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ON-SITE FIELD TESTS FOR STUDY OF LOW-RANK WESTERN COAL FLY ASH

Technical Summary Report, Field Test No. 3, Big Brown Station Electrostatic Precipitator

By
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John P. Gooch

February 1984

Work Performed Under Contract No. AC18-80FC10225

Southern Research Institute
Birmingham, Alabama

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ABSTRACT

This report describes the results of field and laboratory studies of combined NH_3 and SO_3 conditioning at the Big Brown Station of Texas Utilities Generating Company. This unusual combination of conditioning agents is used routinely at the Big Brown Station in order to improve the performance of the cold-side electrostatic precipitators. EPRI is interested in the Big Brown Station from the standpoint of increasing the understanding of flue gas conditioning mechanisms by studying the dual conditioning system used at this plant. The Big Brown Station is of interest to DOE because of its applicability to DOE-sponsored efforts to develop a data base on particulate characteristics and particulate control technologies for low-rank Western coals.

The primary objectives of this field study were to evaluate the performance of one of the Big Brown precipitators, and to obtain data on the concentration, composition, and size distribution of the fly ash, as well as the composition of the flue gas and the overall and fractional collection efficiencies of the precipitator. The laboratory studies of the Big Brown fly ash were intended to further characterize the ash both physically and chemically, and to study the attenuation of the electrical resistivity of the ash associated with the surface film produced by the dual conditioning process and by the use of SO_3 conditioning alone.

The Unit 2 precipitators, one of which was tested in this work, service a Combustion Engineering pulverized coal-fired boiler having a nominal generating capacity of 575 MW. The unit fires a Wilcox group Texas lignite that is mined on site. The lignite fired during this test program had an average heating value of about 7000 Btu/lb and an average ash content of about 17% on an as-received basis. Daily lignite samples showed considerable variability in the composition of the lignite during the test.

Flue gas analyses performed upstream and downstream of the SO_3 injection probes indicated that about 5 ppm of SO_3 was produced from the coal and an additional 9 ppm of SO_3 was contributed by the injection system. The SO_3 was injected ahead of the air preheater. The NH_3 was injected between the air preheater and the precipitator

at a rate of about 5 ppm. At the precipitator inlet, the measured NH_3 and SO_3 concentrations were both below 0.5 ppm. The NH_4^+ content of the fly ash collected at the ESP inlet accounts for about 76% of the NH_3 injected into the flue gas. At most, an additional 10% of the NH_3 is left in the gas phase, so that about 14% is not accounted for. The SO_4^{-2} content of the fly ash is greater than expected for complete adsorption of 14 ppm of SO_3. This may be due to additional uptake of SO_3 by the ash while it resided in the mass train filter, and was exposed to additional flue gas. It is suggested that the dual conditioning system results in a surface film on the fly ash that probably consists of $(NH_4)_2SO_4$ and/or NH_4HSO_4 dissolved in an aqueous solution of H_2SO_4, which results from the adsorption of the excess SO_3 and water vapor.

Laboratory studies showed that the as-received ash (i.e., the ash with the surface film on it) was more responsive to SO_3 conditioning than was the same ash after it had been heated to 450°C and the surface film had been driven off. This suggests that the presence of the NH_3 served to make the ash more receptive to SO_3 conditioning. This may be attributed to a reduction in the vapor pressure of the surface film due to the dissolution of the ammonium compounds in the acid. However, additional work would be required to further investigate this theory. The laboratory studies also showed a significant increase in resistivity after an as-received ash sample was heated to 450°C, and then brought back to the original temperature. This was attributed to the decomposition of the surface film, and the attendant loss of its beneficial effect on the electrical conduction process.

The overall performance of the Big Brown precipitator, in terms of collection efficiency and electrical operation, was quite good, especially considering its small size (SCA $\cong$ 166 ft^2/kacfm). The average mass efficiency determined by EPA Method 17 was about 98.5% with an average inlet mass loading of 6.64 gr/dscf. A plot of collection efficiency versus particle size, based on cascade impactor measurements, showed a minimum at about 0.8 μm. Above 1 μm the fractional efficiency curve was qualitatively consistent with theory. Well-behaved voltage-current curves were obtained for all of the T-R sets tested. The electrical conditions were apparently not limited by the resistivity of the ash, which was measured in the laboratory to be about 1×10^{10} ohm cm at 345°F and in the presence of about 0.3 ppm of SO_3. The in situ resistivity measurements were higher, but they were deemed unreliable because they exhibited an inordinate degree of scatter in the data, and they were inconsistent with the electrical operating conditions of the precipitator.

Given an ash resistivity of 1×10^{10} ohm cm, and assuming 10% gas sneakage around the electrified regions of the ESP and a 25% normalized standard deviation on the gas flow, the predicted efficiency for the Big Brown precipitator obtained by using a mathematical model was 98.5%, almost exactly equal to the average measured efficiency. This exact agreement is probably fortuitous, but it does indicate that there were no major mechanical problems with the precipitator.

ACKNOWLEDGMENTS

The authors are indebted to Texas Utilities Generating Company and their personnel at the Big Brown Station who provided assistance with this study. Special recognition should be given to: Mr. Tom Edling and Mr. Steve Payton, who served as our liaisons with the plant personnel; Mr. Ed Platt, the Plant Manager; and Mr. Billie Bonner and Mr. Richard White, with the TUGCo corporate offices.

The field test described in this report was performed by the Control Device Evaluation Section of Southern Research Institute, under the supervision of Mr. G. H. Marchant, Jr., with the assistance of personnel provided by Guardian Systems, Inc. The following Institute personnel participated in the field test: Messieurs R. S. Dahlin, W. R. Dickson, W. S. Hall, T. F. Hammond, C. V. Lindsey, S. C. Parsons, and M. R. Steele. Mr. Dickson also performed the chemical analyses and wrote the sections of this report dealing with the SO_x and NH_3 measurements and flue gas composition. Dr. R. E. Bickelhaupt supervised the laboratory resistivity work.

This work was jointly funded by the U.S. Department of Energy under Contract No. DE-AC18-80FC10225 and the Electric Power Research Institute under Contract No. RP724-2. The Project Managers were Dr. Ralph F. Altman of the Electric Power Research Institute and Dr. D. Richard Sears and Mr. Harvey M. Ness of the Department of Energy's Grand Forks Project Office. Dr. Sears is now associated with the University of North Dakota Energy Research Center.

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EXECUTIVE SUMMARY

The Big Brown Station of Texas Utilities Generating Company employs a combination of NH_3 and SO_3 injection to condition the fly ash from a relatively low-grade Texas lignite. Station personnel report that this dual conditioning system has been found to be more effective than either NH_3 or SO_3 injection alone in improving the performance of the cold-side precipitators at Big Brown. The mechanisms by which the dual conditioning system works are not fully understood.

The field and laboratory studies described in this report provide additional information concerning the combined NH_3-SO_3 conditioning process. This work provides some new understanding of the mechanisms, but it stops short of a definitive analysis. This is largely because field studies could not be done with one or both of the conditioning agents turned off. Nevertheless, laboratory studies have made it possible to infer some additional information concerning the role of SO_3 and NH_3 conditioning at Big Brown.

The precipitator tested in this study (ESP 2-1) services one-fourth of the flue gas generated by the Unit 2 boiler at Big Brown. The Unit 2 boiler is a Combustion Engineering pulverized-coal fired unit with a rated generating capacity of 575 MW. Both Units 1 and 2 fire a Wilcox group Texas lignite that is mined on site at the plant. Lignite samples taken from one of the Unit 2 feeders during the testing showed an average heating value of 7000 Btu/lb and an average ash content of 17% on an as-received basis. The daily samples also showed considerable variability in the lignite composition.

Laboratory studies indicate that the combined SO_3-NH_3 conditioning results in a surface film on the ash particles which reduces their resistivity by about one order of magnitude. This was found to be roughly comparable to the effect produced by equilibrating the ash with the level of SO_3 present in the gas phase at the ESP inlet. The ash containing the surface film (i.e., the as-received ash) was also found to be more receptive to SO_3 conditioning than the same ash with the surface film removed by thermally annealing the ash at 450°C overnight. This suggests that the NH_3 serves to make the ash more receptive to SO_3 conditioning. It is speculated that this may be due to a reduction in the vapor pressure of the surface film caused by the dissolution of the ammonium compounds in the excess acid on the particle surfaces. Additional work would be required to confirm this conjecture.

The soluble sulfate content of the ash was greater than expected for complete adsorption of the total amount of SO_3 present in the flue gas (5 ppm from the coal and 9 ppm from the injection system). This observation was attributed to additional uptake of SO_3 by the ash as it resided in the mass train thimble and was exposed to flue gas being pumped through it. About 76% of the injected NH_3 was found on the ash surface as NH_4^+, probably in either ammonium sulfate or ammonium bisulfate dissolved in the excess acid condensed on the ash surface.

In terms of electrical operation and collection efficiency, the performance of the Big Brown ESP was quite good, considering its small size (SCA = 166 ft^2/kacfm). The average mass efficiency determined by EPA Method 17 was about 98.5% with a mean inlet grain loading of 6.64 gr/dscf. The fractional efficiency curve for ESP 2-1, which was derived from cascade impactor measurements made at the inlet and outlet of the ESP, showed a minimum efficiency at about 0.8 μm. Above 1 μm the curve was qualitatively consistent with theory. All T-R sets tested had well-behaved voltage-current curves, and the electrical operating conditions of the ESP were apparently not limited by the resistivity of the ash. The actual resistivity of the conditioned ash is estimated to be on the order of 10^{10} ohm cm. This value was measured in the laboratory after equilibration of the as-received ash with the level of SO_3 present at the ESP inlet. This value is lower than the in situ resistivity data, which are inconsistent with the electrical operating conditions of the ESP. Using a resistivity of 1×10^{10} ohm cm along with typical non-ideal correction factors, the theoretically predicted collection efficiency for the Big Brown ESP is almost exactly equal to the measured value. The excellent agreement between theory and measurement may be partly fortuitous, but it does indicate that there were no significant mechanical or electrical problems with the ESP.

The field test results described here tend to confirm the assertions of plant personnel that the combined NH_3-SO_3 conditioning process may be a useful means of maintaining acceptable performance levels in a cold-side ESP. Additional work is still required, however, to determine whether this process can be more effective than using either SO_3 or NH_3 alone. A complete understanding of the mechanisms involved in NH_3-SO_3 conditioning would also require additional work. In particular, field measurements are needed with and without either agent and both agents in use. The effect of NH_3-SO_3 conditioning on rapping reentrainment also needs to be assessed.

Section 1

INTRODUCTION

This report deals with the second jointly-sponsored field test funded by the Department of Energy (DOE) and the Electric Power Research Institute (EPRI) under DOE Contract No. DE-AC18-80FC10225 and EPRI Contract No. RP724-2. The second jointly-sponsored field test was conducted at the Big Brown Station of the Texas Utilities Generating Company during the period of May 9-13, 1983. This report summarizes the results of the field and laboratory measurements. The field test conducted at the Big Brown Station was designed to satisfy the objectives of both the DOE and EPRI projects.

The primary objectives of DOE were to evaluate the performance of the precipitator and to obtain data on the concentration, composition, and size distribution of the fly ash, the flue gas composition, and the overall and fractional collection efficiencies of the precipitator, and to collect coal and size-fractionated ash for further characterization. EPRI's interest in the program was primarily concerned with developing data that could be used to increase the capability for predicting the resistivity of fly ashes of varying compositions as a function of temperature and SO_3 concentration in the flue gas. EPRI is also interested in the combined effects of NH_3 and SO_3 and their reaction products on ash resistivity, so the Big Brown Station was of particular interest since it employed a rather unusual conditioning technique utilizing both of these chemicals.

It is the ultimate objective of DOE to use the data developed from this field test, along with data from other similar tests, to assess the applicability of different types of control devices in controlling particulate emissions from the combustion of low-rank Western coals in utility boilers. It is also the intent of DOE to use these data in assessing the ability of the pilot-scale combustion facility at Grand Forks to reproduce the characteristics of the fly ash and flue gas produced by full-scale utility boilers.

Section 2

SITE SELECTION AND DESCRIPTION

The Big Brown Station was selected as the site of the second jointly-sponsored field test because it burns a low-grade Texas lignite which is of interest to DOE, and it uses a flue gas conditioning system of interest to EPRI. The site was specifically of interest to EPRI because of the opportunity to conduct testing with the combined SO_3 and NH_3 conditioning system mentioned previously.

The Big Brown Station is a mine-mouth facility located in Fairfield, Texas, about 80 miles southeast of Dallas. The plant consists of two pc-fired units. The boilers are Combustion Engineering natural circulation, balanced draft units, with a rated generating capacity of 575 MW each. The furnaces are tangentially fired. Both units fire a Wilcox group Texas lignite that is mined on site at the plant. The composition of the lignite is given in Section 3.

The ESP layout at Big Brown is illustrated in Figure 2-1. The flue gas stream exiting the boiler passes through two air preheaters and then through four separate casings of a Research-Cottrell cold-side, double-Chevron ESP. The flue gas enters the ESP at a nominal temperature of 370°F. One-fourth of the Unit 2 ESP was tested (ESP 2-1). The 2-1 ESP has two chambers with two electrical fields per chamber, as did all of the other precipitators on this unit. The ESP uses a weighted-wire discharge electrode design. The plate spacing is 9 in. All fields are equipped with standard 0.109-in. wire discharge electrodes. The collection plates are 30 ft in height and 9 ft in depth.

As mentioned previously, both SO_3 and NH_3 are injected into the flue gas. The SO_3 is injected ahead of the air preheater at a rate of 9 ppm. The NH_3 is injected between the air preheater and the ESP at a rate of 5 ppm. These injection rates were confirmed by flue gas analyses discussed later.

