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University of Washington Electrostatic Scrubber Tests at a Coal-fired Power Plant

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University of Washington Electrostatic Scrubber Tests at a Coal-fired Power Plant

by

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Abstract

A 1000 acfm University of Washington Electrostatic Spray Scrubber pilot plant was tested on the coal fired boiler unit no. 2 at Centralia Power Plant to demonstrate its effectiveness for controlling the emissions of fine particles. The multiple pass, portable pilot plant operates by combining oppositely charged aerosol particles and water droplets in two spray towers. Aerosol charging sections at a negative polarity precede each spray tower. The pilot plant was operated at gas flows beyond its rated capacity. Inlet gas flow as high as 1600 acfm were recorded. Tests to determine the effect of reducing the size of the unit were performed. The scrubber was operated and tested in two operating modes. The two stage mode included two active particle charging corona sections and two spray towers. The one stage mode utilized only one corona section and one spray tower.

Simultaneous inlet and outlet source tests utilizing University of Washington Cascade Impactors and in-stack filters provided both size-dependent and overall mass basis particle collection efficiency information. Measured overall particle collection efficiencies ranged from 99.30 to 99.99% depending upon scrubber operating conditions and the inlet particle size distribution and mass concentration. Particle mass concentrations measured at the scrubber outlet ranged from .00018 grains/sdcf to .00116 grains/sdcf. The average overall particle collection efficiency for all tests performed in the two stage mode was 99.93% while the one stage average efficiency was 99.825%. An integrating nephelometer was utilized at the scrubber outlet because of low outlet mass concentrations and subsequent low sample weights. The light scattering coefficient was measured as a relative indication of outlet mass concentration for different operating parameters. Tabular and graphical data is presented to illustrate the size dependent and overall collection efficiencies for all tests performed.

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ABBREVIATIONS AND SYMBOLS USED

SCA	Specific collection area (ft^2/scfm)
L/G	Liquid to gas ratio (gallons/1000 scfm)
d_{50}	Aerodynamic cut diameter of cascade impactor stages (microns)
μ	Gas viscosity (gm/cm-sec)
D_j	Jet diameter (cm)
ψ_{50}	Inertial impaction parameter at 50% collection efficiency for particles of diameter d_{50}
C	Cunningham correction factor
V_j	Gas velocity in the jet (m/sec)
B_{scat}	Light scattering coefficient (m^{-1})

Section 1

SUMMARY AND CONCLUSIONS

The University of Washington Electrostatic Spray Scrubber portable pilot plant was tested at the Pacific Power and Light Power Plant in Centralia, WA on coal fired boiler unit no. 2 to demonstrate its effectiveness in controlling the fine particle emissions. The pilot plant consists of a cooling tower, two corona sections which charge the particles to a negative polarity, two spray towers into which positively charged water droplets are sprayed and on electrostatic mist eliminator.

The unit was operated and tested in two operational modes. The two stage mode utilized both particle charging corona sections and both charged droplet spray towers while the one stage mode utilized only one corona section and one spray tower. Overall particle collection efficiencies measured for the two stage mode ranged from 99.30% to 99.99% at corona section specific collection areas (SCA) of 0.050 to 0.068 ft^2/scfm. Overall particle collection efficiencies for one stage operation ranged from 99.50% to 99.89% at an SCA range of .024 to .037 ft^2/scfm. The UW Electrostatic Scrubber SCA range from about 0.024 to 0.068 ft^2/scfm is significantly less in magnitude than the corresponding efficiency electrostatic precipitator with an SCA range of 0.3 to 0.8 ft^2/scfm.

In conclusion it is apparent that the UW Electrostatic Spray Scrubber is effective in the collection of particulate emissions from a coal fired boiler. A 37% reduction in active length of the scrubber resulted in particle collection efficiencies still in excess of 99%. The effect of this size reduction, from a full scale design point of view, results in a decrease in both capital and operating costs of the unit while maintaining high overall particle collection efficiencies.

Section II

RECOMMENDATIONS

To better evaluate the UW Electrostatic Spray Scrubber performance on a coal fired boiler, it is recommended that additional fan capacity be added to the system to provide a greater volumetric gas flow rate. This would result in an even shorter gas residence time and greater particle mass concentrations at the scrubber outlet sampling port. An increased mass concentration at the outlet would result in greater sample weights and consequently greater statistical reliability in the data. The process changes and system perturbations apparent in the Centralia tests would also have less of a relative effect upon the results.

We also recommend that the pilot plant be used to demonstrate its effectiveness for simultaneous control of particulate and SO_2 emissions from coal fired boilers. To accomplish this, it is felt that the installation of continuous SO_2 monitoring equipment would expedite the study as well as increase the accuracy of the measurements.

Design and construction of a larger, improved liquor recycle system is also recommended. This would be particularly appropriate for an SO_2 study.

Future considerations should be given to design and installations of a larger scale (10,000 acfm) pilot plant or demonstration unit with a self contained liquor recycle system.

Section III

RESEARCH OBJECTIVES

The primary objective of the field tests at Pacific Power and Light's Centralia Power Plant was to determine the effectiveness of the UW Electrostatic Spray Scrubber in controlling fine particle emissions from a coal fired power boiler. Simultaneous inlet/outlet particulate collection measurements provided the basis for this study.

The effect of a variation in certain scrubber operating parameters (gas residence time, SCA, L/G, and applied voltages) on particle collection efficiency was also an objective of this research. This information would then be used in the design and economic analysis of a full scale retrofit system for a coal fired boiler.

Section IV

DESCRIPTION OF THE SOURCE

The Centralia Steam-Electric Project located near Centralia, Washington is a coal fired electric power generating station owned by eight Northwest utilities and operated by Pacific Power and Light Company personnel. The plant contains two units which have a combined generating capacity of 1,330,000 kilowatts of electricity (665,000 kilowatts per unit). The two boilers, manufactured by Combustion Engineering, are pulverized coal fired type, each with a designed steam rate of 5,200,000 pounds per hour at 2400 psig at the turbine inlet. The two turbine generators were manufactured by Westinghouse Electric Corporation, each with a guaranteed rating of 664,898 kilowatts. The primary fuel is sub-bituminous C coal which comes from a strip mine adjacent to the plant. The coal is low in sulfur content (0.5 - 0.75%) and has a design heating value of 8100 BTU's per pound. Fly ash particulate emission is controlled by two electrostatic precipitators.

In October, 1977, the U of W Electrostatic Spray Scrubber was transported to the Centralia Power Plant. The sample gas stream (approximately 1500 acfm) was tapped from the outlet of boiler unit number 2. A 12 inch sampling scoop was installed (facing upstream) at the center point of the transition duct between the air preheater and the precipitator. Ten inch diameter aluminum ducting connects the sampling scoop to the scrubber which is located approximately 60 feet below on the ground level. Due to the high negative static pressure in the main duct, a Dayton centrifugal blower was installed at the scrubber inlet to boost the air flow capabilities. Figure IV-1 shows the location of the scrubber trailer (on the right) and the laboratory trailer (on the left). A schematic of the ducting arrangement showing the lengths of duct from the sampling scoop to the inlet of the pilot plant is shown in Fig. IV-2.

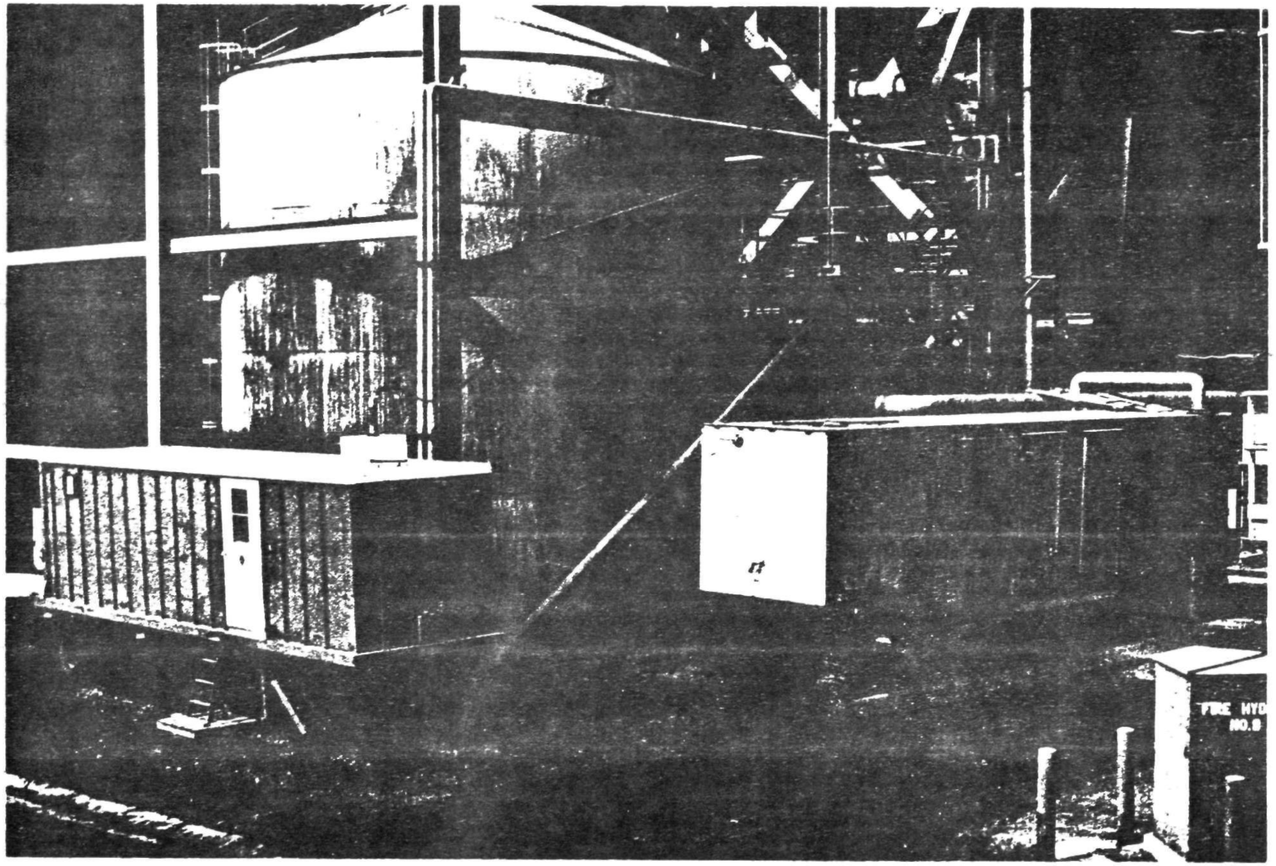


Fig. IV-1. Photograph of UW Electrostatic Spray Scrubber Located at Boiler Unit No. 2, Centralia Power Plant

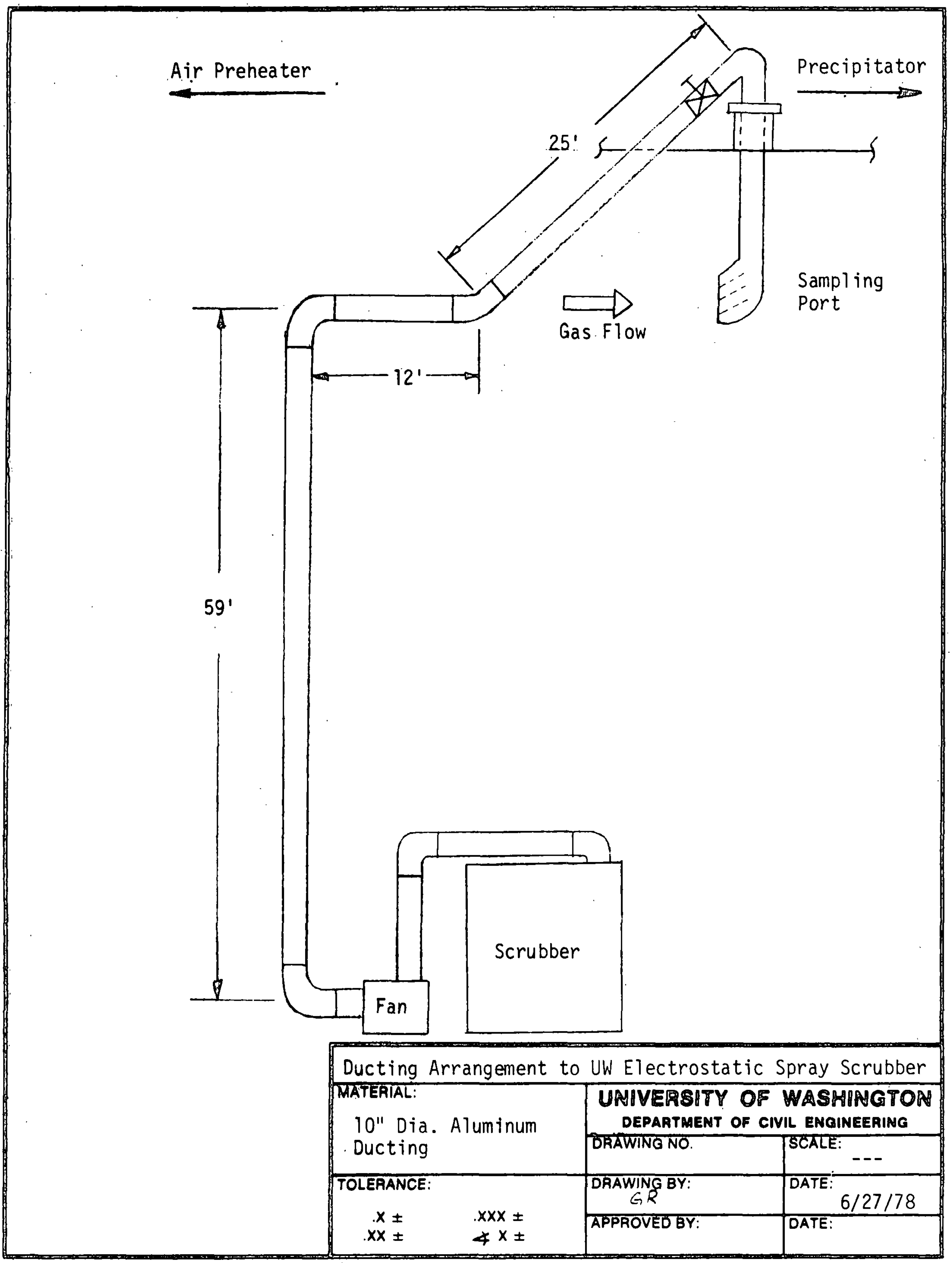


Fig. IV-2. Schematic of Ducting Arrangement to UW Electrostatic Spray Scrubber Pilot Plant at Centralia Power Station

Section V

DESCRIPTION OF UW ELECTROSTATIC SCRUBBER APPARATUS

A. Review of Previous Work

Penney (1944) patented an electrified liquid spray test precipitator involving particle charging by corona discharge and droplet charging by either ion impaction or induction. Penney's system consisted of a spray scrubber with electrostatically charged water droplets collecting aerosol particles charged to the opposite polarity. Kraemer and Johnstone (1955) reported theoretically calculated single droplet (50 micron diameter droplet charged negatively to 5,000 volts) collection efficiencies of 332,000% for 0.05 micron diameter particles (4 electron unit positive charges per particle). Pilat, Jaasund, and Sparks (1974) reported on theoretical calculation results and laboratory tests with an electrostatic spray scrubber apparatus. Pilat (1975) reported on field testing during 1973-74 with a 1,000 acfm UW Electrostatic Scrubber (Mark 1P model) funded by the Northwest Pulp and Paper Association. Pilat and Meyer (1976) reported on the design and testing of a newer 1,000 acfm UW Electrostatic Scrubber (Mark 2P model) portable pilot plant. Pilat, Raemhild, and Prem (1978) reported on tests of the UW Electrostatic Scrubber at a steel plant. The UW Electrostatic Scrubber (Patent Pending) has been licensed to the Pollution Control Systems Corporation (of Renton and Seattle, Washington) for production and sales.

