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Environmental Protection Technology Series

COMPARATIVE U.S./USSR TESTS OF A HOT-SIDE ELECTROSTATIC PRECIPITATOR

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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COMPARATIVE U.S./USSR TESTS OF A HOT-SIDE ELECTROSTATIC PRECIPITATOR

by

Charles H. Gooding, Joseph D. McCain, and Diane K. Sommerer

Research Triangle Institute
P.O. Box 12194
Research Triangle Park, NC 27709

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EPA Project Officers: D.C. Drehmel and D.B. Harris

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, NC 27711

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ABSTRACT

In 1972 the United States of America and the Union of Soviet Socialist Republics signed a bilateral agreement pledging cooperation on environmental protection. As a part of this agreement, the Working Group on Stationary Source Air Pollution Control was subsequently formed by the U.S. Environmental Protection Agency and the U.S.S.R. Research Institute of Industrial and Sanitary Gas Cleaning to conduct cooperative programs in several areas of air pollution control technology, including particulate emission control.

This report describes the cooperative test program that was conducted to quantify and characterize the particulate emissions from a U.S. coal-burning power plant boiler, which is equipped with a hot-side electrostatic precipitator. The tests were conducted at Duke Power Company's Allen Steam Station in March 1976. U.S. and Soviet equipment and procedures were used to determine the flue gas composition and velocity, total particulate mass concentration of the gas stream, particle size distribution, electrical resistivity of the particulate entering the precipitator, evidence of back corona in the precipitator, SO_2 and SO_3 concentrations in the flue gas, and chemical composition of the fuel and fly ash. The test site and test procedures are described. The results of the comparative tests are presented and discussed.

The tests were conducted by York Research Corporation through the support of EPA Contract No. 68-02-1401, Task 27, and by Southern Research Institute under subcontract to York. This final report is submitted in fulfillment of EPA Contract No. 68-02-1398, Task 33, by Research Triangle Institute. This report covers a period from December 2, 1974, to July 31, 1976, and work was completed as of August 31, 1976.

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Appendixes*

*The appendixes to this report are contained in a separately bound volume, copies of which may be obtained from the EPA Project Officers.

FIGURES

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ABBREVIATIONS AND SYMBOLS

The following is a list of abbreviations and symbols which are not explicitly defined where they appear in the text of this report and which may not be familiar to all readers.

ABBREVIATIONS

Nm^3/s	--	normal cubic meters per second (21° C and 760 mm Hg)
ASTM	--	American Society for Testing Materials
DNCMM	--	dry normal cubic meters per minute
DSCFM	--	dry standard cubic feet per minute (70° F and 29.92 in. Hg)
ACMM	--	actual cubic meters per minute
ACFM	--	actual cubic feet per minute
NCM	--	normal cubic meters
SCF	--	standard cubic feet
ACM	--	actual cubic meters
ACF	--	actual cubic feet
ppm	--	parts per million
V - I	--	voltage/current

SYMBOLS

Ω	--	electrical resistance in ohms

UNIT CONVERSION FACTORS

To Convert From	To	Multiply By
inch (in.)	meter (m)	2.540×10^{-2}
foot (ft)	meter (m)	3.048×10^{-1}
mile	meter (m)	1.609×10^{3}
pound-force/inch^2 (lbf/in.^{2} or psi)	newton/meter^2 (N/m^2)	6.895×10^{3}
pound-mass (lbm)	gram (g)	4.536×10^{2}
British thermal unit (Btu)	joule (J)	1.055×10^{3}
British thermal unit/hour (Btu/hr)	watt (W)	2.931×10^{-1}
foot-pound force (ft-lbf)	joule (J)	1.356
degrees Farenheit (°F)	degrees Celsius (°C)	$°C = (°F-32) \times \frac{5}{9}$

Multiplication Factor			Prefix	Symbol
1,000,000	=	10^{6}	mega	M
1,000	=	10^{3}	kilo	k
0.01	=	10^{-2}	centi	c
0.001	=	10^{-3}	milli	m

ACKNOWLEDGMENTS

The successful completion of this project was made possible by the following individuals, whose participation in various phases of the work is gratefully acknowledged.

Dr. Dennis C. Drehmel and Mr. D. Bruce Harris, EPA Project Officers, competently supervised the coordination and overall progress of the project. Mr. Jaroslav Pekar and Ms. Elizabeth Koniuskow, also of EPA, provided invaluable assistance to the written and verbal communications between U.S. and Soviet personnel.

Drs. Yurii S. Milovidov, Natalia G. Bulgakova, and Gelii S. Chekanov of the Soviet Union provided technical direction and assistance in the use of the Soviet test equipment at the Duke Power site.

The management and staff of Duke Power Company displayed outstanding cooperation throughout the planning and execution of the test program. Key personnel were Messrs. Robert R. Carpenter, R. A. Johansen, and Bruce L. Jenkinson of the Duke Power General Offices and Messrs. James R. Park and Al Saunders of Allen Steam Station.

More than 30 engineers, scientists, technicians, and support personnel from York Research Corporation, Southern Research Institute, and Research Triangle Institute made significant contributions to various phases of the cooperative program.

SECTION 1
INTRODUCTION

Over the past few decades the United States of America and the Union of Soviet Socialist Republics have independently developed pollution control methods to protect the environment from liquid, solid, and gaseous contaminants. In 1972, with recognition of the mutual benefits that could be gained from technology exchange, the United States and the U.S.S.R. signed a bilateral agreement pledging cooperation on environmental protection. As a part of this agreement, the Working Group on Stationary Source Air Pollution Control was subsequently formed by the U.S. Environmental Protection Agency and the U.S.S.R. Research Institute of Industrial and Sanitary Gas Cleaning.

In March 1973, the First Meeting of the U.S.-U.S.S.R. Working Group on Stationary Source Air Pollution Control was held in Moscow to begin a cooperative exchange of air pollution control technology and information between the two countries. A second meeting was held in the United States in April 1974. The Protocol of the Second Meeting was signed by the heads of both delegations on April 25, 1974, in Washington, D.C., establishing eight cooperative projects for immediate action and 10 proposed areas of cooperation.

The planned cooperative programs encompass several areas of air pollution control technology, including particulate emission control. High mass-collection efficiencies are now achieved on particulate emissions from industrial processes in both countries by utilizing electrostatic precipitators, baghouses (fabric filters), wet scrubbers, and other innovative devices. Growing concern for the health and environmental effects of fine particulate emissions (3 microns or smaller) has resulted in a need for further improvement of conventional control techniques and for the development of new techniques for fine particulate control.

Projects A4/A6 of the Second Protocol established a cooperative test program to quantify and to characterize physically and chemically the particulate emissions from selected industrial plants in the United States and in the

U.S.S.R., using the sampling and analysis techniques commonly employed by both countries. These projects were further developed during a joint meeting in Moscow in October 1974. In December 1974 Duke Power Company's Allen Steam Station (located near Charlotte, North Carolina) was surveyed, and Allen Unit 3 was selected as the site for the U.S. tests. Allen 3 is a coal-burning, steam-electric generator whose particulate emissions are controlled by a hot-side electrostatic precipitator.

A process description and a U.S. test program were developed for Allen 3 and were transmitted to the Soviet Union. In April 1975 the test program was reviewed and updated to include the Soviet test plans during a joint meeting of Soviet and American specialists in Moscow. The planning culminated in March 1976 when the following tests were actually conducted on Allen 3.

1. Measurement of flue gas velocity and pressure at the inlet and outlet of the precipitator,
2. Determination of electrostatic precipitator collection efficiency by simultaneous measurement of the inlet and outlet particulate mass concentration,
3. Measurement of the gas humidity and molecular weight at the inlet and outlet (using U.S. methods only),
4. Measurement of the particle size distribution at the inlet and outlet,
5. Measurement of electrical resistivity of the fly ash at the inlet,
6. Measurement of SO_2 and SO_3 concentrations at the inlet (using U.S. method only),
7. Measurement of back corona (using Soviet method only),
8. Determination of the chemical composition of collected fuel and fly ash samples.

This report describes the Allen power plant and the hot-side electrostatic precipitator of unit 3. The procedures that were used during the test program are recounted, and the results of the comparative tests are presented and discussed.

SECTION 2
DESCRIPTION OF THE TEST SITE

GENERAL DESCRIPTION OF THE POWER COMPANY AND STATION

Duke Power Company provides electric power for the central portion of North Carolina and the northwestern corner of South Carolina. The approximate boundaries of the Duke Power service area are shown in Figure 1. Duke Power's total generating capacity is over 13,000 megawatts (MW), of which approximately 60 percent can be produced by coal-burning units.

Allen Steam Station is located approximately 16 km (10 miles)* southwest of Charlotte, North Carolina (see Figure 1). Plant Allen has five coal-burning, single-reheat, steam-electric generating units. Units 1 and 2 have nameplate capacities of 165 MW each, and units 3, 4, and 5 are rated at 275 MW each. Each of the five units has a rated main steam pressure of 16.65 MN/m^2 (2,415 $lbf/in.^2$) gauge, a superheat temperature of 566° C (1,050° F) and a reheat temperature of 538° C (1,000° F). The condensers of all five units are cooled by once-through flow of water from the Catawba River. The cooling water is discharged to the South Fork River, which joins the Catawba about 3 km (2 mi) downstream from the plant. When the tubes are clean, the condenser steam-side pressure is approximately 38 mm (1.5 in.) of mercury absolute.

DESCRIPTION OF ALLEN STATION UNIT 3

Units 3, 4, and 5 at Allen Steam Station are identical, including the precipitator installations. Unit 3 was chosen as the test unit after consideration of maintenance outage schedules and test area access of the three units.

Commercial operation of Allen Unit 3 began in 1959. Although the unit has a nameplate rating of 275 MW, it has frequently been operated at a gross

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*Throughout the text of this report metric units are preferentially used, and the commonly used English equivalent is shown in parentheses if appropriate. For further clarification a list of abbreviations and symbols and a table of conversion factors are also included at the beginning of this report.

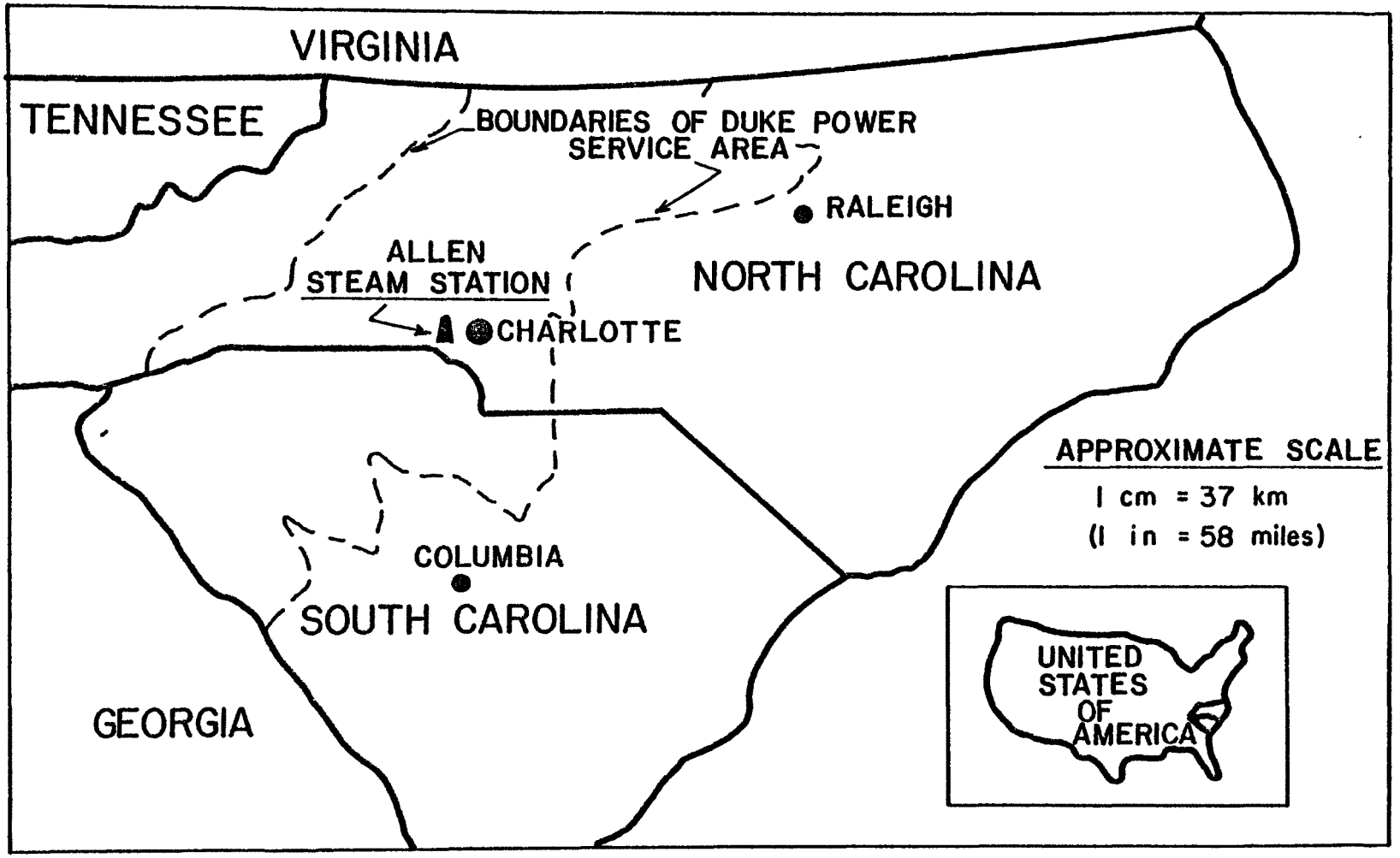

Figure 1. Location of Duke Power Company service area and Allen Steam Station.

load of 300 MW or slightly greater. The gross load during the tests varied from 276 to 279 MW. The unit auxiliaries utilize approximately 6.5 percent of the generated power so that the net efficiency of Allen Unit 3 is approximately 35.9 percent (heat rate of 9,500 Btu/net kWhr). The expected thermal input to the boiler is therefore 729 MW (2,487 x 10^6 Btu/hr) at 280 MW gross electrical output. The typical coal analysis at the plant is given below.