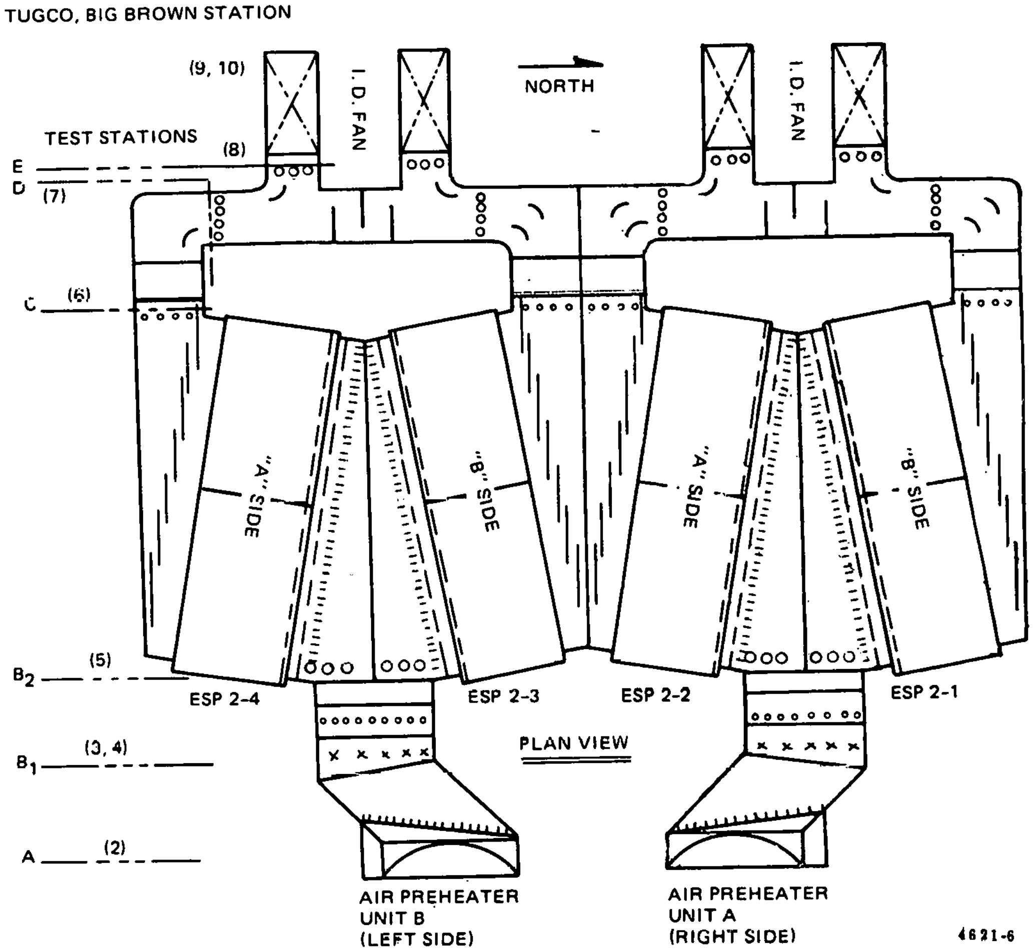


Figure 2-1 Big Brown ESP Layout

Section 3

FIELD TEST RESULTS

SAMPLING AND MEASUREMENT ACTIVITIES

A summary of the sampling and measurement activities performed during the Big Brown test is given in Table 3-1. EPA Method 17 (1) mass trains were used to determine the inlet and outlet mass loadings and the overall efficiency of the ESP. Calibrated cascade impactors were employed to quantify the inlet and outlet particle size distributions and the fractional efficiency of the ESP. The electrical resistivity of the fly ash was measured in situ using a point-plane probe. Relatively large samples of the fly ash were collected in a five-stage cyclone assembly for subsequent laboratory analyses at Grand Forks. The flue gas was sampled and analyzed for CO_2 using a Fyrite analyzer, for O_2 using a Teledyne portable O_2 meter, for H_2O by adsorption in Drierite tubes, and for SO_x using the Cheney-Homolya (2) sampling system. Twenty-five barrels of coal were collected from the Unit 2 coal feeder discharge. This coal was then shipped to Grand Forks for use in the pilot-scale combustor. More detailed descriptions of the sampling and analytical techniques and results are given later in this report.

CHARACTERIZATION OF COAL AND FLY ASH

Samples of the coal taken at the Unit 2 feeder discharge were submitted to Commercial Testing and Engineering Company of Birmingham for proximate and ultimate analyses. The results are given in Table 3-2. The very high ash content and low heating value make this lignite a relatively low-grade fuel. The analyses also indicate that the fuel composition varied considerably during the test period.

Fly ash samples collected in inlet mass train thimbles were analyzed by atomic absorption spectrometry using a digested sample which had been ignited at 750°C. The results are given in Table 3-3. Important features of these ash analyses are the low alkali metal content and high alkaline earth content which contribute to the high resistivity of this ash without SO_3. The loss on ignition was reasonably low.

The NH_4^+ content of the ash indicates that most of the injected NH_3 was adsorbed on the ash. Adsorption of 5 ppm of NH_3 onto fly ash particles having a mass loading of

Table 3-1

SAMPLING AND MEASUREMENT ACTIVITIES

Sampling Location	Measurement	Test Day 1	2	3	4	5	6
ESP inlet	Mass train (ESP Method 17)	T	S	+			P
	Impactor (modified Brink)	R	E		+	+	A
	In situ resistivity (point-plane probe)	A	T	+	+	+	C
	Five-stage cyclone (SoRI-EPA)	V		+	+	+	K
	Gas analysis (CO_2, O_2, H_2O, SO_x, NH_3)	E	U	+	+	+	
		L	P				A
							N
ESP outlet	Mass train (EPA Method 17)		E	+			D
	Impactor (University of Washington Mark III)		Q		+	+	
	Gas analysis (CO_2, O_2, H_2O, SO_x, NH_3)		U	+	+	+	T
			I				R
Coal feeder discharge	Coal sample		P	+	+	+	A
			M				V
			E				E
			N				L
			T				

Table 3-2

PROXIMATE AND ULTIMATE COAL ANALYSES
(as-received basis)[a]

	Date Sampled 5/10/83	5/11/83	5/12/83
Proximate			
% Moisture	21.07	29.37	31.51
% Ash	14.41	23.05	12.91
% Volatile	42.21	22.42	50.45
% Fixed carbon	22.31	25.16	5.13
Btu/lb	8,671	5,978	6,452
% Sulfur	0.91	0.85	0.73
Ultimate			
% Moisture	21.07	29.37	31.51
% Carbon	51.49	35.22	39.50
% Hydrogen	2.81	2.39	2.68
% Nitrogen	1.12	0.71	0.64
% Chlorine	0.06	0.05	0.05
% Sulfur	0.91	0.85	0.73
% Ash	14.41	23.05	12.91
% Oxygen[b]	8.13	8.36	11.98

---

[a] Samples taken from Unit 2 feeder discharge.

[b] Oxygen determined by difference.

Table 3-3

FLY ASH COMPOSITION[a]

Sample No. Date Time	BIGBI-1MT 5/10/83 1039-1237	BIGBI-2MT 5/10/83 1405-1632	BIGBI-3MT 5/10/83 1731-1919
% Li_2O	0.02	0.02	0.02
% Na_2O	0.40	0.34	0.32
% K_2O	0.81	0.94	1.1
% MgO	3.2	3.0	2.6
% CaO	15.2	13.4	11.3
% Fe_2O_3	6.2	5.8	6.2
% Al_2O_3	18.5	19.7	19.7
% SiO_2	49.8	52.3	54.5
% TiO_2	1.7	1.7	1.5
% P_2O_5	0.06	0.05	0.05
% SO_3	1.3	0.98	0.90
% LOI	1.6	1.1	1.2
% NH_4^{+b}	0.0265	0.0196	0.0201
% SO_4^{-2b}	1.2	0.98	0.84

---

[a] Samples taken from inlet mass train thimbles, and analyzed by AA after ignition at 750°C and digestion by standard acid attack.

[b] Soluble NH_4^+ and SO_4^{-2} on unignited ash. NH_4^+ determined by specific ion electrode; SO_4^{-2} by ion chromatography.

6.64 gr/dscf (the average measured mass loading) would be expected to produce an NH_4^+ concentration of 0.029% by weight, assuming complete adsorption. The mean measured NH_4^+ concentration (0.022%) represents 76% of this value.

The measured SO_4^{-2} content of the ash is higher than expected for complete adsorption of 14 ppm of SO_3. Assuming the same mass loading used above, this should produce a sulfate concentration of about 0.4%. However, the measured values ranged from 0.84 to 1.2%. The most likely explanation appears to be that the ash adsorbed additional SO_3 while it resided in the mass train thimble filter. An ash sample taken from one of the outlet ESP hoppers also had a relatively high SO_4^{-2} content as discussed in the section on the laboratory characterization of the ash.

METHOD 17 RESULTS AND MASS EFFICIENCY

Mass loadings were measured at the A side inlet to ESPs 2-1 and 2-2 and at the outlet of ESP 2-1 by EPA Method 17 (1). Each sampling location was traversed with mass trains equipped with in-stack filters. Isokinetic sampling was approximated as closely as possible at each sampling point. The measured mass loadings are given in Table 3-4. During this testing the boiler load was maintained fairly constant in the range of 560 to 580 MW, with excess air in the range of 13 to 19%. The stack opacity recorded by the plant transmissometer was between 26 and 32%.

Table 3-4

MASS TRAIN DATA

Run No.	Load (MW)	Temp. (°F)	SCA (ft^2/ kacfm)	Inlet Loading (gr/dscf)	Inlet Percent Isokinetic	Outlet Loading (gr/dscf)	Outlet Percent Isokinetic	Efficiency (%)	Opacity (%)
1	580	380	171	6.22	105.7	0.111	97.0	98.22	26.4
2	568	385	163	6.37	109.8	0.0783	99.4	98.77	27.5
3	566	385	165	7.32	109.9	0.120	99.1	98.36	31.8

During the test period the average flue gas flow rate through the A side of ESP 2-1 was 1.3 x 10^6 acfm at 370°F, resulting in an operating SCA of 166 ft^2/1000 acfm, almost exactly equal to the design value. The average inlet and outlet mass loadings were 6.64 and 0.103 gr/dscf, yielding an average efficiency of 98.45%.

PARTICLE SIZE DISTRIBUTIONS AND FRACTIONAL EFFICIENCY

The inlet and outlet particle size distributions were determined from in-stack cascade impactor sampling using modified Brink impactors at the inlet and University of Washington Mark III impactors at the outlet. Seven real impactor runs and one blank run were performed in separate sampling ports at the inlet, while six complete traverses of duct area were performed at the outlet with two blanks. Glass fiber substrates were used in the impactors. The blank runs did not reveal any appreciable substrate interference problems.

Figures 3-1 through 3-8 show the inlet and outlet particle size distributions determined from the impactor sampling. Figures 3-1 and 3-5 show the cumulative mass concentration of all particles smaller than the stated diameter, which was obtained by summing the masses collected on each impaction stage and dividing by the volume of flue gas sampled. In order to calculate the mass median diameters, the curves were extrapolated to the total mass concentration at an assumed maximum particle