B. Description of Overall System

The major components of the pilot plant include a gas cooling tower, an inlet and outlet test duct, two particle charging corona sections, two charged water droplet spray towers, and a mist eliminator. Auxiliary equipment includes transition ductwork between major components and a fan. The pilot plant is housed in a 40 ft. long trailer and can be easily transported to different emission sources.

The general layout of the pilot plant is shown in Figure V-1. Incoming gases enter the top of the trailer to be treated in the vertical gas cooling tower and then turn vertically upward to enter the inlet test duct. After moving down through the inlet test duct, the gases enter the first of three horizontal passes.

The first pass contains both particle charging corona sections and the first of two water spray towers. The two coronas are at either end of this pass and are separated by spray tower #1. Spray tower #2 comprises the entire second horizontal pass and the last (third) pass contains the mist eliminator.

At the outlet of the third horizontal pass, the gases enter the top of the outlet test duct and are then directed to the fan before being exhausted through the trailer roof.

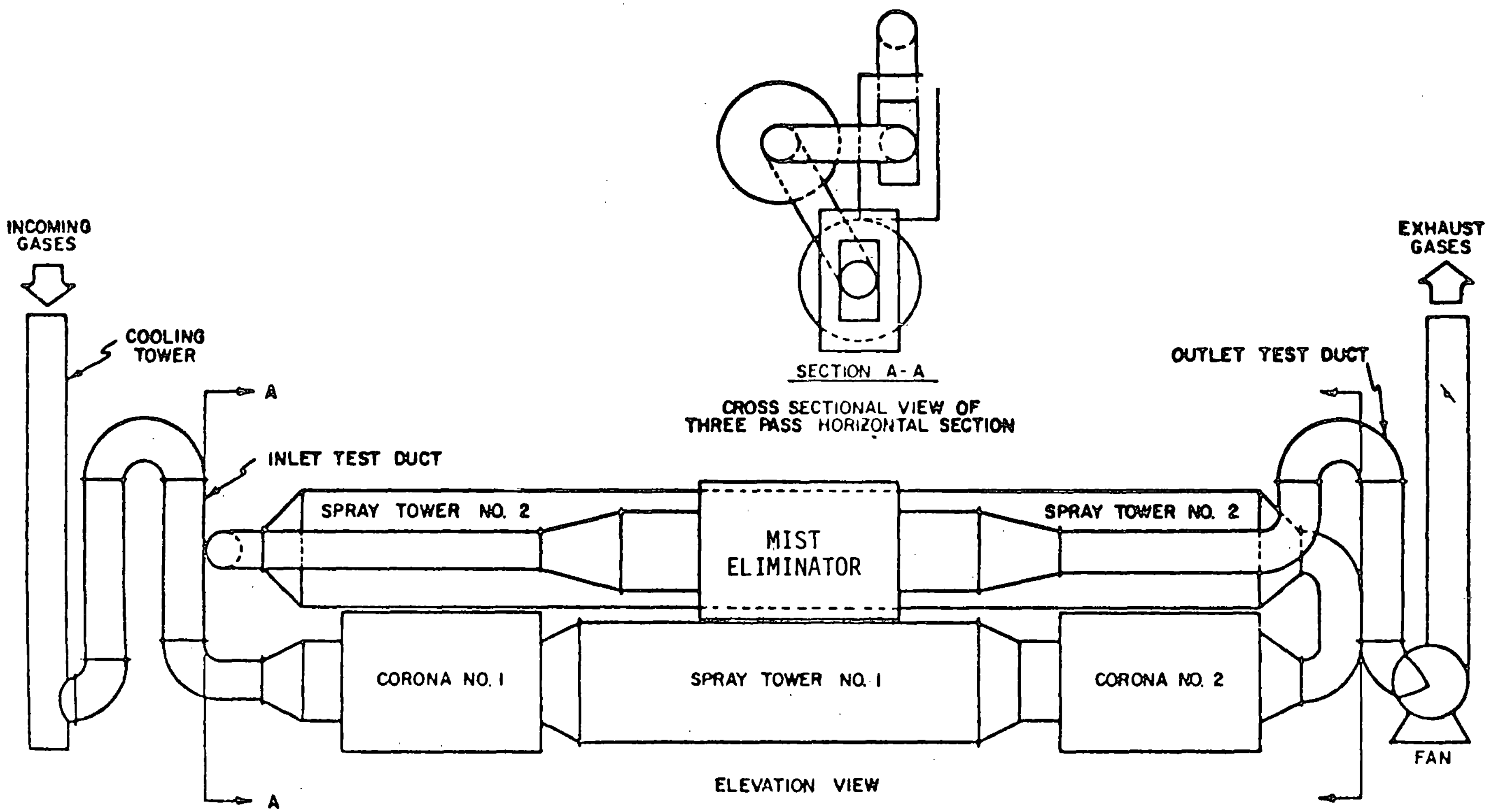


Fig. V-1. General Layout of Electrostatic Scrubber Pilot Plant

C. Cooling Tower

The cooling tower is designed to lower the gas temperature to below 250°F in order to maintain structural integrity of the system which is constructed of steel and fiberglass reinforced plastic. The cooling tower, as shown in Figure V-2 is 1 ft. 2 in. in diameter x 9 ft. 8 in. in height and is constructed of 21 gage T. 304 stainless steel. Cooling water is introduced through four ports spaced at 2 ft. intervals on one side of the tower and is sprayed vertically upward from the tower's centerline. Four Bete Model W 10080 F full cone stainless steel nozzles used for spraying are capable of delivering up to 3.0 gpm at 50 psig. A funnel built into the bottom of the spray tower extends through the trailer floor for cooling water removal.

D. Particle Charging Corona Sections

Particle charging corona sections are located at either end of the first horizontal gas passage. The corona shells are constructed from 3/16 in. wall thickness fiberglass reinforced plastic (FRP) with interior dimensions of 2 ft. wide x 3 ft. 6 in. high x 5 ft. long in the direction of gas flow. Access to a corona interior is through removable 2/16 in. FRP end plates which are normally bolted to 2 in. full perimeter face flanges on either end of a corona.

The coronas are designed to operate in either a single or double lane gas passage mode. Switching from one to another requires rearrangement of the adjustable collection plates and discharge frame(s). The width of individual gas lane(s) for either mode is maintained at 1 ft. and the discharge frame to collection plate spacing is therefore 6 in. Figure V-3 shows a cutaway schematic of a corona set up for single lane operation. The testing at Centralia Power Plant was performed with single lane corona section.

The overall dimensions of the discharge frame shown in Figure V-3 are 27-1/2 in. high x 3 ft. 9 in. long. The frame is constructed of 1/4 in. x 3/4 in. T. 304 stainless steel rectangular bar stock members. Prior to the Centralia test program these frames were modified by welding 1/8 in. diameter stainless steel rods in 1-3/4 in. lengths perpendicular to the vertical members of each discharge frame. The spikes have sharp points on both ends and are welded at 2 in. intervals. This modification has decreased the plate to frame spacing by 1/4 in.

The collection plates shown in Figure V-3 are 41-1/4 in. high x 59 in. long and are constructed from 11 gage T. 316 stainless steel. The plates serve as full chamber baffles to keep the gases within the confines of the single lane passage.

A negative corona is used to charge the particles negatively. This is accomplished by maintaining the discharge frame(s) at a high negative

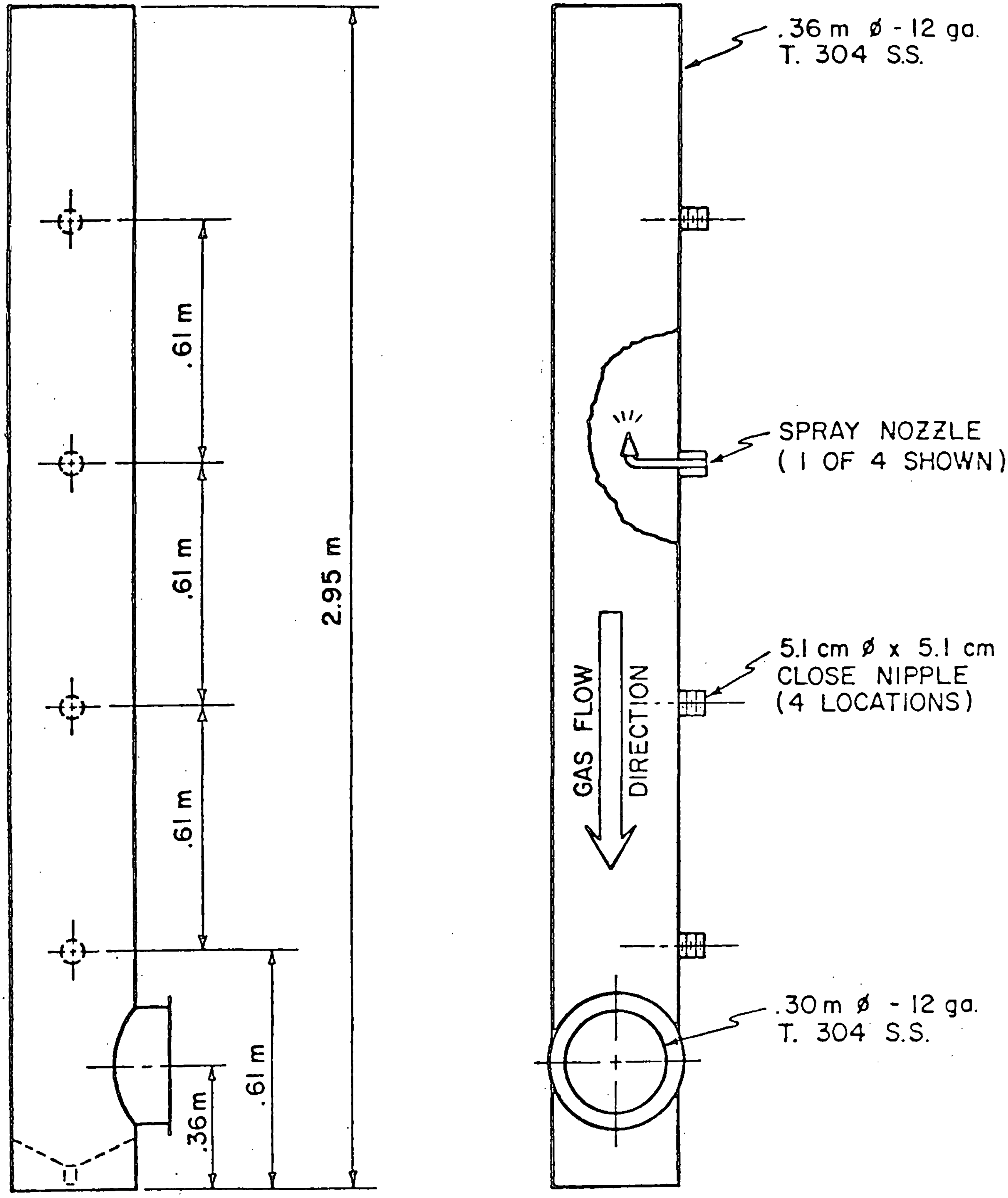


Fig. V-2. Cooling Tower Schematic

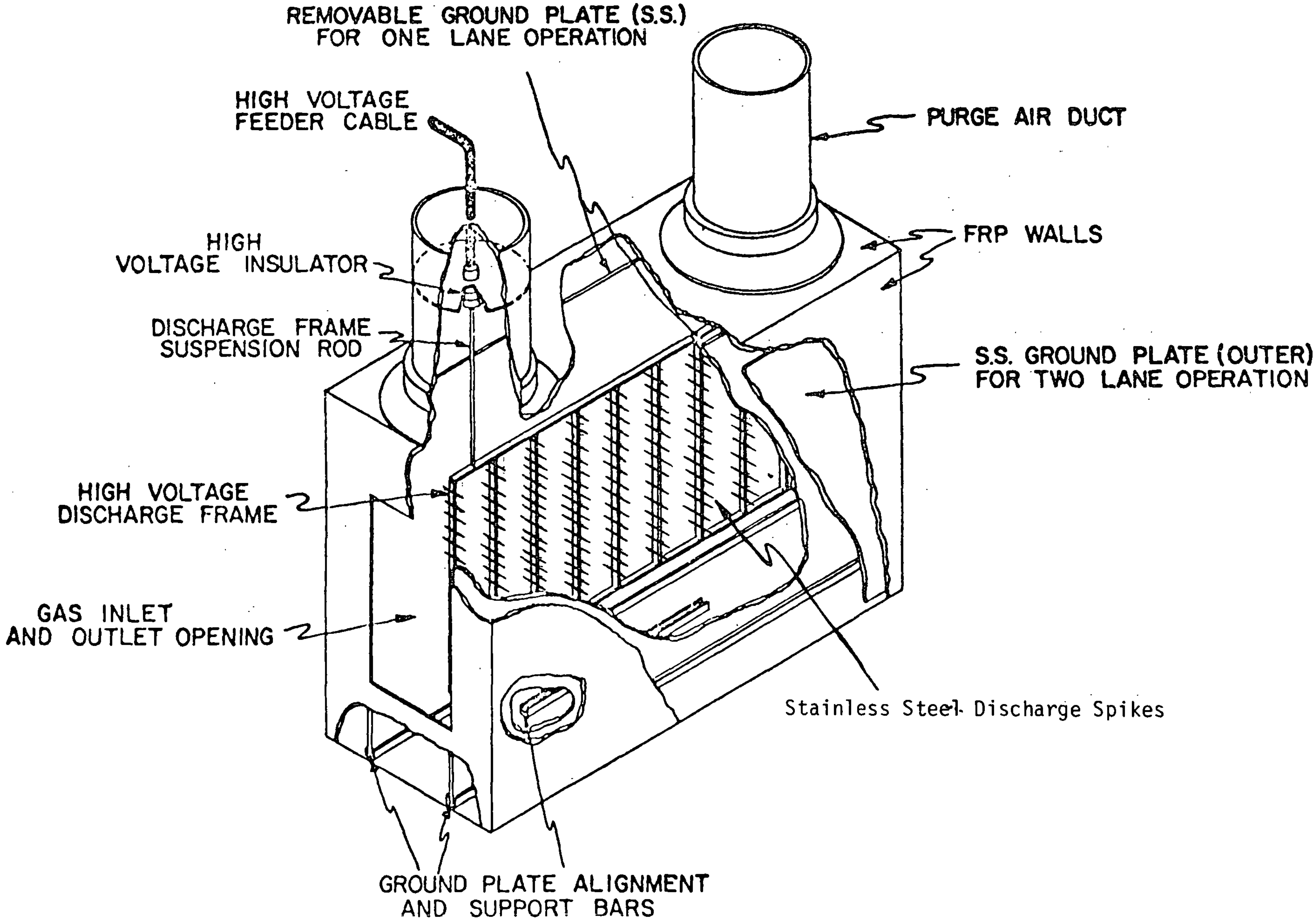


Fig. V-3. Particle Charging Corona Section potential and the collection plates at a neutral or ground potential. Field strengths generated in corona #1 and corona #2 are 13.65 KV/in. and 15.61 KV/in. respectively. Corona power supplies are discussed in a later section. The discharge frame is electrically isolated from all other components inside the corona. This isolation is provided by suspending the frame on two 1 in. diameter T. 303 stainless steel rods which are connected to porcelain insulators. The Ceramaseal Model 902B1353-6 insulators are housed in 1 ft. diameter x 2 ft. long x 1/4 in. wall thickness plexiglass tubes which are centered 3 ft. 6 in. apart and are located on top of the corona shells. Two 1 ft. to 1 ft. 2 in. x 3 in. FRP reducing flanges are used to join the plexiglass tubes to the corona top.