Higher heating value	25.2 - 27.3 MJ/kg (10,850 - 11,750 Btu/lbm)
Ash content	15 - 18 percent
Sulfur content	approximately 1 percent
Moisture content	6 - 9 percent

Depending on the heating value of the coal, the coal-firing rate at 280 MW ranges from approximately 96 to 104 Mg/hr (212,000 to 229,000 lbm/hr). About 25 percent of the ash falls out in the dry-bottom boiler as bottom ash. The remaining 75 percent of the ash leaves the boiler with the hot flue gases. As shown schematically in Figure 2, the gases flow first through the hot-side electrostatic precipitator at about 343° C (650° F), then through the air preheater where the gas temperature is lowered to approximately 138° C (280° F) by preheating the incoming combustion air. The flue gases then flow through the cold-side electrostatic precipitator before the pressure is boosted by the induced draft fan and the gases exit to the atmosphere through the 77 m (252 ft) stack. The typical gas conditions at the inlet and outlet of the hot-side electrostatic precipitator as estimated prior to these tests are given in Table 1. Table 2 lists typical ash characteristics from Duke Power coal-burning plants.

DESCRIPTION OF THE UNIT 3 HOT-SIDE ELECTROSTATIC PRECIPITATOR

Allen Unit 3 was equipped at startup with a cold-side electrostatic precipitator designed to remove approximately 97 percent of the fly ash from the flue gases. The precipitator efficiency was tested twice in 1961 at 96.9 and 96.4 percent. In the late 1960's, Duke Power began upgrading its particulate emission controls by adding additional precipitators in a series or parallel configuration on many of its units. At that time, the estimated precipitator efficiency of Allen Unit 3 was 87 percent. A hot-side electrostatic precipitator was designed and installed on unit 3 in series with the existing cold-side precipitator (see Figure 2). Startup of the new precipitator

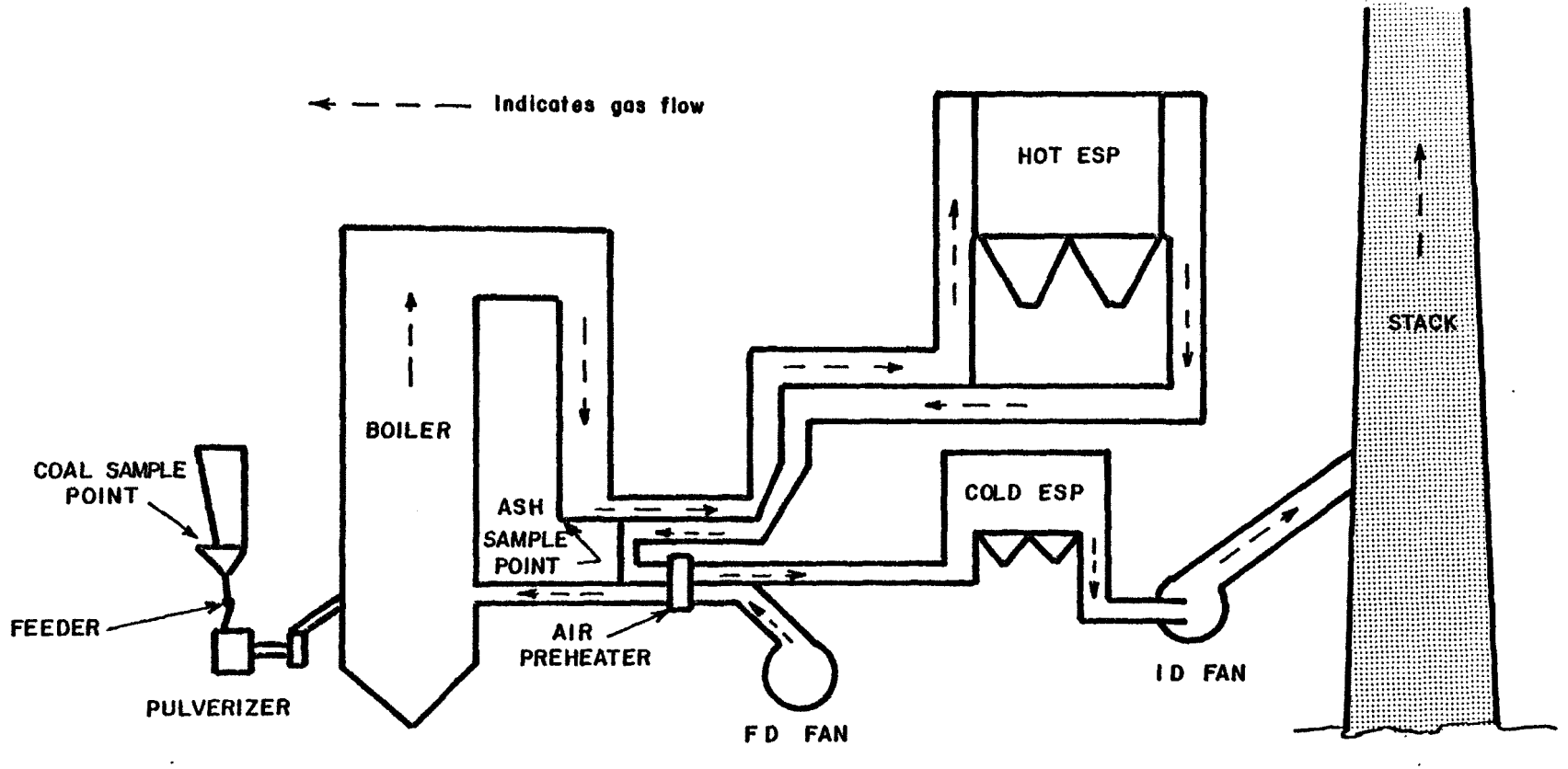

Figure 2. Schematic of Allen Unit 3 flue gas system.

TABLE 1. TYPICAL GAS CONDITIONS AT INLET AND OUTLET OF HOT-SIDE ELECTROSTATIC PRECIPITATOR--ALLEN UNIT 3

	Inlet	Outlet
Flow rate (total for four ducts) Nm^3/s (actual ft^3/min)	226 (1,100,000)	226 (1,000,000)
Temperature, °C (°F)	343 (650)	338 (640)
Pressure, mm Hg gauge (in H_2O gauge)	-11 to -13 (-6 to -7)	-11 to -13 (-6 to -7)
Ash concentration, g/Nm^3 (grains/actual ft^3)	13.1 to 17.3 (2.5 to 3.3)	0.11 to 0.14 (0.020 to 0.027)
Moisture (H_2O), % by volume	6	6
Oxygen (O_2), % by volume	3.5	3.5
Carbon dioxide (CO_2), % by volume	15.6	15.6
Sulfur dioxide (SO_2), % by volume	0.09	0.09
Sulfur trioxide (SO_3), % by volume	Unknown*	Unknown*
Nitrogen oxides (NO_x), % by volume	Unknown†	Unknown†

*Typical values for this type of boiler and fuel are 10 to 50 ppm SO_3 (by volume).

†Typical values for this type of boiler and fuel are 300 to 400 ppm NO_x as NO_2 (by volume).

TABLE 2. TYPICAL ASH CHARACTERISTICS FROM DUKE POWER COAL-BURNING PLANTS

Ash fusibility		
Initial deformation temperature	1,315 - 1,480° C	(2,400 - 2,700° F)
Softening temperature	1,370 - 1,480° C	(2,500 - 2,700° F)
Fluid temperature	>1,480° C	(>2,700° F)

Ash composition	
SiO_2	50 - 55%
Al_2O_3	25 - 30%
Fe_2O_3	6 - 9%
CaO	0.8 - 1.2%
MgO	1.5 - 2.0%
Na_2O	0.4 - 0.6%
K_2O	3 - 5%
TiO_2	0.8 - 1.2%
P_2O_5	0.1 - 0.8%
SO_3	0.6 - 0.8%

occurred in March 1973, raising the total precipitator efficiency to approximately 99 percent.

The configuration of the hot-side electrostatic precipitator is shown schematically in Figure 3. There are four parallel chambers for gas flow, and each chamber consists of four sections in series. Separate ducts carry flue gases into and out of the four chambers. The two center chambers are separated internally by a gas-tight partition, dividing the precipitator into two completely separate sides. In each of the two sides, the eight sections are supplied with power from four transformer-rectifier (T/R) sets. Each of the two parallel sections that is supplied by a single T/R set is electrically isolatable as indicated in Figure 3. Table 3 gives additional design specifications of the hot-side electrostatic precipitator.

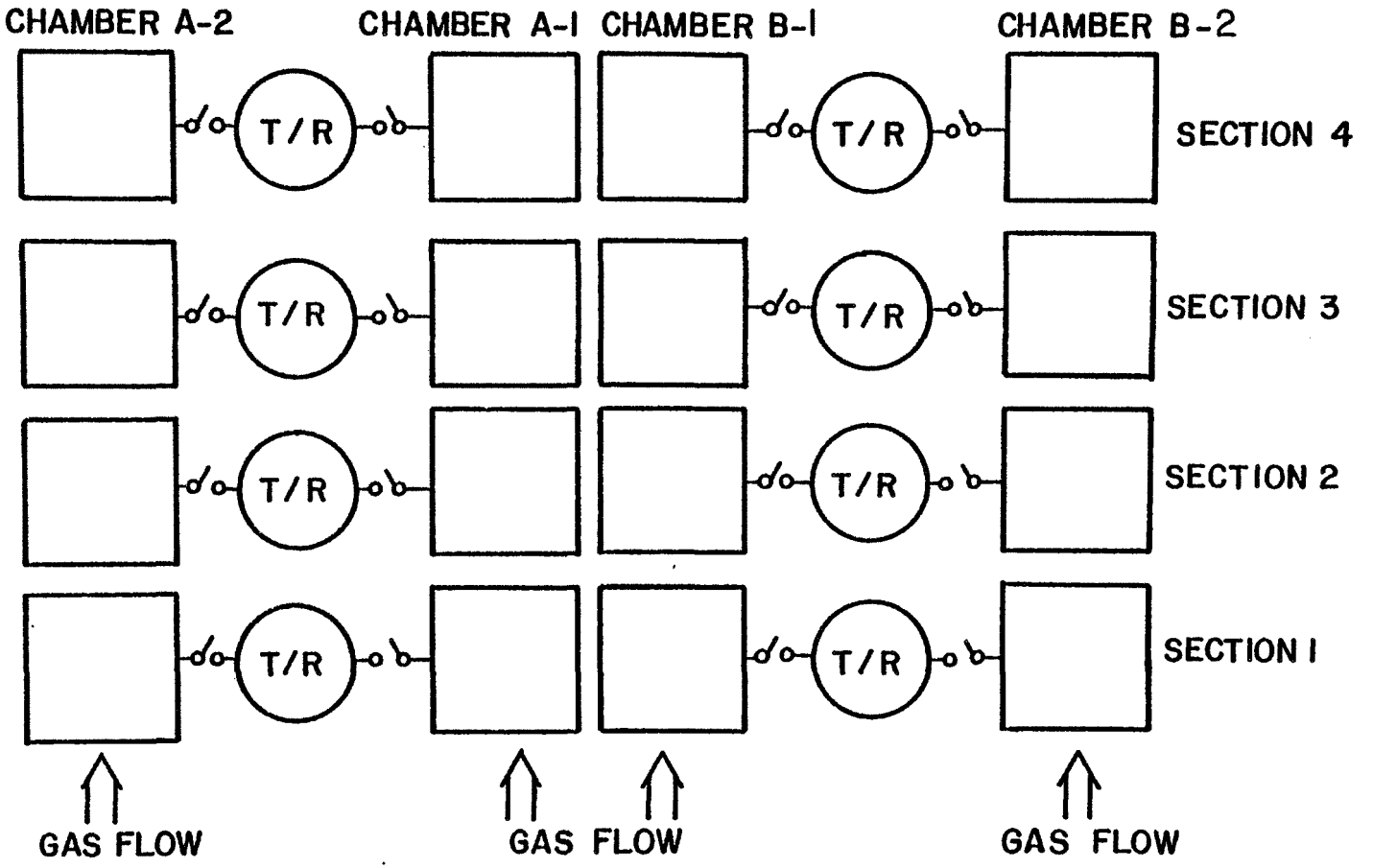

Figure 3. Configuration of hot-side electrostatic precipitator.

