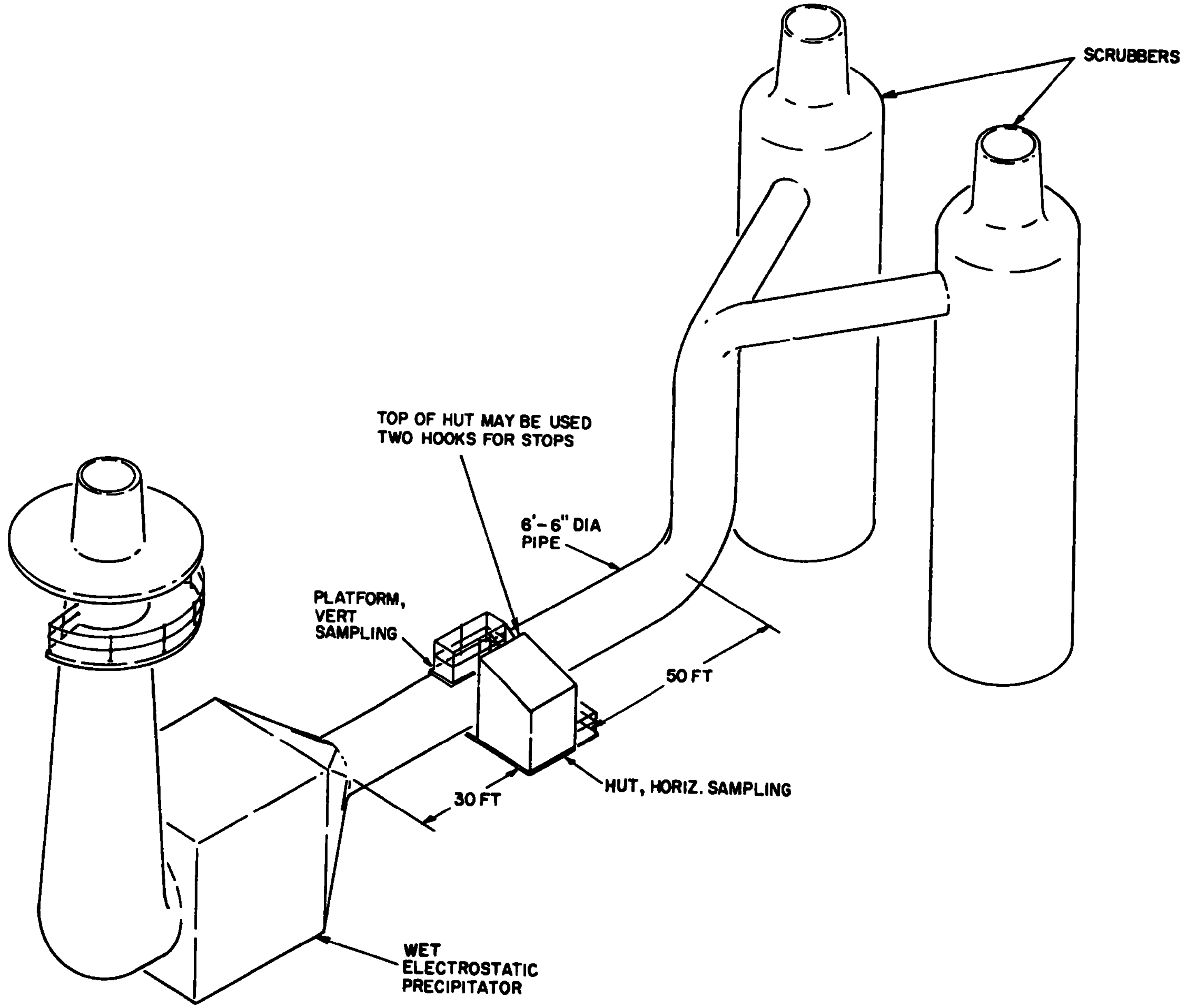

Figure 1. Schematic of scrubber-precipitator system and sampling locations

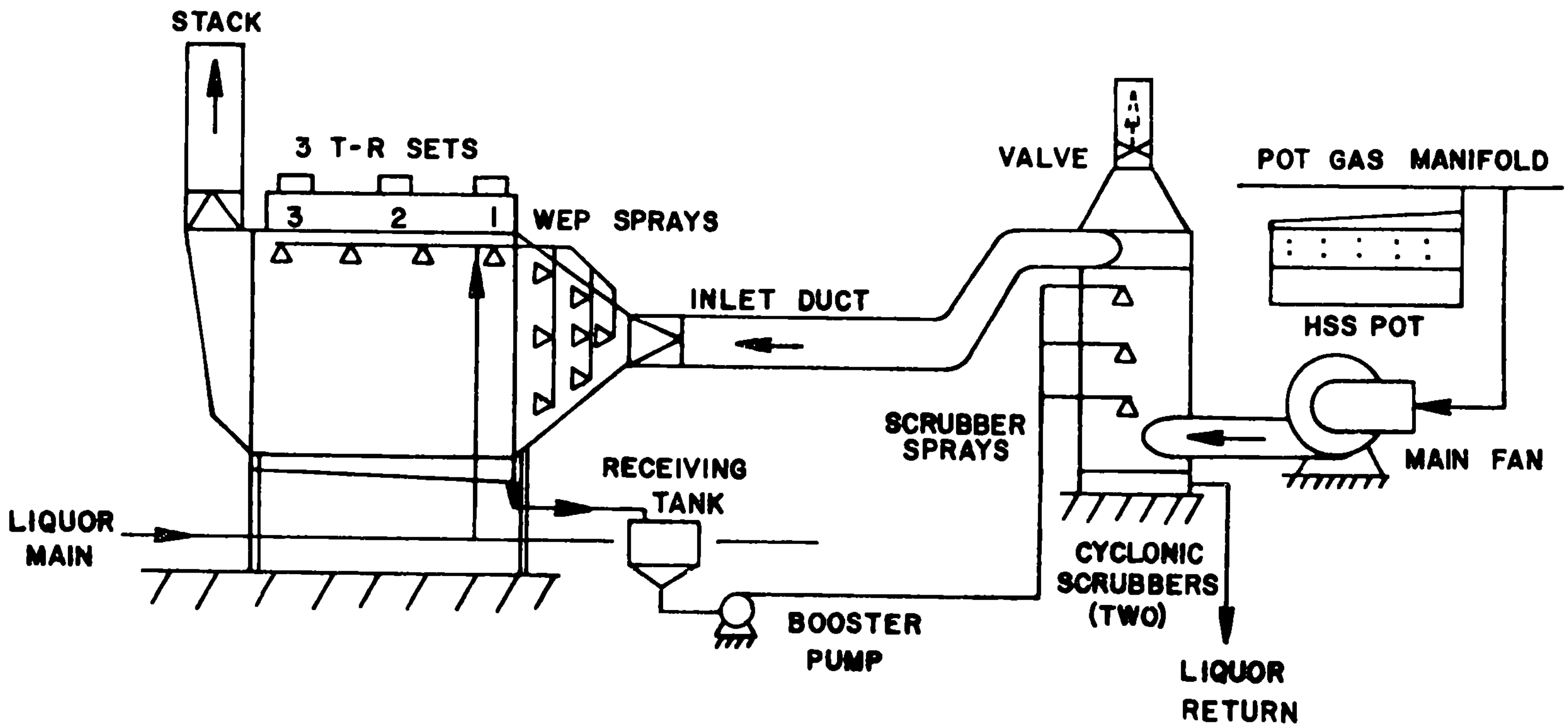

Figure 2. Schematic of primary emission control system [1]

materials, and alumina, cryolite, and other dusts entrained from the bath crust. During the course of the test period, routine operations were in progress on the cells which supply the scrubber-precipitator system. These operations include the breaking of the crust in each cell at approximately 2 hr intervals, and anode maintenance operations known as "pin and channel pulls" and "flex raises". The anode maintenance and the crust breaking is performed on the cells on an individual basis. Thus the effect of the individual operations on the total particulate concentration entering the wet precipitator is somewhat damped. Table A-1 in the Appendix gives the operations performed during the test period on the cells which are vented to the wet ESP.

SECTION III
MEASUREMENT TECHNIQUES

PARTICLE SIZE MEASUREMENTS

Particle size and concentration measurements were conducted using the following methods: (1) diffusional techniques using condensation nuclei counters and diffusion batteries for determining concentration and size distribution on a number basis for particles having diameters less than approximately 0.2 μm, (2) optical techniques for determining concentrations and size distributions for particles having diameters between approximately 0.3 μm and 1.5 μm, (3) inertial techniques using cascade impactors for determining concentrations and size distributions on a mass basis for particles having diameters between approximately 0.25 μm and 5.0 μm. A detailed description of these measurement techniques is given elsewhere,[2] and therefore only a brief discussion will be given in this report.

For optical and diffusional measurements, extensive dilution of the gas stream being sampled is usually required because of the limitations imposed by the useful ranges of both the optical counter and condensation nuclei counter. Dilution ratios ranging from 0 to 20 were used at the outlet, and from 30 to 90 at the inlet. As a general practice, checks of the linearity of particle count with dilution changes are performed to determine whether any anomalies resulting from condensation or other phenomena are occurring within the measurement system.

Due to limitations imposed by equipment availability, it was not possible to obtain simultaneous measurements at the precipitator inlet and outlet with the optical and diffusional instruments. However, the particulate concentrations were sufficiently stable to enable meaningful fractional efficiency data to be derived by first obtaining inlet data, and subsequently moving the equipment to the outlet to obtain the outlet data.

The optical particle counter was calibrated with polystyrene latex spheres. The indicated diameters of the particulate in the stack gas can differ from the true diameters because of the effect of refractive index differences on results obtained from the particle counter. In order to check the diameter obtained for this effluent, the diffusion batteries were used as sedimentation chambers, and particle diameters obtained from calculated sedimentation rates were compared with the indicated optical particle diameters. This comparison is shown in Figure 3, using values for particle density of 1.0 and 2.0 grams/cm^3 in the sedimentation calculations. The plant personnel reported that particle densities are estimated to range from about 1 to 4 grams/cm^3, with 1.5 grams/cm^3 an estimated average for the outlet particulate. The comparison indicates fair agreement between the sedimentation diameters, which are independent of refractive index, and the equivalent optical diameters. Figure 4 shows the optical and diffusional sizing system. The sampling probe was heated to slightly above the stack temperature at the outlet to avoid condensation.

Andersen impactors were used simultaneously at the precipitator inlet and outlet on August 20, 21, 22, and 23. Isokinetic sampling was performed at a single point for both the inlet and outlet. Due to the extremely low mass loadings at the outlet, it was necessary to operate the impactors for approximately 16 hours in order to obtain weighable quantities of particulate. Brink impactors were operated at the