The insulators are continually flushed with a supply of heated purge air. The temperature of the purge air is maintained at about 120°F and an even flow across a plexiglass tube section is obtained by introducing the purge air through a distribution plate having approximately 10% hole area. The flushing face velocity of the purge air is set at about 0.6 ft/sec. This same purge air distribution flange discharge frame(s), is bolted directly to it. The high voltage lead-in to the discharge frame is through one of the two feed-through type insulators.

The collection plate and discharge frame flush system is shown schematically in Figure V-4. A continuous wall wash is supplied to the collection plates through 1 in. FRP square tube which had 1/8 in. diameter holes drilled diagonally into the corner adjacent the collection plate. The discharge frame flush is an intermittent spray supplied by two Bete 80° fan nozzles. Both corona section and the mist eliminator are equipped with this flushing system.

At the nominal gas flow rate of 1,000 acfm, the gas velocity in the corona is 4.76 ft/sec for single lane operation and 2.38 ft/sec for double lane operation. The corresponding gas residence times are 1.05 and 2.10 seconds. By varying the volume of air flow through the system, however, the gas residence time can range from 0.70 seconds (single lane operation at 1,500 acfm to 4.20 seconds (double lane operation at 500 acfm).

E. Water Spray Towers

The first of two spray towers used in the pilot plant is situated in the middle of the first horizontal gas passage (between the two coronas) while the second spray tower comprises the entire horizontal gas passage. Both spray towers are 3 ft. in diameter x 3/16 in wall thickness and are constructed from FRP. The lengths of the two spray towers are 10 ft. and 24 ft. for tower #1 and #2 respectively. Gas velocity in the spray towers at a nominal gas flow of 1000 acfm is 2.36 ft/sec. Corresponding gas residence times are 4.24 and 10.17 seconds for towers #1 and #2 respectively.

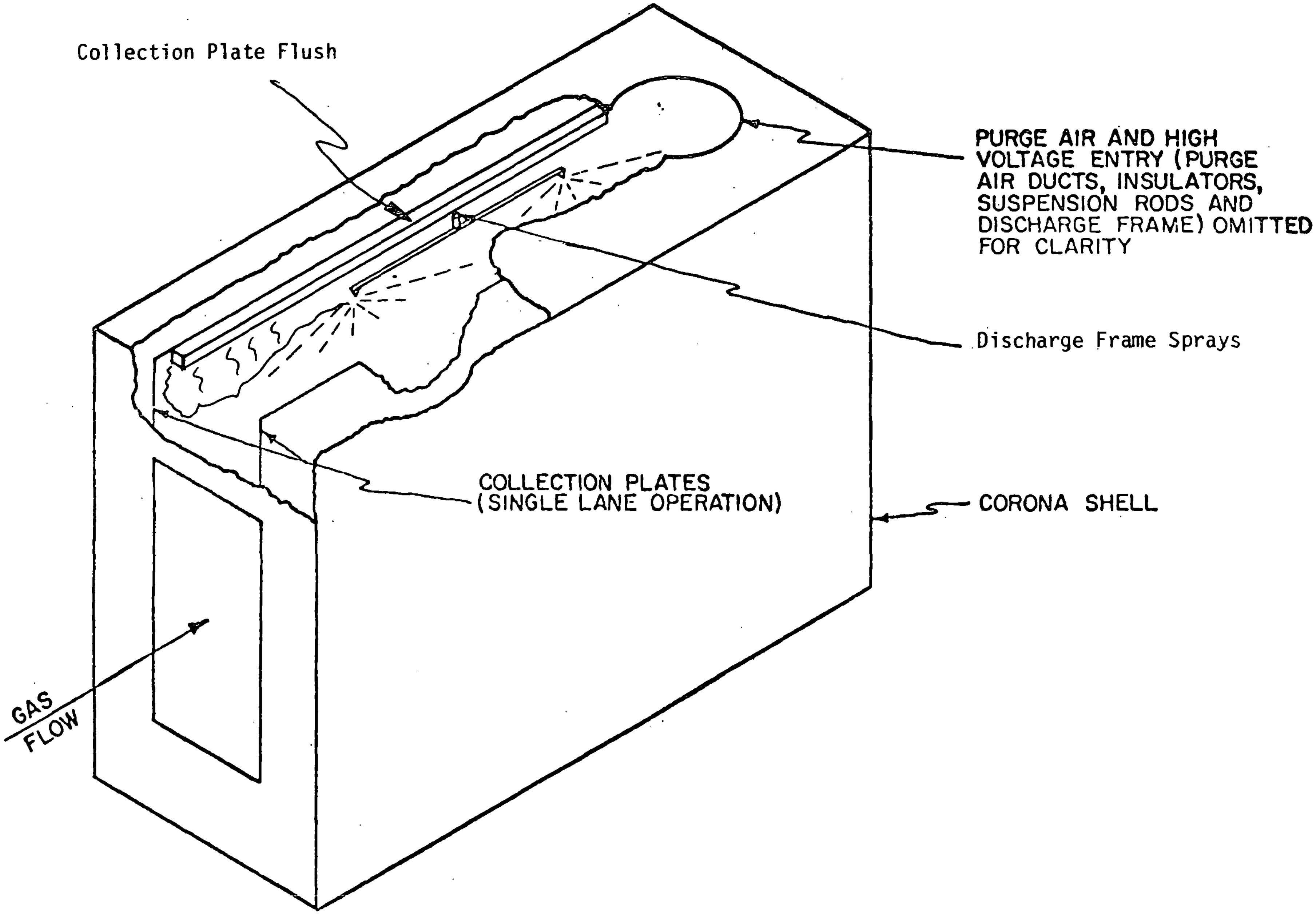


Fig. V-4. Collection Plate Flushing System

Utilizing a single spray header in each tower, a maximum of 21 nozzles can be used in the two towers. The total number of nozzles used can vary depending on the type of nozzle, the total water flow rate and the pressure head desired. All nozzles spray in the direction of gas flow (co-currently). A maximum of 6 nozzles can be used in spray tower #1 although only the 3 nozzles located farthest upstream were used to avoid flooding of corona section #2 with spray droplets. A single spray header in spray tower #2 can accommodate a maximum of 16 nozzles. A total of 5 to 12 nozzles were used in the Centralia tests depending on the desired flow rate. Bete L-80 spiral fog nozzle/header arrangement typical for both spray towers #1 and #2 is shown schematically in Figure V-5.

A positive charge is imparted to the water droplets by maintaining the nozzles at a positive potential (direct charging). The nozzles are electrically isolated from the spray tower walls by introducing heated purge air through 3 in. diameter x 4 in. long polyvinyl chloride (PVC) entry caps which are situated on top of the two spray towers (see Figure V-5). Both the water and the high voltage lead-in cable enter through a 1/4 in. diameter street tee fitting connected to the middle of each entry cap.

F. Mist Eliminator

The mist eliminator is situated in the middle of the third and last horizontal pass and is used to remove entrained water droplets from the airstream. The mist eliminator is identical to the corona sections with the exception of the discharge frame being maintained at a positive potential and the total height being 2 in. shorter (necessitating an equivalent shortening of the discharge frame and collection plates).

G. Test Ducts

The inlet and outlet test ducts are located immediately before the first corona and immediately after the mist elinimator respectively (see Figure V-1). Both test ducts are constructed from 3/16 in. wall thickness FRP and are 12 in. in diameter x 4 ft. long. Vertical gas flow in a downward direction is employed because it allows the most convenient positioning of the particle sizing source test equipment used and described in Section VI, "Particulate Sampling Apparatus." The particle sizing source test equipment also dictated the size of the test ports which are 6 in. wide x 1 ft. 6 in. high. The test ports are located three duct diameters downstream and one duct diameter upstream from flow disturbances.

H. Fan

The fan used to induce the air flow (i.e., clean side) through the pilot plant is a New York Blower Model RFE-12. The straight-bladed

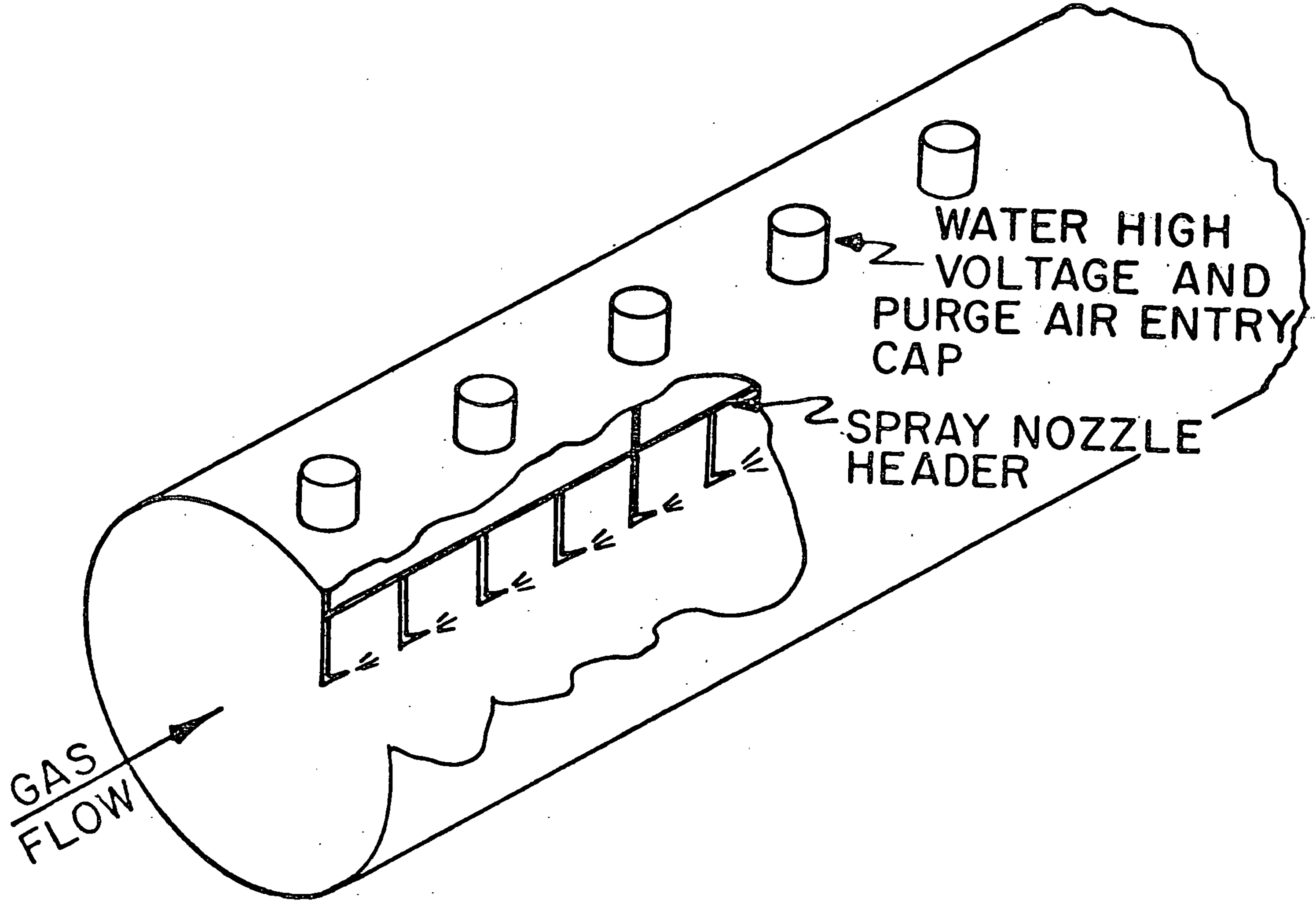


Fig. V-5. Spray Header and Nozzle Arrangement Typical to Spray Towers #1 and #2.

fanwheel and housing are constructed from FRP. The fan is driven through a split pulley belt drive by a Westinghouse 5 H.P., 208 volt, 3-phase motor turning at 1,800 rpm and is capable of delivering up to 1,500 acfm at 8 in. water column (WC) static pressure. The fan has a horizontal inlet and vertical outlet. A 3/16 in. FRP wall thickness x 1 ft. diameter exhaust duct containing an adjustable damper extends up through the trailer roof.

As previously mentioned, a Dayton centrifugal blower was installed at the scrubber inlet to increase the air flow capabilities at the Centralia Power Plant.

I. High Voltage Power Supplies

Four high voltage power supply units used in the pilot plant serve the coronas, mist eliminator, and water droplet charging. All four units operate off a 110 volt, 50 Hz, 1 Ø supply and are equipped with multi-range voltage and current meters on the high voltage output side. The units are also equipped with overvoltage and overcurrent surge protection.

The power supplies used for the two corona sections are equipped with spark rate controllers. The Universal Voltronics unit which energizes corona #1 has a L.L. Little P-30 automatic voltage control and the NWL unit for corona #2 has an integrated NWL spark rate controller. The four power supplies are described in the following table.

Table V-1. High Voltage Power Supply Units.

Source	Model	Polarity	Rated Peak Output	
			KV	mA
Corona #1	Universal Voltronics	Negative	40	25
Corona #2	NWL	Negative	90	30
Mist Eliminator	Hipotronics #860-16	Positive	60	16
Droplet Charging	Hipotronics #825-40	Positive	25	40

J. Water Supply System

The water supply system for the scrubber is controlled with a single control panel situated near the inlet sampling port. Two different sources supply water to the control panel: charged water (either recycled or fresh) and uncharged fresh water. The charged water is used as scrubbing liquor in spray towers #1 and #2 and the uncharged water is used for the corona flushing systems and the cooling tower.

A schematic of the charged scrubbing liquor system is shown in Figure V-6. The arrangement illustrated in Figure V-6 is for recycled liquor with fresh water make up. The Centralia Power Plant tests were performed with fresh (not recycled) water. The 3 in. drain to the settling tank (#3) was disconnected and ducted to the power plant water treatment system. Fresh water was then supplied to the settling tank at the same consumption rate as supplied to spray towers #1 and #2 combined.

A Goulds centrifugal pump model 3196 ST provides the necessary liquor flow requirements of 95 psig and a total flow rate of 17 gpm. A maximum flow of 5 gpm is provided to spray tower #1 while a maximum of 12 gpm is supplied to spray tower #2.

The water in the settling tank (either recycled or fresh) is transferred into the sump tank by a 1ϕ Deming centrifugal pump through the recycle sump sprays.

The fresh water supply is used in the gas cooling tower (approximately 3 gpm) and the corona section flush systems (flow rate is unmonitored).

K. Purge Air Heating System

The new purge air heating system is schematically illustrated in Figure V-7. The system consists of both commercially available and custom built components. The fan is a Barry Blower model BUF-90 Junior Fan employing a 1/3 HP motor with a maximum capacity of 500 cubic feet per minute. The discharge air then passes through a custom design Nelco Duct Heater. It is a 9 Kw heating unit with 4 stages to regulate the degree of heating required. The duct heater operated on 208V, 3ϕ power with a 110V control source which is external of the heater. A custom designed distribution plenum follows the heater and provides an adjustable purge air supply to the high voltage access points on the two corona sections, the mist eliminator section and the recycle sump tank. The basic design criterion for the purge air system is to provide 150°F purge air at a range of up to 500 acfm (total).