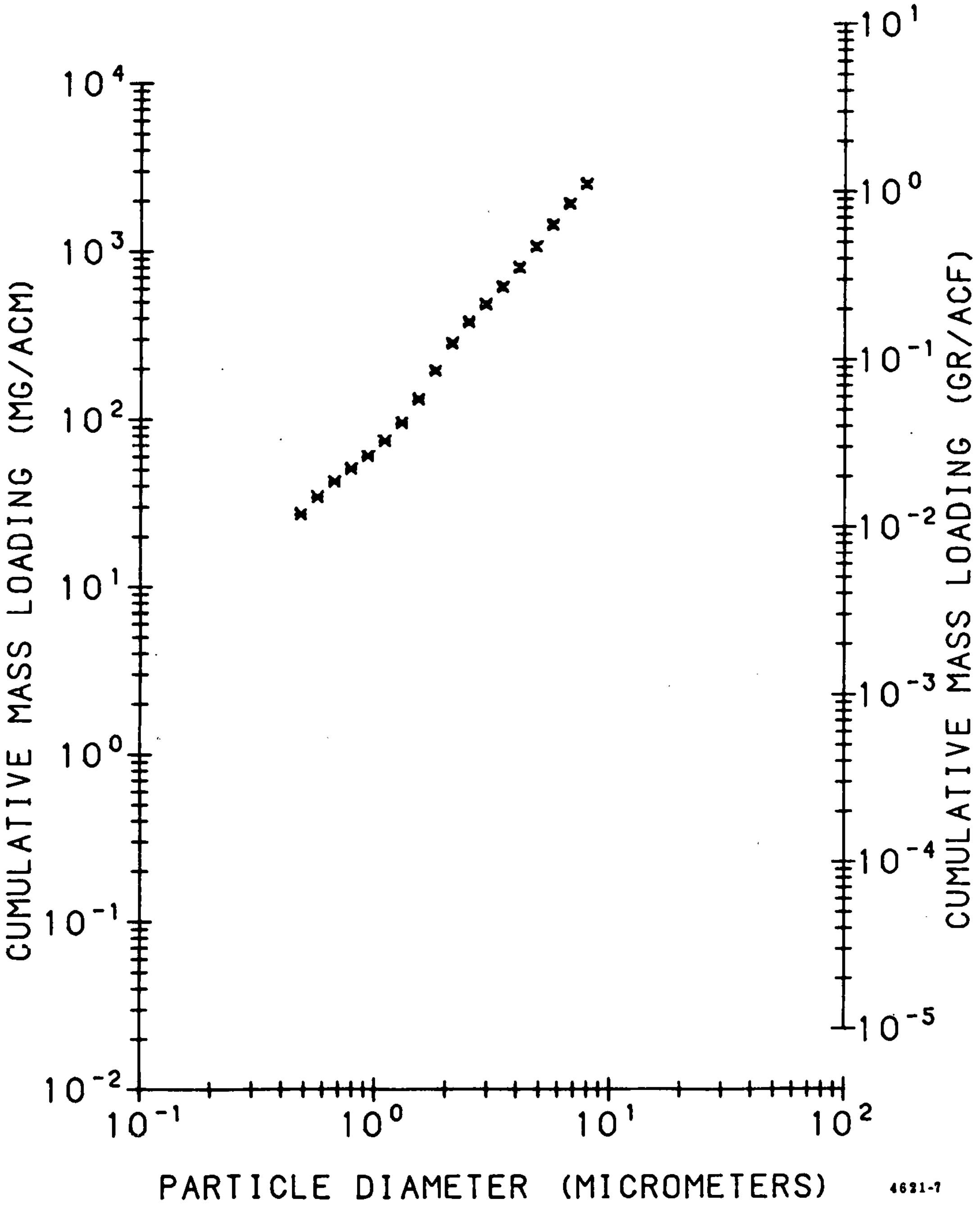


Figure 3-1 Cumulative Mass Loading as a Function of Particle Size at ESP Inlet

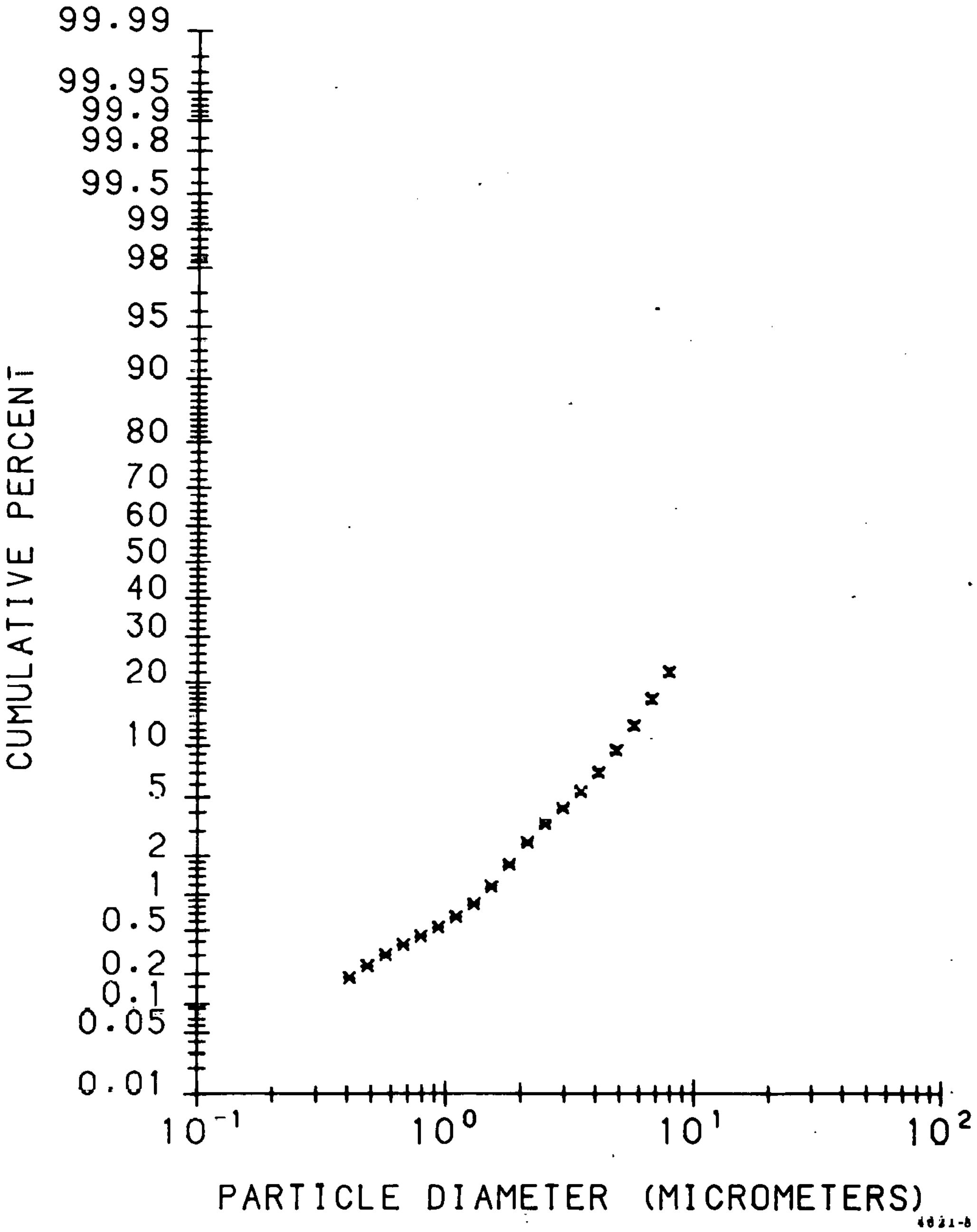


Figure 3-2 Cumulative Weight Percent Less Than Indicated Size at ESP Inlet

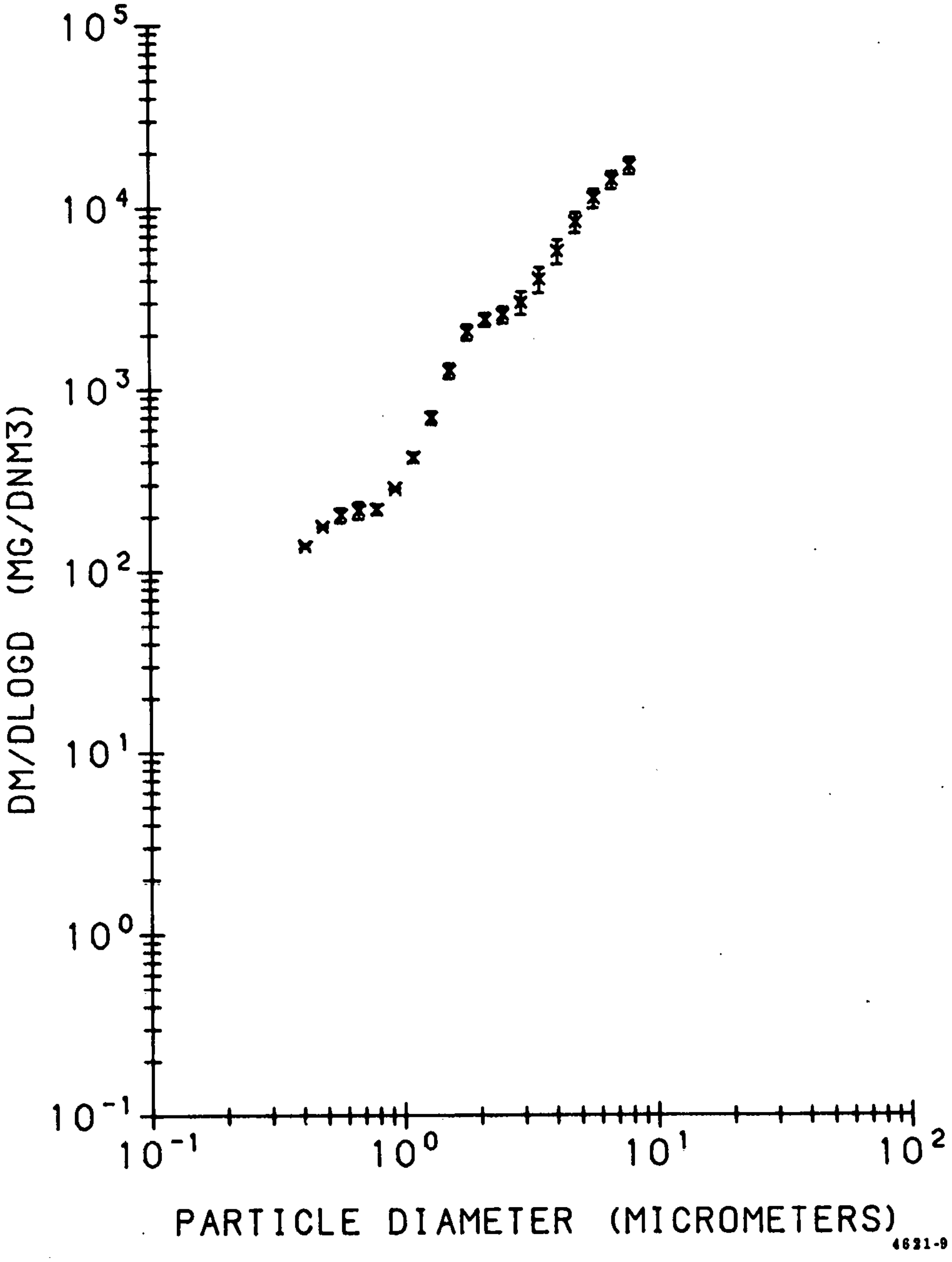


Figure 3-3 Differential Mass Distribution at ESP Inlet

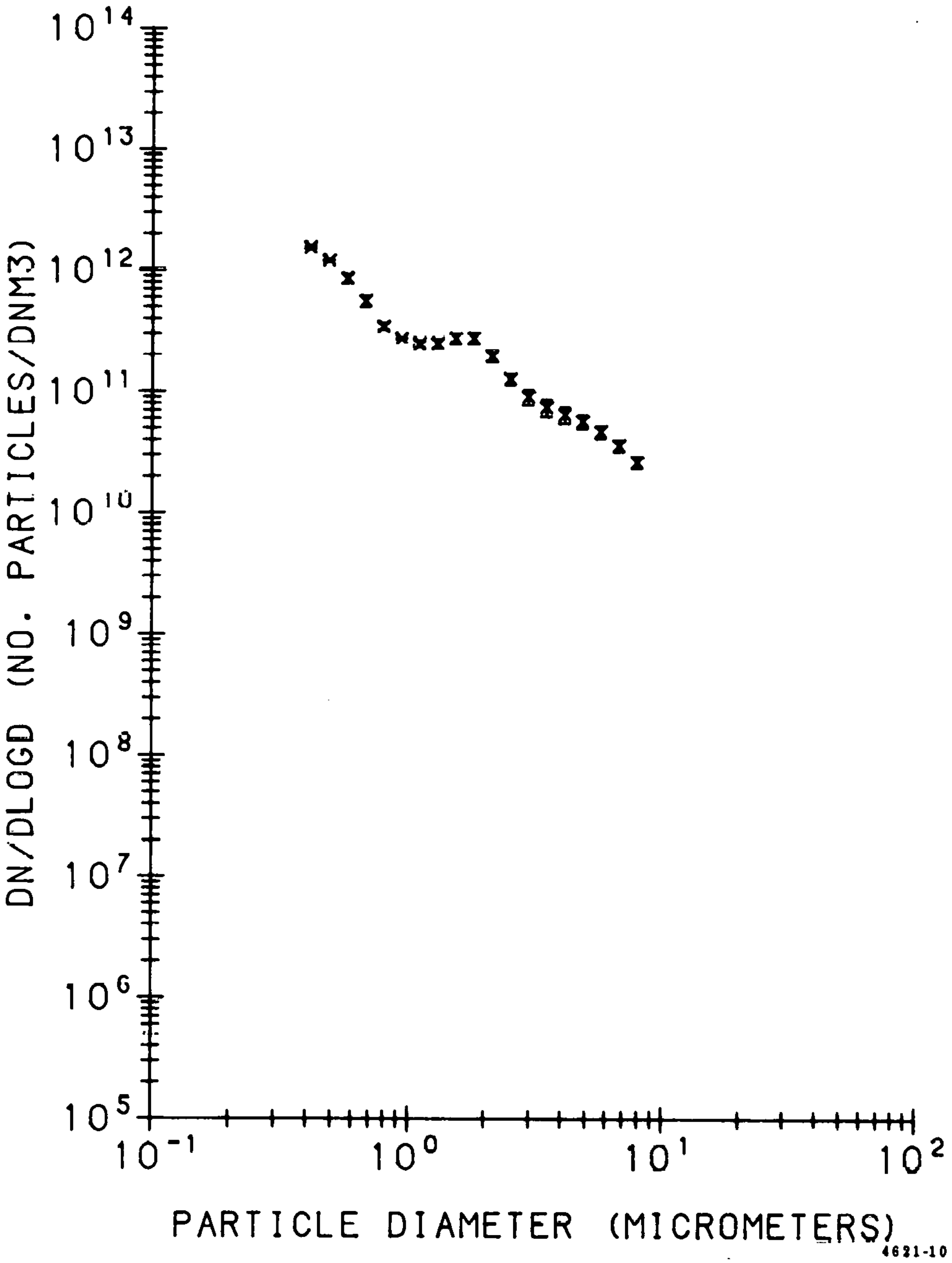


Figure 3-4 Differential Number Distribution at ESP Inlet

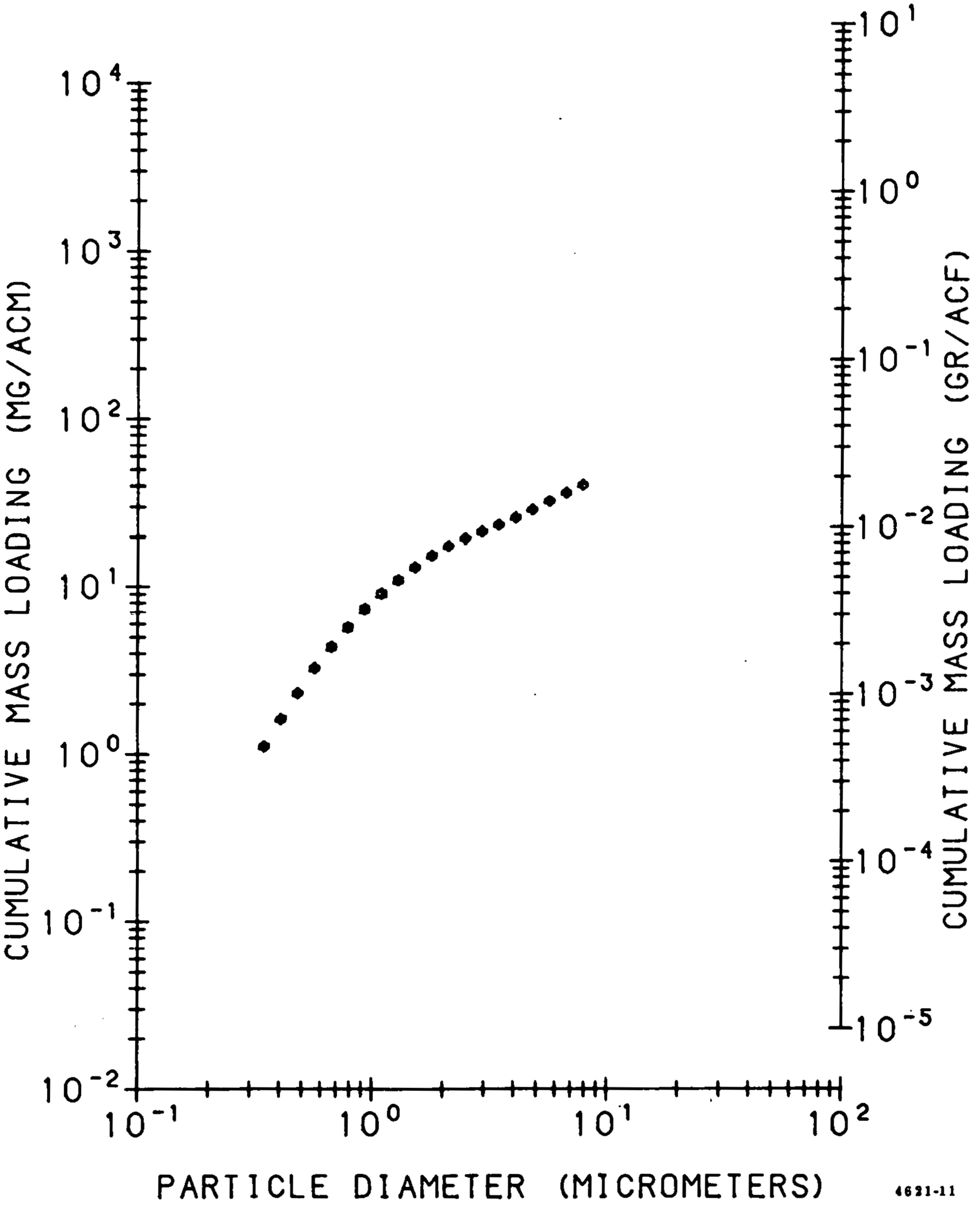


Figure 3-5 Cumulative Mass Loading as a Function of Particle Size at ESP Outlet

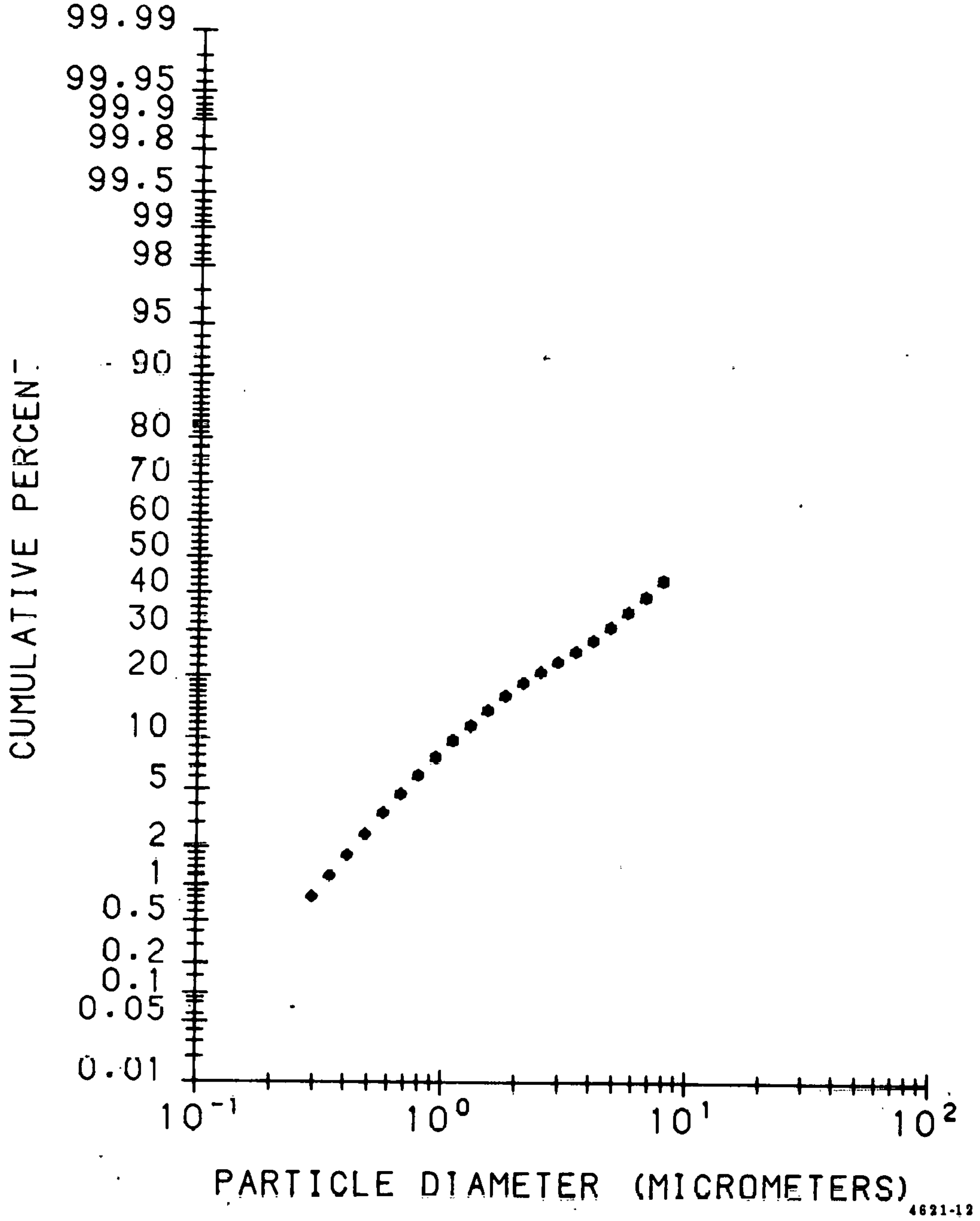


Figure 3-6 Cumulative Weight Percent Less Than Indicated Size at ESP Outlet

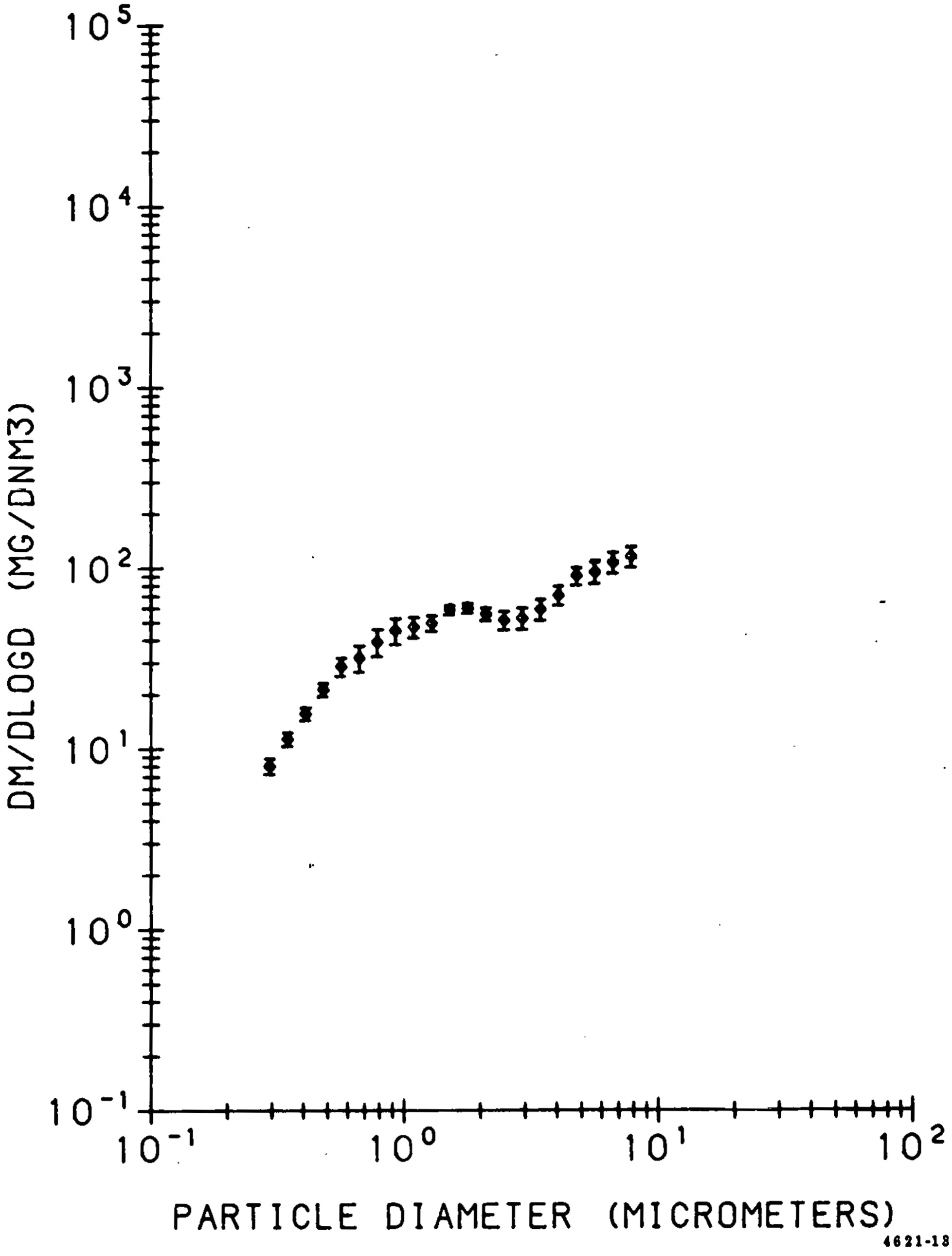


Figure 3-7 Differential Mass Distribution at ESP Outlet

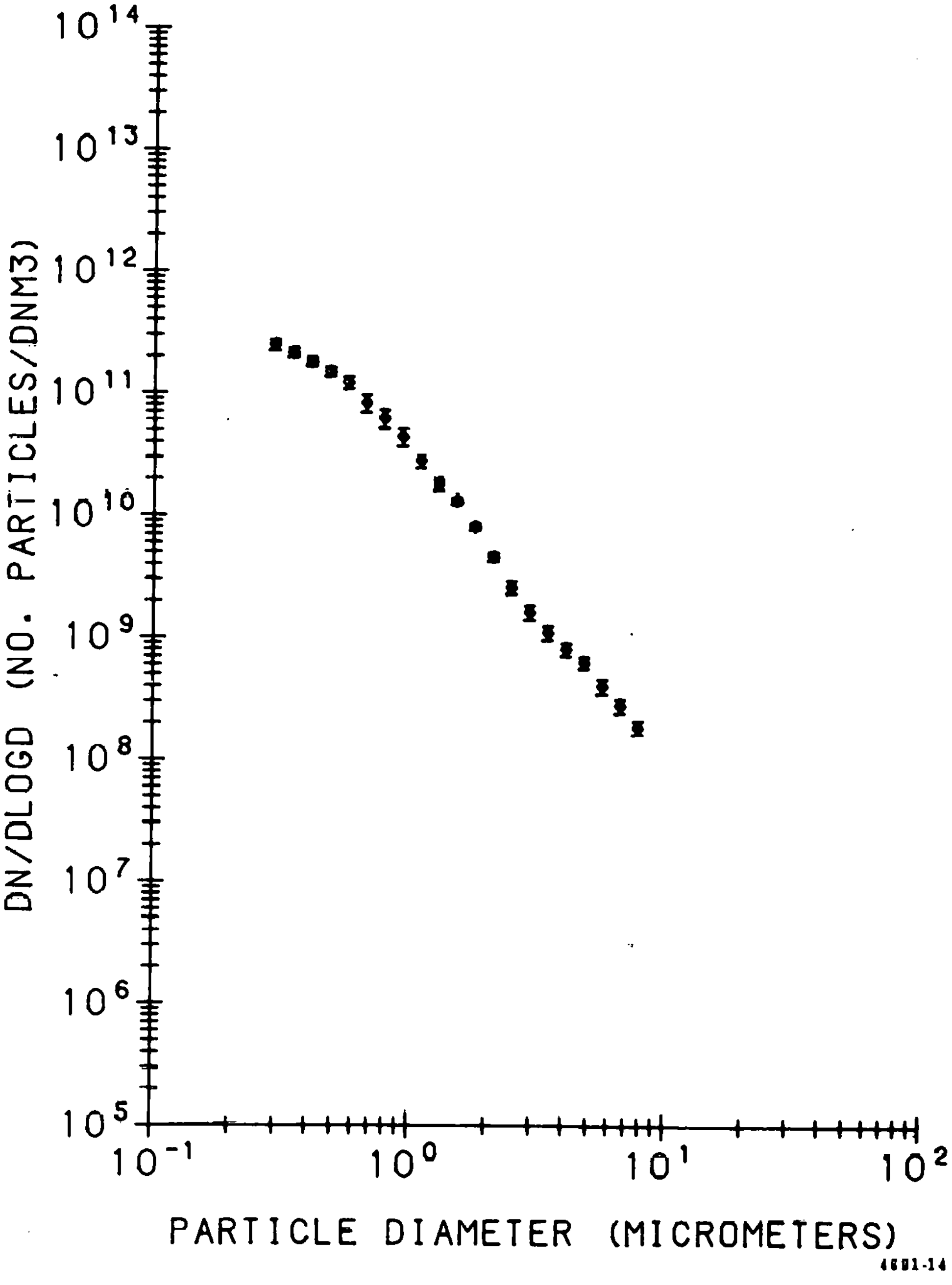


Figure 3-8 Differential Number Distribution at ESP Outlet

diameter of 100 µm at the inlet and 20 µm at the outlet. The mass median diameters of the inlet and outlet size distributions, based on the impactor data, are approximately 14 µm and 9 µm, respectively.

The curves shown in Figures 3-1 to 3-8 were obtained by averaging the spline fits (3) to a number of impactor runs; the points do not represent the raw impactor data, but rather the interpolated points generated by the spline fit.

Figures 3-2 and 3-6 show the inlet and outlet distributions on the basis of cumulative percent smaller than the stated sizes. Figures 3-3 and 3-7 give the differential mass distributions and Figures 3-4 and 3-8 give the differential number distributions, assuming a particle density of 2.4 g/cm^3.

The fractional efficiency curve derived from the inlet and outlet impactor measurements is shown in Figure 3-9. This apparently shows a minimum in the collection efficiency at just below 1 µm. The curve appears to be qualitatively consistent with theoretically predicted fractional efficiency curves in the range of .1 to 10 µm. The fractional efficiencies are also consistent with the measured overall efficiency if one considers that half of the mass is contained in particles larger than 14 µm. The cumulative efficiency for collection of sub-5-µm particles was 97%.

IN SITU RESISTIVITY AND SO_x AND NH_3 MEASUREMENTS