TABLE 3. HOT-SIDE ELECTROSTATIC PRECIPITATOR SPECIFICATIONS

Manufacturer	Research Cottrell, Inc., Boundbrook, N.J.
Startup date	March 5, 1973
Design gas flow	590 actual m^3/s (1,250,000 actual ft^3/min)
Design gas velocity	1.81 m/s (5.94 ft/s)
Design specific collector area	53 m^2 per actual m^3/s (270 ft^2 per 1000 actual ft^3/min)
Design efficiency	99.2%
Overall configuration	4 parallel chambers 4 sections in series per chamber 39 parallel gas passages per chamber
Plates	40 plates per chamber (cold rolled steel sheets) plate height is 9.14 m (30 ft) plate length each section is 2.74 m (9 ft) for total length in direction of flow of 10.97 m (36 ft) plate-to-plate spacing is 0.229 m (9 in) total surface area of plates is 31,305 m^2 (336,960 ft^2)
Wires	48 equally spaced wires per gas passage (hand drawn Bessemer steel with coppered surface) wire diameter is 2.77 mm (0.109 in) wires are hanging type, placed in the center ± 6.35 mm (1/4 in) of the plate-to-plate space
Electrical	8 transformer-rectifier sets 16 electrically isolatable bus sections transformer rating is 96 kVA rectifier rating is 1500 mA wave form is double/half full normal power consumption is approximately 580 kW, 720 kW is maximum consumption

Ash deposits are removed from the wires by vibrators, which have an adjustable cycle of operation. Each vibrator is normally operated twice every half-hour with approximately a 90-second delay between the two vibration periods. Each vibration period lasts 6 seconds. The plates are cleaned by solenoid-activated hammer-type rappers. Each rapper is activated at least once every 2 minutes, and some are activitated twice every 2 minutes. The approximate rapping intensity is 32.5 J (24 ft-lbf). The collected ash falls into hoppers beneath the precipitator. It is periodically removed from the hoppers by a dry, pressurized ash-handling system and flows to a collecting tank from which it is water-sluiced to an ash-settling basin.

DESCRIPTION OF THE TEST FACILITIES

During the tests, operational data from the steam-electric generating unit and the electrostatic precipitator were monitored from inside the plant. In the control room from which units 1, 2, and 3 are operated, charts continuously recorded operational parameters such as electrical load, fuel flow, air flow, steam flow, and flue gas temperatures and pressures. The oxygen concentration of the gas was also continuously recorded in the control room and periodically was manually checked with a portable recorder at several duct sample lines.

The precipitator control panels are also in the boiler building. There are eight control panels for the unit 3 hot-side precipitator (one for each transformer-rectifier set). Instruments on each panel continuously display the transformer primary voltage (a.c.), the transformer primary current (a.c.), the precipitator average current (d.c.), and the precipitator spark rate. These instruments were utilized in the back corona tests.

Coal samples were manually collected during the test from the hoppers located above the coal pulverizer feeders (see Figure 2). Ash samples were collected downstream of the economizer section of unit 3 as indicated in Figure 2.

The identical inlet and outlet ducts of the Allen 3 electrostatic precipitators are separated by the precipitator and fly ash hoppers (Figure 4). The sampling ports are located on the hopper side of the ducts. Only two inlet and two outlet ducts were sampled, as indicated in Figures 5 and 6. The eight sampling ports in each duct have an inside diameter of approximately 154 mm (6.06 in.). The ports are equally spaced and are 0.84 m (2 ft 9 in.) apart. The outside ports of each duct are 0.41 m (1 ft 4.5 in.) from the duct wall (see Figure 7). The ports are 0.457 m (18 in.) above a handrail which is 1.07 m (42 in.) above the platform. The horizontal distance from the ports to the fly ash hoppers is approximately 3 m (10 ft). A beam near the inlet duct designated during these tests as B1 prevented some tests from being conducted in one port.

Two sets of sampling ports were installed for the resistivity tests. The ports were located on a horizontal segment of the hot gas duct downstream from the economizer and about 3 m (10 ft) upstream of the 90° turn which leads to the inlet test ports.

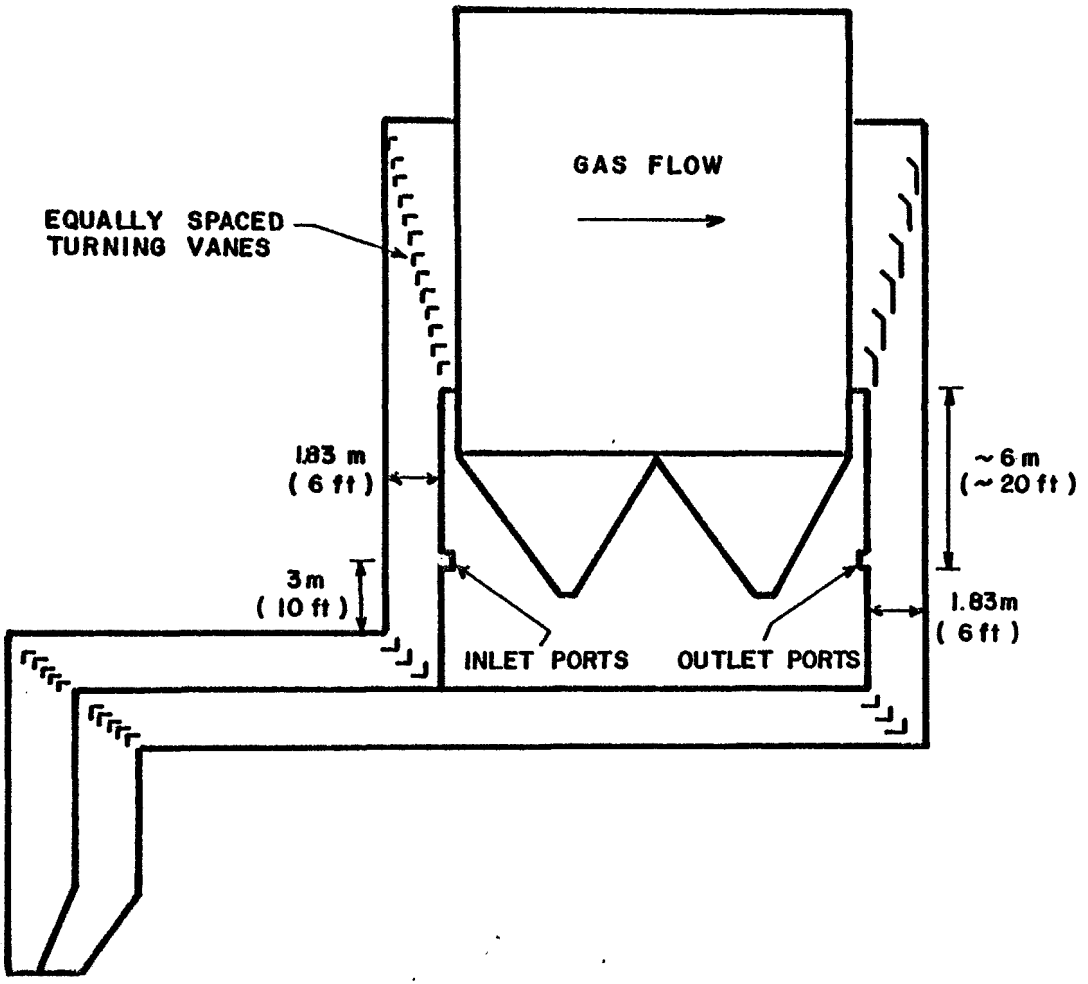

Figure 4. Schematic of Allen Unit 3 hot-side electrostatic precipitator.

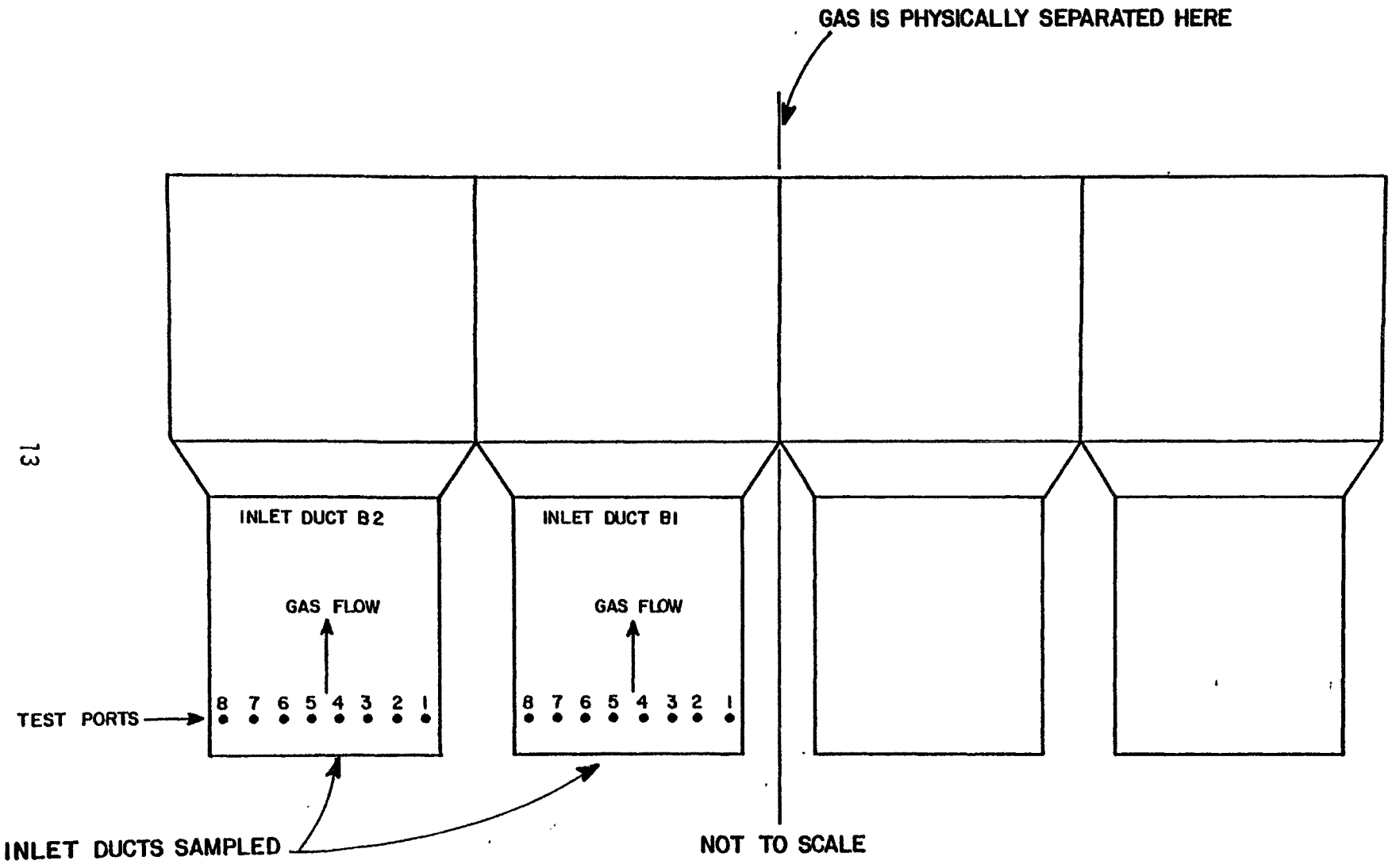

Figure 5. Elevation of inlet ducts viewed from underneath hoppers.

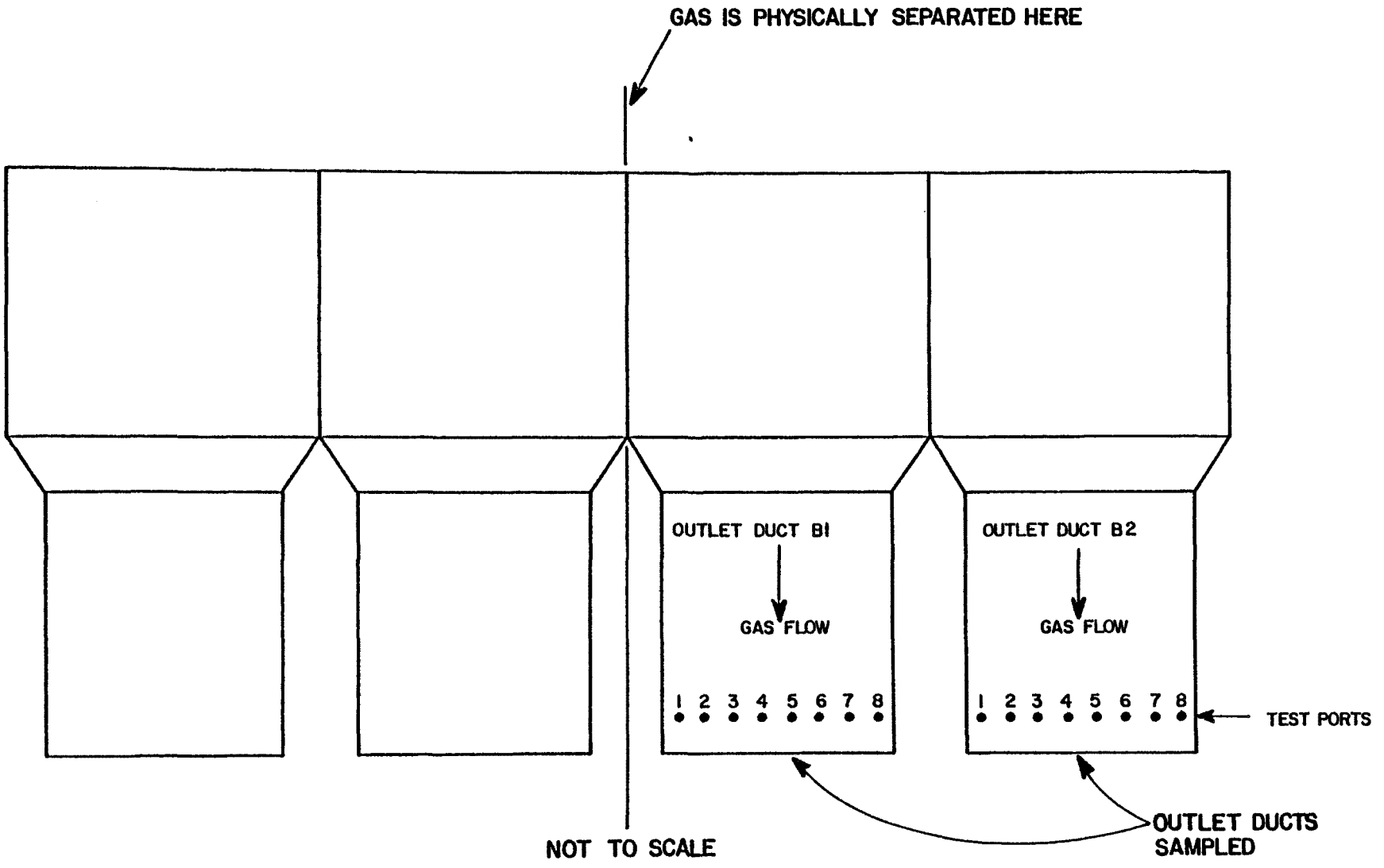

Figure 6. Elevation of outlet ducts viewed from underneath hoppers.

