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CHARGED DROPLET SCRUBBER FOR FINE PARTICLE CONTROL: PILOT DEMONSTRATION

Industrial Environmental Research Laboratory
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CHARGED DROPLET SCRUBBER FOR FINE PARTICLE CONTROL: PILOT DEMONSTRATION

by

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ABSTRACT

This report presents the results of a successful Charged Droplet Scrubber (CDS) pilot demonstration of coke oven emissions control. It includes a description of the design, installation and checkout of the demonstration system.

The CDS is a device that uses electrically sprayed water droplets, accelerated through an electric field to remove particulate material from a gas stream. The pilot demonstration was a continuation of the laboratory and bench scale studies for application of the CDS to fine particle control. The pilot demonstration system included, in addition to the CDS, the ducting, flow transitions and blower necessary to circulate process gas through the CDS.

The test was performed at the Kaiser Steel Company coke oven facility, Fontana, California. A large fraction of the coke oven emissions were submicron and composed of carbon particles and hydrocarbon aerosol. After the system check-out was completed during which the CDS operating parameters were established, the demonstration test series was performed. Results of the demonstration test indicates that the CDS is an effective pollution control device for controlling coke oven stack emissions.

This report was submitted in fulfillment of Contract Number 68-02-1345, by TRW Defense and Space Systems Group, Preliminary Design and Fluid Systems Department, under sponsorship of the Environmental Protection Agency. Work was completed as of March 1976.

ACKNOWLEDGMENTS

The support of Kaiser Steel Company, Fontana, California personnel is acknowledged with sincere appreciation. Special thanks is extended to Messrs. C. Kingsbury and S. Vitt of the KSC Engineering Department for their assistance.

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I. CONCLUSIONS

The Charged Droplet Scrubber (CDS) demonstrated effective control of the emissions from a coke oven battery over widely fluctuating process conditions. Particle removal efficiencies up to 95% were measured and were an increasing function of the time averaged particle loading. Improvements in the gas distribution internal to the equipment should result in additional improvements in collecting efficiency.

The average inlet particulate load varied between 0.05 and 0.33 gr/dscf, associated aerodynamic mean diameters varied between 0.4μ (hydrocarbon aerosol) and 1.5μ (carbon black). The most sensitive design variable affecting efficiency was the gas volume flow rate through the equipment. Low total energy and water consumptions, 0.8-1.2 watts/acfm and 0.8-1.0 gal/1000 acfm, respectively were demonstrated over most of the test conditions. Operation of the CDS with intermittent (8 hour cycle) collector plate over sprays was adequate for deposit control. The CDS gas discharge was not saturated during nominal operating conditions.

II. INTRODUCTION

This report describes the results of a pilot demonstration of the Charged Droplet Scrubber (CDS) to control coke oven flue gas particulate emissions. Heretofore, it was the general concensus of the industry that there was no suitable control technology for this process because of the wide process fluctuations. Emissions consisted of varying relative concentrations of submicron sticky hydrocarbon and micron sized high conductivity carbon black. The CDS applies electrohydrodynamically sprayed water droplets to remove particulate material from a gas stream. The droplets have a size in the range of 60 to 250 μm in diameter and have a surface charge density near that allowed by surface tension forces. The charged droplets are accelerated through the gas stream by an applied electrostatic field.

The objectives of the pilot demonstration were to verify the applicability for removing fine particles from an industrial effluent stack, to determine the influence of CDS operating variables on performance and behavior of the CDS under long term operation. The demonstration unit was to be of sufficient size, at least 17,000 m^3/hr (10,000 acfm), to adequately describe the behavior of a full size unit. The emission source was to be characteristic of those requiring control with a relatively large fraction of particulate material in the submicron range.

The pilot demonstration phase is a continuation of the laboratory and bench scale studies for the application of the CDS to fine particle control. These studies included an analysis of the particle removal interactions between particulate material and charged droplets. The laboratory scale studies included the determination of charged droplet characteristics under system operating conditions. The results of these studies were used to verify some of the models used in the fine particle removal analysis. The particle removal efficiencies of a small size CDS operating under simulated process conditions were measured during the bench scale studies. The results of these tests indicated that the CDS should be effective for fine particle control and was sufficiently developed for a pilot demonstration test. The laboratory and bench scale studies are reported in Reference 1.

A pilot demonstration phase was started at the conclusion of the first phase. The tasks of the pilot demonstration phase are:

- Site Selection and Hardware Preparation
- Pre-Delivery Design Verification Tests
- Pilot Demonstration Field Test
- Summary and Conclusions

The site selection and hardware preparation task covered all of the background work necessary for conduction of the demonstration program. The selected site was to provide an environment consistant with the objectives of the program. It must be adaptable for installation of a CDS and provide the required utilities within a reasonable time span. An acceptable working agreement with the organization providing the site was necessary to allow successful completion of the demonstration test. A test matrix was developed as part of this task to delineate the CDS operating parameters that would be varied during the test phase.

The hardware preparation portion of the first task included the design and fabrication of the CDS, duct work and supporting structure for the demonstration unit. All interfacing requirements between the site and demonstration unit were established. Any special auxilary equipment was identified and either purchased or fabricated.

Prior to delivery to the test site, the CDS was subjected to design and operational verification tests. These tests of Task 2 were designed so that the CDS would be operational when delivered to the test site with a minimum of rework or retrofitting. The checkout of the CDS included high voltage component electrical breakdown tests, electrode water flow distribution and water flow rates, and pressure and power requirements.

Task 3, Pilot Demonstration Field Tests, covers the on site hardware assembly, checkout and operational testing of the CDS. Hardware checkout and parameter checks such as gas flow distribution proceeded simultaneously with the assembly. This would allow any measurements or modifications to be made with a minimum of reassembly. Final checkout of the unit was made after complete assembly and connection to the process stream. The testing includes screening tests to determine the operating parameter levels of the CDS for the test matrix. Following the performance demonstration tests is a long duration test, 500 hours, to identify maintenance requirements and potential failure modes.

The final task, of which this report is a part, includes documentation of the design, fabrication, assembly and checkout of the demonstration unit and a summary of the test results.

III. DEMONSTRATION TEST DESIGN AND ASSEMBLY

The site selected for the CDS pilot demonstration test was a coking oven battery exhaust stack at Kaiser Steel Co. in Fontana, California. A photograph of the stack site is shown in Figure 1. The emissions as originally specified consist of hydrocarbon aerosol and carbon particles of which 42 percent by weight are less than one μm in diameter and 96 percent by weight are less than ten μm. This particle size range was consistant with the requirements for the demonstration test. The nominal effluent temperature is 400°F, and the gas composition as measured in May of 1974 is shown in Table 1.

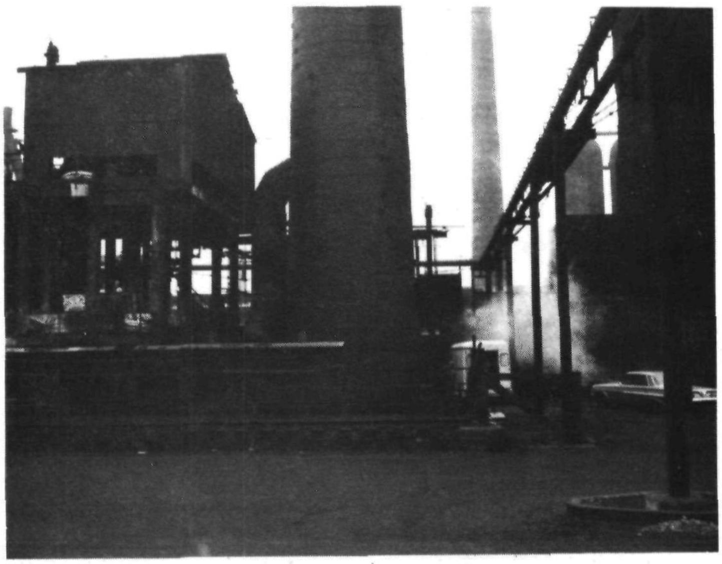

Figure 1. Kaiser - Fontana Coke Oven Battery A Stack

Table 1. Coke Oven Exhaust Stack Gas Composition

Constituent	Volume Percent
CO_2	4.2
O_2	12.6
H_2O	15.0
CO	95 ppm
SO_2	300 ppm
NO_x as NO_2	102 ppm

An existing port used during previous experiments allowed access through the stack wall. The necessary utilities were available either at the stack location or could be supplied through existing piping and conduit. There were two water sources available to use in the experiment. One was recycled industrial water and the other domestic or fresh water. Average values of the water properties taken during the months of June and August 1974 are shown in Table 2.

Table 2. Kaiser Steel Water Sample Analysis

Source	Conductivity μmho/cm	Hardness ppm	pH
Industrial			
6/74	572	137	7.51
8/74	635	152	8.33
Domestic			
6/74	214	58	8.45
8/74	169	57	9.02

Either of these water sources, based on the tabulated properties, could be used without conditioning in the scrubber.

The particulate material properties and loading varied with time during the coke oven operating cycle. A typical cycle included loading an individual oven with coal, discharging coke, and coking with all ovens in the battery closed. The time period during which coal was charged and coke discharged constitute a high stack emission condition. A nominal operating period occurs when all ovens are closed. The previously measured particle loading was 290 mg/m^3 (0.1 gr/ft^3) and the stack Ringlemann 5 during a high emission condition. It was found during the test phase of this program that under these conditions particle loading could be as much as a factor of 3 higher. Under normal operating conditions, the particle loading is of the order of 1.37 mg/m^3 (0.006 gr/ft^3) and the stack Ringlemann 0 to 1.

These sufficiently higher inlet loads resulted in a requirement to derate the equipment flow capacity to achieve higher overall collection efficiencies. As will be discussed later, this resulted in a substantial gas maldistribution problem and some loss in efficiency.

The Charged Droplet Scrubber to be used on the program was purchased from the Development & Applications Division of TRW Inc. The unit was a cost-effective modified version of a Model 300 with a capacity of 51,000 m^3/hr (28,500 acfm) at 1.83 m/s (6 ft/s) gas flow rate. An isometric sketch of the CDS is shown in Figure 2 and a photograph of the delivered unit in Figure 3. A design summary is shown in Table 3.

The scrubber contained three electrostatic spraying stages arranged in series with parallel collecting plates on 0.127 m (5 inch) centers. It had 19 collecting modules. The scrubber structural members and collector plates were fabricated from mild steel. Material thickness of the scrubber housing and collector plates was 20.3 mm (0.080 inches). Although the compatibility problem of mild steel in the stack gas environment was recognized, it was felt that the material would maintain its integrity during the test period. The electrodes which distribute high voltage and water were fabricated from type 316 stainless steel tubing. Each electrode stage was supported from parallel main headers mounted exterior to the gas passages and supported on corner insulator posts. A series of 12 doors, 6 on each side, was provided to allow access to the electrode headers and electrodes. Inspection and alignment of all electrodes on the three stages and the collector plates could be made through these doors.

Table 3. CDS Design Summary

- Three high voltage scrubbing stages with 0.127 m (5 in.) collector plate spacing.
- Nineteen collecting modules, 3.05 m (10 ft) long.
- Flow cross sectional area, 7.36 m^2 (79.2 ft^2).
- High voltage electrode, type 316 stainless steel tubing 190 mm (0.75 in.) diameter, flattened to 0.127 mm (0.5 in.)
- High voltage electrodes contained 67 spray tubes each on 44.5 mm (1.75 in.) centers.
- Spray tubes, titanium with a 12.7 mm (0.050 in) O.D. by 1.52 mm (0.006 in) wall and protruding 25.4 mm (1.0 in) from the electrode.
- Collector plates 3.05 m (10 ft.) long by 1.83 m (6 ft.) high by 20.3 mm (0.080 in) thick mild steel.
- Wall wash system covering each collecting surface.

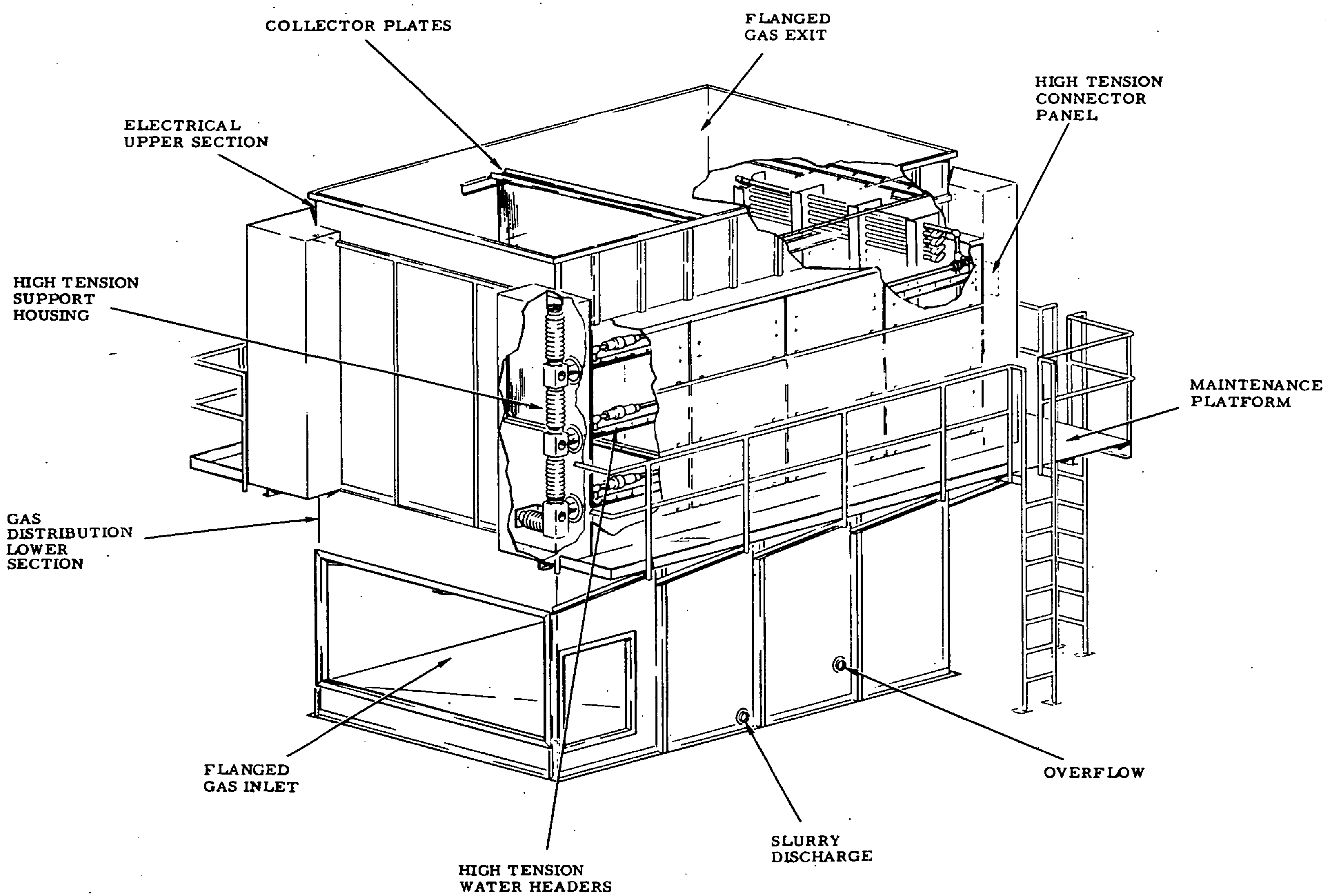

Figure 2. CDS Structural Configuration

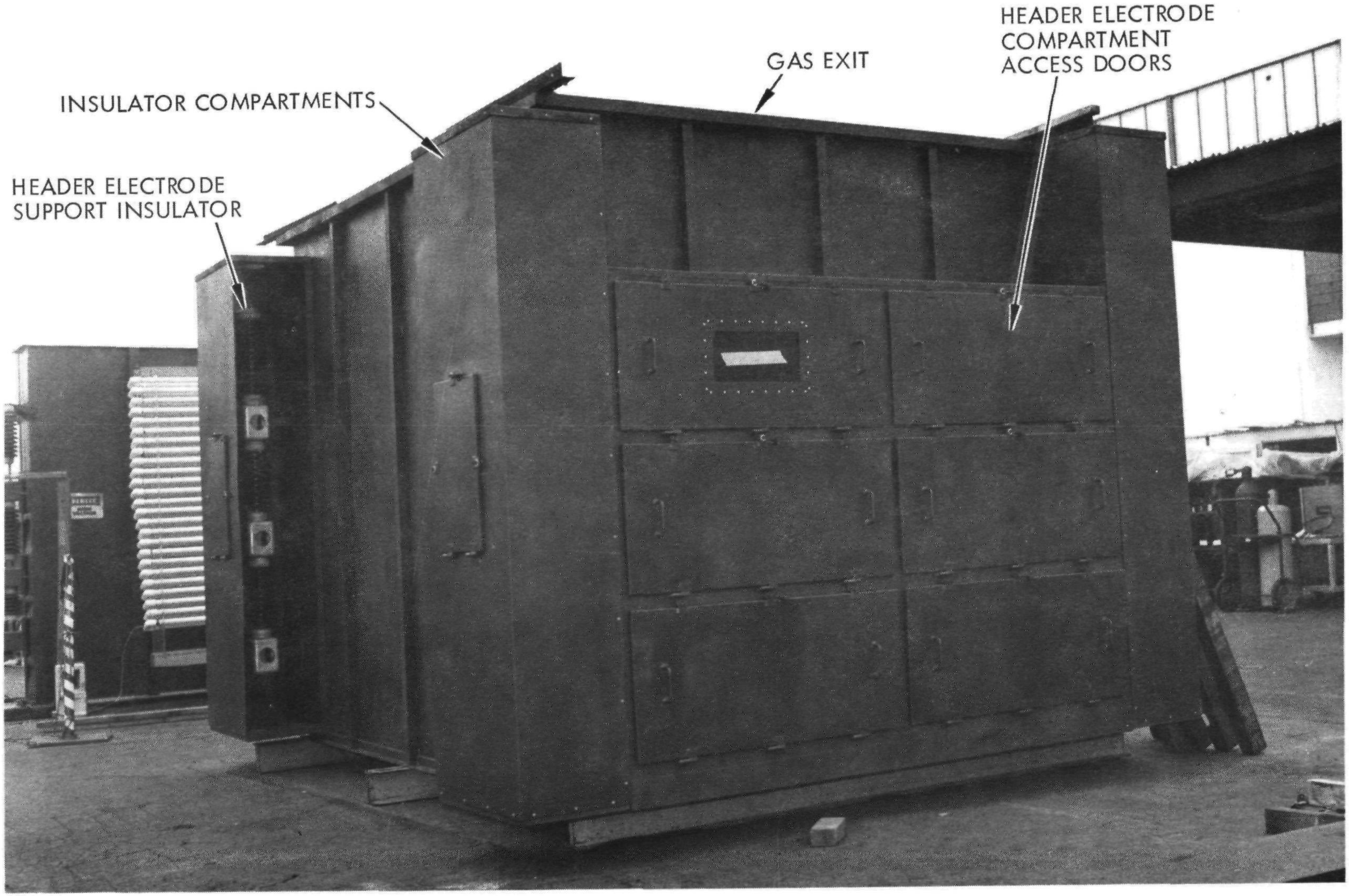

Figure 3. CDS Housing with Header Electrode Support Insulator Column Exposed

A turning section, shown in Figure 4, was also part of the scrubber unit. This section was designed to accept a horizontal flow duct, deflect the flow into a vertical direction and distribute it uniformly over the scrubber cross section. The turning section contained right angle vanes to deflect the gas flow and moveable baffle elements to distribute the flow.