The SoRI in situ point-plane probe was used to measure the electrical resistivity of the ash by the sparkover method. This procedure is described in detail in EPA Report EPA 600/8-80-025 (4). All of these measurements were made at the inlet of the A side of ESP 2-1. The results are given in Table 3-5. The average resistivity determined by the sparkover technique was 1.6 x 10^{11} ohm cm, with considerable scatter in the data.

Although the measured resistivity varied considerably, the SO_3 and NH_3 measurements did not show corresponding variations. Neither did the electrical operating conditions of the ESP. Therefore, it appears that the in situ resistivity measurements are inconsistent with the other data. Given this problem and the large amount of scatter evident in the in situ resistivity data, the reliability of these data must be questioned. This problem is discussed more completely and compared to laboratory results in Section 4.

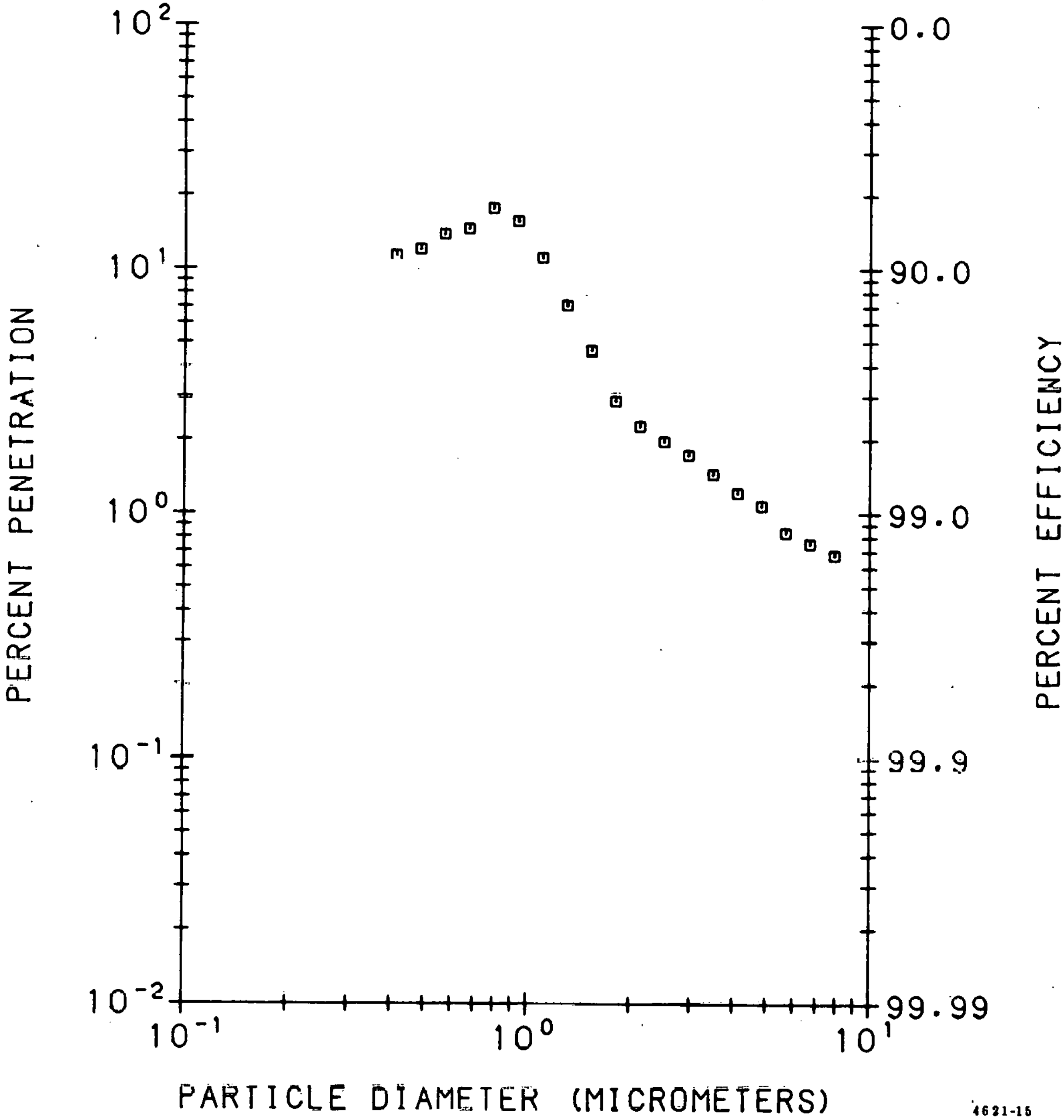


Figure 3-9 Fractional Efficiency Curve

Table 3-5

IN SITU RESISTIVITY MEASUREMENTS

Date	Run No.	Flue Gas Temp (°F)	Resistivity (ohm cm)
5/10	1	320	2.3×10^{10}
	2	343	4.5×10^{11}
	3	367	2.5×10^{11}
5/11	4	343	1.1×10^{11}
	5	341	3.8×10^{11}
5/12	6	351	5.1×10^{10}
	7	348	2.1×10^{10}
	8	348	3.1×10^{10}
	Average	345	1.6×10^{11}

SO_x samples were collected ahead of the air preheater and downstream of the Wahlco SO_3 injection system using the regular Cheney-Homolya sampling system (2). For SO_x and NH_3 sampling at the ESP inlet and outlet locations, the probe and quartz filter temperature was reduced from ~550°F to the prevailing flue gas temperature. This modification of the sampling procedure was necessary to prevent thermal decomposition of the ammonium sulfate particulate assumed to be present in the flue gas at these locations. The system was further modified for NH_3 sampling by removing the condenser and substituting one of the two Greenburg-Smith bubblers for a Greenburg-Smith impinger. A dilute H_2SO_4 solution (0.02 N) was used as the collection medium for all NH_3 samples.

SO_x samples were analyzed by a $Ba(ClO_4)_2$ titration with Thorin indicator; NH_3 samples with a specific ion electrode. The results are given in Table 3-6. The data indicate that about 5 ppm of natural H_2SO_4 (SO_3) was present in the flue gas ahead of the air preheater. Downstream from the SO_3 injection probes about 14 ppm of H_2SO_4 was found. Therefore, it appears that approximately 9 ppm of H_2SO_4 was added to the flue gas by the injection system.