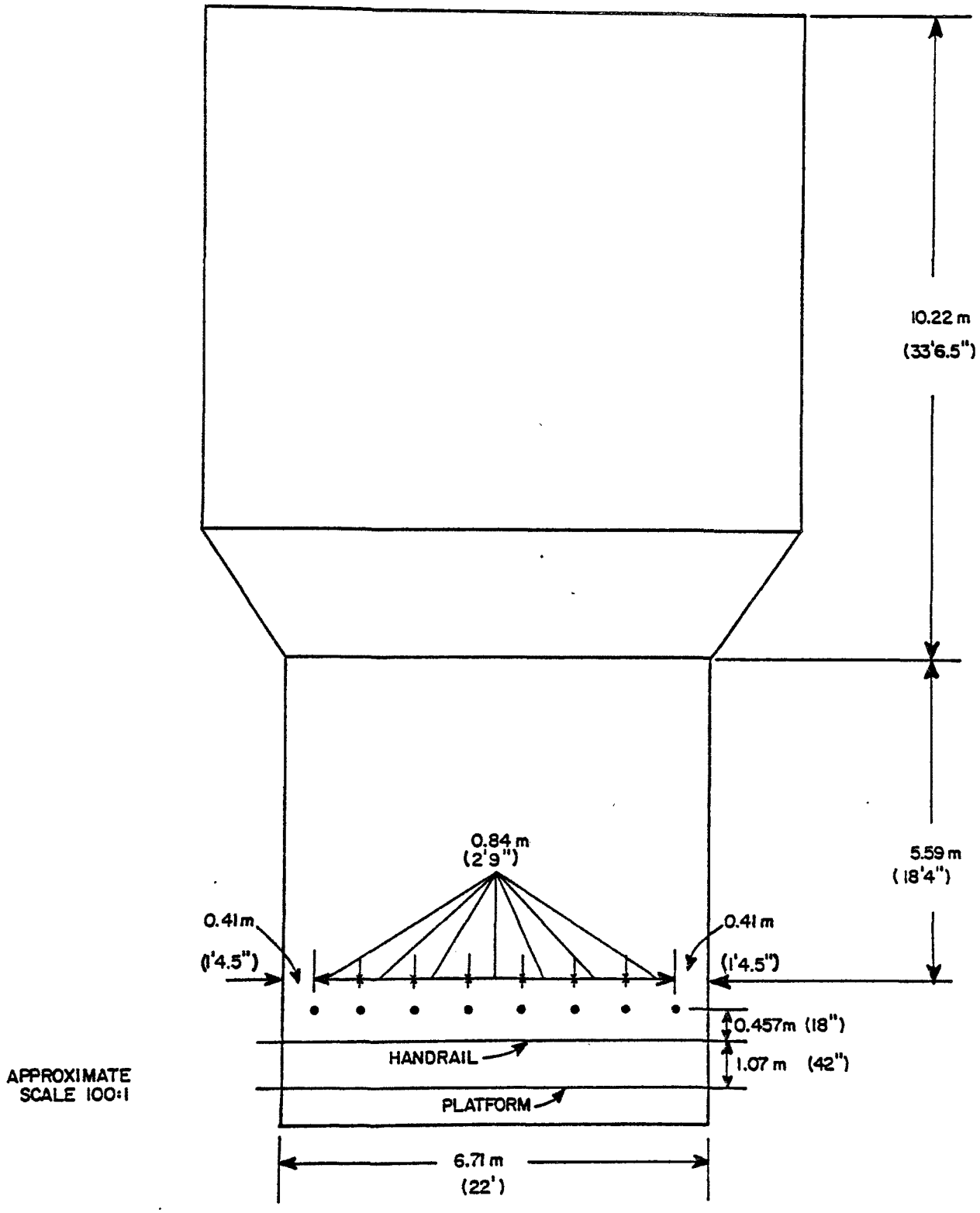

Figure 7. Details of sample port position in ducts.

SECTION 3
TEST PROCEEDINGS

SUMMARY OF TEST PROCEDURES

The test program at Plant Allen involved the measurement of several parameters using U.S. and Soviet equipment and procedures. Replicate runs were made over a period of 8 days from March 12, through March 19, 1976, inclusive. Before each day's tests began, ash was removed from the unit 3 precipitator hoppers and boiler soot blowing was conducted. During the actual sampling both of these operations were suspended. Boiler and precipitator operating parameters were monitored at half-hour intervals during the sampling periods. Daily coal and ash samples were collected for analysis.

The overall scope of the tests is summarized below, and the individual procedures are described in more detail in the remaining paragraphs of this section.

1. The flue gas velocity and static pressure were measured at the inlet and outlet using calibrated pitot tubes supplied by both countries. Preliminary moisture and molecular weight determinations were made concurrent with the pitot traverse with U.S. equipment.
2. To determine the precipitator collection efficiency, mass sampling was conducted at the inlet and outlet using both U.S. and Soviet equipment. The standard EPA Method 5 was used at the inlet, and a hi-volume EPA Method 5 was used at the outlet. The Soviet method utilized zero-type tubes with stainless steel filters.
3. Gas humidity was measured at the inlet with the U.S. equipment concurrent with the mass sampling. Flue gas molecular

weight was determined from samples extracted with a separate Orsat probe attached to the mass sampling probe.

4. Particle size distributions were determined on the inlet and outlet. For the U.S. tests Brink impactors were used at the inlet and Andersen impactors were used at the outlet. A Soviet cascade impactor was also employed for size sampling at the outlet, and at the inlet two types of Soviet impactors and a Soviet series cyclone apparatus were used. Outlet samples for both countries were obtained by complete traverses of the two outlet ducts using 24 sampling points per duct. Because of a combination of short sampling times and poor inlet velocity distributions, the inlet samples were obtained from individual ports, extracting one sample from each of four ports in each inlet duct.
5. Electrical resistivity of the fly ash particles was measured at the inlet by a U.S. method only, using a point-to-plane resistivity probe. Attempts to obtain resistivity data with the Soviet equipment were thwarted by various equipment and weather difficulties.
6. Sulfur dioxide and sulfur trioxide concentrations of the inlet gas were determined by the U.S. only (EPA Method 8) since the Soviet method is identical.
7. Back corona was measured using the Soviet method, which is based on measurement of the precipitator voltage-current relationships during voltage increase and decrease.
8. Fuel analyses were performed to determine the composition of ash, sulfur, hydrogen, carbon, moisture, nitrogen, and oxygen. Heating value was also determined. The collected ash samples were subjected to quantitative analysis to determine their chemical composition.

DAILY PRELIMINARY TESTS

Prior to each day's comparative testing, preliminary tests were conducted with U.S. equipment. Flue gas velocity measurements were made with U.S. pitot

tubes before the first few tests. These measurements provided a starting point for the operating procedure followed in the U.S. mass concentration sampling. Later tests relied on the previous day's results as a starting point.

Preliminary determinations of flue gas moisture and molecular weight were conducted each day to provide information for the conduct of the comparative testing.

Data from the preliminary tests are not discussed in Section 4 but are included for reference in Appendix D.

DETERMINATION OF PARTICULATE MASS CONCENTRATION OF THE FLUE GAS

Particulate mass concentration was determined by the standard U.S. method (EPA Method 5) and by the Soviet method.

U.S. EPA Method 5

Flue gas was extracted isokinetically from the duct through a heated probe and a fiberglass filter. This filter was enclosed in an oven and kept at a constant temperature of 160° C (320° F). Gas velocity and gas temperature were monitored continuously at each test point. Sample flow rate was computed utilizing a preset nomograph, which was adjusted whenever flue gas conditions of velocity and/or temperature changed with respect to time. A measurement of moisture content was performed coincident with particulate determination.

The particulate sampling apparatus consisted of a probe, pitot tube, filter holder, four Greenburg-Smith type impingers, vacuum pump, dry gas meter, and flow meter in a configuration indicated in Figure 8. The 316 stainless steel buttonhook-type probe tip (1) was equipped with a 16-mm (5/8-in.) diameter fitting connected to the probe by a teflon packed stainless steel coupling. The probe itself (4) was a 16-mm (5/8-in.) diameter medium wall pyrex glass tube fitted with a ground glass ball joint on one end. It was wrapped with heater tape capable of maintaining a minimum sample-gas stream temperature of 160° C (320° F) during sampling to prevent condensation from occurring within the probe. There was a reverse type pitot tube attached to the probe in order to provide instantaneous differential pressure readings at each sampling point. In addition, situated next to the nozzle was a type-K chromel-alumel thermocouple (3) connected to a pyrometer (14) for direct measurement of flue gas temperature.

The probe assembly was sealed to prevent ambient air from leaking into the duct and diluting the sample.

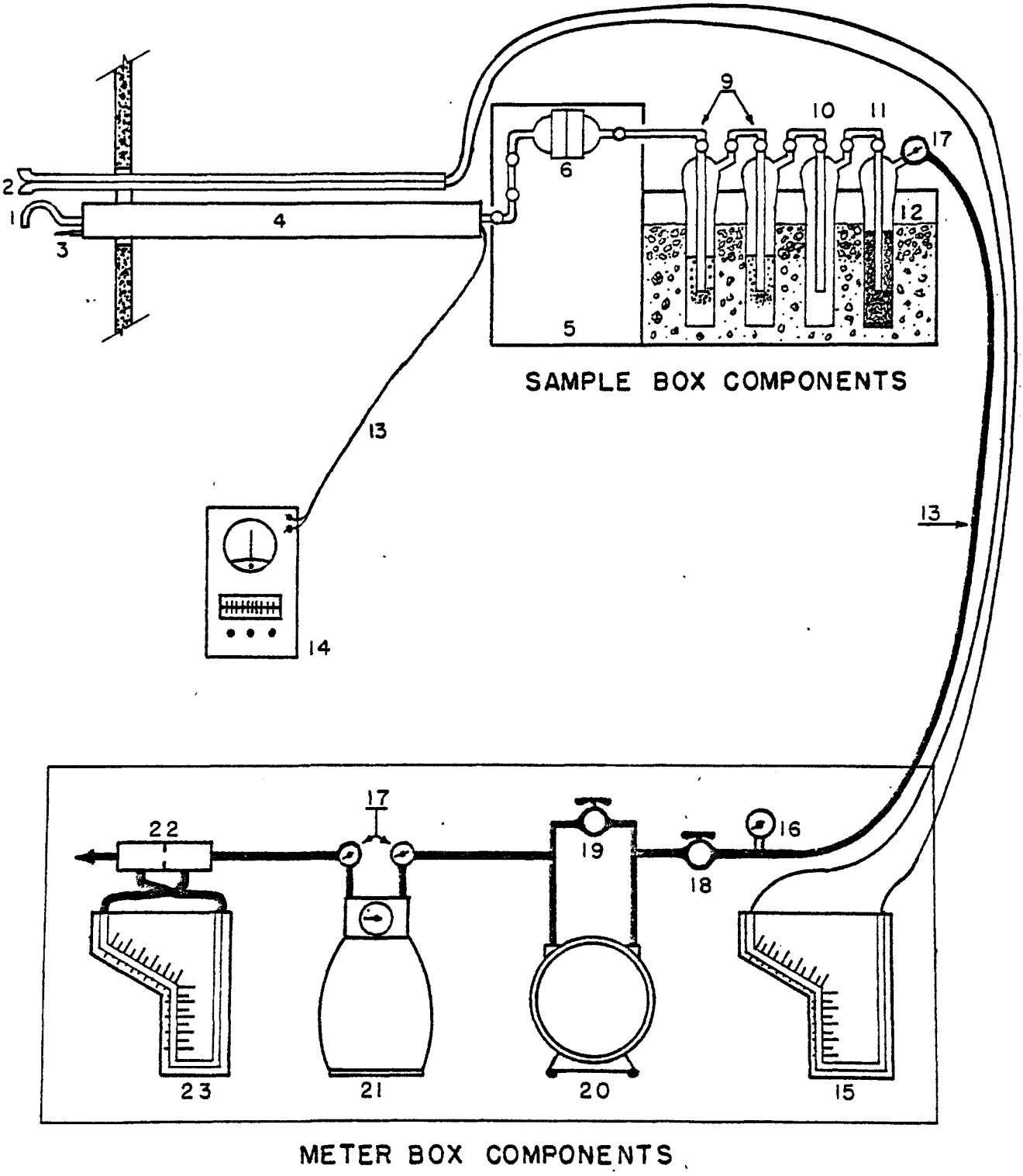

Figure 8. U.S. total particulate mass sampling train.