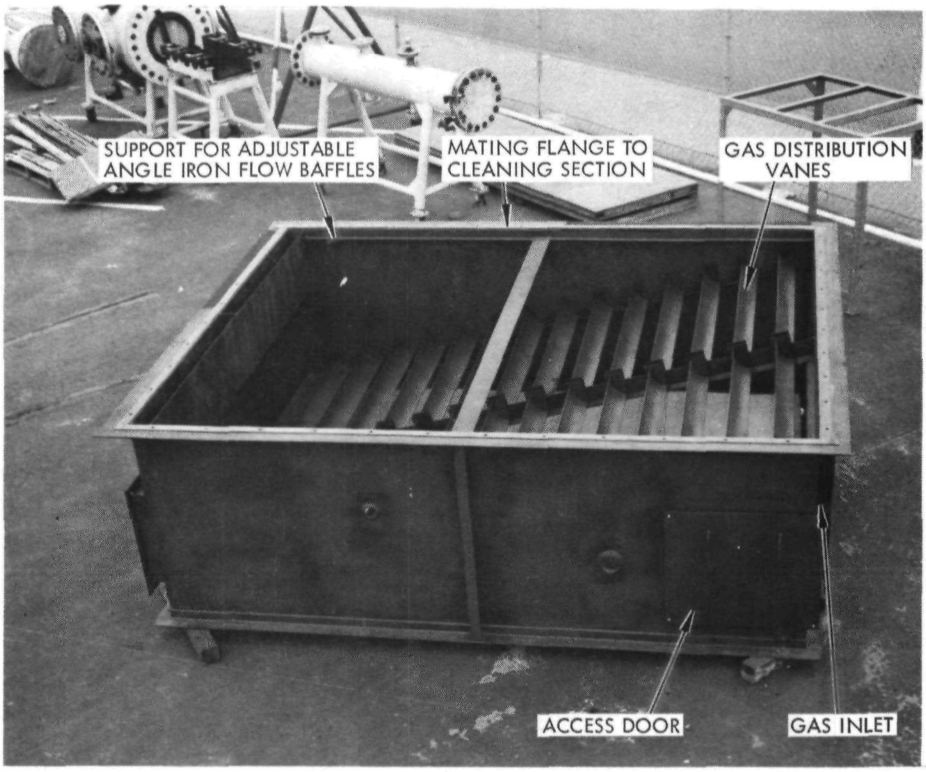

Figure 4. CDS Inlet Turning Section

Electrode feed water is brought up to high voltage through a long length of non-conducting pipe. The piping is sized to restrict the leakage current through the water to an acceptable level when high voltage is applied at the electrode end and the water supply end grounded and to have a tolerable pressure drop. The pipe lengths are supported or nested as close as possible without developing electrical breakdown gradients between the lengths to minimize the containment volume. The pipe nest was enclosed in a sealed housing separate from the scrubber housing. Copper tubing, extending through penetration insulators in both the scrubber shell and pipe nest housing, was used to connect both the water and high voltage to the scrubber electrodes. This pipe nest was formed from thirteen 1.83 m (6 ft.) lengths of Schedule 80 polypropylene pipe interconnected with pairs of elbows.

Isolation resistance between the stages was provided through three nominally 0.38 m (15 in) lengths of 6.35 mm (.25 in) I.D. by 6.35 mm (.25 in) wall Tygon tubing. The tubing was used to complete the water flow path from the end of the pipe nest to the copper tube extension of the individual stages. The high voltage input was connected upstream of the three flow distribution tubes. Therefore, the current path to each stage was through the water in the connecting tubes. The water resistance provided the electrical isolation between stages. A schematic of the pipe nest and electrical circuit is shown in Figure 5.

A purge fan system was installed on the scrubber to provide an ambient air flow over the stage electrode support and penetration insulators. This air flow reduced direct contact of the insulators with the process stream gas eliminated fouling. The air purge fan had a design capacity of 1020 m^3/hr (600 CFM) at a 25.4 mm (1.0 in) water pressure differential. The purge fan and duct was located external to the scrubber housing with the inlets to the scrubber on the top end of each support insulator housing.

The high voltage source was a transformer/rectifier set with a maximum output of 75 kV at 400 ma and a single phase 480 v input. The output voltage from the transformer/rectifier set could be controlled either manually with a potentiometer or by an automatic control circuit using an arc rate sensor for feed

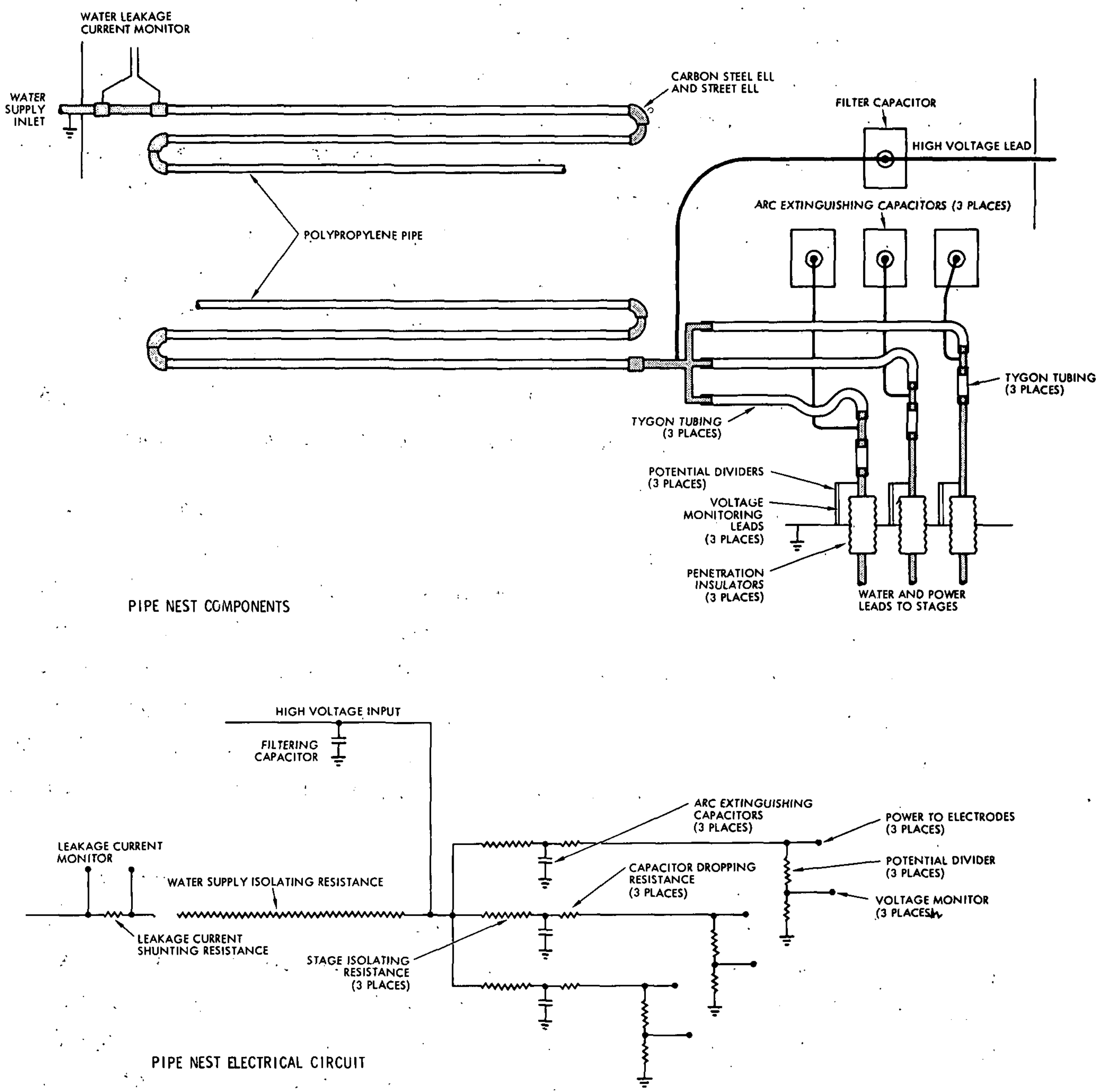

Figure 5. Pipe Nest Component Layout and Electrical Circuit Schematic

back control. The voltage when in the automatic mode would be either the maximum of the transformer/rectifier set or that required to maintain a preset arc rate. An rf coil located within the scrubber housing was used to sense the arcs. The operating voltage on the electrodes was the output of the transformer/rectifier set minus the voltage drop across the stage isolating resistors. Voltage on each stage was monitored through a potential divider located on the input to the stage. The total scrubber current was monitored directly on the ground return leg of the transformer/rectifier. Leakage current through the pipe nest was monitored with a current shunt near the pipe nest ground end. These monitoring circuits are shown in Figure 5.

The structural support and ducting design along with the final working drawings for the CDS installation was made by Trade West of Corona, California. Trade West was the manufacturer of the CDS. A top view of the scrubber experimental layout is shown in Figure 6. Kaiser Steel Manufacturing Division performed the structural and ducting fabrication and installed all components of the demonstration test unit. A portion of the ducting used was salvaged from the previous experiment at the stack location. These items included a 1.52 m (5 ft) diameter flow control damper and a 50 horsepower blower used for drawing gas from the stack and exhausting it through the scrubber. The blower had a capacity of approximately 68,000 m^3/hr (40,000 ACFM) at a draft of 100 mm (4 in) of water. The nominal vacuum in the stack at the position gas was withdrawn was 38 mm (1.5 in) of water.

The ducting from the stack to the blower turning and transition section was 1.52 m (5 ft) in diameter. The straignt duct section between the elbow at the stack and the inlet to the blower transition was approximately 3.66 m (12 ft) long. It was angled approximately 20° relative to the horizontal to accommodate the difference in elevation between the ground level blower inlet and the stack port. Gas stream pre-cooling water spray nozzles were located 0.3 m (1 ft) up stream of the blower transition. The pre-cooling system contained 10 spray nozzles located on the upper 300° section on the duct periphery. CDS inlet gas stream sampling ports were located in the duct straight section 2.9 m (9.5 ft) downstream of the elbow from the main stack. The two sampling ports were located on the top and side of the straight duct section. Each port was equipped with an extension structure to support the sampling trains. The position of the pre-cooling system and inlet sampling ports are shown in Figure 6.

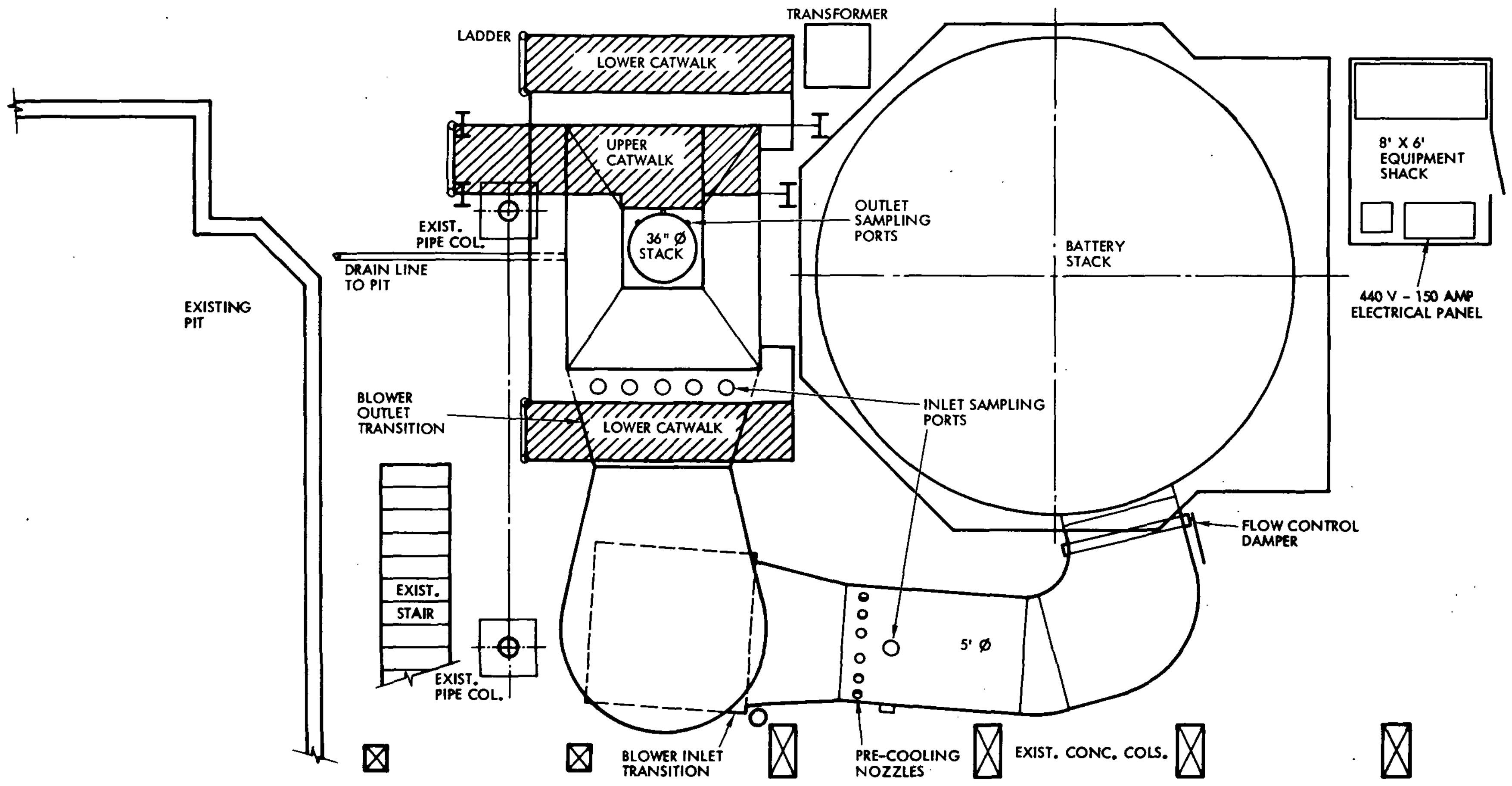

Figure 6. Plan View of CDS Pilot Demonstration System

The flow control damper was bolted directly to the stack outlet flange. It was not designed for complete flow cut-off; therefore, during scrubber non-operating periods, there was a back flow of ambient air through the scrubber into the stack. The damper was pre-set manually to control the flow rate through the CDS during test operation. Because of the fan capacity, the damper was only partially opened during CDS operation.

A flow scoop extended into the stack to assist in diverting gas flow into the scrubber ducting system. The scoop was a half section of a 1.52 m (5 ft) diameter pipe. It was angled at 15° downward from the horizontal into the stack and extended inward 3.05 m (10 ft). Although the scoop may not have been necessary to insure adequate flow through the CDS because of the fan capacity, it would help provide a more representative stack gas sample.

The transition section between the blower and scrubber turning section contained four equally spaced straightening vanes to assist in distributing the gas flow across the scrubber cross section. Gas sampling ports were located in each of the five flow passages formed by the vanes and transition walls. These sampling ports were used by APT, Inc. of San Diego, California who performed the designated EPA sampling tests. The scrubber inlet gas temperature monitoring thermocouple was located in this blower transition section.

The outlet transition section of the CDS was a quadrihedron, truncated by 0.91 m (3 ft) diameter vertical exhaust stack. The exhaust stack was 3.05 m (10 ft) long. Its exhaust plane was 12.2 m (40 ft) from ground level. Three sampling ports, located in a horizontal plane, were in the exhaust stack, three feet below its exit plane. Two of the ports were at right angles and the third was in their enclosed quadrant. This port arrangement allowed simultaneous outlet sampling by the APT group during a test.

A single overhead catwalk was incorporated into the scrubber support structure for access to the outlet sampling ports. Temporary scaffolding was erected for access to the CDS header electrode compartment doors and the vertical inlet sampling port. The temporary scaffolding was also used during scrubbing installation for access to various areas for alignment and checkout.

IV. DEMONSTRATION TEST CHECKOUT AND STARTUP

The fabricated equipment was first assembled and subjected to factory functional electrical and hydraulic tests. After installation additional dynamic tests were performed and modification work identified as described below.

Design Verification Tests

The CDS unit was subjected to design verification tests prior to delivery to the installation site. These included electrical breakdown tests of the high voltage components, both at the scrubber support and penetration insulators and within the pipe nest. Electrode and wall wash water flow distribution were also visually observed. The high voltage isolation tests indicated that the electrical isolation design was capable of withstanding the peak voltage stresses expected during operation. The pipe nest provided an acceptable isolation from ground with leakage currents in the range of 10 to 12 percent of the total scrubber current. The arc rate between the spray tubes and collector plates appeared to be excessive at the CDS operating voltage range. A part of the arcing problem was due to collector plate misalignment. There was adequate collector plate adjustment to allow proper alignment; however, realignment of the plates was deferred until after installation at the test site.

The water spray pattern of both the electrodes and wall wash were adequate for proper scrubber operation. The wall wash gave no indication of the impending problems that were to be encountered later in the program. The nozzles maintained a steady spray pattern on the collector plates with no splashing. The wall wash was operated on domestic water without filtering. After completion of these tests, the CDS was shipped to the test site for installation.