The absence of any significant concentrations of H_2SO_4 (SO_3) at the ESP inlet (<0.5 ppm) is presumably due to adsorption on fly ash and reaction with NH_3. If the theoretical NH_3 injection rate of 5 ppm is correct, 2.5 ppm of H_2SO_4 would have been consumed in the formation of ammonium sulfate, and the remaining 12 ppm adsorbed by the ash. Although low, but measurable, quantities of NH_3 were detected at the ESP

Table 3-6

FLUE GAS SO_x AND NH_3 ANALYSES

Date	Time	Location	Flue Gas (°F)	H_2SO_4 (ppm v/v)	SO_2 (ppm v/v)	NH_3 (ppm v/v)
5/10/83	1058-1111	Below SO_3 injection	785	10	731	--
	1210-1225	Below SO_3 injection	790	13	799	--
		ESP inlet	380	0.1	638	--
	1508-1525	ESP inlet	365	0.3	676	--
		Below SO_3 injection	782	14	863	--
	1627-1645	ESP inlet	380	--	--	0.9
		Below SO_3 injection	780	15	853	--
	1707-1732	ESP inlet	380	--	--	0.4
		Below SO_3 injection	784	15	790	--
5/11/83	1315-1332[a]	Ahead of air heater	775-807	3.0	886	--
	1417-1451	Ahead of air heater	816	5.9	928	--
		ESP inlet	370	0.3	757	--
	1514-1536	Ahead of air heater	824	6.8	890	--
		ESP inlet	380	--	--	0.4
	1600-1638	Ahead of air heater	811	5.8	841	--
		ESP inlet	360	--	--	0.5
5/12/83	0945-1007	Ahead of air heater	842	3.4	794	--
	1102-1124	Ahead of air heater	852	3.4	766	--
	1150-1223	Ahead of air heater	854	3.4	820	--
		ESP outlet	390	0.2	720	--
	1300-1315	ESP outlet	390	0.4	727	--
	1328-1349	Ahead of air heater	849	3.8	802	--
	1406-1430	Ahead of air heater	845	4.5	786	--
		ESP outlet	390	--	--	0.2
	1500-1515	ESP outlet	390	--	--	0.1

---

[a] Possible load change during run.

inlet, it appears that at least 90% of the NH_3 (again assuming a 5 ppm injection rate) was removed from the gas phase.

FIVE-STAGE CYCLONE SIZE FRACTIONATION

A five-stage cyclone system (5) was used to collect relatively large samples of the fly ash entering the ESP in five discrete size fractions. The objective was to collect as much fly ash as possible in each of the five cyclones, with the size fractionation extending into the submicron range, for the purpose of laboratory analyses at UNDERC. The cut-points and masses collected in the five cyclones are given in Table 3-7.

Table 3-7

FIVE-STAGE CYCLONE DATA[a]

Cyclone No.	Aerodynamic Cut-Point (μm)	Stoke's Cut-Point (μm)	Mass Collected (mg)	Cum. Mass $<D_{50}$ (mg)	Cum. $<D_{50}$ (%)
1	7.46	4.79	17,433.7	2,693.2	13.38
2	3.45	2.20	1,596.5	1,096.7	5.45
3	2.53	1.60	613.6	483.1	2.40
4	1.06	0.659	309.6	173.5	0.862
5	0.573	0.346	29.5	144.0	0.715
BUF	--	--	144.0	--	--
		Total	20,126.9		

---

[a] Composite of three runs performed at nearly identical sampling rates. Average flow rate = 1.000 acfm. Total sampling time = 135 min. Average percent isokinetic ≅97%.

A total of three runs were performed, one on each day of testing. Total run time for all three runs was 135 min. The sampling rates and calculated cut-points were nearly identical for all three runs, so they were composited as indicated in the table. The size distribution based on the cyclone data is shown in Figure 3-10.

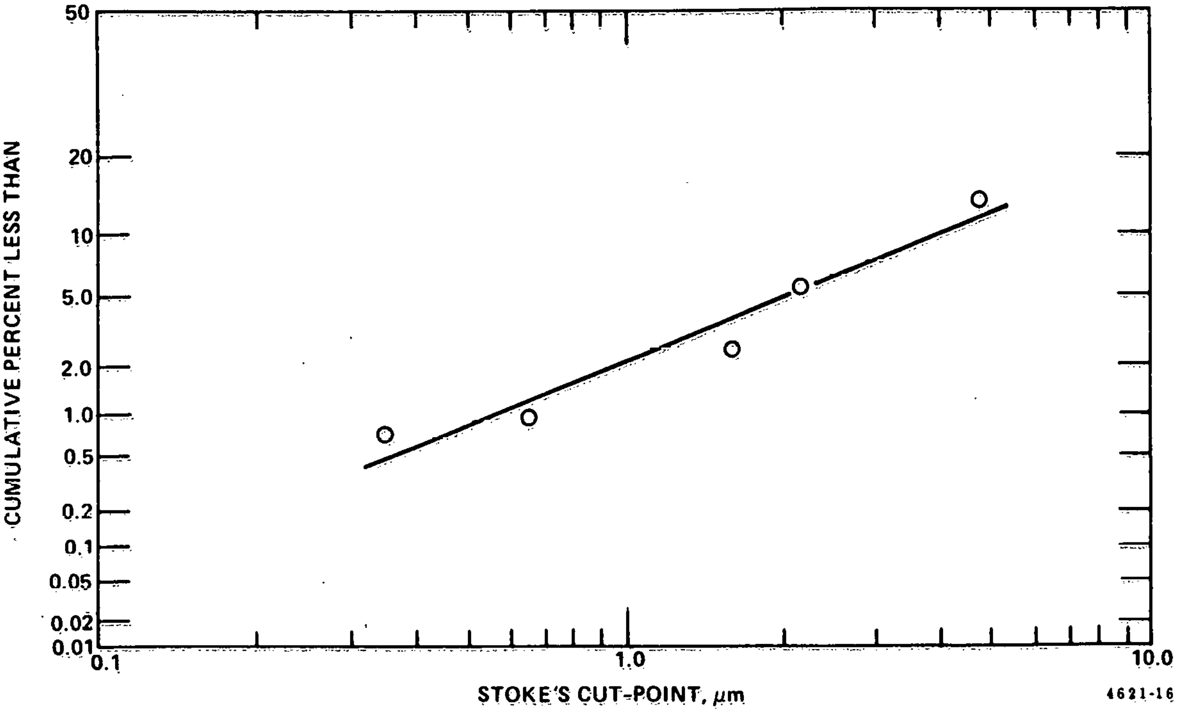


Figure 3-10 Particle Size Distribution Based on Five-Stage Cyclones

ELECTRICAL CHARACTERISTICS OF ESP

Voltage-current curves were obtained for the ESP 2-1 T-R sets. ESP 2-1 contains four fields: East inlet, West inlet, East outlet, and West outlet. V-I curves were obtained for all four fields on May 11 and 12, 1983, and are shown in Figures 3-11 through 3-18.

Figures 3-11 and 3-12 show the V-I curves for the East and West inlet fields on May 11. They are almost identical and are quite well behaved. Figures 3-13 and 3-14 show the V-I curves for the East and West outlet fields on May 11. The curve for the East outlet field is well behaved, but the curve for the West outlet becomes vertical at about 38 kV, indicating electrical breakdown. The achievable current density is still quite high, however. The curves for the inlet fields on May 12 (Figures 3-15 and 3-16) are quite similar to those of May 11 (Figures 3-11 and 3-12), and, again, indicate almost identical electrical performance on both sides of the ESP. On May 12, the outlet curves appeared similar in shape but the curve for the West outlet was shifted to the left, toward lower voltages, relative to the curve for the East outlet. The breakdown that seemed to occur in the West outlet V-I curve on May 11 was not evident on May 12.