The probe was connected to a glass elbow which, in turn, was connected to a very coarse fritted glass filter holder (6). This holder contained a glass filter which had been previously numbered and weighed. The filter holder was contained in an electrically heated enclosed box, which was thermostatically maintained at a temperature of 160° C (320° F) to prevent moisture condensation.

Attached to this heated box were a series of four impingers connected with glass ball joints. The first impinger (9) was of the Greenburg-Smith design, modified by replacing the tip with a 12.7 mm (1/2 in.) inside diameter glass tube extending to within 12.7 mm (1/2 in.) from the bottom of the flask. This impinger was initially filled with 100 ml of water. The second impinger (9) was a Greenburg-Smith with a standard tip and was similarly filled with 100 ml of water. The third impinger (10) was modified like the first, but without water. The fourth impinger (11) was also a Greenburg-Smith type modified like the first and contained 300 grams of dry, indicating, 6-16 mesh silica gel, which had been previously dried at 175° C (347° F) for 2 hours. Both the impingers and heated box were housed together to facilitate removal of all sample components to a "clean" area. After the fourth impinger (11), the sample gas stream flowed past a dial thermometer (17), through a check valve to flexible rubber vacuum tubing (13), vacuum gauge (16), a valve (18), a leakless vacuum pump (20), which was connected in parallel with a bypass needle valve (19), and a dry gas meter rated at 0.1 ft^3 per revolution (21). A calibrated orifice (22) completed the train and was used to measure instantaneous meter flow rates. The three thermometers (17) were dial type with a range of -4° to 52° C (25° to 125° F). A fourth thermometer in the heated portion of the box had a range up to 260° C (500° F). A dual manometer (23) measured pressure drop across the calibrated orifice. This manometer was an inclined-vertical type graduated in hundredths of an inch of water from 0 to 1.0 inch.

Procedure--

Two separate ducts (B1 and B2) were sampled during each test period. Each duct was 1.83 m x 6.705 m (6.0 ft x 22.0 ft) and was divided into twenty-four equal areas with dimensions of 0.61 m x 0.84 m (2.0 ft x 2.75 ft). Test 1 through Test 6 included samples from both ducts B1 and B2. Test 7 included sample only from duct B2 and Test 8 included sample only from duct B1. Each test was performed at the inlet and outlet ducts simultaneously.

The center of each equal area was sampled for 5 minutes. Total test time was 120 minutes per duct. Port number 4 on inlet duct B1 was inaccessible due to structural steel supports, which obstructed the port opening. Accordingly, this port was not sampled during any tests.

A sampling system leak rate not-to-exceed 0.02 ft^3 per minute at a vacuum of 15 inches of mercury was required. This was checked by plugging the probe nozzle while the sampling train was in operation. In order to prevent water back-up in the train, the nozzle was slowly unplugged prior to shutting off the pump. Crushed ice was then placed around the impingers in an insulated box to insure that gases exiting that section were less than 21° C (70° F).

For each test run the following data were recorded every 5 minutes or when changes occurred in the flue gas conditions:

1. Point designation.
2. Clock time.
3. Dry gas meter reading (cubic feet).
4. Velocity head (ΔP in inches of water).
5. Desired pressure drop across orifice (ΔH in inches of water).
6. Actual pressure drop across orifice (ΔH in inches of water).
7. Dry gas temperature (°F) gas meter inlet.
8. Dry gas temperature (°F) gas meter outlet.
9. Vacuum pump gauge reading (in. Hg).
10. Filter box temperature (°F).
11. Dry gas temperature (°F) at the discharge of last impinger.
12. Stack temperature (°F).
13. Stack pressure (in inches of water).

At the start of testing, the probe nozzle was positioned directly into the gas stream and sampling immediately started. When inserting the probe into highly negative pressure, care must be taken. The pump was running to prevent water backup. Isokinetic sampling was maintained by the use of a nomograph which incorporated the relationship of the difference of pitot tube differential pressure (ΔP) and the pressure drop across the orifice meter (ΔH).

The relationship of ΔP reading with the ΔH reading is a function of the following variables:

1. Orifice calibration factor.
2. Gas meter temperature.

3. Percent moisture in the flue gas.
4. Ratio of flue gas pressure to barometric pressure.
5. Stack temperature.
6. Sampling nozzle diameter.
7. Pitot tube correction factor (e.g., other than 0.85).

The use of the nomograph allowed for the direct relationship to be determined within approximately 15 seconds, thus allowing isokinetic conditions to be maintained throughout the test.

Sample Recovery and Analysis--

Careful handling of the sampling apparatus was necessary in moving from the sampling location to the cleanup site. The water collected was first measured volumetrically and then discarded. Samples were placed in designated containers and analyzed in the following manner in the laboratory at the power plant:

Container 1: Each filter was sealed in a covered petri dish and placed in a plastic zippered bag. In the lab the filters were dessicated to a constant weight. The previously recorded tare weight was subtracted and the result was reported to the nearest 0.01 mg.

Container 2: All loose particulate was acetone-washed from all surfaces upstream of each filter, and the wash was sealed in a glass jar with a Teflon lid liner. The acetone washings and particulate matter were later transferred to a tared beaker and allowed to dry at room temperature and pressure. The constant weight was recorded to the nearest 0.01 mg.

Container 3: Silica gel from the fourth impinger of each test was sealed in a plastic jar. The silica gel was later weighed to the nearest gram. The tare weight recorded prior to the tests was subtracted and the difference was converted to volume of water and added to the volume collected in the other impingers.

U.S.S.R. Balanced Tube Method

Each of the ducts was divided into equal areas. A velocity traverse was performed before and after each test using a Soviet pitot tube. The velocity pressure and gas temperature at the center of each equal area were recorded.

To obtain the total mass samples a filtration medium was enclosed in a "zero" balanced tube apparatus, and the entire assembly was inserted into the flue gas duct. The ducts were traversed by placing the nozzle in the center of each area sequentially and adjusting the sampling rate to make it isokinetic. The gas at each point was sampled for a specific period of time. At the end of the test the particulate mass collected on the filter medium was representative of the average particulate concentration at the areas sampled in the duct. The inlet duct and outlet ducts were sampled using identical methods and equipment.

The equipment used in determination of particulate mass concentration is shown in Figure 9. The balanced tube assembly with the internal filter is shown in detail in Figure 10. A partial vacuum was induced in the sample train by a sliding-vane type air pump. Sample flow was actuated by a ball valve located in the sample train between the condenser and the vacuum pump. A needle valve bypass across the pump was used as a fine control for sample flow rate.

Sample gas entered the nozzle under induced vacuum and was drawn through a thimble filter fabricated from sintered stainless steel. Located at a point between the nozzle opening and the flow distributor inside the thimble filter were static pressure taps. The nozzle at this point had an inside diameter of 9 mm (5/16 in.). One set of pressure taps was located inside the nozzle while a second set was exposed to the flue gas static pressure. The pressure taps were extended via one-piece stainless steel tubes to the back end of the probe where they were connected with leak-proof seals to two independent lengths of plastic tubing. The plastic tubes were then connected across an inclined oil manometer. During sampling the flow rate was adjusted so that the static pressures inside and outside of the nozzle were equal. The assumption was made that when the static pressures were equal, isokinetic sampling was in effect.

The probe used in the performance of the pitot traverse is shown in Figure 11. Impact pressure was transmitted through a single tube facing the gas stream. Static pressure was transmitted through the annular space around the single tube. Two pressure tubes were located at the back end of the probe for connection across an inclined manometer by flexible hoses.

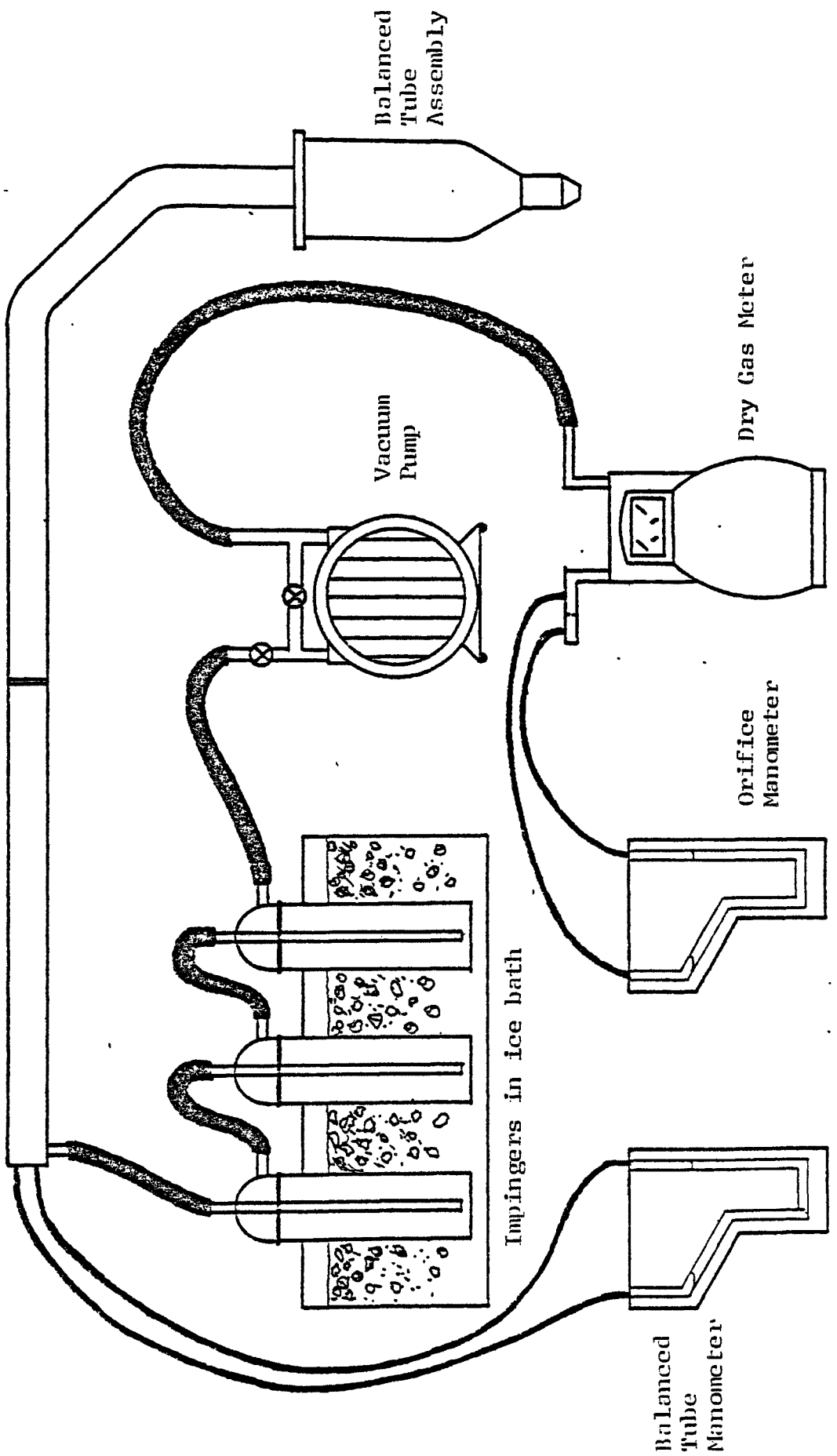

Figure 9. Soviet particulate mass sampling train.