Typical profiles of the gas flow, taken after the distribution baffles were adjusted, are shown in Figure 7. The profiles at an average velocity of 2.70 m/s (8 fps), are marginally outside the design requirements of the scrubber. As the anticipated operating average gas velocity was between 1.5 and 1.7 m/s, no further gas velocity adjustments were attempted at this time. It is necessary to maintain the best possible uniformity in gas flow distribution across the CDS cross sectional area to achieve

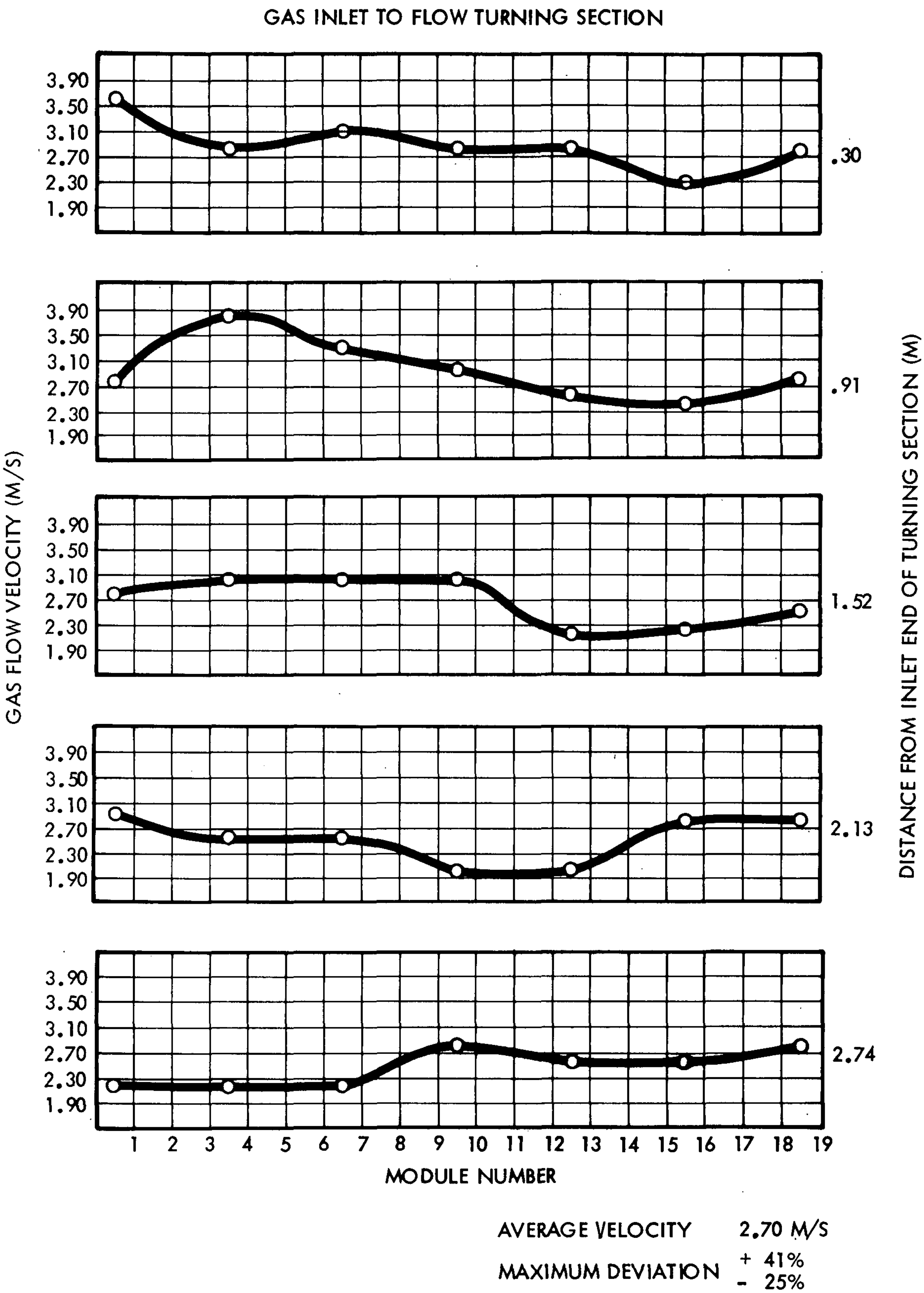

Figure 7. Flow Distribution at 2.70 m/s Average Velocity

high particle removal efficiencies. Particle removal efficiency has a non-linear inverse dependence on gas flow rate; therefore, large variations in flow velocity in the scrubber cross section will result in a reduced efficiency.

The high voltage was applied to the electrodes for one brief period prior to completion of the installation to check the integrity of the high voltage isolation. No sustained high voltage operation could be made until after completion of the installation when all high voltage elements were completely enclosed. After installation was complete, specific high voltage tests and adjustments were made. The tests included locating potential breakdown paths in the isolation, determining maximum operating voltages on the electrodes and monitoring corona and leakage currents. The adjustments included setting the arc rate controls for automatic mode operation and establishing the water tube lengths which served as the dropping resistors to the stages.

Several other site specific, minor operating problems occurred due to the inadvertent hookup of the equipment to the wrong water source. Feed water filter plugging due to abnormally high suspended solids concentrations and inadequate supply pressures were corrected by hookup to the domestic water supply.

Also, at this time the OEM tygon tubing in the pipe nest was replaced with polypropylene pipe as recent commercial experience in Japan indicated this to be a more stable material in a high electrical field gradient and temperature environment.

Startup

The CDS was then put on process and marked change in high voltage electrical stability noted as compared to operation with ambient air. Two effects were noted which potentially could have deteriorated collecting efficiency:

- Abnormally high spark rate in the first electrostatic spraying stage.
- Sustained arcing without sufficient quenching, primarily in the first stage.

The high electrical sparking resulted from the presence of a low mobility particle space charge, primarily within the first or inlet spraying stage. The current from an electrode will decrease with increasing low mobility space charge resulting in the first stage having the smallest voltage drop across its isolating resistor. Under these conditions the first stage controls the operating voltage on the other stages. The dropping resistors to each stage were resized so that each successive downstream stage had a higher nominal operating voltage.

The CDS would operate in a self-extinguishing arcing mode, except during periods of heavy particle loading. When the particle loading was heavy some arcs appeared to become sustained burning arcs. These sustained arcs, actually a series of arcs, resulted from reignition of the plasma left from the previous arc. The sustained arc mode was eliminated by changing the recharge rate, i.e., adding capacitance to each stage.

The gas temperature conditioning spray system was close coupled to the blower in order to position the sampling ports as far as possible from the stack outlet elbow. Unvaporized water droplets were ingested into the fan, but were demisted by the fan blades. Although this did not create an operating problem, the water mass balance was more difficult to estimate. The unvaporized water was drained from a port in the blower inlet transition and the net water flow vaporized was determined measuring both the precooling and overflow water flow rates. The precooler was capable of reducing the gas stream temperature up to 80^{o}C (175^{o}F).

V. DEMONSTRATION FIELD TEST

The objective of the field test was to determine the operating characteristics and particle collecting efficiency of a CDS under actual process conditions as a function of operating parameter levels. The parameters included:

- Electrode voltage
- Gas stream velocity
- Electrode water flow rate
- Electrode polarity

Sampling Procedures

Particle removal efficiency was determined by isokinetically and simultaneously measuring the inlet and outlet particulate material loadings during a test run.

Three different sampling procedures were used to measure particle collection efficiency. During the statistically designed tests both the EPA Method 5 procedure (Reference 2) for overall efficiency and a modified procedure using a Washington State impactor for fractional efficiency were employed. Additional testing was performed with a shortened test period using EPA Method 5. The three procedures are described in more detail in Table 4 and the modified APT sampling train shown in Figure 8. Greased aluminum substrates were used in the impactors to prevent particle bounce and minimize wall losses. The gas stream temperature and kinetic pressure head were measured at each sampling point with the thermocouples and S-pitot tubes on the probes. These values were integrated over the duct areas to determine mean temperature and volumetric flow rates. The temperature monitored at the outlet sampling port corresponded to the outlet temperature of the CDS. The temperature measured at the inlet sampling port was near that of the gas stream in the coke oven battery main stack. The inlet gas temperature to the scrubber was measured with a thermocouple located downstream of the gas precooler and blower. At the CDS inlet, eddy mixing and condensation in the pitot tube was evident indicating negative velocity heads and recirculating gas flow. The best one point sampling location was used during the impactor runs. The eddy mixing would indicate that the inlet gas velocity average and the gas flow rate (volume/time) are questionable

TABLE 4

SUMMARY OF SAMPLING
PROCEDURES EMPLOYED

	Method	Equipment	Sample Location Inlet	Sample Location Outlet	Number of Sample Points Inlet	Number of Sample Points Outlet	Sample Period Min.	Organization
1.	EPA #5	Joy Emission Analyzers	Circular Duct, Up-Stream of Fan	Circular Stack	32[1]	32[1]	90-120	TRW
2.	EPA #5	"	"	"	16-32[2]	16-32[2]	30-90	TRW
3.	Modified EPA #5	Washington, Mark III Impactor	Rectangular Duct, CDS Inlet	Circular Stack	1	8	30-45	APT

Notes

1, Performed along two radial traverses orthogonal to each other.

2, Performed along one or two radial traverses, sometimes on a coarser grid.

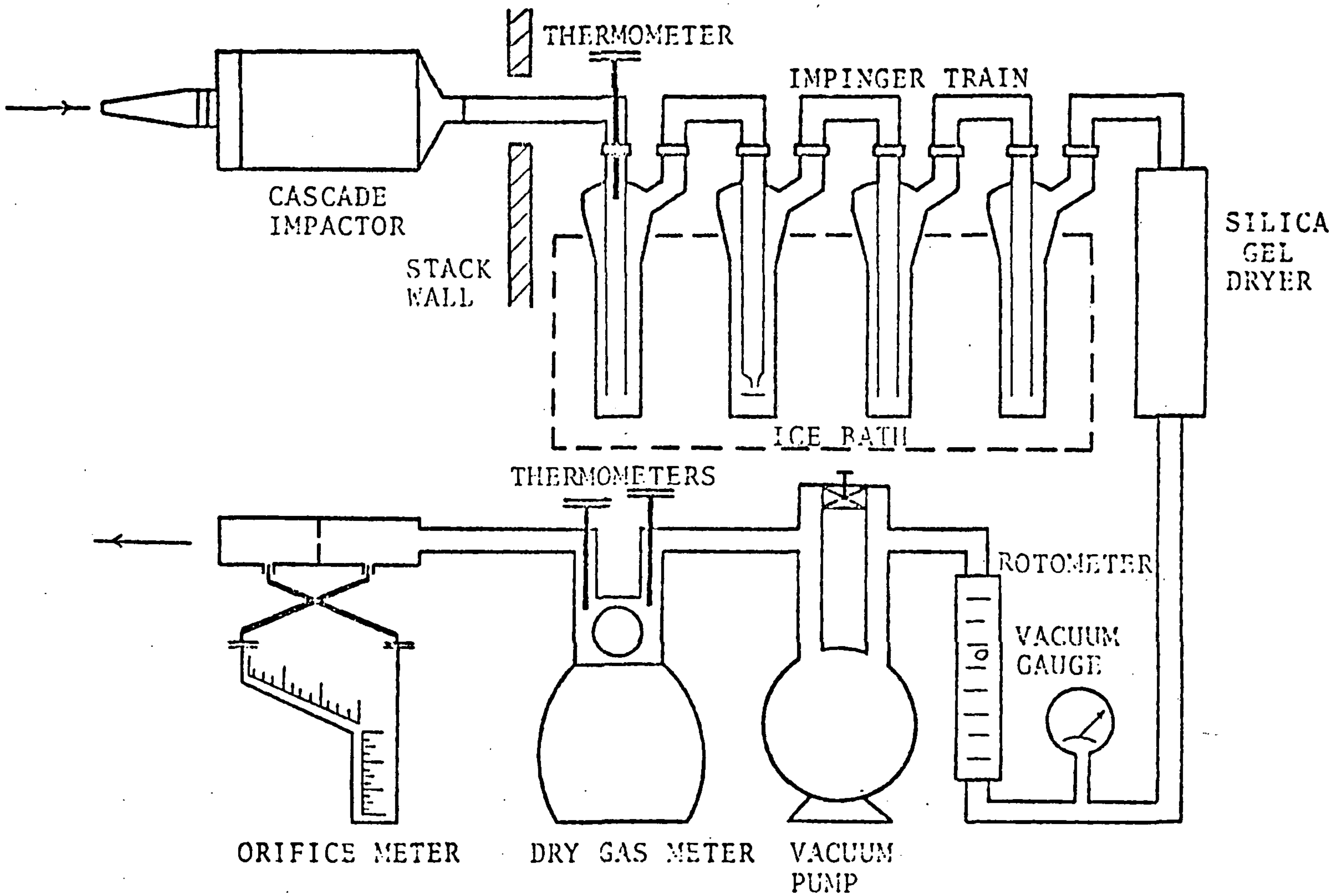

Figure 8. Modified E.P.A. Sampling Train with In-stack Cascade Impactor

based on the inlet traverse. This also was the cause of poor gas distribution internal to the CDS. The outlet port was located three duct diameters downstream of the nearest disturbance and one duct diameter upstream of the stack outlet. Velocity traverses of the outlet revealed fully developed flow profiles.

In addition to the CDS operating parameters, other observations which affect CDS performance were recorded from the power supply meters during a run. These included:

- Electrode arc rate
- Nominal electrode voltages
- Nominal electrode and leakage currents
- Voltage and current of the electrode power supply

The quantities associated with these observations varied during a course of a run. Ranges of values when appropriate are included with the tabulated data and are helpful in interpreting the test results.

The CDS performance testing was divided into four series. These included:

- Screening Tests
- Variable Parameter Tests
- Development
- Long Duration Tests

The screening tests were used to establish the paremeter levels for the parameter test matrix. The test matrix runs constituted the major portion of the testing sequence and the results were used to establish the CDS operating performance. The development tests were performed by the TRW division (DAD) supplying the CDS and the results are presented in this report. These tests were performed to obtain CDS performance data under specific process conditions and to determine means of improving the device's performance. The DAD tests were performed during and after the test matrix sequence. A long duration test of 500 hours was scheduled to start after completion of the test matrix runs. This test was included in the program to identify CDS maintenance schedule requirements and potential failure modes.

The approved test matrix was drafted during the installation phase of the program. The matrix was based on a fractional factorial, two-level design for five independent variables.

Screening Tests

A screening test was first performed to identify several of the parameters and their levels. The following conclusions were drawn from the screening test (see Screening Test Summary, Appendix A, Table 1-A).

- Positive polarity resulted in unstable, high voltage operation and was eliminated as a test variable.
- Insufficient residence time for precooler droplet evaporation resulted in carry-over into the fan.
- Considerable reentrainment of the collector plate auxiliary wash system water spray resulted in atypically high particle outlet loads.
- Extremely variable gas inlet conditions were observed and measured which sometimes exceeded the original design criteria (240 mg/Nm^3) on a time averaged basis and were significantly higher during part of a test period.
- Electrode operating voltages (31 kv) were significantly lower than the tests with ambient air (36-38 kv).

Based upon the above a fractional factorial design blocked with respect to with and without wall wash was adopted. All tests were at negative power supply polarity with manual voltage control. A nomenclature was derived during the screening tests to describe the effluent from the coke oven battery stack. The main coke oven stack description which evolved was:

Normal

Atypical
- Black
- Gray
- White

The condition could be identified also by observing the scrubber arc rate and electrode voltages. During normal operation, the stack effluent was clear. The CDS operated at its pre-set voltage with a low, less than 100 arcs/min arc rate. During an abnormal condition, the stack effluent appeared black, various shades of gray and white and high electrode arc rates were measured, up to 1000 arcs/min. For periods of up to 10 minutes during black stack conditions, the spray pattern on the first stage and intermittently on the second stage would collapse. The scrubber operated normally during gray stack conditions with arc rates up to 350 arcs/min. During white stack operation, the scrubber arc rate was very sporadic, less than 250 to in excess of 500 arcs/min. Derating the gas velocity 20% substantially improved the electrical operation stability.

MATRIX TESTS

The matrix tests are designed by a letter and number series of the form TM-XXX-XXN where the X's are digits. The last two digits are used to identify the test relative to the run number. The first three digits correspond to the sequence in which the test was run during the matrix test series.

The operating parameter levels established during the screening tests are shown in Table 5. Levels for each parameter were the same within both the wall wash and no wall wash blocks except voltage.

High level voltages were selected to conform to conditions of about equivalent spark rate, low level 4-5 kv lower.

A fixed damper opening was used to establish the volumetric flow rate for the test runs. The nominal flow rate at different degrees of damper opening was calibrated with pitot traverses at the sampling ports. The actual gas flow rate changed during and between test runs because of variations in the main stack draft which coincided with the coke oven operating cycle. The damper positions determined during the screening tests were 5th notch for the low level and the 6th for high level. After start of the matrix tests, abnormal conditions were encountered that could not be handled by the scrubber at 6th notch operation. This level was subsequently changed to Notch 4.

Table 5. Test Matrix Parameters

	Wall Wash	No Wall Wash
Electrode Voltage A	A_0 = 31 kV	33 kV
	A_1 = 35 kV	38 kV
Gas Flow Rate B	B_0 = 4th notch (Damper Setting)[a]	
	B_1 = 5th notch	
Electrode Water Flow Rate C	C_0 = 12 gpm	
	C_1 = 16 gpm	
Pre-Cooling Water Flow Rate[b] D	D_0 = 3.75 gpm for B_0	
	= 4.50 gpm for B_1	
	D_1 = 5.00 gpm for B_0	
	= 6.00 gpm for B_1	

a. The damper setting referenced to clamping notches on handle track. First notch is closed position.

b. The actual pre-cooling water absorbed by the gas is the difference between the set flow rate, D, and the quantity measured in the overflow.

The first matrix test series runs included the block with wall wash and are numbered 9 through 16 in the test matrix. The results of these tests are summarized in Appendix A, Table 2-A. The scrubber stack appearance can be characterized as containing a large quantity of entrained water droplets. The presence of these water droplets in the effluent and the location of the stack relative to the structures complicated Ringlemann determinations. Average, high inlet load collecting efficiencies were about 87%. A screen mesh demister was installed in the stack to remove the entrained droplets, but plugged rapidly because of intermittent equipment operation which resulted in screen dryout.

At the conclusion of the first series of matrix tests, a development test series was performed to investigate intermittant wall wash operation and automatic voltage control. Intermittant wall wash with adequate plate deposit control would allow higher voltage operation and eliminate the entrained droplets in the stack gas stream. It was determined during these tests that the scrubber could operate up to eight hours without wall wash and when used, required approximately 5 minutes of operation to clean the system. The wall wash cycle could coincide with periods of clean main stack without jeopardizing performance. There were no entrained droplets in the exhaust stack when operated without wash.

Therefore, the second test block of the matrix, test numbers 1 through 8 were performed without wall wash. The voltage levels used for the tests were increased from those of the first block. The results of these tests are summarized in Appendix A, Table 3-A. With the exception of test number TM-016-03N, the particle removal efficiencies of this series exceeds the first. High inlet load average efficiencies were about 94%. The cause of the one low run may be attributable to pick up of rust particles in the sampling probe. This was the last test of the matrix run and at this point in time rust flakes from the ducting were noted in the scrubber stack. The outlet probe water wash contained 108 mg of material at completion of the run and accounted for 61.7% of all material collected. The average weight of material collected in the water wash of the previous runs was 12.2 mg and accounted for 26% of the material collected. If this run were corrected, based on the sample distribution from previous tests, the particle removal efficiency would be approximately 80%.

