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ELECTROSTATIC PRECIPITATOR EFFICIENCY ON A MULTIPLE HEARTH INCINERATOR BURNING SEWAGE SLUDGE

by

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FOREWORD

The U. S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxic Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

The Water Engineering Research Laboratory must consider the possible effects of the release of toxic substances to the atmosphere from sewage sludge treatment processes such as incineration. The research project that is reported on herein was an investigation of the performance of an air pollution abatement system for controlling toxic metal and organics emitted from a sewage sludge incinerator.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

A pilot scale electrostatic precipitator (ESP) was evaluated for its removal performance for 23 metals and for sulfur containing particles when fitted to a multiple hearth incinerator burning sewage sludge. The small scale ESP was installed to take a slipstream of about three percent of the total incinerator emissions. Particle size fractions were collected from the gas streams entering and leaving the ESP. Each particle size fraction was analyzed for the 24 elemental species and ESP performance was evaluated for overall removal efficiency, size fraction removal efficiency, and for selective removal of specific metals. Total concentrations of each element in the controlled emission stream was determined as well as the proportionate concentrations of species in the solid and volatile states. Concentrations of each metal in the emission stream was compared with the concentrations in a sludge residue.

To obtain comparisons of ESP performance with a more typical emission control device, the performance of the incinerator's full scale wet scrubber was also evaluated.

This report was submitted in fulfillment of Contract No. 68-03-3148 by Radian Corporation under the sponsorhip of the U. S. Environmental Protection Agency. This report covers the period April 10, 1984, to September 30, 1985, and work was completed as of September 30, 1985.

UNIT CONVERSION FACTORS

cubic feet x 2.831685 E-02 = cubic meters (m^3)

degrees Fahrenheit. $t^oC = (t^oF - 32)/1.8$ = degrees Celsius (^oC)

feet x 3.048000 E-01 = meters (m)

gallons x 3.785412 E-03 = cubic meters (m^3)

inches x 2.540000 E-02 = meters (m)

pounds x 4.535924 E-01 = kilograms (kg)

pressure, inch of H_2O (60^oF) x 2.4884 E+02 = pascal (Pa)

pressure, inch of H_2O (32^oF) x 2.60932 E+01 = millimeter of Hg (mm Hg)

pressure, inch of Hg (60^oF) x 3.37685 E+03 = pascal (Pa)

square feet x 9.290304 E-02 = square meter (m^2)

FIGURES

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SECTION 1

INTRODUCTION

OBJECTIVES

A research project was undertaken to determine the particulate removal efficiency of an electrostatic precipitator (ESP) dust removal system on a multiple hearth furnace burning sewage sludge. Of particular interest was the fate of metals found in a city/industrial type of sludge that was incinerated and subjected to ESP air pollution control. A pilot-scale ESP was temporarily fitted to an existing multiple hearth furnace burning sewage sludge. A slipstream of incinerator exhaust gas was taken from the top hearth of the incinerator. This afforded an opportunity to compare ESP performance with the particulate removal performance of the incinerator's wet scrubber. Volatile organic emissions were measured at both incinerator and wet scrubber discharges, and these results are included in a separate report.

The test was conducted at a treatment plant that receives sewage sludge from an industrialized urban area. The sludge feed had been digested and dewatered. The test duplicates a test program to determine the particulate removal efficiency of a fabric filter dust removal system. The same incinerator was used for the ESP test program. Based on the ESP removal efficiency data obtained, a cost estimate for a full-scale ESP installation was prepared (Section 6).

PROCESS DESCRIPTION

A schematic diagram of the incinerator and wet scrubber system is shown in Figure 1. The host plant operates two multiple hearth sewage sludge incinerators (designated by the plant as the No. 1 and No. 2 units). The incinerators are not operated simultaneously. Typically, one of the incinerators burns sludge at 100 percent capacity for 2 to 3 weeks, followed by a 7 to 10 day period of no burning. The alternate incinerator is generally used when the next "burn cycle" begins. The No. 1 unit will be tested in this program. It is a six-hearth incinerator designed by Envirotech with a capacity of 3,400 kg/hr wet sludge.

Digester underflow from the host sewage treatment plant is dewatered by centrifuge. The dewatered sludge fed to the incinerator typically has a solids content of 16 to 17 percent. Sludge was sampled at sampling position No. 1 (see Figure).

The heating value of the sludge is not sufficient to promote autogenous burning. Approximately 100,000 ft^3/day of digester gas and 400 gal/day of No. 2 fuel oil are burned in the incinerator along with the sludge. The digester gas is produced by an anaerobic sludge digestion process at the host plant,

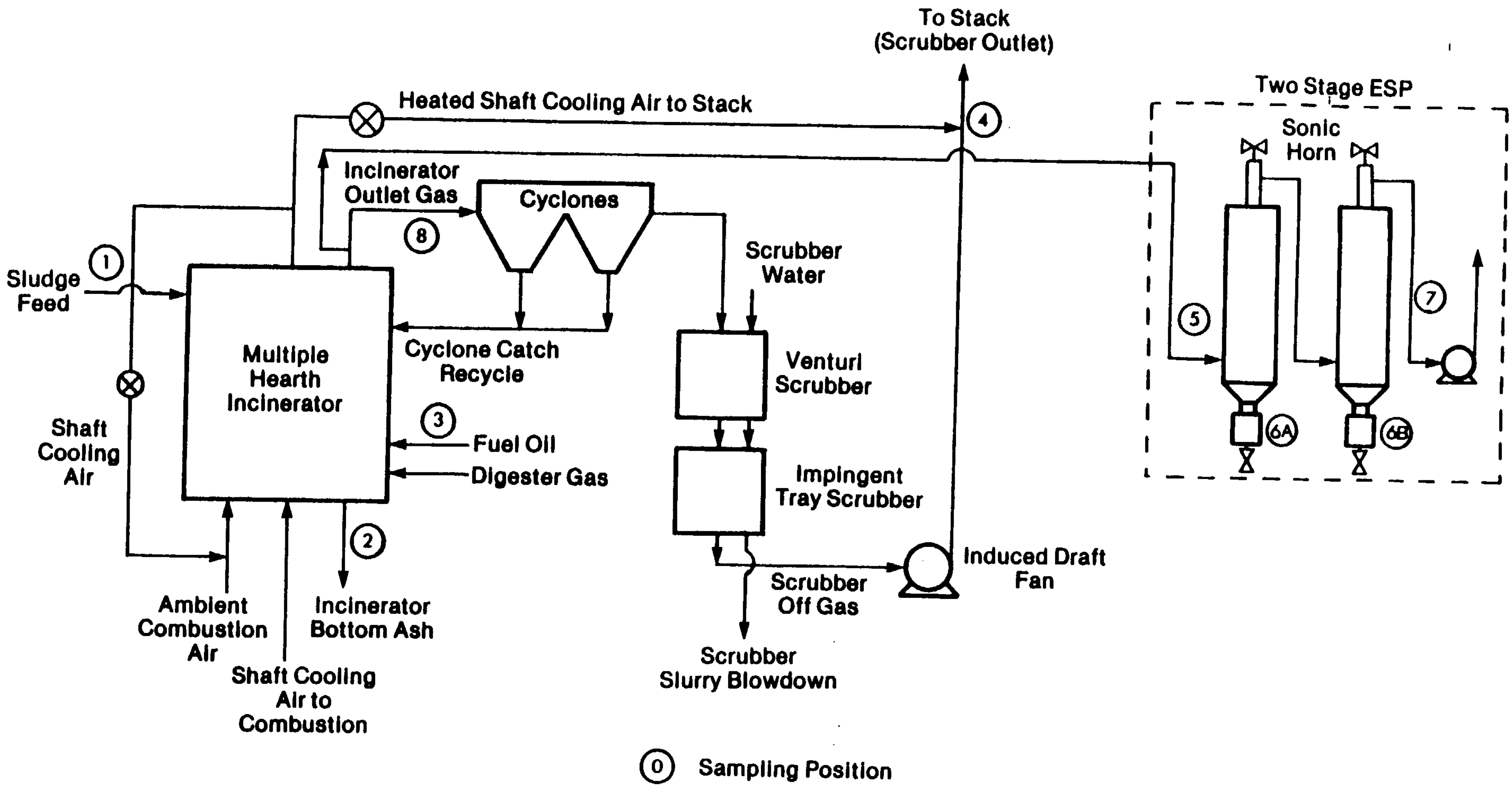


Figure 1. Schematic Diagram of the Incinerator System

and the No. 2 fuel oil is purchased off site. The fuel-firing rates are adjusted to maintain the desired temperature profile within the incinerator. The target temperature for the gas leaving the upper hearth (Hearth No. 1) is $380^{o}C$, and the range of temperatures typically measured for the gas leaving the upper hearth is 315 to $480^{o}C$. Excursions as high as $760^{o}C$ are possible when the burning pattern in the incinerator is out of control. Based on the fabric filter test results, it was anticipated that the temperature of the gas leaving the incinerator would be in the 315 to $480^{o}C$ range during the test program. Continuous sampling for O_2, CO, NO_x, SO_2 and THC of the exit gas occurred at sampling position No. 8.

Combustion air fed to the incinerator can be either at ambient temperature or a preheated temperature, depending on operator preference. The preheated combustion air is supplied by recycling the heated air leaving the shaft cooling system. The design flow of the shaft cooling air is approximately 5000 scfm. The amount of combustion air fed to the incinerator varies with sludge feed rate, fuel flow rate, opacity limitations, furnace draft, and other operating parameters. Typically, the oxygen content of the flue gas at the incinerator outlet (i.e. breeching) is 13 to 17 percent O_2 (wet basis). Lower excess air levels are not achievable because of the onset of significant opacity when the oxygen content is less than 13 to 17 percent O_2. The incinerator is limited to 20 percent opacity by the Federal New Source Performance Standards (NSPS) for sewage sludge incinerators. Furnace draft at the breeching outlet is maintained at -0.15 in W.C.

Bottom ash produced during sewage sludge incineration is screw-conveyed out of the incinerator into a bucket elevator, which carries the ash about 40 ft vertically. The ash is then screw-conveyed from the bucket elevator to a large hopper that is used for intermediate storage before disposal. Design specifications for the incinerator indicate that approximately 250 kg/hr (550 lb/hr) of bottom ash are produced when the feed rate is 3,400 kg/hr (7,500 lb/hr) wet sludge. The bottom ash was sampled at the chute discharging to the hopper (sampling position No. 2).

Emissions from the tested incinerator are controlled by two cyclones in series with a water quench unit, a venturi scrubber, and an impingement tray scrubber. Plant measurements indicate that the cyclones capture about 3.5 kg particulate matter per 1,000 kg of dry solids fed to the incinerator. The particulate matter captured by the cyclones is screw-conveyed directly back into the incinerator.

Exhaust gases from the cyclones pass through a water spray cooling section in the ductwork and are then sent to the venturi and impingement tray scrubbers. The scrubber water system used primary clarifier water that was used once in the scrubber system and sent back to the treatment plant inlet after use. The scrubber system uses a total of approximately 4,500 m^3 (1.2 million gallons) of treatment plant effluent per day. Approximately two-thirds of this water is added to the impingement tray scrubber, and most of the remainder is added to the venturi scrubber. The spray cooler preceding the venturi scrubber and another spray cooler perceding the impingement tray scrubber use about 7 percent of the total scrubber system water. The overall ratio of scrubber water to incinerator exhaust gas (i.e., liquid-to-gas ratio) is approximately 0.025 m^3 water/dscm exhaust gas (0.2 gal/dscf). Pressure drops across the venturi and impingement tray scrubbers are typically 28 and 9 mm Hg (15 and 5 in H_2O), respectively. Exhaust gas exits the scrubber system at a temperature of approximately 27°C (80°F). The exhaust gas is pulled through an induced-draft fan, combined with any shaft cooling air that is not used as preheated combustion air, and sent out a stack. The current rated capacity of the induced-draft fan is 190 acmm at 54°C and 84 mm Hg (6,800 acfm at 160°F and 45 in H_2O).

The scrubber operating data include venturi scrubber and impingement tray scrubber pressure drops (in H_2O), venturi scrubber inlet gas temperature (°F), and induced draft (ID) fan inlet temperature (°F). Because of the proximity of the ID fan to the impingement tray scrubber outlet, the ID fan inlet temperature is essentially the same as the impingement tray scrubber outlet temperature.

PROCESS DATA MONITORED BY THE HOST PLANT

Process data monitored continuously by the host plant include data on both the incinerator and on the venturi/impingement tray scrubber system. The incinerator operating data include wet sludge feed rate (lb/hr), flue gas oxygen content at the breeching outlet (% O_2 wet), furnace draft at the breeching outlet (in W.C.), temperatures at each hearth (°F), and shaft cooling air outlet temperature (°F). The scrubber operating data include venturi scrubber and impingement tray scrubber pressure drops (in H_2O), venturi scrubber inlet gas temperature (°F) and induced (ID) draft fan inlet temperature (°F). Because of the proximity of the ID fan to the impingement tray scrubber oulet, the ID fan inlet temperature is essentially the same as the impingement tray scrubber outlet temperature.

In addition to the continuously operating parameters, the host plant performs daily sewage sludge analysis. The percent solids and the percent volatile solids are measured daily on a 24-hour composite sludge feed sample. The sample is a composite of hourly samples taken off the sludge feed belt leading to the incinerator.

TEST INSTALLATION

A slipstream was taken from the incinerator exhaust ducting and fed to a two-stage ESP. Gas flow was maintained by a fan located downstream of the ESP stages.

Pilot-Scale ESP

The tubular ESP was comprised of two stages oriented in series (Figure 2). The equipment vendor is Beltran Associates, Inc. Either wet or dry collection is possible, and dry collection was used during this test program. Each stage consists of nine (9) square tubes 4 x 4 x 48 in. long. A 3/8 in. ionizing rod is located at the center of each tube. The rod can be fitted with ionizing stars or repelling cylinders depending on efficiency requirements. In the first pass, current suppression can occur because of high particle loading. Therefore 22 ionizing stars were used. In the second pass, six stars and two repelling rods were used.

The two ESP stages and the I.D. fan were connected with 8 in. stainless steel duct. The ductwork and the ESP's were insulated with 6 in. fiberglass batts.

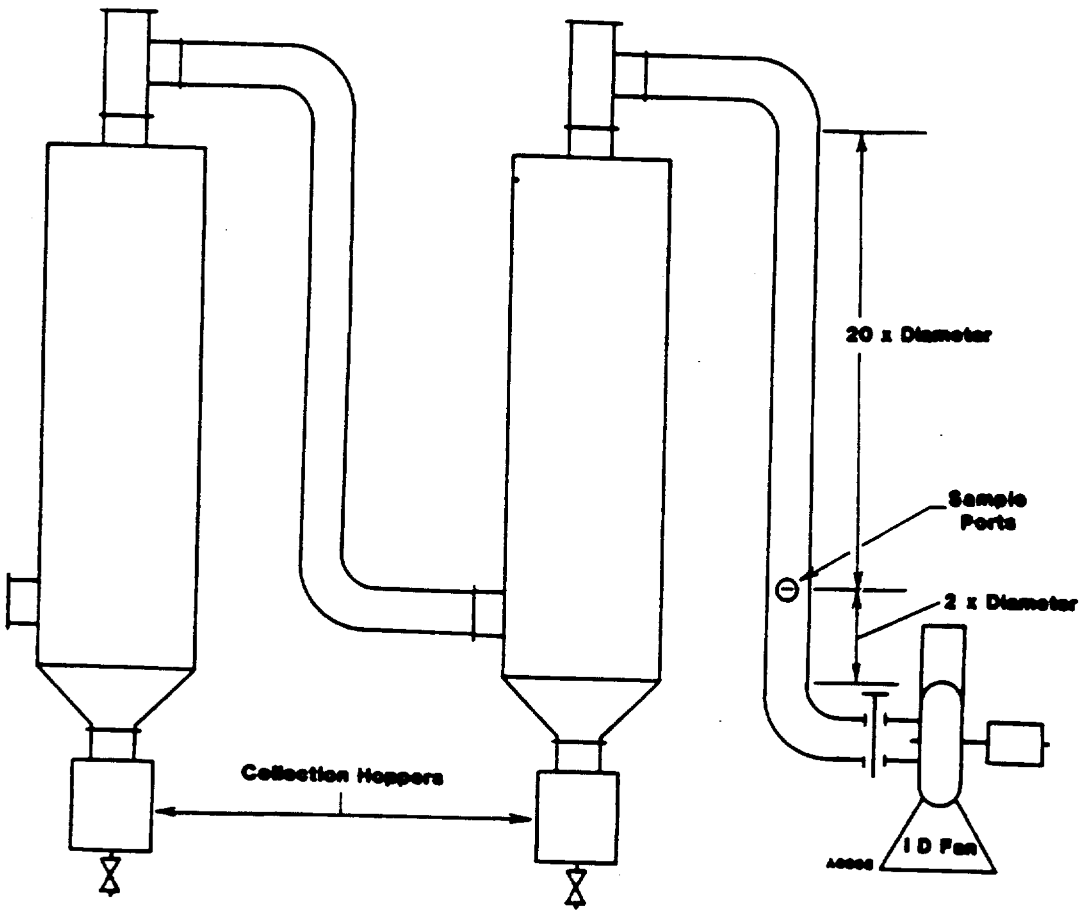


Figure 2. Two-Stage Tubular ESP.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The test program demonstrated the viability of using operating sewage sludge incinerators as sources of typical emission streams to evaluate various types of emission controls. In particular, comparisons can be made with the installed emissions control device. Also, true physical and chemical profiles of incinerator emissions at actual operating conditions are available.

The test program focused on evaluating the performance of an ESP for the emissions control of 23 individual metals. The 23 target metals, including toxic and non-toxic metals, and sulfur were detected in the sludge feed in quantifiable amounts except for selenium and silver. However these two metals were detected in the emissions streams. Specific information regarding emissions concentration, removal performance of the ESP, particle size distribution, and enrichment for the 23 individual metals and sulfur are reported.

As a group the elements that contributed nearly 90 percent of the weight of the species analyzed in the sludge also dominated the same mixture in the uncontrolled emissions stream. The group included five non-toxic metals (calcium, iron, aluminum, magnesium, phosphorus) and sulfur. However, selective removal by the ESP and wet scrubbing concentrates other metals in the particle emission stream so that the five metals cited above no longer continue to provide the bulk of the emissions.

The concentrations of total particulate matter in the emissions from the ESP and from the wet scrubber were similar. Particle emissions from ESP were 12 mg/dscm versus 15 mg/dscm from the scrubber. These include only the dry particles collected in the sampling train. Negligible amounts of the target metals were emitted from the ESP in the volatile state or as aerosols penetrating the sampling train filter. Volatile species were collected in low temperature impingers containing dilute nitric acid. Slightly higher concentrations of volatile metals, amounting to only about one percent of the sulfur free target metals, were found in the scrubber emissions.

ESP data are reported for only the third run of a three run series. ESP particulate matter emissions were substantially higher during the first two runs due to higher throughput and lower temperatures in the ESP. The high throughput and subsequent temperature effect resulted from the injection of purge air across the electrode insulators. This procedure was abandoned for the third run.

Both ESP and scrubber removal efficiencies were about 98 percent. Both the ESP and the wet scrubber removed virtually all of the particles between one micron and ten micron aerodynamic diameter. The ESP removed 93 percent of the particles greater than ten micron diameter and less than one micron diameter. The wet scrubber removed 97 percent of the particles of the same size despite only 9 percent removal efficiency of particles less than one micron diameter.

Individual metal concentrations in the ESP were not proportional to individual concentrations of these metals in the sludge. Enrichment, the concentration of a metal in an emission stream divided by the concentration of the metal in the sludge residue after heating the sludge to 550°C, played a role in reordering the concentrations of the metals. An enrichment ratio of one indicates a concentration proportional to that in the sludge. Metals in the ESP emissions with enrichment ratios between two to one and eight to one were barium, lead, tin, and chromium. Overall enrichment ratios were substantially lower than was found during a companion evaluation of a fabric filter.

Very small quantities of only five metals were detected in the impinger catch of the sampling train. Only Run 3 was considered. Therefore, volatile target metal emissions impacted the atmosphere to only a negligible extent. Volatile target metals in the scrubber emissions were slightly higher on the average but were inconsistent from day to day.

RECOMMENDATIONS

Further resolution of size fractions below one micron diameter is recommended to more thoroughly evaluate selective removal of trace metals according to particle size. As emission controls with higher removal efficiencies are evaluated, a more thorough investigation of submicron particles is warranted regarding their metals concentrations.

SECTION 3

PRESENTATION OF RESULTS

The results of the test program are presented in this section. Three test runs (Runs 1-3) were performed during which emissions testing was conducted simultaneously at the ESP inlet location (i.e., incinerator outlet), the ESP outlet location, and the scrubber outlet location.

PROCESS DATA

Process data were monitored to document the operating conditions of the incinerator, the ESP, and the wet scrubber system during the test runs.

Incinerator Operating Data

Mean incinerator operating parameters are presented in Table 1. The data show that the incinerator was operated similarly during the three test runs. The mean wet and dry sludge feed rates were 3,557 lb/hr and 550 lb/hr, respectively. The maximum deviation from the average for any one run was only 5 percent for both the wet and dry sludge feed rates. With a capacity of 7,500 lb/hr wet sludge, the incinerator was operated at 50 percent of full capacity.

The moisture content and the volatile solids content of a 24-hour composite sludge feed sample were measured. The data indicate that these sludge feed characteristics were uniform between runs. The mean value for the percent moisture was 84.5, while the mean value for the percent volatile solids was 68.3. For both parameters, there was less than 2 percent deviation from the average between runs.

The elemental compositions of the ashed sludge feed samples are presented in Table 2. Twenty-four species were included in the analysis. The total metals content of the dry, volatiles-free sludge feed is obtained by summing the concentrations of the twenty-four metals in a given run. The data show that the total metals content increased with each run. These values were 26.7 wt.%, 29.6 wt.%, and 32.8 wt.% for Runs 1-3, respectively. The average relative standard deviation of the total metals detected was 10.26. Table 3 provides a ranking of the metals in the sludge feed by the average concentrations for Runs 1-3. Based on the average metals content, Aluminum, Calcium, Iron, Magnesium, Phosphorous, and Sulfur were present in the highest concentrations. This group of metals accounted for 88 percent by weight of the species analyzed for. On an individual species basis, it is apparent that Antimony, Gold, and Nickel displayed significant between-run variability. The relative standard deviations of these metals were 33, 173, and 114 percent, respectively. The large relative standard deviation for Gold can be discounted because Gold was not detected in the sludge feed for

TABLE 1. MEAN INCINERATOR OPERATING PARAMETERS DURING ESP TESTS

Parameter	Run 1	Run 2	Run 3	Average
Sludge Feed Rate (lb/hr)				
Wet Cake	3,750	3,460	3,460	3,557
Dry Cake	581	536	533	550
Residue at 600°C	180	172	171	174
Sludge Composition (wt. %)				
Moisture	84.5	84.5	84.6	84.5
Volatile Matter	69.0	68.0	68.0	68.3
Dry Solids	15.5	15.5	15.4	15.5
Percent O_2[a] (Dry Vol. %)	15.1	14.5	14.0	14.5
Auxiliary Fuels				
Fuel Gas (cu ft/hr)	5,060	3,900	3,400	4,120
Fuel Oil (gal/hr)	11.0	16.0	14.0	13.7

[a]Mean excess oxygen in incinerator emissions.

Table 2. ICAP Analyses of the Sludge Feed Samples

	METALS CONTENT OF SLUDGE FEED PPM				
METAL	RUN 1	RUN 2	RUN 3	AVERAGE	REL STD
ALUMINUM	3.01E+04	3.93E+04	4.94E+04	3.96E+04	24.43
ANTIMONY	1.50E+02	1.35E+02	7.51E+01	1.20E+02	33.10
ARSENIC	7.04E+02	6.85E+02	7.98E+02	7.29E+02	8.32
BARIUM	2.62E+03	2.33E+03	2.37E+03	2.44E+03	6.30
CADMIUM	2.88E+02	2.14E+02	1.95E+02	2.33E+02	21.18
CALCIUM	5.20E+04	6.59E+04	7.89E+04	6.56E+04	20.47
CHROMIUM	7.41E+02	7.28E+02	8.61E+02	7.77E+02	9.41
COBALT	6.25E+01	5.54E+01	5.47E+01	5.76E+01	7.51
COPPER	5.25E+03	5.07E+03	5.67E+03	5.33E+03	5.79
GOLD	0.00E+00	9.81E-01	0.00E+00	3.27E-01	173.21
IRON	5.52E+04	5.86E+04	6.70E+04	6.03E+04	10.10
LEAD	9.40E+02	1.02E+03	1.01E+03	9.92E+02	4.61
MAGNESIUM	2.23E+04	2.46E+04	2.40E+04	2.37E+04	5.03
MANGANESE	4.01E+02	4.39E+02	4.90E+02	4.43E+02	10.02
NICKEL	3.27E+02	2.44E+02	1.95E+03	8.40E+02	114.38
PHOSPHOROUS	5.53E+04	5.42E+04	5.14E+04	5.36E+04	3.77
SELENIUM	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00
SILVER	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00
SODIUM	7.57E+03	7.68E+03	8.30E+03	7.85E+03	5.05
SULFUR	1.86E+04	2.06E+04	1.94E+04	1.95E+04	5.24
TIN	4.67E+02	4.18E+02	4.39E+02	4.41E+02	5.60
TITANIUM	7.12E+03	6.43E+03	7.66E+03	7.07E+03	8.73
VANADIUM	1.95E+02	2.06E+02	2.35E+02	2.12E+02	9.90
ZINC	6.57E+03	7.44E+03	7.64E+03	7.22E+03	7.94
TOTAL:	2.67E+05	2.96E+05	3.28E+05	2.97E+05	10.26

$$\text{Relative standard deviation} = \frac{\text{std. dev.}}{\text{mean}} \times 100$$

TABLE 3. RANKED LIST OF METALS IN SLUDGE FEED

Species	Concentration in Sludge (ppm, dry volatiles-free basis)
Species Present at 10^4 ppm (dry, volatiles-free basis)	
Calcium	6.56×10^4
Iron	6.03×10^4
Phosphorous	5.36×10^4
Aluminum	3.96×10^4
Magnesium	2.37×10^4
Sulfur	1.95×10^4
Species Present at 10^3 ppm (dry, volatiles-free basis)	
Sodium	7.85×10^3
Zinc	7.22×10^3
Titanium	7.07×10^3
Copper	5.33×10^3
Barium	2.44×10^3
Species Present at 10^2 ppm	
Lead	9.92×10^2
Nickel	8.40×10^2
Chromium	7.77×10^2
Arsenic	7.29×10^2
Manganese	4.43×10^2
Tin	4.41×10^2
Cadmium	2.33×10^2
Vanadium	2.12×10^2
Antimony	1.20×10^2
Species Present in Trace Quantities	
Cobalt	5.76×10^1
Gold	3.27×10^{-1}
Silver	Not Detected
Selenium	Not Detected

two of the three runs. Likewise, the analytical validity of the concentration readings for Antimony are suspect. Analysis of the NBS Coal Fly Ash Standard on the ICAP spectrometer shows significantly higher levels of Antimony than predicted by the NBS. In two of the standards analyzed, 16 and 26 g of Antimony were detected as compared to the NBS' values of 3 and 6 g, respectively. Even though Nickel varied significantly between runs, Table 3 shows that it was one of the species with a low concentration, approximately 10^2 ppm. The other high-hazard metals, arsenic, cadmium, chromium, lead, and selenium, were also all within the 10^2 ppm concentration range except selenium. Selenium concentration was below the detectable limit.

Gas produced by the anaerobic digester and No. 2 fuel oil were burned in the incinerator as auxiliary fuels. The auxiliary fuel (digester gas and fuel oil) firing rates shown in Table 1 represent an average of hourly readings taken during the testing periods. The average fuel gas firing rate was 4,120 cu ft/hr, while the average fuel oil firing rate was 13.7 gal/hr. Run 1 displayed the most significant deviation from these averages with fuel gas and fuel oil firing rates of 5,060 cu ft/hr and 11.0 gal/hr, respectively. These values correspond to deviations of approximately 20 percent from the average fuel gas and fuel oil firing rates.

A complete set of mean hearth temperatures are shown in Table 4. In the top hearths of the incinerator, hearths 1 and 2, the temperature profiles did not vary significantly between runs. An average temperature of 734°F (390°C) was measured on hearth 1, while 1159°F (626°C) was measured on hearth 2. In both cases, the maximum deviation from the average temperature was only 3 percent for any run. In hearth 3, the main combustion zone, the temperatures between runs varied similarly with a maximum deviation of 3 percent from the average temperature, 1381°F (749°C). The two hearths below the main combustion zone displayed larger differences between runs. On hearth 4, the values ranged from a low of 1137°F (614°C) to a high of 1303°F (706°C). On hearth 5, the values varied from a low of 402°F (206°C) to a high of 559°F (293°C), corresponding to a maximum deviation for any run of 16 percent from the average (Run 1). On hearth 6, the cooling zone, the temperatures were very consistent between runs, with a maximum deviation for any run of only 4 percent from the average temperature, 115°F (46°C).

In summary, the incinerator was operated similarly during the three test runs in terms of sludge feed rate, sludge characteristics and primary combustion zone temperature. Some between-run differences were observed in the individual metals concentrations and in the individual hearth temperatures below the primary combustion zone.

Distribution of Exhaust Gas

To evaluate ESP performance, a slipstream of incinerator exhaust gas was taken upstream of the incinerator's full scale particulate control system (dry cyclones followed by a venturi scrubber and an impingement tray scrubber). Flue gas flow rates and oxygen compositions were measured at the ESP inlet, ESP outlet, and scrubber outlet locations. The flow rates of the scrubber inlet gas stream and the shaft cooling air stream were calculated using a material balance of the overall gas flow rates and oxygen compositions for the entire system. The flow distribution of the various gas

TABLE 4. MEAN HEARTH TEMPERATURES DURING ESP TEST RUNS

Hearth Temperature	Mean Hearth temperature (°F)[a] Run 01	Run 02	Run 03	Average
1	749	742	711	734
2	1,128	1,170	1,178	1,159
3	1,339	1,377	1,426	1,381
4	1,137	1,189	1,303	1,210
5	402	469	559	477
6	112	113	120	115

[a]To convert from °F to °C use the formula °C = (°F - 32)/1.8.

streams is shown on Figure 3. The slipstream for the pilot scale ESP accounted for about 3 percent of the total incinerator exhaust gas. Flow rates for the 3 test runs are reported in Table 5. The average gas flow rate from the incinerator was 116 dscmm (296 acmm). The average inlet flow rates to the ESP and scrubber units were 3 dscmm (8 acmm) and 113 dscmm (288 acmm), respectively. The average outlet flow rates were 7 dscmm (11 acmm) and 226 dscmm (263 acmm), respectively. The increase in flow rate from ESP inlet to ESP outlet occurred as a result of air inleakage, as explained above. The increase in flow rate from the scrubber inlet to the scrubber stack was due to the addition of the shaft cooling air stream. Dry gas flow rates at the stack were nearly double the scrubber inlet flow rates.

ESP Operating Data

The ESP consisted of a two-stage tubular unit: exhaust gas from the first unit was passed to the inlet of the second unit. Dry collection was employed during the test program. A sonic horn was used to loosen the particles from the collector plates.

Mean ESP system operating data during the test runs are presented in Table 6. The specific collection area for the system was calculated by dividing the unit's total surface area (8.9 m^2) by the total inlet flue gas flow rate for a run. The specific collection area varies with the flue gas flow rates. The flue gas flow rates at the ESP inlet ranged from 7.86 acmm during Run 1 to 8.51 acmm during Run 3. The outlet gas flow rates were less consistent, ranging from a low of 8.38 acmm during Run 3 to a high of 12.51 acmm during Run 2. The ESP was operated at negative pressure and was not air tight. Also, the ESP vendor requested that an air purge be kept on the electrode insulators which added to the air dilution. After Run 2, the air purge was discontinued. Gas temperatures decreased significantly from inlet to outlet of the ESP as a result of the air dilution effects and from radiation losses. Purge air was not used during Run 3 and the gas flow out of the ESP decreased to 69 percent of average outlet gas flows for Runs 1 and 2. Nevertheless, gas temperature at the outlet of the ESP was not significantly higher during Run 3.

The average flue gas temperature at the ESP inlet was 525°F (274°C), while the average temperature at the outlet was 177°F (81°C). The average power supplied to the first stage of the ESP unit ranged from 114 kW to 212 kW, while the average power supplied to the second stage ranged from 137 kW to 194 kW. The average pressure drop across the ESP unit was 0.07 in H_2O (0.02 kPa).

Scrubber Operating Data

Mean scrubber system operating data during the test runs are presented in Table 7. The pressure drop data across the venturi and impingement tray scrubbers indicate some within run variations. The mean pressure drop across the venturi scrubber ranged from 14 in H_2O (3.5 kPa) to 18.5 in H_2O (4.6 kPa), with a maximum deviation from the average of about 15 percent. Since the water intake valve was set at a constant opening for all three test runs, oscillations in the following parameters could potentially have affected the pressure drop: water flow rate, flue gas flow rate, and blockage of orifice by particulate matter. The pressure drop across the

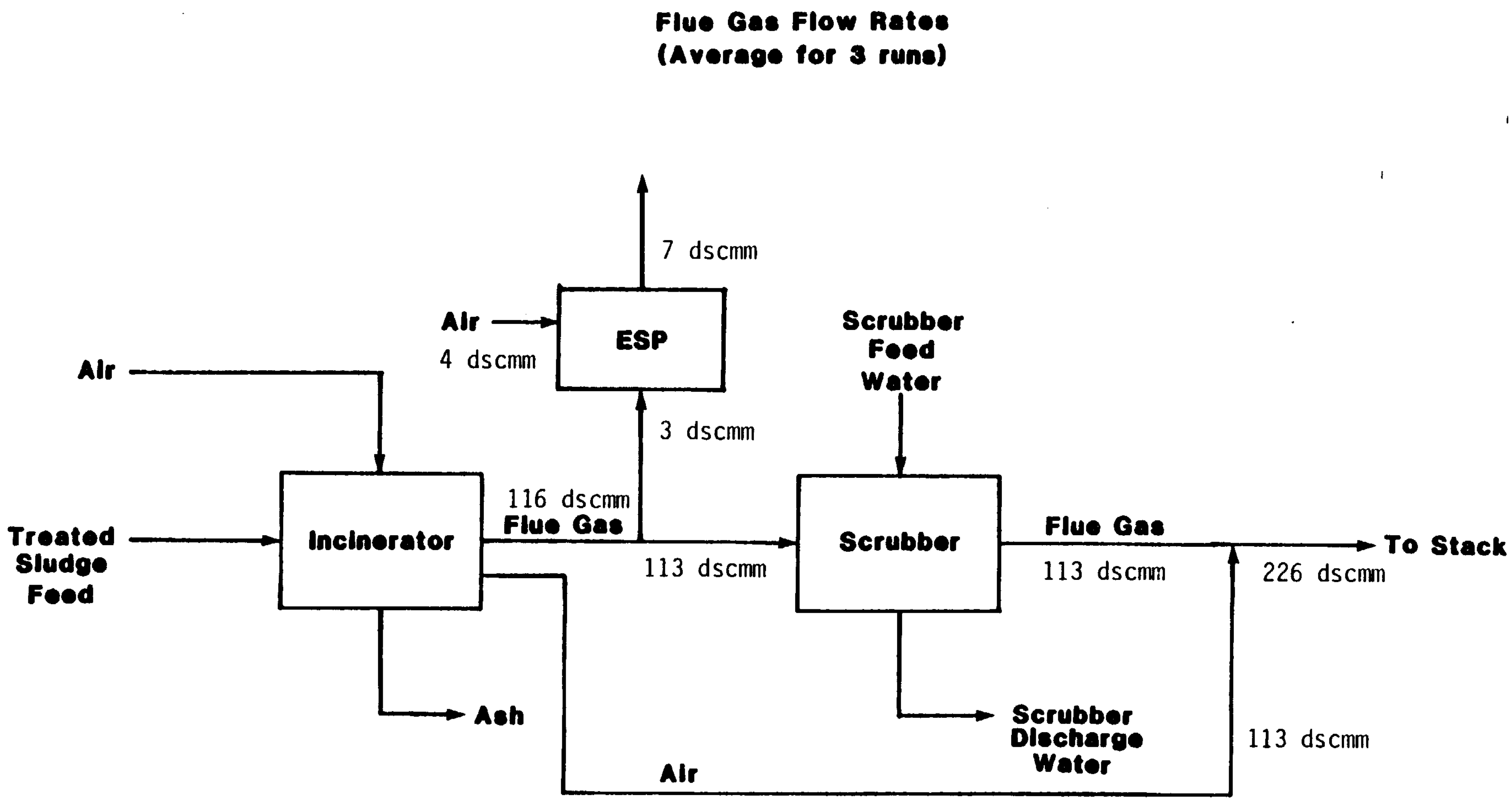


Figure 3. Distribution of Incinerator Exhaust Gas Between the Scrubber and ESP

TABLE 5. FLUE GAS FLOW RATES

Location	dscmm	acmm
Incinerator Outlet[a]		
Run 1	116.17	309.74
Run 2	100.10	259.34
Run 3	130.58	317.85
Average	115.62	295.64
Scrubber Inlet[a]		
Run 1	113.22	301.87
Run 2	97.05	251.43
Run 3	127.08	309.33
Average	112.45	287.54
Scrubber Outlet[b]		
Run 1	223.43	256.93
Run 2	231.08	267.60
Run 3	222.63	263.61
Average	225.71	262.71
Slipstream to ESP		
Run 1	2.95	7.86
Run 2	3.05	7.91
Run 3	3.49	8.51
Average	3.17	8.09
ESP Outlet		
Run 1	7.70	10.61
Run 2	8.92	12.50
Run 3	5.70	8.38
Average	7.44	10.50
Scrubber Outlet/Incinerator Outlet		
Run 1	1.92	.83
Run 2	2.31	1.03
Run 3	1.70	.83
Average	1.98	.90
Slipstream to ESP/Incinerator Outlet		
Run 1	.025	.025
Run 2	.031	.031
Run 3	.027	.027
Average	.028	.028

[a]Calculated from scrubber outlet flow measurements and oxygen balance across scrubbers.
[b]Includes shaft cooling air.

TABLE 6. MEAN ESP OPERATING PARAMETERS

Parameter	Run 1	Run 2	Run 3	Average
Specific Collection Area (m^2/acmm)	1.13	1.13	1.05	1.10
Flue Gas Flow Rates (acmm)				
Inlet	7.86	7.91	8.51	8.09
Outlet	10.61	12.51	8.38	10.50
Flue Gas FLow Rates (dscmm)				
Inlet	2.95	3.05	3.49	3.17
Outlet	7.70	8.92	5.70	7.44
Flue Gas Temperatures (^oF)				
Inlet	541	535	498	525
Outlet	176	176	179	177
Power Supplied (kW)				
Pass 1	111-264	112-265	120-286	114-272
Pass 2	133-184	134-190	144-204	137-194
ESP Pressure Drop (in H_2O)	0.07	0.07	0.06	0.07
Percent O_2 (dry Vol. %)				
Inlet	15.1	14.5	14.0	14.5
Outlet	19.6	19.7	16.7	18.7

TABLE 7. MEAN SCRUBBER OPERATING PARAMETERS DURING ESP TESTS

Parameter	Run 1	Run 2	Run 3	Average
Scrubber Pressures (in H_2O)				
Venturi ΔP	18.5	16.4	13.9	16.3
Impinger ΔP	4	3.8	3.5	3.8
Total ΔP	22.5	20.2	17.4	20.1
Scrubber Gas Temperatures (^{o}F)				
Inlet	748.4	741.7	701.0	730.4
Outlet	61.4	62.2	61.8	61.8
Scrubber Water Flow (gpm)	807	807	807	807
Flue Gas Flow Rates				
Inlet (dscmm)	113.2	97.1	127.1	112.5
Outlet (dscmm)	223.4	231.1	222.6	225.7
Inlet (acmm)	301.8	251.8	309.38	287.6
Outlet (acmm)	256.9	267.6	263.6	262.7
Percent O_2[a] (dry Vol. %)				
Inlet	15.1	14.5	14.0	14.5
Outlet	18.0	18.3	17.0	17.8
Water Vapor Composition of Stack Gas (% Moisture)				
Inlet	28.45	26.80	25.14	26.80
Outlet	1.14	0.83	0.97	0.98

impingement tray scrubber showed less variation with values ranging from 3.5 in H_2O (.87 kPa) to 4 in H_2O (.99 kPa). The total estimated scrubber water flow of 807 gpm (3.1 cu meter/min) was distributed as follows: pre-cooler, 33 gpm (0.1 cu meter/min); venturi scrubber, 247 gpm (0.9 cu meter/min); impingement tray scrubber, 27 gpm (0.1 cu meter/min); and impingement tray scrubber trays, 500 gpm (1.9 cu meter/min). The calculated liquid to gas ratio was 0.20 gal/dscf (0.03 cu meter/dscm). The mean scrubber outlet temperature was 62°F (17°C) for all three runs. After dilution with shaft cooling air, the flow rate of the gas stream exhausted to the atmosphere averaged 226 dscmm (263 acmm).

PARTICULATE EMISSIONS DATA

Total particulate emissions data for the scrubber and ESP were developed using the SASS train to compare the removal efficiencies of the two control devices. The SASS train selectively captures particles according to their aerodynamic diameter; this enables removal efficiencies to be calculated on the basis of size.

Total Particulate Emissions

Total particulate mass concentrations and mass emission rates are presented in Table 8 and Figure 4. These concentrations have been corrected to a level of 12 percent oxygen to normalize for the air inleakage to the ESP and for the mixing of shaft cooling air with the scrubber exhaust gas. Both the as-measured and corrected values are reported. Since the exhaust gas from the incinerator is split between the ESP and scrubber, the concentration at the incinerator outlet is the same as the inlet concentrations at both the ESP and the incinerator air pollution abatement system (including cyclones). Mass emission rates were calculated by multiplying the measured mass concentration by the flue gas flow rate. Particulate removal efficiencies are calculated from inlet and outlet particulate mass flow rates and are reported in Table 9. The total particulate removal efficiency of the scrubber averaged 98.1% and was uniform between runs. Individual runs varied by less than 1% from the average of all runs. During Run 1 and Run 2, ESP removal efficiencies were poor (91.5% and 93.3%). This was probably the result of excessive volumetric flow rates from air purging the electrode insulators. The air purge was not used during Run 3 and the total particulate removal efficiency of the ESP increased to 98.4%. The volumetric flow rate of the ESP exhaust gas during Run 3 was only 72% of Runs 1 and 2 flow rates. With the presumption that performance during Run 3 was more typical of expected ESP performance, subsequent discussion of particle size and metal content data will include Run 3 results separately. The solids mass balance for Run 3 is shown on Figure 5.