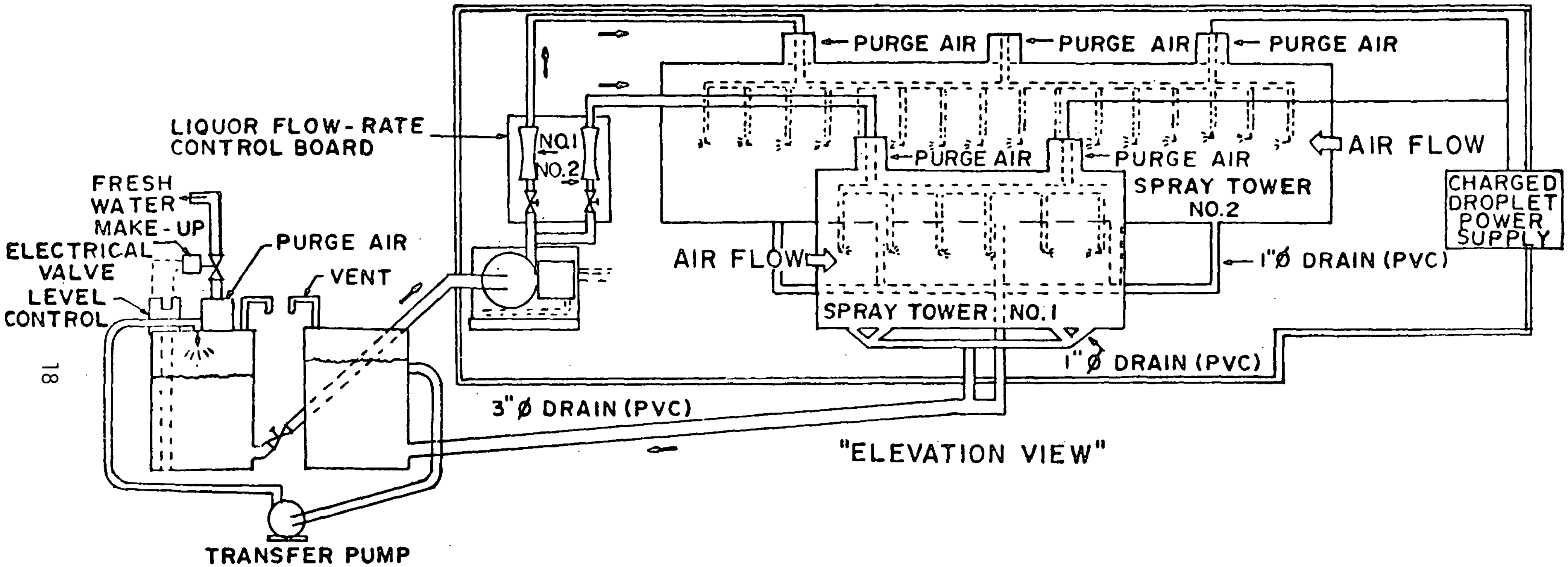


Fig. V-6. Charged Liquor Recycle System

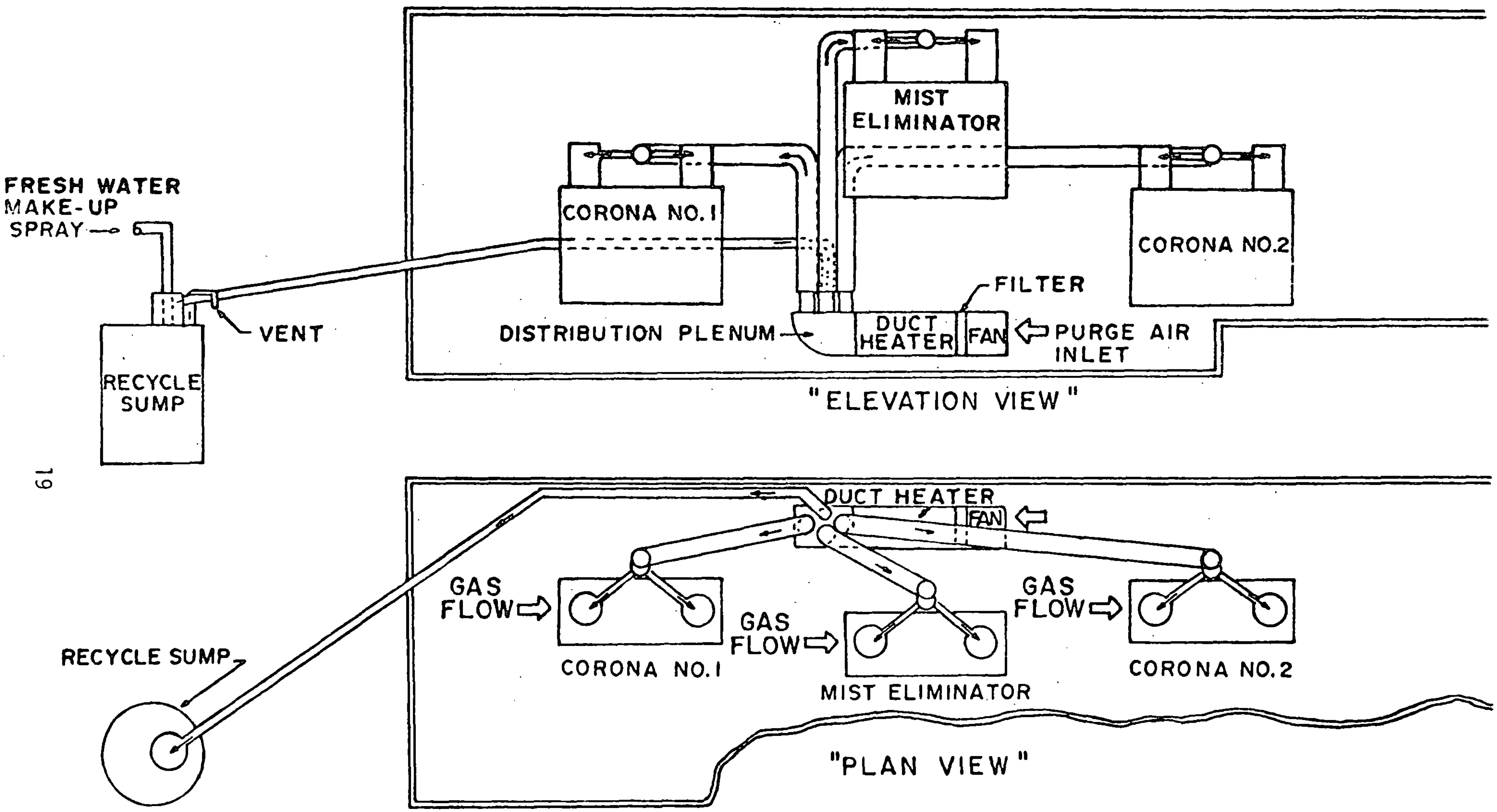


Fig. V-7. Heated Purge Air System

Section VI

EXPERIMENTAL PROCEDURES AND TEST EQUIPMENT

The following table indicates the source test equipment used to measure various parameters. Further information concerning the UW Cascade Impactor is given below.

Table VI-1. Particulate Source Test Parameters and Measurement Techniques.

Parameter	Equipment
1. Air	
a. Velocity and volume	S-type pitot tube with draft gauge
b. Temperature	Thermometer
c. Moisture	Wet and dry bulb thermometer and checked by volume of condensate
2. Water Spray Towers	
a. Water flow	Rotometers
3. Aerosol	
a. Mass concentration	UW Mark III and Mark V Cascade Impactors
b. Size distribution	UW Mark III and Mark V Cascade Impactors

The Mark III and Mark V Cascade Impactors were used to measure both particle size distribution and mass concentration at both the inlet and outlet test ducts respectively. The impactors provide this information by segregating the aerosol sample into discrete size intervals (seven collection plates plus one final filter for Mark III and eleven collection plates plus one final filter for Mark V). The aerosol weight on each plate provides size distribution information and the total weight is used to determine the mass concentration. The basic components of a sampling train utilizing a UW Cascade Impactor are shown schematically in Figure VI-1. The impingers are used to collect water vapor in the sample air stream and provide a basis for calculating the moisture content of gas stream which may be checked against the wet and dry bulb determination. The dry gas meter is used to determine isokinetic sampling conditions as well as the total sample volume.

By conducting simultaneous particle size distribution tests at both the inlet and outlet test ducts, the size-dependent collection efficiency curve of the pilot plant may be measured.

Overall efficiency measurements were also performed using in-stack filters simultaneously at the inlet and outlet of the scrubber. These measurements were performed per EPA Method 17 using a 3.54 in. filter at the scrubber inlet and a 1.85 in. filter at the scrubber outlet. Reeve Angel pre-washed glass fiber filters were used to minimize any SO_2 reaction with the filter material.

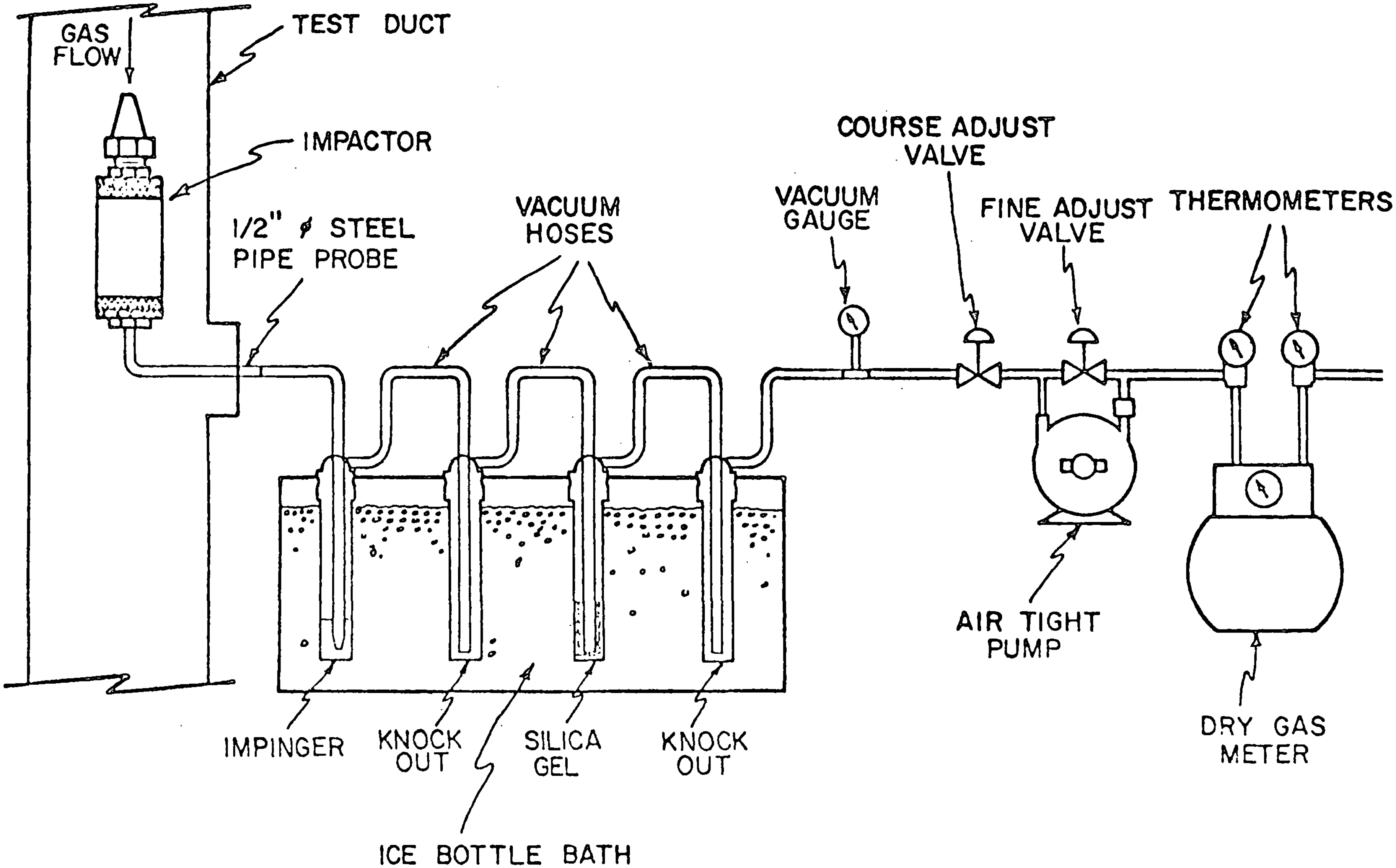


Fig. VI-1. UW Cascade Impactor Sampling Train

Section VII

PARTICULATE COLLECTION EFFICIENCY RESULTS

A. General Test Description

Particulate collection efficiency measurements on the U of W Electrostatic Spray Scrubber were performed with the unit in two basic operating modes. In the first mode (two stage), two particle charging corona sections and two spray towers were used. The components were connected in series (corona #1, spray tower #1, corona #2, spray tower #2) followed by an electrostatic mist eliminator. In the second mode (one stage), only one corona section and one spray tower were on. Water flow and high voltage power to corona #1 and spray tower #1 were turned off and they were utilized as ducting only. Scrubber operating parameters (SCA, L/G, gas residence time, no. of components, etc.) were subsequently reduced. Simultaneous cascade impactor measurements and in-stack filter tests, described in Section VI, were performed on the scrubber in both operating modes.

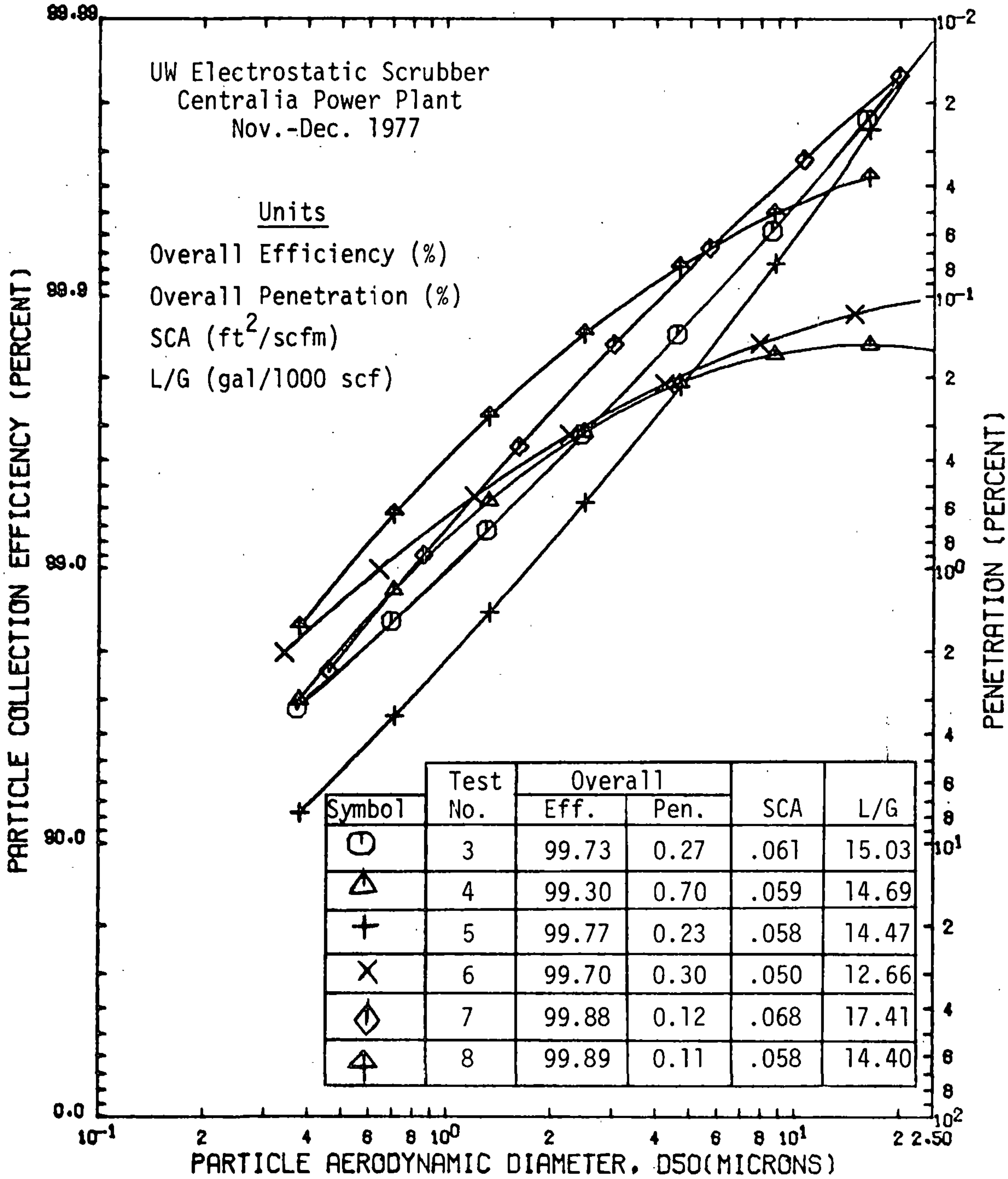
B. Particulate Collection Efficiency (Two Stage Mode)