The main reason for the improved collection efficiency of the last test series over the first is attributed to the elimination of dirty, entrained water droplets. A more detailed analysis of the tests results and conclusions is presented in Section VI.

A measure of the SO_2 and SO_3 removal was made during test number TM-015-05N. These measurements were made in accordance with EPA Method 8. The first impingers of the inlet and outlet sampling trains contained isopropyl alcohol to remove SO_3 from the sample gas and the second and third impingers of each train contained hydrogen peroxide for SO_2 removal. The inlet SO_2 concentration was determined to be 253.6 ppm and the outlet, 160.7 ppm. These values correspond to a removal efficiency of 36.6%. The inlet and outlet

SO_3 concentrations were 3.00 ppm and 3.45 ppm respectively. The higher outlet concentration probably resulted from conversion of SO_2 to SO_3 by ozone generated in the droplet formation corona.

DEVELOPMENT TESTS

These tests, performed by DAD, were designed with specific objectives of determining means to improve the CDS performance, of further characterizing the process stream and of complementing the contractual test program. The sampling procedure and equipment used during these tests were the same as those used in the program tests with the exception that the sampling times at each point were shorter and in some cases only one traverse was used per run. The abbreviated test times were necessary so that a complete test would coincide with a normal or atypical stack emission period.

The tests were conducted during a period between the two blocks of the matrix tests and after the matrix tests were completed. A summary of these tests may be found in Appendix A, Table 3-A. Included with these tests are the Ringlemann range estimates of both the CDS stack and the main stack. The opacity values are more significant for these tests because of their shorter duration and of their specific intent of being run during a limited range of main stack conditions.

The tests were run in automatic voltage mode. During several of the tests, only two stages were operated. The object of the two stage operation tests was to determine the actual influence of staging on scrubber performance.

The main stack and CDS inlet particle concentration were measured simultaneously during atypical and normal coke plant operations. The main stack had a particulate material loading of 764 mg/m^3 (0.334 gr/scf) while the inlet to the CDS was 812 mg/m^3 (0.355 gr/scf) at high emission load. A second run made during nominal operation indicated a main stack loading of 68.0 mg/m^3 (0.0297 gr/scf) and a scrubber inlet loading of 97.7 mg/m^3 (0.0427 gr/scf). As only six sampling points along one traverse axis were used in the 16 foot diameter main stack, the sample may not be representative. There is a possibility that particulate material is stratified along one side of stack. If any stratification in the main stream occurred, then the region from which the CDS flow was withdrawn could have a higher particle concentration.

An access port was cut into the outlet transition section of the CDS after completion of the matrix tests to allow a gas stream velocity profile measurement across the CDS outlet. The results of these tests are shown in Figures 10 and 11. These velocity profiles have considerably more variation than those taken during the system checkout period and shown in Figure 7 and become progressively worse as the average velocity is decreased. At original design flow rates through the scrubber, the pressure drop of the baffles (25% open) appears to be sufficient. Post test calculations indicate that a 12% open area was required at the actual test flow rates.

LONG DURATION TESTS

The long duration test was started at the conclusion of the matrix tests. It was performed concurrently with additional development tests. The CDS was then operated for an additional eight hour day. Operating parameters of the CDS were varied during the sampling periods. However, during the extended daily operating period the parameters were adjusted to correspond to run number 2 of the matrix.

The sixteen hour day scrubber operation was terminated during the second week because of operation problems that had developed which were attributed to the excessive collector plate corrosion. The arc rate was increasing with time and it was more difficult to maintain a pre-set operating voltage because roughened surfaces were initiating arcs. The total operating time during the long duration test was 100 hours. An additional 260 hours of operation were accumulated during the previous testing giving a total of 360 hours.

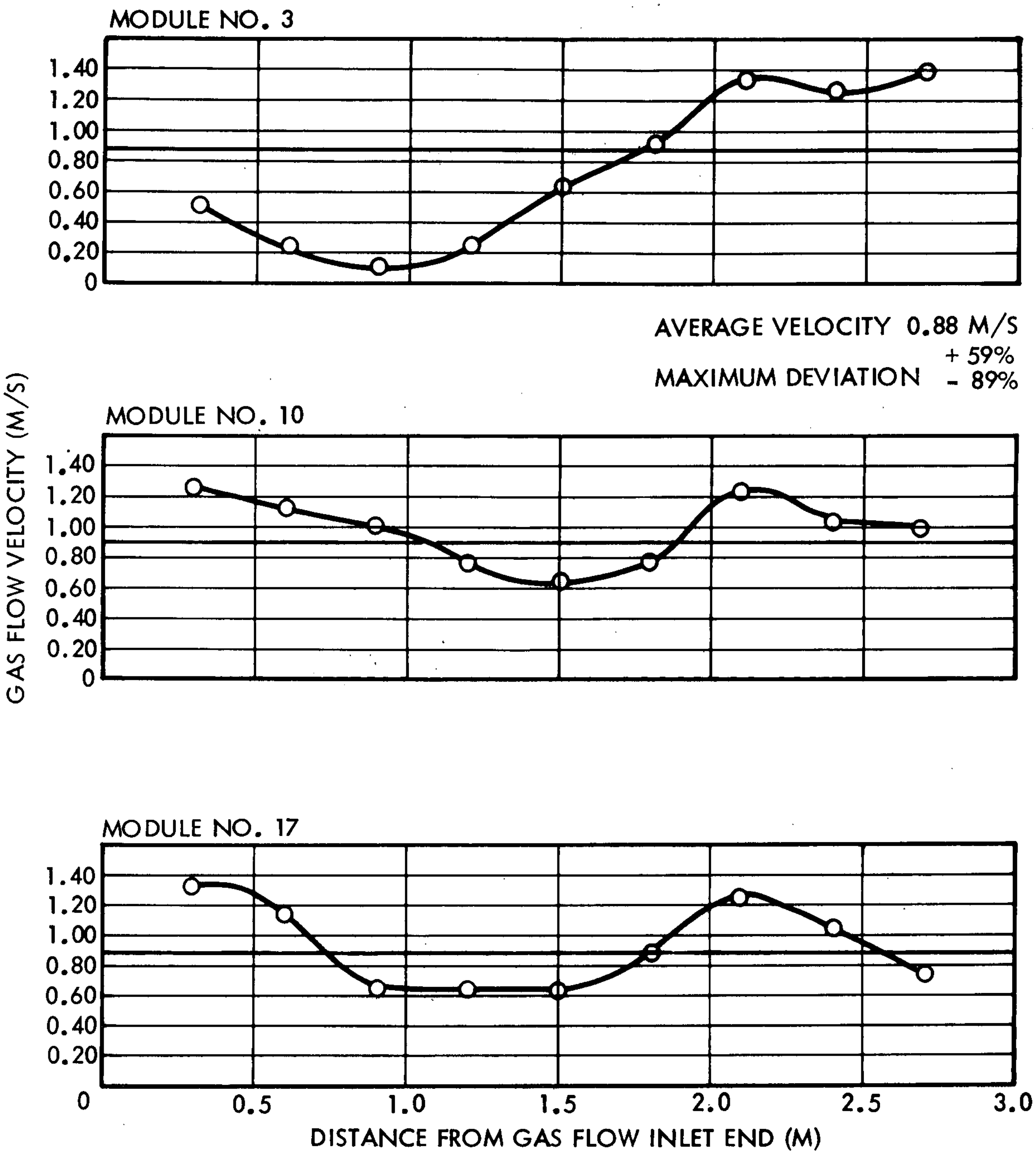

Figure 10. Gas Flow Velocity Distribution After Completion of Test Series

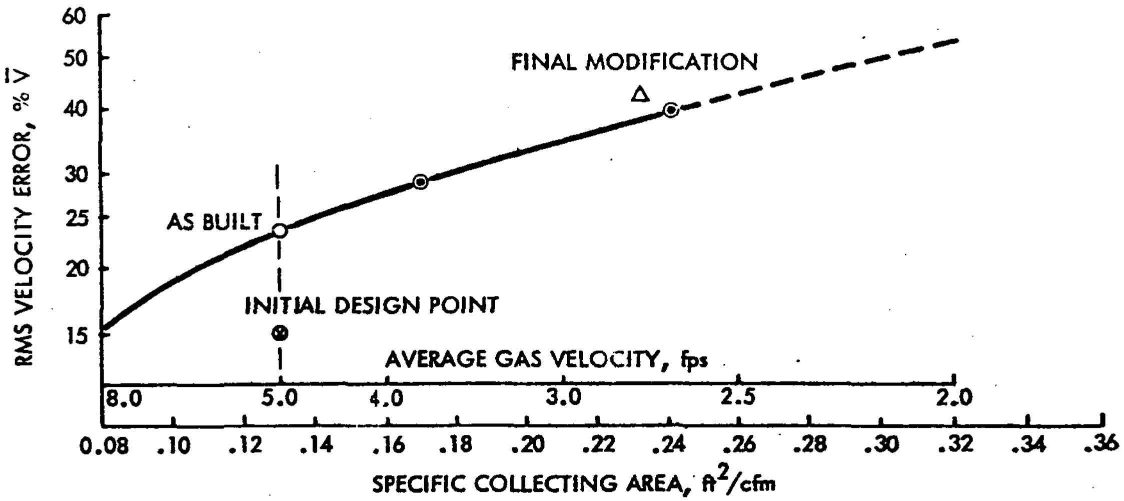

Figure 11. Gas Maldistribution Sensitivity to Specific Collecting Area-RMS Velocity Profile Vs. Average Velocity

VI. DISCUSSION

The test data developed from the statistically designed experiment previously discussed was used to estimate equipment performance over the range of the test parameters. However, efficiency changes due to process variability dominated over the efficiency changes affected by parameter level settings, thus, substantially weakening the statistical power of the experiment. Therefore, resort was made to data pooling, editing and regression analysis to develop the sensitivities of efficiency to the parameter levels.

Methods of Analysis

Three data sets were pooled, the APT and TRW original matrix test data, and the development test data. Preliminary data plotting indicated that the efficiency data with and without continuous wall wash were different, therefore, the data were initially classified into these two populations. The APT particle size distribution data was analyzed and it was determined that the efficiency variability was related to changes in particle aerodynamic mean size. Low inlet loads corresponded to submicron high resistivity hydrocarbon particulate. Observations of the stack plume color under these conditions substantiated these condlusions. High dust loads corresponded to micron sized carbon particulate.

Therefore, a regression analysis was first performed of efficiency vs. inlet dust load for the two segregated populations. This regression analysis was then used to identify statistical outliers and test anomalies. Judicious editing of this data finally evolved an analysis wherein the dominant parameter variables were identified and quantified.

Process Characterization

The APT emission and size distribution data was first investigated to determine if the process conditions could explain the variability in collecting efficiency. Figure 12 is a plot of mean aerodynamic diameter vs. inlet particle load. It can be seen that there is a correlation, lower inlet loads producing the smallest mean particle sizes. The mean particle sizes vary from about .4 microns to about 1.5 microns over the dust load range. Somewhere in the range of 200-250 mg/Nm^3 the aero-

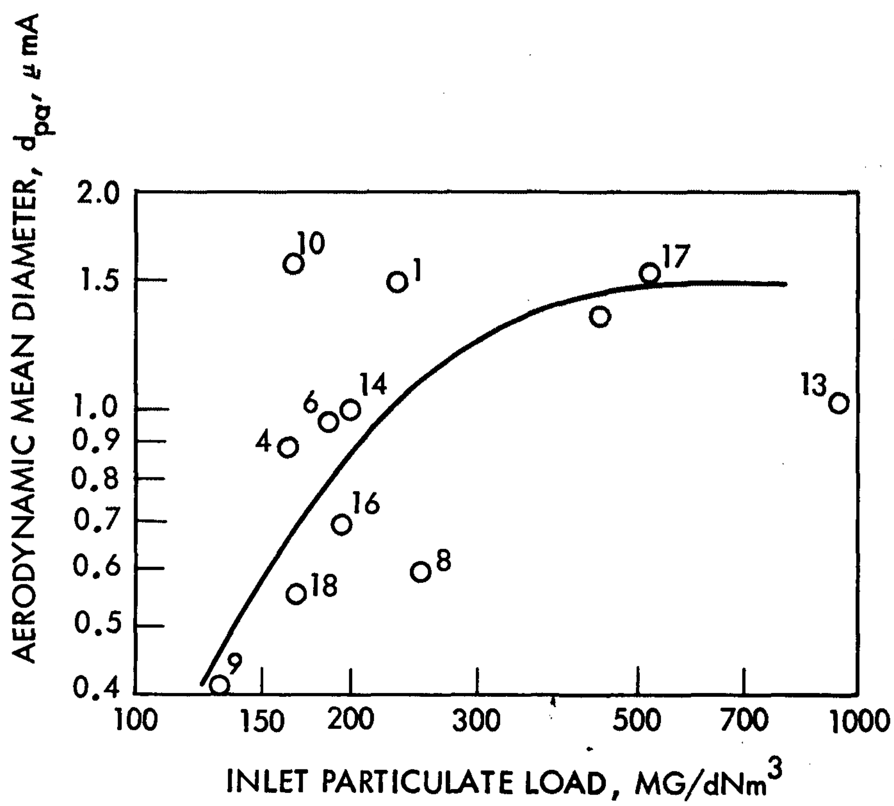

Figure 12. Coke Oven Flue Gas Process Variability, the Relationship of Inlet Dust Load to Particle Size

dynamic mean diameters become more constant. Below this range mean size fluctuates widely. Examination of the particle size distributions plotted on log-probability paper, Figures 13-15, suggest that below about 220 mg/Nm^3 the inlet particle size distribution is highly bimodal. At the higher inlet loadings and for most all outlets distributions, Figures 16 and 17, the distribution approachs a log normal distribution. The bimodal distribution is composed of a hydrocarbon aerosol having a mean size of perhaps 1 or 1 1/2 microns. This suggests a statistical approach to the data wherein the efficiency is first correlated to the inlet dust loads.

Results of Analysis

Regression analyses were first performed on the two data populations classified as with continuous wall wash and without. All of the test points from all three data sets were analyzed within each population. High correlation coefficients were obtained. The results of the regression analysis are shown on Figures 18 and 19. The data analyzed with the continuous wall wash was shown statistically to be significantly lower than the data without wall wash at a high confidence level. In both sets of data the efficiencies tend to assymtote and become nearly constant at inlet dust loadings of about 220-260 mg/Nm^3. This corresponds to the inlet load at which mean aerodynamic diameter becomes constant. It would appear that the most statistical power would lie in the region of the curves exceeding 220 mg/Nm^3.

Efficiencies were about 4 1/2% higher for the population of data wherein the wall wash was not operated. As was previously discussed this was attributed to the elimination of the wash water spray droplet reentrainment problem which gave an atypically high outlet dust loading. Also the standard error of the residuals was substantial lower for the case of no wall wash, again reflecting the high variability of the outlet emission data when the wall wash was operated. The three data sets scattered randomly about the regression line, indicating they were all part of the same population.

In order to determine the parameter effects an analysis of the residual deviations was made (i.e., deviation about the efficiency-inlet load