Particle Size Distribution of Particulate Emissions

A further distinction between the performance of the ESP and the scrubbers can be made by comparing total particulate removal efficiency by SASS size fraction. Particulate mass concentrations and flow rates by SASS size fractions are presented in Tables 10 and 11. Table 10 indicates that the majority of particulate emissions from the incinerator were trapped in the 10 micron and 3 micron cyclones. The average particulate matter size distribution for the incinerator was as follows: 52 percent (0.43 g/dscm @

TABLE 8. TOTAL PARTICULATE MASS CONCENTRATIONS AND MASS EMISSION RATES

		g/dscm (as measured)	g/dscm (12% O_2)	lb/hr	(lb/lb dry sludge) x 10^4
ESP	Inlet				
	Run 1	0.50	0.75	0.20	3.44
	Run 2	0.67	0.93	0.27	5.04
	Run 3	0.61	0.79	0.28	5.25
	Average	0.59	0.82	0.25	4.58
	Outlet				
	Run 1	0.017	0.11	0.017	0.29
	Run 2	0.015	0.10	0.018	0.34
	Run 3	0.0058	0.012	0.0044	0.083
	Average	0.013	0.0.74	0.013	0.24
Scrubber	Inlet				
	Run 1	0.50	0.75	7.48	128.74
	Run 2	0.67	0.93	8.59	160.26
	Run 3	0.61	0.79	10.24	192.12
	Average	0.59	0.82	8.77	160.37
	Outlet				
	Run 1	0.0042	0.013	0.12	2.07
	Run 2	0.0044	0.014	0.13	2.43
	Run 3	0.0084	0.019	0.25	4.69
	Average	0.0057	0.015	0.17	3.06

TABLE 9. TOTAL PARTICULATE REMOVAL EFFICIENCY

	ESP	Scrubber
Run 1	91.50	98.40
Run 2	93.33	98.47
Run 3	98.43	97.56
Average	94.42	98.14

TABLE 10. PARTICULATE MASS CONCENTRATIONS BY SASS SIZE FRACTION
($g/dscm$, 12% O_2)

		Probe and 10 micron Cyclone	3 μm Cyclone	1 μm Cyclone	Filter Catch	Total
Incinerator Outlet						
	Run 1	0.47	0.23	0.012	0.037	0.75
	Run 2	0.43	0.45	0.014	0.034	0.93
	Run 3	0.40	0.30	0.022	0.065	0.79
	Average	0.43	0.33	0.016	0.045	0.82
ESP Outlet						
	Run 1	0.11	0.00	0.00	0.0003	0.11
	Run 2	0.098	0.00	0.00	0.0013	0.10
	Run 3	0.011	0.00	0.00	0.0052	0.012
	Average	0.073	0.00	0.00	0.0023	0.074
Scrubber Outlet						
	Run 1	0.0008	0.00	0.00	0.012	0.013
	Run 2	0.0011	0.00	0.00	0.013	0.014
	Run 3	0.0012	0.00	0.00	0.018	0.019
	Average	0.0010	0.00	0.00	0.014	0.015

TABLE 11. PARTICULATE MASS FLOW RATES BY SASS SIZE FRACTION (lb/hr)

		Probe and 10 micron Cyclone	3 μm Cyclone	1 μm Cyclone	Filter Catch	Total
ESP	Inlet					
	Run 1	0.12	0.06	0.003	0.01	0.20
	Run 2	0.13	0.13	0.004	0.01	0.27
	Run 3	0.14	0.11	0.008	0.02	0.28
	Average	0.13	0.10	0.005	0.013	0.25
	Outlet					
	Run 1	0.017	0.00	0.00	0.0001	0.017
	Run 2	0.017	0.00	0.00	0.0002	0.018
	Run 3	0.0042	0.00	0.00	0.0002	0.0044
	Average	0.013	0.00	0.00	0.0002	0.013
Scrubber	Inlet					
	Run 1	4.62	2.32	0.14	0.40	7.48
	Run 2	3.98	4.18	0.12	0.31	8.59
	Run 3	5.22	3.88	0.28	0.86	10.24
	Average	4.61	3.46	0.18	0.52	8.77
	Outlet					
	Run 1	0.0083	0.00	0.00	0.11	0.12
	Run 2	0.011	0.00	0.00	0.12	0.13
	Run 3	0.015	0.00	0.00	0.23	0.25
	Average	0.011	0.00	0.00	0.15	0.17

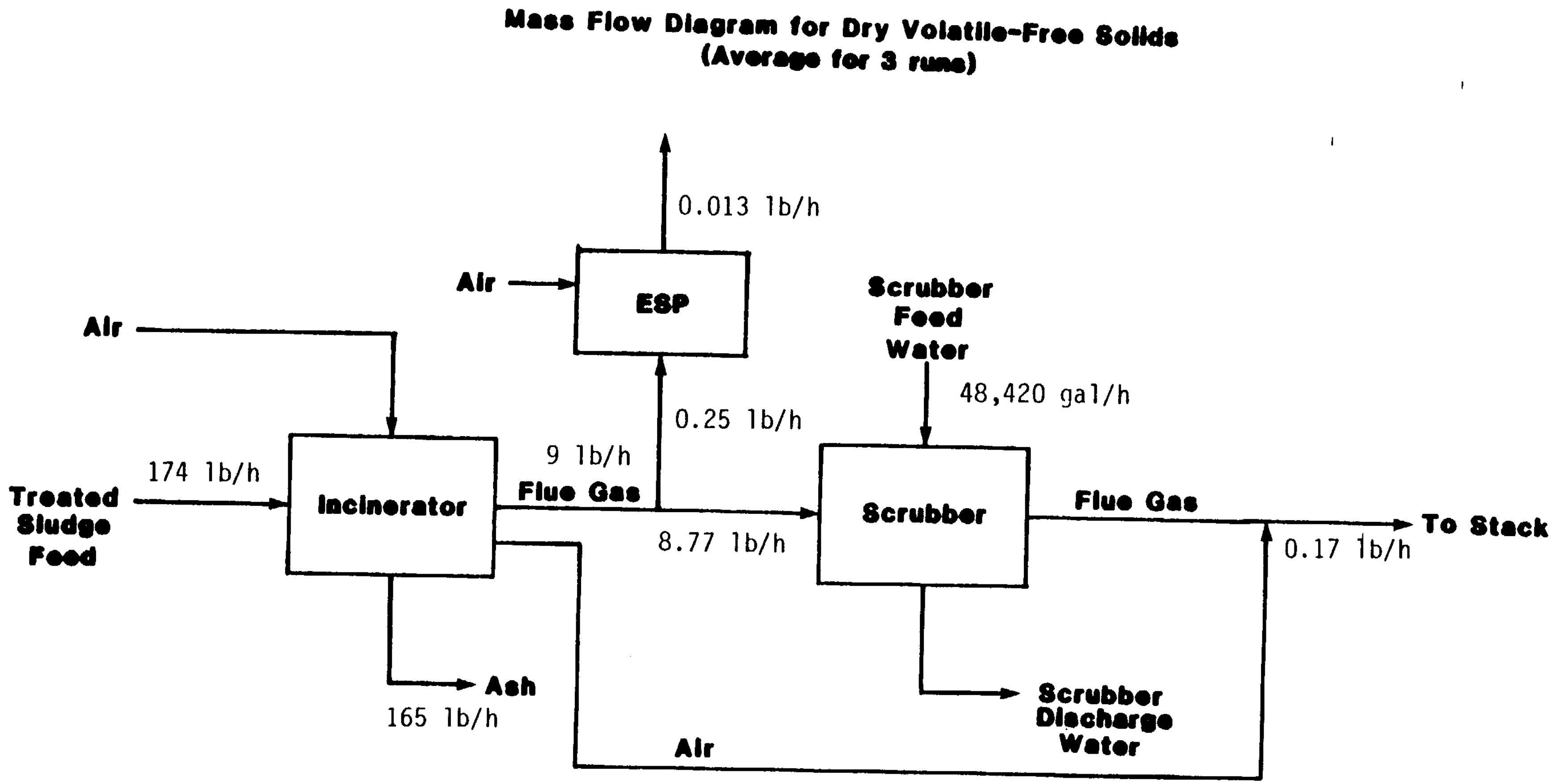


Figure 4. Mass Flow Diagram for Dry Volatile-Free Solids - Average

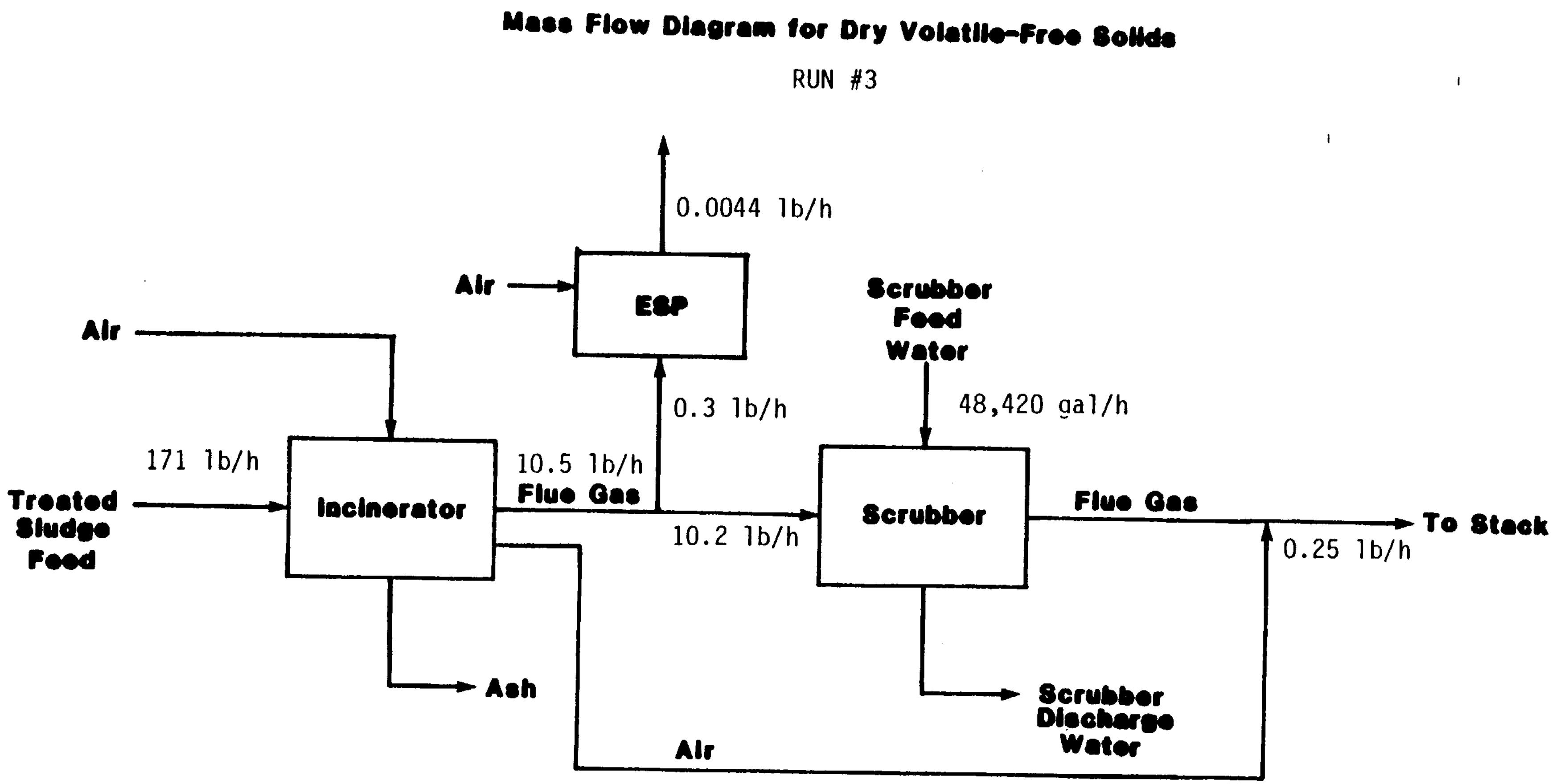


Figure 5. Mass Flow Diagram for Dry Volatile-Free Solids - Run #3

12% O_2) was caught in the probe and 10 micron cyclone, 40 percent (0.33 g/dscm @ 12% O_2) was caught in the 3 micron cyclone, 2 percent (0.016 g/dscm @ 12% O_2) was caught in the 1 micron cyclone and 5 percent (0.045 g/dscm @ 12% O_2) was trapped in the filter catch. This size distribution is shown on Figure 6.

The size distribution of the particulate matter at the ESP outlet is shown in Figure 7. Nearly 97 percent of the particulate emissions from the ESP was captured in the probe and 10 micron cyclone, while 3 percent was trapped in the filter. The average concentrations in the 10 micron cyclone and filter were .073 g/dscm @ 12% O_2 and .0023 g/dscm @ 12% O_2, respectively. No particulate matter was captured in either the 3 micron cycIone or the 1 micron cyclone at the ESP outlet location.

The reverse pattern was observed for the scrubber emissions. The size distribution of the particulate matter at the scrubber outlet is shown in Figure 8. Approximately 93 percent of the particulate emissions was trapped in the filter, the remaining 17 percent was caught in the 10 micron cyclone. The average concentration in the filter catch was .014 g/dscm @ 12% O_2, and .001 g/dscm @ 12% O_2 in the 10 micron cyclone. Again, no particulate matter was captured in the 3 micron cyclone or the 1 micron cyclone.

The particulate removal efficiencies for each SASS fraction were calculated from the inlet and outlet mass emission rates for each SASS fraction. These values are presented in Table 12. The data indicate that the ESP is more efficient than the scrubber at removing smaller particles. In the filter fraction where the average particle diameter is less than 1 micron, the ESP removed an average of 98.7 percent of the particulate compared to 69.0 percent for the scrubber. The scrubber, on the other hand, was more efficient than the ESP at removing larger particles. In the probe rinse and 10 micron cyclone fraction in which particles greater than 10 microns are caught, the scrubber removed an average of 99.8 percent of the particulate matter compared to 89.9 percent for the ESP. Run 3 is an exception in that the ESP removed 97% of the particles with diameters greater than 10 microns. This again suggests that the ESP was not operating at optimal conditions during Runs 1 and 2.

TRACE METAL EMISSIONS DATA

Uncontrolled Trace Metal Emissions from the Incinerator

The total concentrations (g/dscm) of the elements, determined by ICAP analysis, in the uncontrolled emissions from the incinerator for Runs 1-3 are shown in Table 13. Total concentrations normalized to a level of 12 percent oxygen are shown in Tables 14. The total concentrations include the metals found in the impinger catch. All concentrations referred to in this and subsequent sections are on an as measured O_2 basis. The mean elemental concentrations ranged from a low of 3.28×10^{-7} g/dscm for gold to a high of 5.41×10^{-1} g/dscm for sulfur.

A complete ranking of all the metals by concentration is presented in Figure 9. The figure shows that the toxic metals (As, Cd, Cr, Pb, Ni, and Se) were among the metals with the lowest concentrations. The concentrations of Selenium and Gold (4.49×10^{-7} and 3.28×10^{-7} g/dscm) were so small that

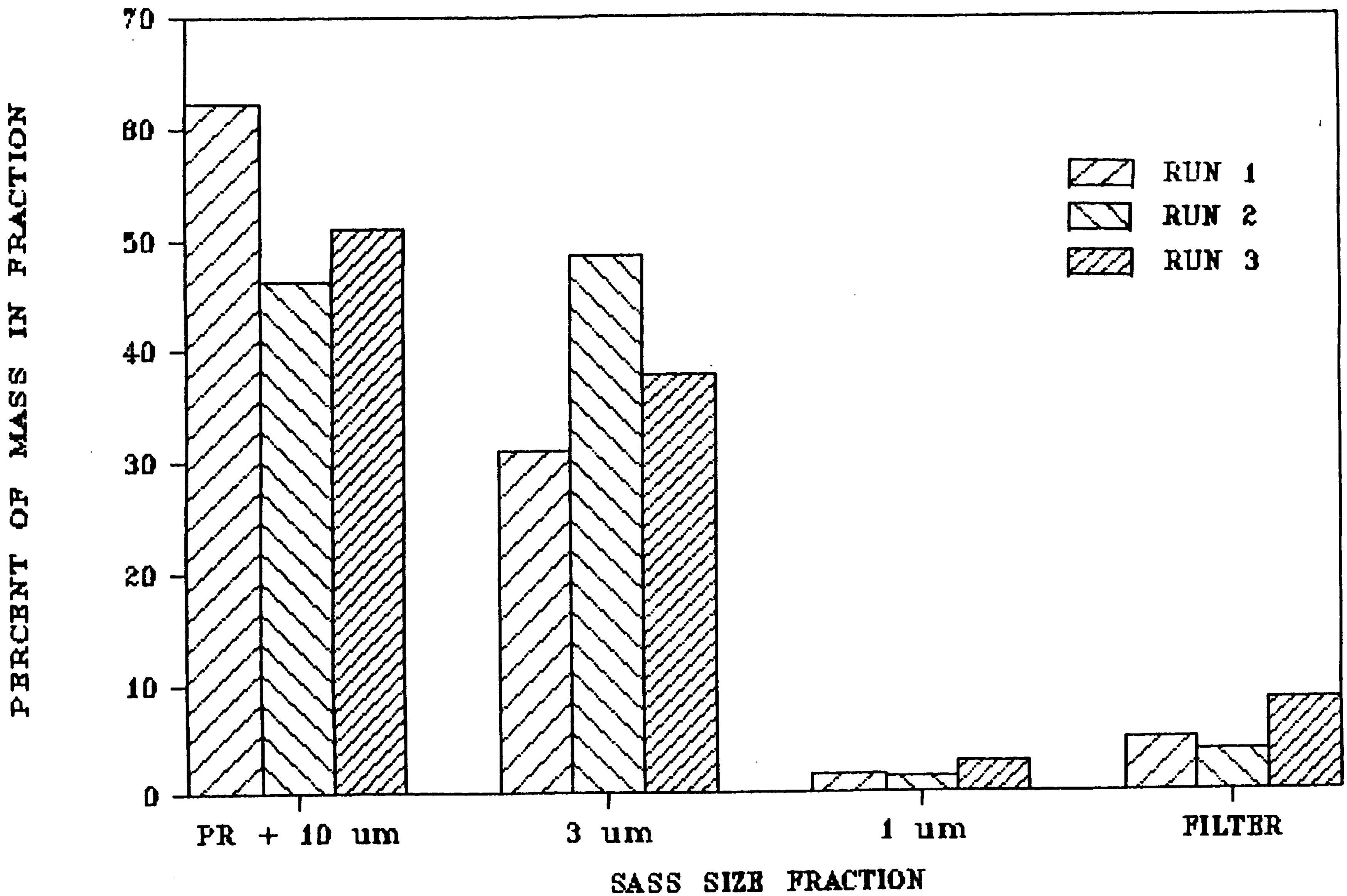


Figure 6. Particle Size Distribution of the Uncontrolled Particulate Emissions from the Incinerator

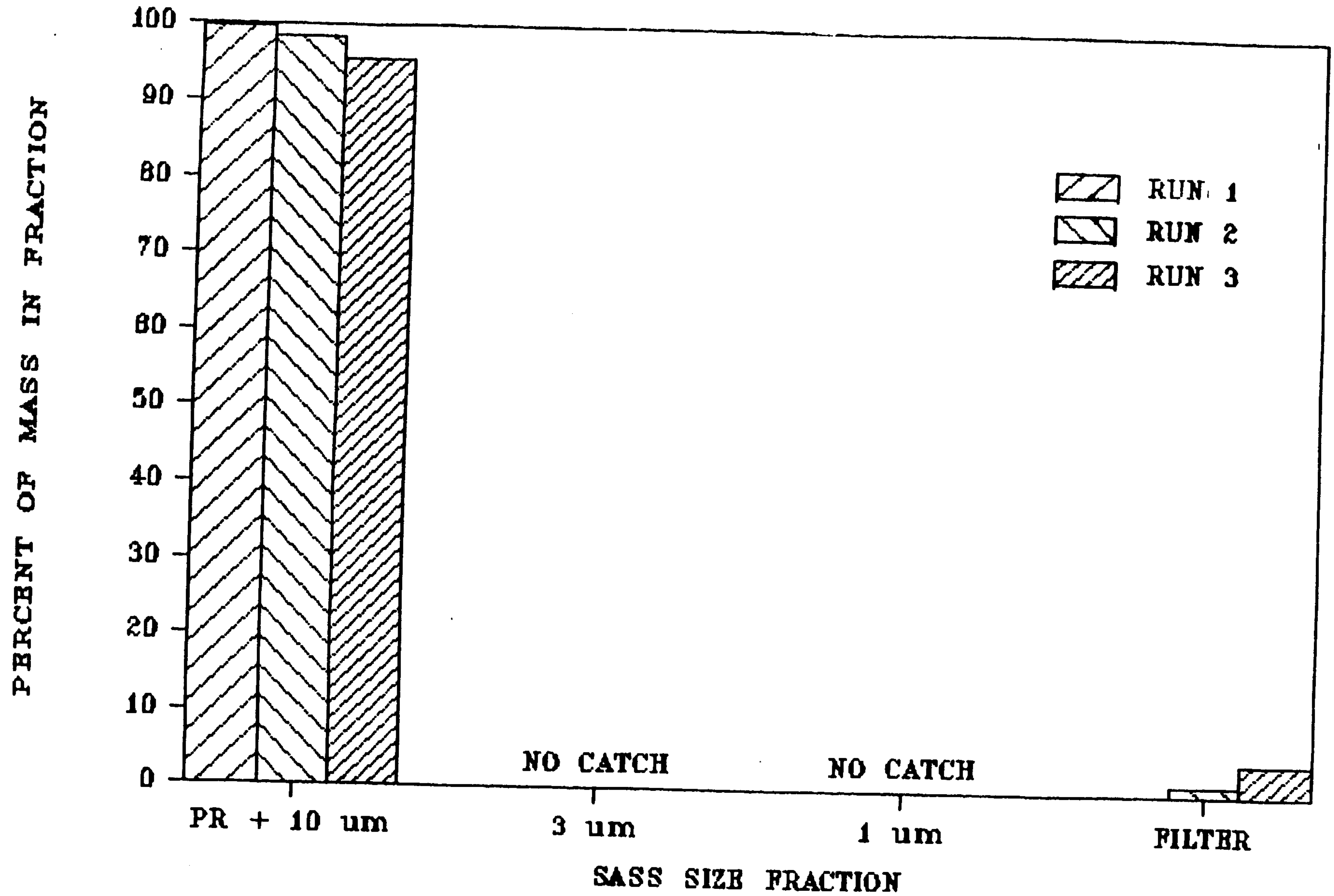


Figure 7. Particle Size Distribution of Particulate Emissions from the ESP

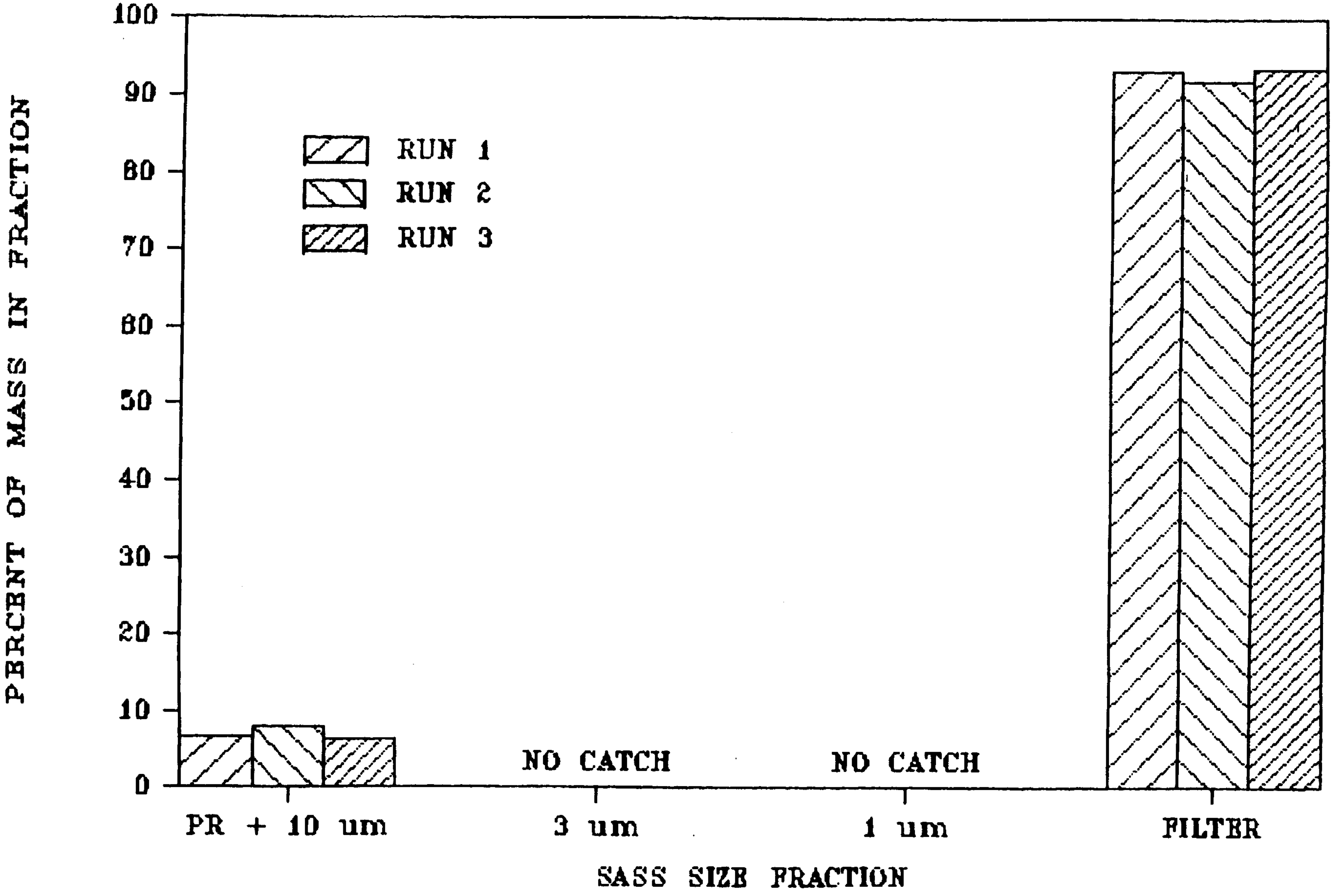


Figure 8. Particle Size Distribution of Particulate Emissions from the Scrubber

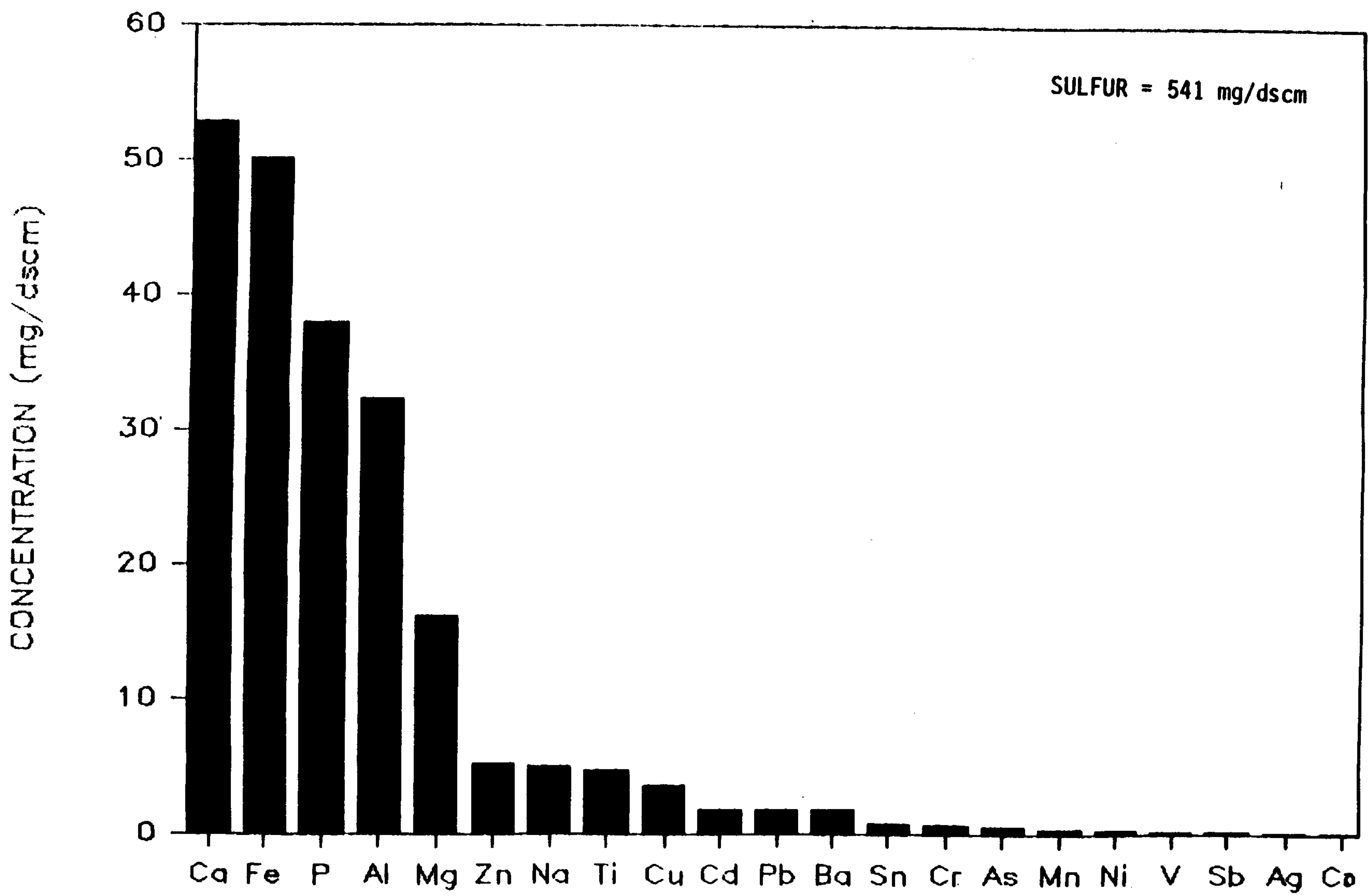


Figure 9. Rank Order of Metal Concentrations in the Uncontrolled Incinerator Emissions.

TABLE 12. PARTICULATE REMOVAL EFFICIENCY BY SASS SIZE FRACTION (Percent)

		Probe + 10 um	3 um Cyclone	1 um Cyclone	Filter Catch	Total
ESP	Run 1	85.83	No Catch	No Catch	99.00	91.50
	Run 2	86.92	"	"	98.00	93.33
	Run 3	97.00	"	"	99.00	98.43
	Average	88.92	"	"	98.67	94.42
Scrubber	Run 1	99.82	No Catch	No Catch	72.50	98.40
	Run 2	99.72	"	"	61.29	98.47
	Run 3	99.71	"	"	73.26	97.56
	Average	99.75	"	"	69.02	98.14

TABLE 13. UNCONTROLLED TRACE METAL EMISSIONS FROM THE INCINERATOR (g/dscm, as measured)

	INCINERATOR OUTLET				
	RUN 1	RUN 2	RUN 3	MEAN	SD
SULFUR	3.20E-01	4.13E-01	8.91E-01	5.41E-01	3.06E-01
CALCIUM	3.83E-02	7.55E-02	4.44E-02	5.27E-02	1.99E-02
IRON	4.50E-02	5.94E-02	4.59E-02	5.01E-02	8.03E-03
PHOSPHOROUS	2.92E-02	4.74E-02	3.70E-02	3.79E-02	9.15E-03
ALUMINUM	2.02E-02	4.15E-02	3.50E-02	3.22E-02	1.09E-02
MAGNESIUM	1.15E-02	2.16E-02	1.54E-02	1.62E-02	5.07E-03
ZINC	3.84E-03	6.27E-03	5.52E-03	5.21E-03	1.25E-03
SODIUM	3.63E-03	6.11E-03	5.42E-03	5.05E-03	1.28E-03
TITANIUM	3.57E-03	5.67E-03	4.93E-03	4.72E-03	1.07E-03
COPPER	2.72E-03	4.45E-03	3.74E-03	3.63E-03	8.70E-04
CADMIUM	1.28E-03	2.20E-03	2.01E-03	1.83E-03	4.87E-04
LEAD	1.10E-03	1.77E-03	2.39E-03	1.76E-03	6.45E-04
BARIUM	1.50E-03	1.84E-03	1.92E-03	1.75E-03	2.19E-04
TIN	4.60E-04	6.53E-04	9.10E-04	6.75E-04	2.26E-04
CHROMIUM	6.77E-04	6.14E-04	5.20E-04	6.04E-04	7.90E-05
ARSENIC	4.95E-04	7.11E-04	4.08E-04	5.38E-04	1.56E-04
MANGANESE	3.51E-04	4.42E-04	3.09E-04	3.67E-04	6.79E-05
NICKEL	1.96E-04	2.12E-04	1.87E-04	1.98E-04	1.28E-05
VANADIUM	1.39E-04	2.22E-04	1.70E-04	1.77E-04	4.22E-05
ANTIMONY	8.51E-05	1.41E-04	9.10E-05	1.06E-04	3.08E-05
SILVER	2.59E-05	5.89E-05	5.19E-05	4.56E-05	1.74E-05
COBALT	2.85E-05	4.59E-05	3.60E-05	3.68E-05	8.72E-06
SELENIUM	0.00E+00	4.69E-07	8.77E-07	4.49E-07	4.39E-07
GOLD	2.11E-07	3.68E-07	4.05E-07	3.28E-07	1.03E-07

TABLE 14. UNCONTROLLED TRACE METAL EMISSIONS FROM THE INCINERATOR ($g/dscm$ @ 12% O_2)

	INCINERATOR OUTLET				
	RUN 1	RUN 2	RUN 3	MEAN	SD
SULFUR	4.87E-01	5.72E-01	1.15E+00	7.35E-01	3.59E-01
CALCIUM	5.82E-02	1.05E-01	5.72E-02	7.33E-02	2.70E-02
IRON	6.84E-02	8.22E-02	5.92E-02	6.99E-02	1.16E-02
PHOSPHOROUS	4.44E-02	6.57E-02	4.76E-02	5.26E-02	1.15E-02
ALUMINUM	3.08E-02	5.75E-02	4.50E-02	4.44E-02	1.33E-02
MAGNESIUM	1.75E-02	2.99E-02	1.98E-02	2.24E-02	6.57E-03
ZINC	5.84E-03	8.69E-03	7.11E-03	7.21E-03	1.43E-03
SODIUM	5.52E-03	8.46E-03	6.98E-03	6.99E-03	1.47E-03
TITANIUM	5.42E-03	7.85E-03	6.35E-03	6.54E-03	1.23E-03
COPPER	4.13E-03	6.16E-03	4.81E-03	5.03E-03	1.03E-03
CADMIUM	1.94E-03	3.04E-03	2.59E-03	2.52E-03	5.53E-04
LEAD	1.68E-03	2.45E-03	3.08E-03	2.40E-03	7.03E-04
BARIUM	2.28E-03	2.54E-03	2.47E-03	2.43E-03	1.33E-04
TIN	7.00E-04	9.04E-04	1.17E-03	9.25E-04	2.37E-04
CHROMIUM	1.03E-03	8.51E-04	6.70E-04	8.50E-04	1.80E-04
ARSENIC	7.52E-04	9.85E-04	5.25E-04	7.54E-04	2.30E-04
MANGANESE	5.34E-04	6.12E-04	3.98E-04	5.15E-04	1.08E-04
NICKEL	2.97E-04	2.93E-04	2.41E-04	2.77E-04	3.17E-05
VANADIUM	2.11E-04	3.08E-04	2.19E-04	2.46E-04	5.37E-05
ANTIMONY	1.29E-04	1.95E-04	1.17E-04	1.47E-04	4.21E-05
SILVER	3.93E-05	8.15E-05	6.68E-05	6.26E-05	2.14E-05
COBALT	4.33E-05	6.35E-05	4.64E-05	5.11E-05	1.09E-05
SELENIUM	0.00E+00	6.49E-07	1.13E-06	5.93E-07	5.67E-07
GOLD	3.20E-07	5.09E-07	5.21E-07	4.50E-07	1.13E-07

they do not appear in the figure. The most abundant elements in the incinerator exhaust gas coincided with those observed in the sludge feed. These consisted of sulfur, calcium, iron, phosphorous, aluminum, and magnesium. This group accounted for 97 percent of the total metals detected in the samples. For many of the metals, there was a significant degree of variability between runs. The average concentration of aluminum, for example, was 3.22×10^{-2} g/dscm, with a maximum individual run deviation from the average of about 37 percent. The other metals had, on the average, a maximum deviation of 27 percent from their respective average concentration. Figure 10 is a rank order diagram that shows the relationship of uncontrolled metals emissions relative to the metals content of the sludge. The data show that the order of species ranked by uncontrolled emission concentrations is nearly identical to the order of species ranked by sludge concentration.

Enrichment ratios in the uncontrolled incinerator emissions for each metal are presented in Table 15 and shown in Figure 11. The enrichment ratio is found by dividing the elemental concentration in the total dry particulate catch emissions (i.e., the front half of the SASS train) by the elemental concentration in the dry, volatiles free sludge. Cadmium had the highest value of all the metals with an average enrichment ratio of 13.7. The remaining metals were enriched less than 3 times relative to their concentrations in the sludge. Figure 11 shows that nineteen of the twenty-four metals had an enrichment ratio near one. A large enrichment ratio is not necessarily an indication of a large concentraion in the particulate emissions. Cadmium, for example, though it had a large enrichment ratio of 13.7, had a mean concentration in the particulate of only 1.83×10^{-3} g/dscm. Iron, on the other hand, had an enrichment ratio of 1.4 and a concentration of 5.01×10^{-2} g/dscm, an order of magnitude higher in concentration than cadmium.

Trace Metal Emissions from the ESP

The total concentrations of the elements in the controlled particulate emissions from the ESP are shown in Table 16. Normalized values are shown in Table 17. The mean elemental concentrations ranged from a low of 3.62×10^{-8} g/dscm for gold to a high of 1.36×10^{-1} g/dscm for sulfur. A ranking of the species by mean ESP emission concentration is shown in Figure 12. The most abundant elements in the ESP exhaust gas were sulfur, calcium, aluminum, iron, and magnesium. This group accounted for approximately 99 percent of the total metals detected.

There appeared to be a significant degree of variability between runs for many species. The emissions concentration of Selenium in Run 1 was 3.34×10^{-5} g/dscm, whereas the concentration in Run 2 decreased 20 times to 1.61×10^{-6} g/dscm. Similar between-run variations were observed with other metals.

Figure 13 is a rank order diagram that shows the relationship of controlled ESP metals emissions to the metals content of the sludge. The data show considerably more scatter about the 45 degree line than the corresponding data for the uncontrolled incinerator emissions. This indicates a wide range of enrichment ratios for the ESP emissions, and a wide range of ESP removal efficiencies for individual species.

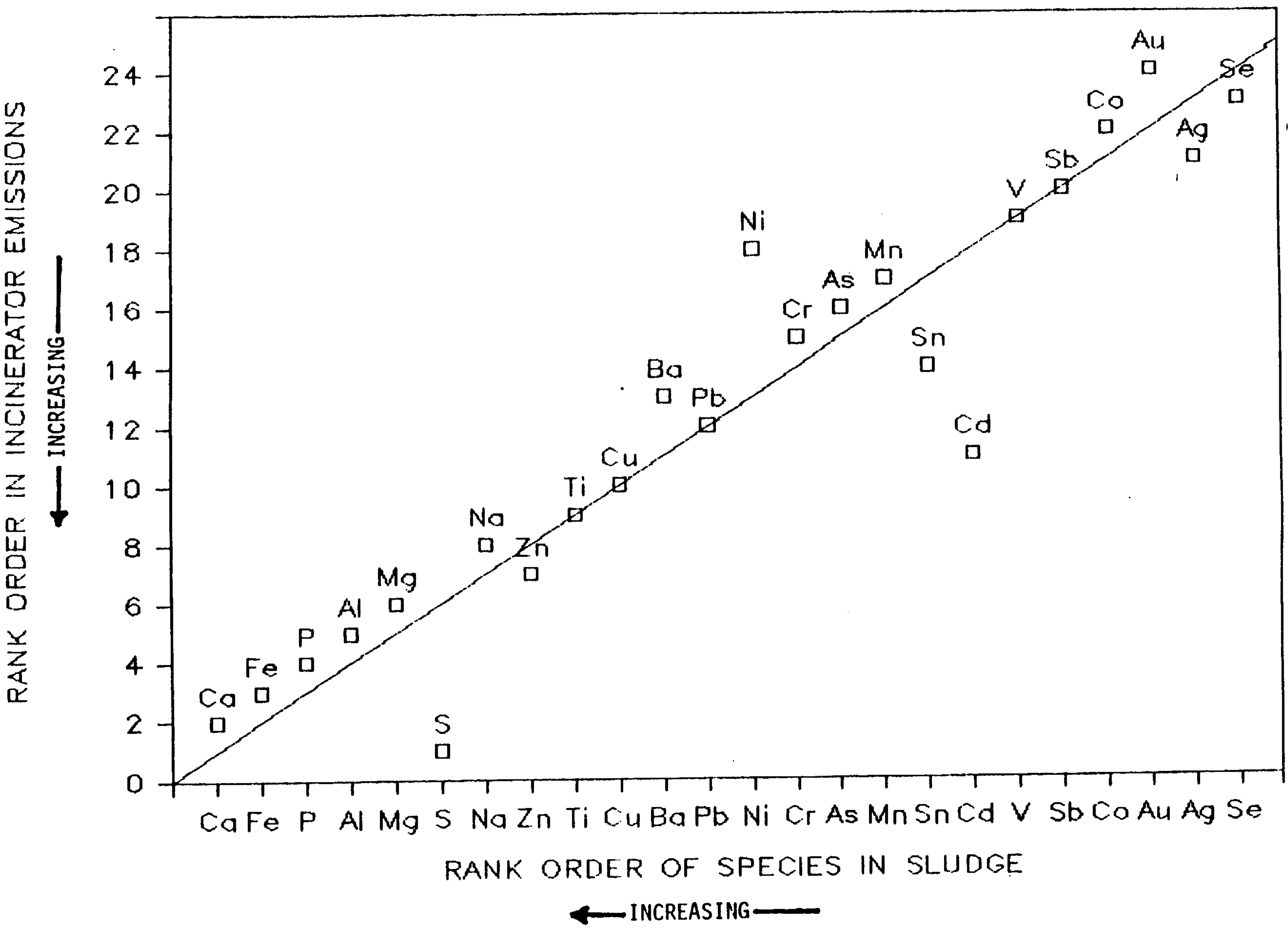


Figure 10. **Rank Order Diagram of Uncontrolled Trace Metals Emissions vs. Sludge Feed Concentrations.**

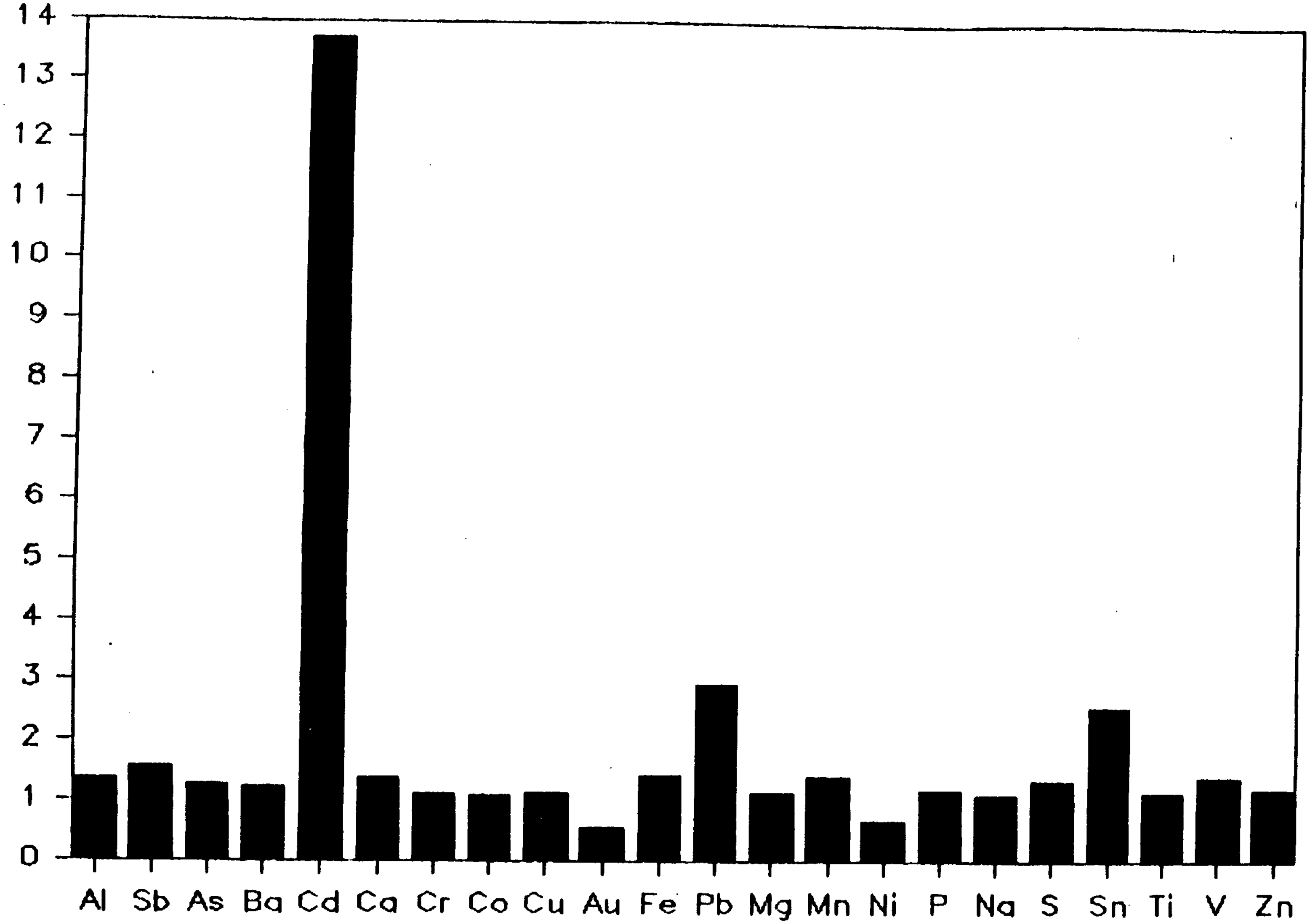


Figure 11. Average Enrichment Ratios for the Uncontrolled Incinerator Emissions

TABLE 15. ENRICHMENT RATIOS FOR THE UNCONTROLLED INCINERATOR EMISSIONS

	ENRICHMENT RATIOS INCINERATOR OUTLET			
	RUN 1	RUN 2	RUN 3	AVG
ALUMINUM	1.36	1.58	1.16	1.36
ANTIMONY	1.14	1.56	1.99	1.56
ARSENIC	1.42	1.55	0.84	1.27
BARIUM	1.16	1.17	1.32	1.22
CADMIUM	8.92	15.30	16.92	13.72
CALCIUM	1.48	1.71	0.92	1.37
CHROMIUM	1.19	1.17	0.94	1.10
COBALT	0.92	1.23	1.08	1.08
COPPER	1.04	1.31	1.08	1.14
GOLD	ND	0.56	ND	0.56
IRON	1.61	1.51	1.12	1.41
LEAD	2.37	2.58	3.87	2.94
MAGNESIUM	1.04	1.31	1.05	1.13
MANGANESE	1.67	1.49	1.04	1.40
NICKEL	0.63	1.22	0.16	0.67
PHOSPHOROUS	1.05	1.30	1.17	1.17
SELENIUM	ND	ND	ND	ND
SILVER	ND	ND	ND	ND
SODIUM	0.97	1.19	1.07	1.08
SULFUR	1.69	1.16	1.14	1.33
TIN	1.99	2.33	3.40	2.57
TITANIUM	1.01	1.31	1.06	1.13
VANADIUM	1.44	1.61	1.18	1.41
ZINC	1.18	1.26	1.18	1.21

TABLE 16. CONTROLLED TRACE METAL EMISSIONS FROM THE ESP (g/dscm, as measured)

	ESP OUTLET				
	RUN 1	RUN 2	RUN 3	MEAN	SD
SULFUR	3.55E-02	8.03E-02	2.93E-01	1.36E-01	1.37E-01
CALCIUM	5.42E-03	5.59E-03	5.24E-03	5.42E-03	1.74E-04
ALUMINUM	1.98E-03	2.31E-03	2.30E-03	2.19E-03	1.88E-04
IRON	8.11E-04	1.56E-04	1.38E-04	3.68E-04	3.84E-04
MAGNESIUM	1.76E-04	8.11E-05	1.60E-04	1.39E-04	5.10E-05
BARIUM	1.08E-04	1.32E-04	1.03E-04	1.14E-04	1.54E-05
PHOSPHOROUS	1.23E-04	8.35E-05	1.17E-04	1.08E-04	2.13E-05
NICKEL	4.13E-05	3.69E-05	6.83E-06	2.83E-05	1.88E-05
LEAD	2.98E-05	2.31E-05	2.31E-05	2.54E-05	3.89E-06
CHROMIUM	4.58E-05	7.27E-06	1.19E-05	2.16E-05	2.10E-05
ARSENIC	1.11E-05	3.39E-05	7.16E-06	1.74E-05	1.45E-05
TITANIUM	1.39E-05	8.59E-06	2.01E-05	1.42E-05	5.77E-06
SELENIUM	3.34E-05	1.61E-06	1.85E-06	1.23E-05	1.83E-05
SODIUM	5.84E-06	1.98E-06	2.11E-05	9.65E-06	1.01E-05
ZINC	1.00E-05	3.23E-06	4.61E-06	5.96E-06	3.60E-06
COBALT	1.00E-05	4.88E-06	1.95E-06	5.61E-06	4.07E-06
MANGANESE	1.26E-05	8.50E-07	4.54E-07	4.64E-06	6.91E-06
TIN	9.50E-07	6.73E-07	9.50E-06	3.71E-06	5.02E-06
COPPER	3.01E-06	1.07E-06	5.99E-06	3.36E-06	2.48E-06
VANADIUM	5.17E-06	2.72E-06	5.32E-07	2.81E-06	2.32E-06
CADMIUM	5.65E-06	1.34E-06	5.89E-07	2.53E-06	2.73E-06
ANTIMONY	8.99E-07	4.01E-07	3.43E-07	5.48E-07	3.06E-07
SILVER	8.33E-08	0.00E+00	2.53E-07	1.12E-07	1.29E-07
GOLD	0.00E+00	0.00E+00	1.09E-07	3.62E-08	6.27E-08

TABLE 17. CONTROLLED TRACE METAL EMISSIONS FROM THE ESP ($g/dscm$ @ 12% O_2)

	ESP OUTLET				
	RUN 1	RUN 2	RUN 3	MEAN	SD
SULFUR	2.33E-01	5.43E-01	6.11E-01	4.62E-01	2.01E-01
CALCIUM	3.56E-02	3.78E-02	1.10E-02	2.81E-02	1.49E-02
ALUMINUM	1.30E-02	1.56E-02	4.79E-03	1.11E-02	5.64E-03
IRON	5.33E-03	1.05E-03	2.88E-04	2.22E-03	2.72E-03
MAGNESIUM	1.16E-03	5.49E-04	3.35E-04	6.81E-04	4.28E-04
BARIUM	7.12E-04	8.92E-04	2.15E-04	6.06E-04	3.51E-04
PHOSPHOROUS	8.08E-04	5.65E-04	2.44E-04	5.39E-04	2.83E-04
NICKEL	2.71E-04	2.49E-04	1.43E-05	1.78E-04	1.43E-04
LEAD	1.96E-04	1.57E-04	4.82E-05	1.34E-04	7.66E-05
CHROMIUM	3.01E-04	4.92E-05	2.49E-05	1.25E-04	1.53E-04
ARSENIC	7.31E-05	2.30E-04	1.49E-05	1.06E-04	1.11E-04
TITANIUM	9.12E-05	5.81E-05	4.20E-05	6.38E-05	2.51E-05
SELENIUM	2.19E-04	1.09E-05	3.86E-06	7.80E-05	1.22E-04
SODIUM	3.84E-05	1.34E-05	4.41E-05	3.20E-05	1.63E-05
ZINC	6.59E-05	2.19E-05	9.62E-06	3.25E-05	2.96E-05
COBALT	6.57E-05	3.30E-05	4.07E-06	3.43E-05	3.08E-05
MANGANESE	8.29E-05	5.75E-06	9.49E-07	2.99E-05	4.60E-05
TIN	6.24E-06	4.55E-06	1.98E-05	1.02E-05	8.38E-06
COPPER	1.98E-05	7.26E-06	1.25E-05	1.32E-05	6.28E-06
VANADIUM	3.40E-05	1.84E-05	1.11E-06	1.78E-05	1.64E-05
CADMIUM	3.71E-05	9.09E-06	1.23E-06	1.58E-05	1.89E-05
ANTIMONY	5.91E-06	2.71E-06	7.16E-07	3.11E-06	2.62E-06
SILVER	5.47E-07	0.00E+00	5.28E-07	3.58E-07	3.11E-07
GOLD	0.00E+00	0.00E+00	2.27E-07	7.55E-08	1.31E-07