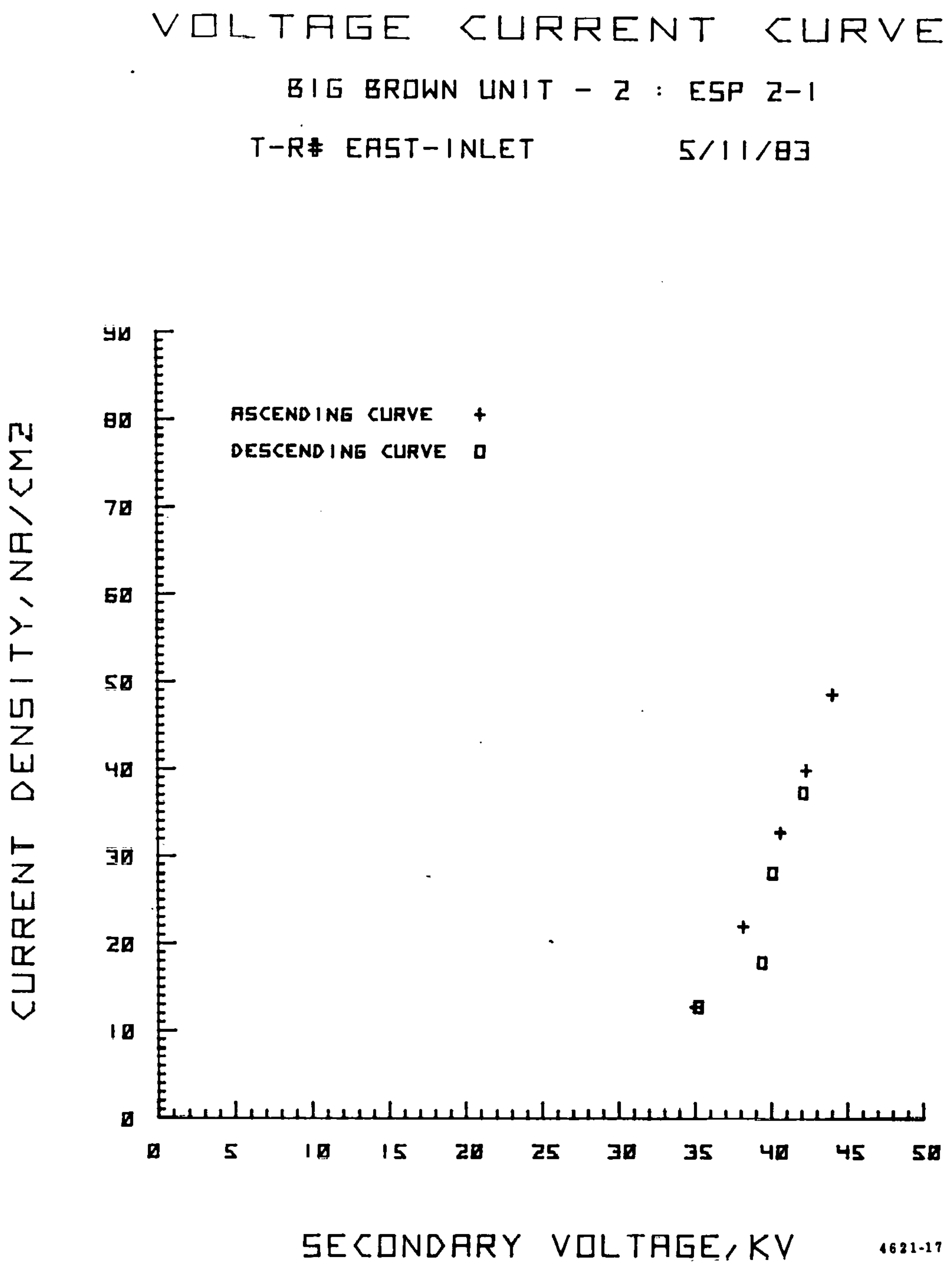


Figure 3-11 Voltage-Current Curve for East Inlet T-R Set on May 11, 1983

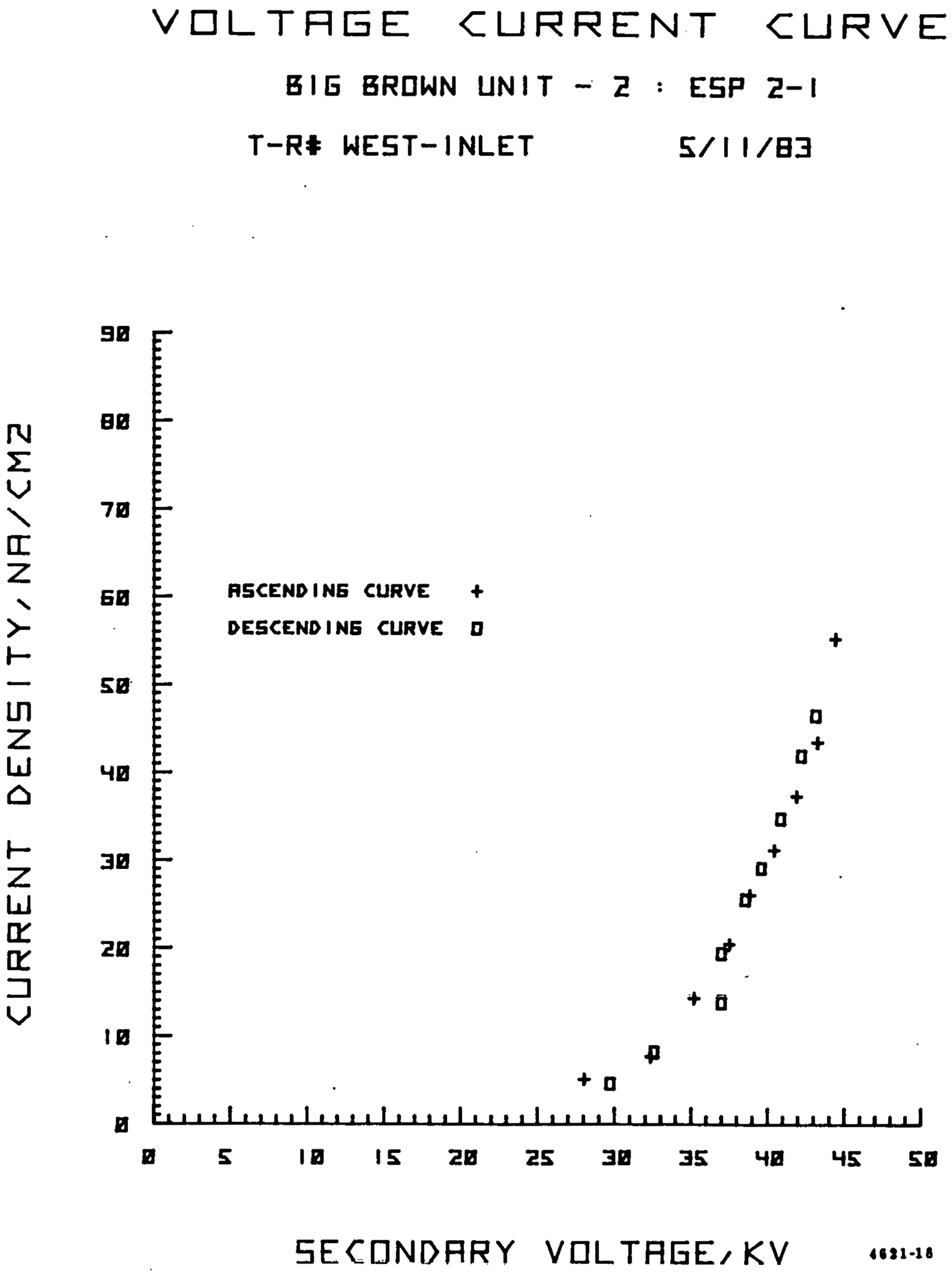


Figure 3-12 Voltage-Current Curve for West Inlet T-R Set on May 11, 1983

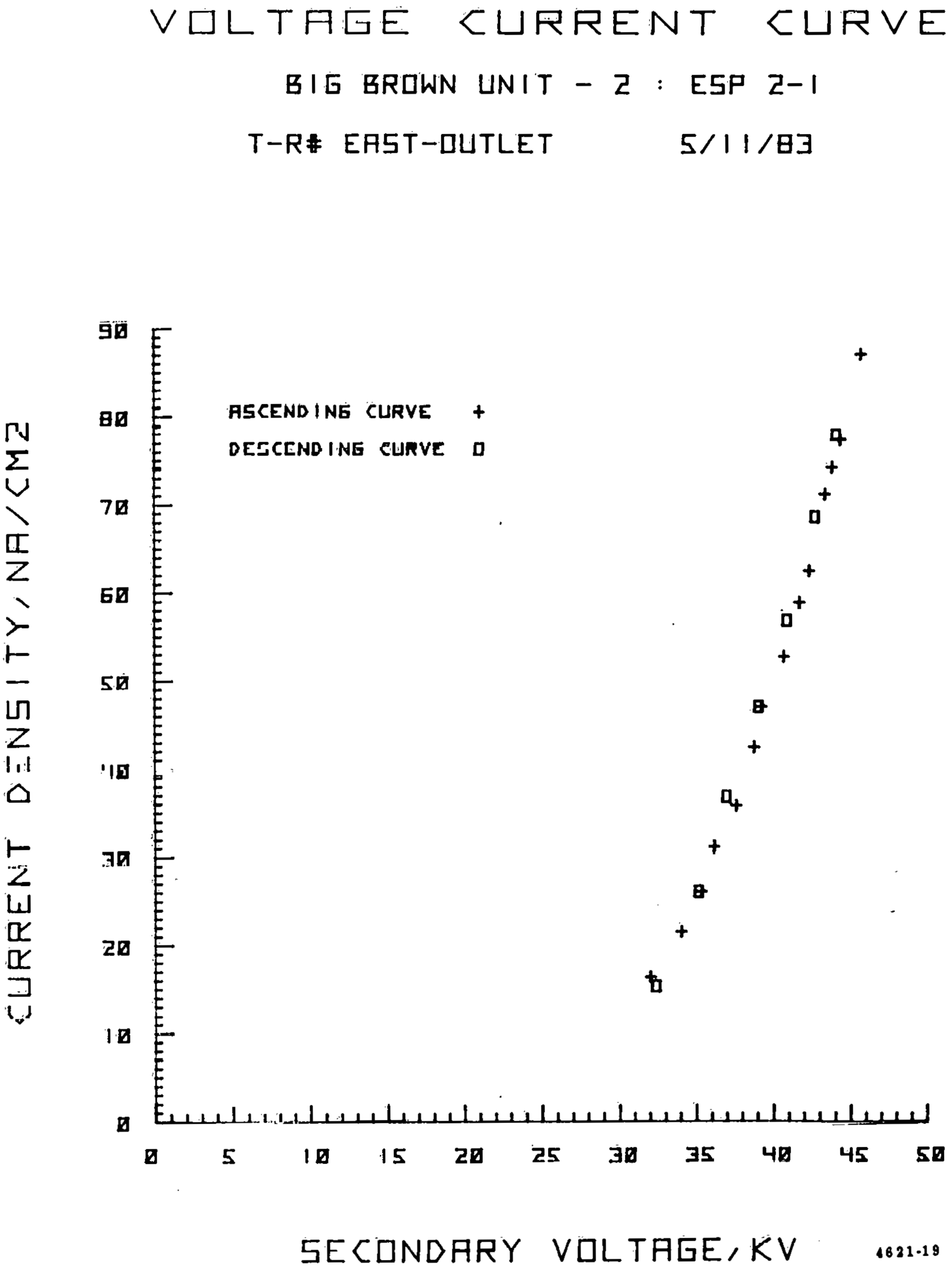


Figure 3-13 Voltage-Current Curve for East Outlet T-R Set on May 11, 1983

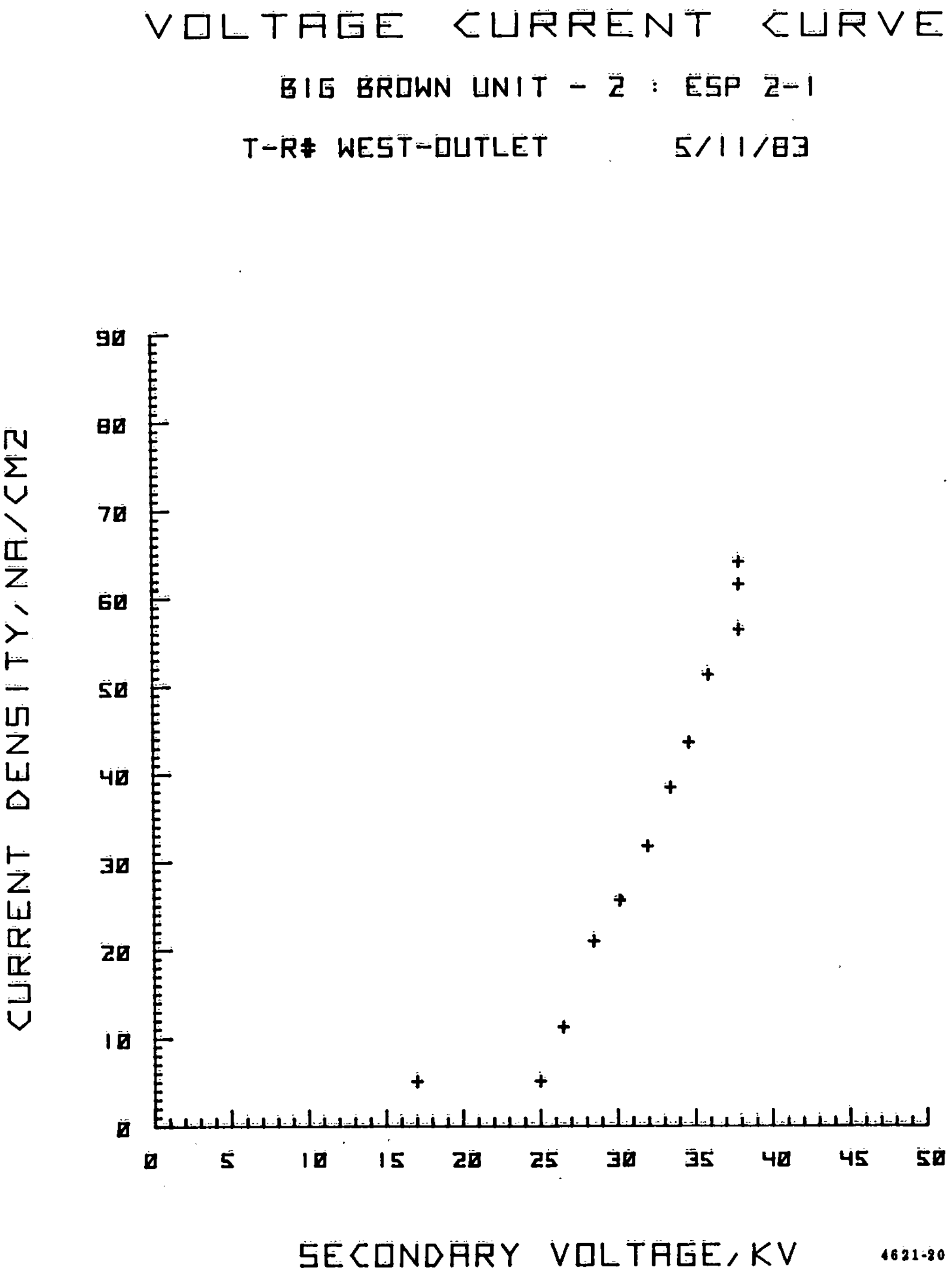


Figure 3-14 Voltage-Current Curve for West Outlet T-R Set on May 11, 1983

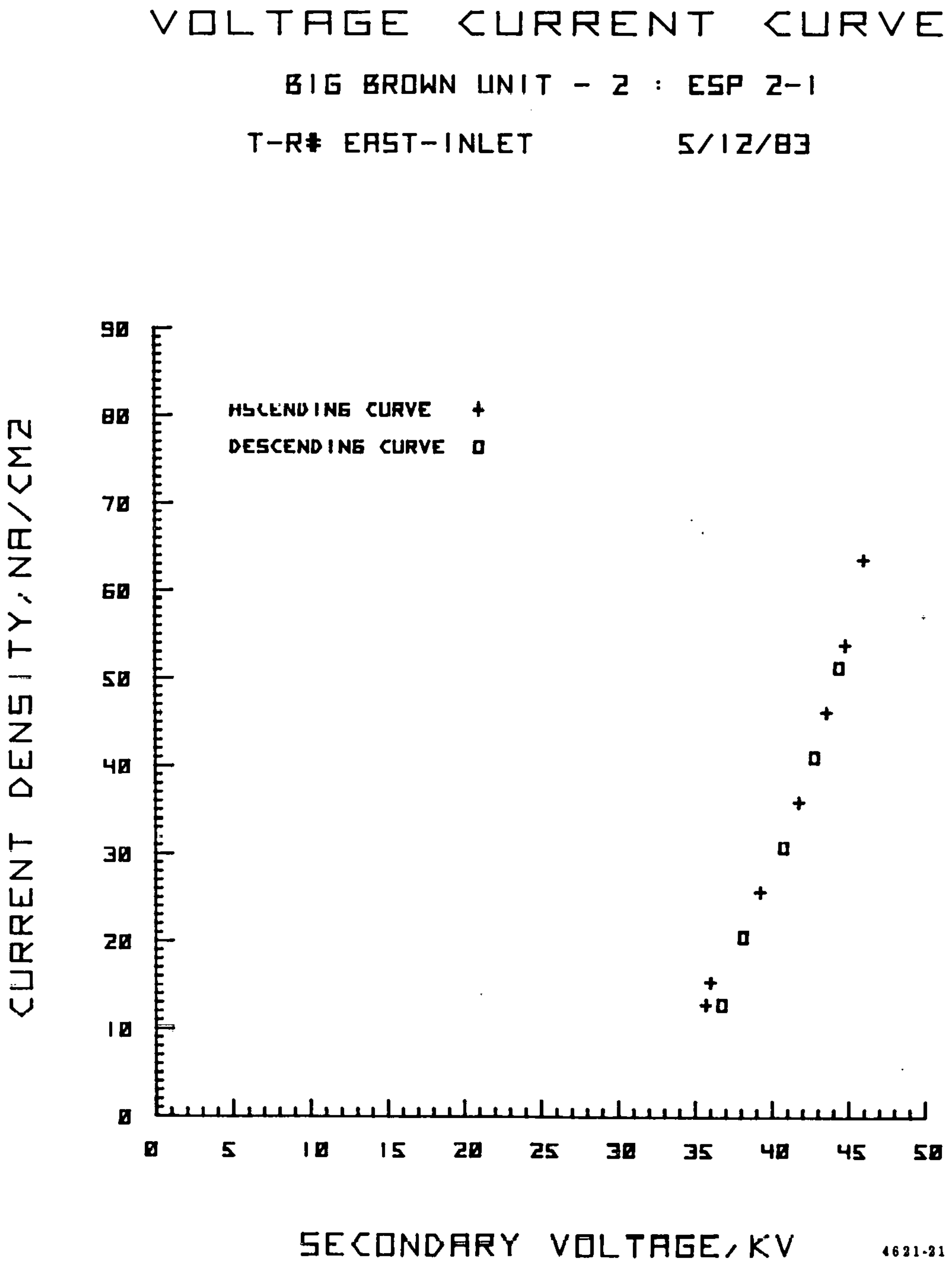


Figure 3-15 Voltage-Current Curve for East Inlet T-R Set on May 12, 1983

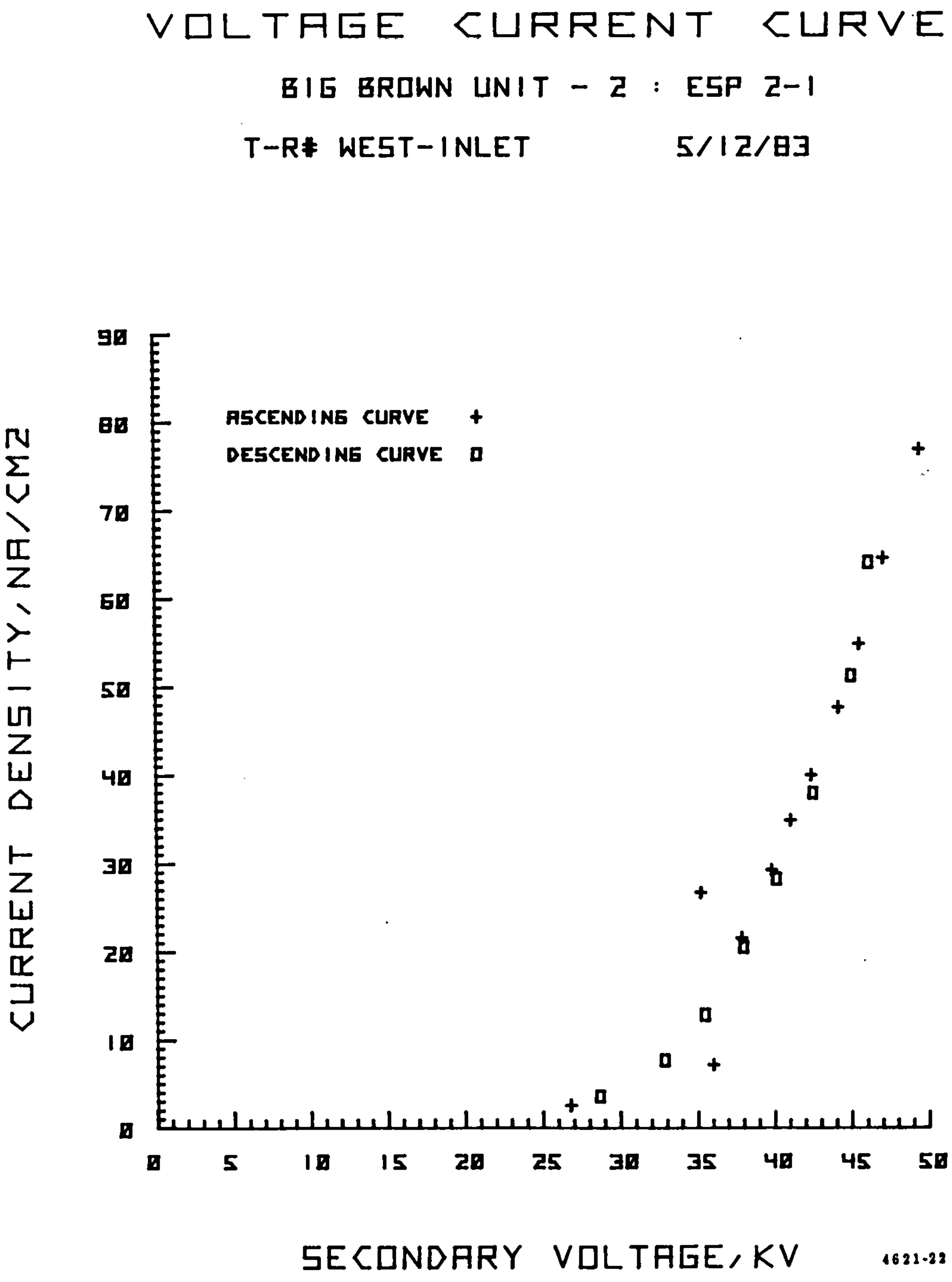


Figure 3-16 Voltage-Current Curve for West Inlet T-R Set on May 12, 1983

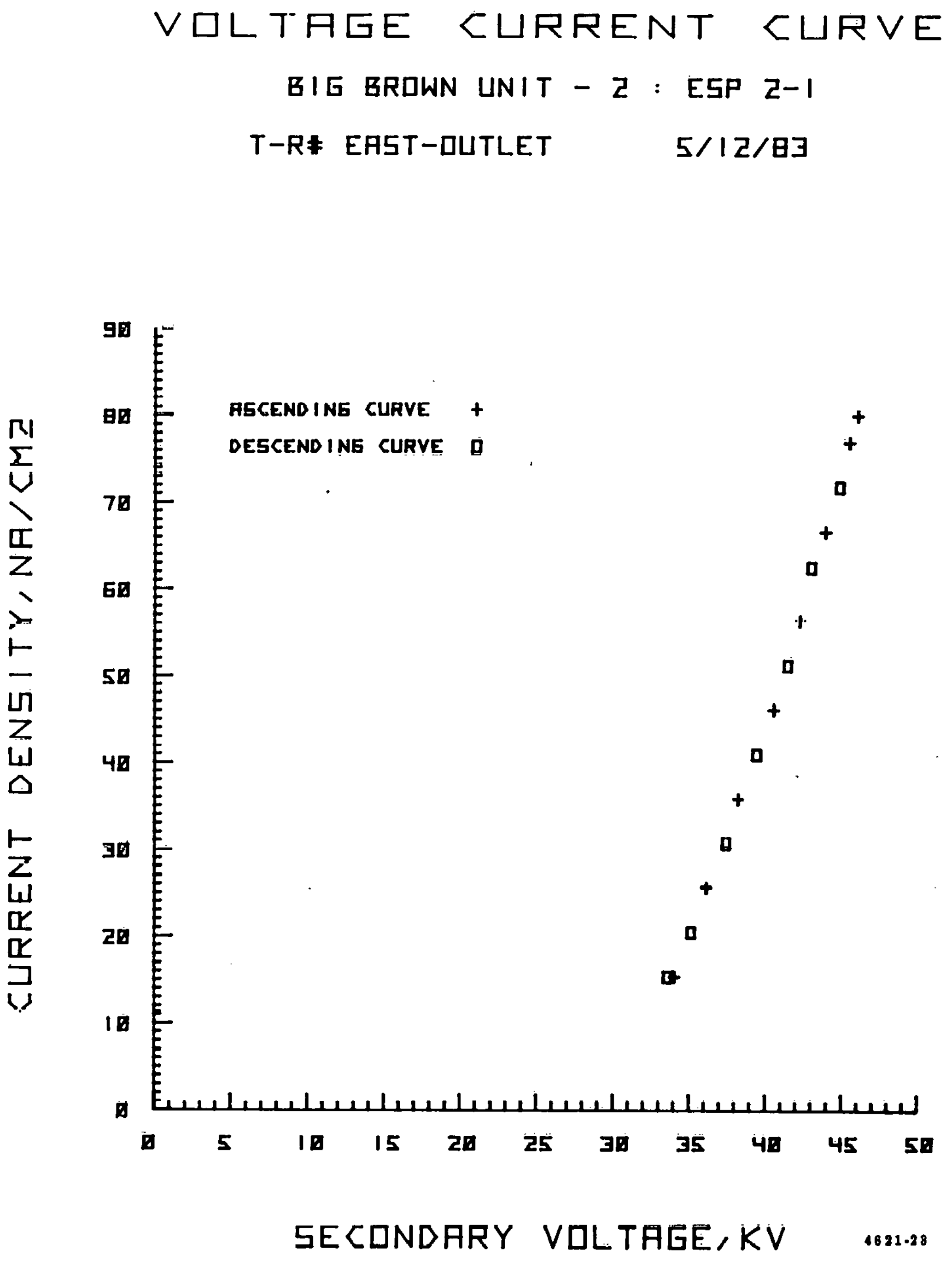


Figure 3-17 Voltage-Current Curve for East Outlet T-R Set on May 12, 1983

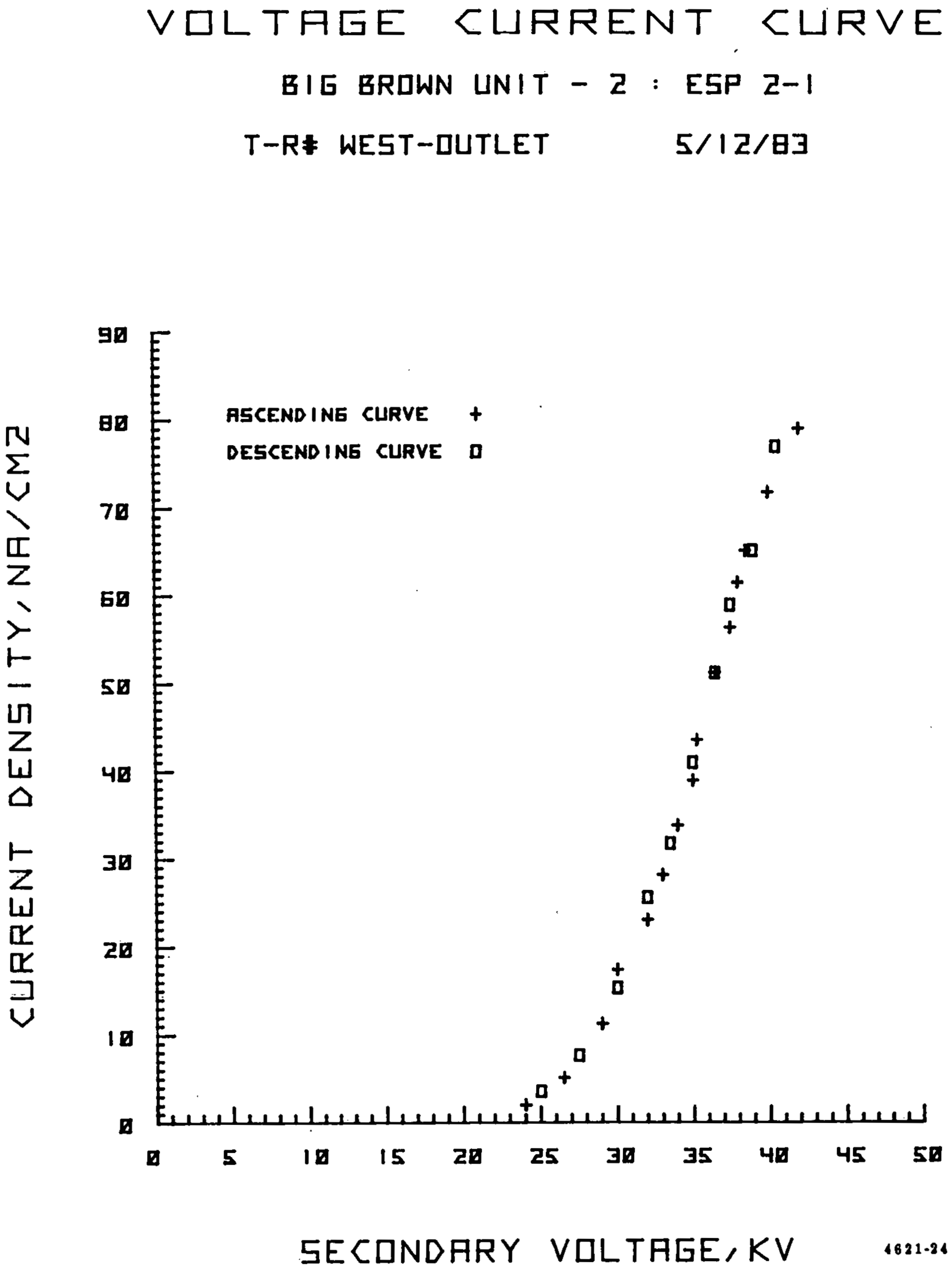


Figure 3-18 Voltage-Current Curve for West Outlet T-R Set on May 12, 1983

Section 4

LABORATORY CHARACTERIZATION OF FLY ASH

A fly ash sample taken from an outlet hopper of ESP 2-1 was characterized in terms of its chemical composition, density, Bahco size classification, and electrical resistivity. Normally a proportionately blended hopper sample is used for this examination; however, an inlet hopper sample was not available.

Chemical composition, Bahco particle size classification, and helium pycnometer density data are given in Table 4-1. None of these data are atypical. Because it is an outlet hopper sample, the amount of material smaller than 2 μm is high and the concentrations of soluble sulfate and ammonia are greater than the concentrations reported elsewhere for mass train samples. The concentrations of both NH_4^+ and SO_4^{-2} were higher in the outlet hopper sample than in any of the inlet mass train samples. This is to be expected since the outlet hopper sample is biased toward the finer particles that have high specific surface areas for adsorption of the NH_3 and SO_3.

Normally, resistivity is measured using the IEEE Standard 548-1981, descending temperature technique, which starts at 450°C. Because of the unique flue gas conditioning practice followed at Big Brown, it was reasoned that an ammonium compound could be produced that was intimately associated with the fly ash particles. This could have an effect on resistivity, and a thermal anneal at 450°C might destroy the effect. This point is irrelevant if only sulfur trioxide is used. Therefore, resistivity was determined in an environment of air containing 12% water using an ascending temperature procedure starting at 95°C and then the descending temperature technique starting at 450°C. The results are illustrated in Figure 4-1.

The ascending temperature resistivity curve is shown with circular data points and arrows pointing to the right. It is obvious that the ascending data are much lower than the data obtained using the decending temperature technique after the 450°C anneal. These data are shown with triangular symbols.

Table 4-1

PHYSICAL AND CHEMICAL DATA FOR OUTLET HOPPER SAMPLE