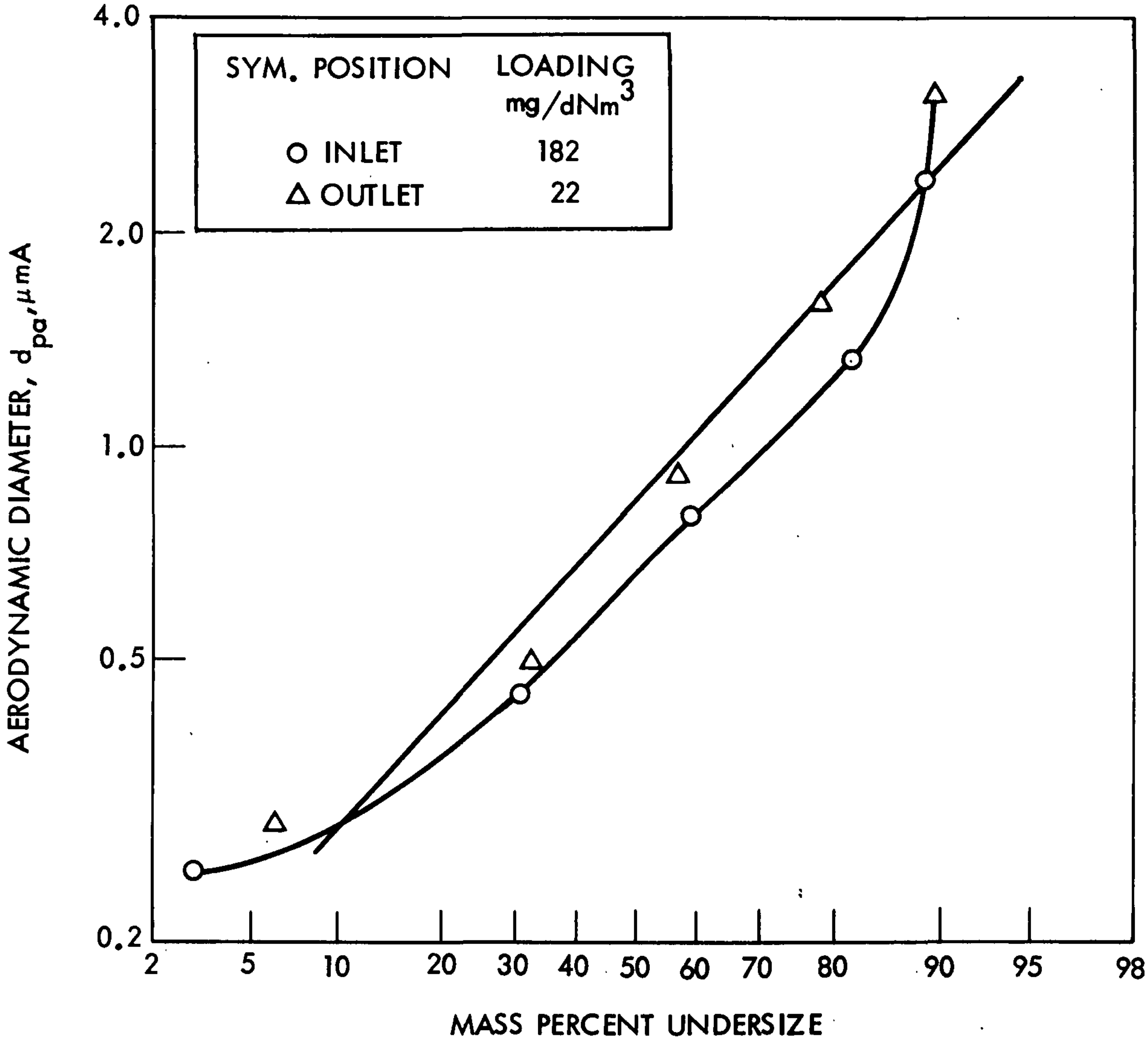

Figure 13. Inlet and Outlet Size Distributions at Low Inlet Load

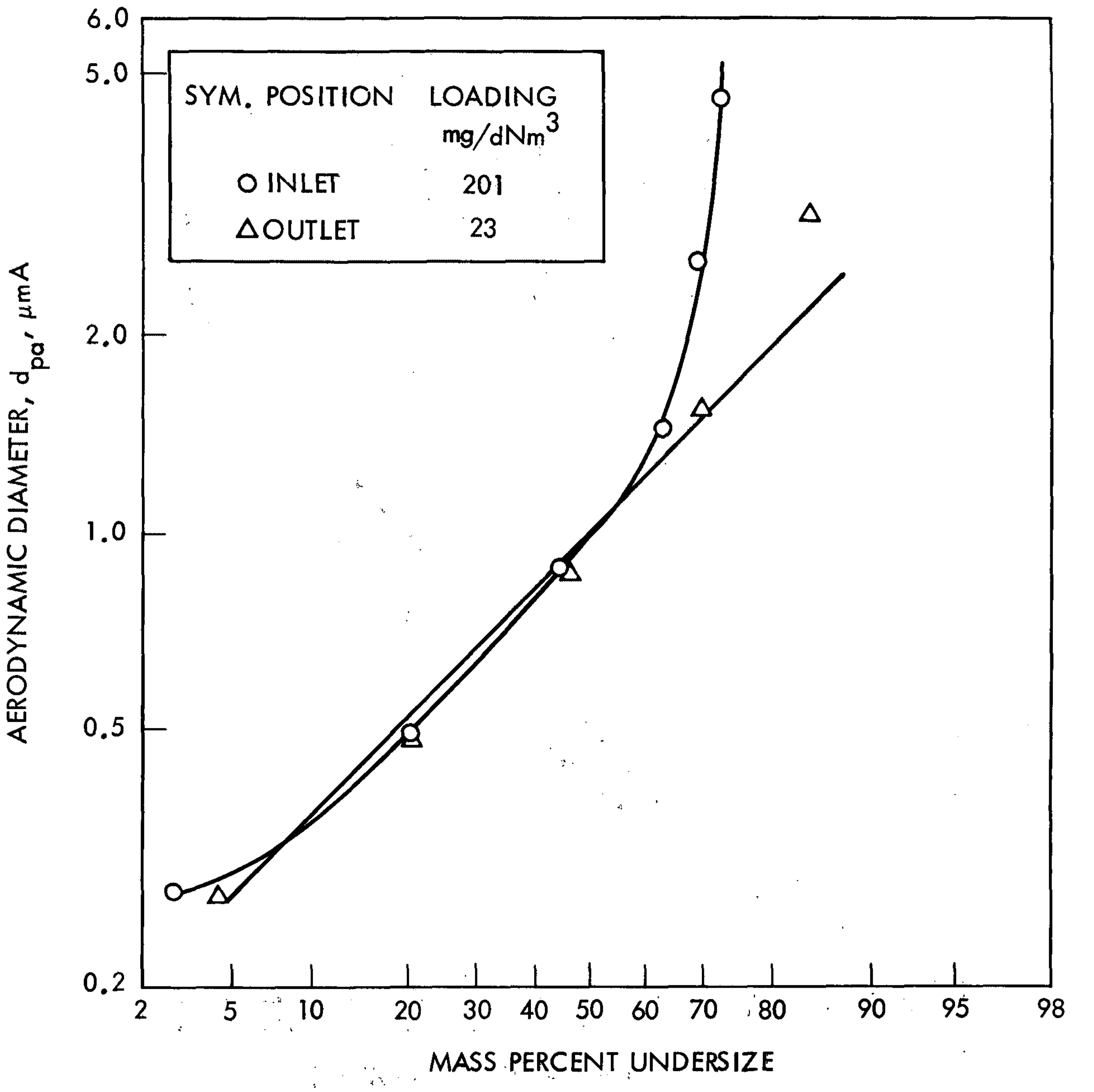

Figure 14. Inlet and Outlet Size Distributions at Low Inlet Load

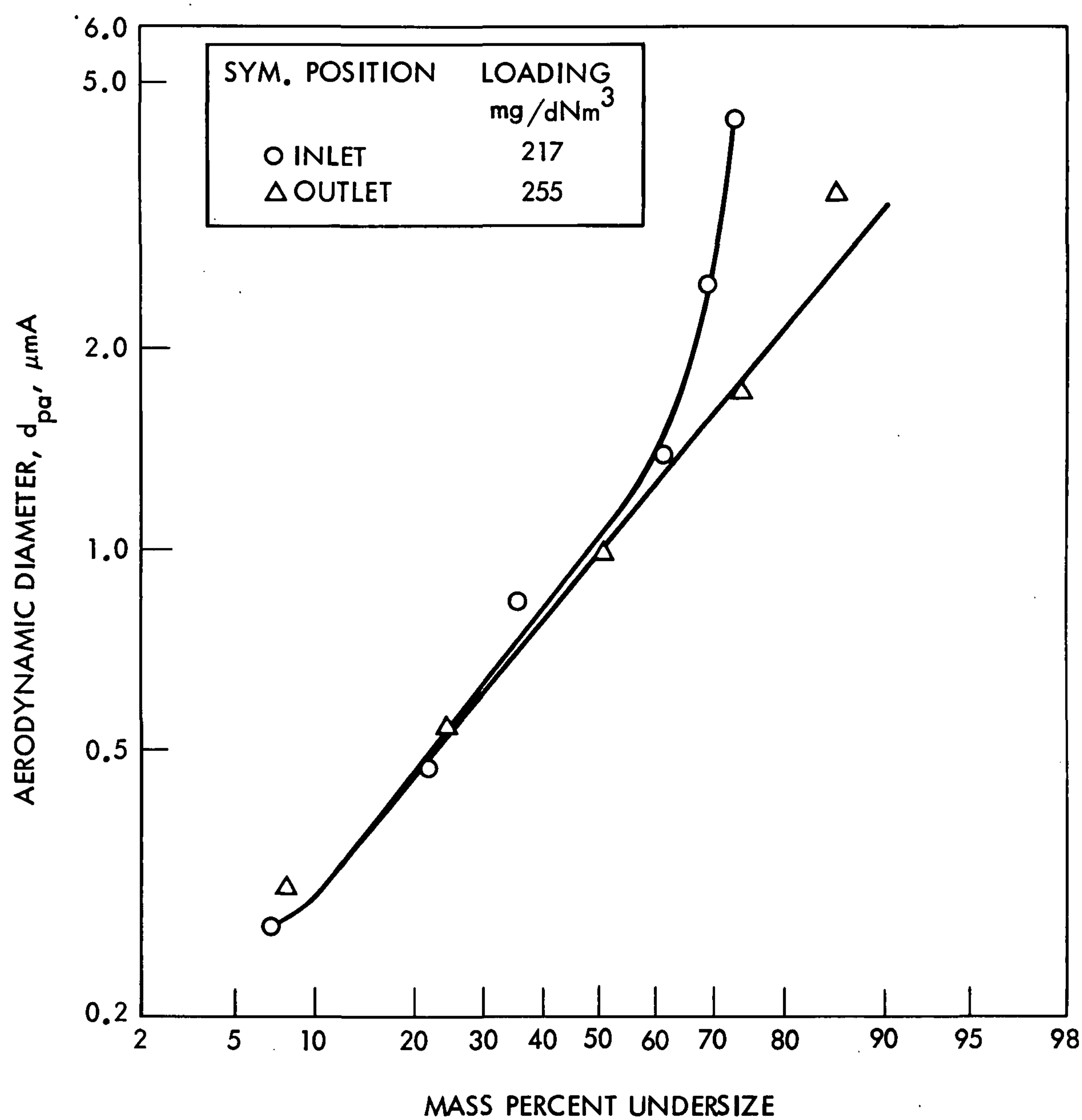

Figure 15. Inlet and Outlet Size Distributions at Low Inlet Load

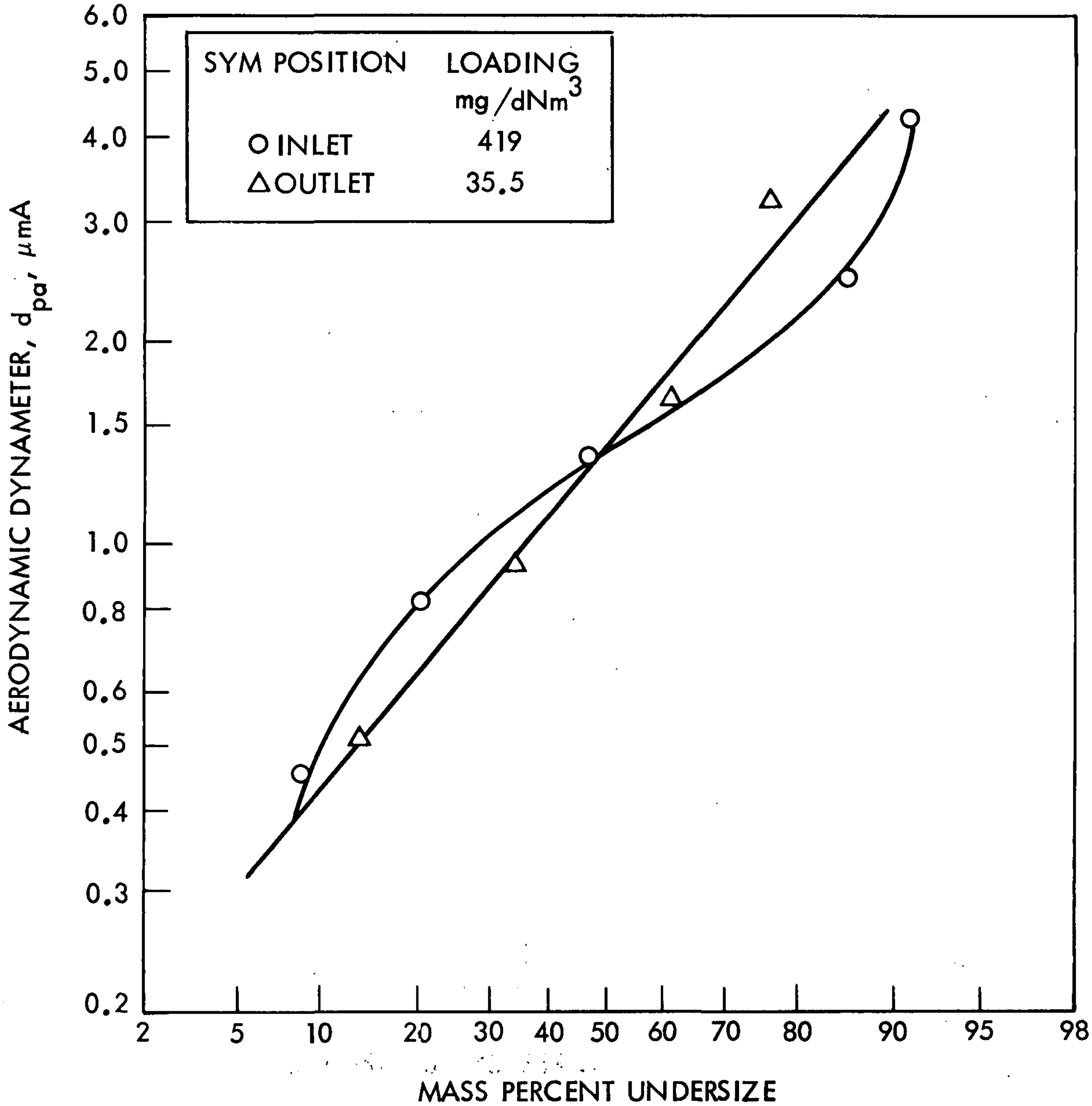

Figure 16. Inlet and Outlet Size Distributions at High Inlet Load

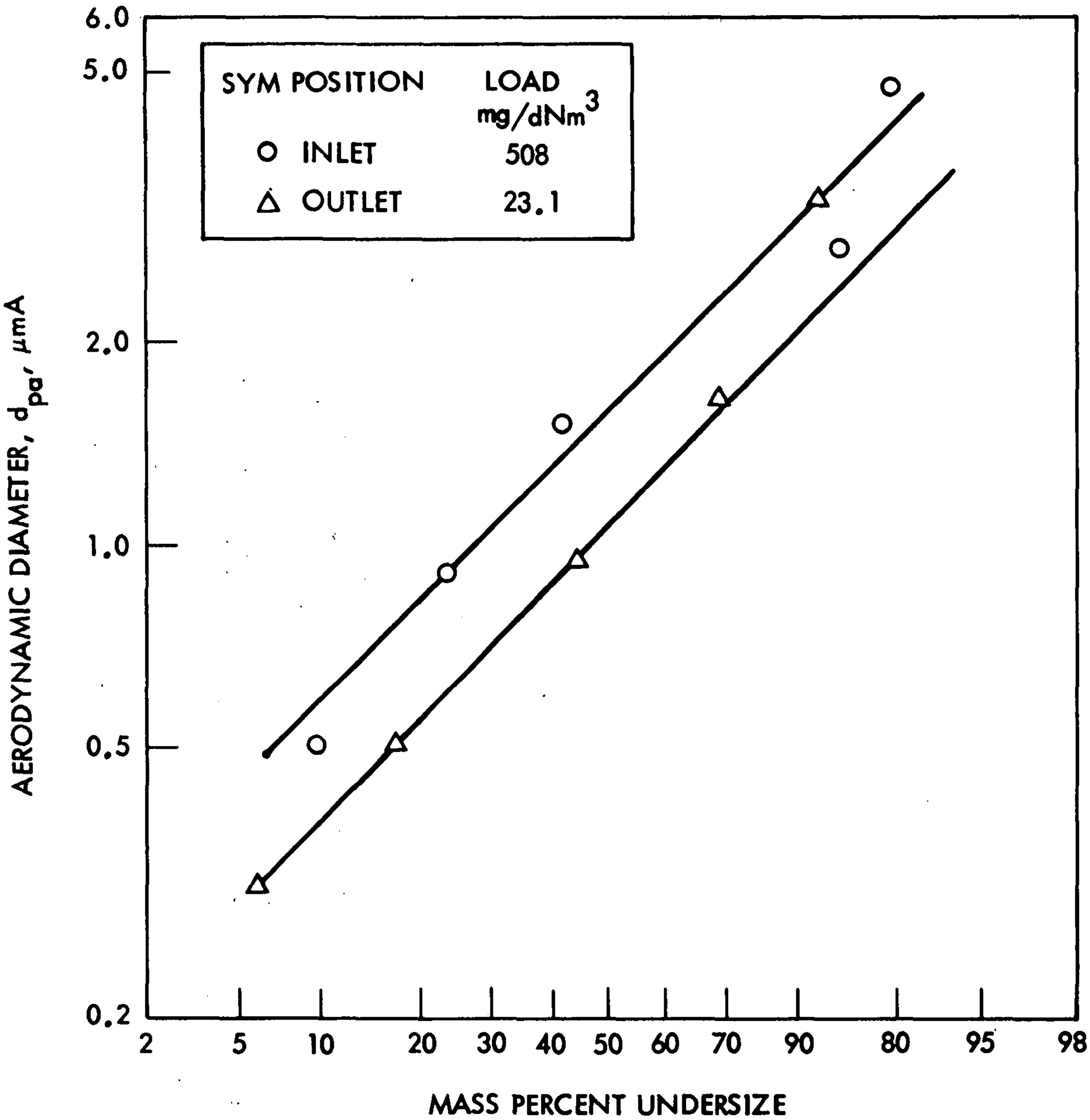

Figure 17. Inlet and Outlet Size Distributions at High Inlet Load

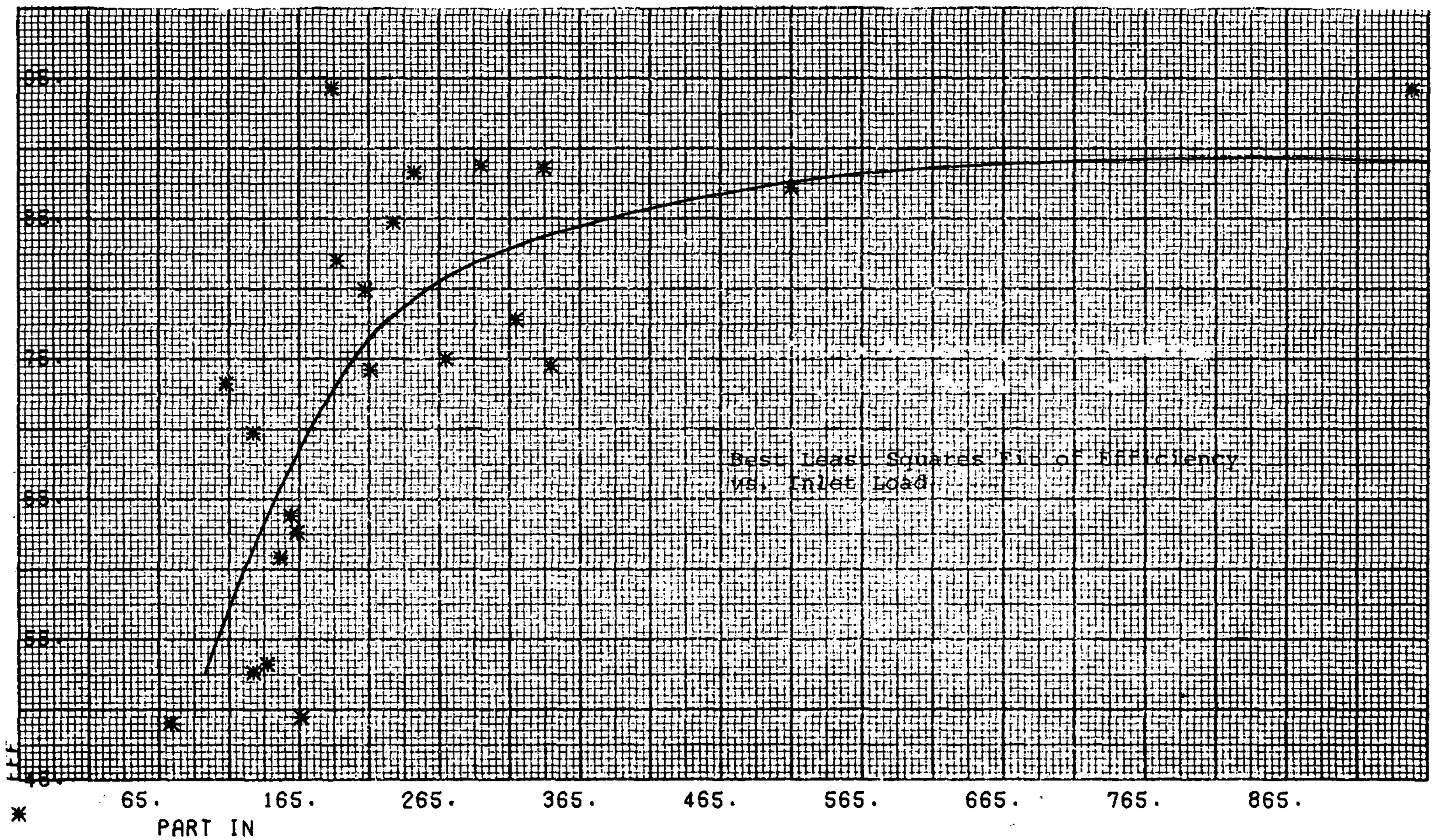

Figure 18. Efficiency Correlation, Total Unedited Data Set With Continuous Wall Wash