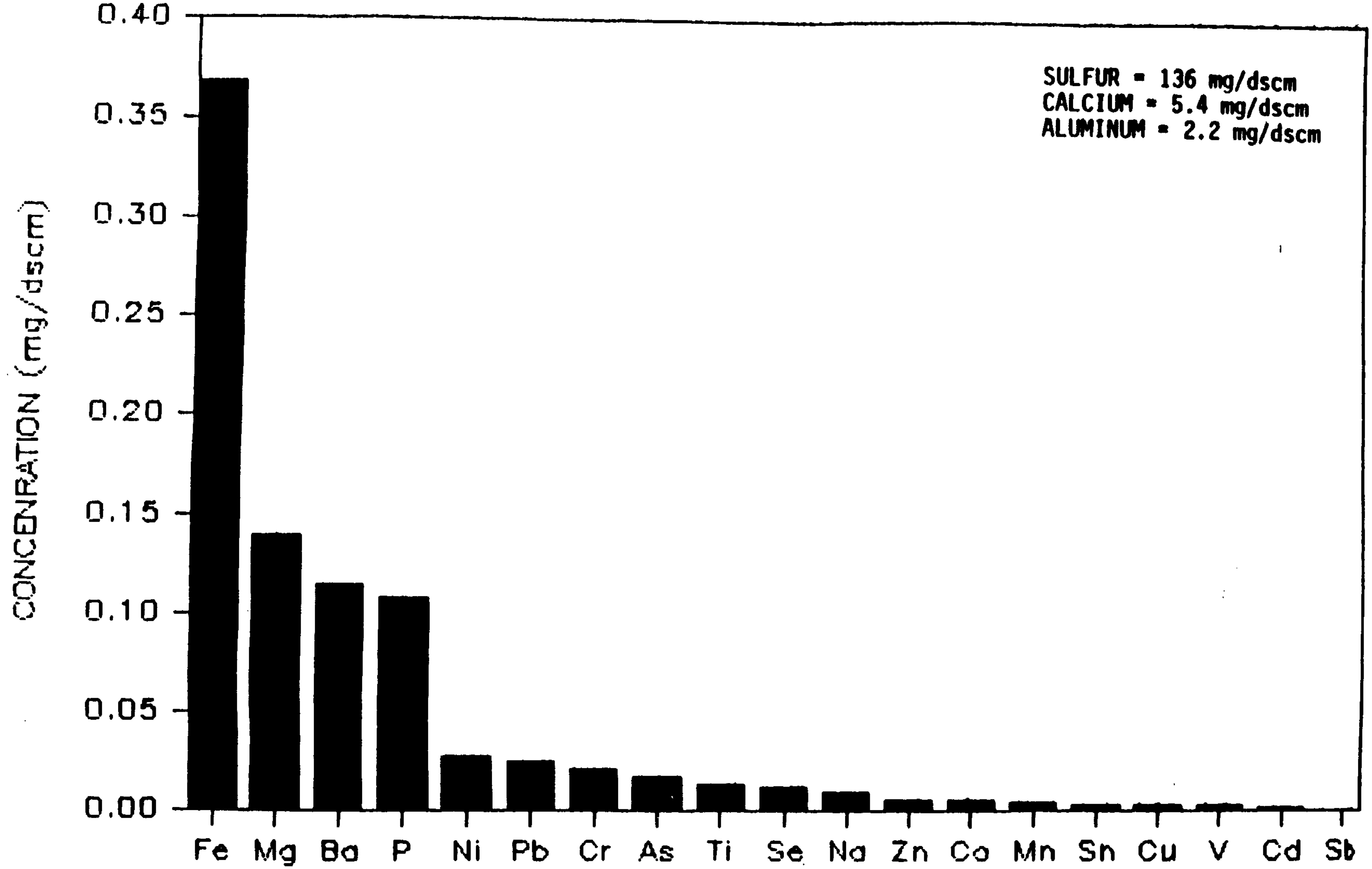


Figure 12. Rank Order of Concentrations in the Controlled ESP Emissions

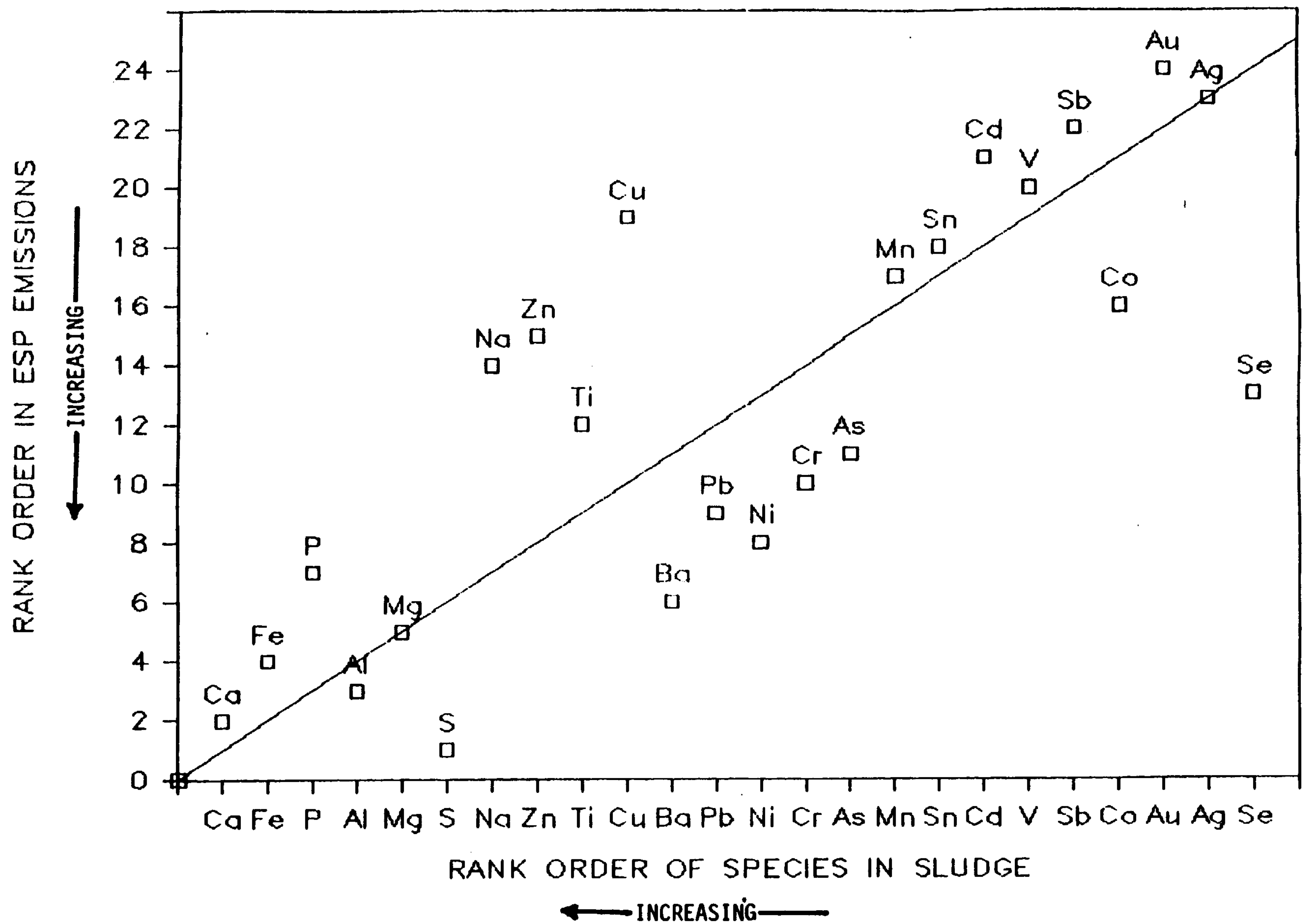


Figure 13. **Rank Order Diagram of Controlled Trace Metals Emissions From the ESP vs. Sludge Feed Concentrations.**

Average enrichment ratios for each metal detected in the ESP emissions are presented in Table 18 and shown on Figure 14. Sulfur, calcium, cobalt, nickel, barium, and aluminum had the highest enrichment ratios. Their enrichment ratios were 10.7, 7.7, 5.4, 4.3, 4.6, and 5.3, respectively. These species had higher enrichment ratios in the ESP emissions than in the uncontrolled incinerator emissions. Most other species showed a decrease in enrichment ratios at the ESP outlet in comparison to the values at the incinerator outlet. Cadmium, for example, had an enrichment ratio of 13.7 at the incinerator outlet as compared to a value of .53 at the ESP outlet. Similarly, thirteen of the twenty-four metals analyzed had enrichment ratios less than 1. The metals with low enrichment ratios tended to have high trace metal removal efficiencies as discussed later in this section.

Trace metal removal efficiencies are reported in Table 19 and summarized in Table 20. The volumetric flow rate was reduced during Run 3 by limiting the air inleakage rate. Table 19 shows substantial improvement during Run 3 in removal of the individual metals. Only eight of the 24 metals analyzed had removal efficiencies below 95 percent. Of these, most of the sulfur species may have been in the vapor state and concentrations of selenium and gold entering the ESP were extremely low.

Trace Metal Emissions from the Scrubber

The total concentrations of the elements in the controlled particulate emissions from the scrubber system are shown in Table 21. Normalized values are shown in Table 22. The mean elemental concentrations ranged from a low of 2.11×10^{-8} g/dscm for gold to a high of 8.81×10^{-3} g/dscm for calcium.

A complete ranking of the metals by mean emissions concentration is shown in Figure 15. The most noticeable change was sulfur's decline in ranking from the scrubber inlet. In the inlet sulfur was the most abundant element; whereas in the outlet, it was the third most abundant. This corresponds to a decrease from 72 percent of the total metals analyzed at the inlet to 18 percent at the outlet.

The most abundant elements in the scrubber exhaust gas were calcium, aluminum, sulfur, and iron. This group accounted for approximately 90 percent of the total metals detected. Only 22% of the sulfur was collected in the impinger catch. This was substantially different from the impinger catches for the incinerator outlet samples (97%) and the ESP samples (99%). It suggests that the sulfur species believed to be in the gas phase were removed in the scrubbers and supports the argument that most of the sulfur is emitted from the incinerator as SO_2. There also seemed to be a significant degree of variability between-runs for the elemental scrubber emission concentrations. Calcium, for example, had a measured concentration of 2.97×10^{-3} g/dscm in Run 2, whereas in Run 3 it was 2.04×10^{-2} g/dscm. This corresponds to a 7-fold increase in concentration between Runs 2 and 3. The same metal in the sludge feed, on a ppm basis, had a concentration of 6.59×10^{4} ppm in Run 2 and 7.89×10^{4} ppm in Run 3. This represents an increase of only 1.2 times from Run 2 to Run 3. Similar between-run variance was observed with other metals.

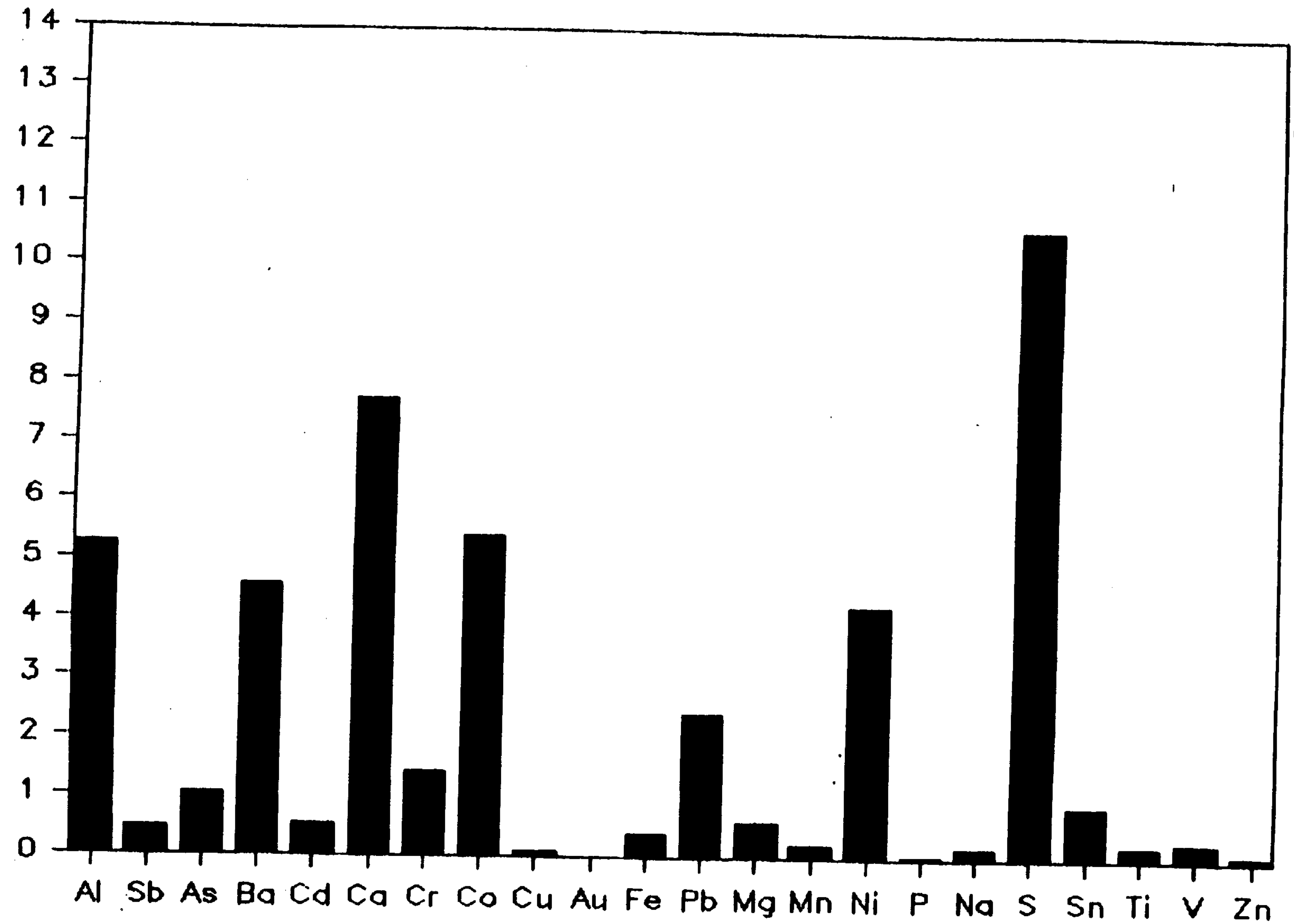


Figure 14. Average Enrichment Ratios for the Controlled ESP Emissions

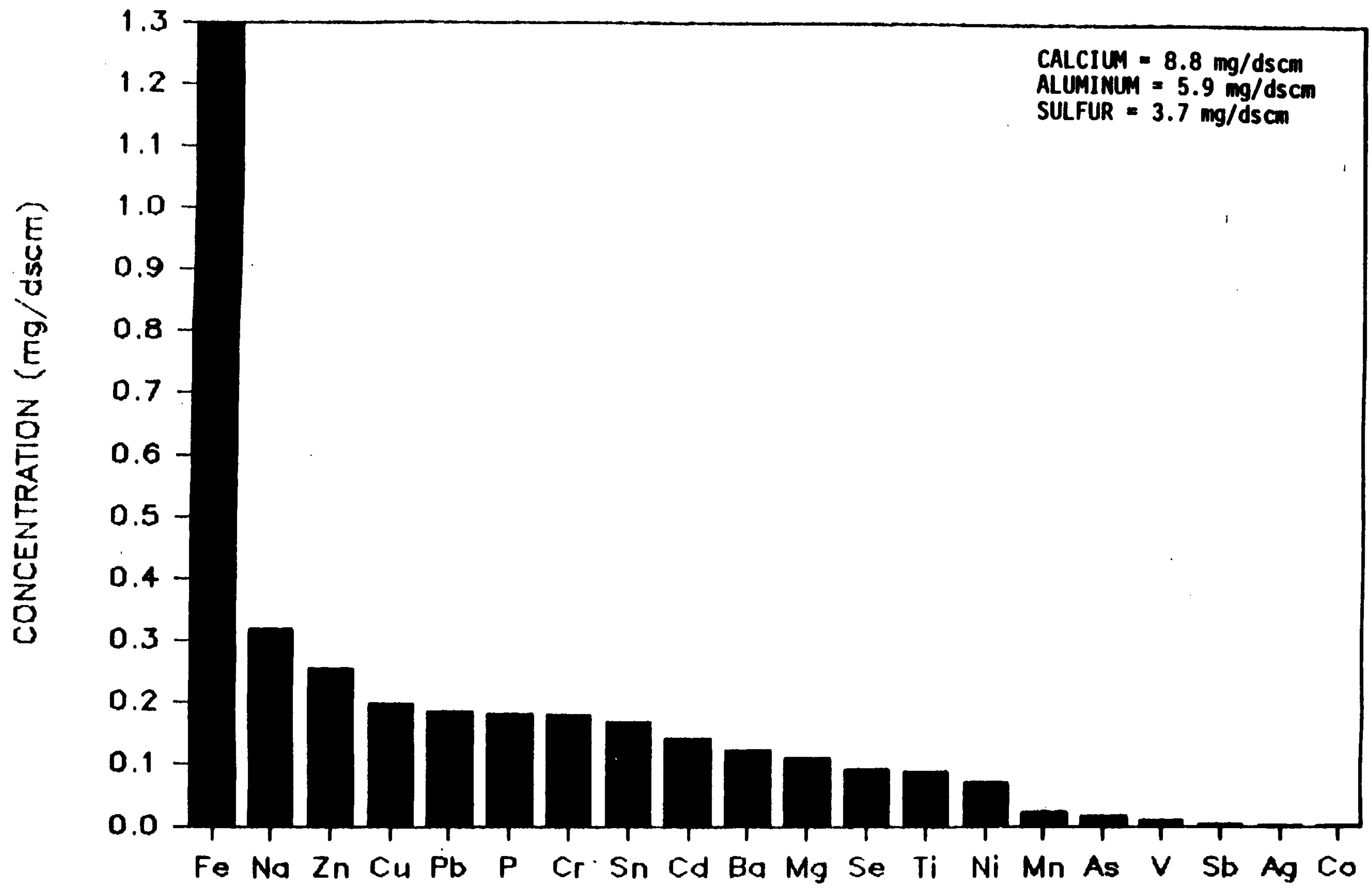


Figure 15. **Rank Order of Concentrations in the Controlled Scrubber Emissions**

TABLE 18. ENRICHMENT RATIOS FOR THE CONTROLLED ESP EMISSIONS

	ENRICHMENT RATIOS ESP OUTLET			
	RUN 1	RUN 2	RUN 3	AVG
ALUMINUM	3.82	3.99	8.02	5.28
ANTIMONY	0.35	0.20	0.79	0.45
ARSENIC	0.92	0.68	1.55	1.05
BARIUM	2.41	3.84	7.49	4.58
CADMIUM	0.63	0.43	0.52	0.53
CALCIUM	5.99	5.75	11.47	7.74
CHROMIUM	1.18	0.68	2.39	1.42
COBALT	4.15	5.98	6.15	5.43
COPPER	0.02	0.01	0.18	0.07
GOLD	ND	ND	ND	ND
IRON	0.67	0.16	0.32	0.38
LEAD	1.85	1.53	3.93	2.44
MAGNESIUM	0.44	0.22	1.14	0.60
MANGANESE	0.32	0.13	0.16	0.20
NICKEL	1.97	10.24	0.60	4.27
PHOSPHOROUS	0.04	0.02	0.04	0.03
SELENIUM	ND	ND	ND	ND
SILVER	ND	ND	ND	ND
SODIUM	0.04	0.02	0.44	0.17
SULFUR	9.66	9.55	12.79	10.66
TIN	0.12	0.11	2.44	0.89
TITANIUM	0.11	0.09	0.45	0.22
VANADIUM	0.34	0.12	0.39	0.28
ZINC	0.09	0.03	0.10	0.07

TABLE 19. TRACE METALS REMOVAL EFFICIENCIES FOR THE ESP

	ESP			
	RUN 1	RUN 2	RUN 3	AVERAGE
ALUMINUM	74.507	83.768	89.286	82.520
ANTIMONY	97.240	99.170	99.385	98.598
ARSENIC	94.122	86.069	97.138	92.443
BARIUM	81.166	79.042	91.233	83.814
CADMIUM	98.843	99.821	99.952	99.539
CALCIUM	63.068	78.369	80.743	74.060
CHROMIUM	82.347	96.545	96.264	91.719
COBALT	8.279	68.917	91.181	56.126
COPPER	99.711	99.930	99.738	99.793
GOLD	100.000	100.000	56.268	85.423
IRON	95.291	99.235	99.511	98.012
LEAD	92.932	96.182	98.426	95.847
MAGNESIUM	96.007	98.903	98.299	97.736
MANGANESE	90.615	99.438	99.760	96.604
NICKEL	44.818	49.234	94.039	62.697
PHOSPHOROUS	98.900	99.487	99.485	99.291
SELENIUM	0.000	0.000	0.000	0.000
SILVER	99.159	100.000	99.205	99.455
SODIUM	99.580	99.905	99.364	99.616
SULFUR	71.054	43.336	46.386	53.592
TIN	99.461	99.699	98.297	99.153
TITANIUM	98.983	99.558	99.334	99.292
VANADIUM	90.269	96.427	99.489	95.395
ZINC	99.317	99.850	99.864	99.677

TABLE 20. SUMMARY OF TRACE METALS REMOVAL EFFICIENCIES - ESP

Average of Three Runs

< 65 %	65 - 85%	86 - 95%	> 95 %
Cobalt	Aluminum	Chromium	Antimony
Nickel	Barium	Gold	Arsenic
Selenium	Calcium		Cadmium
Sulfur			Copper
			Iron
			Lead
			Magnesium
			Manganese
			Phosphorous
			Silver
			Sodium
			Tin
			Titanium
			Vanadium
			Zinc

Run 3 Only

< 65 %	65 - 85%	86 - 95%	> 95 %
Selenium	Calcium	Aluminum	Antimony
Sulfur		Barium	Arsenic
Gold		Cobalt	Chromium
		Nickel	Cadmium
			Copper
			Iron
			Lead
			Magnesium
			Manganese
			Phosphorous
			Silver
			Sodium
			Tin
			Titanium
			Vanadium
			Zinc

TABLE 21. CONTROLLED TRACE METALS EMISSIONS FROM THE SCRUBBER (g/dscm, as measured)

	SCRUBBER OUTLET				
	RUN 1	RUN 2	RUN 3	MEAN	SD
CALCIUM	3.01E-03	2.97E-03	2.04E-02	8.81E-03	1.01E-02
ALUMINUM	3.03E-03	2.19E-03	1.25E-02	5.90E-03	5.70E-03
SULFUR	4.02E-03	5.85E-03	1.20E-03	3.69E-03	2.34E-03
IRON	9.15E-04	2.86E-03	1.27E-04	1.30E-03	1.40E-03
SODIUM	3.68E-04	5.86E-04	6.10E-06	3.20E-04	2.93E-04
ZINC	2.87E-04	3.91E-04	8.58E-05	2.55E-04	1.55E-04
COPPER	1.76E-04	3.09E-04	1.11E-04	1.99E-04	1.01E-04
LEAD	5.32E-05	3.48E-04	1.55E-04	1.85E-04	1.50E-04
PHOSPHOROUS	2.61E-04	6.06E-05	2.26E-04	1.83E-04	1.07E-04
CHROMIUM	9.84E-05	4.42E-04	5.54E-07	1.80E-04	2.32E-04
TIN	2.06E-04	2.49E-04	5.09E-05	1.69E-04	1.04E-04
CADMIUM	1.28E-04	1.99E-04	1.01E-04	1.43E-04	5.05E-05
BARIUM	9.19E-05	7.20E-05	2.05E-04	1.23E-04	7.16E-05
MAGNESIUM	9.97E-05	1.21E-04	1.14E-04	1.11E-04	1.06E-05
SELENIUM	2.53E-07	2.78E-04	9.91E-07	9.32E-05	1.60E-04
TITANIUM	1.72E-04	5.99E-05	3.02E-05	8.74E-05	7.48E-05
NICKEL	5.03E-06	2.08E-04	3.02E-07	7.11E-05	1.19E-04
MANGANESE	1.39E-05	5.11E-05	4.93E-11	2.17E-05	2.64E-05
ARSENIC	1.52E-05	1.01E-05	2.35E-05	1.63E-05	6.76E-06
VANADIUM	3.39E-06	1.97E-05	3.52E-06	8.86E-06	9.37E-06
ANTIMONY	2.87E-06	2.65E-06	5.93E-06	3.82E-06	1.83E-06
SILVER	1.34E-06	1.07E-06	2.86E-06	1.76E-06	9.67E-07
COBALT	8.04E-07	2.44E-06	1.57E-07	1.13E-06	1.18E-06
GOLD	0.00E+00	6.33E-08	0.00E+00	2.11E-08	3.66E-08

TABLE 22. CONTROLLED TRACE METALS EMISSIONS FROM THE SCRUBBER (g/dscm @ 12% O_2)

SCRUBBER OUTLET					
	RUN 1	RUN 2	RUN 3	MEAN	SD
CALCIUM	9.03E-03	9.79E-03	4.61E-02	2.16E-02	2.12E-02
ALUMINUM	9.10E-03	7.22E-03	2.81E-02	1.48E-02	1.16E-02
SULFUR	1.21E-02	1.93E-02	2.71E-03	1.14E-02	8.31E-03
IRON	2.74E-03	9.42E-03	2.86E-04	4.15E-03	4.72E-03
SODIUM	1.10E-03	1.93E-03	1.38E-05	1.02E-03	9.62E-04
ZINC	8.61E-04	1.29E-03	1.93E-04	7.82E-04	5.52E-04
COPPER	5.28E-04	1.02E-03	2.50E-04	5.99E-04	3.88E-04
LEAD	1.60E-04	1.15E-03	3.50E-04	5.52E-04	5.23E-04
PHOSPHOROUS	7.84E-04	2.00E-04	5.09E-04	4.98E-04	2.92E-04
CHROMIUM	2.95E-04	1.46E-03	1.25E-06	5.85E-04	7.70E-04
TIN	6.19E-04	8.20E-04	1.15E-04	5.18E-04	3.63E-04
CADMIUM	3.83E-04	6.55E-04	2.28E-04	4.22E-04	2.16E-04
BARIUM	2.76E-04	2.37E-04	4.62E-04	3.25E-04	1.20E-04
MAGNESIUM	2.99E-04	3.98E-04	2.56E-04	3.18E-04	7.24E-05
SELENIUM	7.60E-07	9.17E-04	2.23E-06	3.07E-04	5.29E-04
TITANIUM	5.16E-04	1.98E-04	6.82E-05	2.61E-04	2.31E-04
NICKEL	1.51E-05	6.85E-04	6.81E-07	2.34E-04	3.91E-04
MANGANESE	4.16E-05	1.69E-04	1.11E-10	7.00E-05	8.78E-05
ARSENIC	4.57E-05	3.33E-05	5.30E-05	4.40E-05	9.94E-06
VANADIUM	1.02E-05	6.49E-05	7.94E-06	2.77E-05	3.22E-05
ANTIMONY	8.61E-06	8.73E-06	1.34E-05	1.02E-05	2.71E-06
SILVER	4.01E-06	3.54E-06	6.46E-06	4.67E-06	1.57E-06
COBALT	2.41E-06	8.05E-06	3.55E-07	3.61E-06	3.98E-06
GOLD	0.00E+00	2.09E-07	0.00E+00	6.96E-08	1.21E-07

Figure 16 is a rank order diagram that shows the relationship of the controlled metals emissions from the scrubber to the metals content of the sludge. As in the corresponding figure for the controlled ESP emissions, Figure 16 shows considerable scatter about the 45 degree line. This indicates a wide range of enrichment ratios for the scrubber emissions and a wide range of scrubber removal efficiencies for individual species.

Enrichment ratios for each metal are presented in Table 23 and shown in Figure 17. Cadmium, tin, nickel, chromium, sulfur, and lead had the highest enrichment ratios. The respective values for these metals were 127, 86, 64, 56, 32, and 36. These same metals had approximate values of 14, 3, 1, 1, 1, and 3 at the incinerator outlet. With the exception of magnesium, and phosphorous, all of the metals experienced significant increased enrichment ratios compared to the incinerator outlet.

Trace metal removal efficiencies are presented in Table 24 and summarized in Table 25. Table 25 shows that, on the average, the scrubber system only removed 4 of the 24 metals analyzed with an efficiency exceeding 95 percent. These included magnesium, phosphorous, sulfur and titanium.

ESP vs. Scrubber

The trace metal emissions data demonstrate that there are obvious differences between the performances of the ESP and scrubber systems. On the basis of enrichment ratios, there is a distinct difference. Table 26 shows the enrichment ratios for both control devices side by side. In every case, with the exception of cobalt, the enrichment ratios are higher for the scrubber than the ESP. Cadmium, chromium, lead, nickel, sulfur, and tin were much larger for the scrubber than the ESP. Though the enrichment ratios for selenium could not be calculated (not detected in the sludge), the mean concentration at the scrubber outlet (9.32×10^{-5} g/dscm) was higher than the mean concentration of the ESP outlet (1.23×10^{-5} g/dscm).

On the basis of trace metal removal efficiencies, there is also a clear distinction between the two control devices. Removal efficiencies for each control device are shown in Table 27 and summarized in Figure 18. The most obvious difference between the two units was the removal of sulfur. As expected, the scrubber system removed 97.97 percent of the sulfur while the ESP only removed 53.59 percent. In terms of the toxic metals, the ESP removed more of the cadmium, chromium, and lead than the scrubber system. The scrubber, however, removed more of the arsenic and nickel than the ESP unit. Selenium passed through both units.

In summary, there appear to be advantages of each unit. Sixteen of the twenty-four metals analyzed were removed more efficiently by the ESP. However, the ESP unit was less efficient than the scrubber in removing arsenic, barium, cobalt, gold, magnesium, nickel, and sulfur.

Size Distribution of Trace Metals

The size distribution of trace metals in the uncontrolled particulate emissions from the sewage sludge incinerator are shown in Table 28. The size distributions of trace metals in the controlled particulate emissions from the ESP and scrubber are shown side by side in Table 29. The values shown

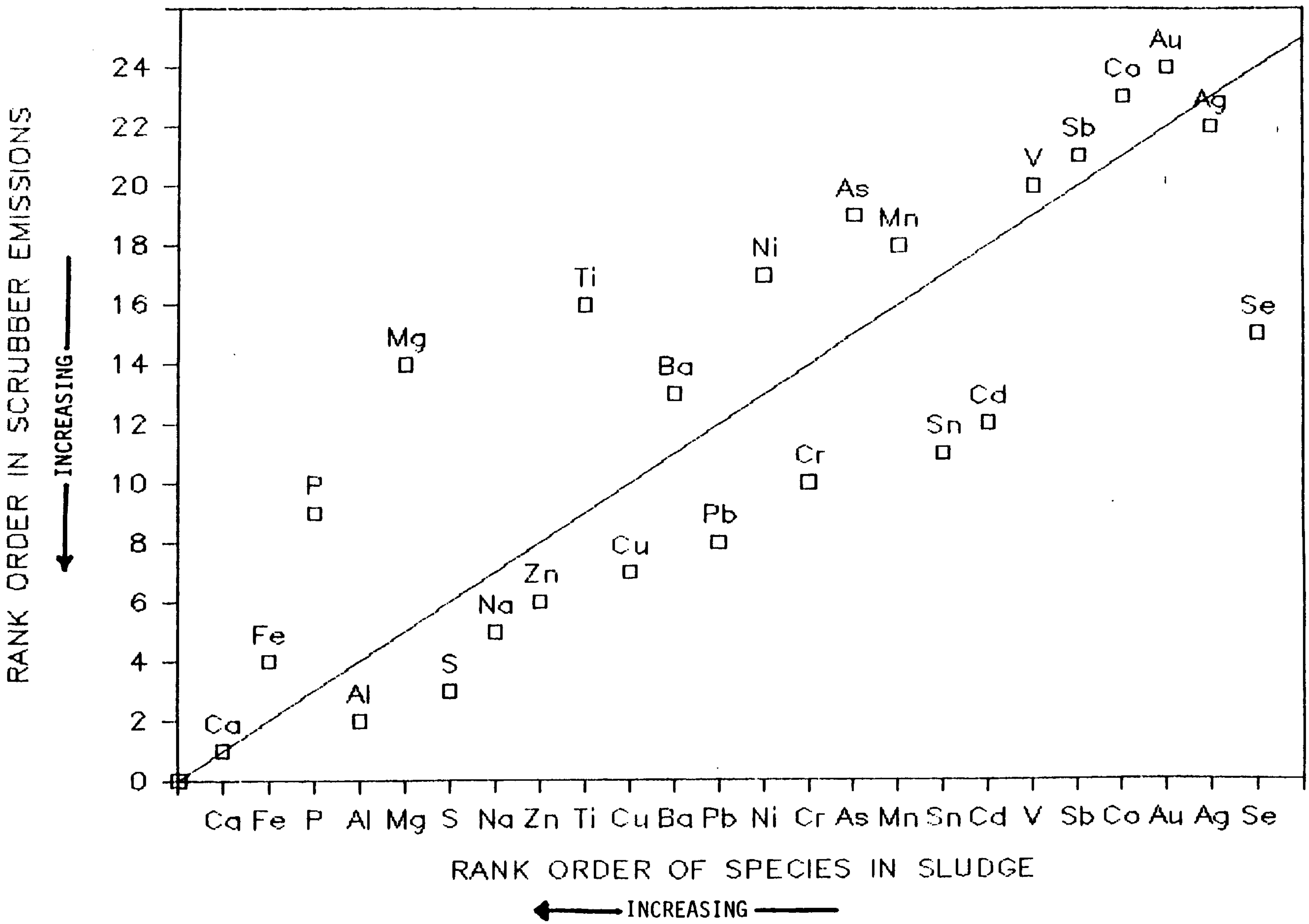


Figure 16. **Rank Order of Concentrations in the Controlled Scrubber Emissions.**

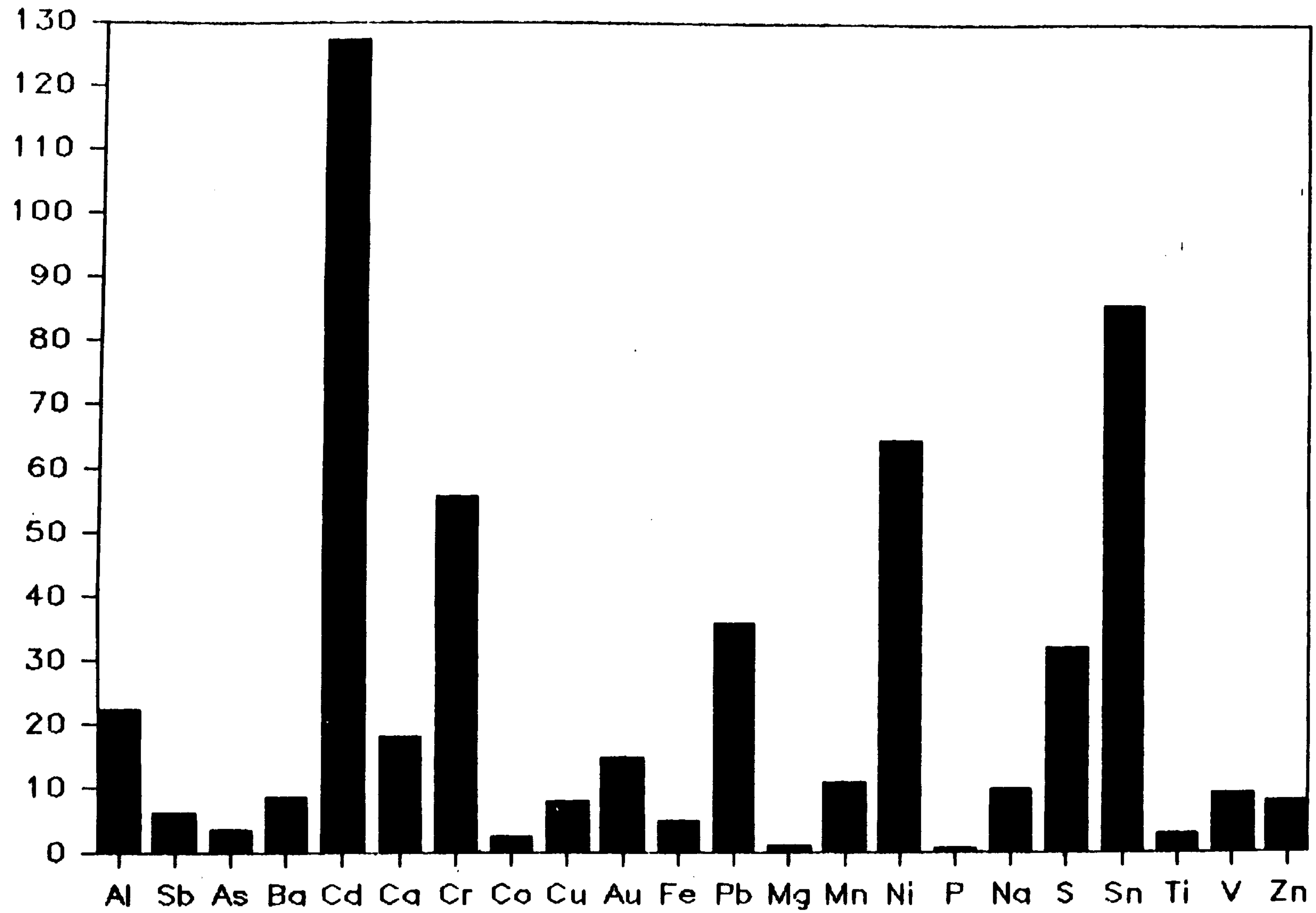


Figure 17. Average Enrichment Ratios for the Controlled Scrubber Emissions

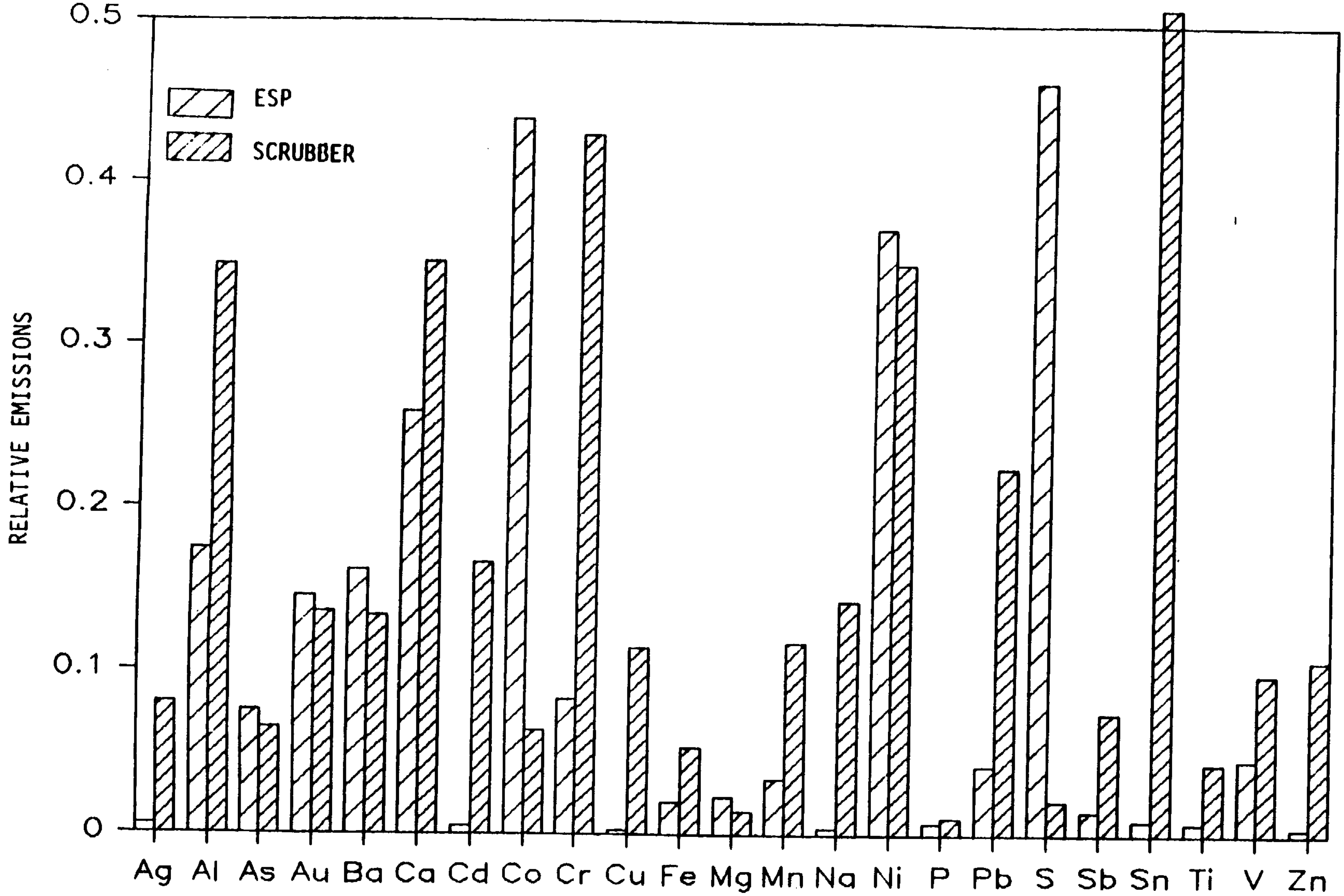


Figure 18. Trace Metal Removal Efficiencies ESP vs. Scrubber

TABLE 23. ENRICHMENT RATIOS FOR THE CONTROLLED SCRUBBER EMISSIONS

	ENRICHMENT RATIOS SCRUBBER OUTLET			
	RUN 1	RUN 2	RUN 3	AVG
ALUMINUM	24.25	12.82	29.86	22.31
ANTIMONY	4.60	4.50	9.35	6.15
ARSENIC	3.49	3.39	3.49	3.46
BARIUM	8.42	7.09	10.22	8.57
CADMIUM	106.47	213.61	61.30	127.13
CALCIUM	13.84	10.30	30.68	18.27
CHROMIUM	29.11	138.08	0.08	55.76
COBALT	0.00	7.10	0.34	2.48
COPPER	8.07	13.98	2.32	8.12
GOLD	ND	14.84	ND	14.80
IRON	3.63	11.03	0.22	4.96
LEAD	11.74	78.05	18.11	35.97
MAGNESIUM	1.06	1.10	0.56	0.91
MANGANESE	6.71	25.99	0.00	10.90
NICKEL	0.00	193.22	0.02	64.41
PHOSPHOROUS	1.06	0.13	0.52	0.57
SELENIUM	ND	ND	ND	ND
SILVER	ND	ND	ND	ND
SODIUM	11.70	17.53	0.09	9.77
SULFUR	43.87	45.21	7.34	32.14
TIN	106.25	136.89	13.75	85.63
TITANIUM	5.82	2.14	0.47	2.81
VANADIUM	4.19	21.94	1.77	9.30
ZINC	10.52	12.08	1.33	7.98

TABLE 24. TRACE METALS REMOVAL EFFICIENCIES FOR THE SCRUBBER

	SCRUBBER			
	RUN 1	RUN 2	RUN 3	AVERAGE
ALUMINUM	70.435	87.429	37.557	65.140
ANTIMONY	93.342	95.530	88.589	92.487
ARSENIC	93.922	96.614	89.907	93.481
BARIUM	87.930	90.657	81.276	86.621
CADMIUM	80.264	78.441	91.209	83.304
CALCIUM	84.496	90.633	19.424	64.851
CHROMIUM	71.333	0.000	99.813	57.049
COBALT	94.425	87.318	99.234	93.659
COPPER	87.229	83.484	94.796	88.503
GOLD	100.000	59.011	100.000	86.337
IRON	95.988	88.543	99.517	94.683
LEAD	90.488	53.221	88.645	77.451
MAGNESIUM	98.295	98.669	98.706	98.557
MANGANESE	92.213	72.457	100.000	88.223
NICKEL	94.926	0.000	99.717	64.881
PHOSPHORO	98.235	99.696	98.931	98.954
SELENIUM	0.000	0.000	0.000	0.000
SILVER	89.801	95.661	90.330	91.931
SODIUM	79.997	77.183	99.803	85.661
SULFUR	97.521	96.631	99.764	97.972
TIN	11.580	9.293	90.192	37.021
TITANIUM	90.474	97.482	98.926	95.628
VANADIUM	95.181	78.916	96.372	90.156
ZINC	85.245	85.153	97.278	89.225

TABLE 25. SUMMARY OF TRACE METALS REMOVAL EFFICIENCIES - SCRUBBER

Average of Three Runs

< 65 %	65 - 85%	86 - 95%	> 95 %
Calcium	Aluminum	Antimony	Magnesium
Chromium	Cadmium	Arsenic	Phosphorous
Nickel	Lead	Barium	Sulfur
Selenium		Cobalt	Titanium
Tin		Copper	
		Gold	
		Iron	
		Manganese	
		Silver	
		Sodium	
		Vanadium	
		Zinc	

Run 3

< 65 %	65 - 85%	86 - 95%	> 95 %
Aluminum	Barium	Antimony	Chromium
Calcium		Arsenic	Cobalt
Selenium		Cadmium	Gold
		Copper	Iron
		Lead	Magnesium
		Silver	Manganese
		Tin	Nickel
			Phosphorous
			Sodium
			Sulfur
			Titanium
			Vanadium
			Zinc

TABLE 26. AVERAGE ENRICHMENT RATIOS: ESP VS. SCRUBBER

Metal	Incinerator Outlet	ESP Outlet	Scrubber Outlet
Aluminum	1.36	5.28	22.31
Antimony	1.56	0.45	6.15
Arsenic	1.27	1.05	3.46
Barium	1.22	4.58	8.57
Cadmium	13.72	0.53	127.13
Calcium	1.37	7.74	18.27
Chromium	1.10	1.42	55.76
Cobalt	1.08	5.43	2.48
Copper	1.14	0.07	8.12
Gold	.56	ND	14.8
Iron	1.41	0.38	4.96
Lead	2.94	2.44	35.97
Magnesium	1.13	0.60	0.91
Manganese	1.40	0.20	10.90
Nickel	0.67	4.27	64.41
Phosphorous	1.17	0.03	0.57
Sodium	1.08	0.17	9.77
Sulfur	1.33	10.61	32.14
Tin	2.57	0.89	85.63
Titanium	1.13	0.22	2.81
Vanadium	1.41	0.28	9.30
Zinc	1.21	0.07	7.98

TABLE 27. TRACE METAL REMOVAL EFFICIENCIES: ESP VS. SCRUBBER

	ESP				SCRUBBER			
	RUN 1	RUN 2	RUN 3	AVERAGE	RUN 1	RUN 2	RUN 3	AVERAGE
ALUMINUM	74.507	83.768	89.286	82.520	70.435	87.429	37.557	65.140
ANTIMONY	97.240	99.170	99.385	98.598	93.342	95.530	88.589	92.487
ARSENIC	94.122	86.069	97.138	92.443	93.922	96.614	89.907	93.481
BARIUM	81.166	79.042	91.233	83.814	87.930	90.657	81.276	86.621
CADMIUM	98.843	99.821	99.952	99.539	80.264	78.441	91.209	83.304
CALCIUM	63.068	78.369	80.743	74.060	84.496	90.633	19.424	64.851
CHROMIUM	82.347	96.545	96.264	91.719	71.333	0.000	99.813	57.049
COBALT	8.279	68.917	91.181	56.126	94.425	87.318	99.234	93.659
COPPER	99.711	99.930	99.738	99.793	87.229	83.484	94.796	88.503
GOLD	100.000	100.000	56.268	85.423	100.000	59.011	100.000	86.337
IRON	95.291	99.235	99.511	98.012	95.988	88.543	99.517	94.683
LEAD	92.932	96.182	98.426	95.847	90.488	53.221	88.645	77.451
MAGNESIUM	96.007	98.903	98.299	97.736	98.295	98.669	98.706	98.557
MANGANESE	90.615	99.438	99.760	96.604	92.213	72.457	100.000	88.223
NICKEL	44.818	49.234	94.039	62.697	94.926	0.000	99.717	64.881
PHOSPHOROUS	98.900	99.487	99.485	99.291	98.235	99.696	98.931	98.954
SELENIUM	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SILVER	99.159	100.000	99.205	99.455	89.801	95.661	90.330	91.931
SODIUM	99.580	99.905	99.364	99.616	79.997	77.183	99.803	85.661
SULFUR	71.054	43.336	46.386	53.592	97.521	96.631	99.764	97.972
TIN	99.461	99.699	98.297	99.153	11.580	9.293	90.192	37.021
TITANIUM	98.983	99.558	99.334	99.292	90.474	97.482	98.926	95.628
VANADIUM	90.269	96.427	99.489	95.395	95.181	78.916	96.372	90.156
ZINC	99.317	99.850	99.864	99.677	85.245	85.153	97.278	89.225

TABLE 28. PARTICLE SIZE DISTRIBUTION OF TRACE METALS IN INCINERATOR EMISSIONS

	INCINERATOR OUTLET				
	PROBE + 10 um	3 um CYCLONE	1 um CYCLONE	FILTER CATCH	IMPINGER CATCH
ALUMINUM	33.45	38.46	1.42	26.67	0.00
ANTIMONY	21.01	66.03	1.68	11.28	0.00
ARSENIC	61.57	30.53	2.15	5.75	0.00
BARIUM	50.59	26.74	6.55	16.11	0.00
CADMIUM	28.22	44.37	11.37	16.04	0.00
CALCIUM	24.97	44.12	2.31	28.58	0.02
CHROMIUM	39.59	36.10	1.76	5.35	17.20
COBALT	50.60	39.93	2.19	7.28	0.00
COPPER	43.80	45.79	3.14	7.27	0.00
GOLD	0.00	37.41	0.00	62.59	0.00
IRON	50.95	43.26	2.27	2.71	0.81
LEAD	29.07	47.04	3.25	20.64	0.00
MAGNESIUM	44.56	47.31	2.12	5.98	0.02
MANGANESE	54.20	41.07	2.13	0.64	1.96
NICKEL	33.45	45.30	2.85	0.61	17.80
PHOSPHOROUS	47.88	46.50	1.96	2.71	0.95
SELENIUM	0.00	0.00	0.00	100.00	0.00
SILVER	19.87	67.28	6.31	6.54	0.00
SODIUM	44.33	44.98	1.34	9.36	0.00
SULFUR	0.96	1.38	0.08	0.35	97.23
TIN	26.23	36.15	2.72	34.90	0.00
TITANIUM	51.45	44.32	2.20	2.03	0.00
VANADIUM	44.13	45.75	2.63	7.48	0.00
ZINC	44.46	46.10	2.65	6.78	0.00

TABLE 29 PARTICLE SIZE DISTRIBUTION OF TRACE METALS IN ESP AND SCRUBBER EMISSIONS

	ESP OUTLET				SCRUBBER OUTLET		
	PROBE + 10 um	FILTER CATCH	IMPINGER CATCH		PROBE + 10 um	FILTER CATCH	IMPINGER CATCH
ALUMINUM	5.00	95.00	0.00	ALUMINUM	6.82	93.18	0.00
ANTIMONY	8.58	91.42	0.00	ANTIMONY	1.22	98.78	0.00
ARSENIC	3.14	45.04	51.82	ARSENIC	5.61	84.10	10.29
BARIUM	1.07	98.93	0.00	BARIUM	0.70	99.15	0.15
CADMIUM	31.45	35.38	33.18	CADMIUM	50.98	49.02	0.00
CALCIUM	3.22	96.36	0.42	CALCIUM	6.00	93.88	0.12
CHROMIUM	52.73	0.00	47.27	CHROMIUM	96.81	0.74	2.45
COBALT	3.96	63.14	32.90	COBALT	54.94	0.00	45.06
COPPER	74.55	10.46	14.99	COPPER	67.05	32.95	0.00
GOLD	17.21	82.79	0.00	GOLD	0.00	100.00	0.00
IRON	17.61	63.81	18.58	IRON	91.41	5.32	3.28
LEAD	16.66	83.34	0.00	LEAD	51.05	47.64	1.31
MAGNESIUM	23.75	73.53	2.71	MAGNESIUM	69.01	29.88	1.11
MANGANESE	25.30	0.00	74.70	MANGANESE	93.65	0.00	6.35
NICKEL	64.47	0.00	35.53	NICKEL	96.50	0.00	3.50
PHOSPHOROUS	15.96	1.83	82.21	PHOSPHOROUS	33.22	58.15	8.63
SELENIUM	13.78	3.31	82.91	SELENIUM	99.27	0.73	0.00
SILVER	0.00	100.00	0.00	SILVER	0.00	100.00	0.00
SODIUM	100.00	0.00	0.00	SODIUM	100.00	0.00	0.00
SULFUR	1.79	0.03	98.18	SULFUR	64.54	13.60	21.86
TIN	65.61	4.67	29.72	TIN	72.68	27.32	0.00
TITANIUM	49.24	50.76	0.00	TITANIUM	94.26	5.74	0.00
VANADIUM	11.10	12.96	75.95	VANADIUM	70.92	29.08	0.00
ZINC	54.48	45.52	0.00	ZINC	78.03	21.97	0.00

No metals were caught in the 3 and 1 um cyclones.

represent the percent by weight of each metal captured in the various SASS train size fractions. Each capture point along the SASS train retained particles of a specific size range. The SASS train fractions have the following approximate particle size characteristics:

SASS SIZE FRACTION	SIZE OF PARTICLES RETAINED (d = particle diameter)
Probe and 10-um cyclone	d > 10 um
3 um cyclone	3 um < d < 10 um
1 um cyclone	1 um < d < 3 um
Filter Catch	.1 um < d < 1 um
Impinger Catch	d < .1 um

At the outlets of both control devices, no particulate matter was captured in the 3 um and 1 um cyclones. These size fractions have been omitted from the appropriate tables. Histograms for Nickel, Lead, and Cadmium are presented in Figures 19 through 24 for the inlets and outlets of both control devices. Since the slipstream to the ESP consisted of the flue gas entering the scrubber, the inlet concentrations of both units are assumed to be identical. The three histograms for the inlet concentrations show that in general the majority of particles had diameters greater than 3 um. For Cadmium, 73 percent of the particles were distributed between the 10 um and 3 um cyclones. For Nickel and Lead, 79 percent and 76 percent of the total particles captured were also in the first two cyclones. Sulfur was the exception to this rule in that 97 percent was captured in the impinger catch.