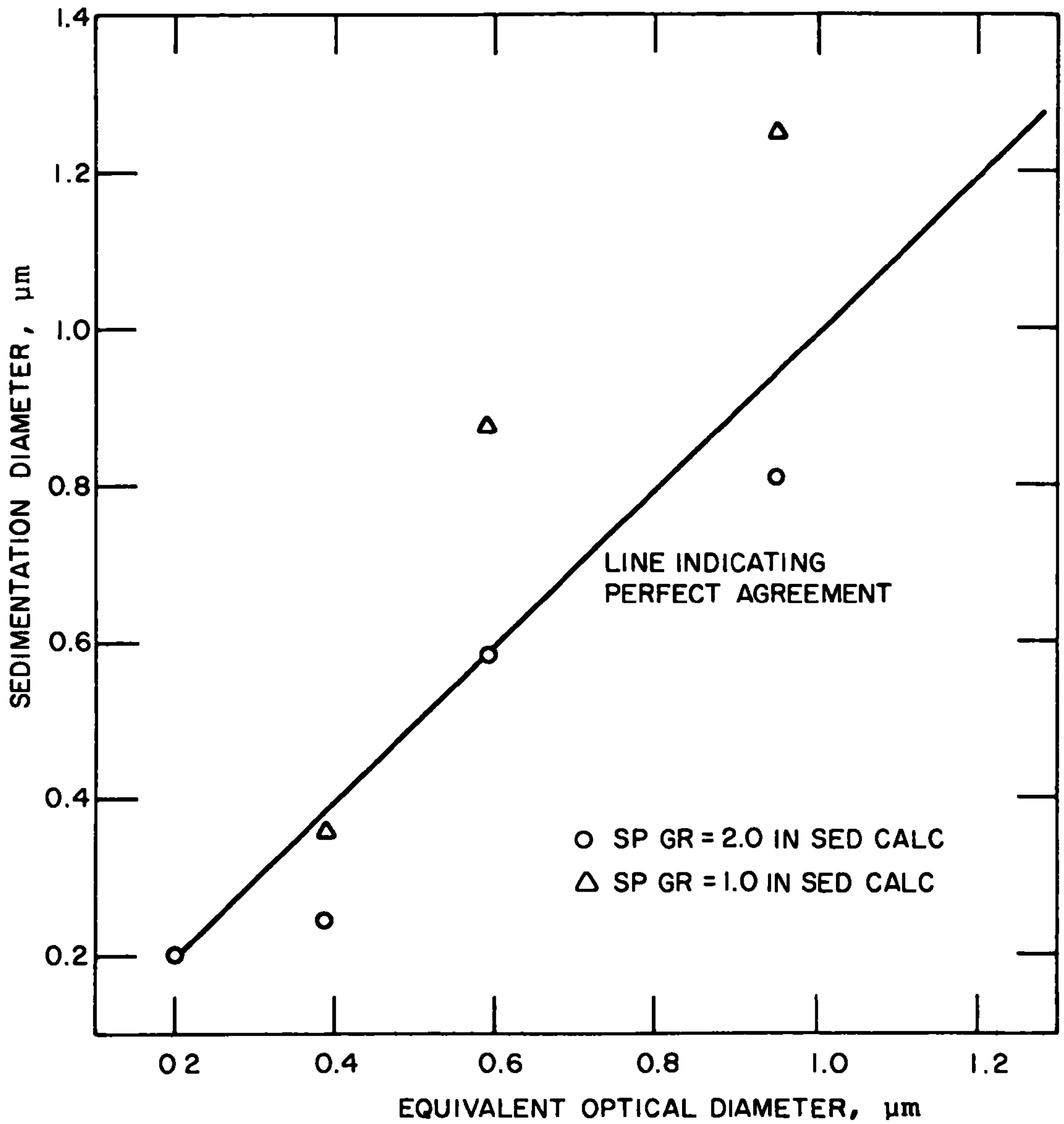

Figure 3. Comparison of sedimentation and equivalent optical diameters

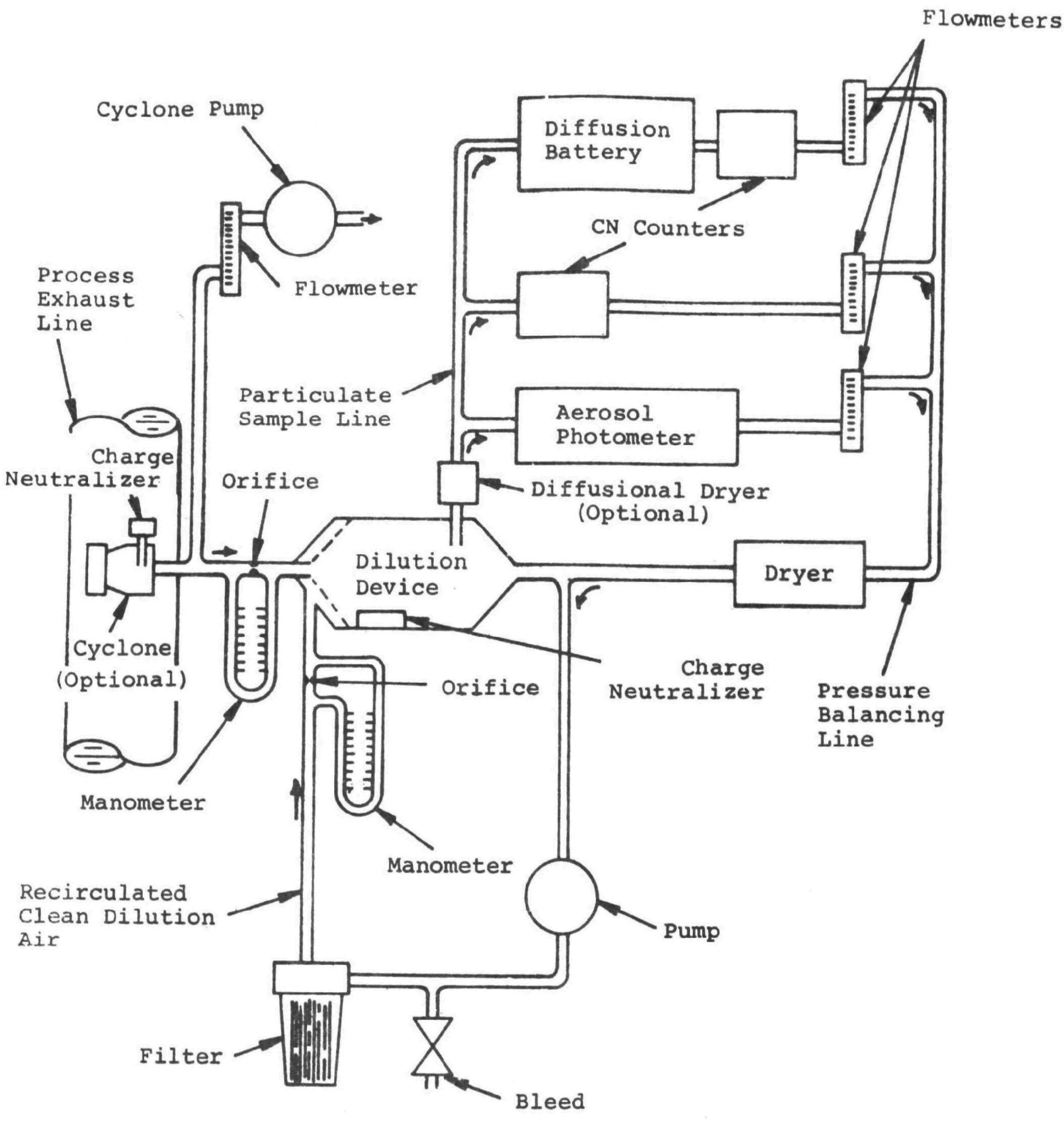

Figure 4. Optical and diffusional sizing system

inlet, but it was not practical to obtain data with this device at the outlet. Since the gas phase contains condensable hydrocarbons, gaseous fluorides, and water vapor, and is near the water vapor saturation temperature, condensation, evaporation, and chemical reaction pose potential interference problems for impactor mass measurements. In an effort to determine the order of magnitude of some of these potential interferences, two Andersen impactor "blank" runs were made with a filter prior to the impactors. The blank runs gave an estimate of the weight loss or gain which could be expected due to reactions between the gas phase and the fiberglass substrates. Although the blank impactors were heated above the stack temperature prior to sampling, condensation occurred in the upper region of the impactor. The condensation was apparently caused by relatively short-term temperature variations in the outlet stack. For the runs used for size determinations, the impactors were heated to about 120°F to avoid the condensation problem.

Table 1 gives the weight changes obtained from the "blank" impactor runs. No data were obtained with the first stage blank due to the condensation problem. These blank changes are not significantly greater than those which may normally occur due to handling of the glass fiber substrates, and are therefore not considered to pose a serious interference problem.

MASS LOADING MEASUREMENTS

A modified EPA sampling train with an in-stack filter holder (the same filter used for the EPA train) was used for the mass loading measurements. The filter holder was teflon-coated to avoid interference problems which might be caused by corrosion of metal surfaces. Mass loading determinations

Table 1. WEIGHT CHANGES OF ANDERSEN SUBSTRATE AFTER SAMPLING FILTERED EFFLUENT FROM WET ESP

Stage	Sampling Time	
	240 min	103 min
1	-	-
2	+0.06 mg	+0.02 mg
3	-0.04	-0.04
4	-0.02	+0.04
5	+0.08	-0.04
6	-0.12	-0.16
7	-0.08	-0.10
8	-0.12	-0.10
	Average, -0.04 mg	

were conducted at the inlet and outlet simultaneously with the impactor runs. An isokinetic traverse across the stack was conducted at both the precipitator inlet and outlet through a single sampling port at each location for all but the last day of the test series. On that date, a single point mass determination was performed at the outlet. As with the Andersen impactors, it was necessary to heat the outlet filter holder to approximately 120°F to avoid gross amounts of condensation. However, the filters were still slightly damp (both inlet and outlet), and consequently were placed in an oven at 120°F for a few hours prior to desiccation and weighing.

SECTION IV
RESULTS

IMPACTOR MEASUREMENTS

Tables 2 and 3 present results obtained from the Andersen impactors during the four days of testing with these devices. The outlet results are tabulated as the mass gain per stage to enable comparison with the "blank" weight changes given in Table 2. It should be noted that the weight changes for the blanks are in general not proportional to the sampling time. Although the blank changes represent a significant fraction of the stage weights obtained during the outlet sampling, there is sufficient mass to enable meaningful conclusions to be drawn from the data. Figures 5 and 6 give the mass loadings at the inlet and outlet respectively on a cumulative basis, and Figure 7 gives the average inlet and outlet size distributions from the Andersen impactor data on log probability co-ordinates. No corrections were made for the blank weight changes. The mass median diameters of both inlet and outlet distributions are less than 1.0 μm. The average outlet size distribution, and all subsequent calculations involving the outlet Andersen impactor measurements, were obtained using runs 04, 05, and 06. Run 03 was discarded because it appeared to collect an anomanously low amount of mass when compared with the other three data sets.

In addition to the Andersen impactor measurements, several runs were made at the inlet using a modified Brink impactor. Outlet measurements with the Brink impactors were not practical due to the long sampling times which are required due to the low mass loading. Figure 8 gives a comparison of the averaged cumulative loadings obtained with these impactors. Both impactors had glass fiber substrates on the stages but the Andersens were operated for approximately 20 minutes, whereas two hours

Table 2. ANDERSEN INLET DATA

Run No.	AI-2	AI-4	AI-5	AI-7	AI-8	AI-9	AI-11	AI-12	AI-14	AI-16	AI-17	Avg.	Avg.%
Date	8/20/74	8/20/74	8/20/74	8/21/74	8/21/74	8/21/74	8/21/74	8/22/74	8/22/74	8/23/74	8/23/74		
Total Mass, mg/am^3	88.2	60.7	57.2	39.7	73.8	83.2	80.9	128.5	82.9	92.6	100.8	80.77	
Lower Size Limit, μm	Cumulative Mass, mg/am^3												
10.0	65.8	53.0	51.2	37.0	63.1	75.8	72.8	112.0	74.9	82.9	91.1	70.87	87.7
7.01	59.9	50.4	47.9	36.0	58.6	72.2	68.1	105.0	72.5	68.1	85.7	65.85	81.52
4.33	57.2	49.8	46.6	35.2	55.9	69.8	65.2	99.8	71.8	65.0	81.1	63.4	78.49
3.05	56.0	49.3	46.2	33.5	53.9	68.5	63.7	96.7	71.5	63.3	78.0	61.87	76.60
1.99	54.6	48.7	45.1	33.0	52.5	67.2	61.9	92.9	70.3	61.6	74.0	60.16	74.48
0.93	44.1	38.7	37.0	29.2	46.1	61.2	57.1	72.6	62.3	54.2	60.1	51.14	63.32
0.56	32.4	27.8	28.1	22.4	34.6	49.4	49.3	47.0	48.3	37.3	37.8	37.67	46.64
0.40	22.4	19.0	20.1	14.5	23.2	34.8	36.5	30.5	31.0	23.9	23.8	25.43	31.48

Table 3. ANDERSEN OUTLET DATA

Stage No.	Cut Point, µm	Run Number 03 mg	03 mg/am^3 cum.	04 mg	04 mg/am^3 cum.	05 mg	05 mg/am^3 cum.	06 mg	06 mg/am^3 cum.	Avg. mg/am^3 for 04,05,06 cum.
1	10.3	0.28	0.582	0.34	0.847	0.40	0.848	0.44	0.719	0.805
2	7.2	0.14	0.570	0.26	0.824	0.32	0.820	0.34	0.691	0.778
3	4.4	0.10	0.561	0.20	0.807	0.44	0.782	0.44	0.655	0.748
4	3.1	0.10	0.552	0.26	0.748	0.44	0.744	0.32	0.628	0.707
5	2.1	0.14	0.540	0.28	0.759	0.44	0.706	0.40	0.596	0.687
6	1.0	0.08	0.533	0.46	0.719	0.22	0.687	0.40	0.563	0.656
7	0.6	0.66	0.476	1.26	0.609	1.38	0.568	1.10	0.472	0.550
8	0.4	1.00	0.389	2.18	0.418	1.94	0.400	1.58	0.343	0.387
F		4.46		4.78		4.62		4.18		
Total Mass Loading, mg/am^3			0.606		0.877		0.882		0.755	0.838