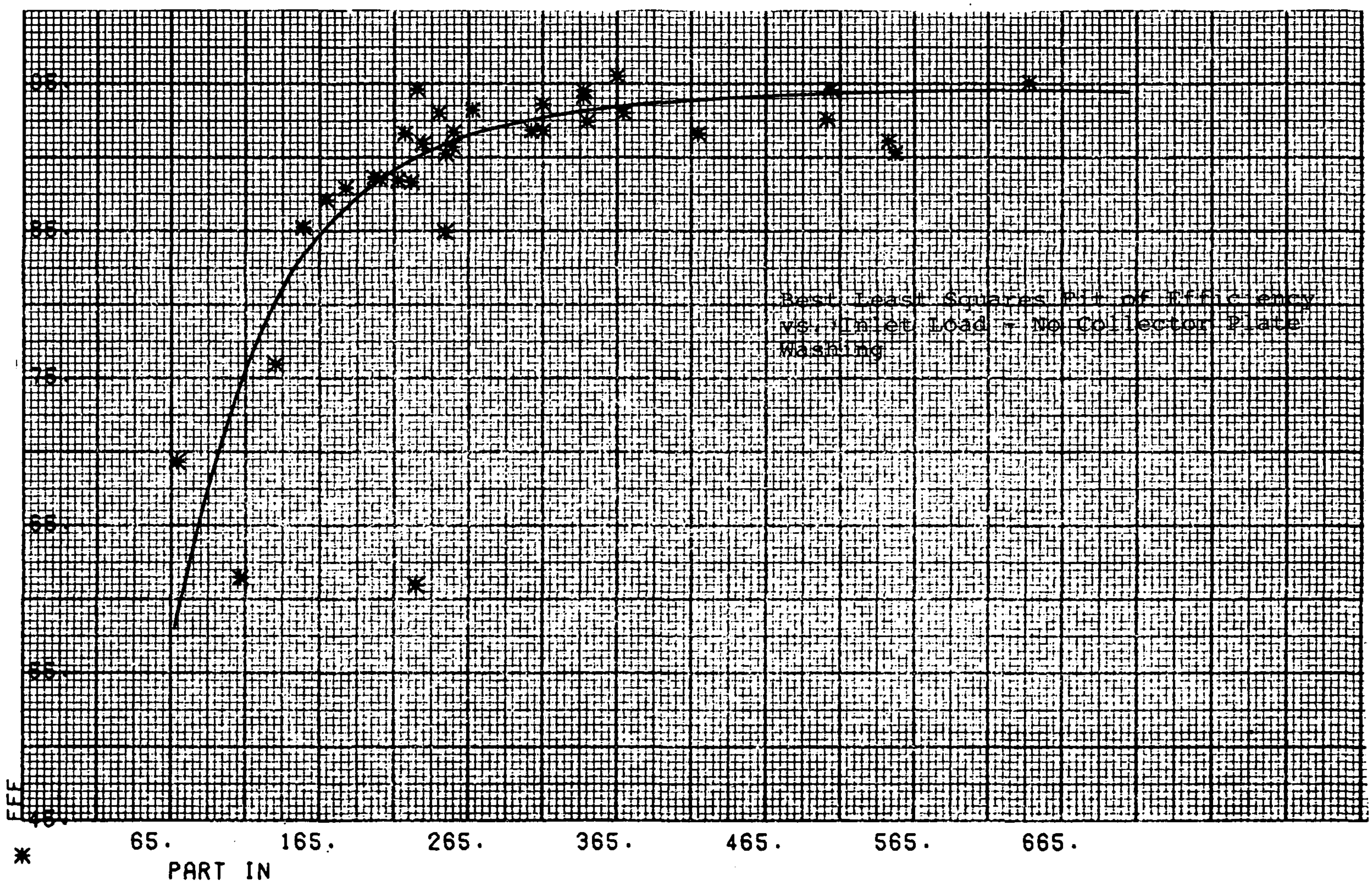

Figure 19. Efficiency Correlation, Total Unedited Data Set Without Wall Wash

regression line). The parameters considered were inlet gas temperature, gas flow rate and voltage and interactions thereof. Analyses were performed after eliminating obvious statistical outliers and reviewing the data for test anomalies, Table 6. Generally, the outliers could be explained in terms of test anomalies particularly with respect to unstable electrode voltage operation or measurement procedure.

For the case of the continuous wall wash the only statistically significant parameter identified was the inlet temperature. Increasing temperature slightly decreases efficiency. The data with the continuous wall wash system is atypical of the real potential of the CDS and is a situation that can be corrected by an improved design. Therefore, the remaining analyses were directed at analyzing the data without wall wash in an attempt to develop the efficiency sensitivities to the parameter levels.

A detailed summary of the regression analyses may be found in Appendix C. The first analysis of the residual deviations for the data population without wall wash and incorporating edited data indicated an interaction between gas flow rate and inlet temperature. However, this data incorporated the low inlet dust loading tests with the highest degree of variability. The more steady process conditions on the assymtotic portion of Figure 18 suggests that more statistical power may be developed with this part of the data. Therefore, efficiency data greater than 90% or inlet loads greater than 227 mg/Nm^3 were incorporated into a final data pool. A regression analysis was performed with first and second stage electrode voltages, inlet gas temperature and actual gas flow rate. The statistical analysis showed that gas flow rate was a highly significant variable having a negative coefficient with a value of $2.9 \times 10^{-4}\%/m^3/m$, Figure 20. High gas velocities result in lower efficiencies. Over a 50% decrease in gas flow rate the efficiency only increased about 2%. This sensitivity is significantly less than that experienced in other pilot programs where the regression coefficients have been a factor of 2 higher. The relatively low sensitivity is attributed to the fact that the gas distribution grew progressively worse as gas flow rate was reduced. Post test velocity profiles of three of 19 CDS modules were measured over a range of gas flow rates. A typical distribution is shown in Figure 10 and the rms error over the test velocity range shown in Figure 11. At a velocity of about 3 fps it is

TABLE 6

SUSPECT KAISER CDS DATA

Data Point		COMMENTS		
		Statistical	Equipment Condition	
No.	Source		Voltage	Wallwash
8	APT	Outlier on load vs d_p	Low voltage operation (~30KV)	Yes
13	APT	Outlier on load vs d_p	Low voltage operation (~30KV)	Yes
10	APT	Outlier on efficiency vs load	Upset 1st stage voltage	Yes
4	APT	Outlier on efficiency vs load	Upset 1st stage voltage	Yes
S-2	Screening Test	Outlier on efficiency vs load	Positive polarity	Yes
S-3	Screening Test	Outlier on efficiency vs load	Arc control on 1st stage only	Yes
3N	EPA	Outlier on efficiency[1] vs load	Satisfactory	No
12N	EPA	Outlier on efficiency vs load	Arc control on 1st and 2nd stages only	Yes
006	DAD	Outlier on efficiency vs load	1st stage voltage collapse	No

[1]Outlet sampling error.

		Measurement Anomally	Position	Efficiency Effect
1	APT	5 & 6th Stages-50% Plugged	Inlet	Fractional
4,10,18	APT	Not 100% Simultaneous With Inlet, Process Change	Outlet, Inlet	Fractional and Overall
9	APT	6 & 7th Stages Wet	Outlet	Fractional
15	APT	3rd & 5th Stages, 20-30% Plugged	Inlet	Fractional

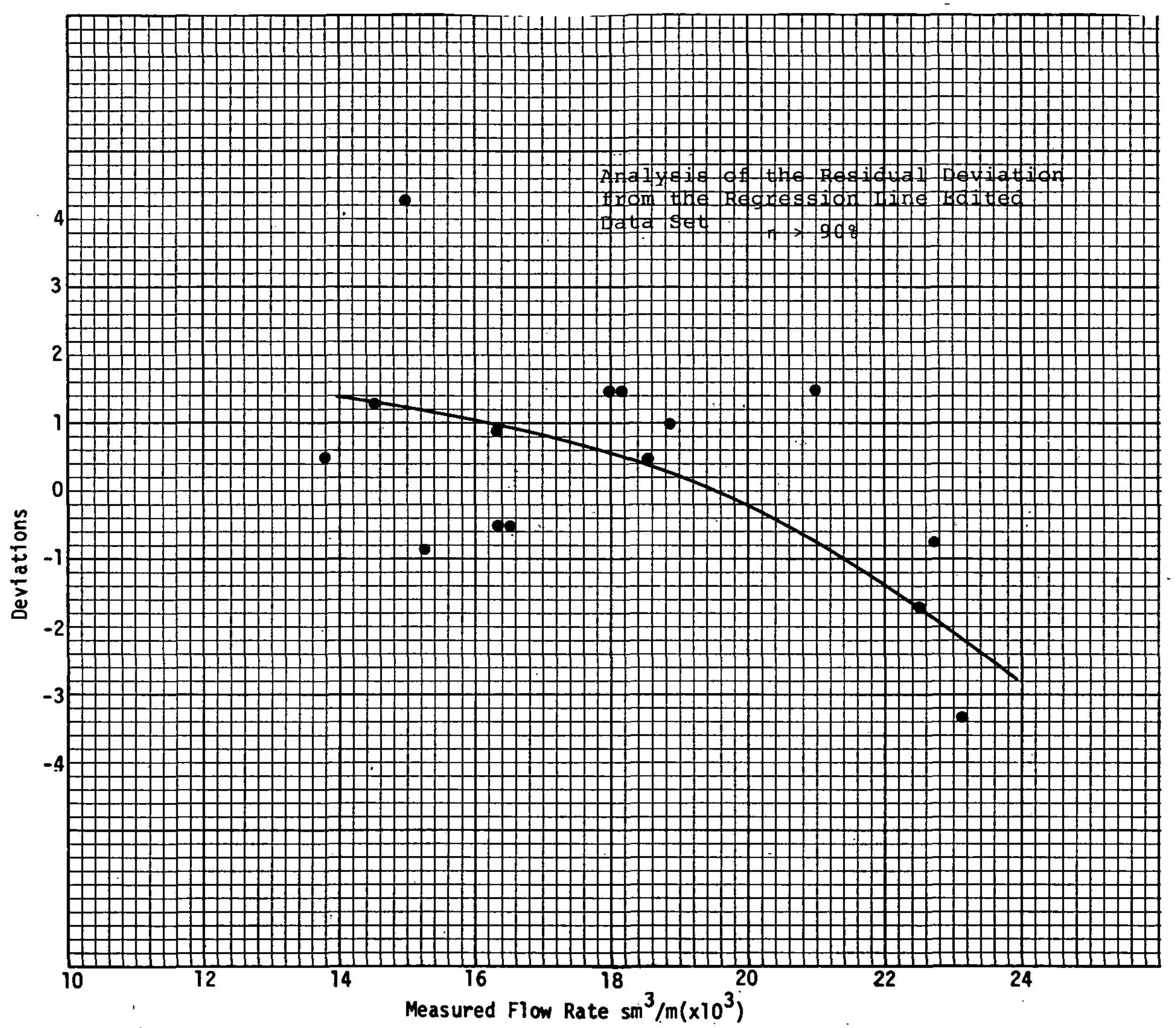

Figure 20

Effect of Gas Flow Rate on Overall Collecting Efficiency substantially out of specification. The rms velocity error increased from 15% to 50%. The non-linear influence on velocity would therefore result in efficiency losses at low gas velocities (2.5 fps) estimated at between 2 1/2 and 3%. The increasingly poor gas distribution is attributed to the loss of pressure drop at the baffle system.

Several regression analyses were attempted to bring out the effects of electrode voltage. The regression of the residual deviations was first attempted using the second stage voltage which is somewhat typical of the average voltage operation across all stages. As no correlation could be developed an additional analysis was conducted by introducing both the first and second stage voltages. It was felt that this would more typically reflect the first stage space charge effect on cleaning efficiency. Again, no influence was uncovered, Figure 21. As can be seen the data fairly well scatters on both sides of the zero deviation line over a range of 33-41 kilovolts. When the voltage is pushed much beyond 40 kv greater statistical variability occurs which may be indicative of the high spark rate conditions. The insensitivity of voltage is surprising and it is attributed to the low gas velocity operation. It is hypothesized that the high space charge due to conducting carbonblack and water droplets and their correspondingly low mobility is affecting the ability of the high voltage to establish a sufficiently higher voltage gradient outside of the corona field. This effect would not be anticipated at higher gas velocities where the space charge is more evenly distributed through the equipment volume.

A summary of the regression analyses discussed above may be found in Table 7. Further analyses did not result in any additional correlations.

Based upon the above the particle size distribution data obtained in the APT test was analyzed to develop fractional efficiencies as a function of the aerodynamic diameter. Only those tests with no test or statistical anomalies and without wall wash were analyzed. The APT data were segregated into both high and low inlet loading conditions as previously discussed. The efficiencies at low inlet conditions (typically 180 mg/Nm^3 to 220), Figure 22, are very similar for all three tests, Nos. 14, 16 and 19. Efficiency improves with the smaller aerodynamic diameters and reaches about 90% at 0.4 microns. This is atypical of other types of electrostatic and wet

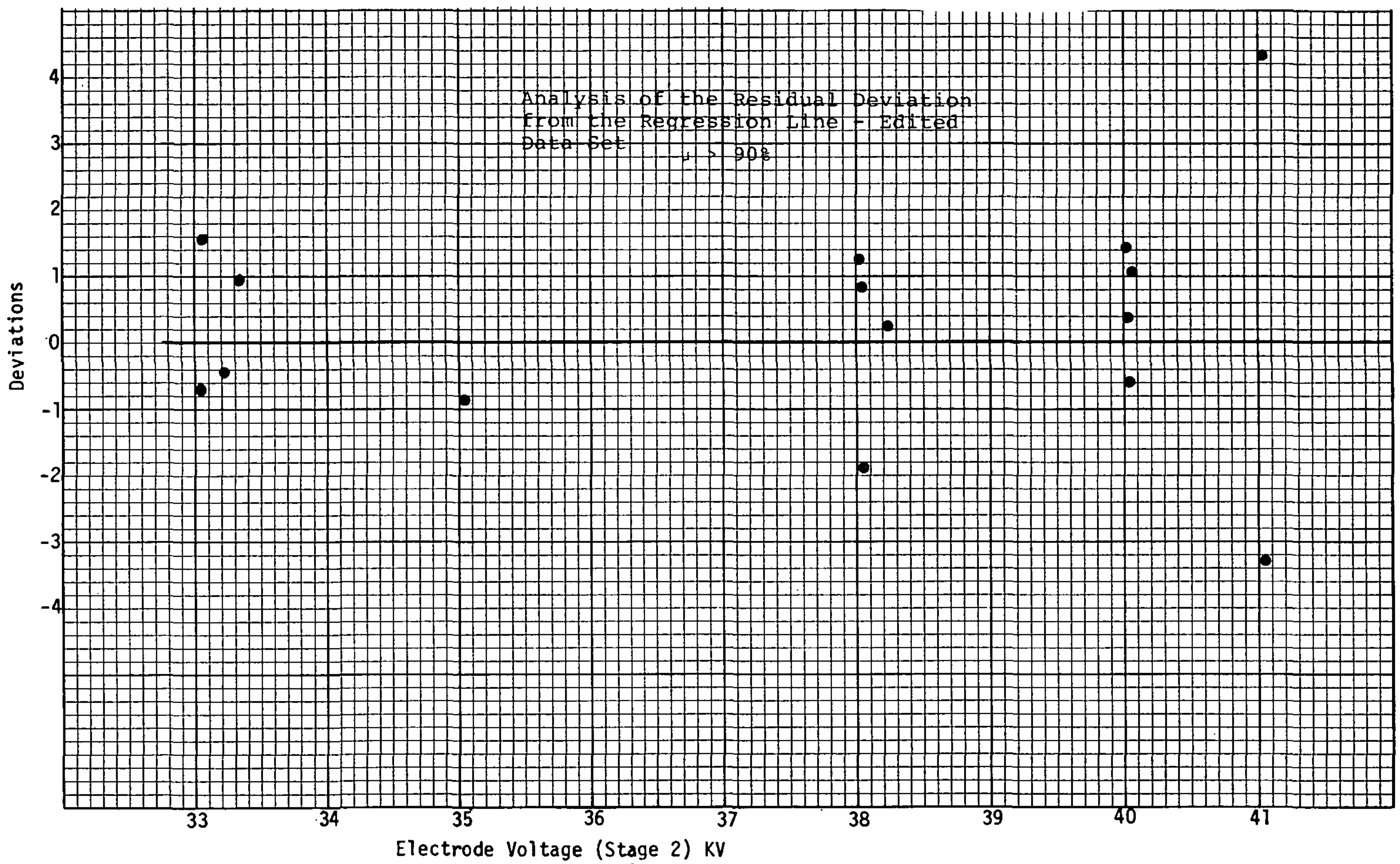

Figure 21
Insensitivity of Efficiency to Second Stage Electrode Voltage

TABLE 7

SUMMARY OF REGRESSION ANALYSES

INDEPENDENT VARIABLES	DATA SET	WALL WASH	STD. ERROR OF RESIDUALS	SIGNIFICANT PARAMETER AND REG. COEFF.
Inlet load, $C_i, \frac{mg}{dNm^3}$	Pooled Data	Yes	8.9	$89.1\ (1-e^{-.0087C_i})$
Residual Errors plus Test Parameters, $T_i\ ^oC$	" "	Yes	6.4	40.6 - .318T
Inlet load, $C_i, \frac{mg}{dNm^3}$	" "	No	3.6	$93.5\ (1-e^{-.014C_i})$
Residual Errors plus Test Parameters, Q, $\frac{Nm^3}{m}$	Edited Data	No	1.57	$5.6-2.9 \times 10^{-4}Q$

scrubbing equipment, but has been experienced in other CDS pilot programs. It should be noted that the particulate under these conditions has a bi-modal distribution of high resistivity hydrocarbon and carbon black. Some hydrocarbon might have condensed on the carbon black increasing its surface electrical resistivity. Therefore, lower efficiency might result as compared with the higher inlet loadings (420-510 mg), Figure 22, at the same cut diameter. It is interesting to note that the low inlet load fractional efficiencies were almost independent of both electrode voltage and gas flow rate. Values of these parameters varied between 33 and 38 kilovolts and 12 and 15 x 10^3 m^3/hr.