The histograms for the trace metals at the scrubber outlet show that only a small percentage of the total particles were captured in the impinger catch. Nickel, for example, was primarily captured by the probe and 10 um cyclone.

The histograms for the trace metals at the ESP outlet show that the impinger fraction contributed a large percentage of many metals. Cadmium, for example, was distributed evenly among the 10 um cyclone, filter and impinger. No general patterns were apparent for the metals as a whole.

Trace Metals Content of Bottom Ash and ESP Hopper Catch

The trace metals content of incinerator bottom ash and ESP hopper catch samples for each test run are presented in Table 30 and Table 31, respectively. The average trace metals contents of the bottom ash samples were generally similar to that of the dry, volatiles free sludge. Arsenic, iron, phosphorous, and zinc were the only metals to increase significantly in content relative to the sludge concentrations. Enrichment ratios for the metals in the bottom ash and ESP hopper catch are shown in Table 32. Zinc had the highest enrichment ratio with a value of 2.32. The contents of nickel and sulfur descreased sharply relative to the sludge concentrations. The enrichment ratios of these species were .39 and .31, respectively.

In the ESP hopper catch, the content of antimony, cadmium, and lead increased significantly relative to the sludge concentrations. The enrichment ratios of these species were 2.77, 7.58, and 2.13, respectively. Sodium was the only metal in the ESP hopper catch to decrease significantly

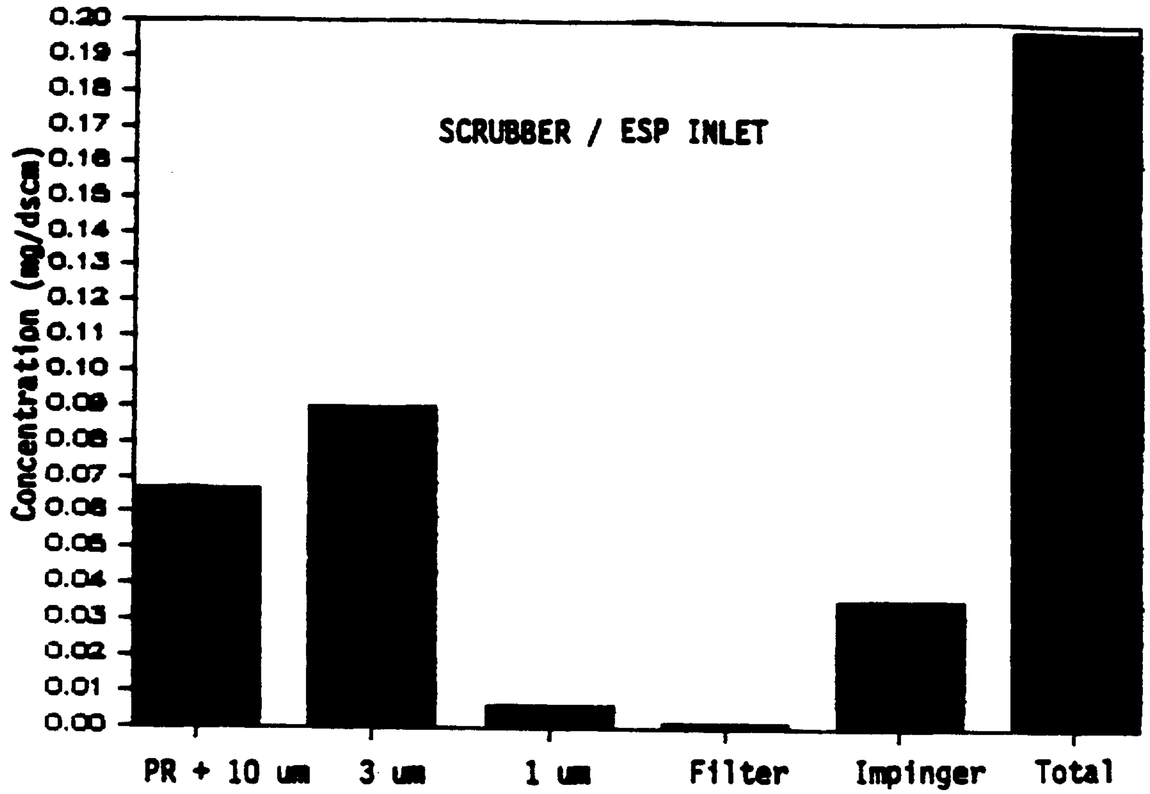


Figure 19. Particle Size Distribution of Nickel in the Uncontrolled Incinerator Emissions.

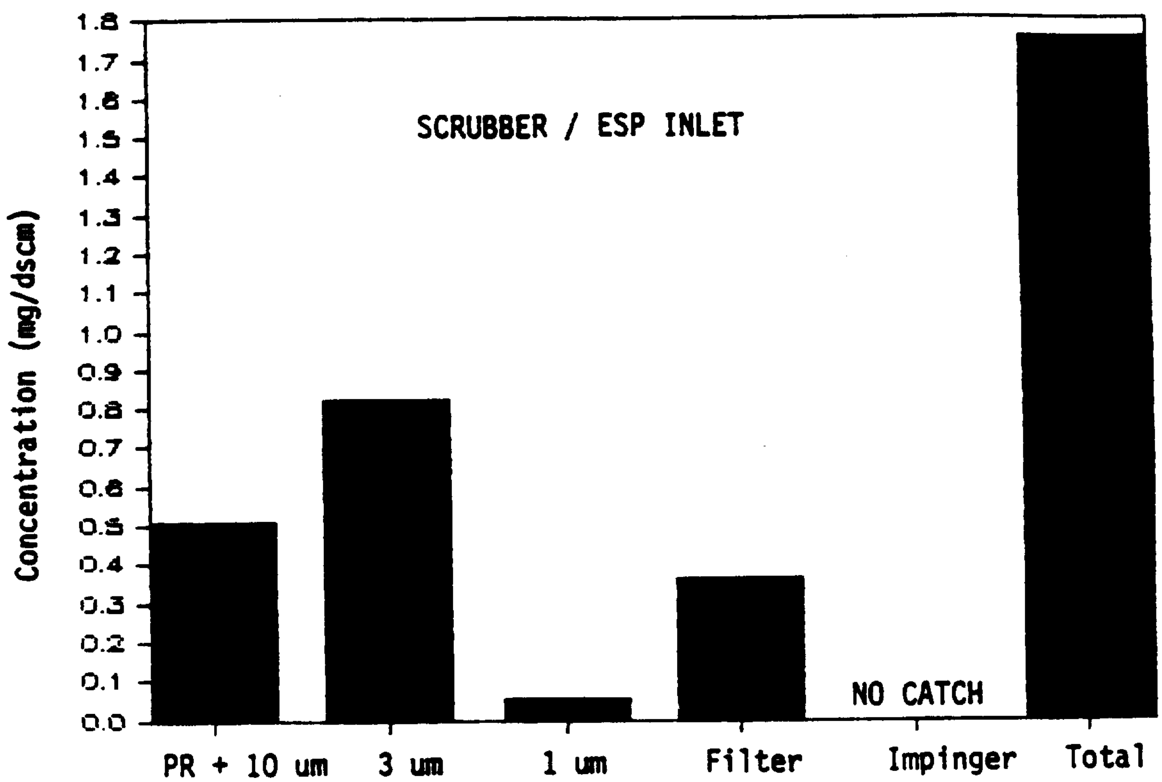


Figure 20. Particle Size Distribution of Lead in the Uncontrolled Incinerator Emissions.

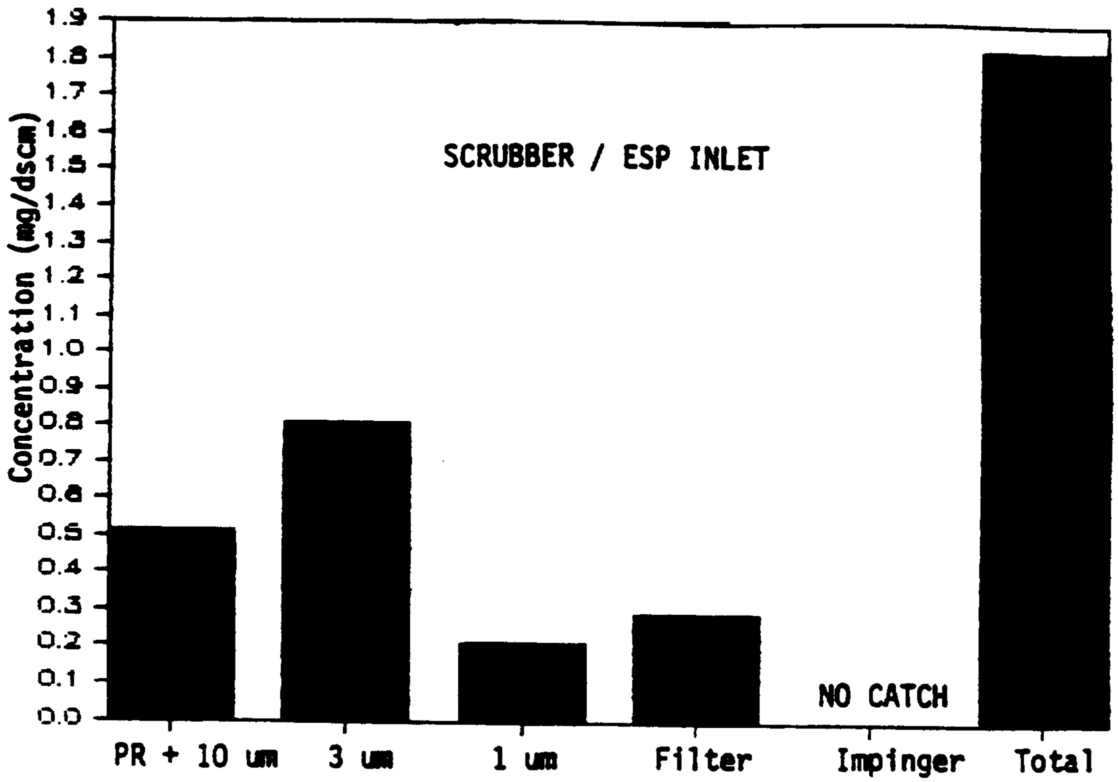
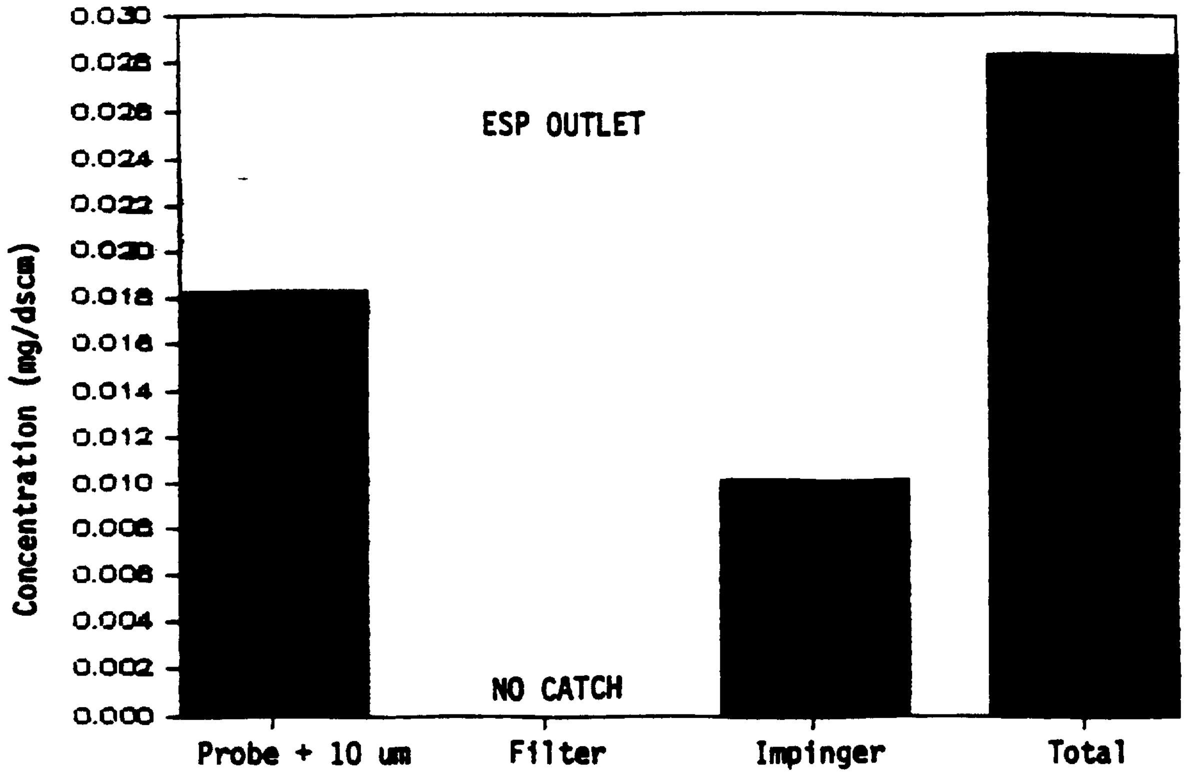


Figure 21. Particle Size Distribution of Cadmium in the Uncontrolled Incinerator Emissions.



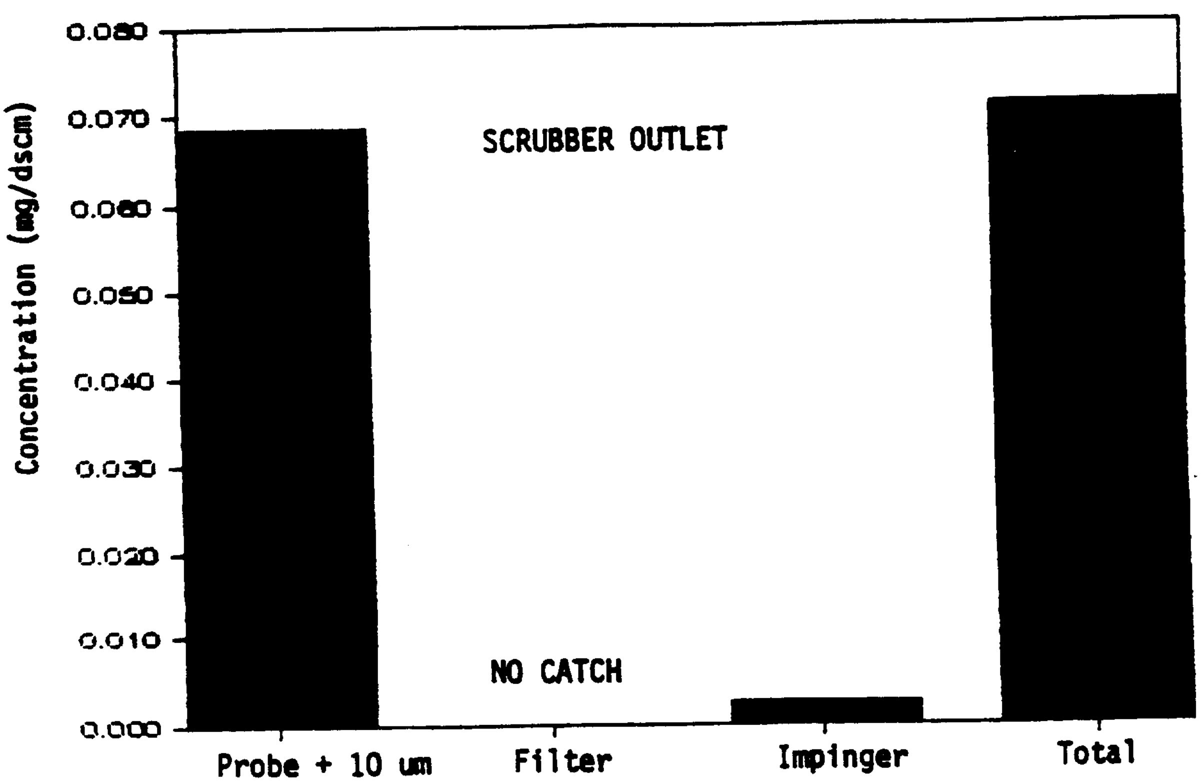


Figure 22. Particle Size Distributions of Nickel in the Controlled ESP and Scrubber Emissions.

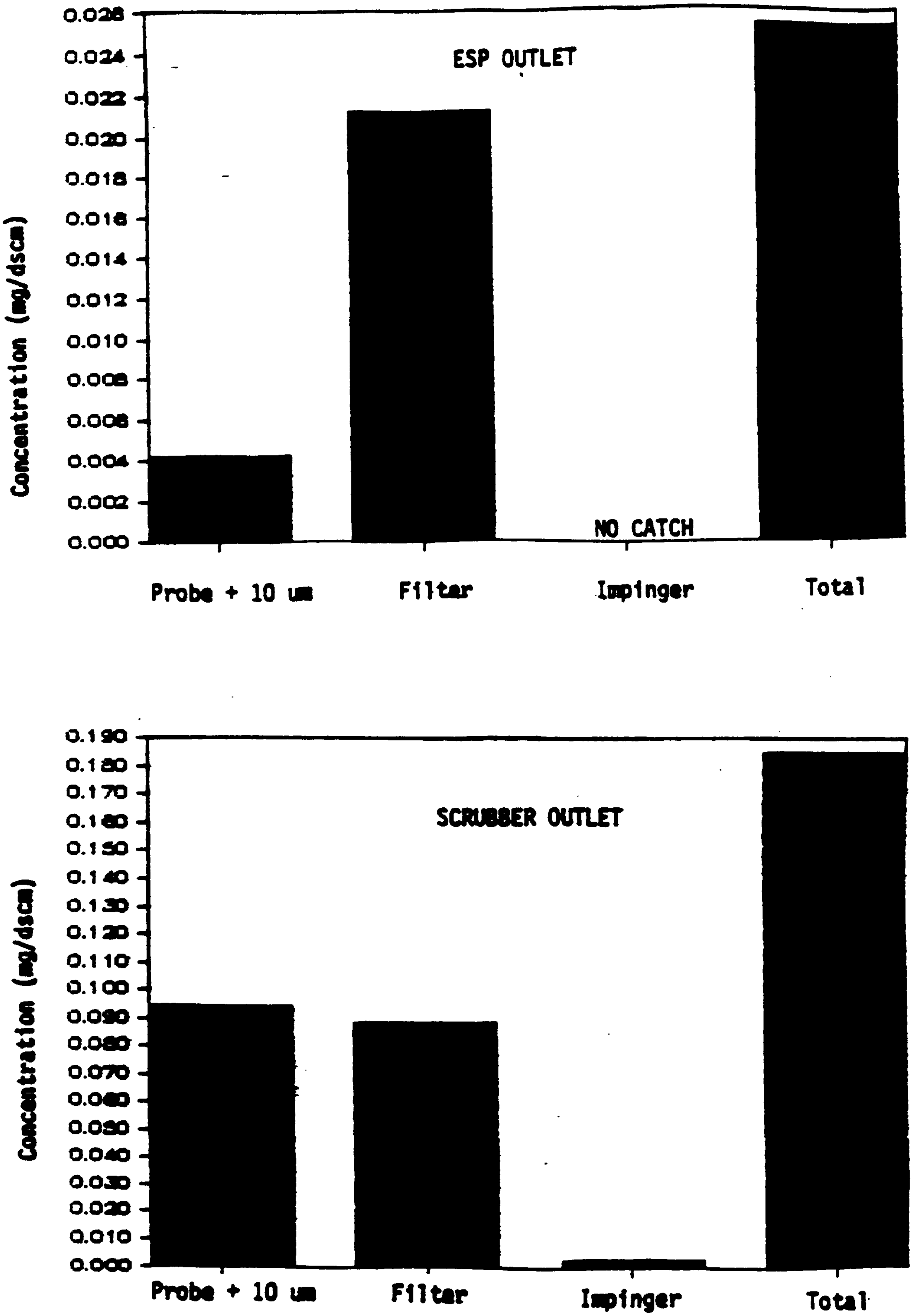
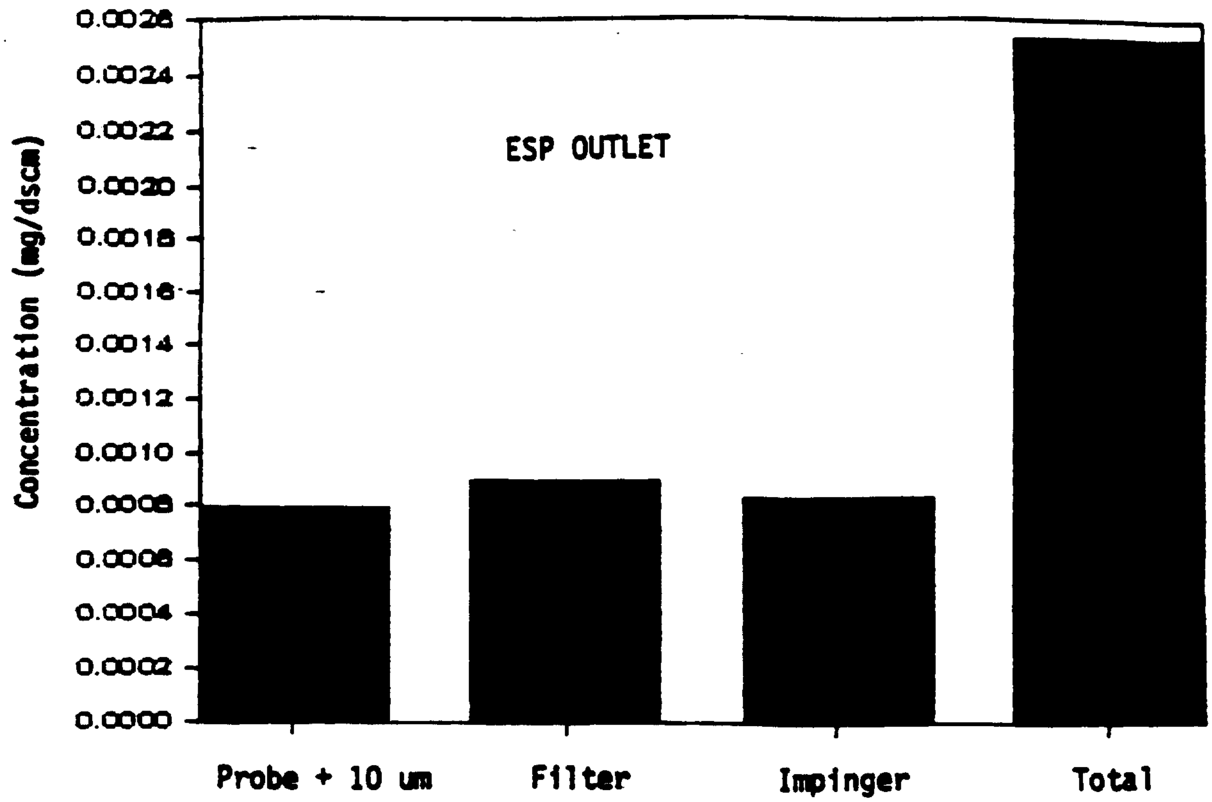


Figure 23. Particle Size Distributions of Lead in the Controlled ESP and Scrubber Emissions.



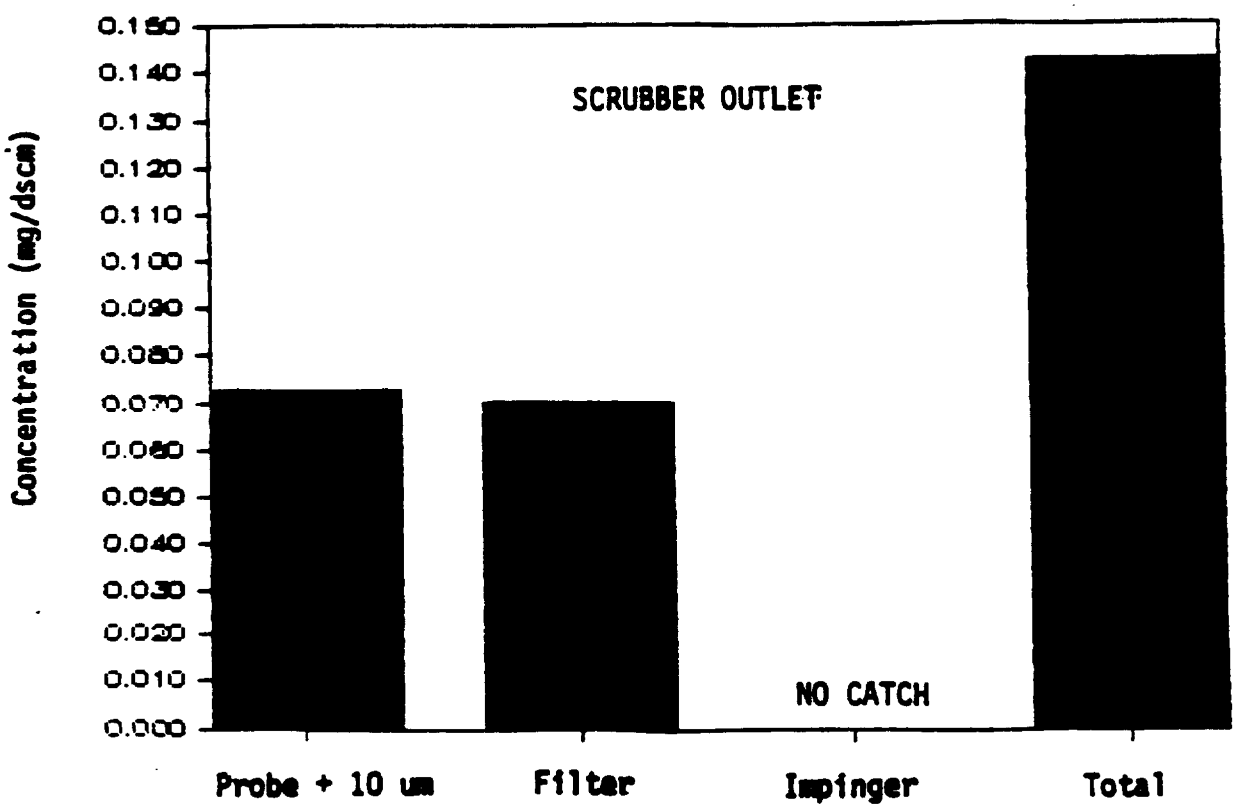


Figure 24. Particle Size Distributions of Cadmium in the Controlled ESP Emissions and Scrubber Emissions.

TABLE 30. TRACE METAL CONCENTRATIONS IN BOTTOM ASH

TRACE METAL CONCENTRATIONS IN BOTTOM ASH
PPM

	RUN 1	RUN 2	RUN 3	AVERAGE
ALUMINUM	4.90E+04	1.79E+04	3.19E+04	3.29E+04
ANTIMONY	1.76E+02	7.17E+01	8.31E+01	1.10E+02
ARSENIC	7.84E+02	9.29E+02	9.70E+02	8.94E+02
BARIUM	2.11E+03	1.07E+03	1.21E+03	1.47E+03
CADMIUM	1.30E+02	1.11E+02	1.00E+02	1.13E+02
CALCIUM	5.40E+04	4.27E+04	6.01E+04	5.23E+04
CHROMIUM	8.08E+02	7.87E+02	8.86E+02	8.27E+02
COBALT	5.20E+01	5.06E+01	6.31E+01	5.52E+01
COPPER	5.36E+03	5.68E+03	5.83E+03	5.62E+03
GOLD	0.00E+00	8.40E-01	3.48E+03	1.16E+03
IRON	7.16E+04	6.72E+04	7.52E+04	7.13E+04
LEAD	8.55E+02	8.61E+02	9.89E+02	9.02E+02
MAGNESIUM	2.65E+04	1.74E+04	2.10E+04	2.16E+04
MANGANESE	4.47E+02	4.07E+02	4.73E+02	4.42E+02
NICKEL	1.68E+02	1.36E+02	1.74E+02	1.59E+02
PHOSPHOROUS	6.06E+04	6.34E+04	6.30E+04	6.23E+04
SELENIUM	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SILVER	5.89E+01	9.54E+01	4.76E+01	6.73E+01
SODIUM	7.41E+03	6.21E+03	7.30E+03	6.97E+03
SULFUR	7.19E+03	5.56E+03	5.52E+03	6.09E+03
TIN	3.91E+02	3.98E+02	4.45E+02	4.12E+02
TITANIUM	7.44E+03	7.75E+03	8.60E+03	7.93E+03
VANADIUM	1.82E+02	1.76E+02	2.22E+02	1.93E+02
ZINC	3.78E+04	8.93E+02	8.32E+03	1.57E+04

TABLE 31. TRACE METAL CONCENTRATIONS IN ESP HOPPER CATCH

	TRACE METAL CONCENTRATIONS IN ESP HOPPER CATCH PPM			
	RUN 1	RUN 2	RUN 3	AVERAGE
ALUMINUM	2.23E+04	2.56E+04	5.66E+04	3.48E+04
ANTIMONY	3.27E+02	3.04E+02	2.92E+02	3.08E+02
ARSENIC	1.67E+03	9.89E+02	9.81E+02	1.21E+03
BARIUM	1.71E+03	2.03E+03	1.16E+03	1.63E+03
CADMIUM	5.68E+02	1.73E+03	2.48E+03	1.59E+03
CALCIUM	4.34E+04	4.79E+04	9.95E+04	6.36E+04
CHROMIUM	7.16E+02	7.48E+02	8.75E+02	7.80E+02
COBALT	4.04E+01	4.65E+01	5.13E+01	4.61E+01
COPPER	3.87E+03	5.31E+03	6.93E+03	5.37E+03
GOLD	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IRON	1.53E+05	7.14E+04	9.45E+04	1.06E+05
LEAD	8.38E+02	1.98E+03	3.60E+03	2.14E+03
MAGNESIUM	1.66E+04	1.97E+04	2.93E+04	2.19E+04
MANGANESE	6.71E+02	4.71E+02	5.44E+02	5.62E+02
NICKEL	6.40E+02	1.63E+02	2.17E+02	3.40E+02
PHOSPHOROUS	5.19E+04	5.96E+04	8.27E+04	6.47E+04
SELENIUM	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SILVER	0.00E+00	1.76E+00	0.00E+00	5.88E-01
SODIUM	3.64E+03	2.89E+03	2.93E+03	3.16E+03
SULFUR	1.86E+04	2.26E+04	2.16E+04	2.10E+04
TIN	3.63E+02	8.28E+02	1.07E+03	7.54E+02
TITANIUM	6.30E+03	7.28E+03	8.36E+03	7.31E+03
VANADIUM	1.91E+02	2.08E+02	2.63E+02	2.21E+02
ZINC	7.71E+03	4.14E+03	1.05E+04	7.46E+03

TABLE 32. AVERAGE ENRICHMENT RATIOS FOR TRACE METALS IN BOTTOM ASH & ESP HOPPER CATCH

Metal	Bottom Ash	ESP Hopper Catch
Aluminum	0.91	0.85
Antimony	0.94	2.77
Arsenic	1.23	1.68
Barium	0.59	0.67
Cadmium	0.49	7.58
Calcium	0.82	0.94
Chromium	1.07	1.00
Cobalt	0.97	0.81
Copper	1.06	1.00
Gold	ND	ND
Iron	1.19	1.80
Lead	0.91	2.13
Magnesium	0.92	0.92
Manganese	1.00	1.29
Nickel	0.39	0.91
Phosphorous	1.16	1.22
Sodium	0.89	0.40
Sulfur	0.31	1.07
Tin	0.94	1.73
Titanium	1.12	1.04
Vanadium	0.91	1.04
Zinc	2.32	1.04

in concentrations relative to the sludge. Its enrichment ratio was 0.40. The total solids and volatiles content data for the process samples are presented in Table 33.

CONTINUOUS MONITORING DATA

Mean values of the continuously monitored gases (O_2, CO, CO_2, SO_2, NO_x, THC) are shown for each run in Table 34. The data show that most of the runs have similar mean concentration values for individual gases. The overall mean values for the three test runs are as follows: oxygen, 16.0 percent by volume (dry); carbon dioxide, 4.7 percent by volume (dry); carbon monoxide, 1403.7 ppmv (dry); sulfur oxides, 348.4 ppmv (dry); nitrogen oxides, 130.3 ppmv (dry); and total hydrocarbons, 43.1 ppmv as propane (wet). The only combustion gas with a mean value that varied significantly between runs was THC. The measured THC concentration for Run 03 (63.8 ppmv) was approximately 2 times higher than that for Run 01 (29.8 ppmv).

Five-minute average values for the continuously monitored combustion gases are tabulated in Appendix B and are shown graphically as functions of time in Figures 25 through 30. These graphs show that although the mean concentration values of the monitored combustion gases were generally similar for the three runs, the instantaneous behavior of these concentrations was different for the three runs.

DISPERSION MODELING PARAMETERS

Dispersion modeling parameters for the existing wet scrubber system and a hypothetical full scale ESP system are listed in Table 35. Parameters for the scrubber are based on measured data from Runs 01-03, adjusted slightly for the presence of the slipstream during the test runs. Parameters for the hypothetical full scale ESP were based on the following assumptions.

(i) The ESP stack height and diameter were assumed identical to that of the existing scrubber stack.

(ii) The ESP stack temperature was calculated based on a heat balance. The outlet ESP temperature was assumed to be 500^oF, the shaft cooling air outlet temperature was assumed to be 260^oF (i.e., average for Runs 01-03), and the incinerator: shaft cooling air flow ratio was assumed identical to that of Figure 3.

(iii) The ESP stack moisture was calculated based on the average incinerator outlet moisture for Runs 01-03 (26.8% H_2O). The ratio of incinerator exhaust gas to shaft cooling air was assumed to be identical to that shown in Figure 3.

(iv) The dry standard ESP stack gas flow rate was assumed to be equal to that of the scrubber. No ambient air inleakage was assumed for the full scale ESP. The actual ESP stack gas flow rate was calculated using the temperature and moisture values from (ii) and (iii) above.

(v) The percent oxygen at the ESP stack (dry basis) was assumed to be equal to that of the scrubber.

(vi) Sludge feed rates were assumed equal to the scrubber average values during the test runs.

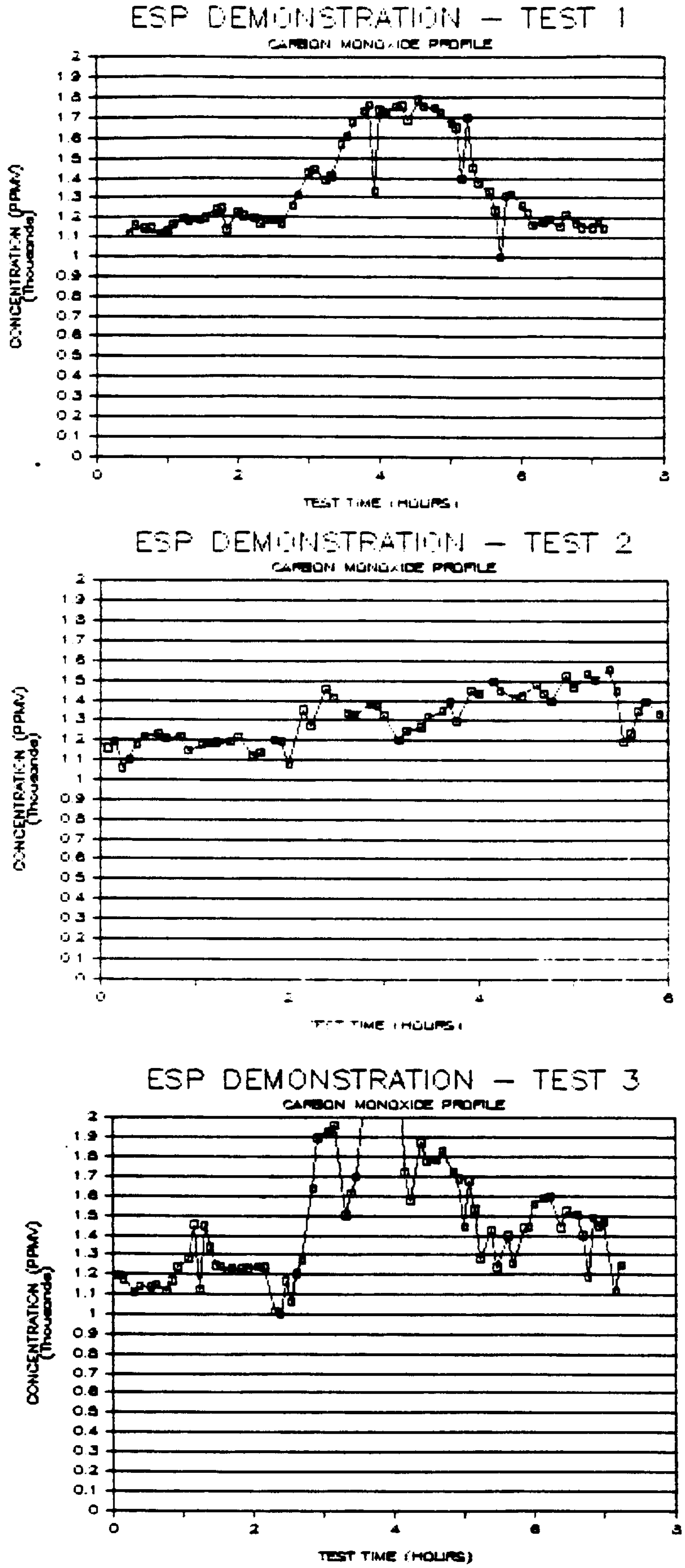


Figure 25. **Continuous Monitoring of CO.**

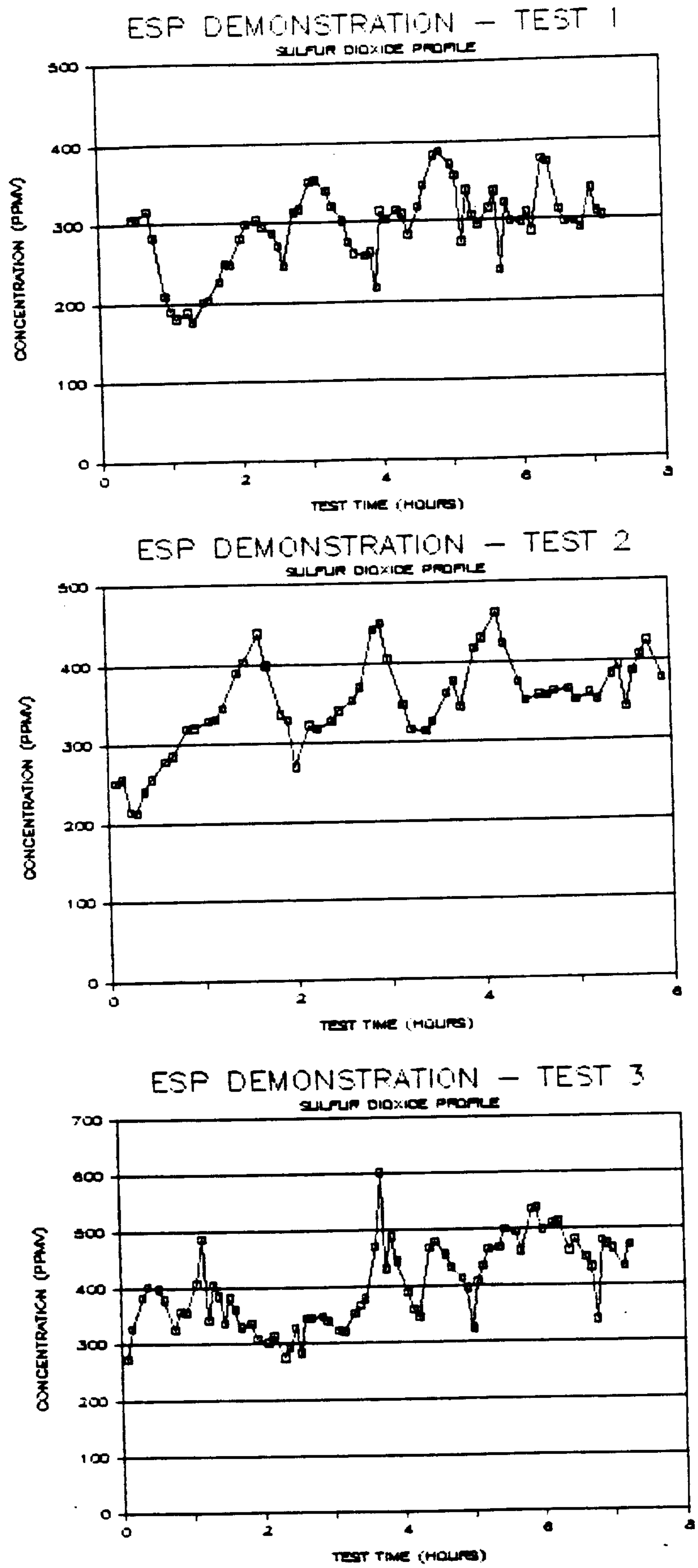
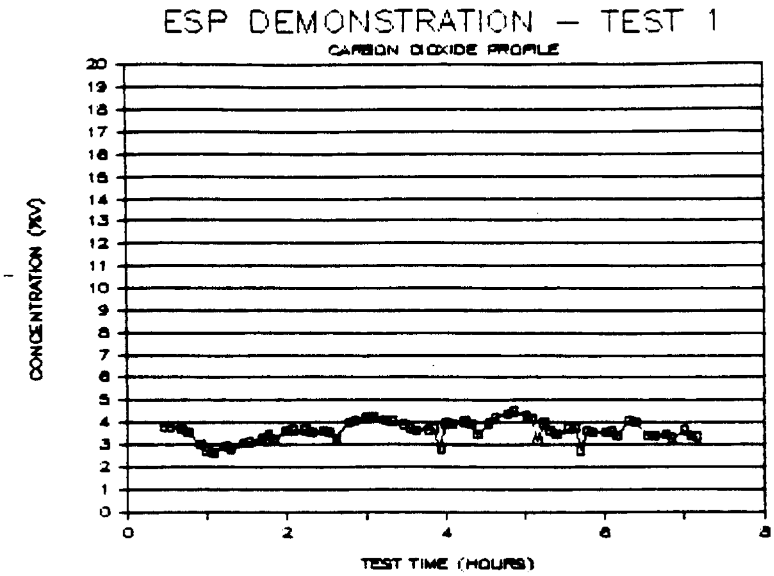
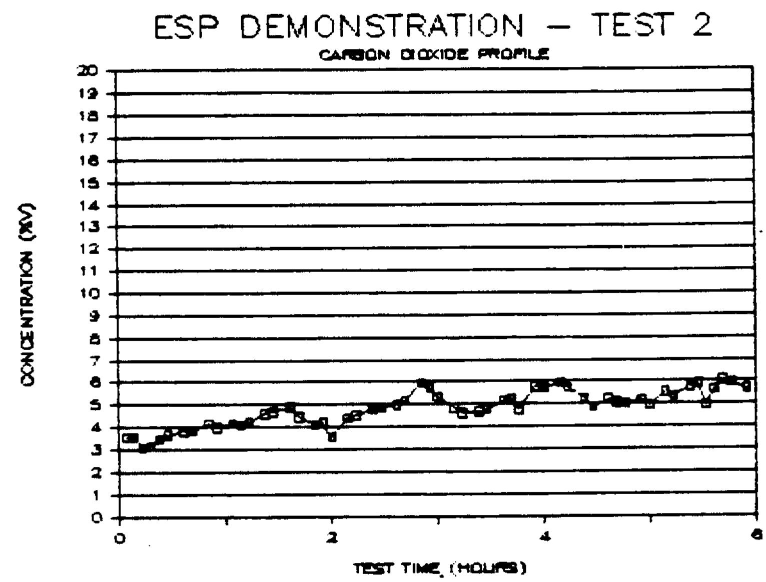


Figure 26. **Continuous Monitoring of SO_2.**





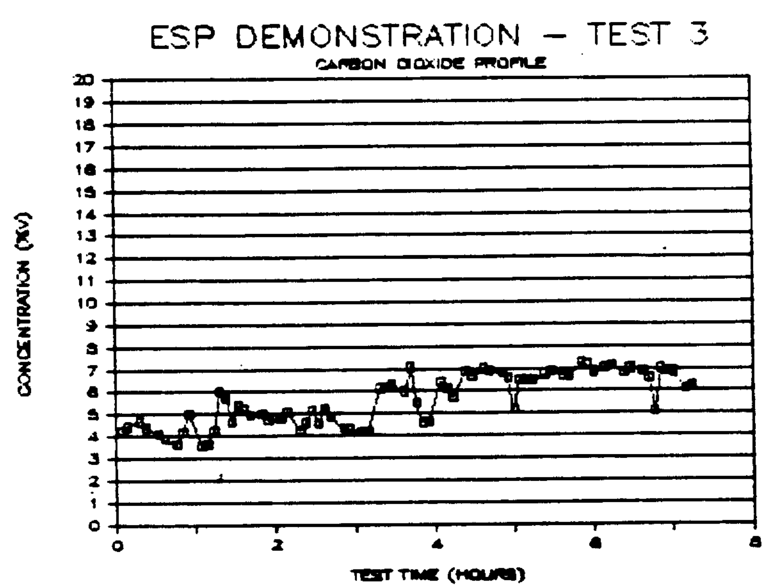


Figure 27. Continuous Monitoring of CO_2.