1. Cascade Impactor Measurements

Initial cascade impactor tests were performed with the scrubber in the two stage mode. Results of simultaneous inlet/outlet impactor tests 3-8 are shown in Table VII-1. Scrubber operating parameters (corona voltage, mist eliminator voltage, and liquor flow rate) were held constant for all tests with a variation in spray voltage from 0 to 10 KV. A significant variation in inlet gas flow from 919 scfm (1179 acfm) to 1244 scfm (1515 acfm) was noted. This variation was unavoidable. With both the scrubber I.D. fan and the booster fan operating at full capacity, a variation in the negative static pressure at the outlet of the air preheater (due to varying boiler conditions) resulted in subsequent variations in inlet gas flow. This created changes in the parameters L/G, SCA, and gas residence time. The levels of these parameters for impactor tests 3-8 are shown in page 2 of Table VII-1. A variation in inlet gas temperature (measured downstream of the cooling tower) from 133°F to 154°F was also noted. Overall particle collection efficiency for these tests ranged from 99.30% to 99.89% (0.11% to 0.70% penetration). The particle collection efficiency and penetration as a function of particle size (aerodynamic cut diameter of cascade impactor stages, d_{50}) for tests 3-8 are shown in Figure VII-1. The aerodynamic cut diameter of the impactor stages is defined as the diameter of the particle of unit density collected with 50% efficiency and is calculated by

Table VII-1. Results of Cascade Impactor Tests 3 Through 8 at Centralia Power Plant (Two Stage System).

Test No./ Date	Inlet Gas Flow (SCFM)	Particle Mass Conc. (grains sdcf)		Overall Coll. Eff. (%)	Penetration (%)	Total Liquor Flow Rate (gpm)	Corona Voltage (KV)		Spray Voltage (KV)		SCA (ft^2/scfm)	L/G (Gal/1000 scf)	Gas Residence Time (sec.)		
		Inlet	Outlet				#1	#2	#1	#2			Corona Section	Spray Tower	Mist Eliminator
3 11/30/77	1031	0.25924	.00052	99.73	0.27	15.5	68	80	0	0	0.061	15.0	1.82	13.99	0.86
4 11/30/77	1055	0.20721	.00099	99.30	0.70	15.5	68	80	0	0	0.059	14.7	1.78	13.67	0.84
5 12/1/77	1071	0.37242	.00056	99.77	0.23	15.5	68	80	2	2	0.058	14.5	1.76	13.46	0.83
6 12/1/77	1244	0.31301	.00068	99.70	0.30	15.5	68	80	2	2	0.050	12.7	1.51	11.59	0.72
7 12/8/77	919	0.53698	.00039	99.88	0.12	16.0	68	80	10	10	0.068	17.4	2.05	15.69	0.97
8 12/14/77	1076	0.37494	.00029	99.89	0.11	15.5	68	80	0	0	0.058	14.4	1.75	13.40	0.83



Symbol	Test No.	Overall Eff.	Overall Pen.	SCA	L/G
O	3	99.73	0.27	.061	15.03
△	4	99.30	0.70	.059	14.69
+	5	99.77	0.23	.058	14.47
X	6	99.70	0.30	.050	12.66
◇	7	99.88	0.12	.068	17.41
△	8	99.89	0.11	.058	14.40

Fig. VII-1. Particle Collection Efficiency and Penetration vs. Particle Size for Impactor Tests 3-8 (Two Stage System)

$$d_{50} = \left[\frac{18\mu\, D_j\, \Psi_{50}}{C\, V_j}\right]^{\frac{1}{2}}$$

where μ is the gas viscosity, D_j the jet diameter, Ψ_{50} the inertial impaction parameter at 50% collection efficiency for particles of diameter d_{50}, C the Cunningham correction factor, and V_j the gas velocity in the jet diameter. The collection of particles of diameter less than 1.0 micron ranged from about 90% to 99.5% (1.5 to 10% penetration). The particle mass concentrations (grains/sdcf) less than the stated particle aerodynamic diameter, d_{50} (microns), for these tests are shown in Figures VII-2 and VII-3. The curves in these graphs illustrate the reduction in the particle mass concentration for a particular particle size range on going from the scrubber inlet to the outlet.

The cumulative particle size distributions (log-normal approximation) measured at the scrubber inlet and outlet are shown in Figures VII-4 and VII-5. The particle mass mean diameter (particle diameter at which 50% of the particle mass is greater than this diameter, and at which 50% is less than this diameter) was in the 11.5 to 29.4 micron diameter range at the scrubber inlet and in the 0.27 to 1.07 micron diameter range at the outlet. A good correlation existed between the actual particle size (as measured with the cascade impactors) and the straight line (log-normal) approximation, this analysis uses the log-normal approximation to the particle size distribution.

Particle mass concentrations measured at the scrubber outlet ranged from .00029 grains/sdcf to .0099 grains/sdcf. Sample weights on the outlet impactor substrates were consequently quite low (.01 to .15 mg). The difference between the particulate grain loading at the scrubber inlet and outlet prevented simultaneous sampling. Despite outlet sampling times as high as 1 hour, low weights were recorded. Details on the sampling techniques (sampling rates, nozzle sizes, types of substrates used, etc.) for both the impactor tests and the in-stack filter tests are listed in Appendix A.

2. In-stack Filter Measurements

Overall particulate collection efficiency measurements using in-stack filters were also performed with the scrubber in the two stage mode. The results of tests 1-F through 8-F are shown in Table VII-2. The isokinetic sampling rate for the outlet filter was increased to collect a larger sample (80 to 100 acf). All scrubber operating parameters were held constant with the exception of spray voltage which was varied between 0 and 10 KV. Inlet conditions (mass concentration, gas flow, etc.) did not vary as significantly as for impactor tests 3-8. Overall particulate collection efficiencies ranged from 99.77% (.23% penetra-

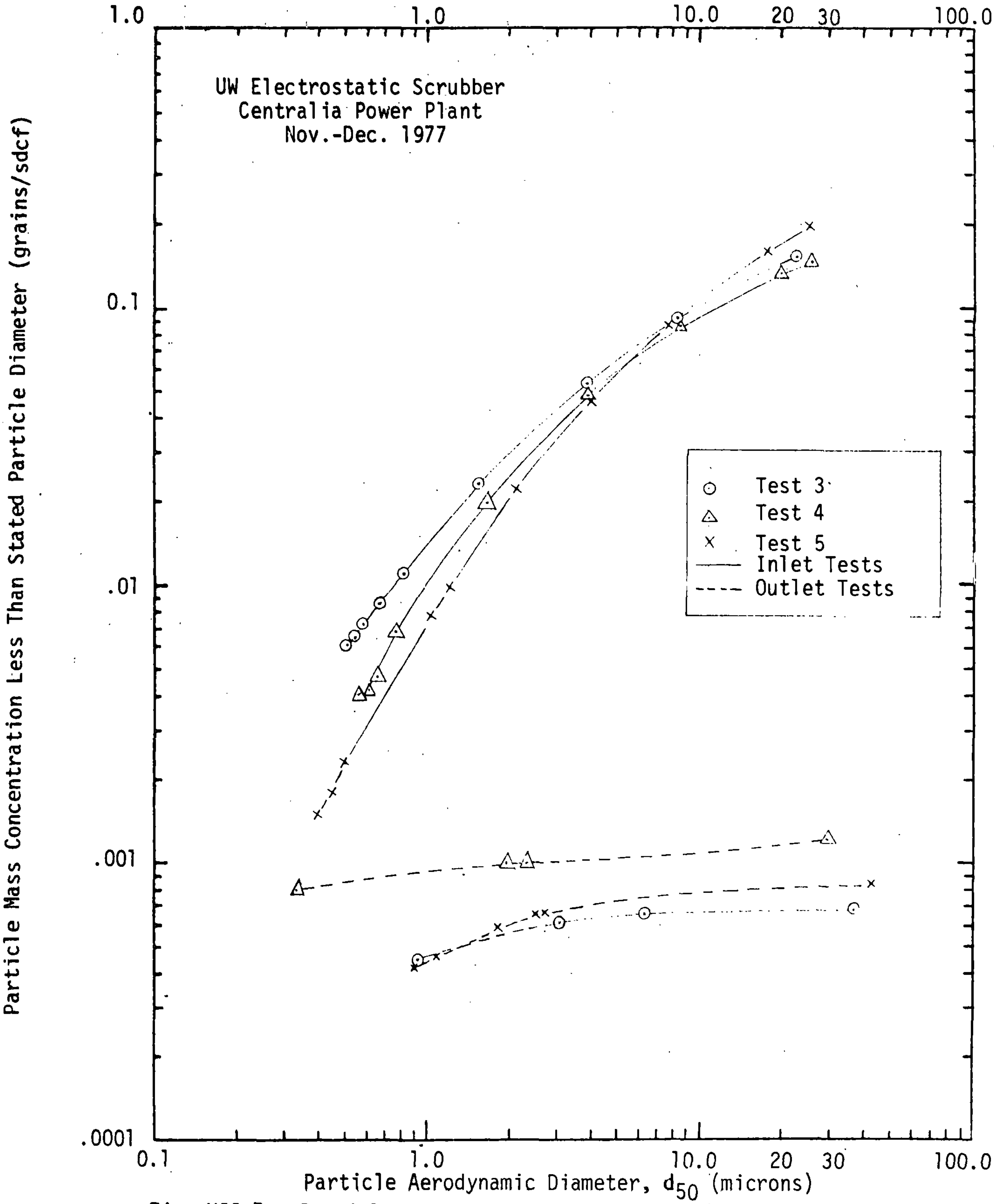


Fig. VII-2. Particle Mass Concentration for Particles Less Than Stated Diameter for Cascade Impactor Tests 3-5.

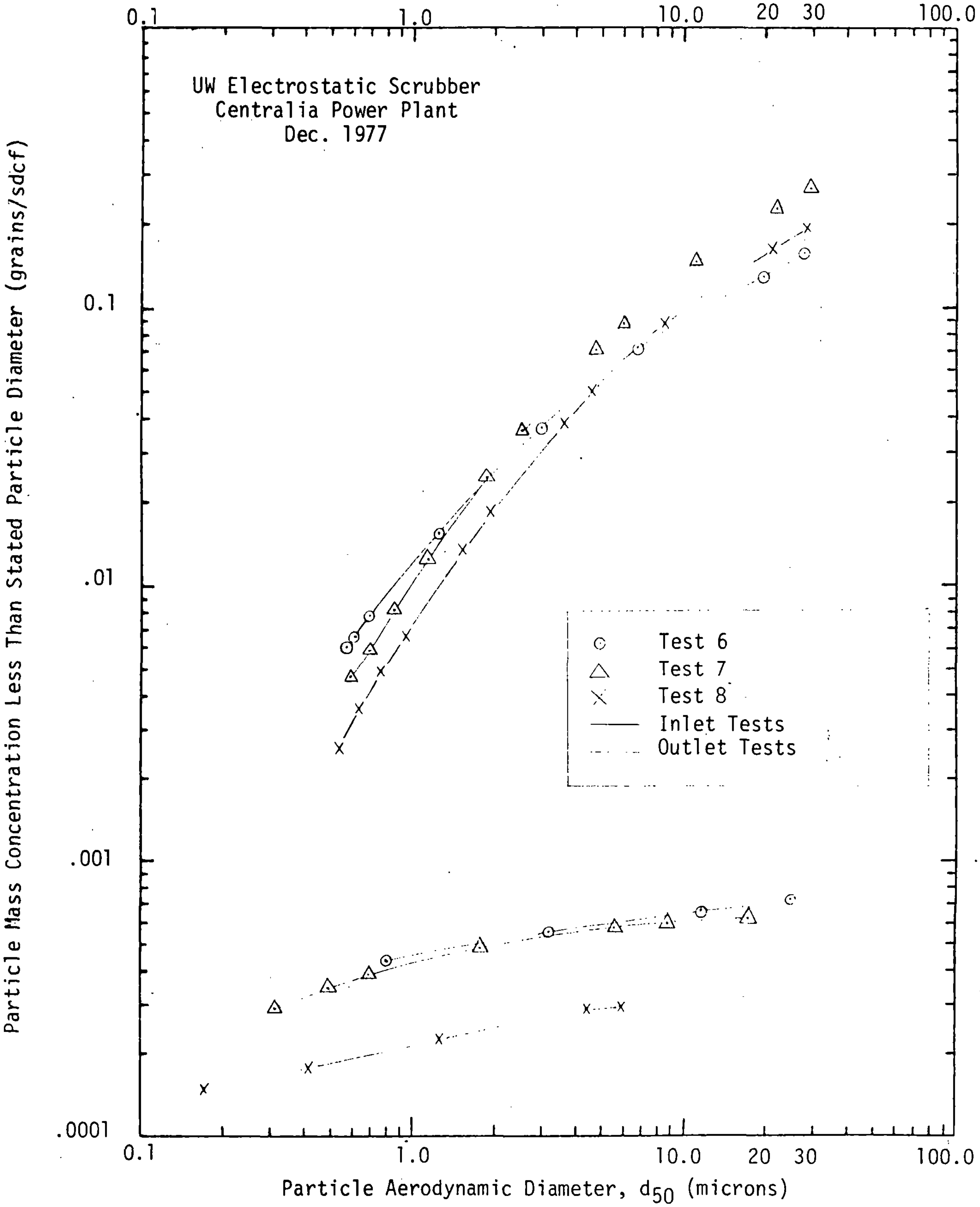


Fig. VII-3. Particle Mass Concentration for Particles Less Than Stated Diameter for Cascade Impactor Tests 6-8.