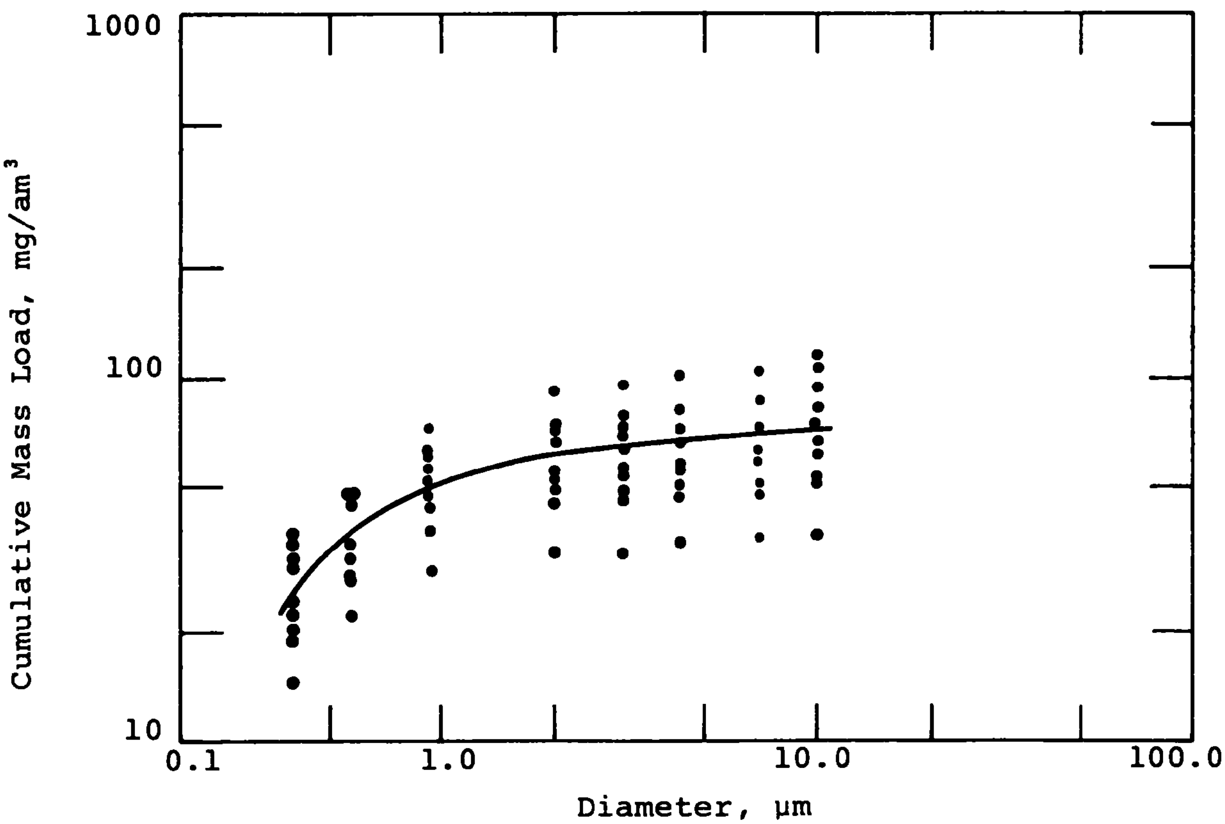

Figure 5. Inlet Andersen data

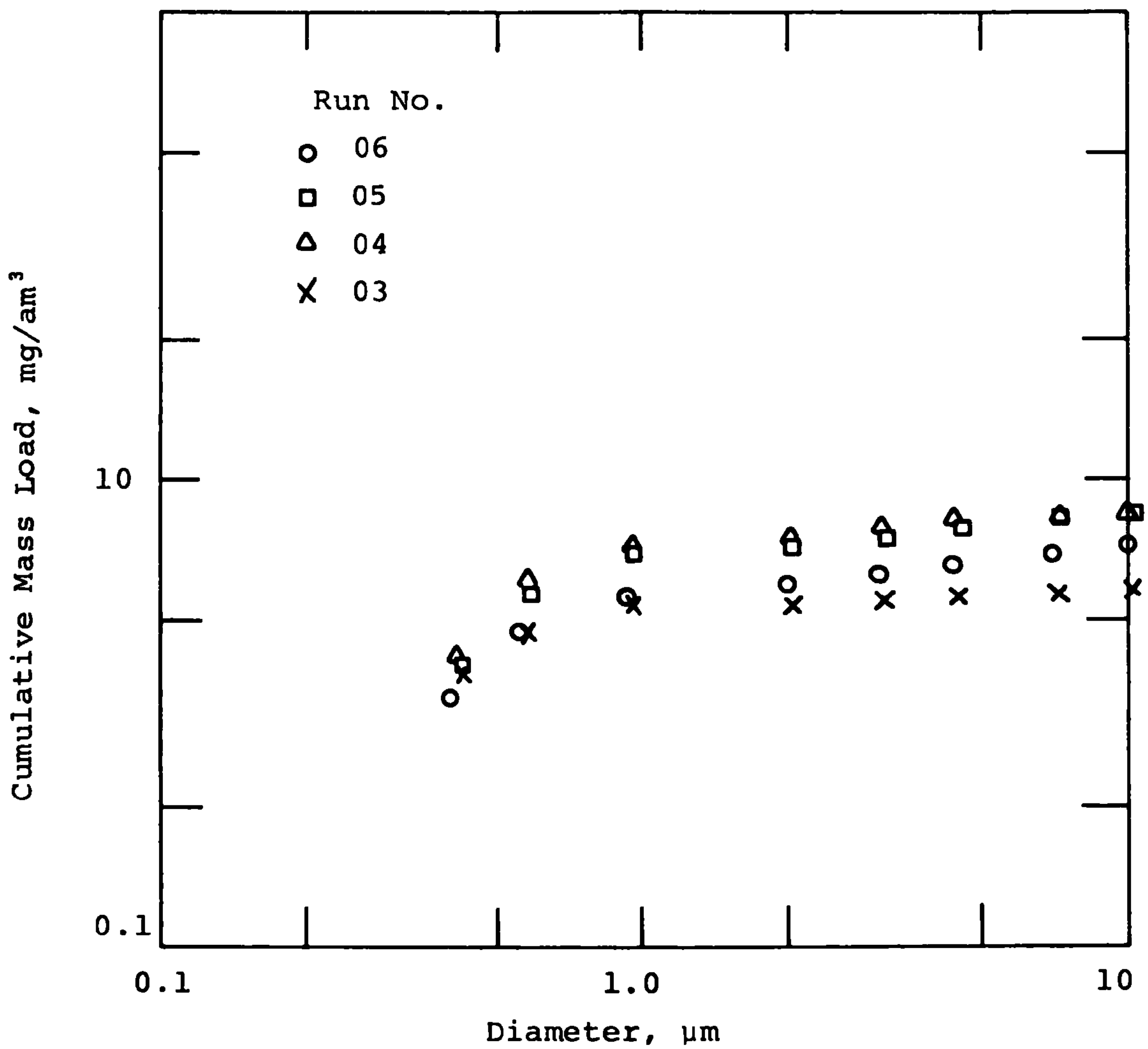

Figure 6. Outlet Andersen data

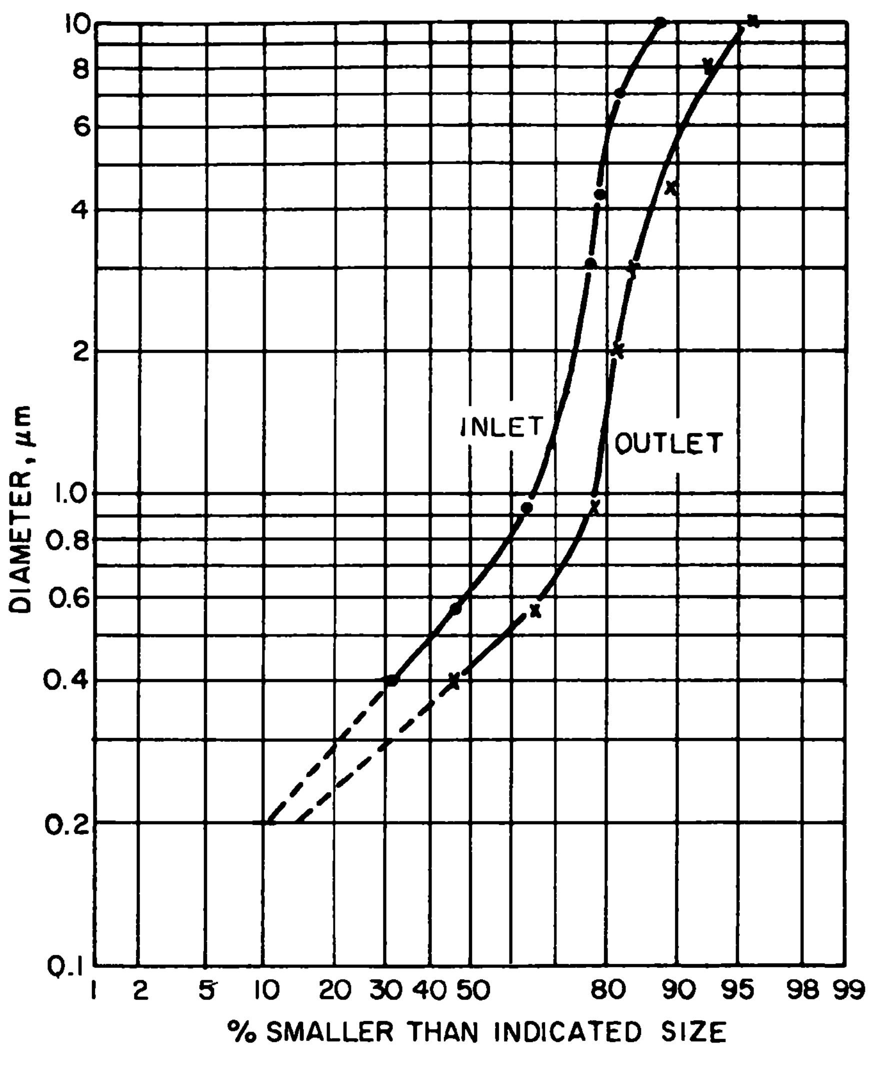

Figure 7. Andersen data on log probability co-ordinates

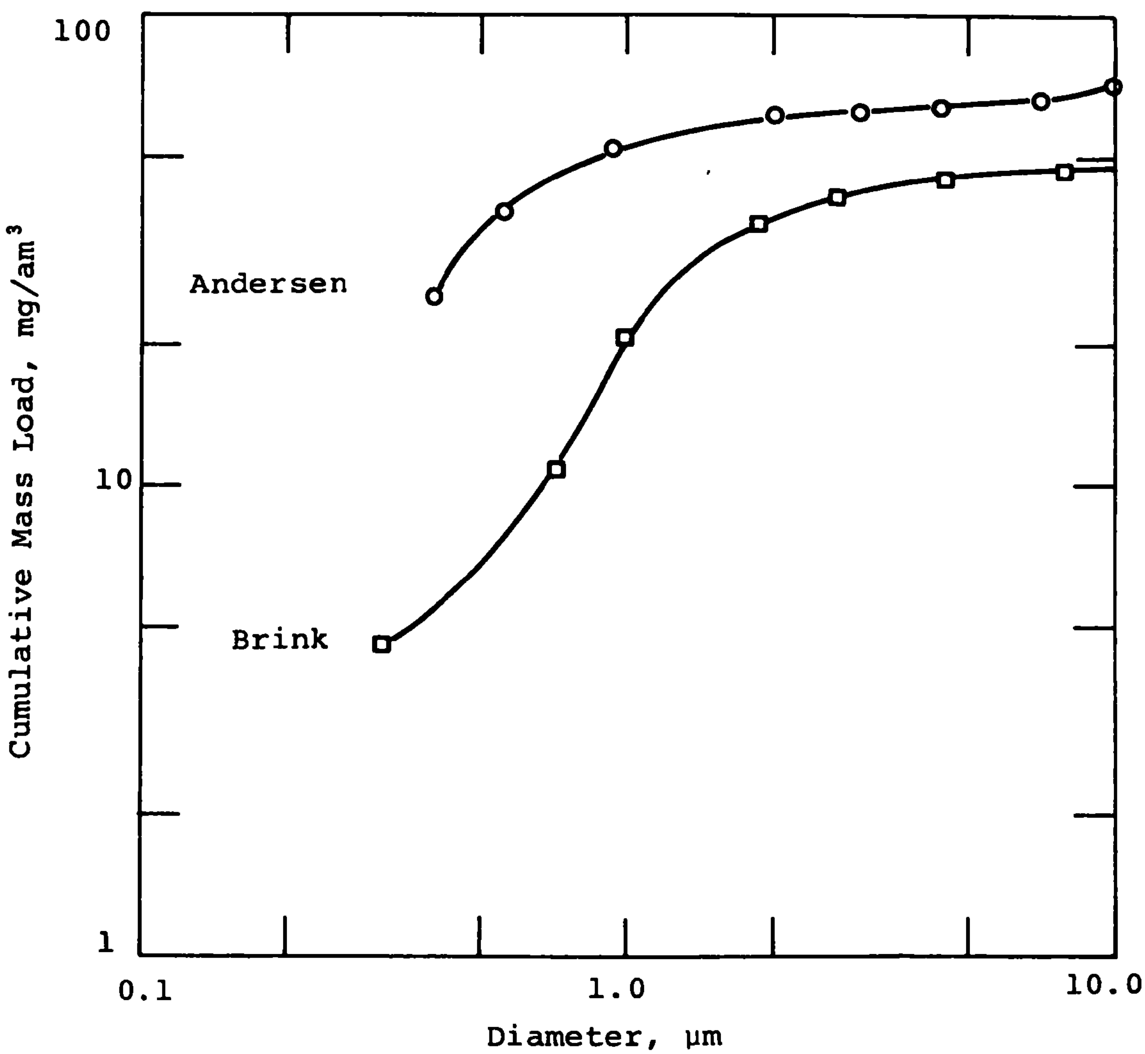

Figure 8. Comparison of Andersen and Brink impactor average inlet data

were required for the Brink runs. The disagreement between the two sets of measurements illustrated in Figure 8 is most pronounced in the fine size range. Previous comparisons at coal-fired power plants had shown reasonable agreement between size distributions obtained at the same location with the two impactors. Additional sampling on this particular effluent and a stage-wise analysis of the collected material would be required to explain the disagreement indicated by Figure 8.