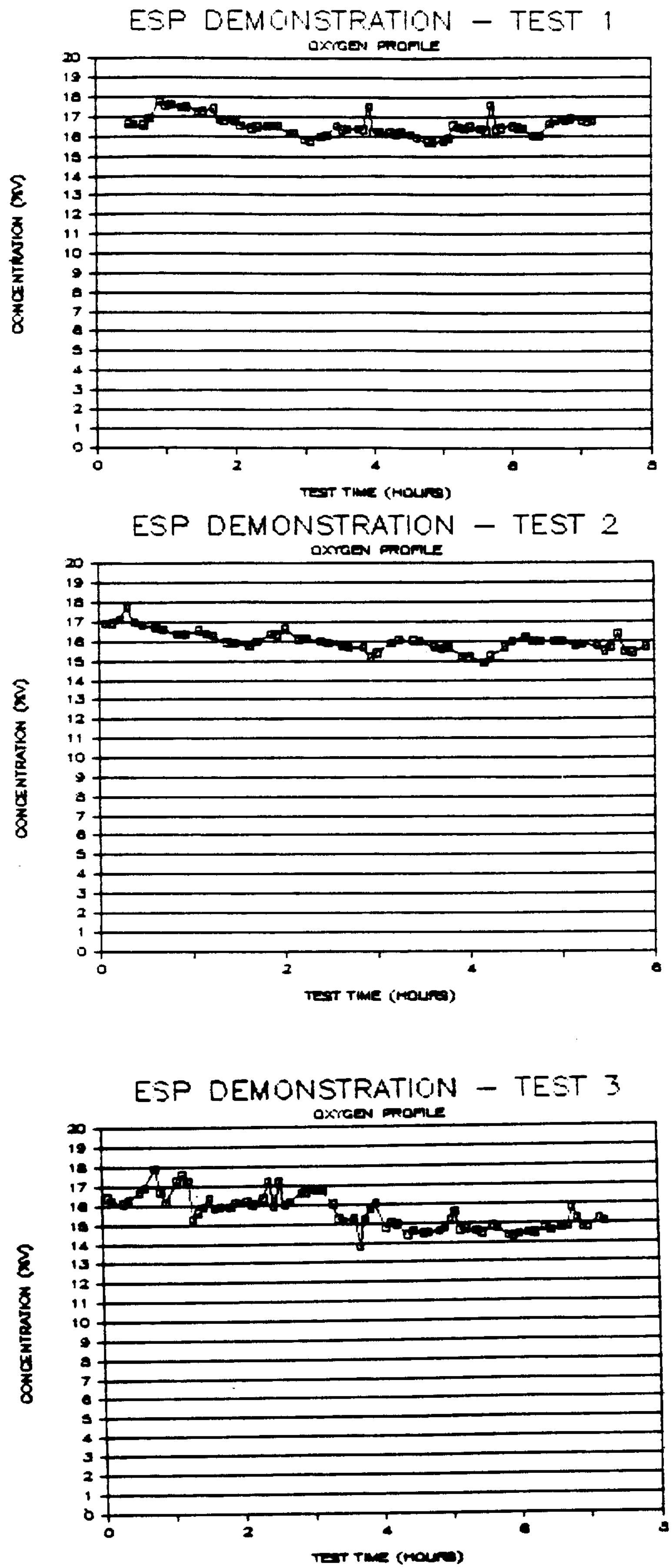


Figure 28. **Continuous Monitoring of O_2.**

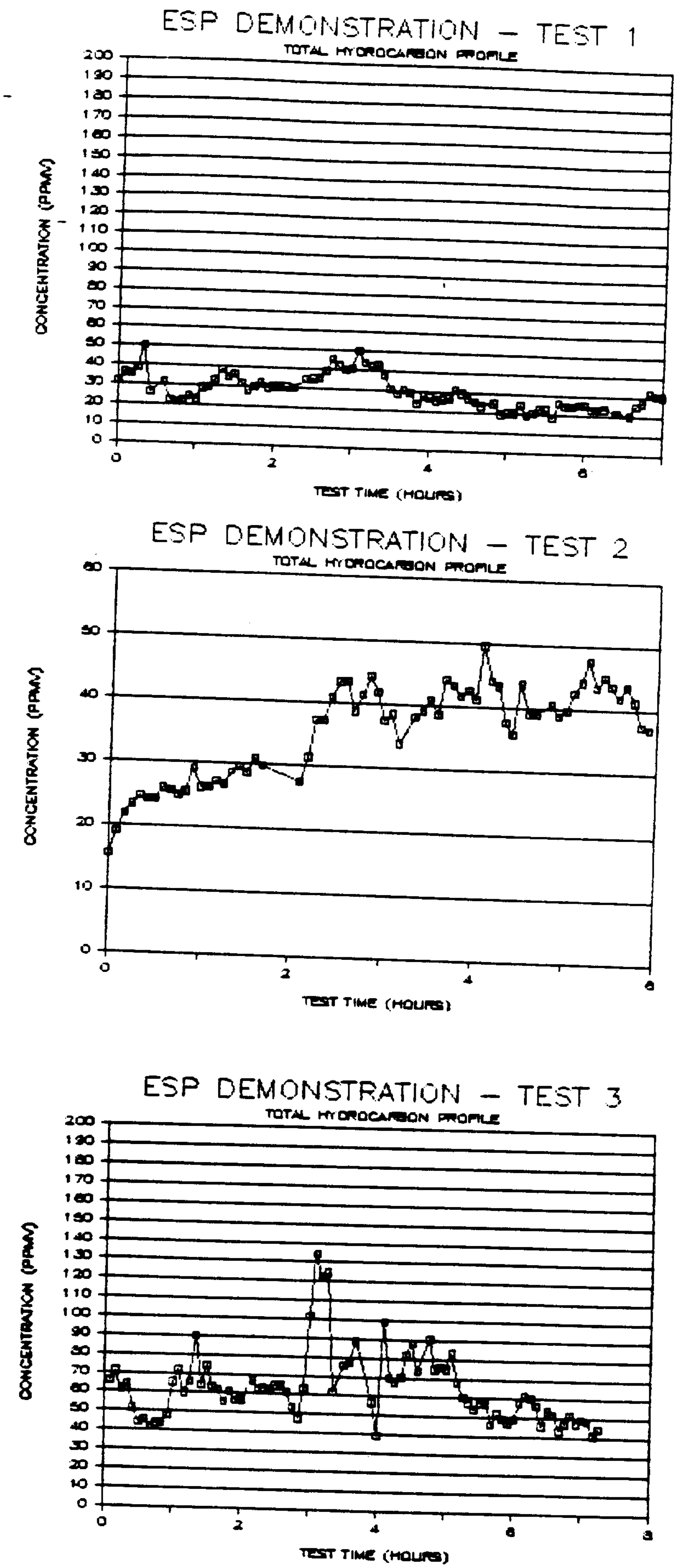


Figure 29. Continuous Monitoring of THC.

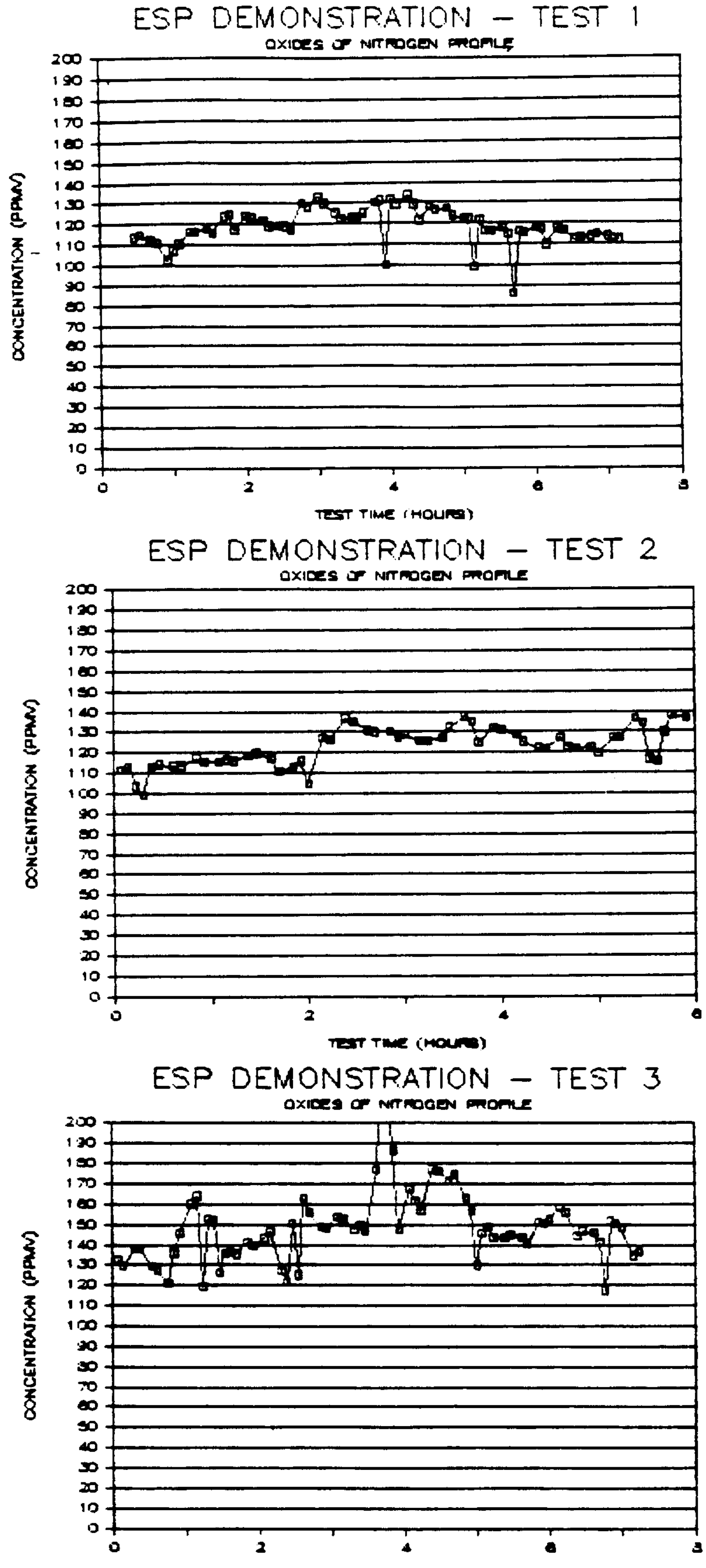


Figure 30. Continuous Monitoring of NO_x.

TABLE 33. TOTAL SOLIDS AND VOLATILES CONTENT DATA FOR THE PROCESS SAMPLES

Sample	Total Solids Content of Sample (wt. %)	Volatiles Content of Sample (wt. %)
<u>Sludge Feed Samples</u>		
Sludge Feed, Run 01	14.9	62.3
Sludge Feed, Run 02[a]	14.4	62.9
Sludge Feed, Run 02	14.3	62.0
Sludge Feed, Run 03	14.6	64.5
<u>Bottom Ash Samples</u>		
Bottom Ash, Run 01	99.9	0.4
Bottom Ash, Run 02	99.9	0.4
Bottom Ash, Run 03[a]	100.0	0.8
Bottom Ash, Run 03	100.0	1.0
<u>ESP Hopper Catch Samples</u>		
ESP Hopper Catch, Run 01	61.0	4.2
ESP Hopper Catch, Run 02[a]	79.4	4.3
ESP Hopper Catch, Run 02	80.4	4.0
ESP Hopper Catch, Run 03	76.3	6.3

[a]Duplicate analyses were performed.

TABLE 34. MEAN VALUES OF CONTINUOUSLY MONITORED COMBUSTION GASES DURING ESP TESTS

Parameter	Run 01	Run 02	Run 03	Average
O_2 (% V)	16.5	16.0	15.6	16.0
CO (ppmv)	1352.2	1308.7	1550.3	1403.7
CO_2 (% V)	3.6	4.8	5.6	4.7
SO_2 (ppmv)	292.9	350.1	402.2	348.4
NO_x (ppmv)	118.8	122.9	149.3	130.3
THC (ppmv)	29.8	35.8	63.8	43.1

TABLE 35. DISPERSION MODELING PARAMETERS FOR THE SCRUBBER AND A FULL SCALE ESP

	Scrubber[a]	ESP
Stack Height (above ground level)	22.0 m	22.0 m
Stack Diameter (inside)	1.2 m	1.2 m
Stack Temperature (outlet)	65°C	206°C
Stack Moisture (outlet)	1%	13.4%
Stack Gas Flow (dry standard)	225 dscmm	225 dscmm
Stack Gas Flow (actual conditions)	263 acmm	417 acmm
% O_2 (dry)	17.8%	17.8%
Sludge Feed Rate (wet basis)	1615 kg/hr	1615 kg/hr
Sludge Feed Rate (dry basis)	250 kg/hr	250 kg/hr

[a]Modeling parameters for the scrubber system were developed from data measured during Runs 01-03, adjusted by the slipstream volume.
[b]Modeling parameters for the full scale ESP system were calculated as discussed in the text.

SECTION 4

SAMPLING PROCEDURES

This chapter describes the flue gas sampling and process sampling methods used during the scrubber and ESP tests.

SASS TRAIN SAMPLING PROCEDURE

This section contains the SASS train sampling description that was originally included in the site specific test plan. The procedures specified in the test plan were carefully followed during the scrubber and ESP test runs. For additional details on the sampling train, see the Operating and Service Manual: Source Assessment Sampling System. A schematic diagram of the SASS train is shown in Figure 31.

Equipment Preparation for Sample Collection

The first stage in preparing a new sampling train and new sample containers for sample collection is prepassivation with a nitric acid solution. All metal and glass surfaces in the sampling train that come in contact with the sample will be prepassivated by a 30-min contact with 15 percent (v/v) aqueous nitric acid. Use a stiff nylon brush or hard Teflon scraper to aid in cleaning the surfaces if necessary. Agitate the parts initially to remove trapped air bubbles. Rinse in a second solution of 15 percent (v/v) HNO_3, then rinse with distilled water. Next, rerinse by spraying thoroughly with alcohol (taking care to cover all surfaces) or dip in alcohol and agitate for 10 seconds. Finally, dry in clean air. If the impingers are to be used immediately after cleaning, they should be thoroughly dried or rerinsed with distilled water to prevent foaming.

A different approach is used for subsequent cleanings of SASS train components and the sample bottles for the ESP test program. In the lab, the sampling train components and sample bottles are cleaned in three successive stages using a different solvent in each stage. The solvents are hot soapy water, distilled water, 0.1 normal nitric acid, and acetone in the order listed. This will remove all extraneous particulate matter and produce a clean, dry surface. A contaminated train component may not be used in a sampling run. All equipment treated in the above fashion must be placed in a clean area to await the test.

The field area in which the sample clean-up operations are performed must be as clean as possible under existing field conditions. An enclosed space is required in which reasonable precaution has been taken to remove spurious dust, dirt, or particulate contaminats. Reasonable precaution is intended to mean that the area has been swept clean, doors or other significant draft-inducing sources have been closed, and all work bench areas have been wiped down.

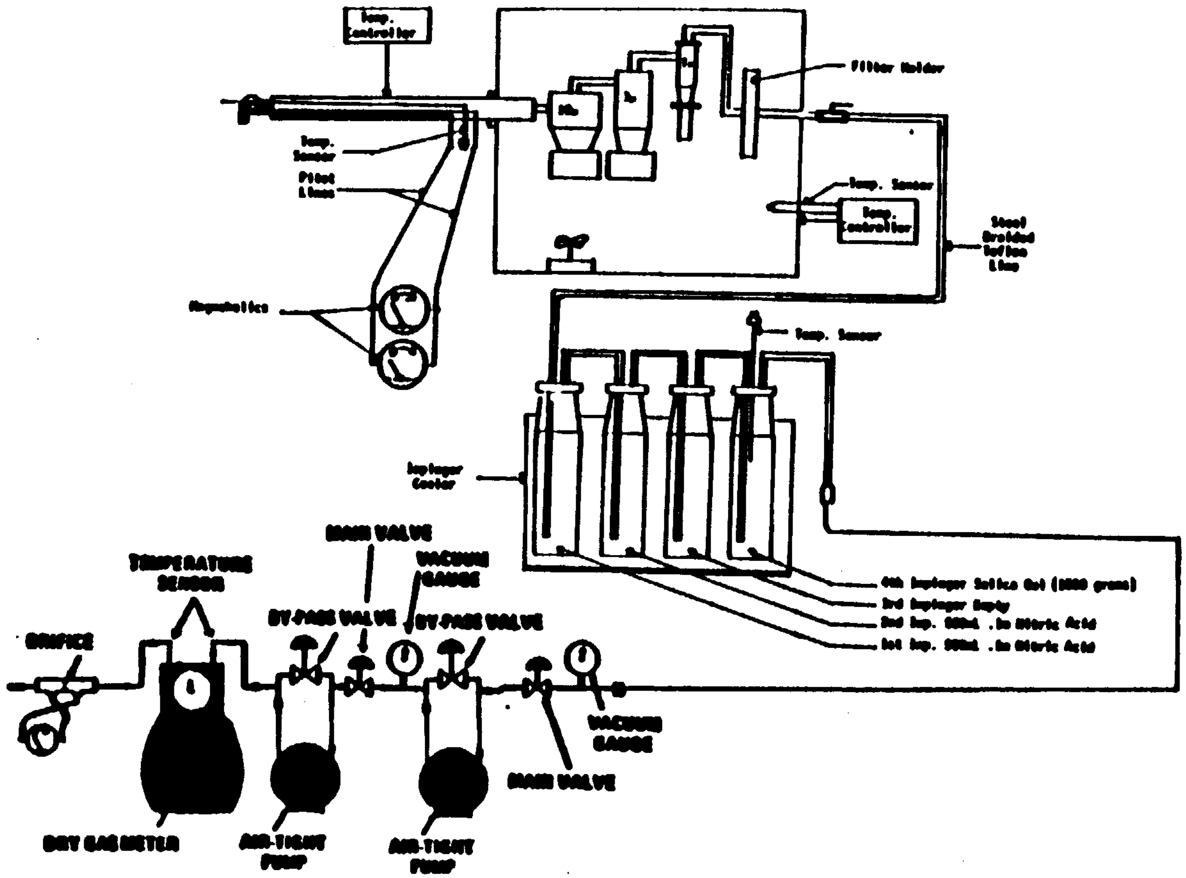


Figure 31. Source assessment sampling train (SASS) schematic.

Apparatus Checkout - SASS Test

The following tasks will be performed in the home base laboratory prior to testing:

a. Assemble all components required for the complete system.

b. Clean components in accordance with the procedures described in reference manual.

c. Obtain a sufficient quantity of solvents to maintain adequate reserves during the elapsed time in the field.

d. Accumulate an inventory of Swagelok fittings for each SASS train.

e. Examine all SASS train parts closely for defects that might induce down-time problems in the field.

f. Leak-check the entire system.

Next to the cleaning procedures, leak-checking the train prior to field use is one of the most important pretest tasks to be performed. This procedure can save many hours in the field. The leak-checking procedure involves assembling the entire train, sealing the probe tip, opening the isolation ball valve, turning on the pumping system, and observing flow meter gauges for the existence of any appreciable flow. Evacuate the train to 127 mm Hg (5 in Hg). The allowable leak rate for the SASS train is 0.0014 m^3/min (0.05 ft^3/min) at this pressure. Close the isolation ball valve and leak check the remainder of the train at 508 mm Hg (20 in Hg). The leak rate should again be less than 0.0014 m^3/min (0.05 ft^3/min). If this criterion is not easily achievable using Teflon gaskets in the system, Viton A gasket substition may facilitate meeting this standard. The instructions accompanying the train present in detail the steps involved in leak-checking the system.

SASS Train Sampling Procedure

The SASS sample is normally acquired at a point of average velocity near the center of the duct (the average velocity being determined by a velocity traverse). During the ESP test program the sample will be drawn from single points. Sample point location will be determined either by EPA Method 1 specifications or in the center of the duct depending on velocity stratification, access and sample time. The sample will be withdrawn at a constant flow rate using a nozzle that is specifically selected for near isokinetic conditions (± 20%) when the test is initiated. Nozzle selection will be determined from preliminary measurements at each location.

The steps involved in using the train to acquire this sample are described in detail in the manuals provided with the SASS train. An outline of the procedure follows:

I. Test Site

A. Prepare sampling port on duct, flue, or stack.

B. Secure electrical power.

II. SASS Train Assembly

A. Attach probe to oven.

B. Place the three cyclones and filter assembly in the oven and connect the 10 um cyclone to the probe. (Note that to achieve the proper size fractionation, the vortex breakers for the ">10 um" and for the "10- to 3-um" cyclones should not be used.)

C. Assemble impinger train.

1. Fill impinger bottles with the reagents listed in Table 37.
2. Place the impingers in the tray in impinger case, cap bottles, and make appropriate connections.
3. Transport to sampling location.
4. Fill impinger case with ice and water.

D. Connect oven outlet (i.e., filter housing outlet) to the first impinger.

E. Connect vacuum pumps (in parallel) to the last impinger outlet.

F. Connect all temperature sensors and power lines to control unit.

III. Checkout and Inspection

A. Run gas flow leak check.

B. Check temperature indicators with all thermocouples at ambient temperature.

C. Heat oven and probe to 204°C (400°F).

D. Note operation of vacuum pumps and gas meter.

E. Inspect pitot tube; also, compare results of volume measured with orifice meter and dry gas meter. Calibrate each as necessary.

IV. Operation

A. Measure stack temperature, moisture content, and velocity profile.

B. Calculate size of probe nozzle needed for isokinetic sampling and select and attach appropriate size nozzle. The stack temperature, gas velocity, and effluent water vapor content must be considered when choosing the proper nozzle size (preliminary measurement).

C. Calculate train gauge reading to achieve train flow rate of 0.184 ACMM (6.5 ACFM) in the cyclones. (This flow rate is necessary for proper operation of the cyclones.)

D. Install probe in stream at desired point and turn on vacuum pumps; adjust train flow rate to the calculated desired rate.

E. If the flow rate cannot be maintained at greater than 75 percent of the desired rate, the filter must be changed.

F. Collect sample. Monitor all temperatures and flow rates, and adjust as necessary.

V. Shutdown

A. Close valves at pumps.

B. Remove the sampling nozzle train from inside the stack.

C. Turn off pumps.

D. Switch off main power.

Replacement of a clogged filter is a time-consuming process that could require as much as 2 hours, depending on the sampling location and the possible difficulties that can be encountered in exchanging the filter housings. Once removed, the housing should be carried intact to a clean area for filter removal. A second, preloaded filter housing should be available for use when the first filter housing is removed for unloading, cleaning, adn reloading. Check this assembled replacement filter assembly for leaks before placing it in service, then make a final check of the pressure drop of the whole SASS system when the unit is again reassaembled. The 1 um cyclone reservoir should be checked for remaining capacity whenever the filter is replaced. Take care not to contaminate the contents during this inspection.

Sample Handling and Shipment

A modular approach will expedite the explanation of the procedures involved in sample transfer and handling. For this reason, the SASS train is considered in terms of the following sections:

A. Nozzle and probe
B. Cyclone system interconnect tubing
C. Cyclones
D. Filter
F. Impingers

At the conclusion of the sampling run, the train is disassembled and transported to the mobile lab unit or prepared work area as follows:

A. Open the cyclone oven to expedite cooling, disconnect the probe, and cap off both ends.
B. Disconnect the line joining the cyclone oven to impinger assembly at the exit side of the filter and cap off (1) the entrance to the 10-um cyclone, (2) the filter holder exit, and (3) the entrance to the joining line, which was disconnected from the filter holder exit point.

C. Cap off the entrance line to the impinger system.

D. Disconnect the line leaving the silica gel impinger at its exit point and cap off the impinger exit. Discard ice and water from the impinger box to facilitate carrying.

At the completion of all sample transfer activities, all SASS train components must be completely clean in preparation for the next sampling run.

SASS Sample Recovery

Figure 32 is a flowchart of the sample handling for those SASS fractions containing particulate matter. Each glass container with the individual cyclone catches will be dessicated and weighed separately. All front half components of the SASS sampling train, including the probe, cyclone(s) and filter assembly will be rinsed with acetone after cyclone sample recovery. A second rinse with 0.1N nitric acid will be used to insure removal of residual metal species. Both rinses will be retained for analysis. The acetone rinses for all stages will be combined and evaporated to dryness, dessicated and weighed. The four (4) individual stage weights will be summed with the combined acetone evaporate and totaled for the front half mass particulate determination.

Figure 33 is a flowchart of the sample handling for the impinger contents. The impinger catch will be used to determine moisture andcondensed metals analysis of metal content will be performed on the impinger contents. An empty third impinger has been added to ensure adequate condensation of moisture from the sample stream. The fourth impinger will contain silica gel (1500 grams).

CONTINUOUS MONITORING OF COMBUSTION GASES

Continuous monitoring was performed at the incinerator outlet (scrubber inlet) sampling location for O_2, CO_2, CO, NO_x, SO_2, and THC. The continuous monitoring was performed throughout the 6-hour period that SASS train sampling was being conducted each test day. Sample acquisition was accomplished using an in-stack filter probe and 24 m (80 ft) of heat-traced Teflon sample line connected to a mobile laboratory. The heat traced sample line was maintained at a temperature of 150°C (300°F) to prevent condensation in the sample line. The stack gas sample was drawn through the filter and heated sample line using pumps located in the mobile laboratory. Sample gas to be analyzed for CO, CO_2, O_2, NO_x and SO_2 was then pumped through a sample gas conditioner, consisting of an ice bath and knockout trap, to remove moisture and thus provide a dry gas stream for analysis. A separate unconditioned gas slip stream was supplied to the THC analyzer for analysis on a wet basis.

An Anarad Model 412 nondispersive infrared (NDIR) analyzer was used to measure CO and CO_2; a Beckman Model 755 paramagnetic analyzer was used to measure O_2; a Teco Model 10 chemiluminescent analyzer was used to measure NO_x; a Teco Model 40 pulsed fluorescence analyzer was used to measure SO_2; and a Beckman Model 402 flame ionization detector was used to measure THC. The calibration procedures for the continuous monitors included a three point (two upscale plus zero) linearity check on the first test day, single point and zero calibration checks daily, and single point drift check at the end of each test day.

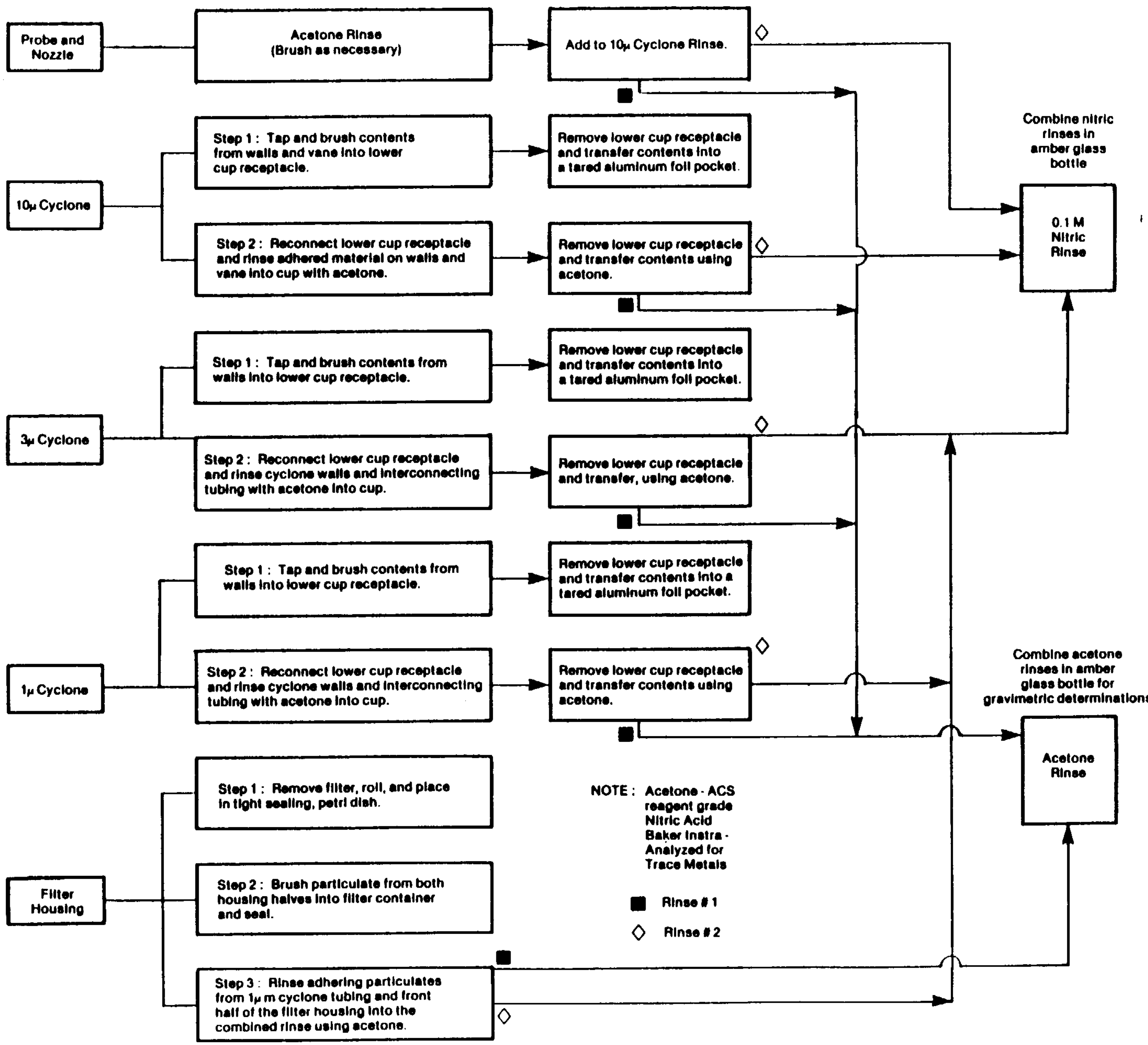


Figure 32. Sample handling and transfer - nozzle, probe, cyclones, and filter.

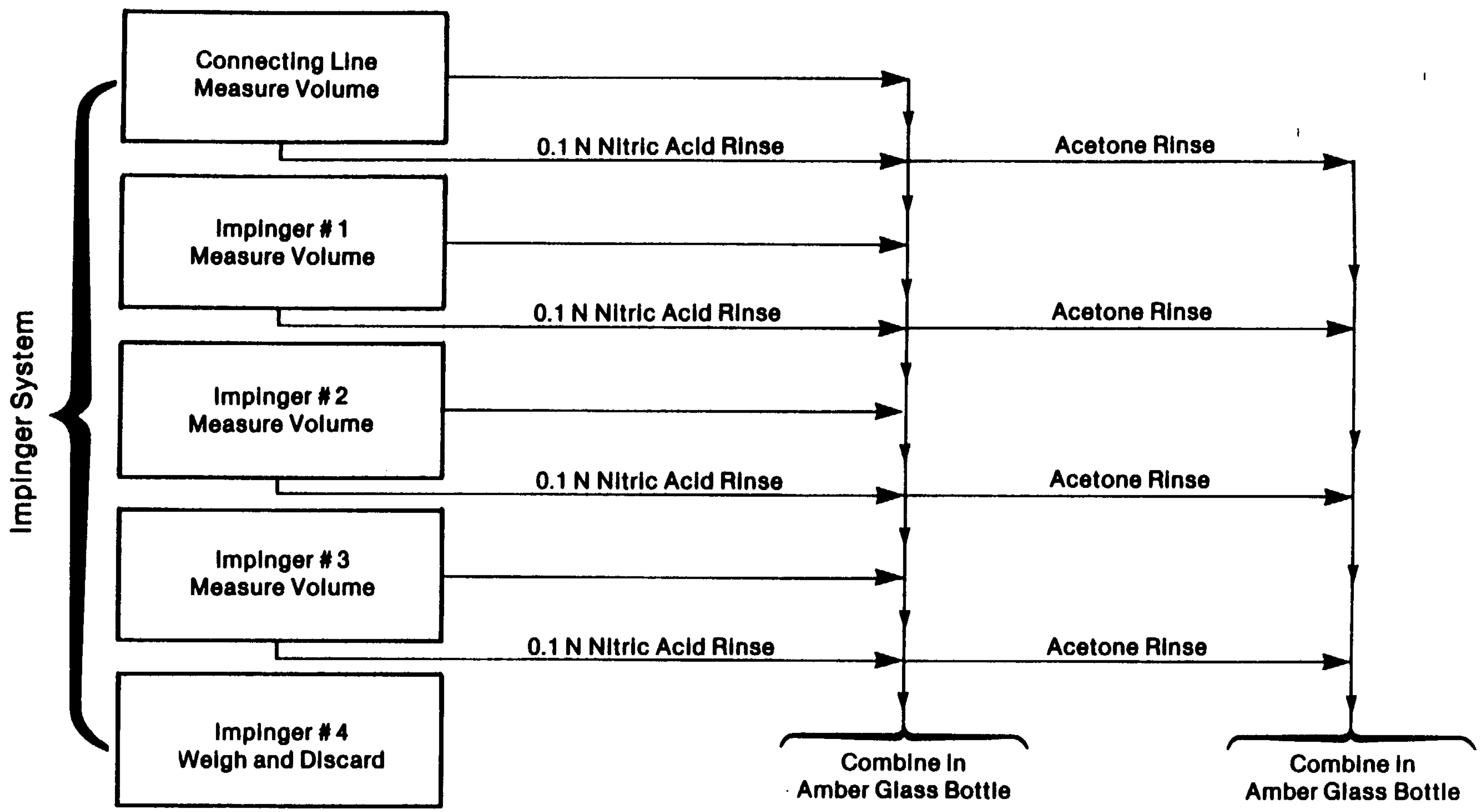


Figure 33. Sample handling and transfer - SASS impingers.

STATIONARY GAS SAMPLING AND MOISTURE DETERMINATION

The integrated sampling technique described in EPA Method 3 was used at the SASS sampling locations to obtain a composite flue gas sample for fixed gas (O_2, CO_2, N_2) analysis. The fixed gas analysis was used to determine the molecular weight of the gas stream and to correct the measured particulate and trace metal concentrations to 12% O_2. A small diaphragm pump and a stainless steel probe were used to extract single point flue gas samples. The samples were collected in a Tedlar[R] bag. Moisture was removed from the gas sample by a water-cooled condenser so that the fixed gas analysis was on a dry basis. The composition of the stationary gas sample was determined using a Shimadzu Model 3BT analyzer instead of the Fyrite or Orsat analyzer prescribed in EPA Method 3. The Shimadzu instrument employs a gas chromatograph and a thermal conductivity detector to determine the fixed gas composition of the sample.

The moisture content of the flue gas was determined at the SASS sampling locations using EPA Method 4. Based on this method, a measured volume of particulate-free gas was pulled through a chilled impinger train. The quantity of condensed water was determined gravimetrically and then related to the volume of gas sampled to determine the moisture content.

PROCESS SAMPLES

Three types of process samples were obtained: incinerator sludge feed, incinerator bottom ash, and ESP hopper catch. Sampling locations and procedures are discussed below.

Sludge Feed Sampling

Sludge feed samples were obtained directly from the belt feeder immediately prior to the incinerator. The host plant routinely samples the sludge on an hourly basis and analyzes the 24-hour sample composites for total solids and volatile solids. Plant personnel were asked to take additional samples for the test program at the same time they took samples for solids/volatiles analyses. Each hourly test sample consisted of approximately 500g (1.1 lb) of sludge. The hourly samples were composited in a large clear glass jar. The composite sample from each run was analyzed for metals content using ICAP spectroscopy.

Incinerator Bottom Ash Sampling

Incinerator bottom ash was sampled at the point of discharge from the screw conveyor that transports the ash from the bottom hearth of the incinerator. The ash was sampled as it was discharged into a large hopper. A pre-cleaned metal bucket attached to a long handle was used for the sampling. The bucket was held directly below the spout to capture the falling bottom ash.

A 1 liter composite bottom ash sample was developed for each test run. The composite samples were prepared from 2, 250 ml samples taken at the beginning and end of each run. The composite bottom ash sample from each run was analyzed for metals content using ICAP spectroscopy.

ESP Hopper Catch Sampling

Particulate matter captured by the ESP was recovered at the end of each test run by emptying the contents of the collection hopper onto a clean piece of cardboard. The hopper catch contained considerable amounts of water. The wet and dry portion were mixed and transferred to an amber glass bottle. The ESP particulate matter catch from each of the test runs was analyzed for metals content using ICAP spectroscopy.

SECTION 5

ANALYTICAL PROCEDURES

SAMPLES PREPARATION FOR ICAP ANALYSIS

Samples collected in the SASS sampling train were analyzed for total particulate concentration, particle size distribution, and metals content. Metals were analyzed by ICAP after weighing the samples on a 5-place analytical balance. Sludge feed, bottom ash, and hopper catch samples were analyzed for metals after the sample preparation desribed below. Daily composites of one-hour increments of sludge were analyzed by the host sites laboratory for moisture and volatiles content. The same procedures were used for both the baghouse and the ESP evaluations.

Three types of samples were generated: (i) liquid, (ii) particulate and (iii) filter with particulate. The individual samples taken are as follows: probe rinse, ten micron cyclone catch, 3 micron cyclone catch, 1 micron cyclone catch, filter, impinger contents, incinerator bottom ash, hopper catch, and sludge feed.

Aliquots of the impinger contents were analyzed by ICAP as is. Aliquots were removed from a well mixed sample. Prior to analysis the sludge feed, bottom ash, and hopper catch samples were dried at 100°C until a constant weight was achieved. Following the drying, these samples were ashed at 600°C to drive off any volatile organics. Aliquots for further samples preparation were taken from the 100°C dried samples for the bottom ash and hopper catch, while the sludge feed aliquot was taken from the 600°C ashed sample.

All particulate samples were digested in acid using a Parr bomb having a Teflon container, prior to analysis by ICAP. The particulate samples include the filter, 1 micron cyclone catch, 3 micron cyclone catch, 100°C dried bottom ash, 100°C dried hopper catch, and 600°C ashed sludge feed. In all possible cases, the dried probe rinse was added to the 10 micron cyclone catch and well mixed, from which an aliquot was taken and digested. After either a filter sample was folded and placed in a Teflon container, or 0.5 g to 1 g of a particulate sample was weighed into a teflon container, 5 ml of concentrated HF was added. This was followed by 5 ml of concentrated HNO_3. The container was then placed into the bomb casing, sealed, and put in an oven at 150°C for 4 to 6 hours. After digestion, the bombs were cooled and opened. The liquid solution was poured into a 50 ml Nalgene volumetric flask and brought to volume with deionized water. The 50 ml samples were then ready for analysis.

If any residue remained, the liquid was carefully decanted and the residue was filtered through glass wool and rebombed with 5 ml of HF and 5 ml of HNO_3. This ensured that all metals were leached into solution from the particulate. Almost all the filter samples had residue remaining after the first bombing, while the other samples did not. This is likely due to the greater amount of material which was to be digested: Not only was 0.5 g to 1.5 g of sample present, but also 1.0 g to 2.0 of glass fiber filter. After redigestion, the rebombed residue samples were analyzed as separate samples, but the results were combined with that from the first bombing.

METALS ANALYSIS BY ICAP

All metals analyses were performed on an Instrumentation Laboratory inductively coupled Argon Plasma 200 (ICAP), having a vacuum monochrometer. Samples are analyzed by aspirating a sample into the ICAP's plasma or torch. The torch destroys any compounds, leaving all metals present in their atomic or ionic state. The metal atoms or ions absorb energy from the torch, which is given off by the atom or ion as light. This light then passes through both a vacuum monochrometer and an airpath monochrometer, and is detected by photomultiplier tubes. Each metal atom or ion emits certain characteristic wavelengths of light, which identify whether or not the metal is present in a sample. The concentrations of the metals present are found by aspirating standard solutions with known concentrations. The intensity of light emitted at certain wavelengths is measured at each concentration level. By comparing the intensities of light generated by the sample at certain wavelengths with the intensities generated by the standards, the concentration of the metals in the sample can be found.

The IL ICAP 200 is a sequential reader: it proceeds from the lowest wavelengths to the highest, measuring each programmed wavelength individually. For these analyses, the ICAP was programmed to measure or read each emission line four (4) times, and then continue to the next wavelegth. The four readings were averaged to find the sample's concentration for that metal. For some metals, such as lead and calcium, two emission lines were measured, rather than one. This was used to either double check the analysis or to increase the calibration concentration range. For example, the 393.37 nn calcium emission line has a calibration range of 0 to 1.0 ppm, while the 317.93 nm emission line has a range up to 50.0 ppm. By measuring both lines, an increased sensitivity is achieved by the 393.37 nm line, while the 317.93 nm line provides a reasonable calibration range. All metal lines were programmed to automatically correct the intensity measurement for background emissions. The vacuum monochrometer was used for all wavelengths below 210 nm. In that range, air becomes a significant interference absorbing much of the wavelength emissions. The vacuum monochrometer eliminates that interference.

At the beginning of each analysis day, the program was recalibrated by measuring the high and low standards. The ICAP automatically readjusts the calibration curves in accordance with the recalibration. A 10 ppm standard was then analyzed to ensure a correct calibration. Any metals calibration having an analysis not within ± 3% of 10 ppm was recalibrated and rechecked until the analysis was within the range of 9.70 ppm to 10.30 ppm. After recalibration, deionized water was analyzed as a background check. Samples were than analyzed. After every high metals concentration sample, deionized water was reanalyzed to ensure that there was no carry-over. The calibration curves were checked every hour by analyzing the 10 ppm standard solution. The response of the torch can change up to 10% hourly due to thermal drift. If necessary, the metals lines were recalibrated and checked before continuing with sample analyses.

After finding the average metals' concentrations in a sample, the known volume of 50 ml was used to find the total micrograms of each metal present. The total micrograms were divided by the original amount of sample weighed into the Parr bombs to give the weight percent of each metal present. Minimum detection limits for the 24 metals analyzed are shown in Table 36.

TABLE 36. MINIMUM DETECTION LIMITS OF THE ICAP

Metal	Detection Limit[a] (ppm)
Al	0.08
Sb	0.07
As	0.08
Ba	0.004
Cd	0.010
Ca	0.007
Cr	0.04
Co	0.01
Cu	0.005
Au	0.04
Fe	0.005
Pb	0.08
Mg	0.003
Mn	0.004
Ni	0.002
P	0.03
Se	0.08
Ag	0.004
Na	0.05
S	0.08
Sn	0.05
Ti	0.009
V	0.010
Zn	0.003

[a]Minimum liquid phase concentration (ug/ml) detectable by the ICAP.

SECTION 6

QUALITY ASSURANCE/QUALITY CONTROL

This section summarizes results of quality assurance and quality control (QA/QC) activities conducted during the ESP test program. A discussion of problems encountered during the program is included.

FIELD SAMPLING

Field sampling QA/QC activities included equipment calibration, SASS train operational procedure checks and preparation of a SASS train field blank. These activities are briefly summarized below.

Equipment Preparation and Calibration

The SASS sampling trains were inspected and prepared for field use as specified (see Sampling Procedures). Pretest calibrations and inspections were conducted on pitot tubes, sampling nozzles, temperature sensors, analytical balances, and dry gas meters.

Calibration of the continuous monitoring equipment included a three point (two upscale plus zero) linearity check on the first test day, single point and zero calibration checks at the beginning of each test day, and single point drift checks at the end of each test day.

SASS Train Operation

The SASS trains were operated to achieve target isokinetics of 100 $\pm$ 20%. The overall average isokinetics were 113.6 percent at the ESP inlet location; 94.0 percent at the scrubber outlet location; and 91.7 percent at the ESP outlet location. The samples from these test runs were not analyzed for metals content. The sample train leak check criteria of 0.05 cfm was met for all sample runs.

SASS Train Field Blank

A SASS train field blank was prepared using glassware that had been used for a previous test run, a filter of the same type as the test run filters, and a nitric acid impinger solution from the same batch as the test runs. The blank train clean-up procedures were identical to those of the test run sample trains. The field blank samples were submitted to the laboratory for metals analysis. The results of the field blank train analysis are discussed as follows.

LABORATORY ANALYSIS

Laboratory QA/QC activities for the ESP test program included ICAP calibration procedures, ICAP analysis of NBS Coal Fly Ash Standard 1633A, duplicate ICAP analyses of several samples from the test program, and ICAP analysis of the SASS train field blank samples. These activities are briefly discussed below.

ICAP Calibration Procedures

The initial programming procedures and the daily calibration procedures for the ICAP instrument have been described (see Analytical Procedures). The daily calibrations required ± 3 percent accuracy for each metal at a solution concentration of 10 ppm per metal.

ICAP Analysis of NBS Coal Fly Ash

As an adjunct to the analyses performed for the test program, samples of NBS Coal Fly Ash 1633A were "ashed" at 3 different temeprature conditions, acid digested in a Parr bomb, and analyzed by ICAP. The purpose of this investigation was to check the temperature effect of the ashing step on the metals analysis, and to compare the ICAP results to the NBS-certified metals content of the sample. The three different ashing conditions were: (i) no ashing; (ii) ashing at 110°C; and (iii) ashing at 600°C.