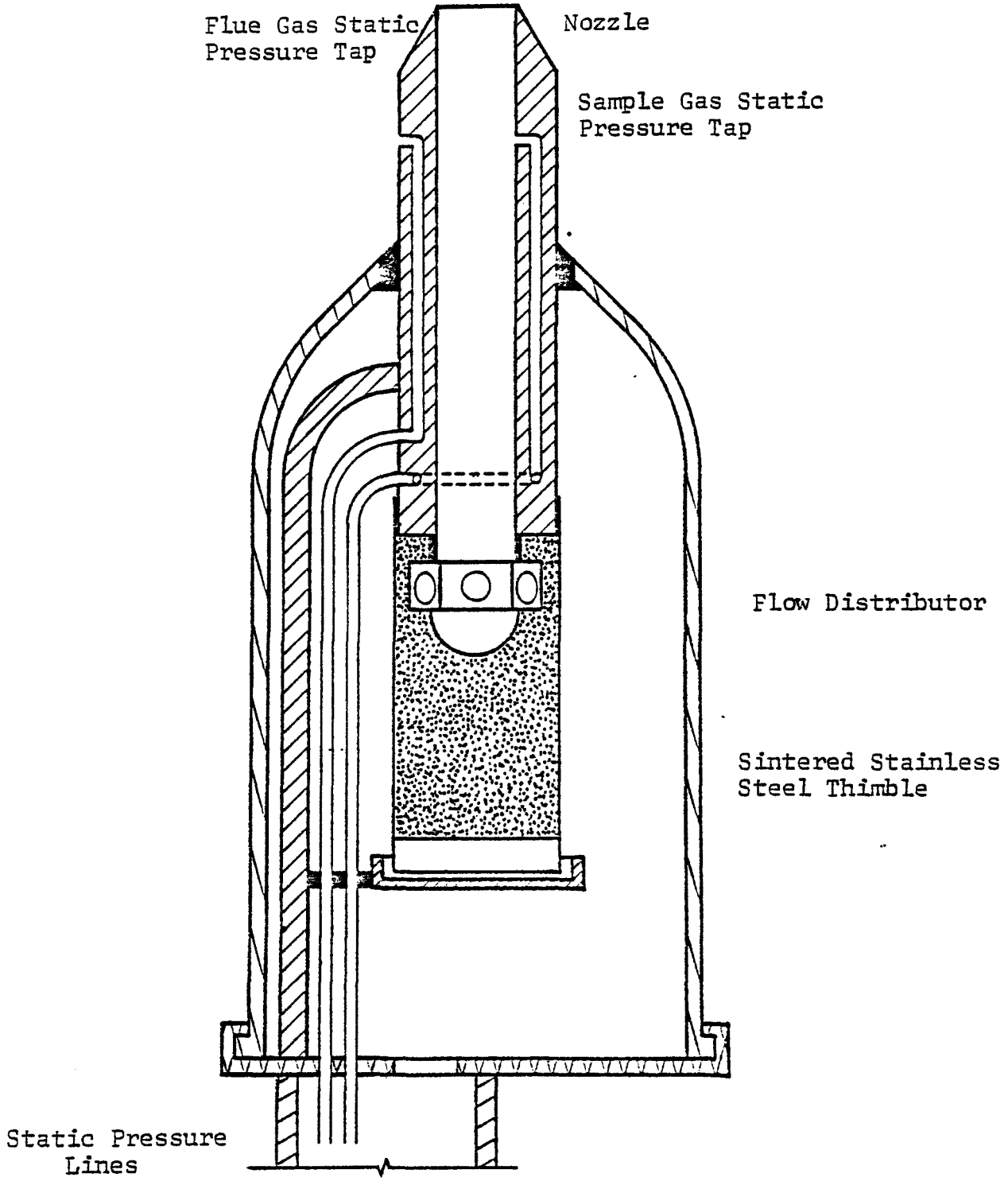

Figure 10. Soviet mass sampling probe detail.

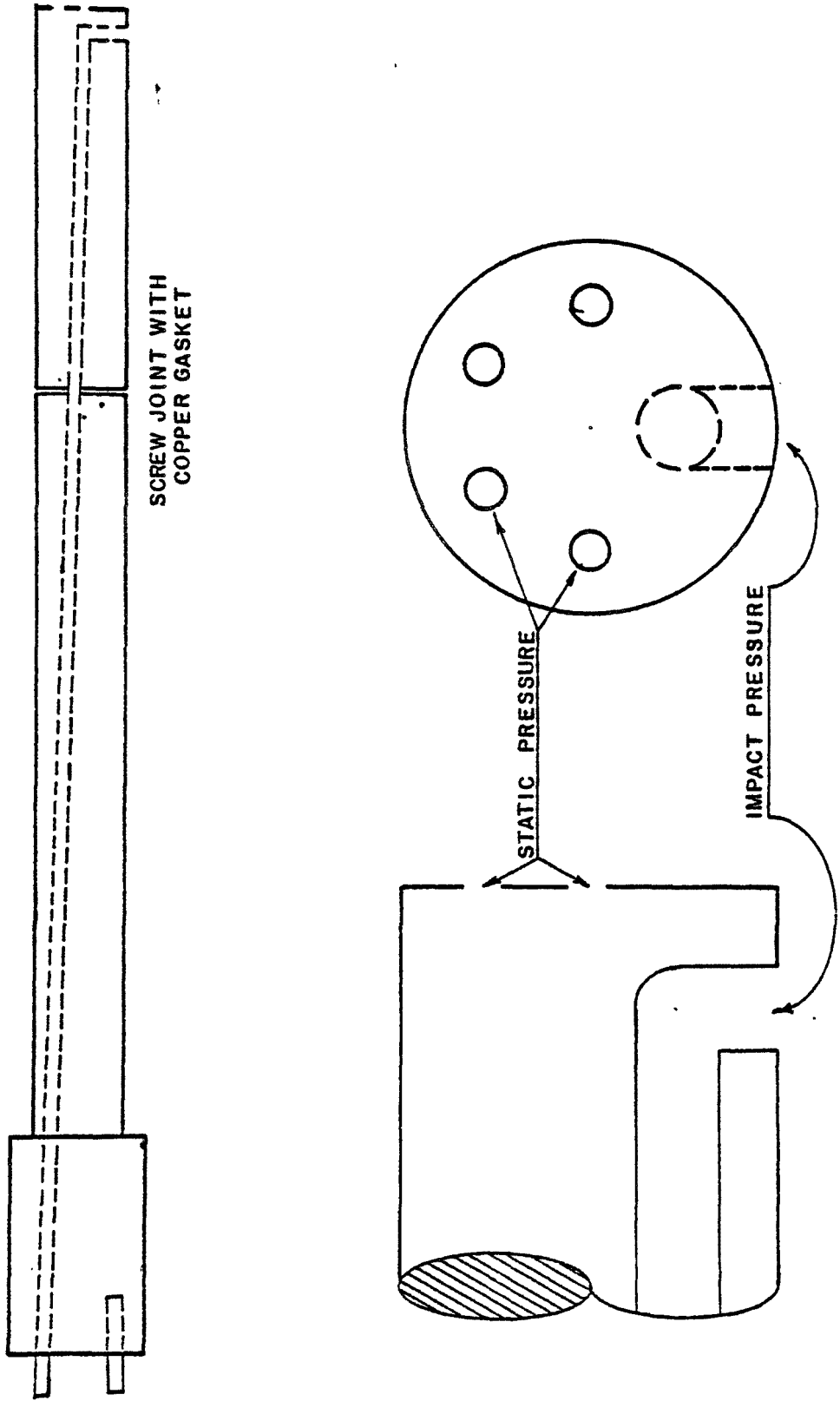

Figure 11. Soviet pitot tube.

Procedure--

Each test was comprised of two separate ducts, B1 and B2. Each duct was divided into 24 equal areas with dimensions of 0.61 m x 0.84 m (2.0 ft x 2.75 ft). The overall inside dimensions of the ducts were 1.83 m x 6.705 m (6.0 ft x 22.0 ft). The ducts B1 and B2 were both sampled during each test, with the exception of Test 7 and Test 8. During the last two tests only one duct was tested, with duct B2 sampled during Test 7 and duct B1 sampled during Test 8. Each test was performed with inlet and outlet samples taken simultaneously.

The center of each equal area was sampled for five minutes; total test time was 120 minutes per duct. Port number 5 on inlet duct B1 was obstructed by a structural steel I-beam and, therefore, was not sampled during any of the tests.

During the first four tests, the sample flow rate was controlled so that the static pressure inside the nozzle was equal to the static pressure outside the nozzle. The sample rate was increased during Tests 5 through 8 to 0.1 in. of water above zero on the null manometer.

When moving the probe to the adjacent port, a shutoff valve in the sample line prevented the vacuum in the flue gas duct from creating a backflow in the train and removing particulate from the filter. However, the direction of the gas flow in the inlet duct was from floor to ceiling, which necessitated that the nozzle be pointed down into the gas flow. In the first few tests this condition is believed to have caused the loss of some particulate through the nozzle when the shutoff valve was actuated. Tests 6 through 8 were performed with an extension on the flow distributor within the balanced tube apparatus. This apparently prevented loss of particulate sample as demonstrated by the higher results obtained in these three tests.

Prior to Test 6 a leak was detected in one of the static pressure tubes on the outlet train. This train was replaced at that time and a leak-test was performed. The remainder of the tests were performed with the proven sampling apparatus.

An attempt was made during Test 5 to filter the sample gas at the back end of the probe with a 47-mm fiberglass filter. Condensation of water caused the filter to plug immediately.

Sample Recovery and Analysis--

At the end of each test the balanced tube apparatus was placed with the nozzle pointing upward while the apparatus cooled. The apparatus was gently tapped to dislodge particulate from the inside surfaces of the nozzle. The thimble filter was carefully removed and placed in a clean glass jar with the open end of the thimble facing upward.

At the end of Tests 5 through 8, the inside nozzle surfaces were washed with acetone and the rinse was saved in a glass jar, sealed with a Teflon-lined lid.

At the end of Tests 4 through 6, the inside surfaces of the probe were washed with acetone and the rinse was saved in a glass jar, sealed with a Teflon-lined lid.

The thimble filters were placed in tared beakers and desiccated overnight. The beakers were then weighed and desiccated repeatedly until the weight was constant. The samples were weighed on an analytical balance with a sensitivity of 0.01 mg.

The acetone rinses were placed in tared beakers and allowed to evaporate at ambient temperature and pressure. The beakers were then desiccated and weighed until weight was constant on the same analytical balance used for thimble filters.

All analyses were performed at the laboratory of the Duke Power Company's Allen Plant.

Particulate Mass Calculations

Results of both the U.S. and U.S.S.R. particulate mass tests were calculated on a ratio of areas method. Because isokinetic sampling was used, it was assumed that the mass of particulate entering the nozzle at each sampling point was representative of the average particulate mass in the flue gas duct. The net particulate mass collected in each test was multiplied by the ratio of the total area of the flue gas duct to the area of the nozzle. The result of this calculation is the total mass of particulate passing through the duct during the test period. Division by the test period in minutes is necessary to compute mass rate. The equation is as follows:

$$E = m \times \frac{Ad}{An} \times \frac{1}{T} \times \frac{1}{1000\ g/kg} \times \frac{60\ min}{hr}$$

where:

E = mass rate (kg/hr),

m = mass filter catch (g),

Ad = Total area of duct sampled (m^2),

An = Area of nozzle (m^2),

T = Test time (min).

The particulate mass concentration was then determined by dividing the mass flow rate by the volumetric flow rate of gas.

DETERMINATION OF PARTICLE SIZE DISTRIBUTION

Particle size distribution was determined using two U.S. and three Soviet instruments. All of these instruments operated on the similar principle of inertial size classification, but the design and operation of the individual instruments varied.

U.S. Particulate Size Determinations

The U.S. particle sizing devices used during these tests were modified Brink-type cascade impactors (Fig. 12) for precipitator inlet measurements and Andersen cascade impactors (Fig. 13) for outlet measurements. The Brink impactors included a cyclone precutter as well as "0" and "6" stages. Both instruments were used with glass fiber mat impaction substrates and final filters. All collection media used during the tests (impaction substrates and final filters) were preconditioned at the test site to minimize potential interferences resulting from uptake of vapor phase components upon exposure to the flue gases. All sampling was done through the ports which were described previously.

Outlet samples were obtained by complete traverses of the two outlet ducts with each impactor using 24 sampling points per duct. The gas velocity profile in each duct was quite uniform with most point velocities in each duct differing by only a few percent from the combined average velocity for both ducts. Nozzles and sampling flow rates were chosen for isokinetic sampling rates to be obtained at the overall average velocity for the combined ducts. "Buttonhook" nozzles were used and the sample rates and gas volumes were determined with orifice meters and a dry gas meter. A total of nine Andersen impactor outlet runs were obtained during the test series, excluding