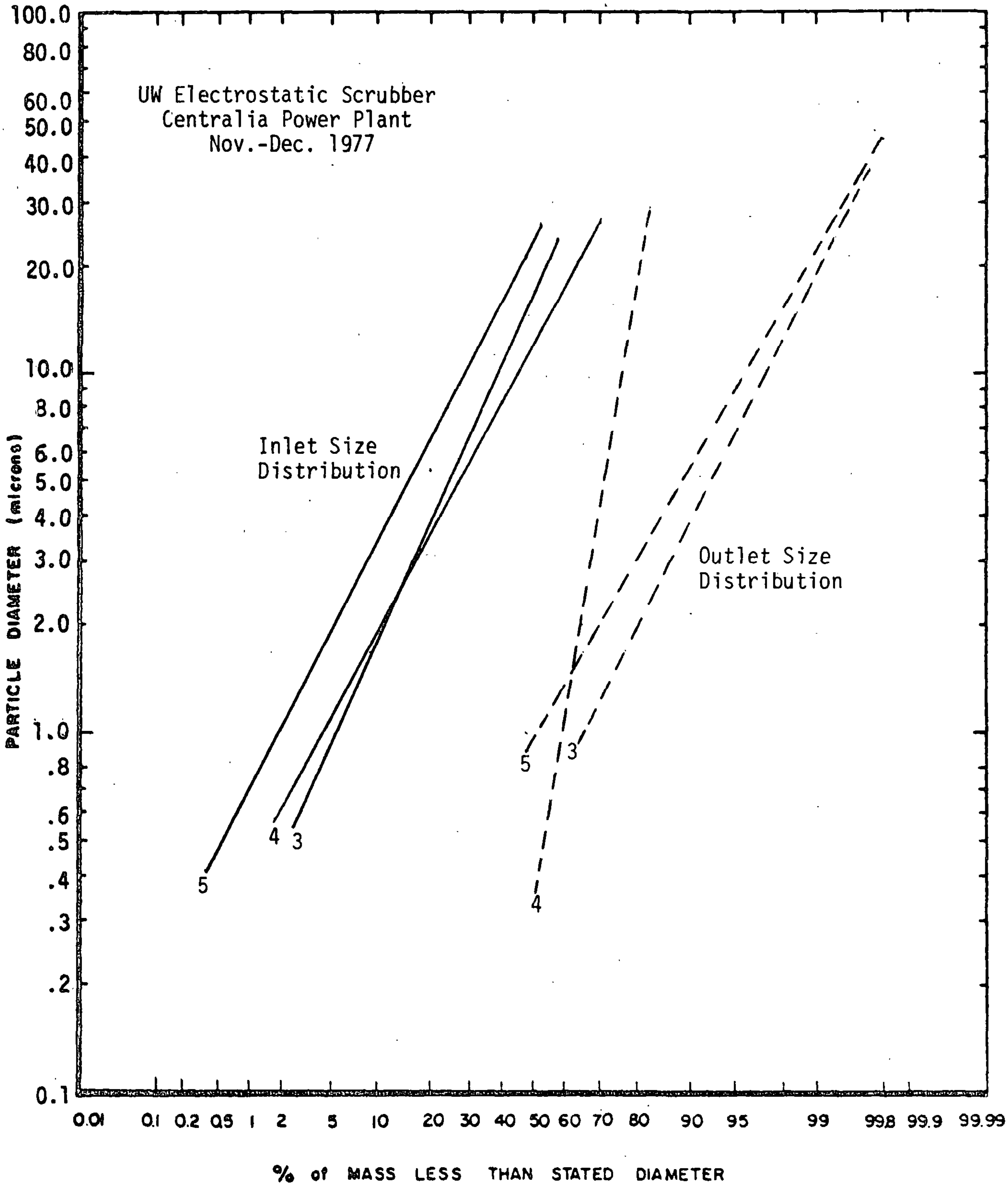


Figure VII-4. Inlet and Outlet Particle Size Distributions for Cascade Impactor Tests 3-5 (Log-Normal Approximation)

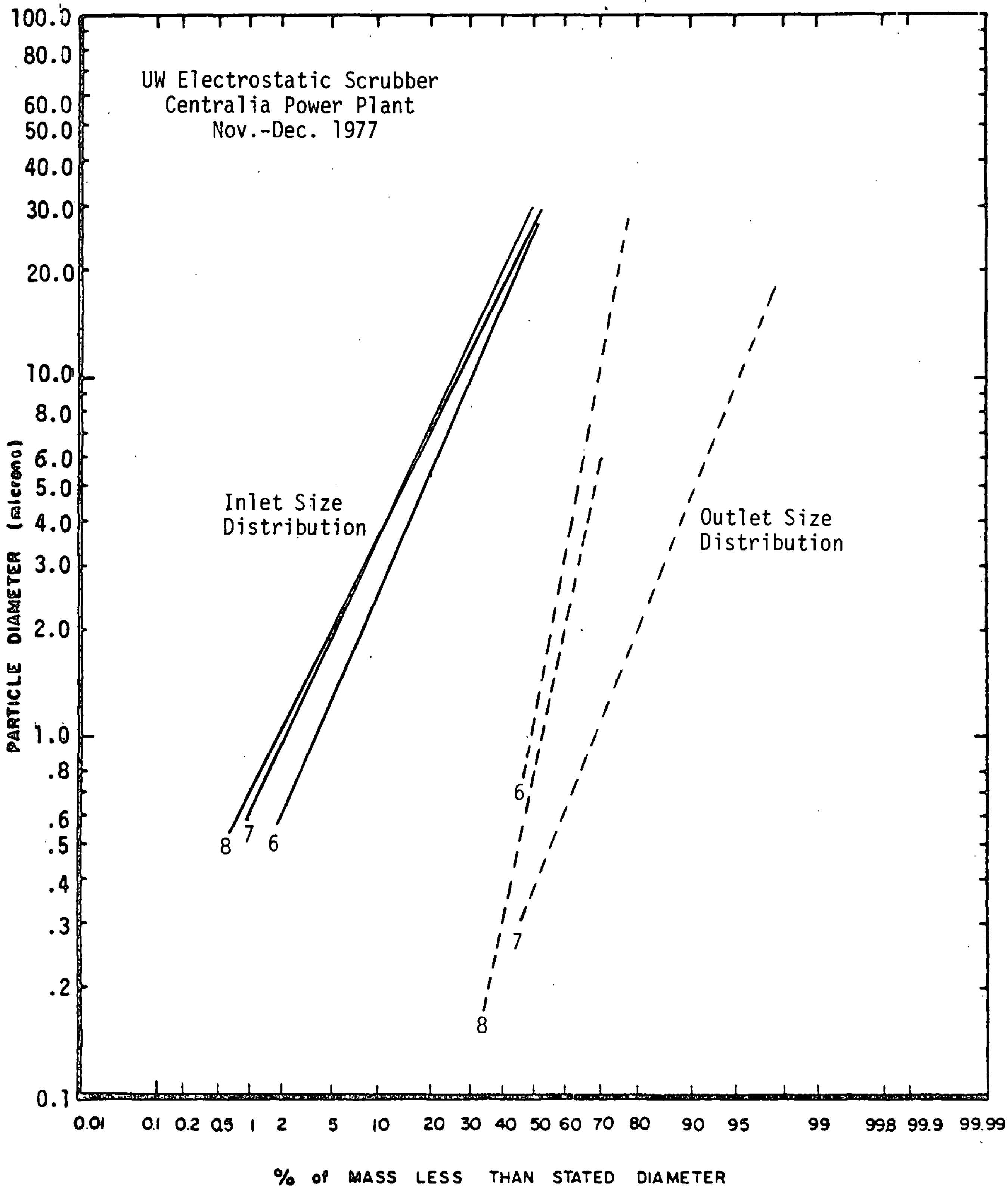


Figure VII-5. Inlet and Outlet Particle Size Distribution for Cascade Impactor Tests 6-8 (Log-Normal Approximation)

Table VII-2. Results of Simultaneous In-stack Filter Tests 1-F Through 8-F at Centralia Power Plant (Two Stage System).

Test No./ Date	Inlet Gas Flow (scfm)	Particle Mass Conc. (grains/sdcf)		Overall Coll. Eff. (%)	Penetration (%)	Total Liquor Flow Rate (gpm)	Corona Voltage (KV)		Spray Voltage (KV)		SCA (ft^2/scfm)	L/G (Gal/1000 scf)	Gas Residence Time (sec.)		
		Inlet	Outlet				#1	#2	#1	#2			Corona Section	Spray Tower	Mist Eliminator
1-F 1/24/78	1072	0.40634	.00052	99.85	0.15	17.5	68	80	0	0	.058	16.32	1.75	13.45	0.83
2-F 1/24/78	1091	0.39347	.00067	99.77	.23	18.5	68	80	0	0	.057	16.96	1.72	13.22	0.82
3-F 1/24/78	1061	0.31080	.00030	99.88	.12	17.5	68	80	0	0	.059	16.49	1.77	13.59	0.84
4-F 1/24/78	1108	0.37958	.00022	99.99	.01	17.5	68	80	5	5	.056	15.79	1.70	13.01	0.80
5-F 1/24/78	1146	0.39473	.00021	99.94	.06	17.5	68	80	5	5	.055	15.70	1.64	12.58	0.78
6-F 1/24/78	1192	0.45178	.00015	99.96	.04	16.1	68	80	10	10	.052	13.51	1.58	12.10	0.75
7-F 2/1/78	1182	0.83886	.00018	99.96	.04	17.0	68	80	0	0	.053	14.38	1.59	12.20	0.75
8-F 2/1/78	1142	0.63517	.00029	99.93	.07	17.0	68	80	10	10	.055	14.98	1.65	12.63	0.78

tion) with no charge on the sprays to 99.99% (.01 penetration) with 5 KV(+) charge on the sprays. A direct correlation between particle collection efficiency and spray voltage was not apparent although the 3 tests exhibiting the highest overall particulate collection efficiencies were either a 5 KV(+) or 10 KV(+) charge on the sprays. The outlet particle mass concentrations measured ranged from 0.00018 to 0.00067 grains/sdcf. Simultaneous sampling at the inlet and outlet of the scrubber was not possible for either the in-stack filter tests or the impactor tests due to the extreme difference between inlet and outlet mass concentrations in this operating mode.

C. Particulate Collection Efficiency (One Stage Mode)

1. General System Description

Operation of the scrubber in the one stage mode involves utilization of corona #2 and spray tower #2 only. With corona #1 and spray tower #1 inactive, the active length (in the direction of gas flow) of particle charging section and spray tower section is reduced 50% and 29% respectively. Gas residence time in the combined active sections is subsequently reduced 32%. The gas cooling tower and the electrostatic mist eliminator were used in both the one and two stage modes. Inlet volumetric gas flow rate remained approximately the same as measured for the two stage tests. Total liquor flow to the spray sections was reduced to approximately 12.0 gpm resulting in a reduction in liquor to gas flow rate ratio of about 27%.

2. In-stack Filter Measurements

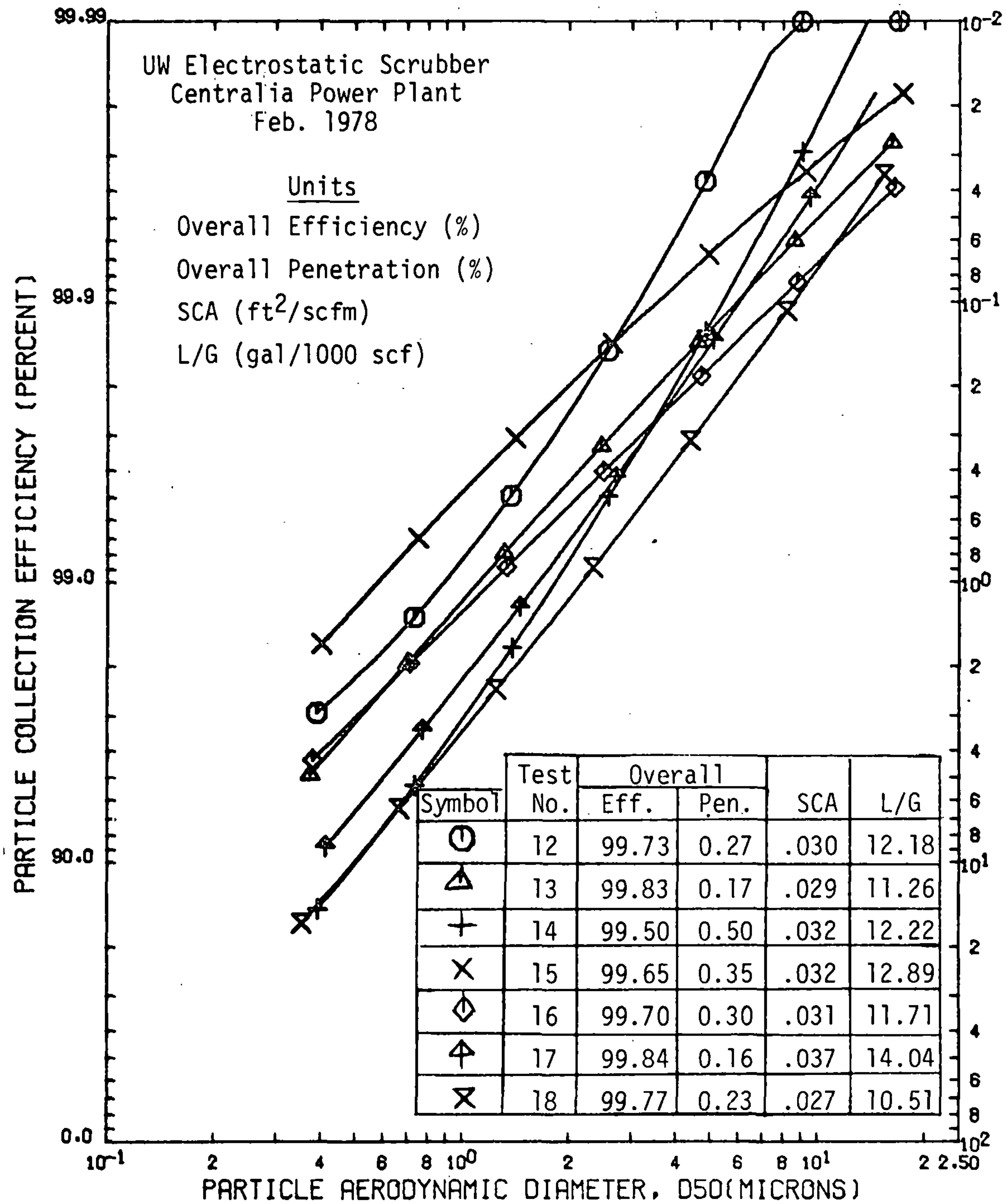
Overall particle collection efficiency measurements (in-stack filter tests) were initially performed on the one stage system. The results of tests 9-F through 16-F are shown in Table VII-3. Overall collection efficiency ranged from 99.77% to 99.89% (0.23% to 0.11% penetration). Particle mass concentration measured at the scrubber inlet ranged from 0.6774 to 1.1390 grains/sdcf while outlet particle mass concentrations varied from 0.00077 to 0.00116 grains/sdcf. Despite the reduction in the operating parameters previously described, outlet particle mass concentrations remained low, resulting in extended sampling time and low outlet sample weights. No direct correlation between spray voltage and particle collection efficiency was noted. Such a correlation is difficult to establish when the low outlet sample weights introduced a significant probable error associated with weighing. In addition to weighing related errors, there are other probable errors inherent in the sampling process. The difference in inlet and outlet sampling times necessitated by the difference in mass concentration also had a possible effect upon the results. During the outlet testing period (up to 60 min.), system upsets and perturbations could affect the outlet sample and not be accounted for by the inlet (10 minute) sample.

Table VII-3. Results of Simultaneous In-stack Filter Tests 9-F Through 16-F at Centralia Power Plant (One Stage System).