The results of this investigation are contained in Appendix D. The metals content data show some variability between samples ashed at 600°C and samples ashed at 110°C. Nickel, selenium, and manganese were not detected by the ICAP although the NBS data indicated that these species were present in the sample. This may be indicative of matrix interference problems for the coal fly ash sample.

Duplicate Analyses

Duplicate ICAP analyses were performed on the eight samples listed in Table 37. These include all sample types that required ashing and/or Parr bombing digestion except for the sample train filters. Duplicate filter analyses could not be run because the entire sample is used in the analytical procedure.

Two types of duplicates were run for sample types that required both ashing and Parr bomb digestion in the analytical scheme (i.e., sludge feed, bottom ash, ESP hopper catch). For samples listed as "ash duplicates," two identical portions of the raw sample were subjected to the entire analytical work-up outlined in Section 3.0 (i.e., ashing, Parr digestion and ICAP analysis). For samples listed as "bomb duplicates," two identical portions of the ashed sample were subjected to the analytical work-up following the ashing step (i.e. Parr bomb digestion and ICAP analysis).

In general, the data showed ± 10 percent reproducibility between duplicates for each metal. The "bomb" duplicates and the "ash" duplicates showed comparable reproducibility. Average metals content data are presented in this report for the eight samples for which duplicate analyses were performed.

TABLE 37. SAMPLES FOR WHICH DUPLICATE ANALYSES WERE PERFORMED

Sample Identification	Duplicate Type
1. 10 micron cyclone/probe rinse catch, Run 02 (ESP inlet)	Bomb
2. 10 micron cycline/probe rinse catch, Run 03 (ESP inlet)	Bomb
3. 3 micron cyclone catch, Run 03 (ESP inlet)	Bomb
4. 1 micron cyclone catch, Run 03	Bomb
5. Sludge Feed, Run 01	Bomb
6. Sludge Feed, Run 02	Ash
7. Bottom Ash, Run 01	Ash
8. Bottom Ash, Run 03	Ash

Field Blank Analyses

ICAP analyses of the filter field blank SASS train are contained in Appendix D.

The data show that the common metals aluminum, calcium, iron, magnesium, and sodium were the most prevalent species in the filter blank. The filter metals analyses for the test runs were blank-corrected by subtracting the filter blank values from the as-measured values. Because of the relative amounts of particulate matter collected, the filter blank correction had a more significant impact on the data from the scrubber outlet and the ESP outlet than it did on the data from the inlet location. Appendix D contains sample analysis sheets that show as-measured and blank-corrected filter data for Run 02 (inlet and outlet locations). At the inlet location, the filter blank correction significantly affected the reported value for five metals: gold, magnesium, manganese, nickel, and sodium. At the outlet location, the filter blank correction significantly affected the reported value for eight metals: calcium, chromium, cobalt, magnesium, manganese, nickel, sodium, and titanium. For Run 01, there were more than 106 ppm detected for aluminum, barium, calcium, iron and magnesium in the filter samples taken at the ESP outlet. Similar patterns were observed for Runs 02 and 03. It is suspected that the filters being used contained higher concentrations of these metals than the field filter blanks. It is advised that filters with lower metals content be obtained for any future studies of this type.

The impinger blank was found to be relatively metal-free, with the most prevalent species being arsenic and phosphorus. With the exception of arsenic, field blank correction of the impinger analyses resulted in very little impact on the reported data for the various metals.

SECTION 7

ESP COST ANALYSIS

The objective of this chapter is to develop cost estimates for an electrostatic precipitator applied to a full scale sewage sludge incinerator (design burn rate = 28,800 dry tons sludge/day). The Sections below describe the design basis, costing methodology, and the resulting estimates of capital, operating, and annualized costs.

DESIGN BASIS

For an electrostatic precipitator, the three most important design criteria are the precipitation rate (W_e, the collection area (A), and the flue gas velocity (V). The precipitation rate is a function of resistivity, particle size distribution, gas velocity distribution, rapping, and electrical factors. Since precipitation rate can vary with the above mentioned parameters, an effective migration velocity is usually adopted. The effective migration velocity is usually determined experimentally. However, since the necessary experimental data was unavailable, the particulate matter (PM) from the sewage sludge was compared to PM emissions from other fuels which are commonly controlled by electrostatic precipitators.

The gas temperature at the exit to the sewage sludge incinerator ranges from 700°F to 900°F. However, it is more economical to construct an ESP designed for low temperature ranges (300°F-400°F). At high temperatures an ESP must be designed to handle a larger gas flow. Also, stronger, heat-resistant fabrication materials are required. Therefore it is recommended that the gas be cooled before entering the ESP. This can be done by adding uninsulated duct work and/or a spray cooler.

Figure 34 graphically compares the particle size distribution of coal, oil, municipal solid waste, and sewage sludge fly ash. This figure shows that the particle size distribution of sewage sludge falls between that of a coal-fired boiler and a municipal solid waste-fired boiler. The effective migration velocity of these two fuels ranges from 0.3 to 0.6 feet/second at a flue gas temperature of 300°F. For this cost analysis, a migration velocity of 0.4 feet/second is assumed. The sensitivity of the cost estimates to migration velocity will also be investigated.

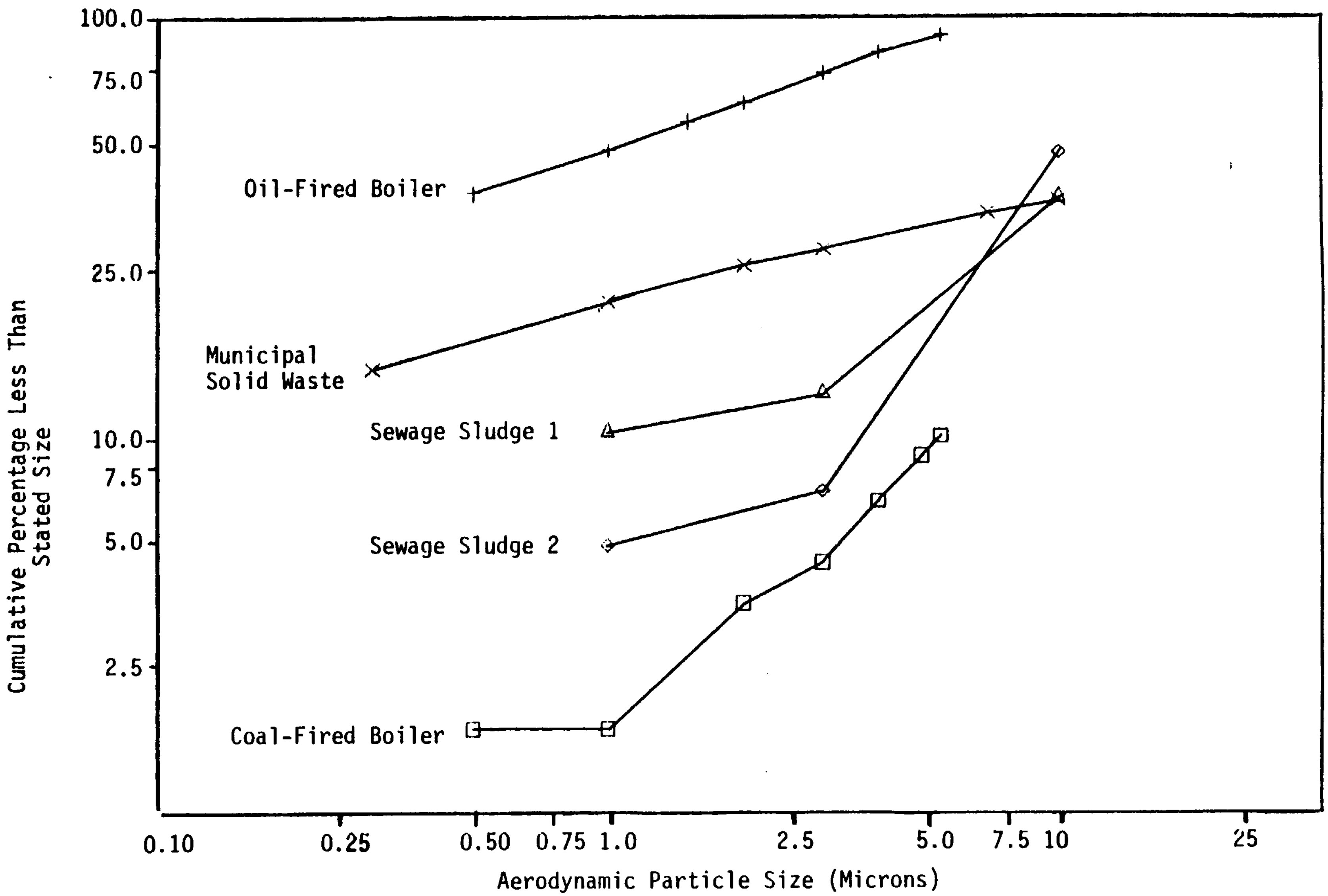


Figure 34. Particle Size Distribution of Various Fly Ash

Once the effective migration velocity is determined the Deutsch-Anderson equation can be used to predict the plate area required.

$$\text{Deutsch-Anderson} \quad A = \frac{-V}{W_e(60)} \ln \frac{100-n}{100}$$

Where: A = plate area (ft^2)

V = Flue gas flow rate (acfm)

W_e = effective migration velocity (ft/sec)

N = removal efficiency (percent)

Table 6-1 presents the design basis used in this cost analysis.

COSTING METHODOLOGY

Capital and operating costs were estimated using a cost algorithm developed for coal-fired industrial boilers. This algorithm calculates costs based on a given plate area and flue gas flow rate. The inputs (plate area and flow rate) into the algorithm were adjusted to represent the parameters expected from a sewage sludge incinerator. Also the cost estimates obtained from this algorithm were adjusted to account for the use of stainless steel as opposed to carbon steel) as the material of construction. The costs predicted in this chapter are for an electrostatic precipitator installed at a new sewage sludge incinerator site.

The costs of the electrostatic precipitator unit can be broken down into three major cost categories:

- Capital Costs (total capital investment required to construct and make operational the ESP unit),
- Operation and Maintenance (O&M) costs (total annual cost necessary to operate and maintain the ESP unit), and
- Annualized Costs (total O&M cost plus annualized capital-related charges).

These cost estimates were first performed for the design specifications listed in Table 38. In addition, for each cost category the flue gas flow rate was varied from 10,000 to 30,000 acfm and the migration velocity was varied from 0.3 to 0.6 ft/sec. The results are then presented graphically to illustrate the influence of these two design variables on the three cost estimates.

CAPITAL COSTS

A breakdown of the capital cost components is given in Table 39. The equipment cost, as discussed earlier, was estimated using an adapted version of a cost algorithm developed for an ESP control system operating on a

TABLE 38. ESP DESIGN SPECIFICATIONS

Incinerator	
	Design Capacity (wet sludge) = 7,500 lb/hr
	Design Capacity (dry sludge) = 1,200 lb/hr
	Flue Gas Outlet Temperature = 700-900^oF
ESP	
	Migration Velocity = 0.40 ft/sec
	Flue Gas Flow Rate = 20,000 acfm
	Removal Efficiency = 98.0%
	Inlet Grain Loading = 0.0944 grains/ft^3
	Inlet Temperature = 400^oF
	Power Demand = 3 W/ft^2
	Pressure Drop = 1 in. H_2O gauge
	Construction Material = Stainless Steel

TABLE 39. CAPITAL COST COMPONENTS

(1) Total Direct and Indirect Capital[a]	Total Direct and Indirect Capital = 4.1 x carbon steel equipment cost
(2) Contingencies[b]	Contingencies = 20% of Total Direct and Indirect Capital
(3) Total Turnkey[b]	Total Turnkey = Total Direct and Indirect Capital + Contingencies
(4) Working Capital[b]	Working Capital = 25% of Direct Annual Operating Cost
(5) Interest During Construction[c]	Interest During Construction = 3.6% of Total Turnkey
(6) Total Capital Cost[d]	Total Capital Cost = Total Turnkey + Interest During + Construction + Working Capital

[a] Reference 1, pages 275-313
[b] Reference 2, pages 8-18 through 8-19
[c] Reference 3, pages 2-5
[d] Reference 3, pages 2-3

coal-fired industrial boiler. This algorithm calculates the carbon steel equipment cost (in June 1978 dollars) as a function of flue gas flow rate and total ESP plate area. The Chemical Engineering Plant Index was used to update the equipment cost from June 1978 (CE Plant Index = 217.7) to June 1985 (CE Plant Index = 324.8).[4] The total direct and indirect capital is approximated as being directly proportional to the equipment cost. In Table 30 the factor of 4.1 is used to describe the relationship between the carbon steel equipment cost and the total direct and indirect capital costs with stainless steel as the material of construction.

All other capital cost components listed in Table 39 are calculated based on the total direct and indirect capital cost except for the working capital which is based on the operating and maintenance cost (see Table 41). Land cost is not included in the capital cost estimate. Land cost would normally be associated with the capital cost of the sewage sludge incinerator. Also, no allocations were made for retrofit conditions.

For the ESP design specifications given in Table 40, a capital cost estimate of $919,300 (June 1985 dollars) was calculated. Capital cost estimates were also performed at other design specifications. This is illustrated in Figure 35, which shows capital cost as a function of gas flow rate and migration velocity. As expected, capital costs increase as the flue gas flow rate increases. On the other hand, the capital costs decrease as the migration velocity increases. At higher migration velocities, less collection plate area is needed. For example, at a flue gas flow rate of 20,000 acfm, a 235 percent increase in the migration velocity (from 0.4 to 0.5 ft/sec) results in an 11 percent reduction in capital costs. The migration velocity assumed in this analysis is considered conservative. Since the flue gas temperature for a sewage sludge incinerator is higher than the temperature in a coal-fired or municipal solid waste-fired boiler, the migration velocity will probably be higher than the 0.4 ft/sec assumed. However, since costs decrease with increasing W_e, the cost estimates are conservative.

OPERATING AND MAINTENANCE (O & M) COSTS

Table 41 lists the breakdown of the operating and maintenance costs into its individual cost components. The O&M costs are divided into direct and indirect O&M costs include operating labor, maintenance labor, replacement parts, electricity, water, and ash disposal cost. The indirect O&M costs include payroll and plant overhead and are calculated as a function of the direct O&M cost components.

Table 42 presents the unit cost rates, in June 1985 dollars, used to calculate the O&M cost components. The Producer Price Index was used to update the cost rates from June 1983 to June 1985 dollars. The Producer Price Index listed values of 315.3 and 324.7 for June 1983 and 1985 respectively.[5]

For the ESP design specifications given in Table 43, an O&M cost estimate of $78,700/year was calculated. This estimate was based on an operating schedule of 365 days per year and 24 hours per day. Figure 36 illustrates the effect of changes in migration velocity and gas flow rate on

TABLE 40. SUMMARY OF CAPITAL COSTS

ESP Design Specifications:

- Migration Velocity = 0.40 ft/sec
- Gas Flow Rate = 20,000 acfm
- Efficiency = 98.0%
- Inlet Grain Loading = 0.0944 grains/ft^3

Captial Cost Breakdown:

	Cost (June 1985)
Equipment (Using Carbon Steel)	177,500
Total Direct and Indirect Capital (using Stainless Steel)	727,900
Contingencies	145,600
Total Turnkey	873,500
Working Capital	14,400
Interest During Construction	31,400
Total Captial Cost	919,300

TABLE 41. OPERATING AND MAINTENANCE COST COMPONENTS[a]

(1) Total Direct Operating Cost

Operating Labor +
Maintenance Labor +
Replacement Parts +
Electricity +
Water +
Ash Disposal =

Total Direct Operating Cost

(2) Total Indirect Operating Cost

56% of Operating Labor +
26% of Maintenance Labor +
26% Replacement Parts =

Total Indirect Operating Cost

(3) Total Annual Operating and Maintenance Cost

Total Direct Operating Cost +
Total Indirect Operating Cost =

Total Annual Operating and Maintenance Cost

[a]Reference 2, page 2-8.

TABLE 42. ANNUAL UNIT COSTS FOR OPERATION AND MAINTENANCE[a,b]

Cost Factors	Rate (June 1985)
Electricity (\$/kwh)	.0401
Water (\$/10^3 gal)	.23
Ash Disposal (\$/ton)	23.6
Direct Labor (\$/man hour)	18.70
Maintenance Labor (\$/man hour)	22.76

[a] All rates have been adjusted from June 1983 up to June 1985 using the Producer Price Index, Reference 5.

[b] Reference 3, page 2-9

TABLE 43. SUMMARY OF OPERATING AND MAINTENANCE COST

ESP Design Specification:

Migration Velocity = 0.40 ft/sec
Gas Flow Rate = 20,000 acfm
Efficiency = 98.0%
Inlet Grain Loading = 0.0944 grains/ft^3

Operating and Maintenance Cost Breakdown:

	Cost (June 1985)
Operating Labor	24,760
Maintenance Labor	23,580
Replacement Parts	4,190
Water	20
Electricity	3,440
Ash Disposal	1,620
Total Direct Operating Cost	57,610
Total Indirect Operating Cost	21,090
Total Annual Operating and Maintenance Cost	78,700

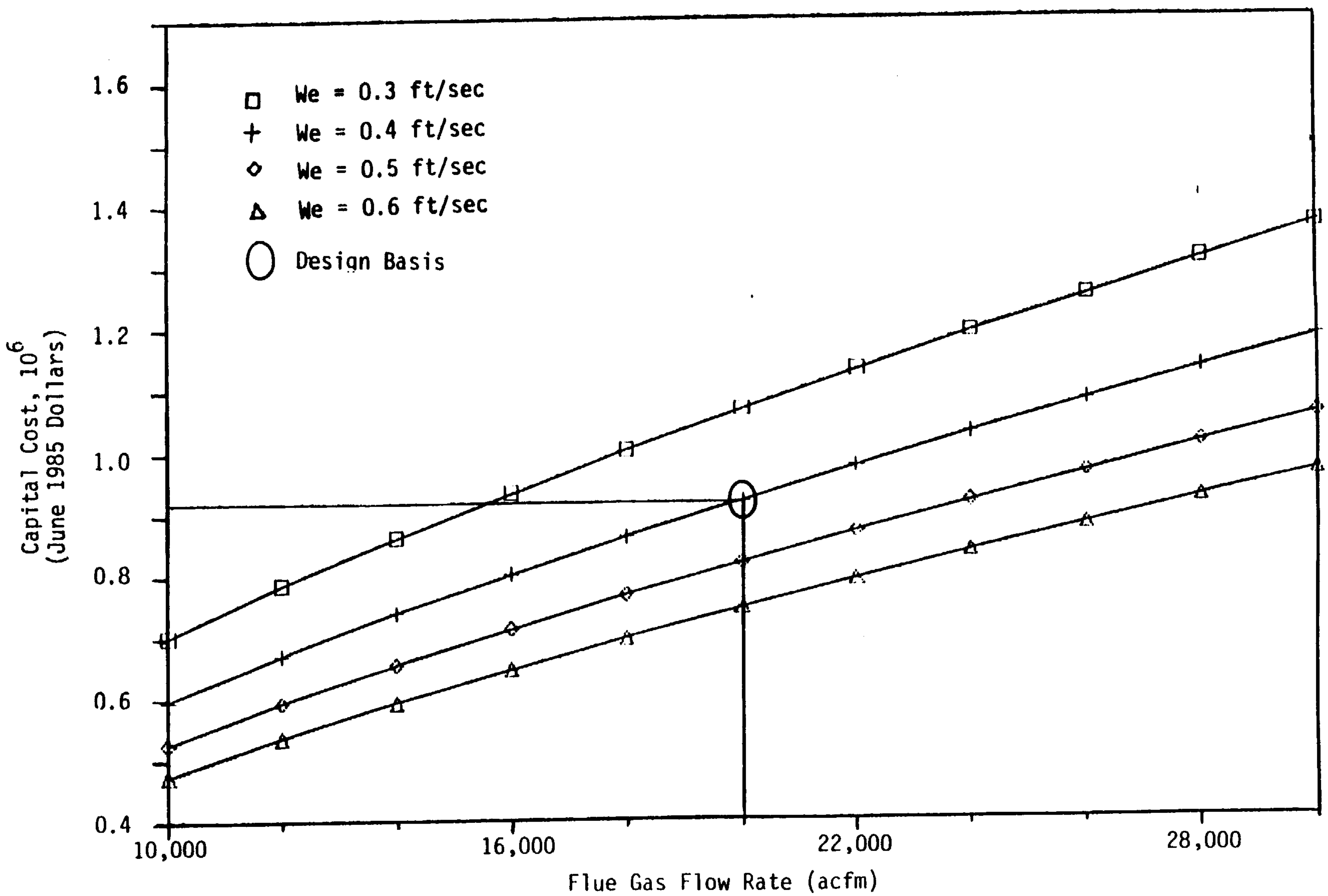


Figure 35. Capital Cost as a Function of Flue Gas Flow Rate and Migration Velocity

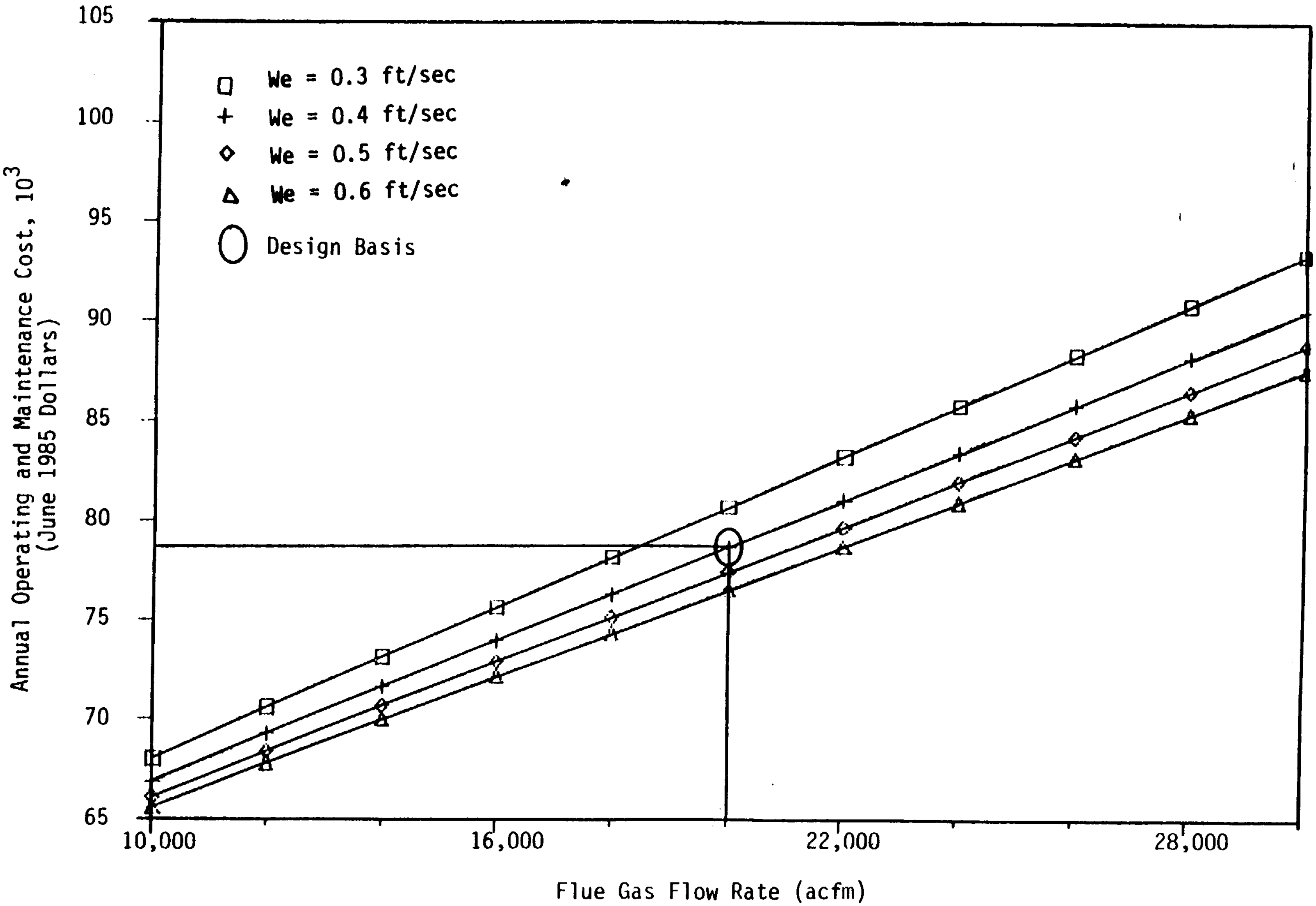


Figure 36. Annual Operating and Maintenance Cost as a Function of Flue Gas Flow Rate and Migration Velocity

the total O&M cost. As with capital costs, the O&M costs are directly related to the flue gas flow rate. Also, as the migration velocity increases the O&M costs decrease. For example, when the migration velocity increases from 0.4 to 0.5 ft/sec (at 20,000 acfm) the O&M costs decrease by 1.6 percent.

ANNUALIZED COST

Total annualized cost represents the sum of the annual O&M cost and the capital charges. The capital charges include the capital recovery (payoff of the capital investment), interest on working capital, general and administrative cost, taxes, and insurance. Table 44 presents the methodology used to calculate the annualized cost.

Table 45 includes an itemized list of the total annualized costs. A total annualized cost estimate of $229,900 (June 1985 dollars) was calculated for the ESP unit specified. This estimate assumes a straight line amortization of the total turnkey along with an interest rate of 10 percent and an equipment life of 15 years. Figure 37 illustrates the annualized cost as a function of gas flow rate and migration velocity. Since annualized costs are based on O&M costs and turnkey capital, the annualized costs vary directly with flow rate and indirectly with migration velocity.

TABLE 44. ANNUALIZED COST COMPONENTS[a,b]

(1) Capital Recovery

$$\text{Capital Recovery} = \left[\frac{i\,(1 + i)n}{(1 + i)n - 1}\right] \times \text{Total Turnkey}$$

i = interest rate

n = number of years of useful life of control system

(2) Interest of Working Capital

Interest of Working Capital = 10% of Working Capital

(3) General & Administrative (G & A), Taxes and Insurance

G & A, Taxes and Insurance = 4% of Total Turnkey

(4) Capital Charges

Capital Recovery +
Interest on Working Capital +
G & A, Taxes and Insurance =

Capital Charges

(5) Total Annualized Cost

Annual Operating and Maintenance Cost +
Capital Charges =

Total Annualized Cost

---

[a] Reference 3, page 2-12.
[b] An interest rate of 10%, and equipment life of 15 years was assumed.

TABLE 45. SUMMARY OF ANNUALIZED COST

ESP Design Specifications:

Migration Velocity = 0.40 ft/sec

Gas Flow Rate = 20,000 acfm

Efficiency = 98.0 %

Inlet Grain Loading = 0.0944 grains/ft^3

Annualized cost Breakdown:

	Cost (June 1985)
Capital Recovery	114,900
Interest on Working Capital	1,400
G & A, Taxes and Insurance	34,900
Capital Charges	151,200
Annual Operating and Maintenance	78,700
Total Annualized Cost	229,900

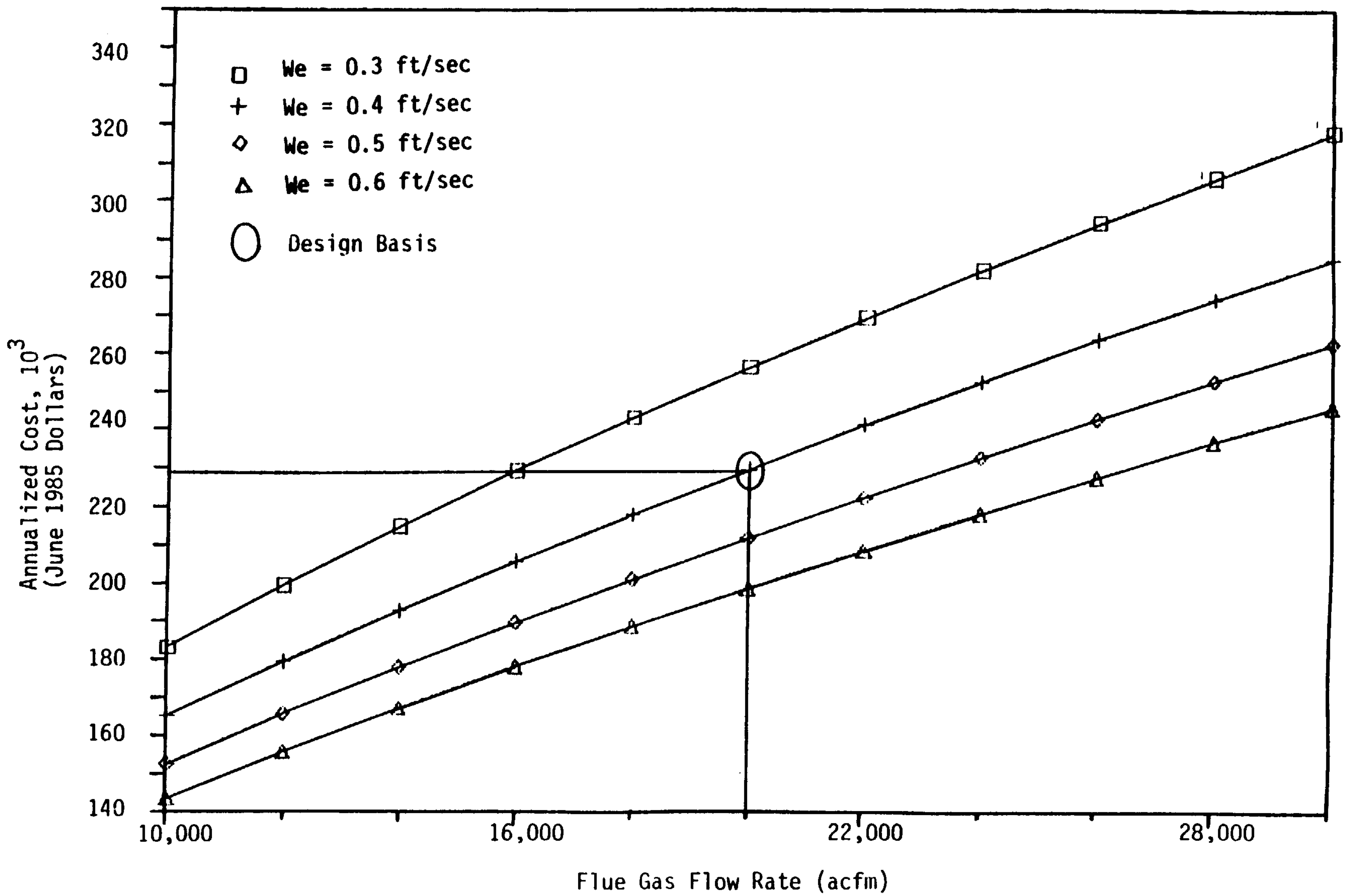


Figure 37. Annualized Cost as a Function of Flue Gas Flow Rate and Migration Velocity

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7. Reference 2. p. 3-42.

APPENDIX A

ESP VENDOR REPORT

Appendix A contains a brief discription of the ESP unit and a summary of ESP operating conditions as supplied by the vendor.

PURPOSE: I-V Performance

UNIT OF OPERATION: Two-pass dry pilot ESP system on the slip stream from sewage sludge incinerator exhaust

DATE PROJECT STARTED: February 11, 1985
DATE PROJECT ENDED: February 16, 1985

TESTED BY : Mr. Isaac Ray, Beltran Associates

INTRODUCTION

Particulate sample was withdrawn from the upper hearth of the sewage sludge incinerator (Before the air enters dry cyclones) via 1" diameter nozzle (1) to insure isokinecity of the sample collected (Fig. 1). The gas passes vertically downward through 3.5" diameter, 60 ft. long pipe a transition that goes from 3.5" dia. to 8" dia., and then the first pass of Beltran Electrostatic Precipitator.

Equipment comprised of a two-pass system, each pass is a pilot size electrostatic precipitator measuring 133"H x 55" x 24". There are nine (9) square tubes, 4" x 4" x 48" long representing the collector. In the center of each tube, there is a 3/8"Ø ionizing rod. Depending upon the efficiency requirements, this 3/8" rod can be stafted with Beltran's patented parts such as ionizing stars or repelling cylinders. In the first pass, for instance, where current suppression can occur due to high particulate loading, 22 ionizing stars are used. In the second pass, however, there are only six stars and two repelling rods 1" diameter.

In each pass sample gas with particles passes vertically upward. Corona discharge occurs between the high voltage ionizing stars and grounded collector walls. Intensity of corona discharge (current) is dependent on the applied voltage to the stars and can be represented by the I-V curve.

Particulate matter is charged in the corona region by "negative" ions and is collected on the "positive" collector (ground).

The gas, after being cleaned in the first pass, enters the second pass. The cleaned gas is then exhausted through the exhaust fan.

Particles of ash which are collected in the ESP are periodically removed by sonic vibrators and are collected in the hoppers. After each test, the samples were collected from each pass.

---

*Prepared for Radian Corporation
by
Beltran Associates, Inc.
1133 E. 35th Street
Brooklyn, New York 11210

This report summarizes the results of three tests, each of six-hour duration.

RESULTS AND DISCUSSION

1. All tests were performed at the following conditions:

--Face velocity V_f= 250 - 300 fpm in ESP.

--Inlet Gas Temperature in Pass No. 1; $T_{inl} = 450 \div 550^oF$

--Outlet Gas Temperature from Pass No. 2; $T_{out} + 140 \div 180^oF$

Corona Power input from High voltage power supply to Pass No. 1 - 400 ÷ 950 Watts/1,000 CFM.

Corona Power to Pass No. 2 - 480 ÷ 680 Watts/1,000 CFM.

2. Current suppression ratio for this application (See Fig. 14) in] Pass No. 1 is:

$$K_s = \frac{I_2}{I_1} = \frac{6.6}{5.4} - \frac{1}{2.3}$$

in other words, particles of ash suppressing current in the Pass No 1 by 2.3 times.

For Beltran's tubular ESP system, this kind of suppression does not present any problems because "All Star" design can handle suppressions of $\frac{1}{100}$ or even $\frac{1}{100}$.

3. Tests performed on collector cleaning system have shown that this type of fly ash is more sensitive to low frequency vibrations and also periodical rapping of ionizer system contribute to stable performance.

Isaac Ray, Ph.D.

Manager R/D

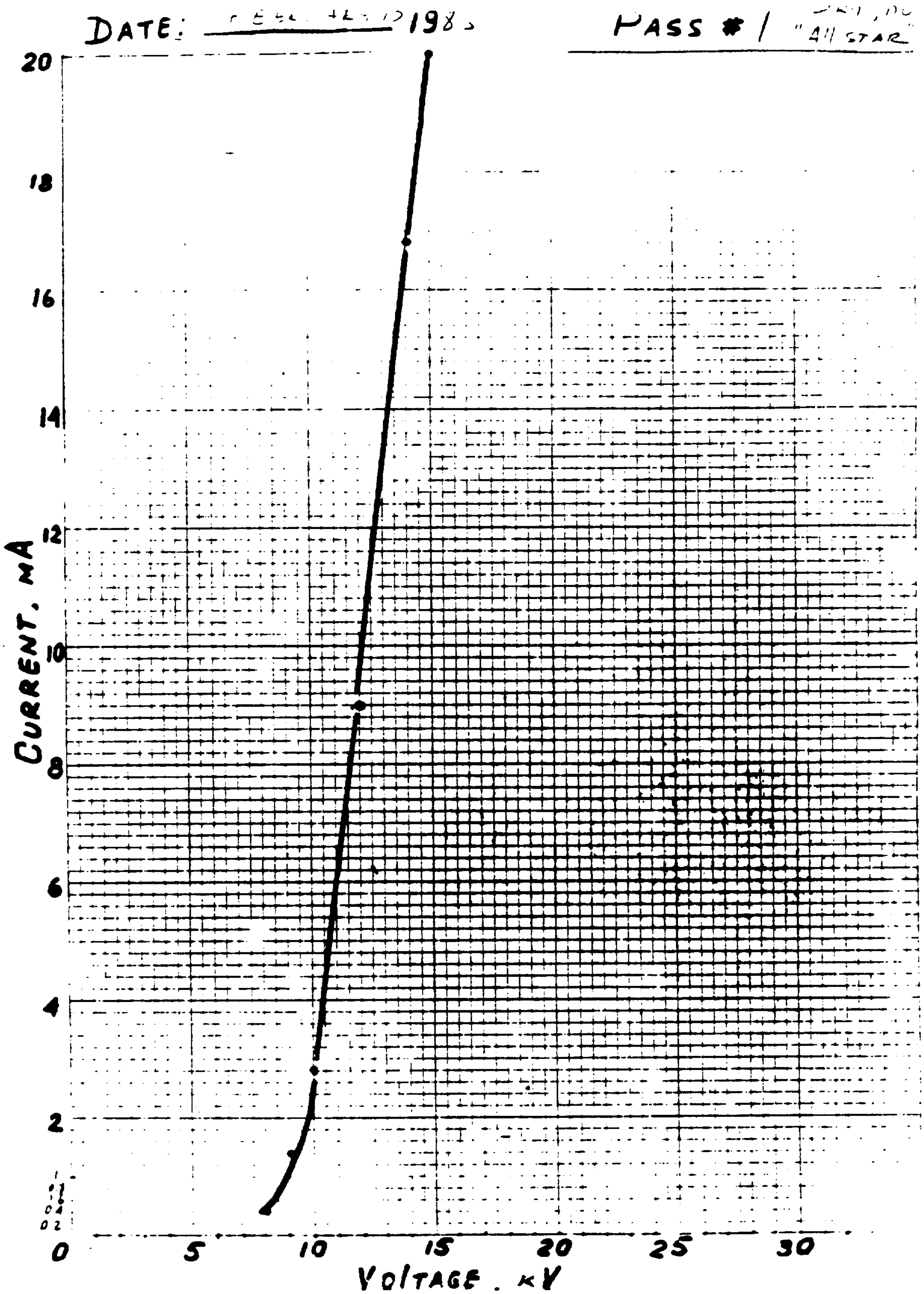

DATE:
PASS # 1
"All STAR"
20
18
16
14
12
10
8
6
4
2
0
CURRENT, mA
5
10
15
20
25
30
VOLTAGE, kV

FIG 2

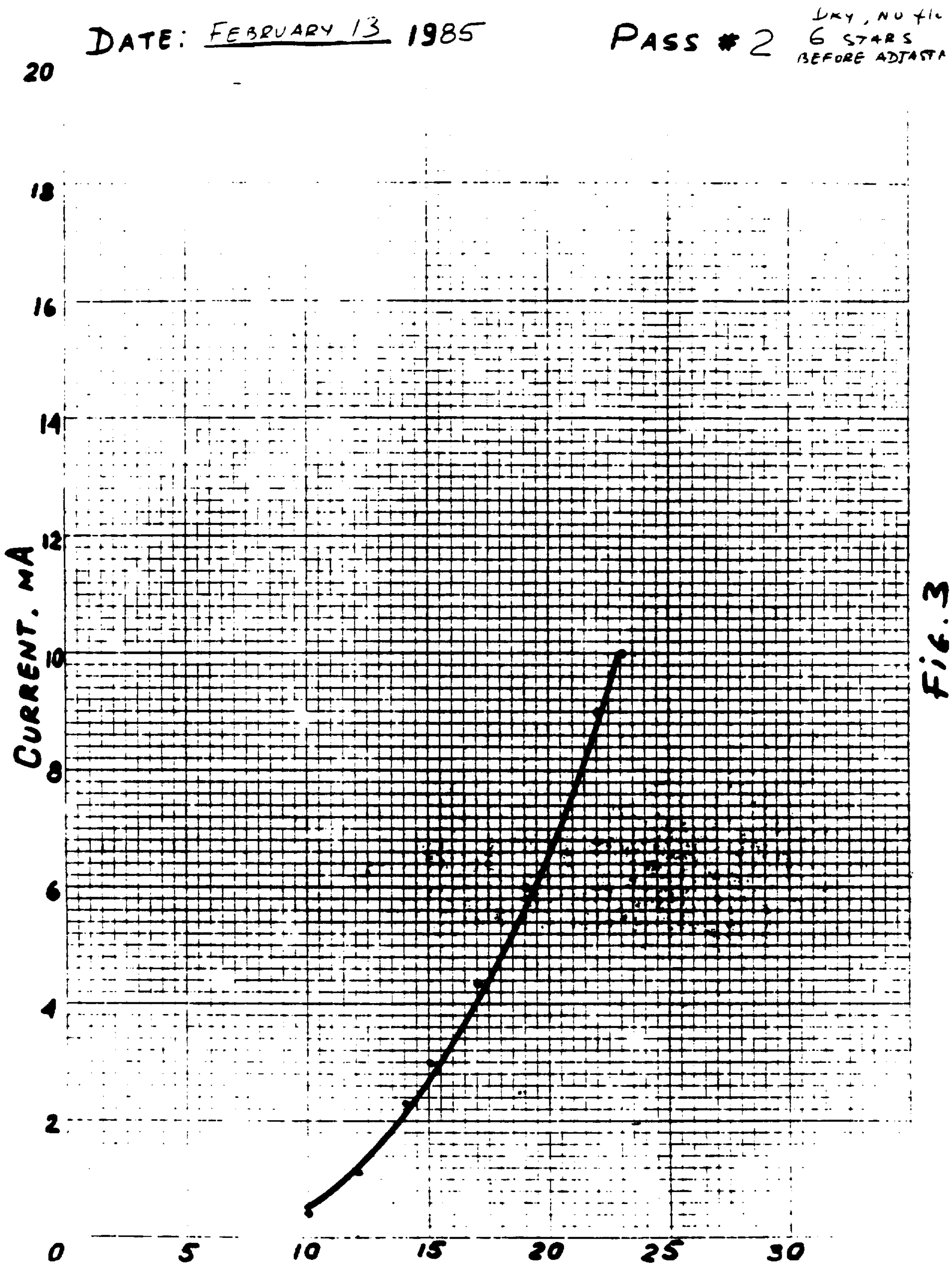
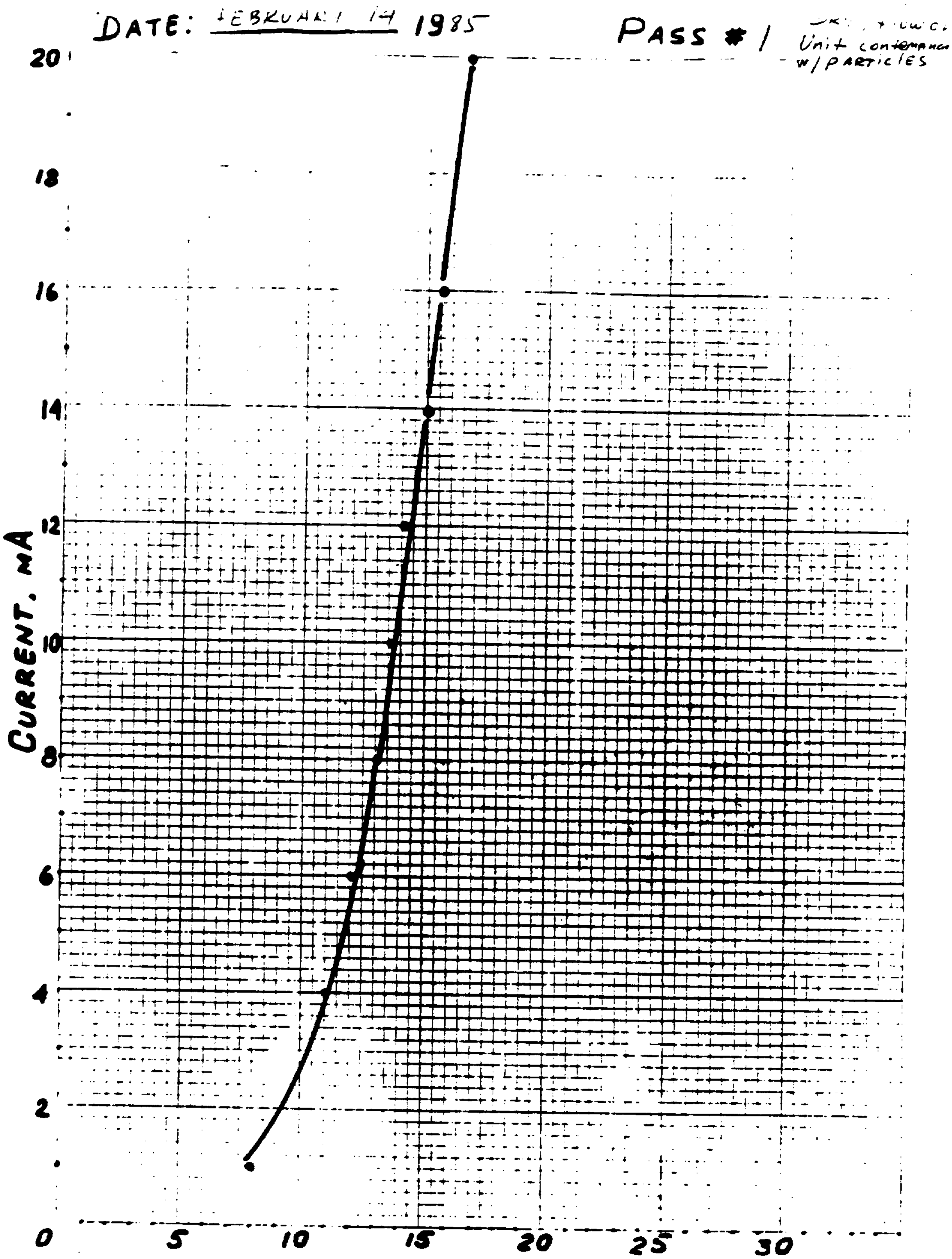
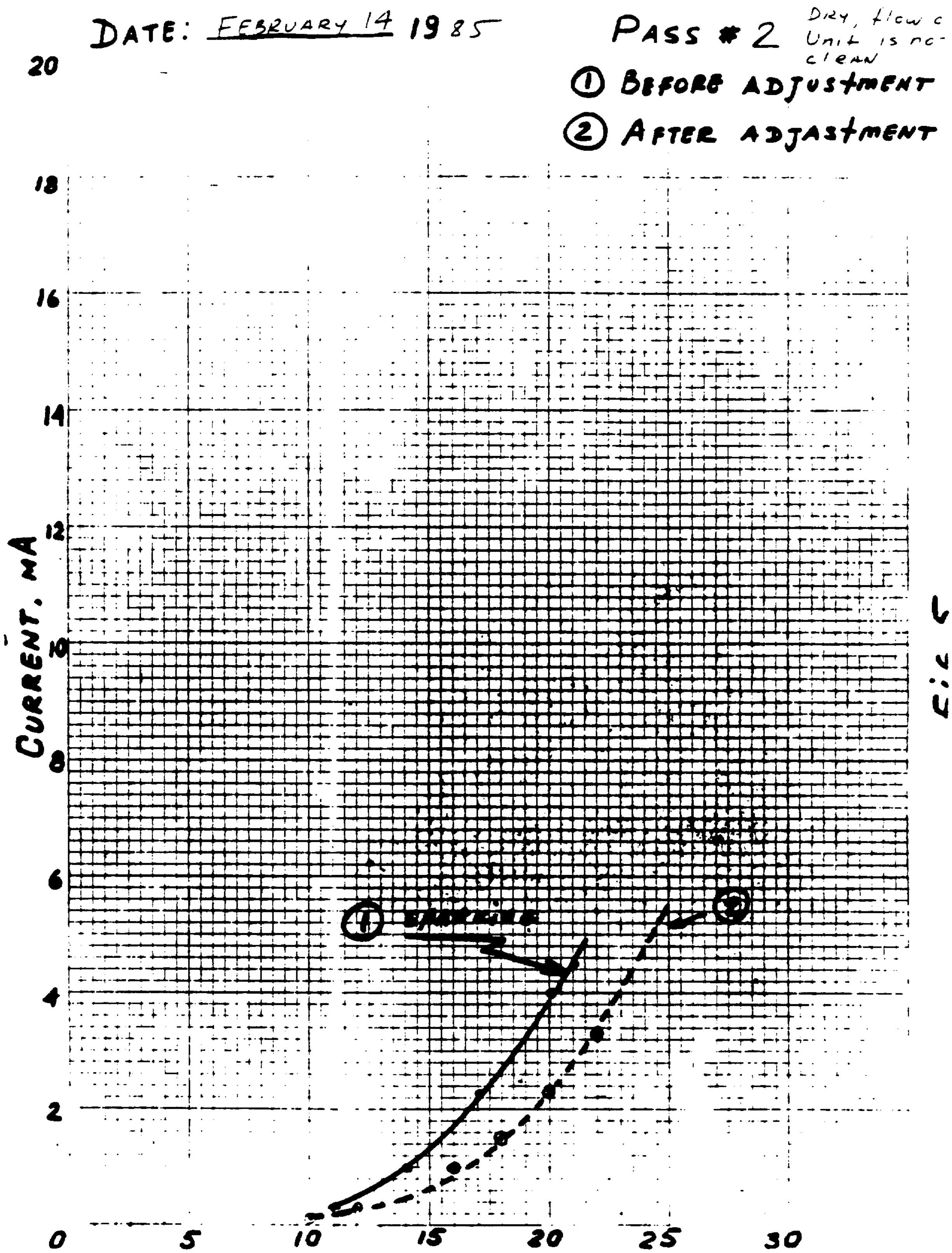
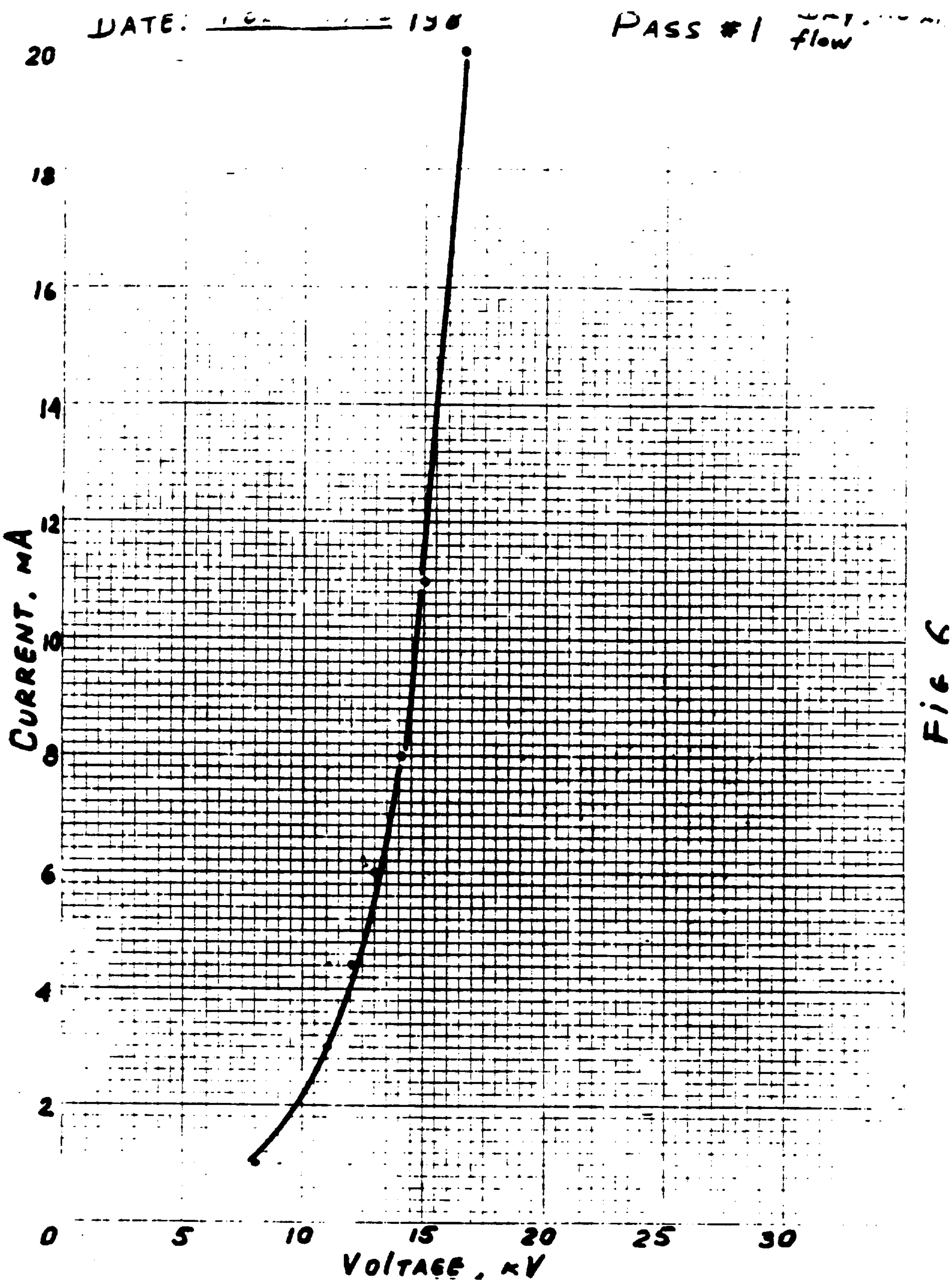