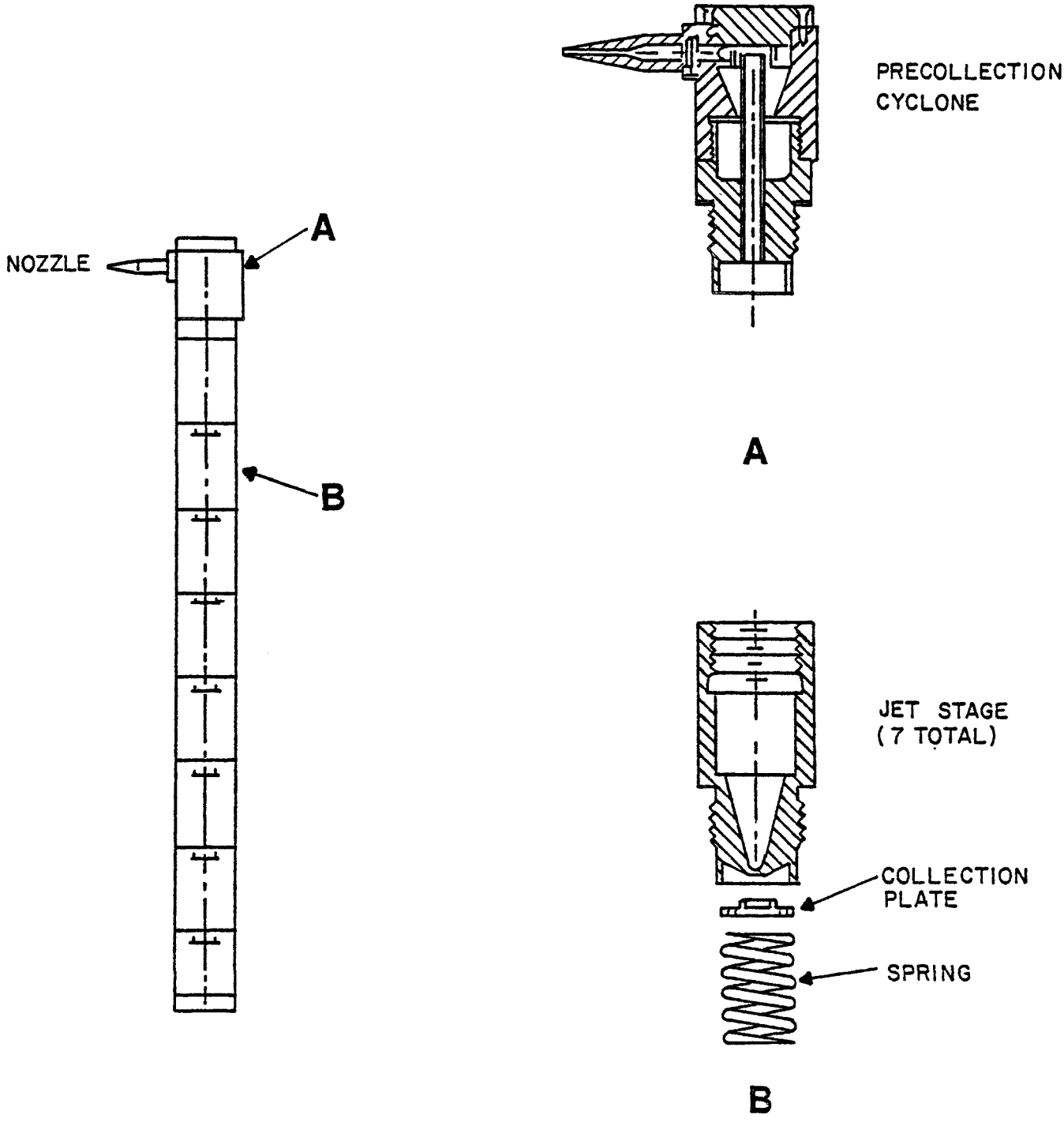

Figure 12. Brink cascade impactor.

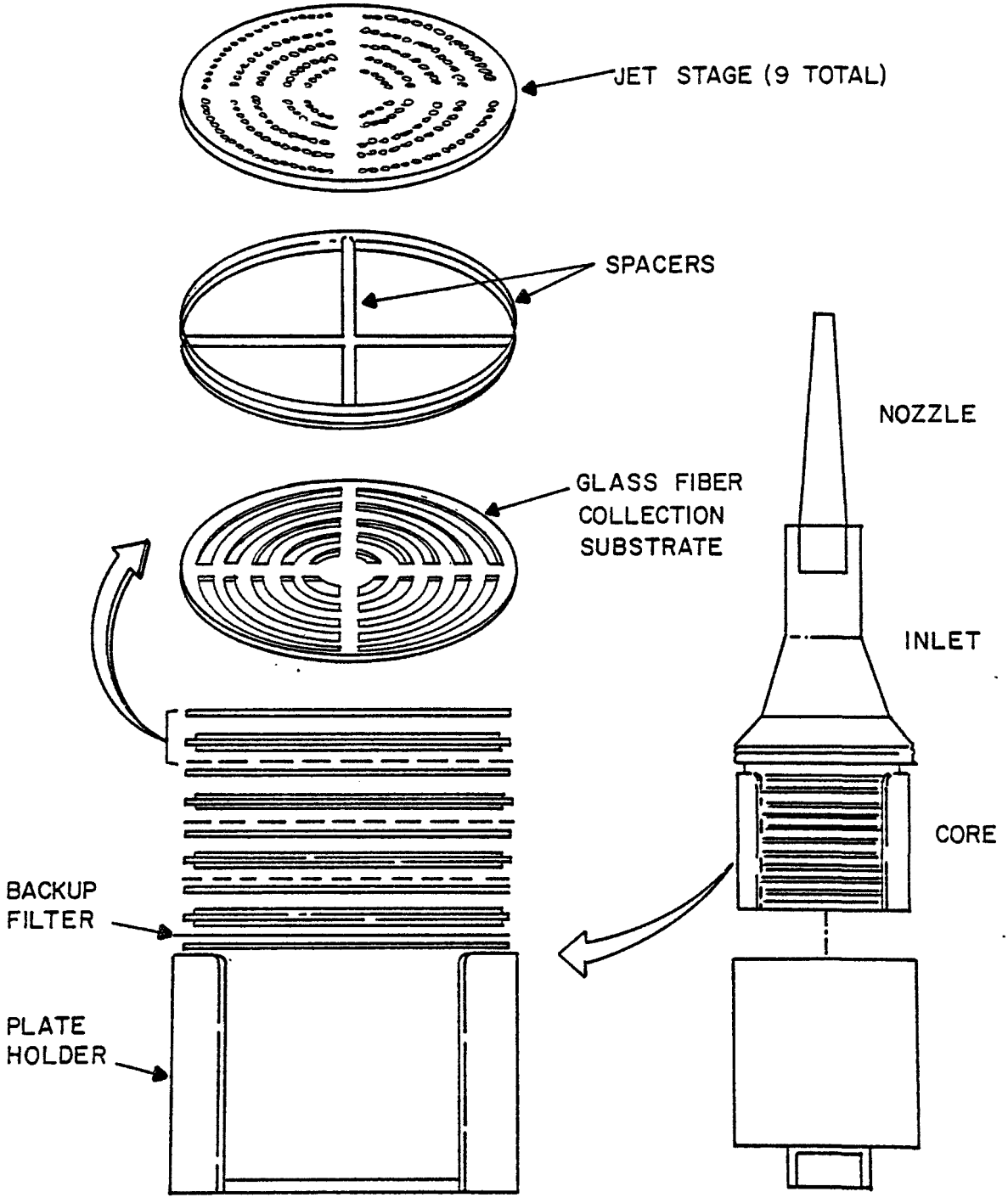

Figure 13. Andersen cascade impactor.

blanks. In addition, eight Andersen blank (or control) runs were made to determine the extent to which interferences from gas phase components might be affecting the outlet data. Outlet sampling times ranged from 120 to 360 minutes.

A total of nine Brink inlet samples were obtained. In addition, three blank or control runs were made with Brink impactors. Because of a combination of short sampling times (0.5 to 20 minutes) and poor inlet velocity distribution, each inlet sample was obtained from a single port. Four of the eight ports in each inlet duct were sampled. Sampling was accomplished using a combination of nozzle diameter and sampling rate to provide isokinetic conditions for the particular location at which the run was made. Straight sampling nozzles were used, and the sampling rates and gas volumes were determined with orifice meters.

U.S.S.R. Particulate Size Determinations

The Soviet particle-sizing devices included two cascade impactors: Model I, an impactor using multiple round jets at each stage with substrates of glass fiber mats or similar materials; Model II, a hybrid cylindrical slot/round hole impactor using the metal walls of the impactor as substrates; and a series cyclone system. All three devices were designed to use a backup filter plug of a glass wool or "Fiber-Frax" type material. These plugs were replaced during some tests by conventional flat glass fiber filter media. All three Soviet devices were used to obtain precipitator inlet size distributions but only Model I was used at the outlet. All filter media used during the tests were preconditioned at the test site to minimize potential interferences resulting from uptake of vapor phase components upon exposure to the flue gases.

Operation of the Soviet equipment was done in accordance with instructions from the Soviet test delegation. The operation of the Soviet equipment departed from their standard practices only in the case of Impactor Model II. In the case of the Model II their normal practice is to determine tare weights of the individual stage assemblies before sampling and then to reweigh the assembly with the dust attached or contained within it after sampling--the weight difference being that of the collected dust. The balances available during these tests were not suitable for this procedure; consequently, the collected particulate from each component of the Model II impactor was removed as completely as possible and transferred to low tare weight aluminum foils in order to determine the weight of the particulate matter caught by each stage.

Some small portion of the collected particulate was inevitably lost during this transfer; however, the losses are generally believed to be small compared to the total catch.

A total of seven Soviet Model I impactor outlet runs were obtained during the test series, excluding blanks. As with the Andersen complete traverses were made in both outlet ducts using sample rates which were calculated to be isokinetic for the overall average velocity of the combined ducts. Soviet orifice meters were used to determine the sample rates and gas volumes. Sample times ranged from 120 to 360 minutes. Straight sample nozzles were used. In addition to the sample runs, two blank or control runs were made to determine the extent to which interference from gas phase components might be affecting the outlet data.

A total of five Model I's, eight Model II's, and eight series cyclone samples were obtained at the inlet. In the same procedure used with the Brink impactor, each sample was drawn from a single port using what was thought to be an isokinetic sample rate. Soviet orifice meters were used to determine the sampling rates and gas volumes. Straight sample nozzles were used.

Calibrations of the Soviet orifice meters with a dry gas meter at the test site subsequent to the actual testing indicated that the Soviet orifice meter used at the inlet indicated 9 percent less than the true flow and the outlet orifice meter, as used, indicated 19 percent less than the true flow. The flow rates and all concentrations and size cuts reported herein have been adjusted for this discrepancy.

DETERMINATION OF FLY ASH RESISTIVITY

Fly ash resistivity was measured with a U.S. in-situ point-to-plane-type resistivity probe. Separate ports, located in the horizontal segment of the inlet ducts about 3 m (10 ft) from the other inlet ports, were used for the resistivity testing. These special ports were installed to accommodate the Soviet resistivity measurement device which is similar to what is described in the U.S. as a Lurgi-type probe. However, attempts to obtain resistivity data with the Soviet equipment were thwarted by various equipment and weather difficulties.

To use the U.S. point-to-plane resistivity probe, which was designed by Southern Research Institute, the probe was lowered into the duct and a thin

layer of dust was deposited on a small plate by electrostatic precipitation. The resistivity of the dust was then determined by measuring the voltage-current relationship across the thin layer. A total of eight resistivity determinations were made on four different days at the Allen tests.

DETERMINATION OF SULFUR DIOXIDE AND SULFUR TRIOXIDE CONCENTRATION OF THE FLUE GAS

The U.S. EPA Method 8 and the Soviet method of determining the sulfur dioxide and sulfur trioxide of flue gases are identical. Both methods are based on the absorption of SO_2 and SO_3 from an extracted flue gas sample, followed by separate measurement using the barium chloride/thorin titration method. Since the methods are identical only the U.S. train was utilized. A total of six SO_2/SO_3 determinations were made.

Equipment

The SO_2/SO_3 sampling apparatus consisted of a probe, pitot tube, filter, four Greenburg-Smith impingers, dry gas meter, vacuum pump, and flow meter as shown in Figure 14. The probe assembly was of the same configuration as the U.S. total particulate mass probe described previously.

The probe was connected to a standard Greenburg-Smith impinger (24) which was filled with 100 ml of 80% isopropanol ($CH_3CHOHCH_3$). After the first impinger was a very coarse fritted pyrex filter holder (6) which held a tared glass fiber filter. This was connected to a second Greenburg-Smith impinger (25), which was modified by replacing the standard tip with a 12.7 mm (1/2 inch) ID glass tube extending to 12.7 mm (1/2 inch) from the bottom of the impinger flask. The second impinger was filled with 100 milliliters of a 3% hydrogen peroxide (H_2O_2) solution.

The third impinger was also a standard Greenburg-Smith like the first. However, it was filled with 100 ml of a 3% hydrogen peroxide (H_2O_2) solution. The fourth and last impinger was modified like the second and was filled with 300 g of dry, indicating, 6-16 mesh silica gel, which had been previously dried at 175° C (347° F) for 2 hours.