Test No./ Date	Inlet Gas Flow (scfm)	Particle Mass Conc. (grains/sdcf)		Overall Coll. Eff. (%)	Penetration (%)	Total Liquor Flow Rate (gpm)	Corona Voltage (KV)		Spray Voltage (KV)		SCA (ft^2/scfm)	L/G (Gal/1000 scf)	Gas Residence Time (sec.)		
		Inlet	Outlet				#1	#2	#1	#2			Corona Section	Spray Tower	Mist Eliminator
9-F 2/2/78	1279	1.1390	.00095	99.89	.11	12.5	--	80	--	0	.024	9.77	0.74	7.96	0.70
10-F 2/2/78	1122	0.8584	.00116	99.80	.20	12.5	--	80	--	2	.028	11.14	0.84	9.07	0.79
11-F 2/2/78	1179	0.6774	.00077	99.84	.16	12.0	--	80	--	5	.027	10.18	0.80	8.63	0.75
12-F 2/2/78	1253	0.6920	.00088	99.82	.18	12.0	--	80	--	10	.025	9.58	0.75	8.12	0.71
13-F 2/2/78	1210	0.7530	.00101	99.82	.18	12.0	--	80	--	0	.026	9.92	0.78	8.41	0.74
14-F 2/3/78	1141	0.7650	.00115	99.79	.21	12.5	--	80	--	5	.027	10.96	0.82	8.92	0.78
15-F 2/3/78	1190	0.7110	.00085	99.83	.17	12.5	--	80	--	2	.026	10.50	0.79	8.55	0.75
16-F 2/3/78	1173	0.7030	.00113	99.77	.23	12.0	--	80	--	10	.027	10.23	0.80	8.68	0.76

Table VII-4. Results of Simultaneous Impactor Tests 12-18, Centralia Power Plant (One Pass System).

Test No./ Date	Inlet Gas Flow (scfm)	Particle Mass Conc. (grains/sdcf)		Overall Coll. Eff. (%)	Penetration (%)	Total Liquor Flow Rate (gpm)	Corona Voltage (KV)		Spray Voltage (KV)		SCA (ft^2/scfm)	L/G (Gal/1000 scf)	Gas Residence Time (sec.)		
		Inlet	Outlet				#1	#2	#1	#2			Corona Section	Spray Tower	Mist Eliminator
12 2/8/78	1026	.33605	.00060	99.73	.27	12.5	--	80	--	0	.030	12.18	0.92	9.92	0.87
13 2/8/78	1066	.57211	.00071	99.83	.17	12.0	--	80	--	2	.029	11.26	0.88	9.55	0.83
14 2/8/78	982	.26609	.00088	99.50	.50	12.0	--	80	--	2	.032	12.22	0.96	10.37	0.91
15 2/8/78	970	.20468	.00045	99.65	.35	12.5	--	80	--	0	.032	12.89	0.97	10.49	0.92
16 2/9/78	1025	.22907	.00047	99.70	.30	12.0	--	80	--	0	.031	11.71	0.92	9.93	0.87
17 2/9/78	855	.42355	.00042	99.84	.16	12.0	--	80	--	0	.037	14.04	1.10	11.91	1.04
18 2/9/78	1142	.48158	.00081	99.77	.23	12.0	--	80	--	10	.027	10.51	0.82	8.91	0.78



Symbol	Test No.	Overall Eff.	Overall Pen.	SCA	L/G
O	12	99.73	0.27	.030	12.18
△	13	99.83	0.17	.029	11.26
+	14	99.50	0.50	.032	12.22
X	15	99.65	0.35	.032	12.89
◇	16	99.70	0.30	.031	11.71
✢	17	99.84	0.16	.037	14.04
⧖	18	99.77	0.23	.027	10.51

Fig. VII-6. Particle Collection Efficiency and Penetration vs. Particle Size for Impactor Tests 12-18 (One Stage System)

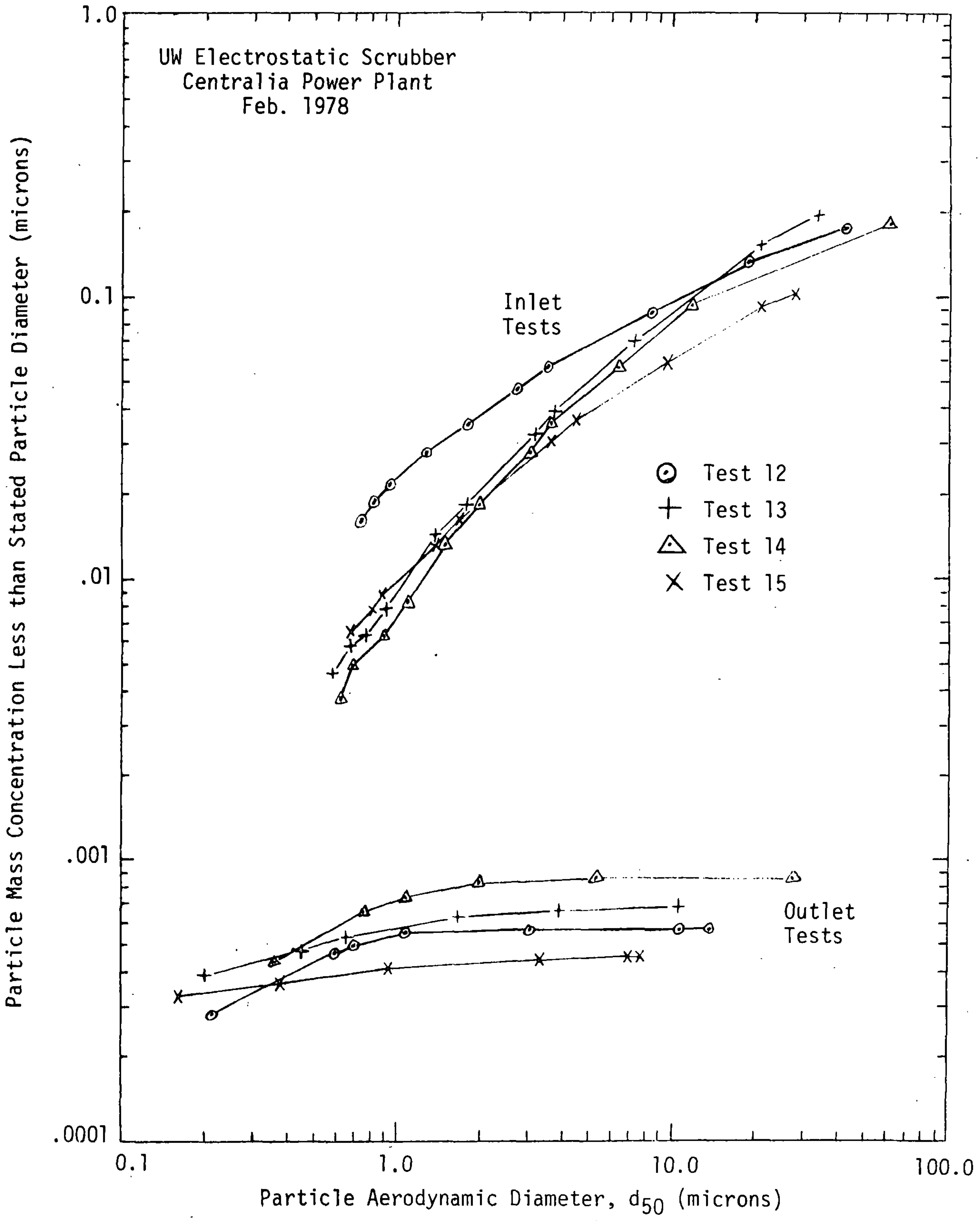


Fig. VII-7. Particle Mass Concentration for Particles Less Than Stated Diameter for Cascade Impactor Tests 12-15.

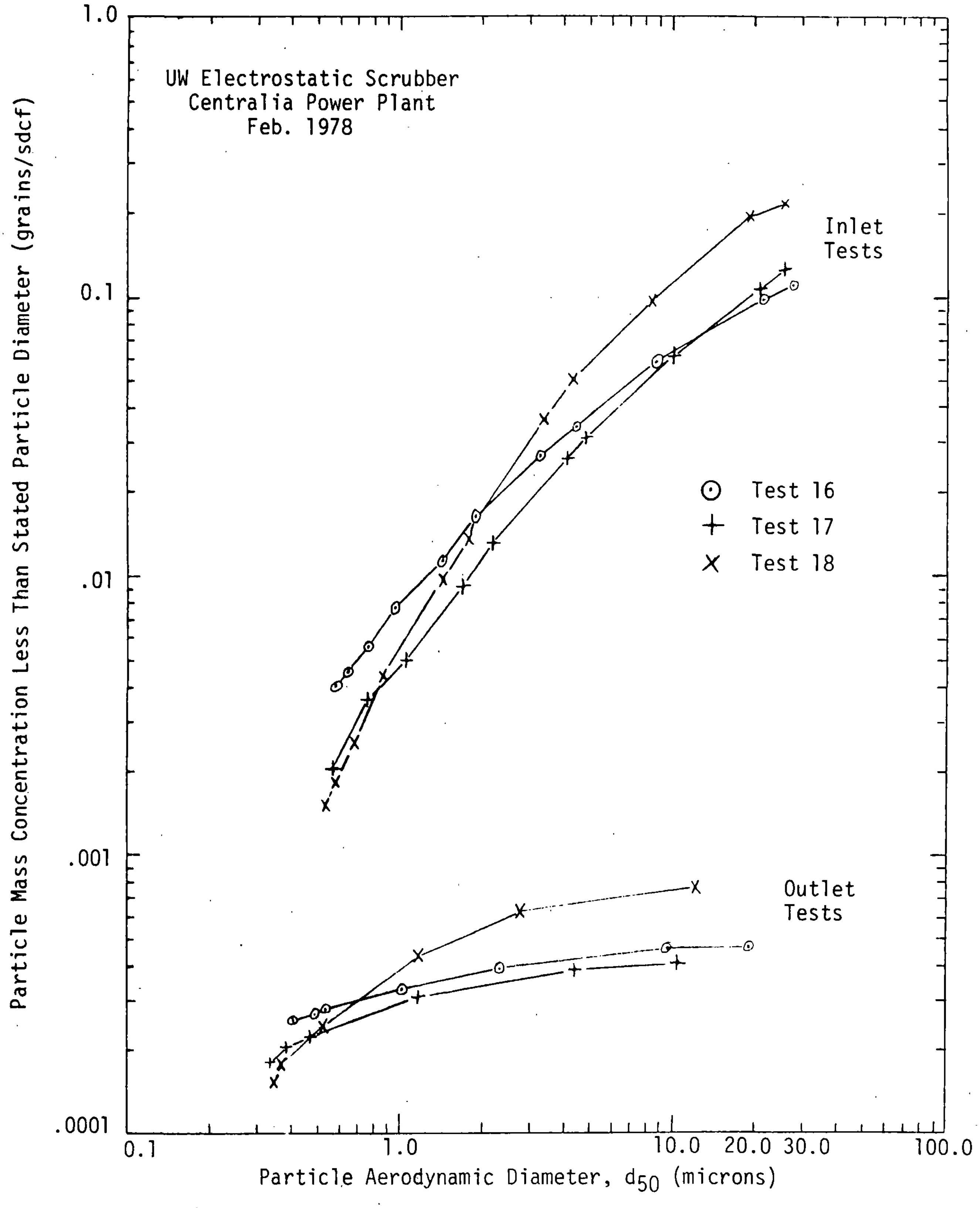


Fig. VII-8. Particle Mass Concentration for Particles Less Than Stated Diameter for Cascade Impactor Tests 16-18.

Comparing the composite results of the two stage and one stage systems, the decrease in certain operating parameters as previously discussed has only a slight affect on the overall particle collection efficiency of the system. The average overall particle collection efficiency of the two stage system (tests 1-F through 8-F) is 99.93% (0.07 penetration). The results of tests 9-F through 15-F (one stage system) show an average overall particle collection efficiency of 99.825% (0.18% penetration).

3. Cascade Impactor Measurements

Particle collection efficiency measurements using cascade impactors were also performed with the scrubber operating in the one stage mode. The results of these tests are shown in Table VII-4. Overall particle collection efficiency ranged from 99.50% to 99.84% (0.16% to 0.50% penetration). Particle mass concentration measured at the scrubber inlet varied from 0.30458 to 0.57211 grains/sdcf while outlet concentrations ranged from 0.00042 to 0.00088 grains/sdcf. Particle collection efficiency as a function of particle size for these tests is illustrated in Figure VII-6. The collection efficiency for particles smaller than 1.0 micron in diameter ranged from about 83% to 99%. Figures VII-7 and VII-8 illustrate the particle mass concentration (grains/sdcf) less than stated particle diameter (microns) for the cascade impactor tests on the one stage system. Relative particulate concentrations (grains/sdcf) measured at the scrubber inlet and outlet for a particular size range can be directly obtained from these curves. The cumulative particle size distributions (log-normal approximations) measured at the scrubber inlet and outlet for impactor tests 12-18 are shown in Figures VII-9 and VII-10. Mass mean diameter (d_{50}) ranged from 23.13 to 76.5 microns at scrubber inlet and from 0.0324 to 1.032 microns at the scrubber outlet.

A comparison of the particle collection efficiency as a function of particle size between the two stage and one stage system is shown in Table VII-5. The incremental particle collection efficiencies are shown in the mean values for all the cascade impactor tests performed in either the one stage or two stage modes. The particle diameter is represented by the midpoint of the increment. The reduction of certain operating parameters (SCA, L/G, gas residence time) on changing from the two stage to one stage mode resulted in an increase in the particle penetration from 3.35% to 7.29% at 0.4 microns diameter and from 0.76 to 1.4% at 1.2 microns diameter. In general the particle penetration for these submicron particle sizes doubled on going from two stage to one stage operation.