DATE: FEBRUARY 13 1985
PASS # 2
6 STARS
CURRENT. mA
0
2
4
6
8
10
12
14
16
18
20
5
10
15
20
25
30

FIG. 3


DATE: FEBRUARY 14 1985
PASS # 1
Unit contaminated w/ PARTICLES
CURRENT, mA
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30


DATE: FEBRUARY 14 1985
PASS # 2
DRY, flow c
Unit is nc-
clean
① BEFORE ADJUSTMENT
② AFTER ADJUSTMENT
CURRENT, mA
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
①
②


DATE:
PASS #1
flow
20
18
16
14
12
10
8
6
4
2
0
CURRENT, mA
0
5
10
15
20
25
30
VOLTAGE, kV
Fig 6

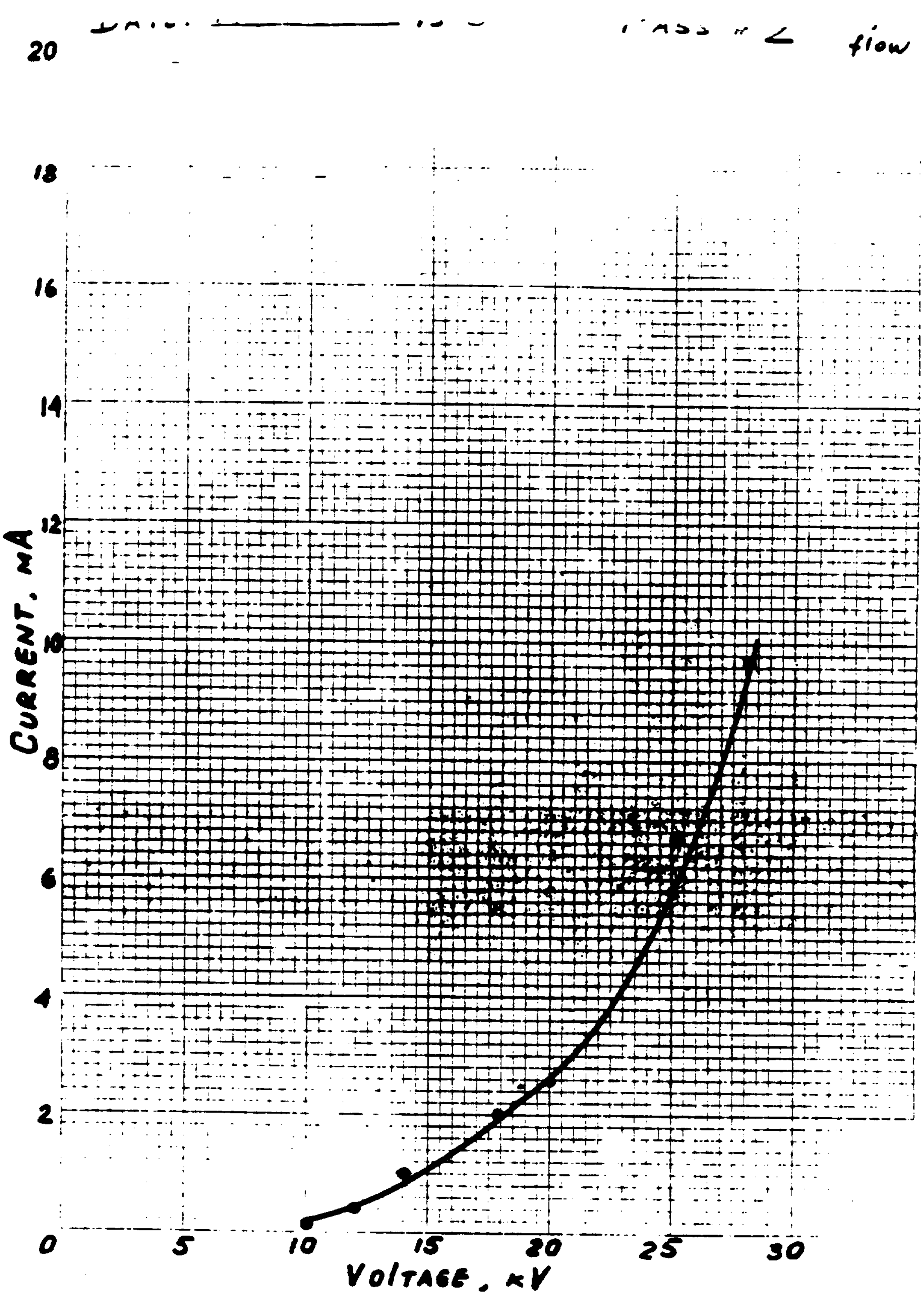
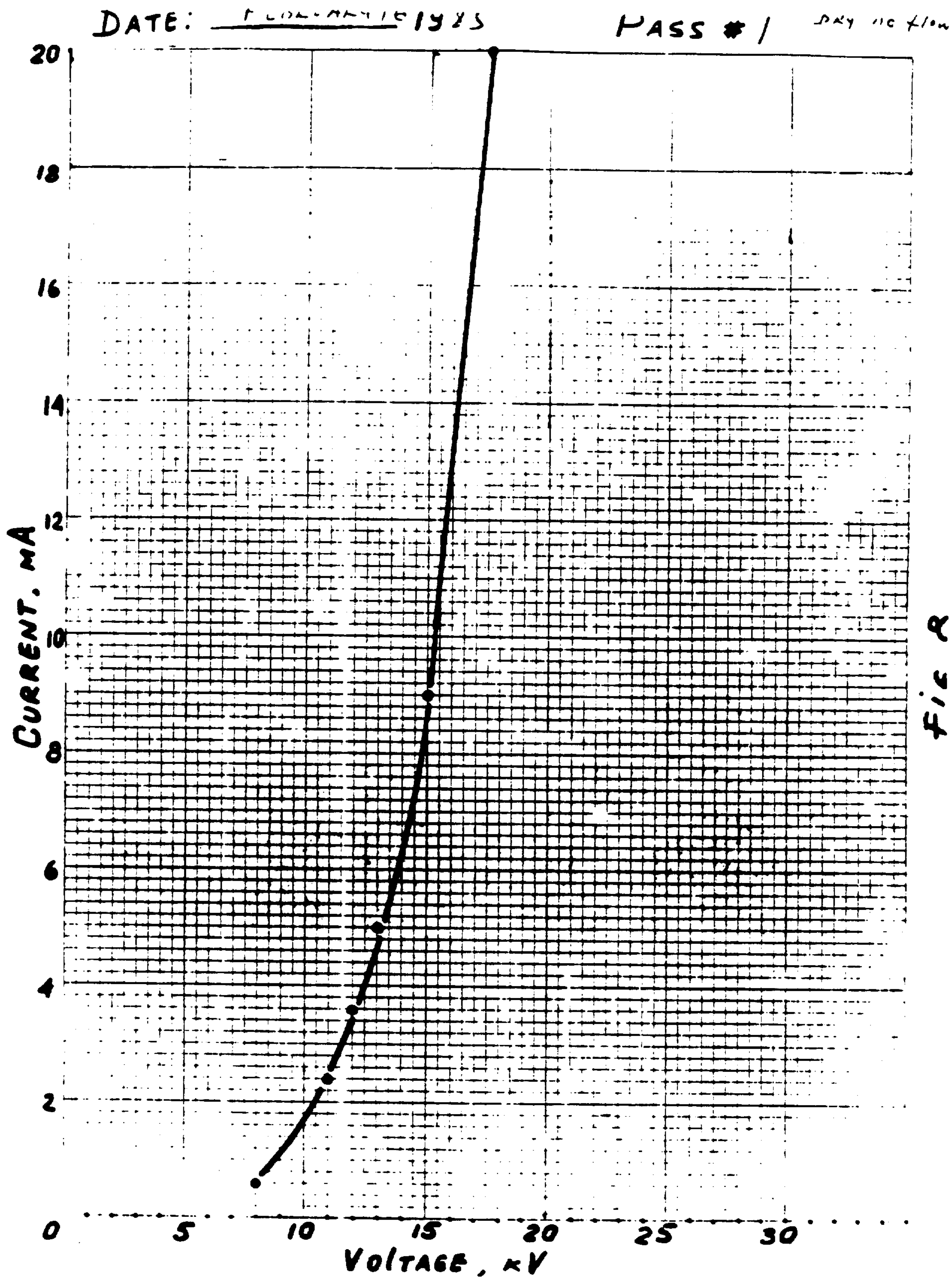

flow
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
CURRENT, mA
VOLTAGE, kV

Fig 7


DATE:
PASS # 1
CURRENT, mA
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
VOLTAGE, kV
FIG 2

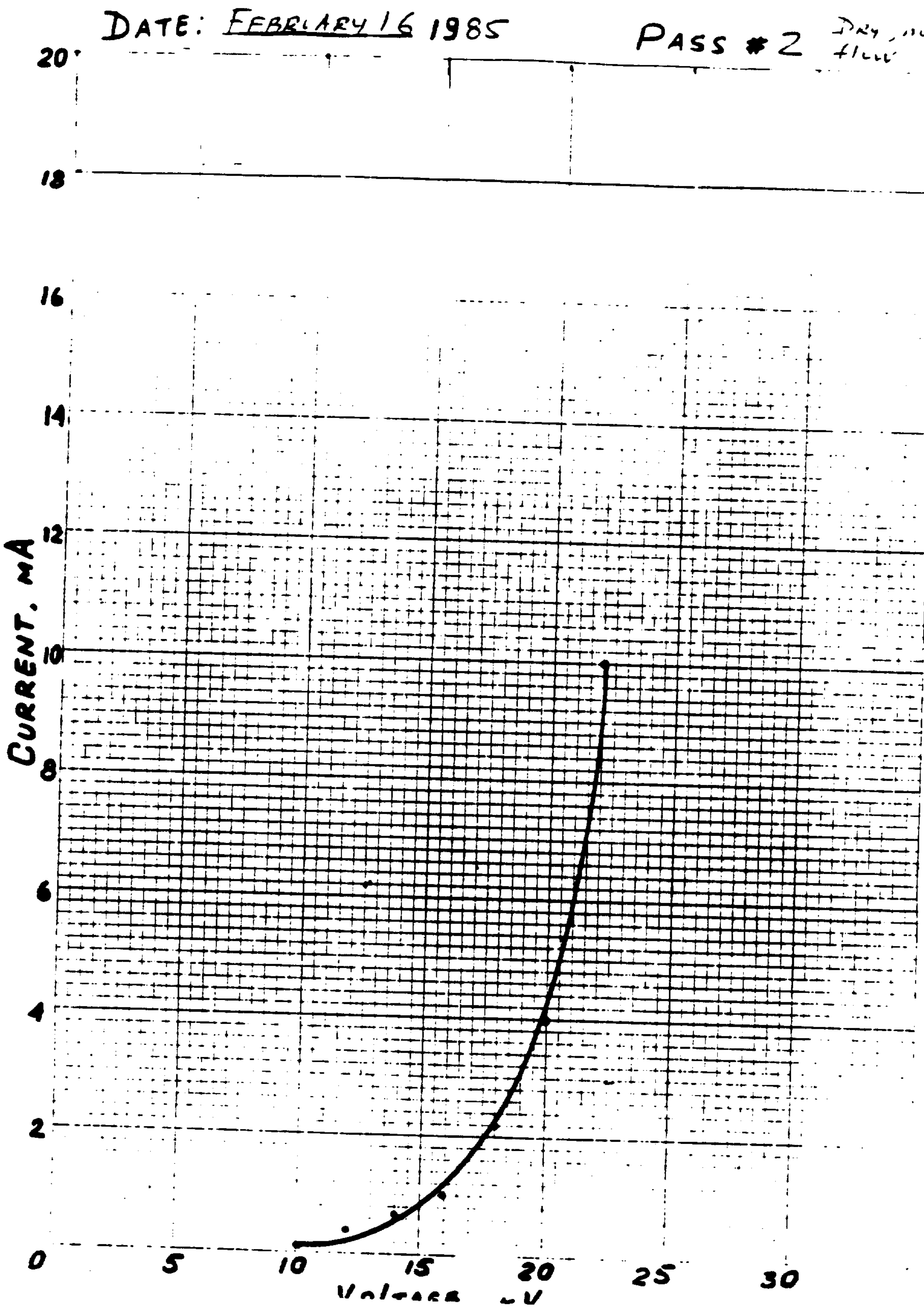
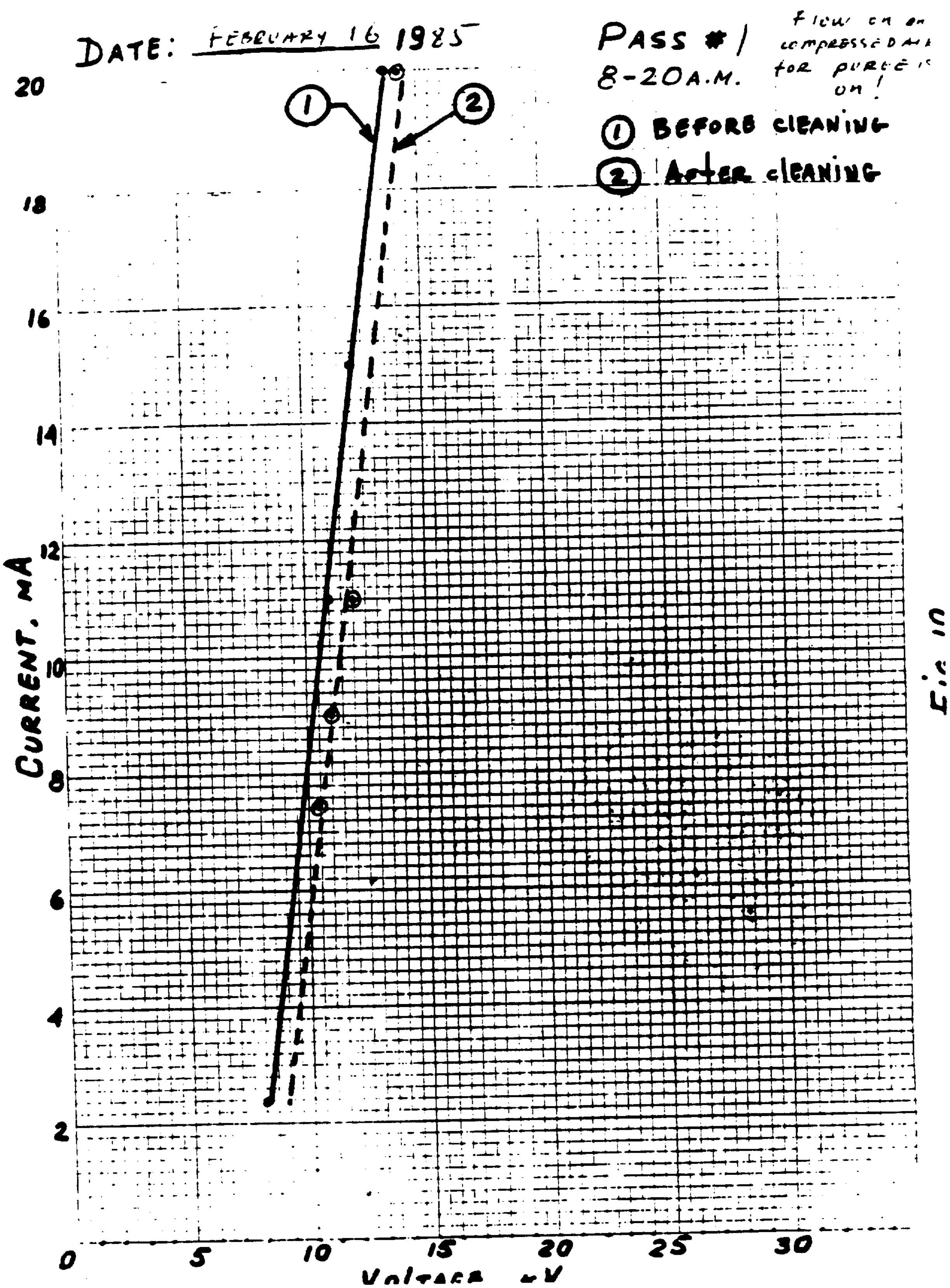

DATE: FEBRUARY 16 1985
PASS #2
CURRENT, mA
0
2
4
6
8
10
12
14
16
18
20
5
10
15
20
25
30

Fig 9


DATE: FEBRUARY 16 1985
PASS # 1
8-20 A.M.
① BEFORE CLEANING
② After cleaning
CURRENT, mA
0
5
10
15
20
25
30
2
4
6
8
10
12
14
16
18
20

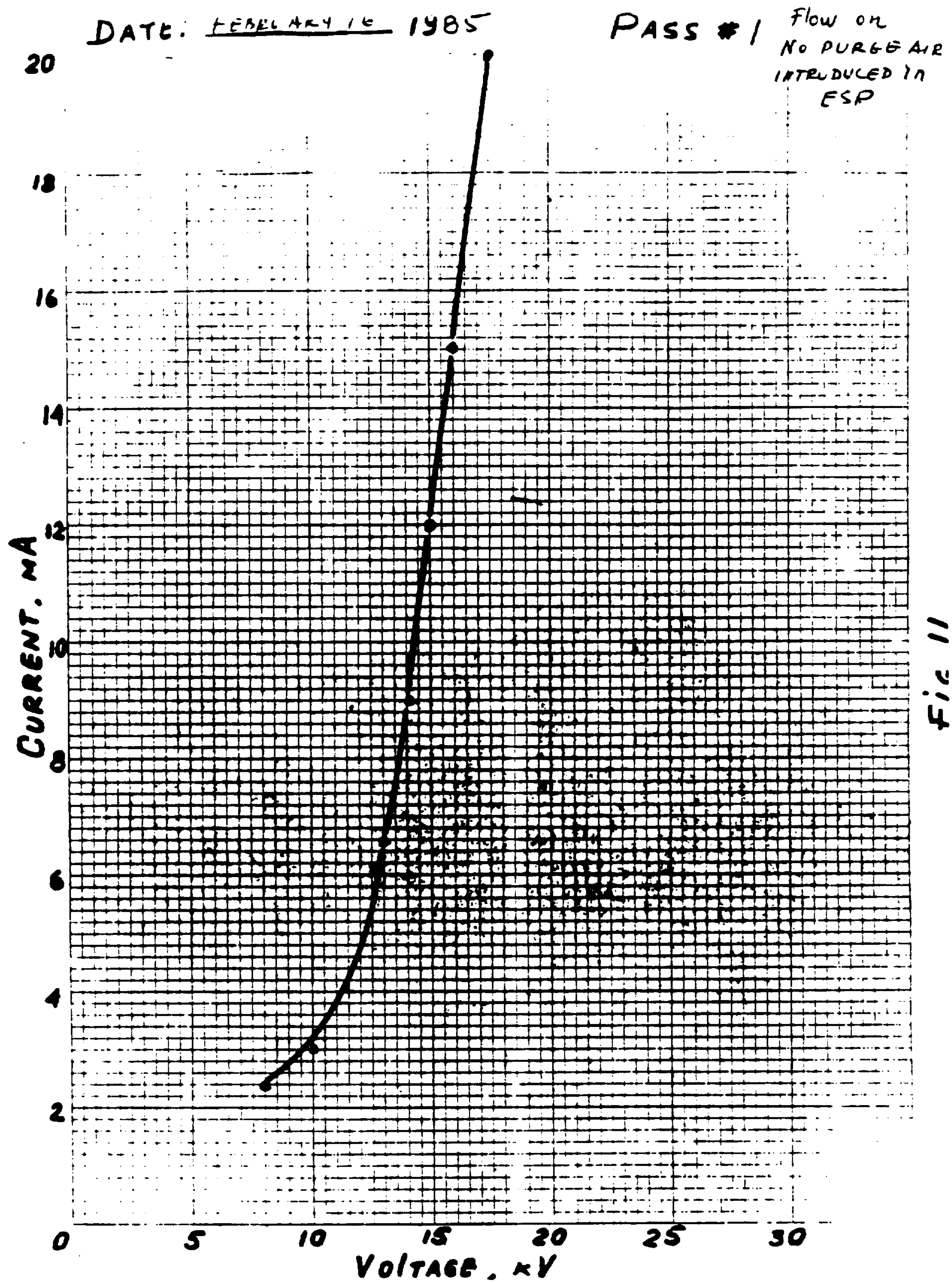

DATE:
1985
PASS #1
Flow on
No PURGE AIR
INTRODUCED In
ESP
CURRENT, mA
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
VOLTAGE, kV

Fig 11

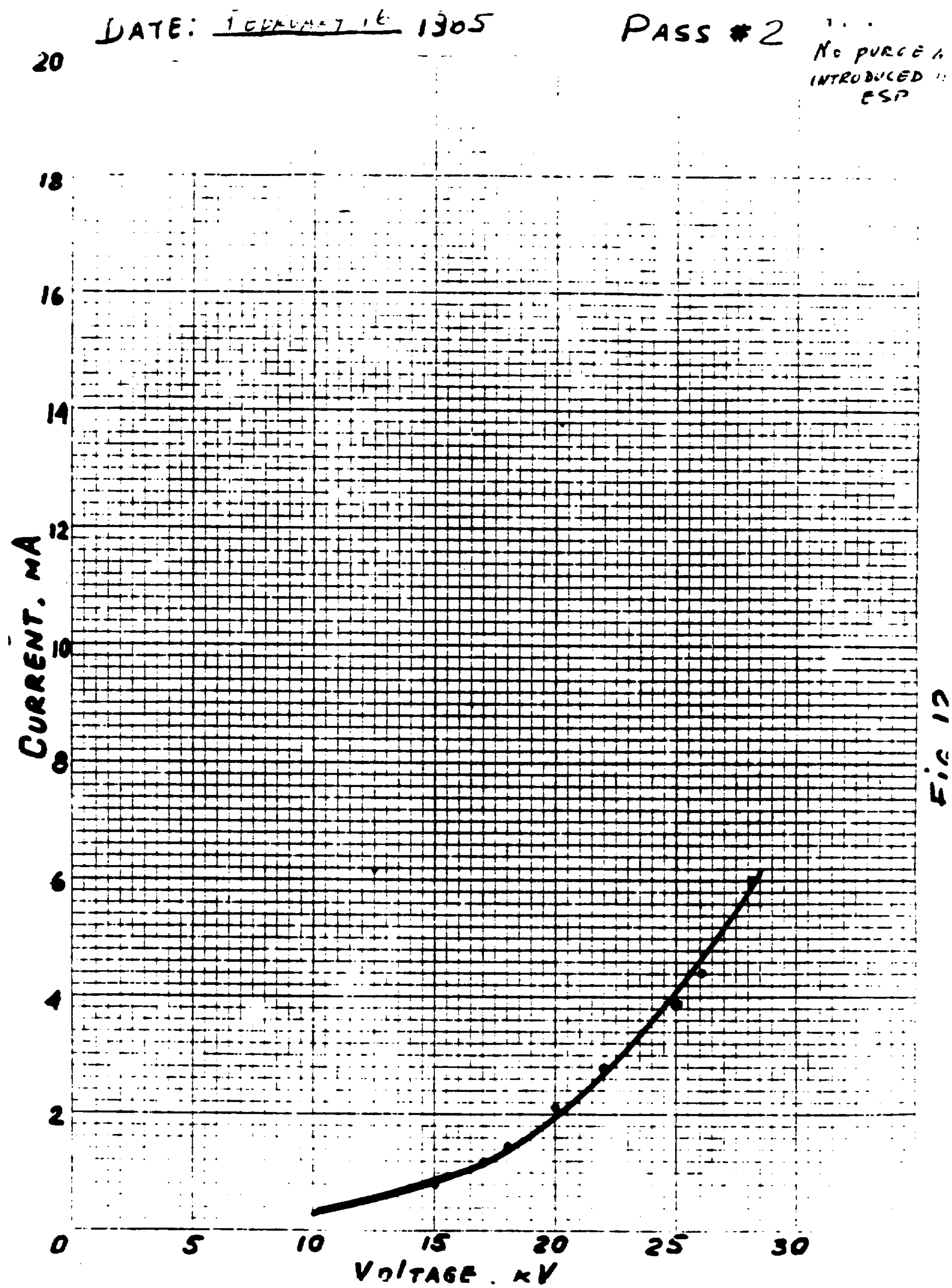
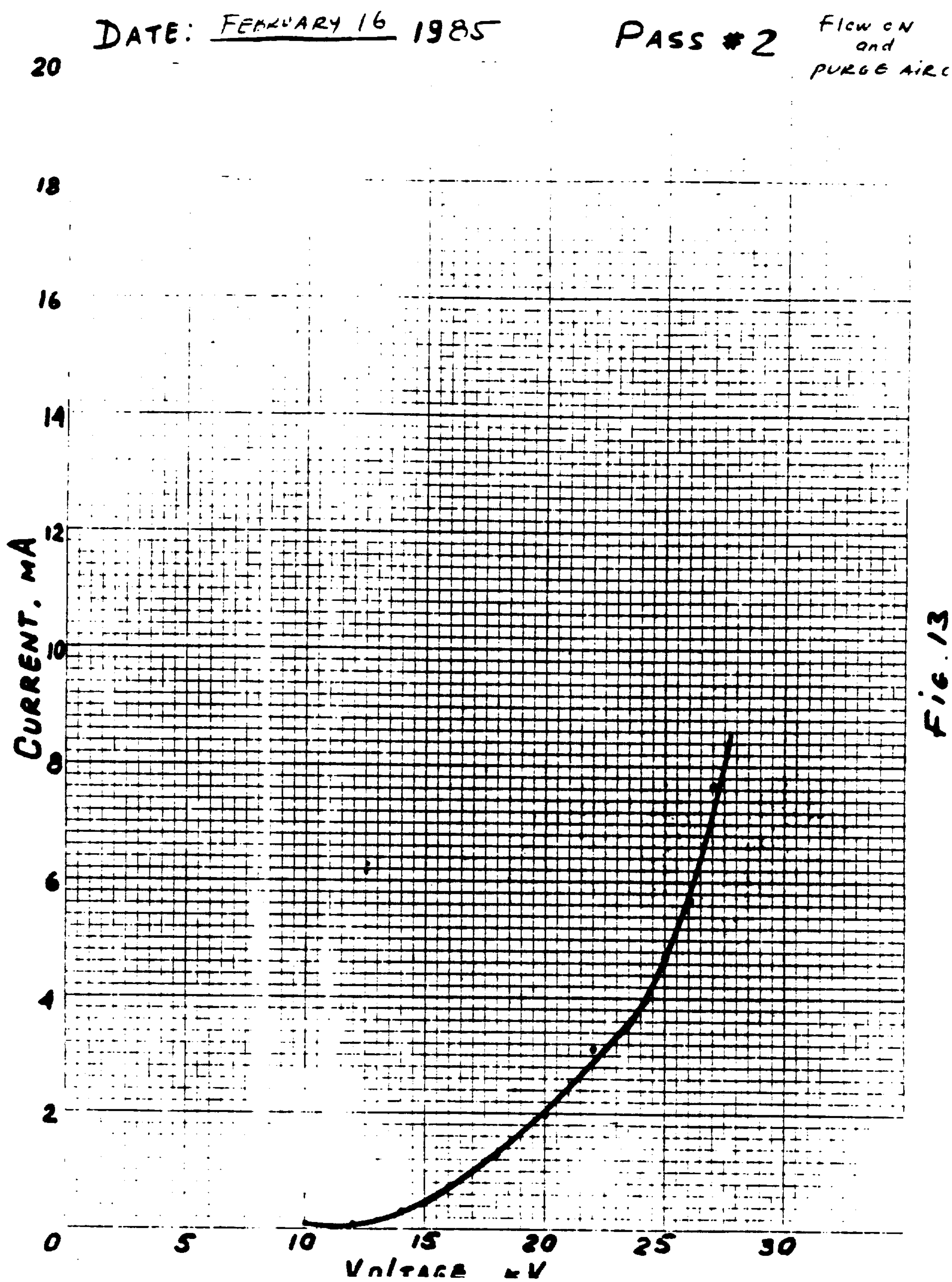
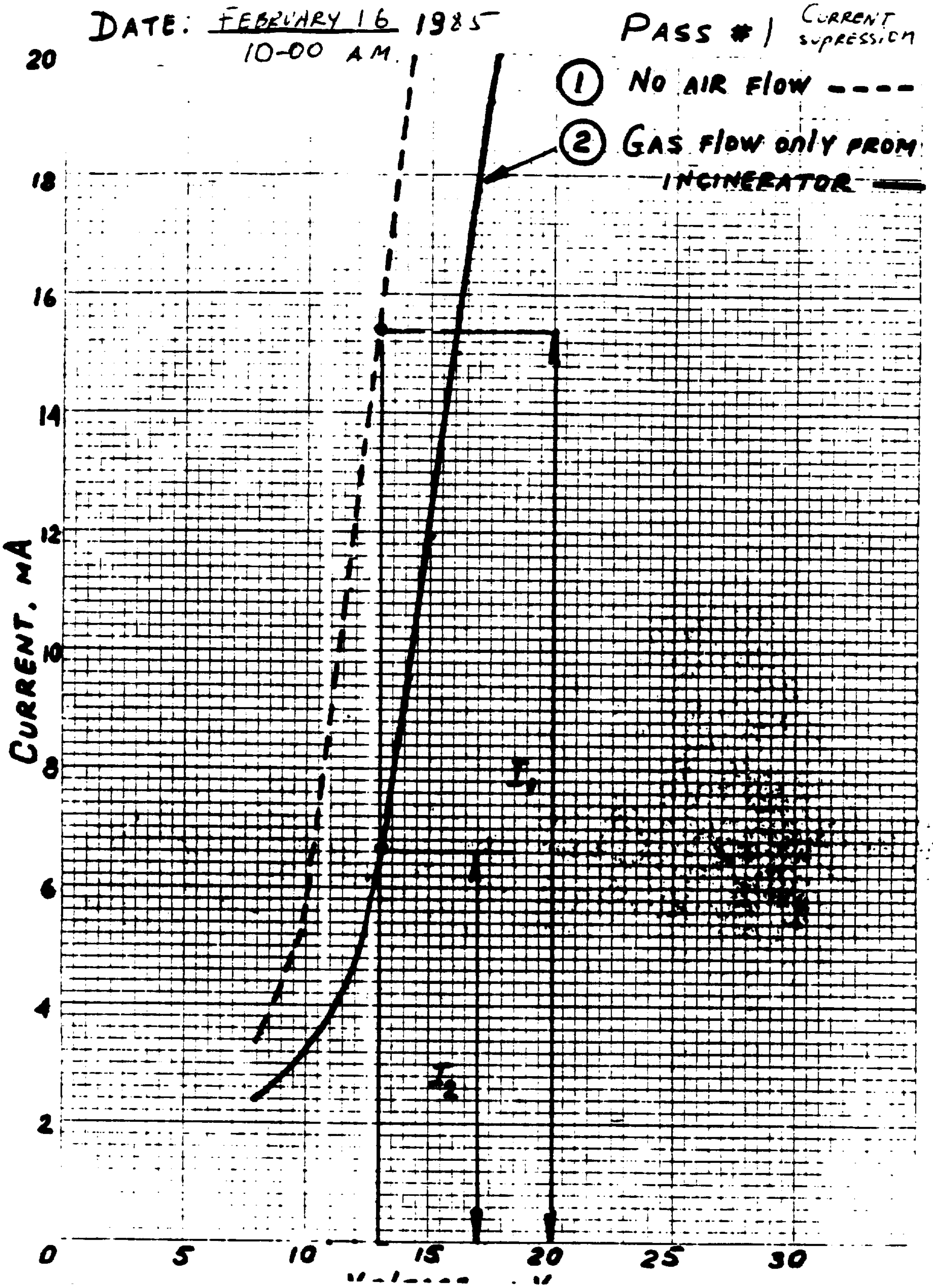

DATE:
PASS #2
No purge introduced ESP
CURRENT, mA
VOLTAGE, kV
0
2
4
6
8
10
12
14
16
18
20
5
10
15
20
25
30

Fig 12


DATE: FEBRUARY 16 1985
PASS #2
Flow ON and PURGE AIR
CURRENT, mA
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
Voltage kV
Fig. 13



DATE: FEBRUARY 16 1985
10-00 A.M.
PASS # 1 CURRENT SUPRESSION
① No AIR FLOW ----
② GAS FLOW ONLY FROM INCINERATOR ——
CURRENT, mA
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
I1
I2

FIG. 14

APPENDIX B

CONTINUOUS MONITORING DATA

Appendix B contains tabular summaries of the continuous monitoring data for Runs 01 - 03.

CONTINUOUS MONITORING DATA : RUN 02

ESP DEMONSTRATION - TEST 2

TIME	O2 (%V)	CO (PPMV)	CO2 (%V)	SO2 (PPMV)	NOX (PPMV)	THC (PPMV)
09:22:57						15.5
09:27:28	16.9	1161.1	3.6	251.5	111.8	19.0
09:32:02	17.0	1192.2	3.6	256.9	113.3	21.8
09:36:35	17.2	1058.3	3.1	215.3	103.5	23.4
09:41:08	17.8	1102.1	3.2	213.0	99.4	24.6
09:45:41	17.0	1183.5	3.5	241.0	113.0	24.2
09:50:14	16.9	1220.6	3.7	256.7	114.3	24.2
09:54:47						25.9
09:59:21	16.7	1231.8	3.8	279.6	113.6	25.5
10:03:54	16.6	1207.7	3.8	285.8	113.7	25.0
10:08:28						25.4
10:13:01	16.4	1218.0	4.2	320.0	117.4	29.0
10:17:34	16.4	1146.1	4.0	321.1	115.7	26.1
10:22:08						26.3
10:26:41	16.6	1176.6	4.2	329.5	115.7	27.2
10:31:15	16.4	1186.0	4.1	331.2	116.8	26.7
10:35:48	16.3	1189.5	4.2	344.9	116.0	28.6
10:40:22						29.6
10:44:55	15.9	1192.4	4.6	389.5	118.9	28.7
10:49:28	15.9	1216.0	4.7	403.2	119.9	30.9
10:54:02						29.8
10:58:35	15.7	1125.6	4.9	439.2	117.2	
11:03:09	16.0	1141.7	4.4	398.5	111.1	
11:07:42						
11:12:16	16.4	1201.8	4.1	336.7	113.4	
11:16:49	16.3	1196.0	4.2	329.8	115.9	27.5
11:21:23	16.6	1079.2	3.5	270.6	104.6	31.2
11:25:56						37.2
11:30:30	16.1	1352.3	4.4	322.9	127.4	37.3
11:35:03	16.1	1270.8	4.5	317.5	126.6	41.0
11:39:36						43.4
11:44:10	16.0	1460.8	4.8	327.1	136.9	43.5
11:48:44	15.9	1409.6	4.9	340.5	135.1	38.8
11:53:17						41.5
11:57:51	15.7	1335.0	5.0	353.8	130.8	44.5
12:02:24	15.7	1326.7	5.2	369.8	130.0	42.0
12:06:57						37.5
12:11:31	15.6	1381.9	5.9	442.9	130.5	38.5
12:16:05	15.2	1375.4	5.7	450.1	127.2	33.9
12:20:38	15.4	1325.8	5.3	404.6	129.0	
12:25:12						38.1
12:29:45	15.9	1202.9	4.8	347.6	125.7	39.1
12:34:19	16.1	1249.5	4.6	315.8	125.6	41.0
12:38:53						38.6
12:43:27	16.0	1267.6	4.7	314.0	127.2	44.3
12:48:01	16.0	1317.7	4.8	326.1	132.2	43.3
12:52:35						41.6
12:57:09	15.7	1351.9	5.2	360.9	137.7	42.6
13:01:42	15.6	1392.6	5.2	377.0	134.9	41.1
13:06:16	15.7	1295.6	4.8	343.6	125.1	49.7
13:10:49						44.2
13:15:22	15.2	1449.1	5.8	416.5	131.7	43.4
13:19:55	15.2	1436.6	5.7	429.7	131.4	37.7
13:24:29						35.9

ESP DEMONSTRATION - TEST 2

13:29:02	14.9	1498.0	6.0	461.9	128.8	43.9
13:33:36	15.2	1452.5	5.7	423.6	125.1	39.0
13:38:09						39.1
13:42:43	15.7	1410.6	5.3	375.0	122.1	
13:47:16	16.0	1425.2	4.9	351.5	121.7	40.7
13:51:50						38.8
13:56:23	16.2	1483.3	5.2	357.6	127.2	39.8
14:00:57	16.0	1435.2	5.1	356.5	122.4	42.6
14:05:31	16.0	1395.6	5.0	362.9	121.9	44.3
14:10:04						47.7
14:14:38	16.0	1528.3	5.2	364.4	122.4	43.5
14:19:11	16.0	1464.0	5.0	350.9	119.5	45.3
14:23:45						43.7
14:28:18	15.8	1535.8	5.5	359.5	127.4	41.8
14:32:51	15.8	1505.5	5.3	351.3	127.4	42.7
14:37:25						41.7
14:41:59	15.8	1561.2	5.8	383.5	136.4	37.5
14:46:32	15.5	1449.2	5.9	394.6	134.0	32.0
14:51:06	15.7	1195.3	4.9	341.9	116.7	
14:55:39	16.4	1236.3	5.7	386.5	115.7	
15:00:13	15.4	1352.1	6.1	407.5	130.0	
15:04:46	15.4	1398.3	6.0	423.9	138.1	
15:09:20						
15:13:54	15.7	1334.9	5.7	376.7	136.6	
NO. PTS.	56	56	56	56	56	66
MEAN	16.0	1308.7	4.8	350.1	122.9	35.8
STD. DEV.	0.5	129.6	0.8	56.9	9.1	8.0

NOTE: THC DATA WAS RECORDED IN FIVE MINUTE INTERVALS BEGINNING AT 9:20

CONTINUOUS MONITORING DATA : RUN 02

ESP DEMONSTRATION - TEST 2

TIME	O2 (%V)	CO (PPMV)	CO2 (%V)	SO2 (PPMV)	NOX (PPMV)	THC (PPMV)
09:22:57						
09:27:28	16.9	1161.1	3.6	251.5	111.8	15.5
09:32:02	17.0	1192.2	3.6	256.9	113.3	19.0
09:36:35	17.2	1058.3	3.1	215.3	103.5	21.8
09:41:08	17.8	1102.1	3.2	213.0	99.4	23.4
09:45:41	17.0	1183.5	3.5	241.0	113.0	24.6
09:50:14	16.9	1220.6	3.7	256.7	114.3	24.2
09:54:47						24.2
09:59:21	16.7	1231.8	3.8	279.6	113.6	25.9
10:03:54	16.6	1207.7	3.8	285.8	113.7	25.5
10:08:28						25.0
10:13:01	16.4	1218.0	4.2	320.0	117.4	25.4
10:17:34	16.4	1146.1	4.0	321.1	115.7	29.0
10:22:08						26.1
10:26:41	16.6	1176.6	4.2	329.5	115.7	26.3
10:31:15	16.4	1186.0	4.1	331.2	116.8	27.2
10:35:48	16.3	1189.5	4.2	344.9	116.0	26.7
10:40:22						28.6
10:44:55	15.9	1192.4	4.6	389.5	118.9	29.6
10:49:28	15.9	1216.0	4.7	403.2	119.9	28.7
10:54:02						30.9
10:58:35	15.7	1125.6	4.9	439.2	117.2	29.8
11:03:09	16.0	1141.7	4.4	398.5	111.1	
11:07:42						
11:12:16	16.4	1201.8	4.1	336.7	113.4	
11:16:49	16.3	1196.0	4.2	329.8	115.9	
11:21:23	16.6	1079.2	3.5	270.6	104.6	27.5
11:25:56						31.2
11:30:30	16.1	1352.3	4.4	322.9	127.4	37.2
11:35:03	16.1	1270.8	4.5	317.5	126.6	37.3
11:39:36						41.0
11:44:10	16.0	1460.8	4.8	327.1	136.9	43.4
11:48:44	15.9	1409.6	4.9	340.5	135.1	43.5
11:53:17						38.8
11:57:51	15.7	1335.0	5.0	353.8	130.8	41.5
12:02:24	15.7	1326.7	5.2	369.8	130.0	44.5
12:06:57						42.0
12:11:31	15.6	1381.9	5.9	442.9	130.5	37.5
12:16:05	15.2	1375.4	5.7	450.1	127.2	38.5
12:20:38	15.4	1325.8	5.3	404.6	129.0	33.9
12:25:12						
12:29:45	15.9	1202.9	4.8	347.6	125.7	38.1
12:34:19	16.1	1249.5	4.6	315.8	125.6	39.1
12:38:53						41.0
12:43:27	16.0	1267.6	4.7	314.0	127.2	38.6
12:48:01	16.0	1317.7	4.8	326.1	132.2	44.3
12:52:35						43.3
12:57:09	15.7	1351.9	5.2	360.9	137.7	41.6
13:01:42	15.6	1392.6	5.2	377.0	134.9	42.6
13:06:16	15.7	1295.6	4.8	343.6	125.1	41.1
13:10:49						49.7
13:15:22	15.2	1449.1	5.8	416.5	131.7	44.2
13:19:55	15.2	1436.6	5.7	429.7	131.4	43.4
13:24:29						37.7
						35.9

ESP DEMONSTRATION - TEST 2

TIME	O2 (%V)	CO (PPMV)	CO2 (%V)	SO2 (PPMV)	NOX (PPMV)	THC (PPMV)
13:29:02	14.9	1498.0	6.0	461.9	128.8	
13:33:36	15.2	1452.5	5.7	423.6	125.1	43.9
13:38:09						39.0
13:42:43	15.7	1410.6	5.3	375.0	122.1	39.1
13:47:16	16.0	1425.2	4.9	351.5	121.7	
13:51:50						40.7
13:56:23	16.2	1483.3	5.2	357.6	127.2	38.8
14:00:57	16.0	1435.2	5.1	356.5	127.2	39.8
14:05:31	16.0	1395.6	5.0	362.9	122.4	42.6
14:10:04						44.3
14:14:38	16.0	1528.3	5.2	364.4	121.9	47.7
14:19:11	16.0	1464.0	5.0	350.9	122.4	43.5
14:23:45						45.3
14:28:18	15.8	1535.8	5.5	359.5	127.4	43.7
14:32:51	15.8	1505.5	5.3	351.3	127.4	41.8
14:37:25						43.7
14:41:59	15.8	1561.2	5.8	383.5	136.4	41.3
14:46:32	15.5	1449.2	5.9	394.6	134.0	37.5
14:51:06	15.7	1195.3	4.9	341.9	116.7	37.0
14:55:39	16.4	1236.3	5.7	386.5	115.7	
15:00:13	15.4	1352.1	6.1	407.5	130.0	
15:04:46	15.4	1398.3	6.0	423.9	138.1	
15:09:20						
15:13:54	15.7	1334.9	5.7	376.7	136.6	
NO. PTS.	56	56	56	56	56	66
MEAN	16.0	1308.7	4.8	350.1	122.9	35.8
STD. DEV.	0.5	129.6	0.8	56.9	9.1	8.0

NOTE: THC DATA WAS RECORDED IN FIVE MINUTE INTERVALS BEGINNING AT 9:20

APPENDIX C

RAW METALS DATA

Appendix C contains the raw analytical data for the SASS train catches (ug/g).