The fractional efficiency data for the higher inlet loadings, Figure 22, are more typical of the results normally expected from precipitators and high energy wet scrubbers. Efficiencies in the 1 to 2 micron range approach 99%. For this size particulate removal mechanisms consist of both high energy impaction of charged water droplets and electrostatic charging and precipitation. Below 1 micron the collection mechanism is probably by electrostatic precipitation either through charge transfer upon interaction of a charged water droplets or through direct corona charging of the plasma. The fractional efficiencies at high inlet load and submicron particle sizes approach those of the low inlet load case. This is again attributed to the fact that most of the particulate in this range is hydrocarbon having the same electrical and physical properties as that of the lower inlet load case.

Some additional equipment optimization probably could have been affected by running unbalanced electrode waterflow rates between the stages. This would result in optimally sizing the water droplet for high energy impaction and removal of the carbon black in the first stage and the electrostatic precipitation of the hydrocarbon in the second stage.

Limited testing with a two-stage unit, (i.e., the third stage removed from the process) showed that about a 2 or 3% loss in efficiency results. Conversely had a fourth stage been added it is believed that approximately a 1.5 to 2.0% efficiency improvement could have been affected. The fourth stage would also protect against infrequent high dust loads which would normally cause a collapse of the first stage. In this event even with a

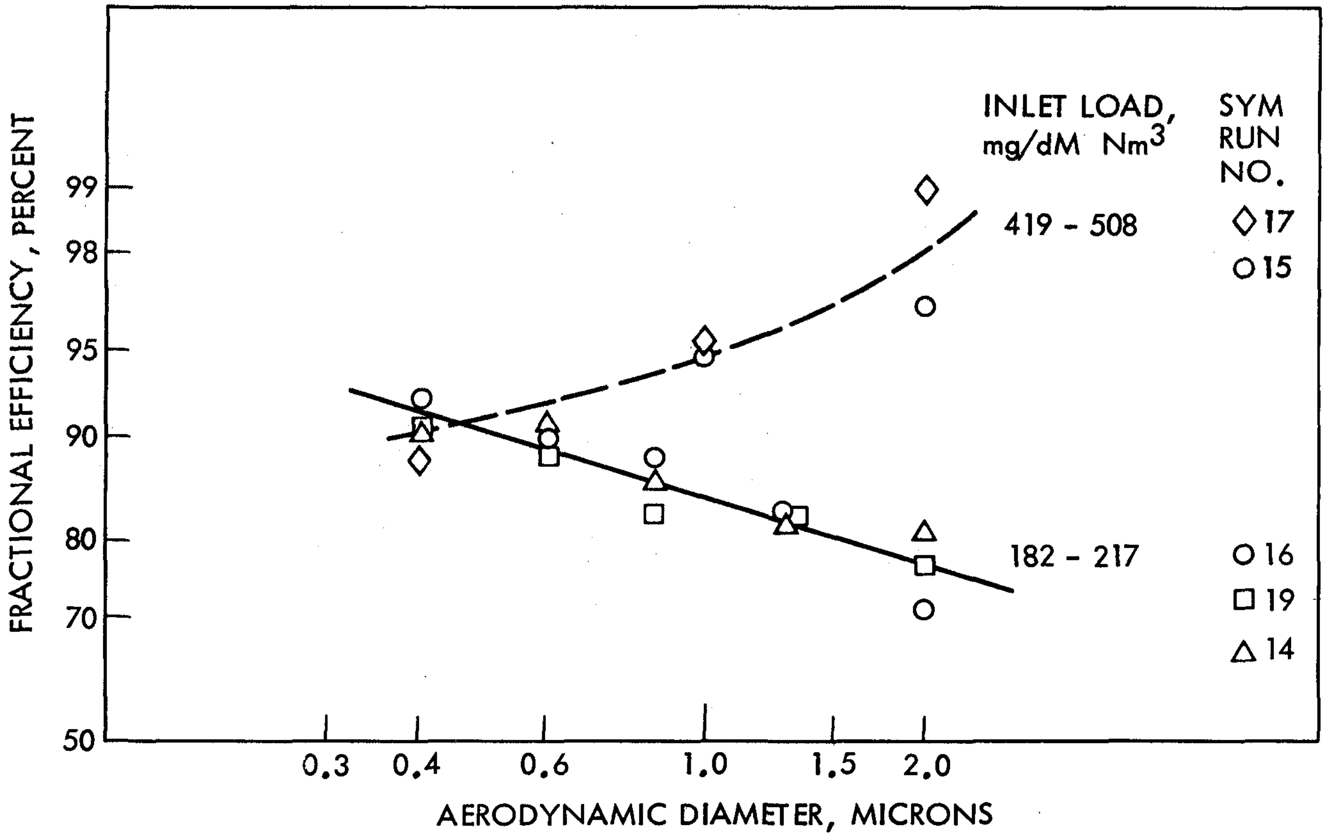

Figure 22. Fractional Efficiency Data for the Higher Inlet Loadings

partial loss of the first stage the equipment would basically perform as an optimized three stage unit.

The above performance was achieved in a unit consuming very little power and at a low liquid to gas ratio. Under typical gas flow rate conditions of about 15,000 Nm^3/h (13,000 acfm), the total power supply consumption was of the order 0.7-1 watt/hr/Nm^3 (.85-1.2 watts/acfm) at a nominal 35 kv electrode voltage. Pressure drops between the CDS inlet and the stack discharge were extremely low, about 1.3 cm/wc. System pressure drops, coke oven breeching to CDS stack, were of the order of 10 cm/wc. This is probably an atypically high pressure drop in that there were numerous expansions and elbows of ductwork which would increase the pressure drop. The liquid to gas ratio at the nominal conditions were of the order of 0.18 ℓ/Nm^3 (0.9 gal/1000 acf) gas treated. Energy consumption is typical of energy requirements for wet electrostatic precipitators. Liquid to gas ratios are substantially lower than high energy venturis and most other types of high performance wet systems.

Limited CDS stack opacity observations were made to correlate time averaged outlet loads capable of meeting a 20% opacity criteria, Table 8. The stack opacities varied between 5 and 25%. The 15% opacity was not exceeded during Test No. 002 for an average discharge load of 33.4 mg/dNm^3 (.0146 gr/dscf). Values of 23 mg/dNm^3 consistently resulted in a stack opacity of 0-5, Tests Nos. 003, 010, 011, 012 and 015. During Test No. .006, performed during a major upset, the 20% opacity was exceeded during two 5-minute periods. The actual discharge load during this period most certainly exceeded the measured average value of 37.8 mg/dNm^3 as the first stage electrical voltage collapsed. It would appear that a design point emission discharge of 23 mg/dNm^3 would satisfy the requirement.

Using 95% as the maximum efficiency for high voltage on three stages, the maximum permissable inlet load corresponds to 700 mg/dNm^3 (.3 gr/scf). For inlet loads less than this progressively larger margins of safety result. It should be noted that most data from coking emissions is in the range of 230 to 500 mg/dNm^3. The Kaiser Coking Furnace conditions and production rates are such that abnormally high smoking conditions are currently being experienced. It is felt that this results in a sufficiently conservatively CDS design and operating point.

TABLE 8

KAISER OBSERVED CDS STACK OPACITIES

Test No.	Outlet mg/Nm^3	Dust Load gr/scf	Observed Opacities, % Time Sequence	Average
002	33.4	.0146	15,10,10,15,15,10,10	12
003	16.9	.008	10,15,5,0,0,0	5
010	26.8	.0117	5 ←——→ 5	5
011	23.8	.0104	5 ←——→ 5	5
012	23.8	.0104	⑤ ←——→ ⑤	5
006	37.8	.0165[1]	⑤, 5, 5, 10,15, ㉕, ㉕, ⑳[2]	14
015	22.9	.0100	(5, 5, 5, 5, 5, ⑮ 5 2)	7

1, 1st stage voltage severely deteriorated

2, Every other observation recorded

3, Circled nos. Stack A 80% opacity

REFERENCES

1. "Charged Droplet Scrubber for Fine Particle Control - Laboratory Study", Report prepared for the Environmental Protection Agency under Contract Number 68-02-1345 by TRW Systems Group, February 13, 1976.

2. Federal Register, Vol 36, No. 247, pp 24887-24890, December 23, 1971.

3. Private Communication from Di-Gerald Shaughnessy of the University of Dayton, dated January 31, 1975.

4. Charged Droplet Scrubber Pilot Demonstration for Fine Particle Control, Test Matrix; Contract Number 68-02-1345, prepared for the Environmental Protection Agency, July 28, 1975.

LIST OF TABLES AND FIGURES - APPENDICES A - B - C

APPENDIX A

SUMMARY OF PERFORMANCE DATA

Table A-1. Screening Test Summary

TEST NO. AND DATE	VOLTAGE[a] (kV) STAGE 1	2	3	TR SET	WATER FLOW RATE (l/min) ELECTRODE	WALL WASH	PRE-COOLING	GAS FLOW RATE (sm^3/hr) INLET	OUTLET	GAS TEMPERATURE (°C) STACK[b]	INLET[c]	OUTLET	PERCENT MOISTURE INLET	OUTLET	PARTICLE LOADING[f] (mg/sm^3) INLET	OUTLET	CLEANING EFFICIENCY PERCENT	DAMPER SETTING (NOTCH)	OUTPUT CURRENT (mA) TOTAL	LEAKAGE	POWER INPUT (AC) VOLTS	AMPS	ARC RATE (ARCS/MIN.)[d] NOMINAL	MAXIMUM	COMMENTS
1 9/23/75	30	34	32	73	62	106	22.7	20 835	13 528	199	107	52	8.7	14.4	211.9	42.79	79.8	5	195	45.5			50	150	Negative polarity. One upset during test. Main stack light gray, except black during major load.
2 9/24/75	29	32.5	32.5	65	59	114	22.7	18 750	12 537	205	120	46	6.6	73.2	73.2	37.41	48.9	5	195	43	330	36	125	300	Positive polarity. Main stack medium gray to clear. Sustained arcing during test. Power supply off periodically to quench arcs.
3 10/7/75	32	32	30	65.5	61	106	170 5.19[e]	18 443	13 344	191	138	52	4.55	13.0	132.0	62.70	52.5	5	170	25	368	38	70	>500	Negative polarity. Main stack clear to medium gray. One major load. Arc quenching capacitor on first stage only.
4 10/8/75	29	31	30	62	61	106	17.0[e] 6.70[e]	19 770	17 417	201	162	53	10.4	15.2	343.9	88.10	74.4	6	175	25.2	388	38	150	>500	Negative polarity. Main stack light gray to black. Power supply off periodically to quench sustained arcs. Arc quenching capacitor in first stage only.
5 10/9/75	31	31.5	31.5	71	45	106	17.0 6.51[e]	17 930	14 554	187	128	54	8.27	13.2	215.8	55.84	74.1	5	170	23			50	150	Negative polarity. Main stack light gray. Major load started toward end of run. Arc quenching capacitor in first stage only.
6 10/10/75	29.5	30	29.5	64.5	61	106	17.0 6.32[e]	21 470	18 130	191	156	58	8.97	14.8	151.3	59.50	60.7	6	160	22	372	37.5	150	230	Negative polarity. Main stack light gray. Arc quenching capacitor in first stage only. Several collecting troughs were overflowing.

a. Nominal set voltage. Mean voltage during periods of high arc rate was considerably lower.

b. Stack gas temperature measured at same position as inlet particle sampling port.

c. Inlet gas temperature to CDS turning section. Measured after pre-cooling.

d. Maximum arc rate readable - 500 arcs/min.

e. Net flow rate adsorbed by gas stream.

f. gr/dscf = 2288 mg/dNm^3

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Table A-3. Development Test[a] Summary

TEST NO. AND DATE	VOLTAGE (kV) STAGE 1	2	3	OUTLET GAS FLOW RATE (sm^3/hr)	GAS TEMPERATURE (°C) INLET	OUTLET	PERCENT MOISTURE OUTLET	ELECTRODE CURRENT (mA)	ARC RATE LOW/HIGH (ARC/MIN.)	SAMPLING NO. OF TRAVERSES	NO. OF POINTS	SAMPLE TIME (min)	DAMPER SETTING (NOTCHES)	PARTICLE LOADING (mg/sm^3) INLET	OUTLET	CLEANING EFFICIENCY (PERCENT)	STACK OPACITY (PERCENT) MAIN	CDS	COMMENTS
D-002 10/29/75	36	32	37	11 693	121	51	12.2	285	250/575	1	16	3	4	294.7	33.41	88.7	35-95	10-15	With wall wash.
D-003 10/29/75	36	37	36		135	68	6.8	220	100/375	2	32	3	4	244.6	16.93	92.9	15	10-15	Pitot probe data in error.
D-004 10/30/75	38	36	39	8 160		51	12.3	250	50/100	1	16	3	2	364.8	16.93	95.4			Main stack medium gray
D-006 10/31/75	36	35	39	10 079	120	69	11.6	358	400/500	2	32	3	4	505.5	37.76	92.5			Main stack medium gray.
D-007 11/3/75	36	41	40	9 689	123	74	12.9	233	150/270	2	32	3	4	230.0	12.81	94.5	15		Main stack clear to light gray.
D-008 11/20/75	35	40	39	11 433	135	69	12.0	248	>500	2	32	3	4	642.1	31.58	95.0			Main stack black to dark gray.
D-009 11/20/75	39	40.5	39.5	9 219	132	69	22.2	258	400/450	2	16	4	4	342.1	20.37	94.0			Main stack black.
D-010 11/21/75	40	40	39	10 245	144	64	12.0	244	250/350	2	16	4	4	225.9	26.77	88.2	10	<5	Main stack white.
D-011 11/21/75	35	40	0	10 058	146	71	12.8	222	>500	2	16	4	4	253.6	23.80	90.6	10	<5	Two stage operation.
D-012 11/24/75	38	42	0	10 639	137	77	11.7	227	>500	2	16	4	4	204.8	23.80	88.4	82	<5	Two stage operation.
D-013 11/25/75	40	40	40	11 200	144	73	11.8	277	>500	2	16	4	4	248.5	37.76	84.8			Main stack black to light gray.
D-014 12/1/75	40	41	38	14 338	141	77	12.8	260	>500	1	8	3	5	551.5	54.23	90.2			Main stack black to dark gray.
D-015 12/1/75	40	41	38	10 804	140	72	11.2	260	250/500	1	16	4	4	153.3	22.88	85.1	80	15	Main stack light to dark gray.
D-016 12/4/75	40	40	40	8 629	139	66		261	300/>500	2	32	3	4	233.4	21.51	90.8			Main stack black to light gray.
D-017[b] 12/5/75				66 110[c]	210[d]	176[e]								68.0[f]	97.7[g]				Nominal Stack Condition
D-018[b] 12/9/75				64 528[c]	226[d]	202[e]								764.3[f]	812.4[g]				Load

a. All DAD tests were run with an electrode flow rate of 53 ℓ/min. and in automatic voltage control mode.
b. Tests D-017 and D-018 were run to obtain a comparison between particle loading in main stack gas stream and stream to CDS.
c. Volumetric flow rate of main stack.
d. Main stack gas stream temperature.
e. Cut off stream to CDS temperature.
f. Particle loading in main stack gas stream.

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Table A-5. Inlet and Outlet Size Distribution Data Summary
Air Pollution Technology, Inc.

Run No. APT	TRW	Inlet Load mg/Nm^3	Inlet Mean Size d_{pa}, μmA	Inlet Std.Dev. σ_g	Outlet Load mg/Nm^3	Outlet Mean Size d_{pa}, μmA	Outlet Std.Dev. σ_g	Efficiency
1	001	232	1.50	2.7	35.8	0.57	2.6	85.7
4	003	163	0.89	2.0	61.0	0.69	1.9	62.9
6	004	188	0.96	2.0	11.0	0.96	2.0	94.2
8	005	247	0.59	2.1	29.2	0.41	2.7	88.4
9	005	132	0.41	2.6	41.5	0.61	1.8	69.5
10	006	166	1.60	4.3	84.5	0.95	2.1	49.6
13	008	953	1.02	1.9	56.6	1.13	2.0	94.2
14	009	201	1.00	4.2	23.1	1.00	2.2	88.9
15	010	419	1.35	2.1	35.5	1.40	2.5	91.6
16	010	182	0.67	2.5	22.2	0.83	2.3	88.0
17	011	508	1.55	2.2	23.1	1.06	2.2	95.6
18	011	168	1.55	8.0	21.9	1.25	2.7	87.3
19	012	217	1.00	2.8	25.5	0.98	2.5	88.6
10P(1)		244	0.78	1.7	166	2.10	4.3	
13P(1)		1789	1.92	1.8	953	1.02	1.9	

(1) Runs 10P and 13P were samples taken before the water quench sprays; therefore, the inlets for Run 10 and 13 are the outlets for Runs 10P and 13P respectively.