Figures 9 and 10 are plots of dM/d log D from the Andersen impactor measurements at the inlet and outlet, respectively. Both of the distributions appear to be bimodal. The first peak occurs at about the same particle diameter for both the inlet and outlet data, but the second peak for the outlet is shifted to the left on the diameter axis. These data were used to obtain the efficiency as a function of particle diameter given in Figure 11. The midpoints were obtained from the average values of dM/d log D. The bands were obtained by: (1) calculating the standard deviation at the indicated points for the inlet and outlet data sets, (2) plotting dM/d log D values which represent plus and minus one standard deviation from the average at each particle diameter, (3) drawing curves through the points representing plus and minus one standard deviation for both inlet and outlet data sets, (4) calculate a minimum efficiency for each diameter from

$$\text{Minimum eff.} = \left[\frac{(\text{inlet average} - 1\sigma) - (\text{outlet average} + 1\sigma)}{\text{inlet average} - 1\sigma}\right]100$$

(5) similarly, calculate a maximum efficiency

$$\text{Maximum eff.} = \left[\frac{(\text{inlet average} + 1\sigma) - (\text{outlet average} - 1\sigma)}{\text{inlet average} + 1\sigma}\right]100$$

These maximum and minimum values are plotted as bars in Figure 11.

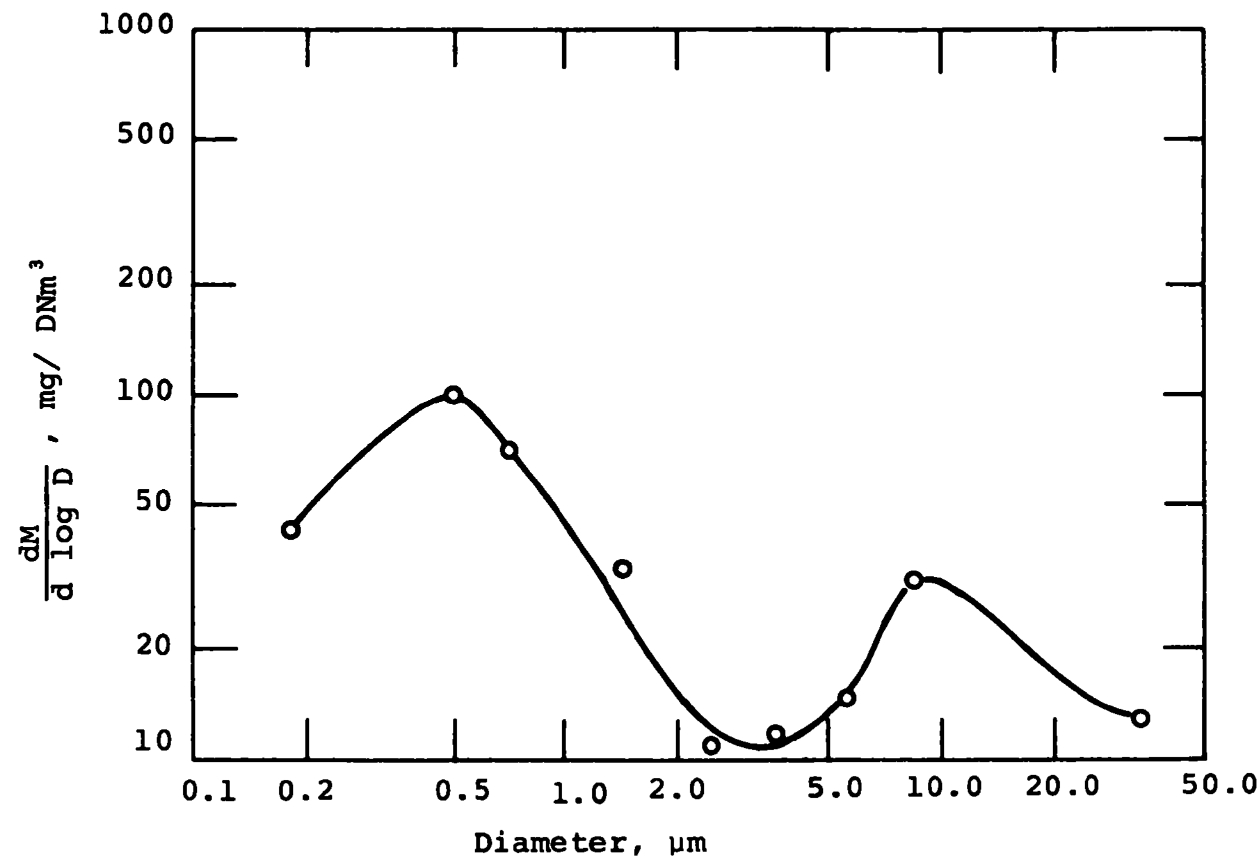

Figure 9. Inlet differential size distribution

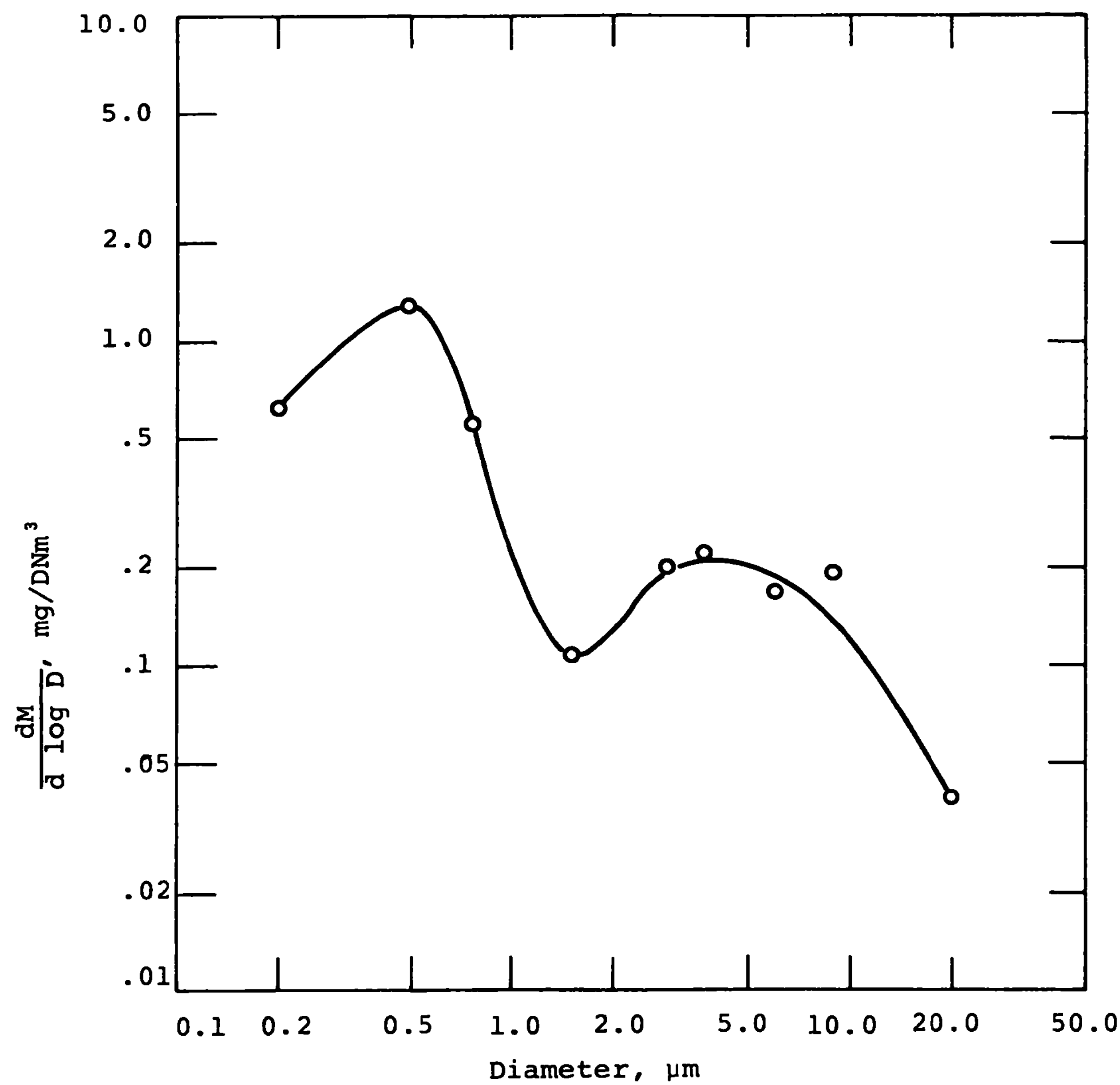

Figure 10. Outlet differential size distribution

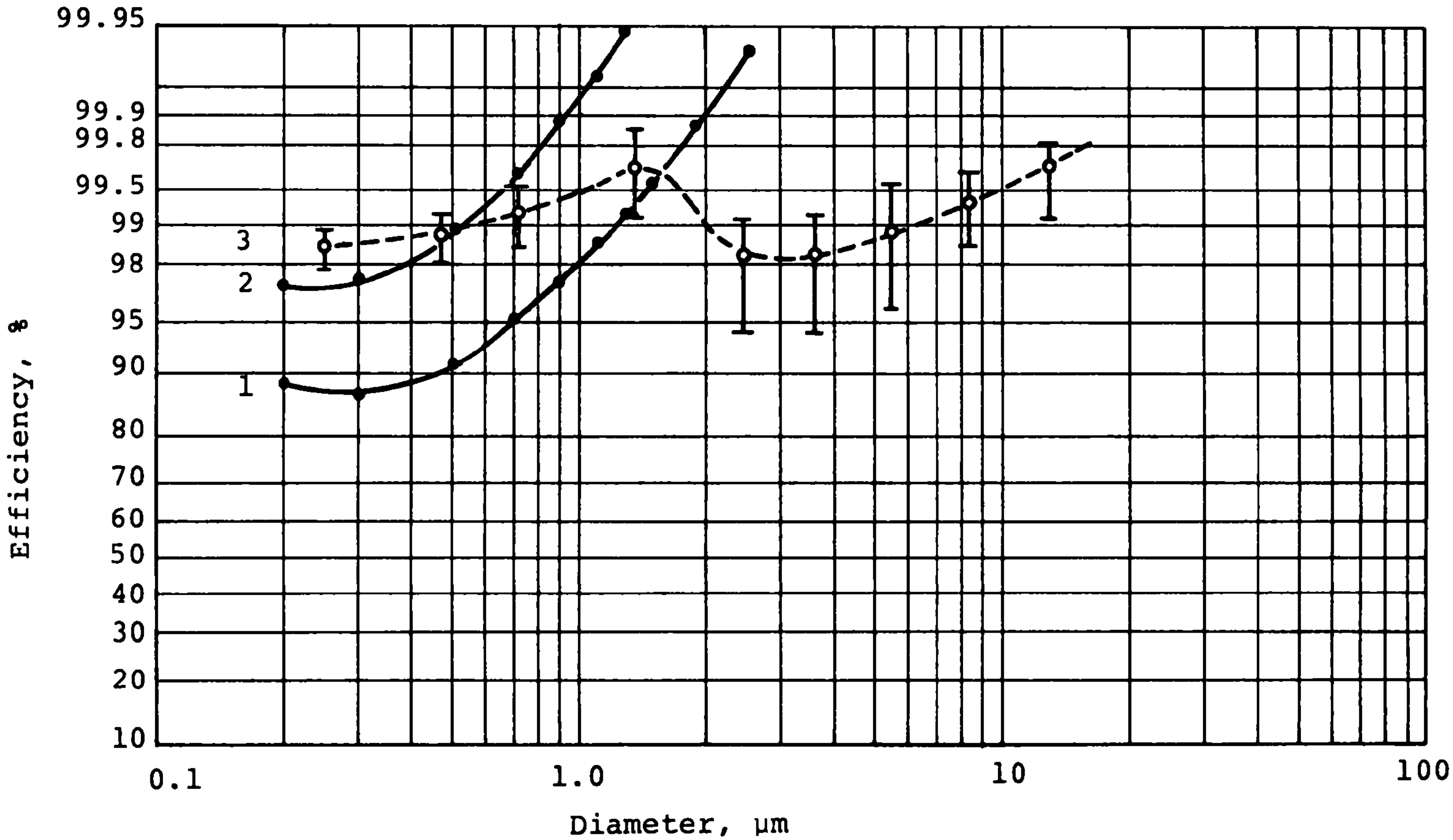

Figure 11. Andersen fractional efficiency data

1. Computed from modified field and diffusion charging calc.
2. Computed from a charging theory developed by Smith and McDonald[3]
3. Andersen data

The apparent decrease in efficiency which occurs between 1.4 and 2.0 μm in diameter in Figure 11 is a reflection of the second peak which occurs on Figure 10. Also plotted on Figure 11 are curves obtained from a mathematical model of an electrostatic precipitator developed by SRI under EPA contract. These computer curves and the results obtained from the impactor data are discussed further in a subsequent section.