Chemical Composition[a]	Weight (%)
Li_2O	0.02
Na_2O	0.35
K_2O	0.79
MgO	3.5
CaO	15.7
Fe_2O_3	6.9
Al_2O_3	21.2
SiO_2	48.4
TiO_2	1.7
P_2O_5	0.06
SO_3	1.6
Total	100.2
LOI	0.4
Sol. NH_4^+	0.046
Sol. SO_4^{-2}	1.54

Bahco Size Classification	
Size (µm)	Weight % Less Than
1.3	5.37
2.1	12.31
4.2	32.74
7.8	46.06
12.4	55.06
21.8	65.96
29.0	70.25
32.5	71.87

MMD - 11.41 µm
GSD - 4.56
<10 µm - 46.54%
<2 µm - 12.57%

Helium Pycnometer Density

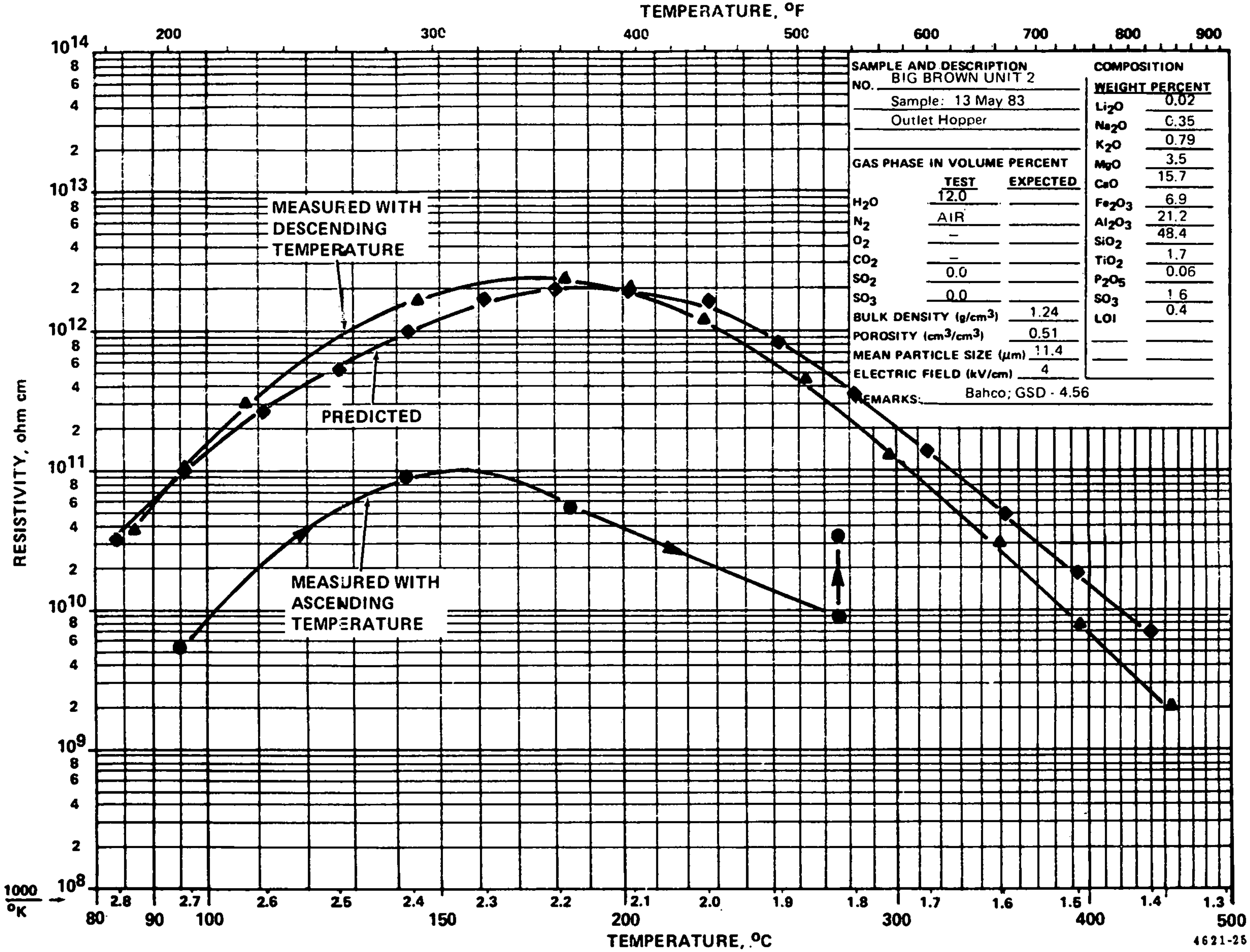
Grams/cc - 2.54

---

[a] Eleven element analysis performed on ignited sample.

The ascending test was terminated at 277°C, slightly below the handbook decomposition temperature of 280°C listed for ammonium sulfate. Without applied voltage, the test cell was held at 277°C for 20 hr in the air/water environment. After this, the resistivity had increased from 8.8×10^9 to 3.5×10^{10} ohm cm. This resistivity value was still about a factor of 9 lower than the value at 277°C for the descending technique data. Apparently the anneal at 450°C in dry air for about 16 hr was sufficient to completely remove the remaining effect of the conditioning agent. Excellent agreement was found between the lab-measured data using the descending technique and the predicted resistivity (diamond symbols). The resistivity was predicted by the technique developed by Bickelhaupt (6).

Since there is no lasting effect on resistivity due to sulfur trioxide conditioning with respect to laboratory measurements, one concludes that the observed result is associated with the ammonia injection. This same result was observed several years



SAMPLE AND DESCRIPTION

NO. BIG BROWN UNIT 2

Sample: 13 May 83

Outlet Hopper

GAS PHASE IN VOLUME PERCENT

	TEST	EXPECTED
H_2O	12.0	
N_2	AIR	
O_2	–	
CO_2	–	
SO_2	0.0	
SO_3	0.0	

BULK DENSITY (g/cm^3) 1.24

POROSITY (cm^3/cm^3) 0.51

MEAN PARTICLE SIZE (μm) 11.4

ELECTRIC FIELD (kV/cm) 4

REMARKS: Bahco; GSD - 4.56

COMPOSITION

	WEIGHT PERCENT
Li_2O	0.02
Na_2O	0.35
K_2O	0.79
MgO	3.5
CaO	15.7
Fe_2O_3	6.9
Al_2O_3	21.2
SiO_2	48.4
TiO_2	1.7
P_2O_5	0.06
SO_3	1.6
LOI	0.4

Figure 4-1 Resistivity Measurements Made with Ascending and Descending Temperature and Predicted Resistivity as a Function of Temperature

ago when laboratory measurements were made on another fly ash produced from a high sulfur coal. In this case, ammonia was injected into a flue gas containing a substantial concentration of natural sulfuric acid vapor. In the past, chemical transference experiments were conducted to demonstrate that the ammonium ion can participate in the conduction process. Based on the water soluble ammonium ion data reported in Table 4-1, this sample may contain about 0.2% ammonium sulfate. It is conceivable that this small concentration distributed on the surface of the ash could cause the large difference in ascending and descending resistivity values. Obviously the ammonium ion does not have to be on the surface as the sulfate. $(NH_4)_2SO_4$ may not be the form in which the ammonium ion is present on the surface. Identification of the specific form will require further study.