TRACE METALS CONTENT OF PARTICULATE MATTER BY PARTICULATE SIZE FRACTION (SASS SIZE FRACTION BASIS)

RUN: 1

	ESP INLET SASS SIZE FRACTIONS						ESP OUTLET SASS SIZE FRACTIONS					
	1	2	3	4	5	TOTAL	1	2	3	4	5	TOTAL
METAL	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g
ALUMINUM	2.73E+04	3.33E+04	3.78E+04	2.60E+05	0.00E+00	4.08E+04	1.10E+03	0.00E+00	0.00E+00	3.69E+07	0.00E+00	1.15E+05
ANTIMONY	7.96E+01	3.12E+02	1.87E+02	4.46E+02	0.00E+00	1.72E+02	8.23E+00	0.00E+00	0.00E+00	1.43E+04	0.00E+00	5.33E-01
ARSENIC	1.47E+03	0.00E+00	1.70E+03	1.09E+03	0.00E+00	9.97E+02	1.44E+01	0.00E+00	0.00E+00	2.05E+05	0.00E+00	6.48E+02
BARIUM	2.97E+03	2.08E+03	2.79E+03	9.86E+03	0.00E+00	3.03E+03	5.16E+01	0.00E+00	0.00E+00	2.02E+06	0.00E+00	6.30E+03
CADMIUM	1.39E+03	3.51E+03	4.71E+03	1.08E+04	0.00E+00	2.57E+03	8.38E+01	0.00E+00	0.00E+00	3.20E+04	1.50E-02	3.29E+02
CALCIUM	5.47E+04	6.76E+04	8.50E+04	4.19E+05	3.60E-02	7.72E+04	1.53E+03	0.00E+00	0.00E+00	1.00E+08	3.62E-01	3.15E+05
CHROMIUM	7.61E+02	1.06E+03	1.28E+03	1.07E+03	6.44E-01	1.37E+03	8.79E+02	0.00E+00	0.00E+00	0.00E+00	1.83E-01	2.66E+03
COBALT	5.54E+01	5.88E+01	1.08E+02	5.63E+01	0.00E+00	5.74E+01	1.82E+01	0.00E+00	0.00E+00	7.81E+04	3.30E-02	5.82E+02
COPPER	4.35E+03	7.30E+03	1.10E+04	6.54E+03	0.00E+00	5.48E+03	8.54E+01	0.00E+00	0.00E+00	6.54E+02	9.00E-03	1.75E+02
GOLD	0.00E+00	0.00E+00	0.00E+00	8.60E+00	0.00E+00	4.25E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IRON	9.82E+04	7.80E+04	9.12E+04	3.70E+04	2.59E+00	9.07E+04	5.46E+03	0.00E+00	0.00E+00	1.02E+07	1.04E+00	4.72E+04
LEAD	1.44E+03	2.45E+03	5.03E+03	9.77E+03	0.00E+00	2.22E+03	1.37E+01	0.00E+00	0.00E+00	5.58E+05	0.00E+00	1.74E+03
MAGNESIUM	2.11E+04	2.74E+04	3.20E+04	2.16E+04	1.20E-02	2.33E+04	3.18E+02	0.00E+00	0.00E+00	3.07E+06	4.70E-02	1.03E+04
MANGANESE	7.52E+02	6.02E+02	8.40E+02	2.32E+01	4.90E-02	7.08E+02	1.29E+02	0.00E+00	0.00E+00	0.00E+00	6.20E-02	7.34E+02
NICKEL	9.98E+01	4.19E+02	7.79E+02	0.00E+00	2.50E-01	3.94E+02	6.48E+02	0.00E+00	0.00E+00	0.00E+00	1.90E-01	2.40E+03
PHOSPHOROUS	5.39E+04	6.91E+04	8.39E+04	3.53E+04	9.80E-01	5.99E+04	1.81E+03	0.00E+00	0.00E+00	5.85E-04	5.30E-01	7.16E+03
SELENIUM	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.66E+02	0.00E+00	0.00E+00	0.00E+00	1.82E-01	1.94E+03
SILVER	6.18E+00	1.30E+02	2.92E+02	6.35E+01	0.00E+00	5.22E+01	0.00E+00	0.00E+00	0.00E+00	1.57E+03	0.00E+00	4.35E+00
SODIUM	6.29E+03	9.44E+03	4.86E+03	7.91E+03	0.00E+00	7.32E+03	3.41E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.40E+02
SULFUR	2.37E+04	3.77E+04	5.92E+04	7.93E+04	8.13E+02	6.46E+05	1.79E+05	0.00E+00	0.00E+00	4.75E+05	1.93E+02	2.07E+05
TIN	5.15E+02	8.52E+02	1.62E+03	6.40E+03	0.00E+00	9.28E+02	4.83E+01	0.00E+00	0.00E+00	2.29E+03	0.00E+00	5.53E-01
TITANIUM	6.71E+03	8.54E+03	8.15E+03	4.52E+03	0.00E+00	7.19E+03	1.42E+02	0.00E+00	0.00E+00	2.16E+05	0.00E+00	8.08E+02
VANADIUM	2.46E+02	3.12E+02	3.79E+02	4.72E+02	0.00E+00	2.80E+02	2.41E+01	0.00E+00	0.00E+00	1.37E+04	2.40E-02	3.01E+02
ZINC	6.85E+03	8.82E+03	1.18E+04	1.09E+04	0.00E+00	7.74E+03	3.73E+02	0.00E+00	0.00E+00	6.85E+04	0.00E+00	5.84E+02

SASS SIZE FRACTIONS

FRACTION 1 = PROBE RINSE + 10 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 2 = 3 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 3 = 1 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 4 = FILTER CATCH (SOLID SAMPLE)
FRACTION 5 = IMPINGER CATCH + NITRIC IMPINGER RINSE (LIQUID SAMPLE)
TOTAL = SUM OF FRACTIONS 1-5

RUN: 2

TRACE METALS CONTENT OF PARTICULATE MATTER BY PARTICULATE SIZE FRACTION (SASS SIZE FRACTION BASIS)

	SCRUBBER INLET SASS SIZE FRACTIONS						SCRUBBER OUTLET SASS SIZE FRACTIONS					
	1	2	3	4	5	TOTAL	1	2	3	4	5	TOTAL
METAL	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g
ALUMINUM	3.48E+04	5.90E+04	5.28E+04	4.62E+05	0.00E+00	6.19E+04	1.48E+06	0.00E+00	0.00E+00	4.20E+05	0.00E+00	5.03E+05
ANTIMONY	6.26E+01	3.44E+02	1.23E+02	3.47E+02	0.00E+00	2.10E+02	0.00E+00	0.00E+00	0.00E+00	6.61E+02	0.00E+00	6.09E+02
ARSENIC	9.60E+02	1.14E+03	9.44E+02	1.32E+03	0.00E+00	1.06E+03	0.00E+00	0.00E+00	0.00E+00	2.52E+03	0.00E+00	2.32E+03
BARIUM	2.37E+03	1.97E+03	2.35E+03	1.15E+04	0.00E+00	2.74E+03	0.00E+00	0.00E+00	0.00E+00	1.79E+04	4.00E-03	1.66E+04
CADMIUM	1.68E+03	3.04E+03	4.42E+04	9.84E+03	0.00E+00	3.27E+03	4.15E+05	0.00E+00	0.00E+00	1.41E+04	0.00E+00	4.57E+04
CALCIUM	6.43E+04	1.06E+05	1.35E+05	9.07E+05	1.60E-02	1.13E+05	1.35E+06	0.00E+00	0.00E+00	6.22E+05	3.02E-01	6.92E+05
CHROMIUM	7.65E+02	9.16E+02	8.67E+02	1.07E+03	1.08E-01	9.16E+02	1.27E+06	0.00E+00	0.00E+00	6.23E+02	9.40E-02	1.02E+05
COBALT	6.72E+01	6.45E+01	5.57E+01	1.39E+02	0.00E+00	6.83E+01	5.00E+03	0.00E+00	0.00E+00	0.00E+00	1.50E-02	5.61E+03
COPPER	5.62E+03	7.39E+03	8.28E+03	8.79E+03	0.00E+00	6.63E+03	7.60E+05	0.00E+00	0.00E+00	1.21E+04	0.00E+00	7.09E+04
GOLD	0.00E+00	1.13E+00	0.00E+00	0.00E+00	0.00E+00	5.48E-01	0.00E+00	0.00E+00	0.00E+00	1.58E+01	0.00E+00	1.46E+01
IRON	7.63E+04	1.01E+05	1.12E+05	5.45E+04	3.88E-01	8.85E+04	8.00E+06	0.00E+00	0.00E+00	1.74E+04	9.48E-01	6.56E+05
LEAD	1.47E+03	3.11E+03	4.24E+03	1.06E+04	0.00E+00	2.64E+03	8.00E+05	0.00E+00	0.00E+00	1.94E+04	0.00E+00	7.99E+04
MAGNESIUM	2.48E+04	3.82E+04	3.45E+04	4.43E+04	1.00E-02	3.22E+04	1.00E+05	0.00E+00	0.00E+00	2.10E+04	4.70E-02	2.77E+04
MANGANESE	6.77E+02	6.77E+02	5.62E+02	9.57E+01	8.00E-03	6.59E+02	1.45E+05	0.00E+00	0.00E+00	0.00E+00	3.00E-02	1.17E+04
NICKEL	2.53E+02	3.63E+02	3.26E+02	0.00E+00	3.00E-02	3.16E+02	6.00E+05	0.00E+00	0.00E+00	0.00E+00	5.00E-02	4.79E+04
PHOSPHOROUS	6.29E+04	8.06E+04	3.76E+04	4.16E+04	6.70E-01	7.07E+04	0.00E+00	0.00E+00	0.00E+00	7.59E+03	6.20E-01	1.39E+04
SELENIUM	0.00E+00	0.00E+00	0.00E+00	1.92E+01	0.00E+00	6.99E-01	8.10E+05	0.00E+00	0.00E+00	2.02E+02	0.00E+00	6.39E+04
SILVER	2.65E+01	1.34E+02	2.09E+02	1.99E+02	0.00E+00	9.78E+01	0.00E+00	0.00E+00	0.00E+00	2.68E+02	0.00E+00	2.47E+03
SODIUM	6.60E+03	1.08E+04	9.34E+03	1.91E+04	0.00E+00	9.11E+03	1.71E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.35E+05
SULFUR	1.26E+04	3.24E+04	1.84E+04	6.03E+04	9.88E+02	6.16E+05	1.17E+07	0.00E+00	0.00E+00	1.31E+04	3.58E+01	1.34E+05
TIN	5.59E+02	1.01E+03	1.27E+03	5.68E+03	0.00E+00	9.74E+02	5.90E+05	0.00E+00	0.00E+00	1.17E+04	0.00E+00	5.72E+04
TITANIUM	8.14E+03	9.04E+03	8.95E+03	4.40E+03	0.00E+00	8.45E+03	1.75E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.38E+04
VANADIUM	2.74E+02	3.71E+02	3.32E+02	5.22E+02	0.00E+00	3.31E+02	5.00E+04	0.00E+00	0.00E+00	6.36E+02	0.00E+00	4.52E+03
ZINC	7.66E+03	1.06E+04	1.17E+04	1.30E+04	0.00E+00	9.35E+03	1.01E+06	0.00E+00	0.00E+00	1.13E+04	0.00E+00	9.99E+04

SASS SIZE FRACTIONS

FRACTION 1 = PROBE RINSE + 10 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 2 = 3 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 3 = 1 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 4 = FILTER CATCH (SOLID SAMPLE)
FRACTION 5 = IMPINGER CATCH + NITRIC IMPINGER RINSE (LIQUID SAMPLE)
TOTAL = SUM OF FRACTIONS 1-5

TRACE METALS CONTENT OF PARTICULATE MATTER BY PARTICULATE SIZE FRACTION (SASS SIZE FRACTION BASIS)

RUN: 3

	SCRUBBER INLET SASS SIZE FRACTIONS						SCRUBBER OUTLET SASS SIZE FRACTIONS					
	1	2	3	4	5	TOTAL	1	2	3	4	5	TOTAL
METAL	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g
ALUMINUM	4.21E+04	5.69E+04	3.19E+04	1.62E+05	0.00E+00	5.74E+04	7.13E+05	0.00E+00	0.00E+00	1.53E+06	0.00E+00	1.48E+06
ANTIMONY	7.25E+01	2.14E+02	1.54E+02	3.25E+02	0.00E+00	1.49E+02	2.66E+02	0.00E+00	0.00E+00	7.31E+02	0.00E+00	7.02E+02
ARSENIC	7.76E+02	5.25E+02	6.73E+02	6.70E+02	0.00E+00	6.69E+02	5.22E+03	0.00E+00	0.00E+00	2.62E+03	0.00E+00	2.78E+03
BARIUM	2.72E+03	1.92E+03	1.78E+04	6.46E+03	0.00E+00	3.14E+03	4.91E+03	0.00E+00	0.00E+00	2.55E+04	0.00E+00	2.42E+04
CADMIUM	1.92E+03	3.91E+03	8.39E+03	7.42E+03	0.00E+00	3.31E+03	4.08E+02	0.00E+00	0.00E+00	1.27E+04	0.00E+00	1.20E+04
CALCIUM	8.36E+03	1.08E+05	9.55E+04	3.03E+05	1.30E-02	7.29E+04	1.38E+06	0.00E+00	0.00E+00	2.49E+06	1.91E-01	2.42E+06
CHROMIUM	7.85E+02	8.30E+02	7.57E+02	8.82E+02	6.60E-02	8.53E+02	1.06E+03	0.00E+00	0.00E+00	0.00E+00	2.88E-01	6.56E+01
COBALT	5.73E+01	6.05E+01	5.78E+01	6.47E+01	0.00E+00	5.91E+01	3.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.96E+01
COPPER	5.42E+03	6.32E+03	1.01E+04	8.30E+03	0.00E+00	6.13E+03	9.12E+02	0.00E+00	0.00E+00	1.40E+04	0.00E+00	1.31E+04
GOLD	0.00E+00	0.00E+00	0.00E+00	8.03E+00	0.00E+00	6.64E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IRON	7.23E+04	9.65E+04	9.14E+04	3.64E+04	2.23E-01	7.54E+04	2.40E+04	0.00E+00	0.00E+00	1.44E+04	1.35E+00	1.50E+04
LEAD	2.03E+03	4.70E+03	5.21E+03	1.17E+04	0.00E+00	3.93E+03	1.96E+04	0.00E+00	0.00E+00	1.94E+04	0.00E+00	1.34E+04
MAGNESIUM	2.38E+04	2.72E+04	2.51E+04	2.56E+04	8.00E-03	2.52E+04	2.17E+05	0.00E+00	0.00E+00	0.00E+00	1.50E-02	1.35E+04
MANGANESE	4.96E+02	6.03E+02	6.53E+02	9.25E+01	0.00E+00	5.07E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.90E-02	5.84E-03
NICKEL	2.88E+02	3.74E+02	4.33E+02	7.13E+01	0.00E+00	3.06E+02	5.75E+02	0.00E+00	0.00E+00	0.00E+00	1.50E-01	3.58E+01
PHOSPHOROUS	5.87E+04	6.90E+04	6.92E+04	2.38E+04	1.10E+00	6.07E+04	0.00E+00	0.00E+00	0.00E+00	2.85E+04	2.60E-01	2.67E+04
SELENIUM	0.00E+00	0.00E+00	0.00E+00	1.74E+01	0.00E+00	1.44E+00	0.00E+00	0.00E+00	0.00E+00	1.25E+02	0.00E+00	1.17E+02
SILVER	5.47E+01	1.22E+02	2.46E+02	5.01E+01	0.00E+00	8.51E+01	0.00E+00	0.00E+00	0.00E+00	3.62E+02	0.00E+00	3.39E+02
SODIUM	9.76E+03	8.02E+03	4.72E+03	1.51E+04	0.00E+00	8.89E+03	1.16E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.22E+02
SULFUR	1.43E+04	2.61E+04	4.05E+04	4.47E+04	2.16E+03	1.46E+06	1.94E+04	0.00E+00	0.00E+00	1.50E+05	2.98E+01	1.42E+05
TIN	6.37E+02	1.18E+03	1.74E+03	8.15E+03	0.00E+00	1.49E+03	3.75E+03	0.00E+00	0.00E+00	6.19E+03	0.00E+00	6.03E+03
TITANIUM	8.64E+03	9.74E+03	9.24E+03	1.36E+03	0.00E+00	8.09E+03	3.15E+04	0.00E+00	0.00E+00	1.73E+03	0.00E+00	3.58E+03
VANADIUM	2.35E+02	3.20E+02	4.50E+02	3.06E+02	0.00E+00	2.79E+02	6.19E+02	0.00E+00	0.00E+00	4.03E+02	0.00E+00	4.17E+02
ZINC	7.89E+03	1.03E+04	1.20E+04	9.43E+03	0.00E+00	9.06E+03	2.37E+03	0.00E+00	0.00E+00	1.07E+04	0.00E+00	1.02E+04

SASS SIZE FRACTIONS

FRACTION 1 = PROBE RINSE + 10 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 2 = 3 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 3 = 1 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 4 = FILTER CATCH (SOLID SAMPLE)
FRACTION 5 = IMPINGER CATCH + NITRIC IMPINGER RINSE (LIQUID SAMPLE)
TOTAL = SUM OF FRACTIONS 1-5

TRACE METALS CONTENT OF PARTICULATE MATTER BY PARTICULATE SIZE FRACTION (SASS SIZE FRACTION BASIS)

RUN: 1

	SCRUBBER INLET SASS SIZE FRACTIONS						SCRUBBER OUTLET SASS SIZE FRACTIONS					
	1	2	3	4	5	TOTAL	1	2	3	4	5	TOTAL
METAL	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g
ALUMINUM	2.73E+04	3.33E+04	3.78E+04	2.60E+05	0.00E+00	4.08E+04	1.16E+06	0.00E+00	0.00E+00	6.99E+05	0.00E+00	7.30E+05
ANTIMONY	7.96E+01	3.12E+02	1.87E+02	4.46E+02	0.00E+00	1.72E+02	0.00E+00	0.00E+00	0.00E+00	7.41E+02	0.00E+00	6.91E+02
ARSENIC	1.47E+03	0.00E+00	1.70E+03	1.09E+03	0.00E+00	9.97E+02	0.00E+00	0.00E+00	0.00E+00	2.63E+03	1.00E-01	3.67E+03
BARIUM	2.97E+03	2.08E+03	2.79E+03	9.86E+03	0.00E+00	3.03E+03	0.00E+00	0.00E+00	0.00E+00	2.36E+04	7.00E-03	2.21E+04
CADMIUM	1.39E+03	3.51E+03	4.71E+03	1.08E+04	0.00E+00	2.57E+03	2.70E+05	0.00E+00	0.00E+00	1.34E+04	0.00E+00	3.07E+04
CALCIUM	5.47E+04	6.76E+04	8.50E+04	4.19E+05	3.60E-02	7.72E+04	1.43E+06	0.00E+00	0.00E+00	6.69E+05	3.29E-01	7.24E+05
CHROMIUM	7.61E+02	1.06E+03	1.28E+03	1.07E+03	6.44E-01	1.37E+03	3.15E+05	0.00E+00	0.00E+00	3.90E+02	1.73E-01	2.37E+04
COBALT	5.54E+01	5.88E+01	1.08E+02	5.63E+01	0.00E+00	5.74E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.60E-02	1.93E+02
COPPER	4.35E+03	7.30E+03	1.10E+04	6.54E+03	0.00E+00	5.48E+03	4.95E+05	0.00E+00	0.00E+00	9.64E+03	0.00E+00	4.23E+04
GOLD	0.00E+00	0.00E+00	0.00E+00	8.60E+00	0.00E+00	4.25E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IRON	9.82E+04	7.80E+04	9.12E+04	3.70E+04	2.59E+00	9.07E+04	2.89E+06	0.00E+00	0.00E+00	6.04E+03	1.62E+00	2.20E+05
LEAD	1.44E+03	2.45E+03	5.03E+03	9.77E+03	0.00E+00	2.22E+03	0.00E+00	0.00E+00	0.00E+00	1.18E+04	1.45E-01	1.29E+04
MAGNESIUM	2.11E+04	2.74E+04	3.20E+04	2.16E+04	1.20E-02	2.33E+04	2.95E+05	0.00E+00	0.00E+00	4.05E+03	2.80E-02	2.40E+04
MANGANESE	7.52E+02	6.02E+02	8.40E+02	2.32E+01	4.90E-02	7.08E+02	4.00E+04	0.00E+00	0.00E+00	0.00E+00	5.30E-02	3.33E+03
NICKEL	9.98E+01	4.19E+02	7.79E+02	0.00E+00	2.50E-01	3.74E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E-01	1.21E+03
PHOSPHOROUS	5.38E+04	6.91E+04	8.39E+04	3.53E+04	9.80E-01	5.89E+04	6.50E+05	0.00E+00	0.00E+00	1.60E+04	3.40E-01	6.29E+04
SELENIUM	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.53E+01	0.00E+00	6.09E+01
SILVER	6.18E+00	1.30E+02	2.92E+02	6.35E+01	0.00E+00	5.22E+01	0.00E+00	0.00E+00	0.00E+00	3.45E+02	0.00E+00	3.22E+02
SODIUM	6.29E+03	9.44E+03	4.86E+03	7.91E+03	0.00E+00	7.32E+03	1.32E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.85E+04
SULFUR	2.37E+04	3.77E+04	5.92E+04	7.93E+04	8.13E+02	6.46E+05	1.12E+07	0.00E+00	0.00E+00	6.77E+04	1.26E+01	9.58E+05
TIN	5.15E+02	8.52E+02	1.62E+03	6.40E+03	0.00E+00	9.28E+02	5.85E+05	0.00E+00	0.00E+00	1.10E+04	0.00E+00	4.96E+04
TITANIUM	6.71E+03	8.54E+03	8.15E+03	4.52E+03	0.00E+00	7.19E+03	6.10E+05	0.00E+00	0.00E+00	3.57E+02	0.00E+00	4.14E+04
VANADIUM	2.46E+02	3.12E+02	3.79E+02	4.72E+02	0.00E+00	2.80E+02	5.00E+03	0.00E+00	0.00E+00	5.13E+02	0.00E+00	8.15E+02
ZINC	6.85E+03	3.82E+03	1.18E+04	1.09E+04	0.00E+00	7.74E+03	8.90E+05	0.00E+00	0.00E+00	9.80E+03	0.00E+00	6.91E+04

SASS SIZE FRACTIONS

FRACTION 1 = PROBE RINSE + 10 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 2 = 3 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 3 = 1 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 4 = FILTER CATCH (SOLID SAMPLE)
FRACTION 5 = IMPINGER CATCH + NITRIC IMPINGER RINSE (LIQUID SAMPLE)
TOTAL = SUM OF FRACTIONS 1-5

TRACE METALS CONTENT OF PARTICULATE MATTER BY PARTICULATE SIZE FRACTION (SASS SIZE FRACTION BASIS)

RUN: 2

	ESP INLET SASS SIZE FRACTIONS						ESP OUTLET SASS SIZE FRACTIONS					
	1	2	3	4	5	TOTAL	1	2	3	4	5	TOTAL
METAL	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g
ALUMINUM	3.48E+04	5.80E+04	5.29E+04	4.63E+05	0.00E+00	6.19E+04	1.32E+03	0.00E+00	0.00E+00	1.17E+07	0.00E+00	1.57E+05
ANTIMONY	6.26E+01	3.44E+02	1.23E+02	3.47E+02	0.00E+00	2.10E+02	0.00E+00	0.00E+00	0.00E+00	2.04E+03	0.00E+00	2.72E+01
ARSENIC	9.60E+02	1.14E+03	9.44E+02	1.32E+03	0.00E+00	1.06E+03	0.00E+00	0.00E+00	0.00E+00	3.51E+04	1.60E-01	2.30E+03
BARIUM	2.97E+03	1.97E+03	2.35E+03	1.15E+04	0.00E+00	2.74E+03	1.76E+01	0.00E+00	0.00E+00	6.71E+05	0.00E+00	8.95E+03
CADMIUM	1.69E+03	3.04E+03	4.42E+04	9.84E+03	0.00E+00	3.27E+03	5.74E+01	0.00E+00	0.00E+00	2.59E+03	0.00E+00	9.12E+01
CALCIUM	6.43E+04	1.06E+05	1.35E+05	8.07E+05	1.60E-02	1.13E+05	3.28E+02	0.00E+00	0.00E+00	2.85E+07	2.60E-02	3.80E+05
CHROMIUM	7.65E+02	9.16E+02	8.67E+02	1.07E+03	1.08E-01	9.16E+02	5.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.94E+02
COBALT	6.72E+01	6.45E+01	5.57E+01	1.39E+02	0.00E+00	6.83E+01	7.11E+00	0.00E+00	0.00E+00	2.44E+04	0.00E+00	3.31E+02
COPPER	5.62E+03	7.39E+03	8.28E+03	8.79E+03	0.00E+00	6.63E+03	6.85E+01	0.00E+00	0.00E+00	3.90E+02	0.00E+00	7.28E+01
GOLD	0.00E+00	1.13E+00	0.00E+00	0.00E+00	0.00E+00	5.48E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
IRON	7.63E+04	1.01E+05	1.12E+05	5.45E+04	3.98E-01	9.85E+04	2.87E+03	0.00E+00	0.00E+00	4.75E+05	9.95E-02	1.06E+04
LEAD	1.47E+03	3.11E+03	4.24E+03	1.06E+04	0.00E+00	2.64E+03	2.22E+00	0.00E+00	0.00E+00	1.18E+05	0.00E+00	1.57E+03
MAGNESIUM	2.48E+04	3.82E+04	3.45E+04	4.43E+04	1.00E-02	3.22E+04	4.45E+01	0.00E+00	0.00E+00	4.02E+05	1.00E-02	5.51E+03
MANGANESE	6.77E+02	6.77E+02	5.62E+02	9.57E+01	8.00E-03	6.59E+02	5.85E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.77E+01
NICKEL	2.53E+02	3.63E+02	3.26E+02	0.00E+00	3.00E-02	3.16E+02	2.54E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.50E+03
PHOSPHOROUS	6.28E+04	9.06E+04	3.76E+04	4.16E+04	6.70E-01	7.07E+04	7.65E+02	0.00E+00	0.00E+00	6.50E+03	4.20E-01	5.66E+03
SELENIUM	0.00E-00	0.00E+00	0.00E+00	1.92E+01	0.00E+00	6.99E-01	1.11E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.09E+02
SILVER	2.65E+01	1.34E+02	2.09E+02	1.99E+02	0.00E+00	8.78E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
SODIUM	6.60E+03	1.08E+04	8.34E+03	1.91E+04	0.00E+00	9.11E+03	1.36E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.35E+02
SULFUR	1.26E+04	3.24E+04	1.84E+04	6.03E+04	9.88E+02	6.16E+05	1.97E+05	0.00E+00	0.00E+00	1.87E+05	4.57E+02	5.45E+06
TIN	5.59E+02	1.01E+03	1.27E+03	5.68E+03	0.00E+00	9.74E+02	4.63E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.57E+01
TITANIUM	9.14E+03	9.04E+03	8.95E+03	4.40E+03	0.00E+00	8.45E+03	3.78E+01	0.00E+00	0.00E+00	4.10E+04	0.00E+00	5.83E+02
VANADIUM	2.74E+02	3.71E+02	3.32E+02	5.22E+02	0.00E+00	3.31E+02	8.45E+00	0.00E+00	0.00E+00	1.16E+03	1.40E-02	1.85E+02
ZINC	7.66E+03	1.06E+04	1.17E+04	1.30E+04	0.00E+00	9.35E+03	9.83E+01	0.00E+00	0.00E+00	9.20E+03	0.00E+00	2.20E+02

SASS SIZE FRACTIONS

FRACTION 1 = PROBE RINSE + 10 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 2 = 3 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 3 = 1 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 4 = FILTER CATCH (SOLID SAMPLE)
FRACTION 5 = IMPINGER CATCH + NITRIC IMPINGER RINSE (LIQUID SAMPLE)
TOTAL = SUM OF FRACTIONS 1-5

TRACE METALS CONTENT OF PARTICULATE MATTER BY PARTICULATE SIZE FRACTION (SASS SIZE FRACTION BASIS)

RUN: 3

	ESP INLET SASS SIZE FRACTIONS						ESP OUTLET SASS SIZE FRACTIONS					
	1	2	3	4	5	TOTAL	1	2	3	4	5	TOTAL
METAL	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g	ug/g	ug/g	ug/g	ug/g	ug/ml	ug/g
ALUMINUM	4.21E+04	5.69E+04	3.19E+04	1.62E+05	0.00E+00	5.74E+04	5.25E+04	0.00E+00	0.00E+00	9.00E+06	0.00E+00	3.96E+05
ANTIMONY	7.25E+01	2.14E+02	1.54E+02	3.25E+02	0.00E+00	1.49E+02	0.00E+00	0.00E+00	0.00E+00	1.37E+03	0.00E+00	5.92E+01
ARSENIC	7.76E+02	5.25E+02	6.73E+02	6.70E+02	0.00E+00	6.69E+02	2.51E+02	0.00E+00	0.00E+00	2.30E+04	0.00E+00	1.24E+03
BARIUM	2.72E+03	1.92E+03	1.78E+04	6.46E+03	0.00E+00	3.14E+03	4.59E+02	0.00E+00	0.00E+00	4.00E+05	0.00E+00	1.78E+04
CADMIUM	1.92E+03	3.91E+03	8.39E+03	7.42E+03	0.00E+00	3.31E+03	2.06E+01	0.00E+00	0.00E+00	1.90E+03	0.00E+00	1.02E+02
CALCIUM	9.36E+03	1.08E+05	9.55E+04	3.03E+05	1.30E-02	7.29E+04	8.90E+04	0.00E+00	0.00E+00	1.89E+07	1.30E-02	9.06E+05
CHROMIUM	7.85E+02	8.30E+02	7.57E+02	8.82E+02	6.60E-02	8.53E+02	2.15E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.06E+03
COBALT	5.73E+01	6.05E+01	5.78E+01	6.47E+01	0.00E+00	5.91E+01	4.53E+01	0.00E+00	0.00E+00	6.77E+03	0.00E+00	3.36E+02
COPPER	5.42E+03	6.33E+03	1.01E+04	8.30E+03	0.00E+00	6.13E+03	9.12E+02	0.00E+00	0.00E+00	3.76E+03	0.00E+00	1.04E+03
GOLD	0.00E+00	0.00E+00	0.00E+00	8.03E+00	0.00E+00	6.64E-01	3.37E+00	0.00E+00	0.00E+00	3.58E+02	0.00E+00	1.87E+01
IRON	7.23E+04	8.65E+04	9.14E+04	3.64E+04	2.23E-01	7.54E+04	1.07E+04	0.00E+00	0.00E+00	2.55E+05	6.60E-02	2.38E+04
LEAD	2.03E+03	4.70E+03	5.21E+03	1.17E+04	0.00E+00	3.93E+03	2.24E+03	0.00E+00	0.00E+00	4.26E+04	0.00E+00	3.79E+03
MAGNESIUM	2.38E+04	2.72E+04	2.51E+04	2.56E+04	8.00E-03	2.52E+04	1.68E+04	0.00E+00	0.00E+00	2.61E+05	8.00E-03	2.77E+04
MANGANESE	4.96E+02	6.03E+02	6.53E+02	8.25E+01	0.00E+00	5.07E+02	8.20E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.35E+01
NICKEL	2.98E+02	3.74E+02	4.33E+02	7.13E+01	0.00E+00	3.06E+02	1.23E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.18E+03
PHOSPHOROUS	5.87E+04	6.90E+04	6.92E+04	2.38E+04	1.10E+00	6.07E+04	1.72E+03	0.00E+00	0.00E+00	6.08E+03	4.80E-01	2.02E+04
SELENIUM	0.00E+00	0.00E+00	0.00E+00	1.74E+01	0.00E+00	1.44E+00	1.14E+02	0.00E+00	0.00E+00	4.86E+03	0.00E+00	3.19E+02
SILVER	5.47E+01	1.33E+02	2.46E+02	5.01E+01	0.00E+00	8.51E+01	0.00E+00	0.00E+00	0.00E+00	1.01E+03	0.00E+00	4.77E+01
SODIUM	8.76E+03	8.02E+03	4.72E+03	1.51E+04	0.00E+00	8.89E+03	3.81E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.65E+03
SULFUR	1.43E+04	2.61E+04	4.05E+04	4.47E+04	2.16E+03	1.46E+06	2.51E+05	0.00E+00	0.00E+00	1.88E+05	1.32E+03	5.05E+07
TIN	6.37E+02	1.18E+03	1.74E+03	8.15E+03	0.00E+00	1.49E+03	1.05E+03	0.00E+00	0.00E+00	1.59E+03	1.50E-02	1.64E+03
TITANIUM	9.64E+03	8.74E+03	9.24E+03	1.36E+03	0.00E+00	8.09E+03	3.25E+03	0.00E+00	0.00E+00	8.51E+03	0.00E+00	3.47E+03
VANADIUM	2.35E+02	3.20E+02	4.50E+02	3.06E+02	0.00E+00	2.79E+02	7.19E+01	0.00E+00	0.00E+00	5.35E+02	0.00E+00	9.20E+01
ZINC	7.89E+03	1.03E+04	1.20E+04	9.43E+03	0.00E+00	9.06E+03	3.45E+02	0.00E+00	0.00E+00	1.07E+04	0.00E+00	7.96E+02

SASS SIZE FRACTIONS

FRACTION 1 = PROBE RINSE + 10 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 2 = 3 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 3 = 1 MICRON CYCLONE CATCH (SOLID SAMPLE)
FRACTION 4 = FILTER CATCH (SOLID SAMPLE)
FRACTION 5 = IMPINGER CATCH + NITRIC IMPINGER RINSE (LIQUID SAMPLE)
TOTAL = SUM OF FRACTIONS 1-5

APPENDIX D

- NBS COAL FLY ASH DATA
- FIELD FILTER BLANK DATA
- SAMPLE LABORATORY DATA: BLANK CORRECTED USING THE FILTER BLANK

TABLE D-1. NBS COAL FLY ASH DATA
SAMPLE WAS NOT ASHED

38/23/85. E.V. Robb

FOR SAMPLE NBS COAL FLY ASH STANDARD. 1633A

analyst sample i.d.: p-14/NBS Coal Fly Ash/not ashed

****

GRAMS OF SAMPLE ANALYZED = 0.49250

	TOTAL MICROGRAMS FOUND (ug)	NBS MICROGRAMS (ug)	WEIGHT PERCENT FOUND (%)	NBS WEIGHT PERCENT (%)
AS:	63.90	71.41 +/- 7	---	---
CD:	0.8650	0.493 +/- 0.07	---	---
CA:	---	---	0.8213	1.11 +/- 0.01
CR:	75.00	96.53 +/- 3.0	---	---
CU:	64.15	58.12 +/- 1.5	---	---
FE:	---	---	4.583	9.40 +/- 0.10
PB:	18.30	35.46 +/- 0.19	---	---
MG:	---	---	0.3530	0.455 +/- 0.01
NI:	1.500	62.55 +/- 1.9	---	---
SE:	< 4	5.07 +/- 0.3	---	---
NA:	---	---	0.6340	0.17 +/- 0.01
ZN:	113.0	108.4 +/- 4.9	---	---

TABLE D-1. NBS COAL FLY ASH DATA
SAMPLE WAS NOT ASHED

08/23/85. E.V. Robb

FOR SAMPLE NBS COAL FLY ASH STANDARD. 1633A

analyst sample i.d.: p-14/NBS Coal Fly Ash/not ashed

****

GRAMS OF SAMPLE ANALYZED = 0.49250

	TOTAL MICROGRAMS FOUND (ug)	NBS MICROGRAMS (ug)	WEIGHT PERCENT FOUND (%)	NBS WEIGHT PERCENT (%)
	**********	**********	*******	*************
AS:	63.90	71.41 +/- 7	---	---
CD:	0.8650	0.493 +/- 0.07	---	---
CA:	---	---	0.8213	1.11 +/- 0.01
CR:	75.00	96.53 +/- 3.0	---	---
CU:	64.15	58.12 +/- 1.5	---	---
FE:	---	---	4.583	9.40 +/- 0.10
PB:	18.30	35.66 +/- 0.19	---	---
MG:	---	---	0.3530	0.455 +/- 0.01
NI:	1.500	62.55 +/- 1.9	---	---
SE:	< 4	5.07 +/- 0.3	---	---
NA:	---	---	0.6340	0.17 +/- 0.01
ZN:	113.0	108.4 +/- 4.9	---	---

TABLE D-1. (Continued)

NBS COAL FLY ASH STANDARD 1633A CONTINUED: PAGE 2 OF 2

E.V.R..08/23/85

analvst sample i.d.: p-14/NBS Coal Fly Ash/not.ashed

****

THE FOLLOWING METALS ARE NOT CERTIFIED, BUT ARE GIVEN BY NBS FOR INFORMATION ONLY.

	TOTAL MICROGRAMS FOUND (ug)	NBS MICROGRAMS NOT CERTIFIED (ug)	WEIGHT PERCENT FOUND (%)	NBS WEIGHT PERCENT NOT CERTIFIED (%)
	**********	*************	*******	*************
AL:	---	---	7.354	14.0
SB:	15.95	3.45	---	---
BA:	---	---	0.05665	0.15
CO:	41.80	22.66	---	---
MN:	< 0.2	93.58	---	---
TI:	---	---	0.7284	0.8
V:	220.3	147.8	---	---

TABLE D-2. NBS COAL FLY ASH DATA
SAMPLE WAS ASHED AT 110°C

08/23/85. E.V. Robb

FOR SAMPLE NBS COAL FLY ASH STANDARD. 1633A

analyst sample i.d.: p-18/NBS Coal Fly Ash/ashed at 110'C

****

GRAMS OF SAMPLE ANALYZED = 0.92092

	TOTAL MICROGRAMS FOUND (ug)	NBS MICROGRAMS (ug)	WEIGHT PERCENT FOUND (%)	NBS WEIGHT PERCENT (%)
AS:	144.9	133.5 +/- 13.8	---	---
CD:	2.235	0.9209 +/- 0.14	---	---
CA:	---	---	0.8130	1.11 +/- 0.01
CR:	207.2	180.5 +/- 5.53	---	---
CU:	92.05	108.7 +/- 2.8	---	---
FE:	---	---	7.472	9.40 +/- 0.10
PB:	48.53	66.67 +/- 0.37	---	---
MG:	---	---	0.3526	0.455 +/- 0.01
NI:	< 0.1	116.9 +/- 3.7	---	---
SE:	< 4	9.49 +/- 0.55	---	---
NA:	---	---	0.1089	0.17 +/- 0.01
ZN:	224.1	202.6 +/- 9.21	---	---

TABLE D-2. (Continued)

NBS COAL FLY ASH STANDARD 1633A CONTINUED: PAGE 2 OF 2

E.V.R..08/23/85

analyst sample i.d.: p-18/NBS Coal Fly Ash/ashed.at.110'C

****

THE FOLLOWING METALS ARE NOT CERTIFIED, BUT ARE GIVEN BY NBS FOR INFORMATION ONLY.

	TOTAL MICROGRAMS FOUND (ug)	NBS MICROGRAMS NOT CERTIFIED (ug)	WEIGHT PERCENT FOUND (%)	NBS WEIGHT PERCENT NOT CERTIFIED (%)
AL:	---	---	11.94	14.0
SB:	25.79	6.45	---	---
BA:	---	---	0.004865	0.15
CO:	82.15	42.36	---	---
MN:	< 0.2	175.0	---	---
TI:	---	---	0.7378	0.8
V:	253.7	276.3	---	---

TABLE D-3. NBS COAL FLY ASH DATA
SAMPLE WAS ASHED AT 600°C

08/23/85. E.V. Robb

FOR SAMPLE NBS COAL FLY ASH STANDARD, 1633A

analyst sample i.d.: p-19/NBS Coal Fly Ash/ashed.at.600'C

****

GRAMS OF SAMPLE ANALYZED = 0.60749

	TOTAL MICROGRAMS FOUND (ug)	NBS MICROGRAMS (ug)	WEIGHT PERCENT FOUND (%)	NBS WEIGHT PERCENT (%)
	**********	**********	*******	*************
AS:	120.2	88.1 +/- 9.1	---	---
CD:	1.840	0.607 +/- 0.09	---	---
CA:	---	---	0.3997	1.11 +/- 0.01
CR:	89.50	119.07 +/- 3.6	---	---
CU:	82.40	71.68 +/- 1.8	---	---
FE:	---	---	8.173	9.40 +/- 0.10
PB:	41.45	43.98 +/- 0.24	---	---
MG:	---	---	0.1626	0.455 +/- 0.01
NI:	< 0.1	77.15 +/- 2.4	---	---
SE:	< 4	6.26 +/- 0.36	---	---
NA:	---	---	0.3038	0.17 +/- 0.01
ZN:	145.3	133.6 +/- 6.07	---	---

TABLE D-3. (Continued)

NBS COAL FLY ASH STANDARD 1633A CONTINUED: PAGE 2 OF 2

E.V.R..08/23/85

analyst sample i.d.: p-19/NBS Coal Fly Ash/ashed.at.600'C

****

THE FOLLOWING METALS ARE NOT CERTIFIED, BUT ARE GIVEN BY NBS FOR INFORMATION ONLY.

	TOTAL MICROGRAMS FOUND (ug)	NBS MICROGRAMS NOT CERTIFIED (ug)	WEIGHT PERCENT FOUND (%)	NBS WEIGHT PERCENT NOT CERTIFIED (%)
AL:	---	---	11.29	14.0
SB:	19.50	4.25	---	---
BA:	---	---	0.01176	0.15
CO:	64.85	27.94	---	---
MN:	< 0.2	115	---	---
TI:	---	---	0.8737	0.8
V:	214.9	182.3	---	---

TABLE D-4. FIELD FILTER BLANK ANALYSIS (FIRST BOMB)

J

08/21/85. E.V. ROBB

FOR SAMPLE 6276/HR-C-BL/HR-13/FIELD BLANK/FIRST BOMB:

****

THE GRAMS OF SAMPLE ANALYZED = 2.1E-03.

THE SAMPLE WAS ANALYZED ON 07/05/85.

	ORIGINAL PPMS (UG/ML)	TOTAL MICROGRAMS (UG)	WEIGHT PERCENT (UG/G) X 100%
AL:	76.784	3839.2	182819048
SB:	<.07	<3.5	<166666.667
AS:	.29	14.5	690476.191
BA: 455	.662	33.1	1576190.48
CD:	.094	4.7	223809.524
CA: 317	930.5	46525	2.21547619E+09
CR:	2.78	139	6619047.62
CO:	.426	21.3	1014285.71
CU:	.352	17.6	838095.238
AU:	.058	2.9	138095.238
FE: ave.	31.825	1591.25	75773809.5
PB: ave.	1.05	52.5	2500000
MG: 279.08	137	6850	326190476
MN:	1.779	88.95	4235714.29
NI:	4.15	207.5	9880952.38
P:	<.03	<1.5	<71428.5715
SE:	.327	16.35	778571.429
AG:	<4E-03	<.2	<9523.80953
NA:	57	2850	135714286
S: ave.	12.39	619.5	29500000
SN:	.71	35.5	1690476.19
TI:	12.85	642.5	30595238.1
V:	.256	12.8	609523.81
ZN:	3.67	183.5	8738095.24

NOTE: Field Filter Blank

TABLE D-4. FIELD FILTER BLANK ANALYSIS (REBOMB)

1

08/21/85. E.V. ROBB

FOR SAMPLE 6276/F/HR-C-BL-F/HR-13/FIELD.BLANK/REBOMB.OF.RESIDUE.FROM.FIRST.BOMB

****

THE GRAMS OF SAMPLE ANALYZED = 2.1E-03.

THE SAMPLE WAS ANALYZED ON 07/05/85.

	ORIGINAL PPMS (UG/ML) *************	TOTAL MICROGRAMS (UG) ****************	WEIGHT PERCENT (UG/G) X 100% **************
AL:	128.09	6404.5	304976191
SB:	<.07	<3.5	<166666.667
AS:	1.03	51.5	2452380.95
BA: 455	.097	4.85	230952.381
CD:	.027	1.35	64285.7143
CA: 317	449	22450	1.06904762E+09
CR:	.875	43.75	2083333.33
CO:	.107	5.35	254761.905
CU:	.133	6.65	316666.667
AU:	<.04	<2	<95238.0953
FE: ave.	13.175	658.75	31369047.6
PB: ave.	.78	39	1857142.86
MG: 279.05	63.5	3175	151190476
MN:	.039	1.95	92857.1429
NI:	.18	9	428571.429
P:	<.03	<1.5	<71428.5715
SE:	<.08	<4	<190476.19
AG:	<4E-03	<.2	<9523.80953
NA:	133.05	6652.5	316785714
S: ave.	2.028	101.4	4828571.43
SN:	.234	11.7	557142.857
TI:	.536	26.8	1276190.48
V:	.038	1.9	90476.1905
ZN:	.204	10.2	485714.286

Note: Field Filter Blank

TABLE D-5. TRACE METALS ANALYSIS OF PARTICULATE MATTER COLLECTED IN THE FILTER (FIRST BOMB)

08/29/85, ESTHER V. ROBB
FOR SAMPLE (8634/8635/8636)/FILTER/HRE-C2-F/(HRE-40/41/42)/FI:
****

THE SAMPLE WAS ANALYZED ON 05/08/85.

THE GRAMS OF SAMPLE ANALYZED = 0.56689.

	ORIGINAL UG (UG)	BLANK CORRECTED UG (UG)	WEIGHT % (UG/G)
	************	****************	*********
AL:	132300	128460.8	226606.219
SB:	190.45	190.45	335.955829
AS:	716.2	701.7	1237.80627
BA: 233	5677	5643.9	9955.89973
CD:	5383	5378.3	9487.3785
CA: 317	330000	283475	500052.92
CR:	728.75	589.75	1040.32528
CO:	92.05	70.75	124.803753
CU:	4931.5	4913.9	8668.17195
AU:	2.25	-0- <2	-0- < 3.528
FE: ave.	26027.5	26027.5	45912.7873
PB: ave.	5772.5	5720	10090.1409
MG: ave.	23360	16510	29123.8159
MN:	143.25	54.3	95.7857785
NI:	198	-0- <0.1	-0- <0.1764
P:	22350	22350	39425.6381
SE:	<4	-0- <4	-0- < 7.056
AG:	66.95	66.95	118.100513
NA:	7786.5	4936.5	8708.03859
S: ave.	33407.5	32788	57838.3813
SN:	2860.5	2825	4983.33009
TI:	3070	2427.5	4282.13586
V:	302.8	290	511.563089
ZN:	7222.5	7039	12416.8709

TABLE D-5. TRACE METALS ANALYSIS OF PARTICULATE MATTER COLLECTED IN THE FILTER (REBOMB)

03/29/85, ESTHER V. ROBB
FOR SAMPLE (8535/8535/8536)/FILTER/HRE-C2-F/(HRE-40/41/42)/RE:
****

THE SAMPLE WAS ANALYZED ON 05/07/85.

THE GRAMS OF SAMPLE ANALYZED = 0.55689.

	ORIGINAL UG (UG)	BLANK CORRECTED UG (UG)	WEIGHT % (UG/G)
AL:	139682.5	133278	235103.812
SB:	5.15	6.15	10.8485655
AS:	98.95	47.45	83.7023055
BA: ave.	853.3	848.45	1496.67483
CD:	200.05	198.7	350.508917
CA: 317	155375	173925	306805.553
CR:	61.95	18.2	32.1049939
CO:	13.5	8.15	14.3766868
CU:	74.9	68.25	120.393727
AU:	<2	~~1.7~~ <2	~~[illegible]~~ < 3,528
FE: ave.	4879.65	4879.65	8607.75459
PB: ave.	342.15	303.15	534.759829
MG: ave.	11773	8598	15165.9536
MN:	<0.2	~~0~~ <0.2	~~0~~ <0.3528
NI:	6	~~0~~ <0.1	~~0~~ <0.1764
P:	1233	1233	2175.02513
SE:	10.9	10.9	19.2277161
AG:	45.85	45.85	80.8798885
NA:	12538	5885.5	10382.0847
S: ave.	1469.25	1367.85	2412.90197
SN:	404.65	392.95	693.167986
TI:	92.9	66.1	116.601104
V:	7.65	5.75	10.1430612
ZN:	339.3	329.1	580.535906