It should be noted that the diameters reported here for the inertial data are based on an assumed particle density of 2.0 grams/cm^3. If the true densities are lower than this value, the diameters as given should be increased by a factor equal to the square root of the ratio of the assumed density to true density.

OPTICAL AND DIFFUSIONAL MEASUREMENTS

Since it was necessary to obtain optical and diffusional data at different times for the inlet and outlet, source stability was investigated by obtaining particle concentration as a function of time data with the optical and diffusional sampling system at the outlet. A representative data set is shown for the condensation nuclei counter and optical particle counter in Figures 12 and 13. The CN counter and the 0.3-0.5 μm channel on the optical counter are reasonably stable, but the 0.5-0.7 μm and the 0.7-1.3 μm channels show a considerable decrease with time. However, the indicated variations are small in comparison with those observed on effluents from other metallurgical processes. These data suggest that the process was stable enough to enable meaningful nonsimultaneous measurements. Figure 14 gives the cumulative size distribution on a number basis for this test series and several other sources which have been tested by SRI with this equipment.

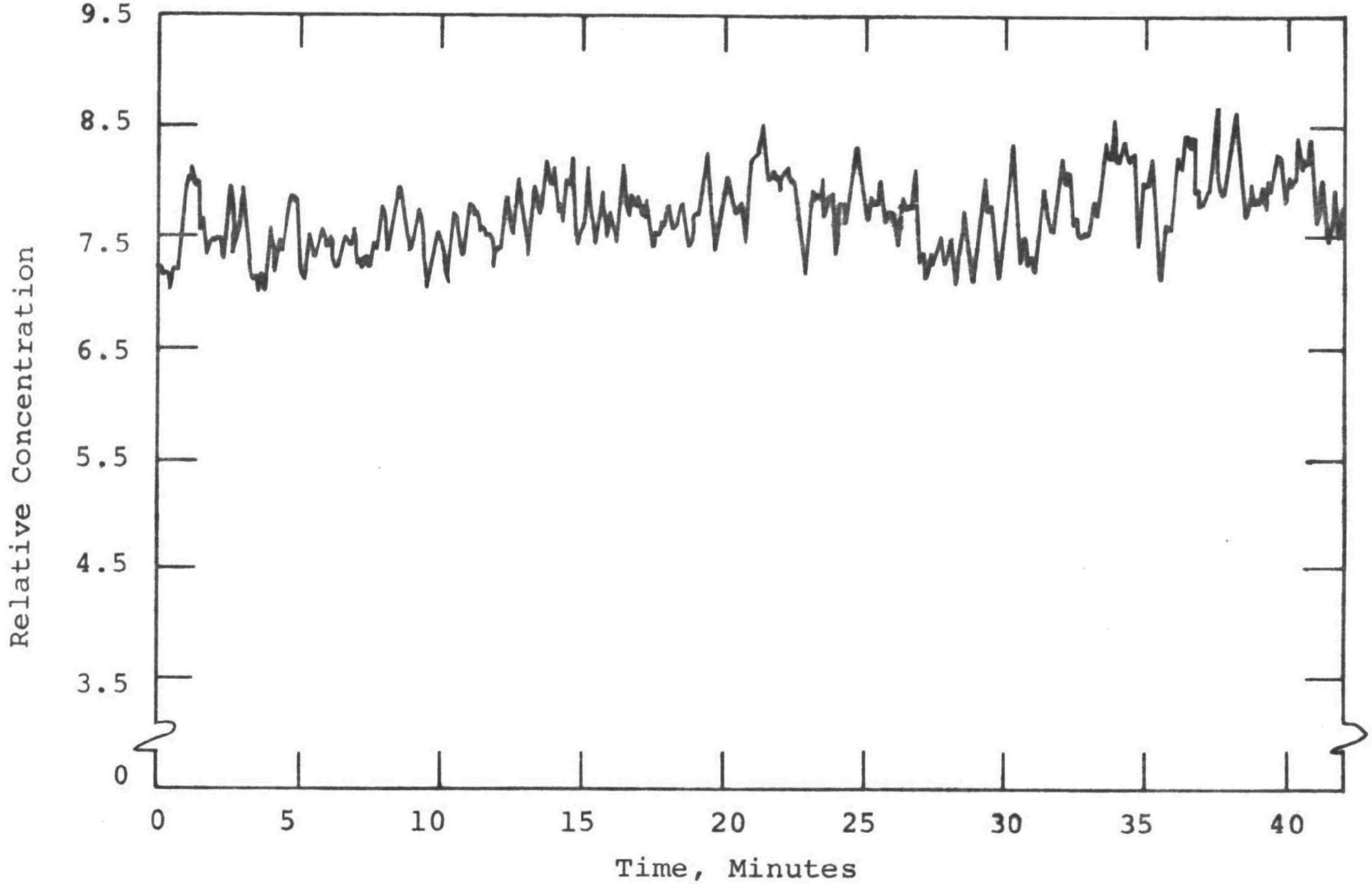

Figure 12. Relative Concentration Variation from Condensation Nuclei Counter

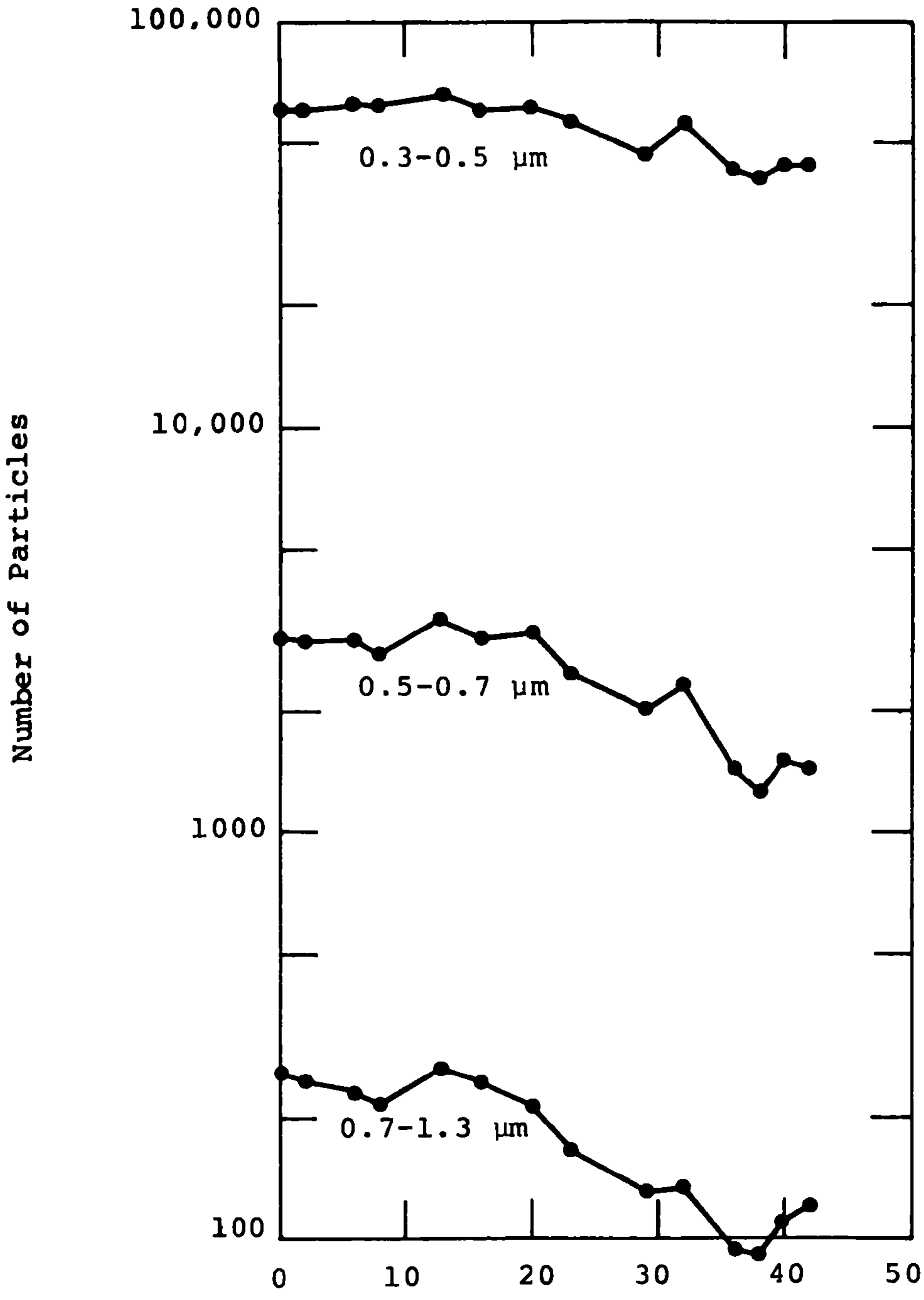

Figure 13. Relative concentration variation from optical particle counter

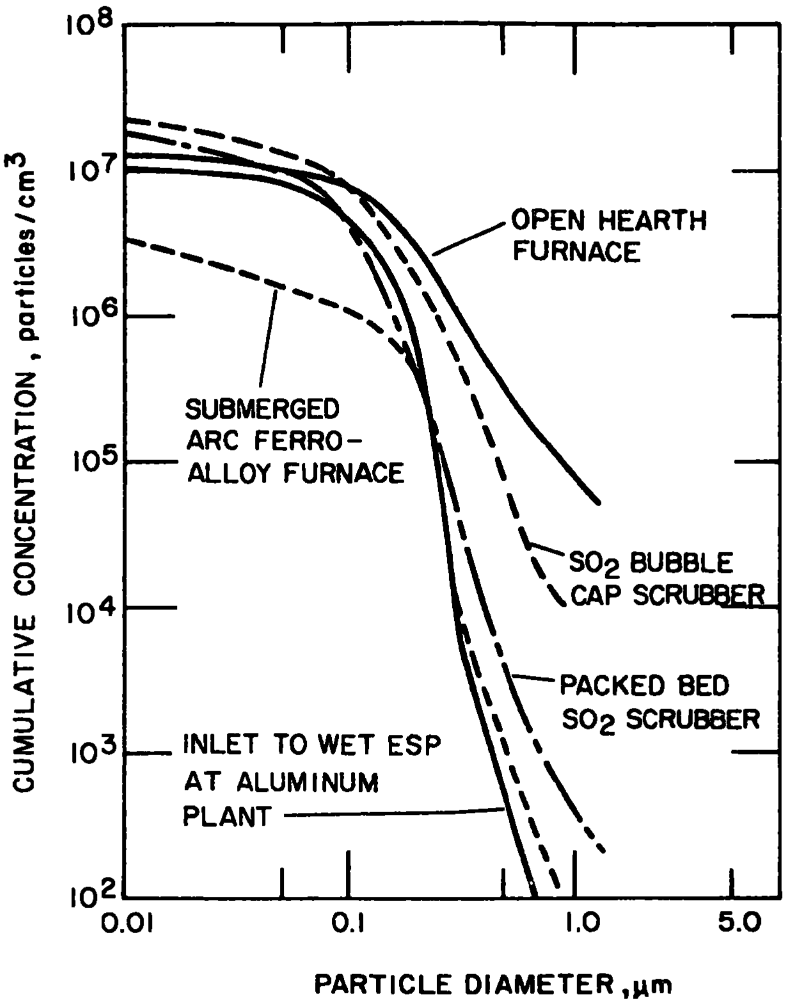

Figure 14. Cumulative size distributions on a number basis for various industrial particulate sources as measured by optical and diffusional methods