APPENDIX B

SUMMARY OF FRACTIONAL EFFICIENCY DATA

Table B-1. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #1

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Precutter & Nozzle	232	---	35.8	---
1	232	27.3	35.8	23.8
2	232	12.0	35.0	10.4
3	232	5.7	34.7	4.0
4	230	2.3	34.0	2.0
5	180	1.3	33.2	1.2
6	99.8	0.74	27.0	0.64
7	50.8	0.45	20.2	0.37
Filter	42.9	---	15.9	---
Sample Volume (DNm³)	0.134		0.585	

Table B-2. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #4

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Precutter & Nozzle	163	---	61.0	---
1	159	27.4	61.0	23.6
2	159	12.0	60.8	10.3
3	159	4.6	60.6	4.0
4	158	2.3	59.8	2.0
5	157	1.3	58.9	1.2
6	120	0.74	45.4	0.64
7	65.8	0.45	22.9	0.37
Filter	28.9	---	17.2	---
Sample Volume (DNm³)	0.087		0.475	

Table B-3. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #6

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Precutter & Nozzle	188	---	11.0	---
1	187	25.6	10.8	24.3
2	186	11.2	10.6	10.6
3	186	5.3	10.6	4.1
4	186	2.2	10.6	2.1
5	177	1.3	10.0	1.2
6	132	0.69	7.2	0.66
7	67.0	0.42	2.8	0.38
Filter	26.4	---	1.0	---
Sample Volume (DNm³)	0.099		0.602	

Table B-4. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #8

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Precutter & Nozzle	247	---	29.2	---
1	247	21.6	27.5	26.0
2	246	9.5	26.0	11.4
3	245	4.5	25.3	4.4
4	245	1.8	25.3	2.2
5	238	1.1	25.3	1.3
6	194	0.58	24.9	0.70
7	134	0.35	21.0	0.41
Filter	59.0	---	14.2	---
Sample Volume (DNm³)	0.134		0.466	

Table B-5. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #9

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (µmA)	M_{cum} (mg/DNm³)	d_{pc} (µmA)
Precutter & Nozzle	132	---	41.5	---
1	119	24.5	41.3	26.6
2	113	10.7	40.6	11.6
3	113	4.2	40.6	4.5
4	113	2.1	40.6	2.3
5	113	1.2	40.6	1.3
6	113	0.66	39.5	0.72
7	95.4	0.40	23.0	0.41
Filter	65.21	---	13.9	---
Sample Volume (DNm³)	0.106		0.438	

Table B-6. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #10

IMPACTOR STAGE NUMBER	INLET PRIME		INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (µmA)	M_{cum} (mg/DNm³)	d_{pc} (µmA)	M_{cum} (mg/DNm³)	d_{pc} (µmA)
Precutter & Nozzle	244	---	166	---	84.5	---
1	244	32.1	107	24.7	84.5	26.0
2	244	14.0	105	10.8	83.6	11.4
3	244	5.4	103	5.1	82.8	4.4
4	244	2.7	100	2.1	81.6	2.2
5	244	1.6	100	1.2	76.5	1.3
6	224	0.87	54.7	0.67	48.8	0.70
7	137	0.52	29.6	0.40	22.4	0.40
Filter	57.6	---	27.4	---	16.2	---
Sample Volume (DNm³)	0.045		0.044		0.353	

Table B-7. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #13

IMPACTOR STAGE NUMBER	INLET PRIME		INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Precutter & Nozzle	1789	---	953	---	56.6	---
1	1678	26.9	945	26.6	54.8	23.2
2	1651	11.8	938	11.7	53.7	10.2
3	1636	4.6	935	4.5	52.0	3.9
4	1569	2.3	923	2.3	50.2	2.0
5	1247	1.3	857	1.3	44.1	1.1
6	477	0.73	644	0.72	29.0	0.63
7	108	0.44	233	0.42	12.5	0.36
Filter	27.7	---	113	---	2.5	---
Sample Volume (DNm³)	0.115		0.088		0.279	

Table B-8. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #14

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Precutter & Nozzle	201	---	23.1	---
1	168	11.1	23.1	17.3
2	156	4.6	22.1	7.6
3	146	2.6	21.0	2.9
4	138	1.4	19.5	1.5
5	126	0.88	16.2	0.85
6	90.8	0.48	10.5	0.47
7	41.4	0.28	4.4	0.27
Filter	5.9	---	1.0	---
Sample Volume (DNm³)	0.051		0.771	

Table B-9. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #15

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Precutter & Nozzle	419	---	35.5	---
1	410	8.4	35.2	18.8
2	399	4.2	33.5	8.2
3	382	2.4	31.4	3.2
4	360	1.3	27.2	1.6
5	195	0.81	21.6	0.92
6	84.5	0.45	12.3	0.51
7	36.8	0.26	4.9	0.29
Filter	7.4	---	1.8	---
Sample Volume (DNm³)	0.054		0.554	

Table B-10. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #16

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Precutter & Nozzle	182	---	22.2	---
1	177	10.1	22.2	18.0
2	174	4.2	21.8	7.9
3	168	2.4	21.2	3.1
4	163	1.3	20.0	1.5
5	149	0.80	17.6	0.89
6	108	0.44	12.9	0.49
7	58.0	0.25	7.4	0.28
Filter	5.5	---	1.4	---
Sample Volume (DNm³)	0.036		0.933	

Table B-11. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #17

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Precutter & Nozzle	508	---	23.1	---
1	476	9.4	23.0	18.6
2	467	4.8	22.2	8.1
3	456	2.7	21.1	3.2
4	433	1.5	19.1	1.6
5	214	0.90	15.9	0.91
6	119	0.50	10.3	0.50
7	50.2	0.29	4.1	0.29
Filter	9.3	---	1.4	---
Sample Volume (DNm³)	0.054		0.876	

Table B-12. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #18

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (μmA)	M_{cum} (mg/DNm³)	d_{pc} (μmA)
Precutter & Nozzle	168	---	21.8	---
1	129	11.3	21.8	19.2
2	126	4.7	21.0	8.4
3	121	2.7	19.8	3.2
4	116	1.5	17.5	1.6
5	111	0.89	14.3	0.94
6	103	0.49	9.8	0.52
7	78.4	0.28	5.2	0.30
Filter	24.5	---	1.1	---
Sample Volume (DNm³)	0.061		0.943	

Table B-13. INLET AND OUTLET SAMPLE PARTICLE DATA FOR RUN #19

IMPACTOR STAGE NUMBER	INLET		OUTLET	
	M_{cum} (mg/DNm³)	d_{pc} (µmA)	M_{cum} (mg/DNm³)	d_{pc} (µmA)
Precutter & Nozzle	217	---	25.5	---
1	170	8.7	25.5	19.5
2	166	4.4	24.6	8.5
3	160	2.5	23.7	3.3
4	151	1.4	21.9	1.7
5	135	0.83	19.0	0.96
6	77.5	0.46	13.3	0.53
7	50.3	0.27	6.3	0.30
Filter	15.0	---	2.1	---
Sample Volume (DNm³)	0.074		0.663	

APPENDIX C

REGRESSION ANALYSIS SUMMARY

Table C-1. Analysis of Data - With Wall Wash

OBJECTIVE	DATA SAMPLED	RESULTS AND COMMENTS
1. Fit curve to eliminate effect of inlet particle loading on efficiency, η. Must meet initial conditions that at $X = 0$ $\eta = 0$, and at $X = \infty$, $\eta < 100$.	TRW DATA: 9N, 10N, 11N, 12N, 13N, 14N, 15N, 16N, D002, S1 * S2, S3, S4, S5, S6. ATP DATA: 10N, 11N, 12N, 13N, 15N.	$\eta = K_0(1 - e^{-K_1X})$, $K_0 = 89.1$, $K_1 = .008746$, $s(K_0) = 4.7$, $s(K_1) = .0013$, $s(R) = 8.9$. (See Figure 1) This curve is significantly different from the curve obtained without wall wash.
2. Determine additional reduction in residuals after correcting for inlet loading. Parameters considered were inlet gas temperature, outlet gas flow rate, and interaction.*** The outlet gas flow rate was corrected to standard dry condition.	TRW DATA ONLY.** (Same as No. 1 above)	Indicated addition correction for inlet gas temperature, T. The correction is $40.6 - .318T$. The standard error of residuals, $s(R) = 8.0$, was reduced to 6.4. (Completely opposite of results without wall wash)

* denotes screening tests.

** ATP data wasn't utilized because it was assumed that all input data was not available.

*** Electrode Voltage was eliminated via visual examination of the plots of the parameters versus the residuals.

Table C-2. Analysis of Data - Without Wall Wash

OBJECTIVE	DATA SAMPLED	RESULTS AND COMMENTS
1. Fit curve to eliminate effect of inlet particle loading, X, on efficiency, η. Must meet initial conditions that at $X = 0$, $\eta = 0$, and at $X = \infty$, $\eta < 100$.	TRW DATA: 1N, 2N, 4N, 5N, 6N, 7N, 8N, D003, D004, D006, D007, D008, D009, D010, D011, D012, D014, D015, D016, D019, D020, D021, D022, D023, D024, D025. ATP DATA: 2N, 4N, 7N,7N, 8N, 8N.	$N = K_0(1 - e^{-K_1 X})$, $K_0 = 93.5$, $K_1 = .014468$, $s(K_0) = .92$, $s(K_1) = .0009669$, $s(R) = 3.6$. (See Figure 2) This curve significantly different from the curve obtained with wall wash.
2. Determine addition reduction in residuals after correcting for inlet loading. Parameters considered* were inlet gas temperature, outlet gas flow rate and interaction. The outlet gas flow rate was corrected to standard dry condition.	TRW DATA: ** 1N, 2N, 4N, 5N, 6N, 8N, D006, D007, D008, D009, D010, D011, D012, D014, D015, D016.	Indicated additional correction for gas flow rate and interaction. The correction is 4.1 + .00057R - .000007RT The standard error of residuals, s(R) = 1.7 was reduced to 1.5. (Completely opposite of results with wall wash)
3. Determine additional reduction in residuals after correcting for inlet loading. Censured data. (η >90%, X >227 mg/m^3). Parameters considered were electrode voltage (stage 1 and stage 2), inlet gas temp and the actual measured flow rate at the prevailing ambient condition.	TRW DATA:*** 1N, 2N, 4N, 5N, 6N, 8N, D006, D007, D008, D009, D011, D014, D016 ATP DATA 15, 17.	Indicated additional correction for gas flow rate. The correction is 5.6 - .00029R. The standard error of residuals, s(R) = 1.76 was reduced to 1.57.

Table C-2. Analysis of Data - Without Wall Wash (Continued)

OBJECTIVE	DATA SAMPLED	RESULTS AND COMMENTS
4. Same as No. 3. except gas flow rate corrected to standard dry condition.	Same as No. 3.	No additional correction indicated.
5. Same as No. 3. except used actual efficiencies. It is assumed the censored data is in a region where inlet loading has a minimal effect.	Same as No. 3.	No additional correction indicated.
6. Same as No. 5. except used gas flow rate corrected to standard dry conditions.	Same as No. 3.	No additional correction indicated.

* Electrode Voltage was eliminated via visual examination of the plot of the parameters versus the residuals.

** ATP data wasn't utilized because it was assumed that all input data was not available.

*** All data obtained after 12/31/75 was deleted. Test equipment considered to be degraded.

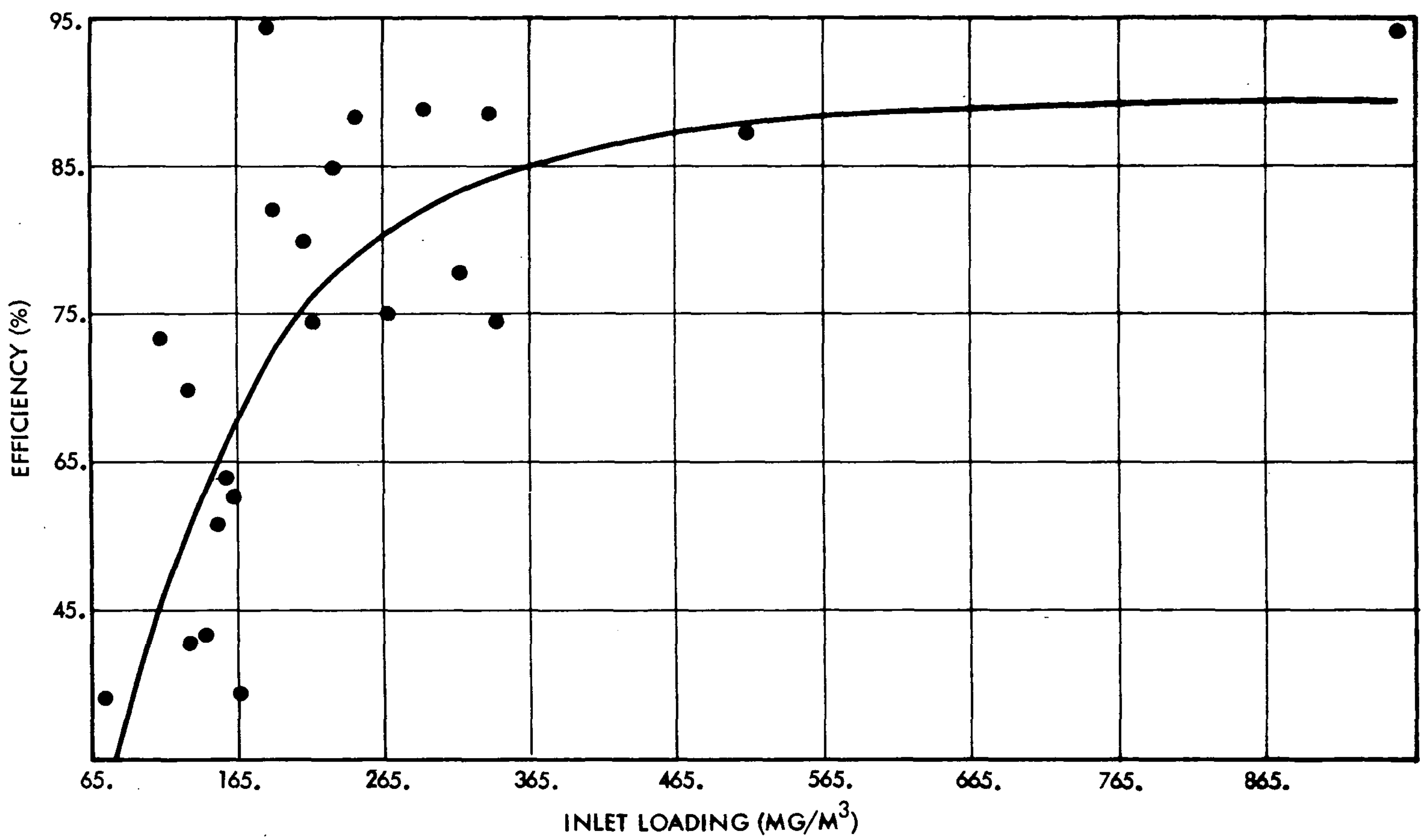

Figure C-1. Particle Loading Effect on Removal Efficiency With Wall Wash

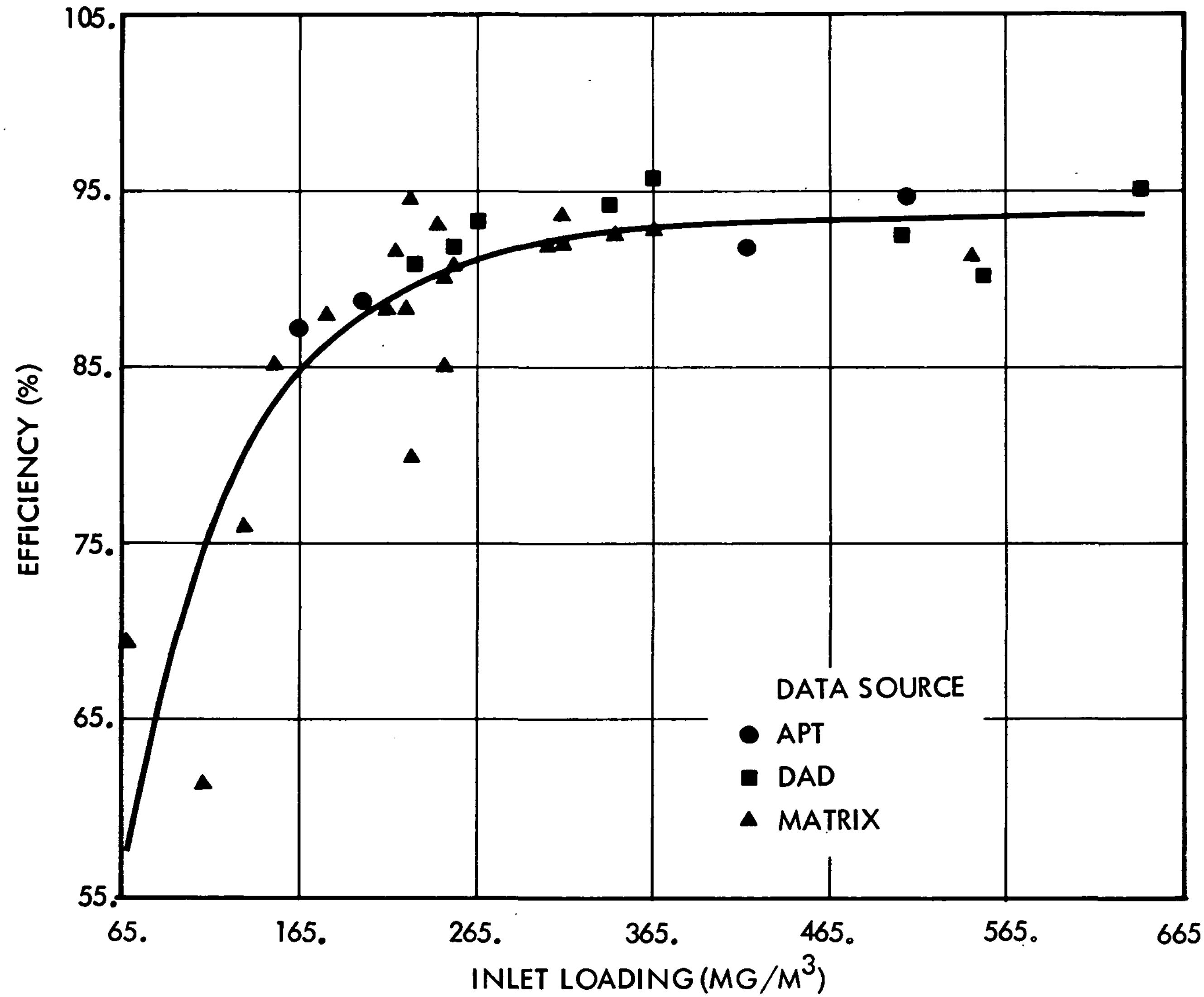

Figure C-2. Particle Loading Effect on Removal Efficiency Without Wall Wash

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

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16. ABSTRACT The report gives results of a successful Charged Droplet Scrubber (CDS) pilot demonstration of coke oven emissions control. It also describes the design, installation, and checkout of the demonstration system. The CDS uses electrically sprayed water droplets, accelerated through an electric field, to remove particulate material from a gas stream. The pilot demonstration was a continuation of laboratory and bench scale studies for application of the CDS to fine particle control. The pilot demonstration included, in addition to the CDS, the ducting, flow transitions, and blower necessary to circulate process gas through the CDS. The test was performed at the Kaiser Steel Company coke oven facility, Fontana, California. A large fraction of the coke oven emissions were submicron and composed of carbon particles and hydrocarbon aerosol. After the system checkout was completed, during which CDS operating parameters were established, the demonstration test series was performed. Results of the demonstration test indicate that the CDS is an effective pollution control device for controlling coke oven stack emissions.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Hydrocarbons	Air Pollution Control	13B	07C
Scrubbers	Aerosols	Stationary Sources	07A	07D
Dust		Particulate	11G	
Electrostatics		Charged Droplets	20C	
Coking		Charged Droplet Scrubber	13H	
Carbon			07B	

18. DISTRIBUTION STATEMENT
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19. SECURITY CLASS (This Report)
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20. SECURITY CLASS (This page)
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21. NO. OF PAGES
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22. PRICE

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