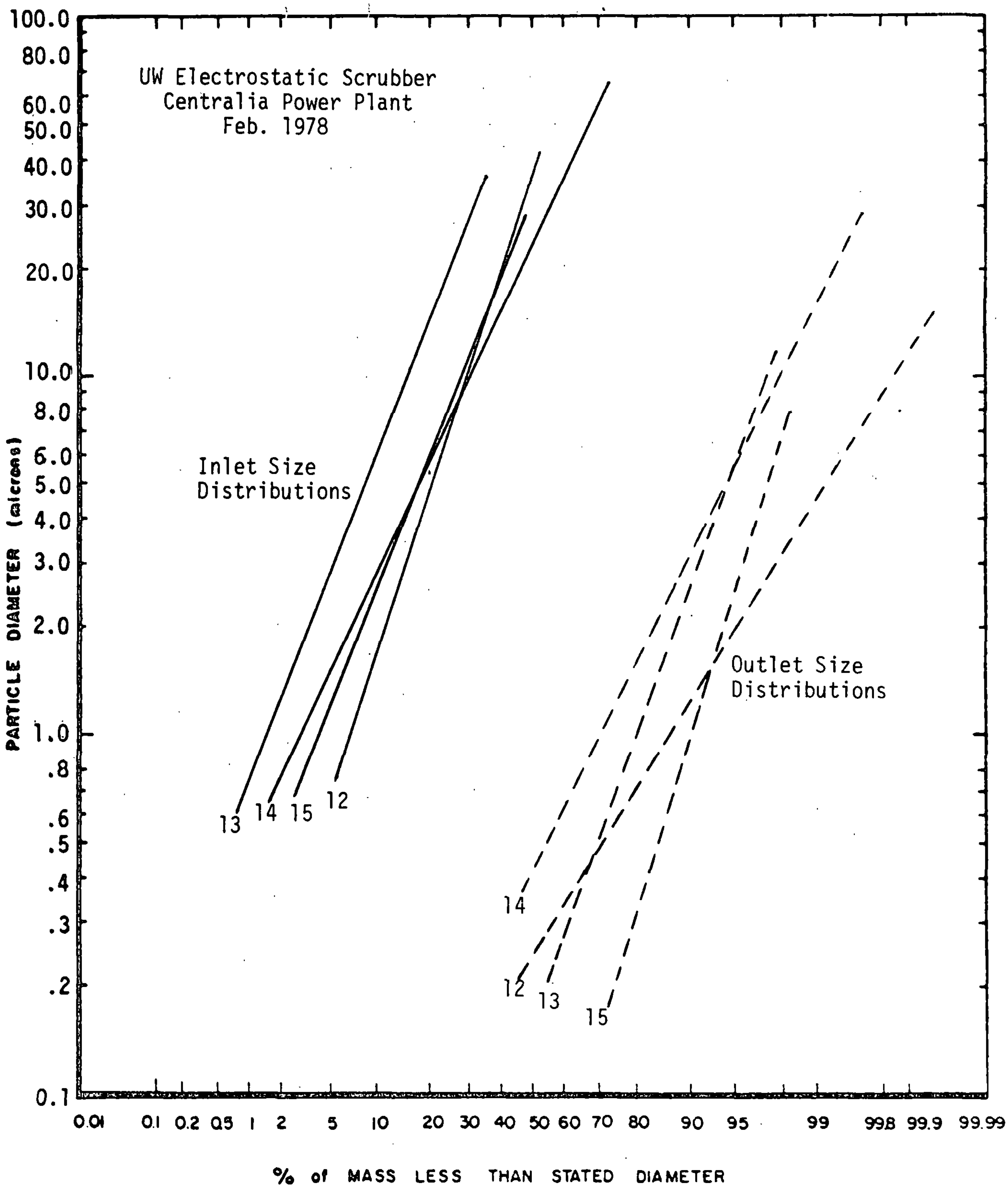


Figure VII-9. Inlet and Outlet Particle Size Distributions for Cascade Impactor Tests 12-15 (Log-Normal Approximation)

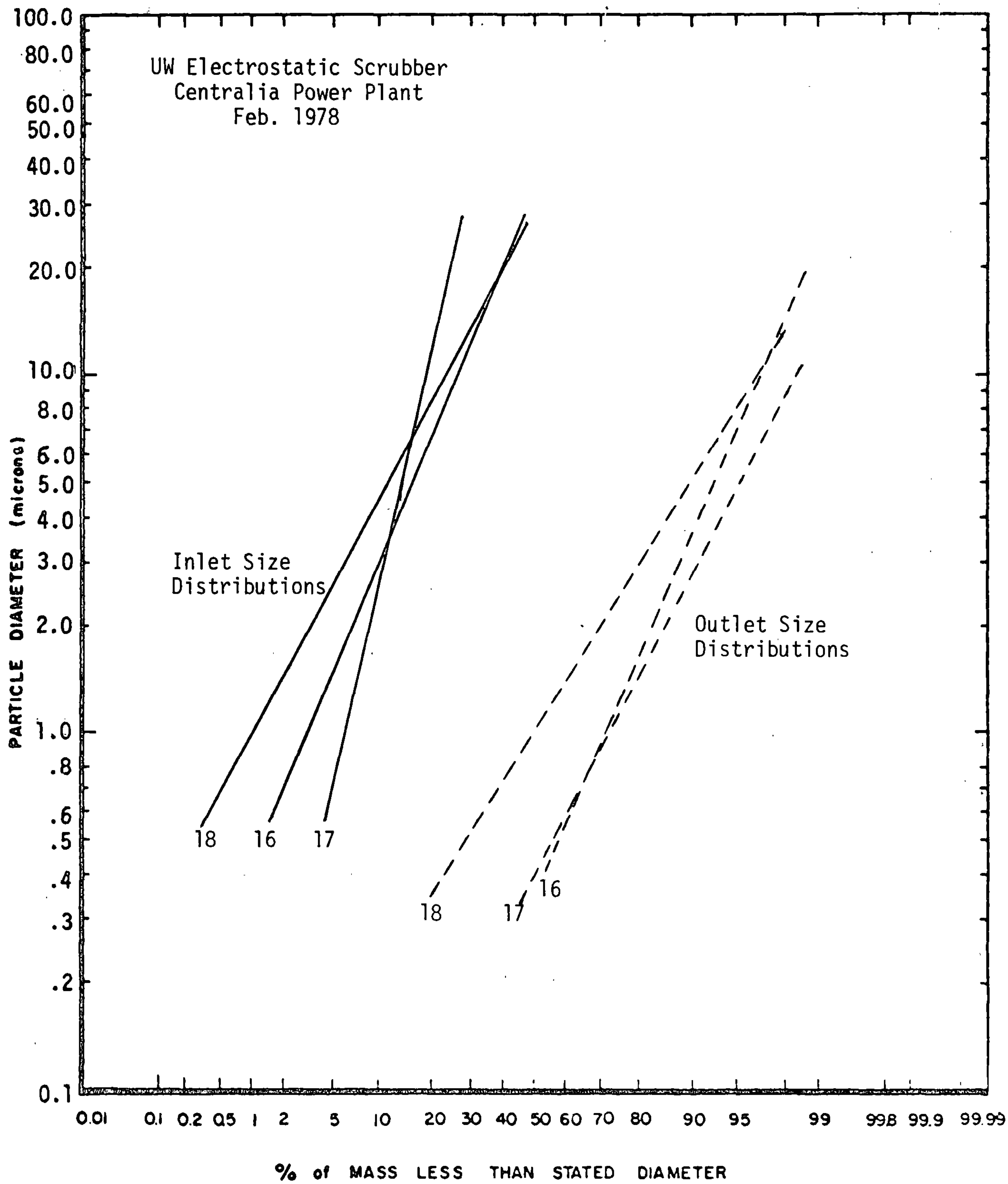


Figure VII-10. Inlet and Outlet Particle Size Distributions for Cascade Impactor Tests 16-18 (Log-Normal Approximation)

Table VII-5 Comparison of Particle Collection Efficiencies Between the Two Stage and One Stage System

Particle Diameter (microns)	Two Stage		One Stage	
	Coll. Eff. (%)	Penetration (%)	Coll. Eff. (%)	Penetration (%)
0.4	96.65	3.35	92.71	7.29
0.5	97.60	2.40	94.76	5.24
0.6	98.13	1.87	96.02	3.98
0.75	98.60	1.40	97.17	2.83
0.95	98.97	1.03	98.04	1.96
1.20	99.24	0.76	98.60	1.40

4. Integrating Nephelometer Measurements

An integrating nephelometer was used to measure the light scattering coefficient at the scrubber outlet where the particle mass concentration was typically 0.0004 to 0.0015 grains/sdcf. A sample gas volume was extracted from the outlet test port through a heated probe (to prevent condensation) and into the nephelometer. The single wavelength (530 nm) nephelometer is an instrument which measures the scattering portion of the extinction coefficient due to particles in the sample gas. It provides an instantaneous, continuous readout of the coefficient B_{scat} (M^{-1}) which is a direct indication of particle concentration, particularly in the 0.1 to 1.0 micron size range. The nephelometer was originally designed for atmospheric measurements and is consequently sensitive to extremely low particle concentrations. Since no means of monitoring the inlet particle mass concentrations was available, the results of this test provide only a relative measurement of particle mass concentration at the scrubber outlet with variations in spray voltage.

For this test the scrubber was operated in the one stage mode with the voltage to corona #2 at 80 KV(-), mist eliminator voltage at 60 KV (+) and liquor flow rate at 12 gpm. The voltage to the liquor sprays was held at 0, 2, 5, 10, 15, and 20 KV with 5 minute time intervals for each voltage setting. During this time period the light scattering coefficient, B_{scat}, was measured using the integrating nephelometer. The light scattering measurement results of this test are presented in Figure VII-11.

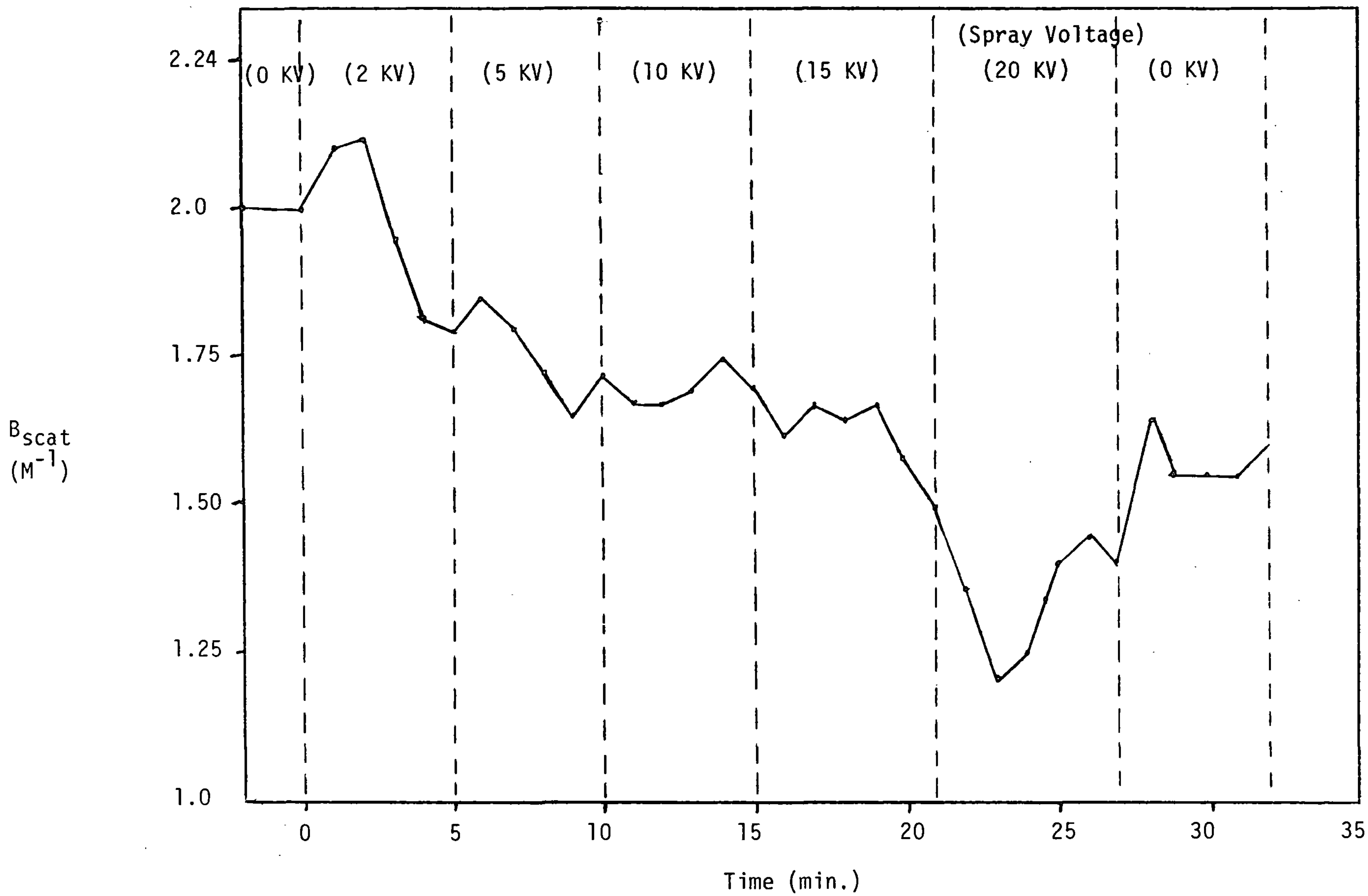


Figure VII-11. Light Scattering Coefficient, B_{scat}, Measured at the Outlet of the UW Electrostatic Spray Scrubber for Various Spray Voltages (All Other Parameters Held Constant)

Section VIII

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APPENDIX A

Details on Sampling Techniques

Sampling Details

Test Sequence		3 - 8	1F - 8F	9F - 16F	12 - 18
Type of Test		Simultaneous Cascade Impactor	Simultaneous In-Stack Filter	Simultaneous In-Stack Filter	Simultaneous Cascade Impactor
Collector Used	Inlet	11 stage MK5 Cascade Impactor	90 mm Filter	90 mm Filter	11 Stage MK5 Cascade Impactor
	Outlet	7 stage MK3 Cascade Impactor	47 mm Filter	47 mm Filter	7 stage MK3 Cascade Impactor
Type of Substrate	Inlet	Ungreased, s.s. Impaction Insert	Reeve Angel 934AH Filter	Reeve Angel 934AH Filter	Ungreased, s.s. Impaction Insert
	Outlet	Ungreased, s.s. Impaction Insert	Reeve Angel 934AH Filter	Reeve Angel 934AH Filter	Ungreased, s.s. Impaction Insert
Sampling Nozzle Dia.	Inlet	3/16 in.	3/16 in.	3/16 in.	3/16 in.
	Outlet	1/4 in.	1/4 in.	1/4 in.	1/4 in.
Sampling Time	Inlet	8-15 min.	10 min.	10 min.	20 min.
	Outlet	18-60 min.	40 min.	40 min.	60 min.
Gas Volume Sampled (acf)	Inlet	2.8-3.5	1.8-3.0	2.8-3.5	5.0-7.16
	Outlet	13.4-66.4	60.5-113.5	88.3-111.3	80.5-95.4

APPENDIX B

Converting Units of Measure

Appendix B

CONVERTING UNITS OF MEASURE

Environmental Portection Agency policy is to express all measurements in Agency documents in metric units. In this report, however, to avoid undue costs or lack of clarity, English units are used throughout. Conversion factors from English to metric units are given below.

To convert from	To	Multiply by
pounds	Kg	0.45359
psig	dynes/cm2	+14.7 x 68947.6
f^2	m^2	0.0929
f^3	m^3	0.028317
feet	meters	0.3048
inches	meters	0.0254
BTU	joules	1054.35
BTU/lb	joules/gm	2.235
acfm	acm/hr	1.699
gpm	l/m	3.79
grains/sdcf	gm/sdcm	2.29
f^2scfm	m^2scm/hr	0.0547
^oF	^oC	5/9

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

1. REPORT NO. EPA-600/7-78-177b	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE University of Washington Electrostatic Scrubber Tests at a Coal-fired Power Plant		5. REPORT DATE December 1978
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) M. J. Pilat and G. A. Raemhild		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Washington, Department of Civil Engineering, Seattle, Washington 98195		10. PROGRAM ELEMENT NO. EHE624A
		11. CONTRACT/GRANT NO. Grant R804393
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development, Industrial Environmental Research Laboratory, Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 6/77 - 10/78
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Dale L. Harmon, Mail Drop 61, 919/541-2925.

16. ABSTRACT The report gives results of tests of a 1700 cu m/hr University of Washington Electrostatic Spray Scrubber pilot plant on a coal-fired boiler to demonstrate its effectiveness for controlling fine particle emissions. The multiple-pass, portable pilot plant combines oppositely charged aerosol particles and water droplets in two water spray towers. Aerosol negative-charging sections precede each spray tower. The scrubber was tested in two modes: two-stage, including two active particle charging corona sections and two spray towers; and single-stage, including only one corona section and one spray tower. Simultaneous inlet and outlet source tests provided both size-dependent and overall mass basis particle collection efficiency information. Measured overall particle collection efficiencies ranged from 99.30 to 99.99%, depending on scrubber operating conditions , inlet particle size distribution, and mass concentration. Particle mass concentrations measured at the scrubber outlet ranged from 0.00041 to 0.0027 g/cu m. The average overall particle collection efficiency for all tests performed in the two-stage mode was 99.93%; single-stage average efficiency was 99.83%.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Dust	Pollution Control	13B	11G
Gas Scrubbing	Aerosols	Stationary Sources	07A,13H	07D
Scrubbers		Particulate	13I	
Electrostatics		University of Washington Scrubber	20C	
Coal			21D	
Combustion			21B	

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 58
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