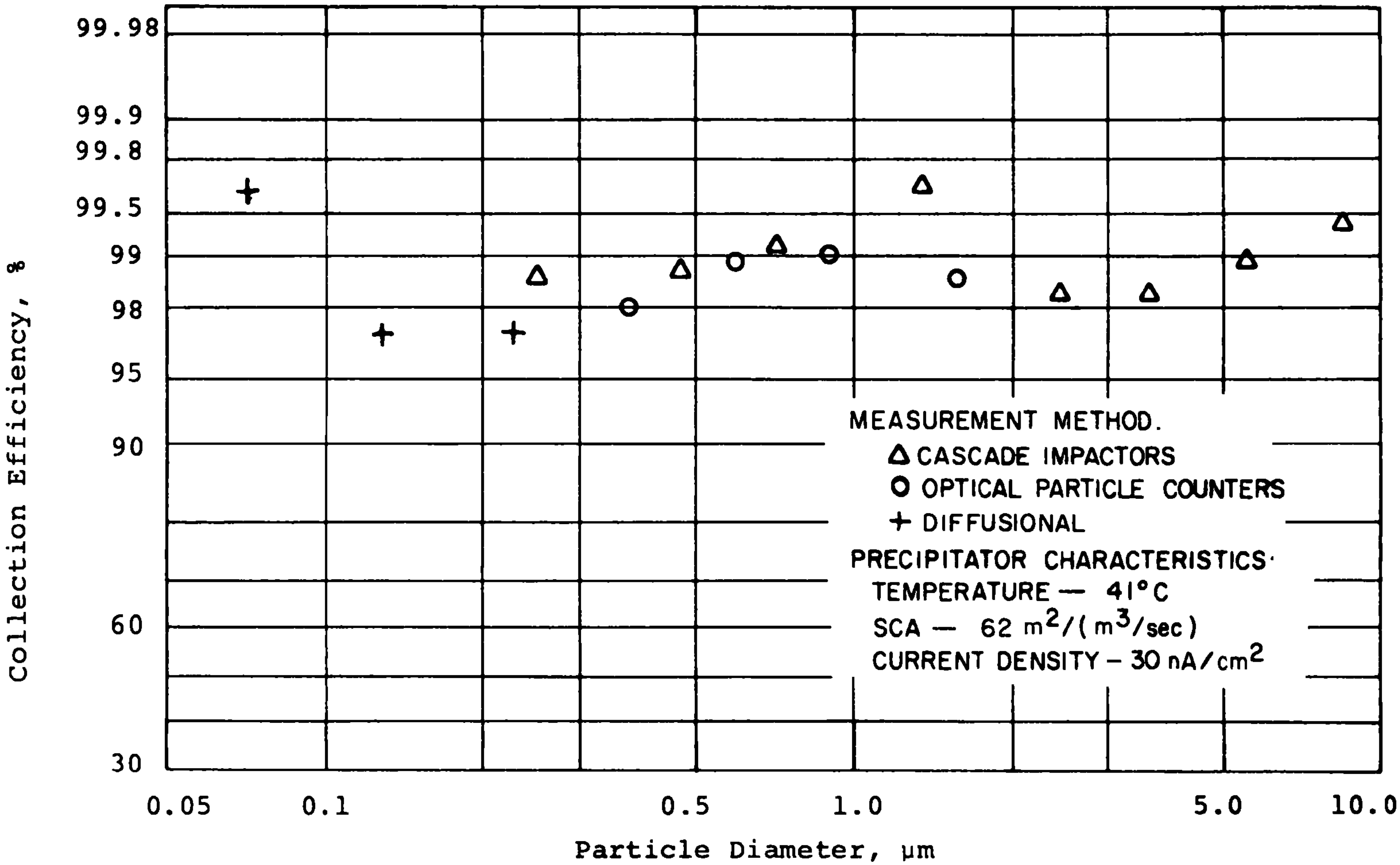

Figure 15. Measured fractional efficiencies for a wet electrostatic precipitator with the operating parameters as indicated, installed downstream of a spray type scrubber on an aluminum reduction pot line.

Fractional efficiencies were computed from the optical and diffusional data, based on inlet measurements conducted on August 20 and 21, and outlet measurements conducted on August 22 and 23. Figure 15 gives the results of these calculations, together with the inertially determined fractional efficiencies. The optical and inertial efficiency data show fair agreement over the size range 0.3 to about 0.7 μm. However, when the optically determined particle concentrations were converted to mass using a density of 2.0 g/cm^3, the mass loadings obtained were consistently much lower than those obtained for the same size interval with the Andersen impactors. These observations suggest that the Andersen impactors were collecting mass which was not detected by the optical particle counter at both the inlet and outlet.

A pronounced increase in the collection efficiency is indicated by the diffusional methods for particle sizes below 0.1 μm but larger than 0.05 μm. This behavior is consistent with theoretical considerations and has been observed at other installations utilizing electrostatic precipitators.[4]

MASS LOADING MEASUREMENTS

Mass train measurements were obtained by Guardian Systems, Inc., of Anniston, Alabama under subcontract to Southern Research Institute on August 20, 21, 22, and 23. The results of these measurements are given in Table 4. Results obtained by a local pollution control agency on October 9-10, 1973 are given for comparative purposes in Table 5. In general, fair agreement is expected between the total mass loading obtained with cascade impactors and that obtained with a mass train. A comparison of the total average mass loading obtained with the Andersen impactors at the inlet

Table 4. MASS TRAIN TEST RESULTS - 553 WET ESP

	Inlet				Outlet			
Run No.	1	2	3	4	1	2	3	4[4]
Date	8/20	8/21	8/22	8/23	8/20	8/21	8/22	8/23
Sampling Time, min.	300	250	280	310	376	375	375	360
H_2O, % by vol in gas	5.09	4.91	5.45	6.03	5.19	4.96	5.22	5.95
Avg. Gas Temp., °C	40.9	40.9	40.9	40.9	[2]34.2	38.1	38.1	38.1
[1]Flow, am^3/sec	67.2	62.5	54.9	62.5	44.6	43.5	44.4	43.9
[3]Flow, DN m^3/sec	55.4	51.7	45.1	51.1	37.6	36.3	36.9	36.3
mg/am^3	89.0	94.5	95.7	100.9	4.58	4.26	3.57	1.97
gr/acf	0.0389	0.0413	0.0418	0.0441	0.00200	0.00186	0.00156	0.00086
gr/Dscf	0.0443	0.0449	0.0476	0.0494	0.00220	0.00209	0.00166	0.00098
Efficiency, %					95.03	95.34	96.51	98.02

Notes:
1. Based on traverse across one sampling port and area of 3.05 m^2(32.85 ft^2) - see text.
2. Based on traverse across one sampling port and area of 3.54 m^2(38.10 ft^2).
3. 0°C and 760 mm Hg.
4. Obtained at a single point near the center of the stack.

(Table 2) with the average inlet mass loading from Table 4 indicates that the impactors collected about 90% of the material collected by the mass train. A total average mass loading of 0.0426 gr/acf was reported by Hofer[5] from 37 tests on the outlet of one of the spray towers at this plant site. These results are consistent with those reported in Tables 2 and 4. The inlet gas flows reported in Table 4, however, are anomalously high. Possible reasons for these results are: 1) there may have been an undetected calibration error in the stack sampling system used at the inlet, 2) the velocity profile obtained at the single port available for the mass train measurements may be nonrepresentative of the average flow. The outlet flow rates reported in Table 4 are considered to be the correct flow rates since they show good agreement (within about 5%) with those obtained by a local pollution control agency.

In contrast to the agreement shown between mass loadings obtained with the Andersen impactors and the mass train at the inlet, severe disagreement was obtained at the outlet. The total mass obtained with a traverse using the mass train at the outlet was greater than that collected with the impactors by a ratio of approximately 5 to 1. When the mass filter was operated near the center of the stack and the sampling location used for the impactors, the disagreement was reduced to a ratio of about 3 to 1. A comparison of outlet loadings between Tables 4 and 5, however, indicates that the mass train results obtained during this test series are in fair agreement with those obtained previously by a local pollution control agency. Note that the Andersen data in Table 3 and the mass data in Table 4 show good reproducibility.

Table 5. RESULTS FROM TESTS CONDUCTED BY A LOCAL POLLUTION CONTROL AGENCY
October 9 and 10, 1973

[1]Total particulate, LVS	0.0029 gr/Dscf = 7.02 mg/DNm^3
[2]Total particulate, IVS	0.00208 gr/Dscf = 5.03 mg/DNm^3
Percent water vapor	5.2%
Gas flow	99,000 acfm = 46.7 m^3/sec

[1]Low volume sampler.

[2]Intermediate volume sampler.

Reasons which have been hypothesized for the disagreement between the Andersen impactor and the mass train data are:

- The conditions in the impactor lead to evaporation of gross amounts of previously condensed hydrocarbons.
- Relatively large water droplets, containing about 5% by weight of dissolved solids, were collected by the mass filter, but not by the impactor. Evaporation of these droplets would leave a residue which could account for the greater mass observed with the mass filter.

In an effort to resolve the disagreement, the substrates from one Andersen run and the outlet filters from runs 3 and 4 of Table 4 were submitted to Southern Research Institute's Analytical Services Section for analysis with a gas chromatograph (GC). The objective of this analysis was to determine the relative volatility and approximate mass, if possible, of the hydrocarbons remaining on the filters and fiberglass substrates. The instrument and conditions used were as follows:

Instrument:	Hewlett Packard Model 5750B, with Flame Ionization Detector
Column:	10% UC W-98 on Gas Chrom Q
Temperature:	25°C to 250°C at 30°C/min-held at maximum
Standards:	C_8, C_{12}, C_{16}, C_{22} in CS_2 at concentration of 100 μg/ml CS_2
Sensitivity:	∿1 μg/ml sample
Extraction:	Extract filter or substrate, or a portion thereof, with 1 ml of CS_2

Five ml of the CS_2 extract were injected into the GC at the conditions stated above. Analysis of the standard solutions of hydrocarbons under these same conditions gave the following results.

Compound	Retention Time, min
Octane, C_8	4.3
Dodecane, C_{12}	7.4
Octadecane, C_{16}	11.4
Docosane, C_{22}	20.0

The retention time of extracts of the filters and substrates indicated that very little of the hydrocarbons were in the C_6 to C_{12} retention time range. The major components were eluted at times greater than that indicated for C_{16}. It is apparent from these results that the hydrocarbons remaining on both the filters and substrates are relatively non-volatile, and therefore, the discrepancy cannot be explained by comparing the volatility and mass of the hydrocarbons remaining. It is possible, however, that if the above analyses were conducted immediately upon removal of the sampling devices from the stack, that significant differences may have been observed between the hydrocarbons on the filters and substrates.

It is our conclusion that the most probable cause of the mass loading discrepancy is the collection of large water droplets containing solids by the mass filter. Such droplets would be subject to stratification in the stack, and this is qualitatively indicated by the decrease in loading which occurred when the mass train was operated at a single point. Additional work with a traverse using a sampling device designed to provide sizing information above 10 μm diameter would be required to resolve the problem.

SECTION V

DISCUSSION

DESCRIPTION OF THE WET ELECTROSTATIC PRECIPITATOR

The wet electrostatic precipitator on which this test series was conducted is a wire and plate design with three electrical sections in series in the direction of gas flow. Plate-to-plate spacing is 30.5 cm (1 ft), and each collecting electrode is 1.83 m long (6 ft) and 7.52 m high (25 ft). Thus, the total parallel plate collecting electrode length is 5.48 m, or 18 ft. Each electrical set powers 28 gas passages. Figures 16 and 17, taken from the manufacturer's literature, illustrate the overall precipitator arrangement and the electrode design, respectively. The total parallel plate collecting area is 2342 m^2(25,200 ft^2), and the "transverse baffles", which are perpendicular to the gas flow, provide additional collecting electrode area. The effective collecting area provided by these baffles was estimated as 390 m^2(4200 ft^2), resulting in a total collection area of 2732 m^2(29,400 ft^2). Average specific collecting area during the test series was therefore 62 $m^2/(m^3/sec)$, or 315 $ft^2/(1000\ cfm)$.

Electrode irrigation is provided by sprays at the precipitator inlet and above the collection plates. The sprays provide a mist which is collected along with the particulates in the flue gas, and the electrode cleaning is accomplished by the coalescence and subsequent downward flow of the collected spray droplets. The sprays are operated continuously, except for those installed near the precipitator outlet, which are operated only periodically. These spray nozzles were not in operation during the test program.