Since a very small concentration of sulfuric acid vapor (0.3 ppm) was detected at the precipitator inlet, laboratory resistivity determinations were made at 174°C in an air environment containing 12% water and approximately 0.3 ppm of sulfuric acid vapor. These isothermal tests were conducted with as-received ash and ash that had been equilibrated in dry air at 450°C overnight. The results are shown in Table 4-2.

Table 4-2

EFFECT OF SULFUR TRIOXIDE ON LAB-MEASURED RESISTIVITY

Temp (°C)	H_2O (%)	SO_3 (ppm)	E (kV/cm)	Resistivity (ohm cm)	
				As-Received	Annealed at 450°C
174	12.0	0.00	4	1.1E11	--
174	12.0	0.28	4	1.4E10	--
174	12.0	0.28	14	1.0E10	--
174	12.1	0.00	4	--	9.1E11
174	12.1	0.18	4	--	6.8E10
174	12.1	1.18	4	--	5.5E10
Post-test soluble sulfate (%)				1.69	1.81

Just prior to electrical breakdown, the resistivity values for the as-received ash and the annealed sample were 1.0×10^{10} and 5.5×10^{10} ohm cm, respectively. These values are much lower than one would expect for such a small acid concentration at 174°C.

Recently unrelated experiments were conducted with a fly ash somewhat similar to Big Brown fly ash in which the acid concentration was 0.3 ppm and the test temperature was about 150°C. Under these conditions the resistivity was only slightly decreased by the acid vapor.

In the present case, one can speculate with respect to the as-received sample that the small amount of adsorbed acid has a synergistic effect when coupled with the undefined surface film left on the ash as a result of the dual conditioning process carried out at Big Brown. The very small increase in soluble sulfate (1.69% post-test and 1.54% as-received) is not consistent with the large decrease in resistivity.

Suggesting an explanation for the results observed with the annealed ash is even more difficult. Since the measured resistivity of the annealed ash in an environment of air and water was similar to the predicted values (Figure 4-1), one would expect only a small attenuation of resistivity for the annealed ash due to the presence of ~0.2 ppm of sulfuric acid vapor. However, with a small increase in soluble sulfate (1.81% post-test and 1.54% as-received), the resistivity decreased by a factor of about 17. It would seem that this ash has some unknown, unique characteristic or the 450°C anneal makes the commercially conditioned ash surface inactive with respect to adsorbed water but still active with regard to adsorbed acid vapor.

Figures 4-2 and 4-3 show the predicted resistivity data based on the ash composition given in Table 4-1, 12.0% water, several acid concentrations, and electric field intensities of 4 and 12 kV/cm, respectively. The data from Figure 4-2 without sulfuric acid present were plotted in Figure 4-1 for comparison with the lab-measured data without acid.

Superimposed on Figure 4-3 are the in situ resistivity data and the lab-measured data for the as-received and annealed ash samples tested with about 0.2 to 0.3 ppm of sulfuric acid vapor, the amount reported for the precipitator inlet. The data are plotted at 174°C. This was the temperature at the in situ resistivity measurement port. The limit bar associated with these data indicates the high and low in situ values, and the solid square represents the average in situ value.

At 174°C, the predicted resistivity value is about 5.0×10^{11} ohm cm for $E =$ 12 kV/cm and an environment containing 12.0% water and 0.3 ppm of sulfuric acid vapor. The lab-measured data under these conditions were 5.5×10^{10} ohm cm for the

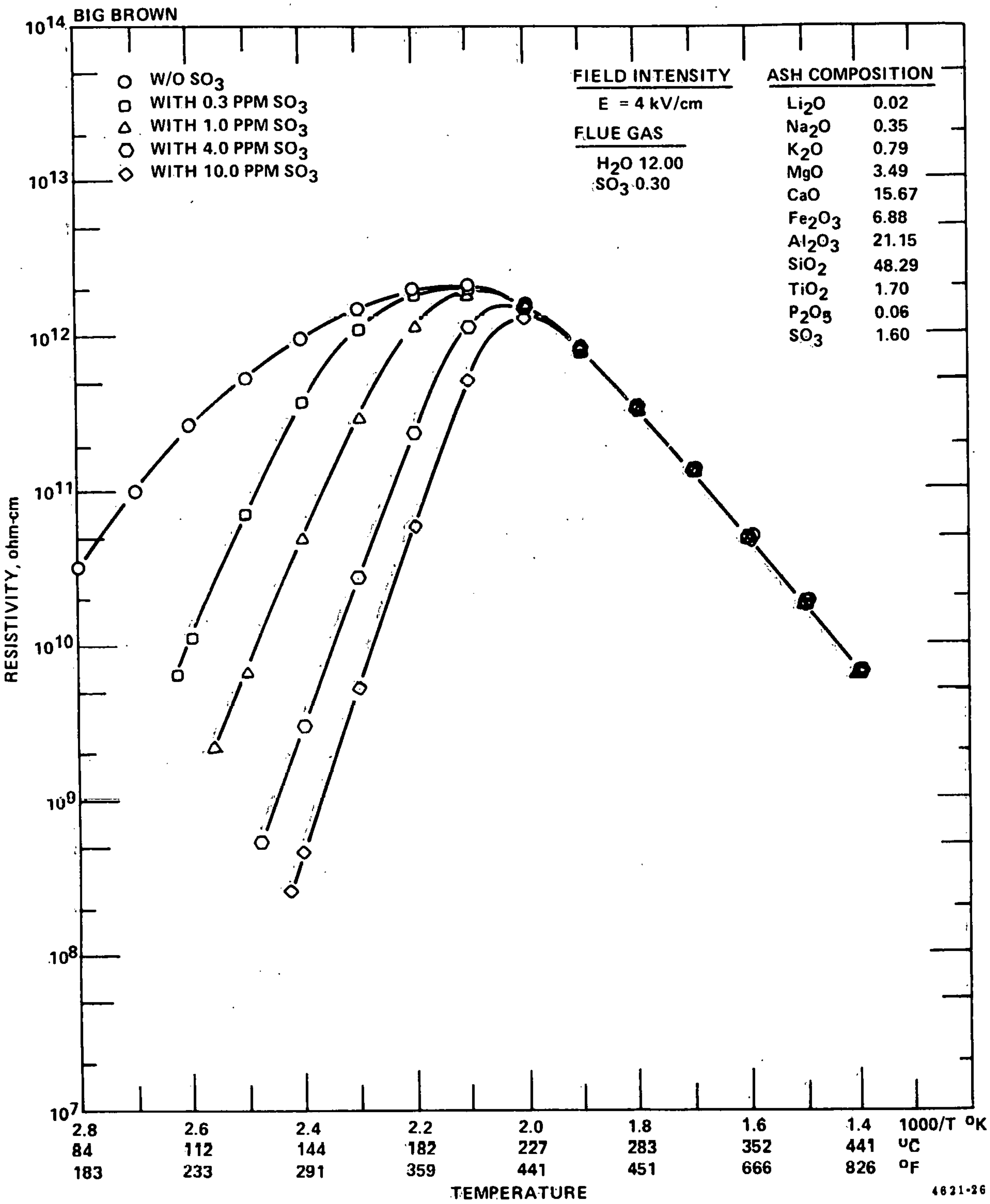


Figure 4-2 Predicted Effect of SO_3 on Resistivity at an Electric Field Intensity of 4 k V/cm

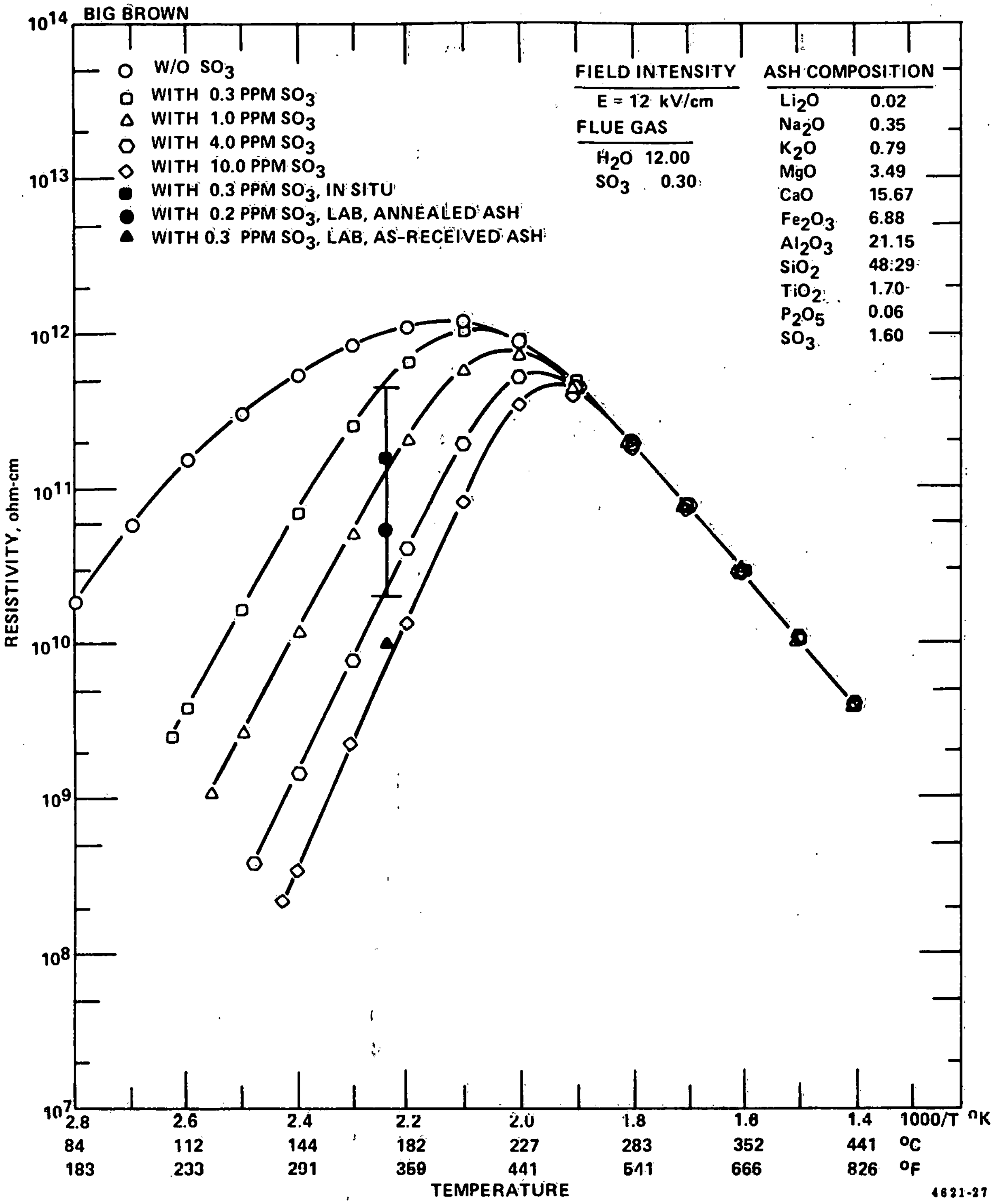


Figure 4-3 In Situ and Laboratory Resistivity Measurements with SO_3 and Predicted Resistivity for Various SO_3 Levels

annealed sample and 1.0 x 10^{10} ohm cm for the as-received sample. It has been suggested above that the lab-measured data are significantly below the predicted value because of the retained effect of the ammonia conditioning at the power station.

Based on the above discussion, the in situ data seem high. Consideration of the data is complicated by the large spread in data from 1.2 x 10^{10} to 4.5 x 10^{11} ohm cm. Assuming the average in situ value of 1.6 x 10^{11} ohm cm is correct, two possible explanations exist to explain why the in situ values are greater than the laboratory data. Perhaps there really isn't 0.3 ppm of sulfuric acid vapor in the gas phase or the concentration was less in the region of the in situ resistivity measurement. Also, it is conceivable that the ash collected in the in situ probe does not contain as much ammonium salt as the ash available to the laboratory. Considering all of these possibilities, it seems more likely that the in situ resistivity data are in error since they exhibit so much scatter, and they are not consistent with the electrical operation of the ESP or the predicted resistivity values. In view of the scatter in the in situ resistivity data, the laboratory data have been used in this study.

Section 5

SUMMARY AND CONCLUSIONS

Considering the relatively small size of the Big Brown ESP (SCA = 166 ft^2/kacfm), its overall performance appears to be quite good. The overall mass collection efficiency for all particle sizes was found to be within the range of 98.22 to 98.77%, with a mean of 98.45%. The mean value is in good agreement with the overall collection efficiency predicted by a semi-empirical computer model of electrostatic precipitation, assuming that 10% of the flue gas bypasses the electrified regions of the ESP and that the standard deviation on the gas velocity profile is equal to 25% of the mean (rms) velocity.

The measurements of collection efficiency versus particle size showed that the Big Brown ESP was also a reasonably good collector of fine particles. The cumulative collection efficiency for all particles smaller than 5 μm, for example, was found to be about 97%.

The voltage-current curves showed good electrical operation in all of the fields of the Big Brown ESP. This is, of course, a direct result of the low resistivity of the Big Brown ash. A resistivity of 1×10^{10} ohm cm was measured in the laboratory when the as-received ash was equilibrated with the level of SO_3 found to be present in the flue gas at the ESP inlet. A much higher value (1.6×10^{11} ohm cm) was obtained from the in situ measurements, but these data are questionable because they are not consistent with the electrical and overall performance of the ESP and the laboratory resistivity data.

The surface film, which is believed to be deposited on the fly ash as a result of the NH_3-SO_3 conditioning process, appears to be contributing to the low resistivity of the ash. The hysteresis between the laboratory resistivity curves obtained with ascending and descending temperatures indicates at least an order of magnitude effect of the surface film on the resistivity (i.e., the descending curve was obtained after the ash had been heated to a temperature sufficient to decompose the surface film, and the resultant resistivity value at about 150°C was about an order of magnitude higher than the corresponding point on the ascending curve). The surface film also appears to have a synergistic effect with a small amount of adsorbed sulfuric acid (i.e., the resistivity of the as-received ash is attenuated by the equilibration with a given level of SO_3 to a greater degree than is the thermally annealed ash in which the surface film has been decomposed). The observations noted above suggest that the addition of NH_3 to the flue gas improves upon the efficacy of the SO_3 conditioning.

The combined NH_3-SO_3 conditioning process appears to be a feasible and useful method of maintaining acceptable performance levels in a cold-side electrostatic precipitator. Additional work is needed, however, to fully understand the mechanisms by which the NH_3 and SO_3 act together to condition the fly ash and affect precipitator performance. A more thorough investigation of the NH_3-SO_3 conditioning process is justified in view of the potential for improving ESP performance, or reducing the size of a new ESP. There is a need for field measurements to be made with and without NH_3, SO_3, and both agents injected ahead of the ESP. There is also a need for measurements of the effect of NH_3-SO_3 conditioning on rapping reentrainment. Further laboratory studies are also needed to elucidate the nature and chemical speciation of the ash surface film produced by the NH_3-SO_3 conditioning process.

Section 6

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