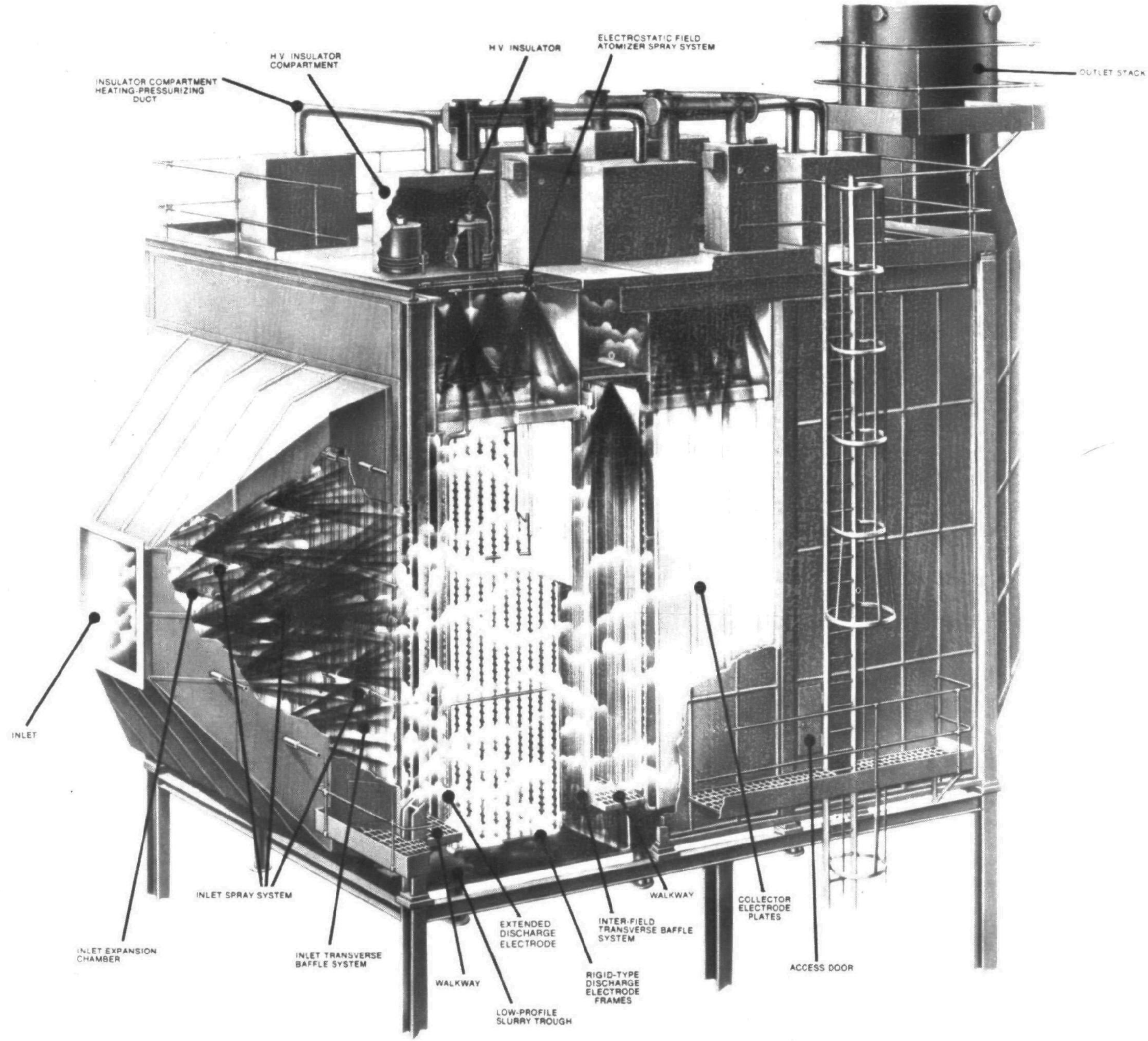

Figure 16. Wet electrostatic precipitator

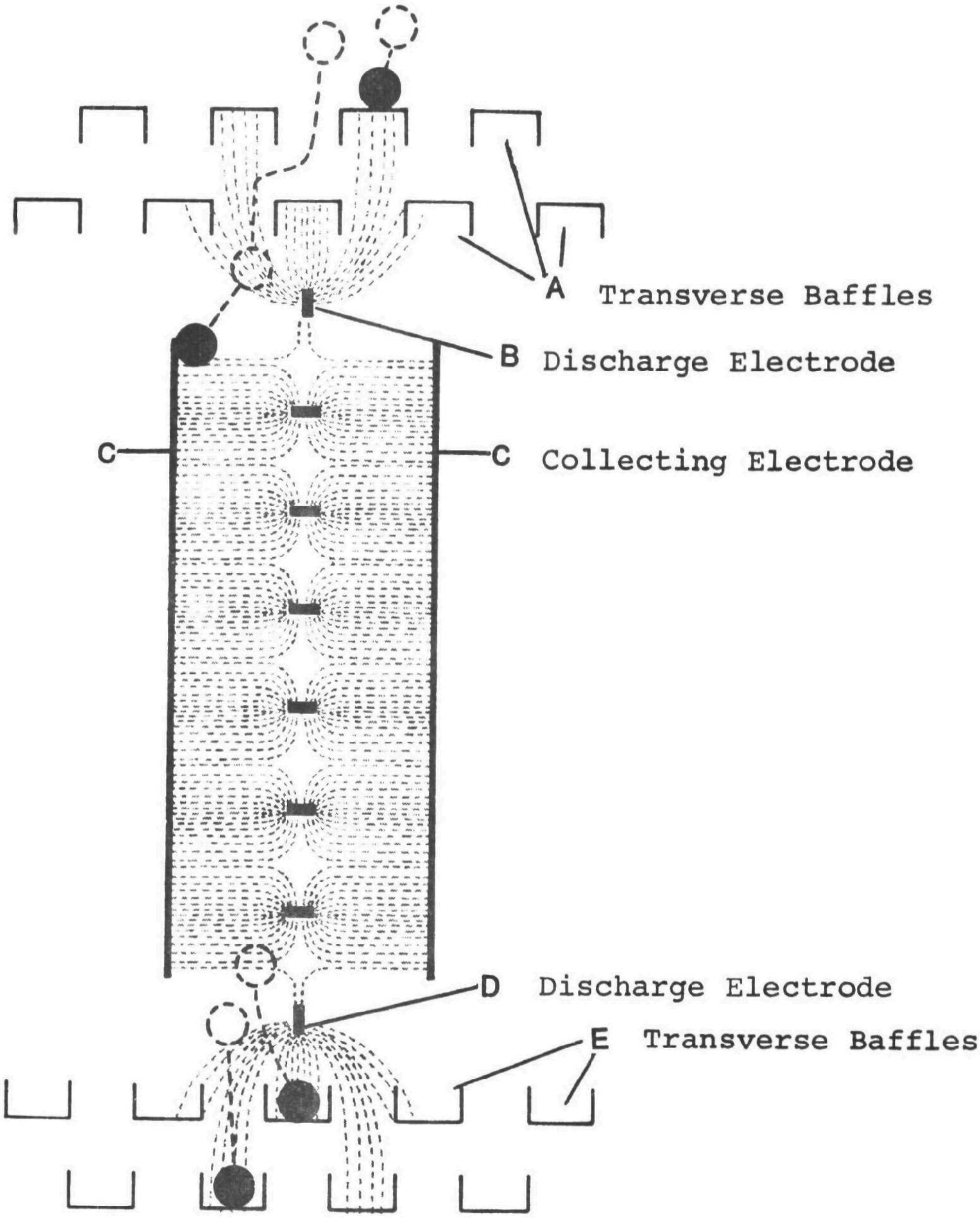

Figure 17. Schematic of electrode arrangement

Table 6, provided by the manufacturer,[1] summarizes the specifications for the wet precipitator installation. The irrigating fluid is a high pH sodium based liquid which is returned to clarifiers and a cryolite recovery plant. Plant personnel reported that the cryolite recovery system is essentially a closed liquid loop, which results in a solids content of about 5% by weight being returned to the wet ESP - scrubber system. Liquor flow through the wet ESP during the test program was constant at 31.5 l/sec (500 gal/min), which gives a liquid to gas ratio of about 0.7 l/m^3 (5.3 $gal/1000\ ft^3$). Liquor temperature, based on measurements reported by plant personnel, ranges from 90 to 104°F, and is usually 94 to 95°F. No significant temperature drop has been observed in the liquor loop across the precipitator.

ELECTRICAL CONDITIONS

Voltage and current readings were obtained from the panel meters of the 553 precipitator periodically during the test program. These data are given in the Appendix, Table A-2. At the conclusion of the test program, voltage-current curves were obtained for the unit with the spray system operating normally. The secondary voltage-current relationships are given in Figure 18, along with the range of operation that was observed for each electrical set during the test program. The difference between the voltage-current curves and the operating ranges is a result of the fact that, in normal operation, the power supplies are operating under automatic control with a certain spark rate, whereas the V-I curves were obtained by manually increasing the applied voltage until sparking occurred. The plant personnel were operating the power supplies at a spark rate which was believed to maximize the time-averaged electric field.

Table 6. SUMMARY OF SPECIFICATIONS FOR THE WET ELECTROSTATIC PRECIPITATORS[1]

Gas Flow	100,000 scfm, or 47.2 m^3/sec at standard conditions
Inlet Temperature to Scrubbers	121°C
Inlet Temperature to WESP	38.1 - 43.7°C
Total Particulate Inlet Loading (solids and condensables, excluding water)	0.05 gr/scf, or 0.114 g/m^3 at standard conditions
No. of Electrostatic Fields	3
Liquor, Flow Rate at 60 psi (5.08 atm. absolute)	500 gpm or 31.5 l/sec
Liquor, pH in	7-10
Outlet Loading for an Inlet Loading of 0.05 gr/scf or less (0.114 g/m^3)	0.003 gr/scf, or 0.0069 g/m^3 at standard conditions
Minimum Collection Efficiency for Outlet Loadings Greater than 0.003 gr/scf (0.0069 g/m^3)	95%
Face Velocity	2.38 ft/sec, or 0.726 m/sec
Maximum Pressure Drop	1" W.G., or 2.54 cm
Treatment Time	10.1 sec
Housing Material, Hot Rolled MS, Thickness	3/16", or .476 cm
Collection Plates, Hot Rolled MS, Thickness	10 GAUGE
Discharge Electrodes, Flatbars MS	1" x 1/8", or 2.54 cm x 0.318 cm
Piping Materials	PVC
Spray Nozzles, SS 316, Type	Full Cone
No. of Transformer Rectifiers	3
Rectifier Type	Silicone
Wave Form	Full
Minimum Output per T-R Set	60 kV, 1000 ma
Primary Voltage	480 V, 60 Hz
Manual and Automatic Voltage and Spark Rate Control	

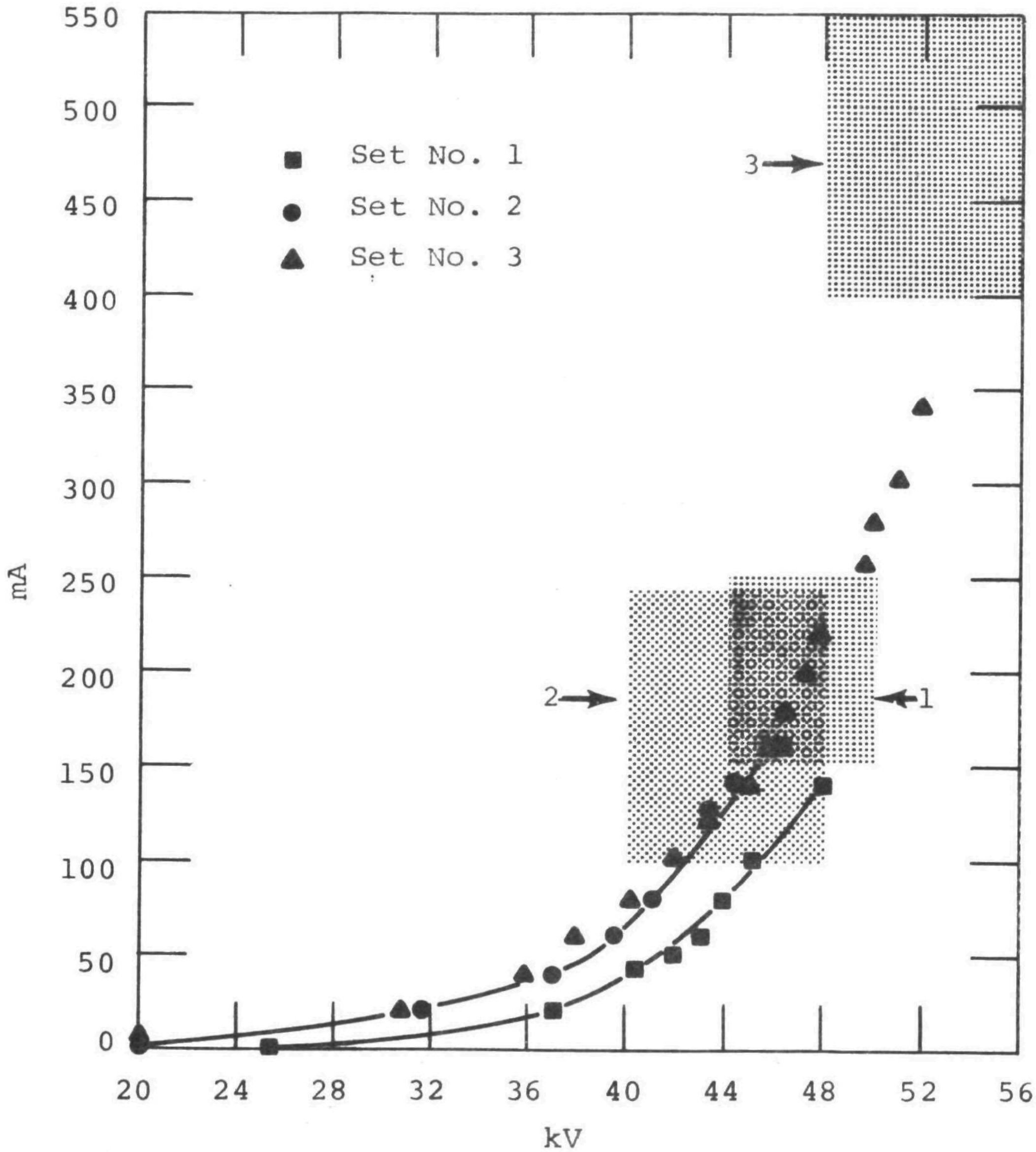

Figure 18. Voltage current relationship (Manual Control) and operating ranges (Automatic Control)

The V-I curve for the first electrical set is shifted toward high voltages for a given current when compared with readings from the other electrical sets. This behavior is often observed and is a reflection of the higher space charge density contributed by the higher particulate loadings which exist in the inlet field. Although the third field operates at a relatively high current, the average current density for all three sets was only about 30 na/cm^2. The current density limitation was imposed by sparking, since the electrical resistivity of the particulate is not a factor in the wet mode of operation.

COMPARISON OF RESULTS WITH THEORETICAL PREDICTIONS

Figure 11 presented the inertially determined fractional efficiencies and two predicted curves obtained from a theoretically based computer model of an electrostatic precipitator.[6] This mathematical model calculates theoretically expected collection efficiencies for representative particle diameters as a function of precipitator operating conditions. Predicted collection efficiencies for each particle diameter are a function of the electric field, the charge on the particle, and the ratio of collection area to gas volume flow rate. Curve 1 was based on a procedure for calculating particle charge as described by Gooch and Francis,[6] whereas curve 2 was based on a recently developed particle charging theory described by Smith and McDonald.[3] The latter charging theory gives better agreement with the available experimental data on particle charge over the indicated diameter range, and is therefore considered to be the preferred basis for predicting collection efficiencies. It can be seen that fair agreement is obtained between curve 2 and the inertially determined efficiencies over the particle diameter range 0.25-1.3 μm, but that the measured values depart drastically from the predictions at diameters larger than 1.5 μm. This apparent departure from the expected functional form may be caused by the generation of particles within the device, possibly originating from the liquid sprays or from reentrained liquid that is not captured by the outlet transverse baffles, which are considered by the manufacturer to function as an electrostatically augmented mist eliminator. It should be noted that the diameter band 0.25-1.3 μm, based on the Andersen measurements, represents 54% of the mass at the inlet and 56% of the mass at the outlet.

Since a major portion of the particulate entering the precipitator is known to consist of condensed hydrocarbons, it is of interest to consider the effect of dielectric constant on predicted collection efficiencies. The predictions shown in Figure 11 were based on the assumption that the particulate in the wet environment may be characterized by high values of dielectric constant. In order to examine the effect of low values of dielectric constant on the predicted efficiencies, the computer program for calculating particle charge used in obtaining curve 2 on Figure 11 was employed with dielectric constants (ε) of 2 (the lowest value which might be representative of a hydrocarbon droplet) and 100. The results of these calculations are presented in Table 7.

Table 7. EFFECT OF DIELECTRIC CONSTANT ON PREDICTED PENETRATION (Smith-MacDonald Theory Used for Calculating Particle Charge)

Particle Diameter, μm	Penetration, % for ε = 100	Penetration, % for ε = 2
0.2	2.95	3.45
0.50	1.135	1.88
0.70	0.384	0.82
1.30	0.011	0.05
1.70	9.1×10^{-4}	0.007

It can be seen that this range of variation of dielectric constant has a significant effect on predicted performance, with the largest effect being observed for the larger particles. Since the particulate consist of both organic and inorganic matter in a wet atmosphere, it is reasonable to expect a major portion of the mass would exhibit a relatively high dielectric constant under these conditions.

Electrostatic precipitator performance is often described by an empirical performance parameter termed the precipitation rate parameter. The parameter is obtained by evaluating the Deutsch equation using the overall mass efficiency and the ratio of volume flow to plate area:

$$w_p = \frac{V}{A} \ln \left(\frac{100}{100-\eta}\right)$$

Evaluation of this relationship using the data in Table 4 gives the results presented in Table 8. A predicted precipitation rate parameter may be obtained from the computer model based on the inlet size distribution obtained from the Andersen impactor measurements. Based on the predicted efficiencies indicated by curve 2 of Figure 11, numerical integration over the inlet size distribution gives a total predicted penetration of 1.1% (98.9% efficiency), and predicted precipitation rate parameter of 7.3 cm/sec, which shows fair agreement with the data in Table 8. Figure 11 shows, however, that the model underpredicts fine particle collection efficiencies, and overpredicts collection for particles larger than about 0.60 μm.

Table 8. PRECIPITATION RATE PARAMETERS

Run No.	Gas flow, m^3/sec	Mass Efficiency, %	Precipitation Rate Parameter, cm/sec
1	44.6	95.03	4.90
2	43.5	95.34	4.88
3	44.4	96.51	5.45
4	43.9	98.02	6.30

QUALITATIVE COMPARISON OF MASS MEASUREMENTS

Results obtained from performance tests on precipitators collecting fly ash from coal-fired boilers usually indicate that: 1) the mass obtained from the particle size measuring techniques used during this test series are in fair agreement with each other in the regions of overlap, and 2) the total mass from the impactor measurements is in fair agreement with the mass train determinations. The disagreement found during this test series is summarized qualitatively in Table 9.

Table 9. QUALITATIVE COMPARISON OF MASS MEASUREMENTS

Inlet	Outlet
Andersen $\cong$ mass train	Mass train > Andersen
Brink < Andersen	
Andersen > optical	Andersen > optical

Andersen efficiency $\cong$ optical efficiency

Since the results obtained by each measurement technique were fairly reproducible, we conclude that the disagreement was caused by sampling procedures or conditions peculiar to each of the instruments. The Andersen impactor results appear to provide the best data for fine particle collection efficiencies and mass loading in the fine particle range, whereas the mass train data should be used to obtain the overall particulate collection efficiency and the total outlet mass loading. The optical data are believed to be less reliable, since dilution and out-of-stack sampling are required to obtain results.

COST ESTIMATES

The estimates operating power required for operation of the wet electrostatic precipitator is given in Table 10. If power costs are $0.01/kwh, the power costs would be about $27.00 per day of operation for the precipitator. Bakke[1] has reported that the installed flange to flange capital costs of the wet precipitator are between $3.00 and $4.00 per cfm, based on mild steel construction. The operators reported that their total costs for installing the wet precipitators at the reduction plant would approximate $18,000,000 or about $6.00/cfm.

Table 10. OPERATING POWER ESTIMATED FOR WET ELECTROSTATIC PRECIPITATOR NO. 553

Item	Basis	Power, kw
Power supplies	Primary meter readings	49.0
Pumping power	100 psig total head, 31.5 l/sec, 60% pump efficiency	36.0
Fan power	1.27 cm H_2O ΔP, 50% fan efficiency, 44.1 m^3/sec	11.0
Insulator heater power	6 kw/field, from Bakke[1]	18.0
	TOTAL	114.0 kw

SECTION VI
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SECTION VII

APPENDIX

TABLE A-1

POT OPERATIONS DURING TESTS

Date	Operation	Pot No.
Monday, 8/19/74	Pin and channel pull	630,633,639,553
Tuesday, 8/20/74	Flex raise	632,555
Wednesday, 8/21/74	Flex raise	638
	Pin and channel pull	632,637,555
Thursday, 8/22/74	Flex raise	629,640,641
	Pin and channel pull	638
Friday, 8/23/74	Flex raise	543
	Pin and channel pull	629,640,641

TABLE A-2

WESP #553
Voltage-Current Readings

Field No. 1

Prim. Amp.	Prim. Volts	Sec mA	Sec kV	Date	Time
35-45	290-310	100-250	40-48	8/19/74	11:30 am
50	300-310	200-250	42-48	"	1:30 pm
40-50	280-320	∿200	46-50	8/20/74	9:15 am
40-50	280-300	150-200	42-48	"	11:55 am
40-50	260-300	200-300	42-48	"	2:25 pm
40-55	280-310	150-250	46-50	"	4:25 pm
40-55	280-300	200-300	44-48	"	6:25 pm
30-55	280-320	150-250	42-50	8/21/74	8:50 am
35-55	280-320	150-250	42-50	"	11:10 am
40-55	260-300	200-250	44-48	"	2:50 pm
40-55	280-320	150-250	42-48	"	5:30 pm
40-55	260-300	150-220	44-48	8/22/74	8:45 am
50-60	250-280	180-250	42-48	"	1:55 pm
55-65	260-300	200-250	42-48	"	3:40 pm
35-55	290-330	150-250	40-48	8/23/74	8:30 am
35-55	280-320	150-250	42-48	"	1:10 pm
40-50	260-320	150-250	44-48	"	4:20 pm

TABLE A-2
(Continued)

WESP #553
Voltage-Current Readings

Field No. 2

Prim. Amp.	Prim. Volts	Sec mA	Sec kV	Date	Time
40-50	240-280	150-240	40-45	8/19/74	11:30 am
55	260-280	200	40-44	"	1:30 pm
45-55	260-280	150-200	40-46	8/20/74	9:15 am
55-65	240-280	200-250	40-48	"	11:55 am
50-60	240-280	150-250	40-48	"	2:25 pm
30-40	210-230	100-150	40-44	"	4:25 pm
40-50	200-220	100-150	40-44	"	6:25 pm
30-45	210-230	100-150	40-44	8/21/74	8:50 am
30-40	200-220	100-180	40-44	"	11:10 am
40-55	240-280	180-250	42-48	"	2:50 pm
45-55	220-260	180-250	42-48	"	5:30 pm
50-65	270-300	200-280	42-48	8/22/74	8:45 am
50-60	250-280	180-250	42-48	"	1:55 pm
55-65	260-300	200-250	42-48	"	3:40 pm
45-55	240-280	200-280	40-46	8/23/74	8:30 am
50-65	260-300	200-260	40-48	"	1:10 pm
40-55	260-300	180-240	42-46	"	4:20 pm

TABLE A-2
(Continued)

WESP #553

Voltage-Current Readings

Field No. 3

Prim. Amp.	Prim. Volts	Sec mA	Sec kV	Date	Time
90-100	320-360	350-600	50-54	8/19/74	11:30 am
90-100	340	500	50-54	"	1:30 pm
90-110	320-340	400-550	50-54	8/20/74	9:15 am
90-110	320-360	450-550	50-54	"	11:55 am
90-105	340-360	400-500	50-56	"	2:25 pm
90-100	320-360	400-550	50-56	"	4:25 pm
90-110	310-330	400-550	50-54	"	6:25 pm
90-110	340-360	450-550	48-54	8/21/74	8:50 am
80-100	300-360	400-500	50-58	"	11:10 am
95-105	340-380	400-500	50-56	"	2:50 pm
95-105	320-360	480-550	50-56	"	5:30 pm
90-110	300-340	350-500	48-56	8/22/74	8:45 am
95-110	320-360	450-550	48-56	"	1:55 pm
100-110	340-360	450-550	48-56	"	3:40 pm
90-110	340-380	400-550	50-58	8/23/74	8:30 am
95-110	340-360	450-550	50-56	"	1:10 pm
95-110	330-360	450-550	50-56	"	4:20 pm

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1 REPORT NO. EPA-650/2-75-033	2	3 RECIPIENT'S ACCESSION NO.
4 TITLE AND SUBTITLE Particulate Collection Efficiency Measurements on a Wet Electrostatic Precipitator		5 REPORT DATE March 1975
		6 PERFORMING ORGANIZATION CODE
7 AUTHOR(S) J. P. Gooch and J.D. McCain Southern Research Institute, Birmingham, AL 35205		8 PERFORMING ORGANIZATION REPORT NO SORI-EAS-74-415 3296-I
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		11 CONTRACT/GRANT NO 68-02-1308, Task 21
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		14 SPONSORING AGENCY CODE

15 SUPPLEMENTARY NOTES

16 ABSTRACT The report gives results of fractional and overall particulate collection efficiency measurements of a plate-type wet electrostatic precipitator (ESP) collecting fume from an aluminum pot line. Overall collection efficiencies, based on a mass train with an in-stack filter, ranged from 95.0 to 98.0%. The mass filter obtained much higher total outlet mass loadings than did the Andersen impactors, presumably because of large entrained liquor droplets which were captured by the mass traverse, but not by the single-point impactor measurements. The average minimum collection efficiency in the size range 0.2 to 1.0 micrometer diameter (based on the Andersen data) was 98.5%. Comparisons between measured (with Andersen impactors) and predicted collection efficiencies obtained from a mathematical model of an ESP indicated fair agreement in the size range 0.2 to about 1.3 micrometers. For larger particles, the collection-efficiency/particle-size relationship departed drastically from the expected pattern, possibly because of liquor carryover from the electrode irrigation system.

17. KEY WORDS AND DOCUMENT ANALYSIS

a DESCRIPTORS	b IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Air Pollution Control	13B
Dust	Stationary Sources	11G
Measurement	Particulate	14B
Electrostatic Precipitators		
Collection		
Efficiency		

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