Sampling Procedure

The sampling procedure was identical to that described in the U.S. total particulate mass concentration procedure. Two separate inlet ducts were

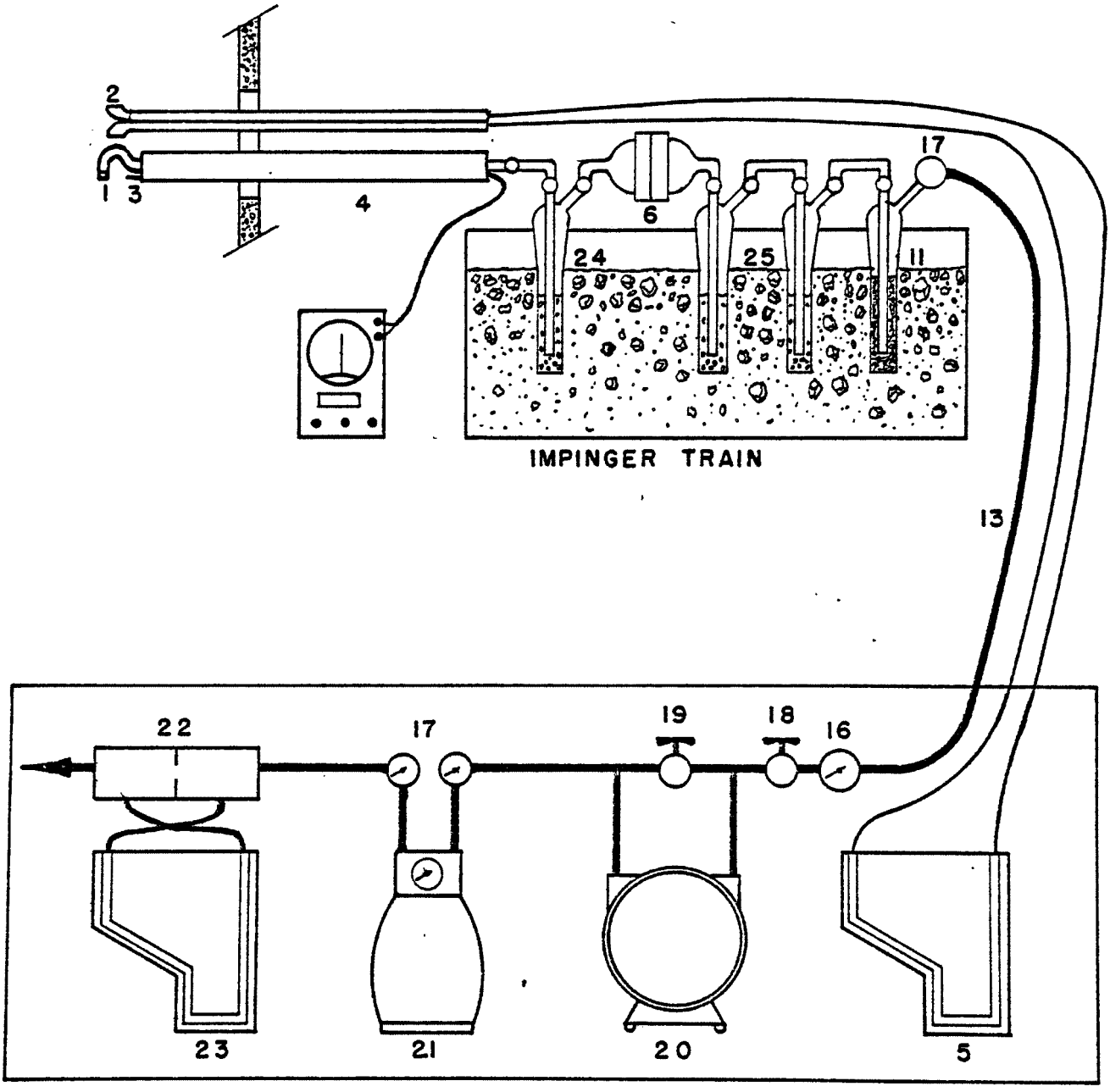

Figure 14. U.S. sulfuric acid mist sampling train.

sampled during each test period. Each duct was 1.83 m x 6.705 m (6.0 ft x 22.0 ft) and was divided into 24 equal areas with dimensions of 0.61 m x 0.84 m (2.0 ft x 2.75 ft). The center of each area was sampled for five minutes; total test time was 120 minutes per duct. Port number 4 on inlet duct B1 was inaccessible due to structural steel supports which obstructed the port opening. This port was not sampled during any of the tests.

Sample Recovery

The 80% isopropanol absorbing solution from the first impinger was transferred to a 250 ml graduated beaker. Everything upstream of the filter was rinsed with an 80% isopropanol solution and added to the 250 ml beaker with the impinger rinse. The beaker contents were then diluted to 250 ml with 80% isopropanol. The filter was added to the solution, which was mixed and stored.

The solutions from the second and third impingers were transferred to a 500-ml graduate beaker. All glassware downstream of the filter and upstream of the silica gel was rinsed with deionized, distilled water which was added to the 500-ml beaker. This solution was then diluted to 500 ml with deionized distilled water and stored.

Analysis

The container holding isopropanol and the filter was shaken. If the filter broke into pieces, the fragments were allowed to settle for a few minutes before the sample was removed. A 100 ml aliquot of sample was pipetted into a 250 ml Erlenmeyer flask and 2 to 4 drops of thorin indicator were added. The sample was titrated with barium perchlorate to a pink end point. This titration procedure was repeated with the samples from the second and third impingers.

The SO_3 concentration was calculated from the titration results of the solution from the first impinger and filter. The SO_2 concentration was calculated from the titration results of the second and third impinger solution.

EVALUATION OF BACK CORONA IN THE PRECIPITATOR

Back corona or reverse ionization is a frequent operating problem in electrostatic precipitators used to collect high resistivity dust. Back corona is a condition where the electrical breakdown strength of the gas in the interstitial regions of the dust deposited on the plates is exceeded. The electric field in the deposit is proportional to the current density and the resistivity

of the dust. If the electric field exceeds a critical value, a corona glow forms on the dust deposit and inhibits precipitator operation.

The Soviets have devised a method of evaluating the occurrence of back corona in electrostatic precipitators. Basically the procedure involves varying the secondary voltage to the precipitator and recording the corresponding secondary current. This procedure was followed on two occasions at Allen in the morning before the other tests were begun.

DETERMINATION OF FLUE GAS MOLECULAR WEIGHT

The carbon dioxide, molecular oxygen and carbon monoxide content of the flue gas were measured primarily to determine the molecular weight of the stack gas. These parameters were also used along with fuel analysis in determining the theoretical gas volume.

Equipment

Figure 15 illustrates the integrated gas sampling train utilized for molecular weight determination. It consisted of:

1. A stainless steel or pyrex glass probe fitted with a glass wool filter to remove heavier particles from the gas stream. This was followed by:
2. An air-cooled condenser for removal of excess moisture.
3. The sample was evacuated using a leak-free diaphragm pump. The flow rate was adjusted by means of a needle valve and measured by a rate meter which had a range of 0 to 0.035 ft^3 per minute.
4. This system was attached by a "quick disconnect" fitting to a flexible Tedlar bag housed in a rigid container.

Procedure

The equipment was set up as shown in Figure 15. After verifying that all the equipment was leak free, the sample bag was then evacuated to within three inches of mercury absolute pressure. The probe was then inserted into the flue and purged. The bag was connected and the sample was drawn in at a rate proportional to the flue gas velocity.

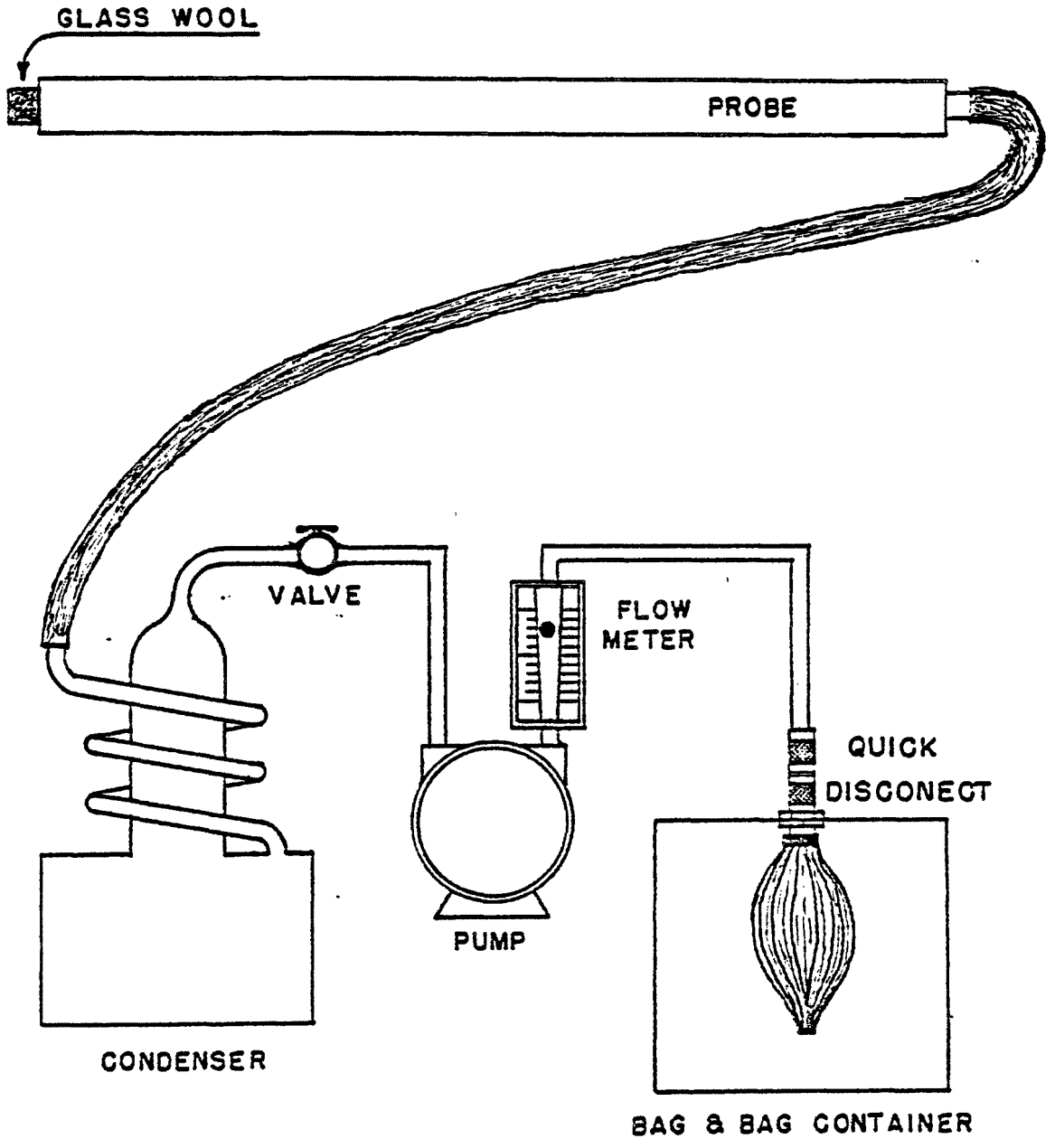

Figure 15. U.S. integrated gas sampling train.

Analysis

Analysis was performed immediately by passing the collected gas through an "Orsat" apparatus as many times as was necessary to arrive at a constant reading. The absorption solution was replaced when more than 10 passes were required. This analysis was repeated until three consecutive analyses of the sample varied no more than 0.2 percent by volume for each component.

COAL SAMPLING AND ANALYSIS

During each test, Duke Power chemical technicians obtained coal samples from the hoppers located above the coal pulverizer feeders (see Figure 2). Individual samples were collected at each of 12 sample points at 20-minute intervals throughout each test. The coal corresponding to each test was then composited, systematically divided into smaller samples, pulverized, and air dried. The samples were then transported to York Research Corporation's Laboratory in Stamford, Connecticut, for analysis. The following standard procedural methods were used in the performance of the coal analyses:

BTU value: ASTM D2015 - Adiabatic bomb calorimeter method.

Moisture: ASTM D3173 - Weight loss of sample measured when sample was heated under controlled conditions.

Fixed carbon: ASTM D3172 - By difference of summation of percent moisture, ash, volatile matter from 100.

Sulfur: ASTM D3177 - Method B - Barium sulfate precipitated from oxygen-bomb calorimeter washings, and precipitate was filtered, ashed, and weighed.

Carbon, hydrogen, and nitrogen: Sample was burned in an oxygen atmosphere in a closed system, while products of combustion passed through an absorption medium. Gases were analyzed by a Perkin-Elmer Model 240 Elemental Analyzer.

ASH SAMPLING AND ANALYSIS

Fly ash samples were also collected by Duke Power chemical technicians during each test. One sample was collected from each of the two boilers associated with unit 3. The sample point for each boiler was located downstream of the economizer where the flue gas turns from vertical downflow to

horizontal flow. The two samples from each test were composited and analyzed by York Research.

PLANT DATA ACQUISITION

To insure a record of important test influences, boiler and precipitator operating data were recorded throughout the tests at approximately half-hour intervals. The only noteworthy incidents were several electrical trips in individual sections of the precipitator. These trips were of short duration and none was thought to have significantly influenced test results.

Complete records of the boiler and precipitator operating data are contained in Appendixes N and P, respectively.

SECTION 4
RESULTS AND DISCUSSION

GAS FLOW AND TOTAL MASS CONCENTRATION DETERMINATIONS

Eight separate tests were conducted using both U.S. and Soviet equipment. In the first six tests, both U.S. and Soviet equipment was used to traverse ducts B1 and B2 on the inlet and outlet. The only difference in the sampled areas was that the U.S. train was unable to sample port 4 of duct B1 on the inlet because of a physical obstruction, and the Soviet train was unable to sample port 5 of duct B1 on the inlet for the same reason. With both sample trains, test 7 was a traverse of duct B2 only, and test 8 was a traverse of duct B1 only.

For direct comparison of the U.S. and Soviet determinations, the results of gas flow and total mass concentration tests are presented in Tables 4 and 5, respectively. The results are expressed in metric and English units and in actual gas conditions (as measured in the ducts) as well as dry standard or normal gas conditions (defined here as dry gas corrected to 21° C (70° F) and 760 mm (29.92 in.) of mercury absolute pressure).

The precipitator collection efficiency as measured by the U.S. train averaged 99.69 percent with a standard deviation of 0.08 percent. The precipitator collection efficiency as measured by the U.S.S.R. train averaged 99.03 percent with a standard deviation of 0.57 percent. It should be noted that the last three U.S.S.R. tests, which were conducted after several equipment and procedural modifications, agreed more closely with the U.S. tests than did the previous Soviet tests.

The following paragraphs discuss significant features of the comparative tests. Complete records of the gas flow and mass concentration data are contained in Appendixes D, E, F, G, H, and I.

TABLE 4. SUMMARY OF COMPARATIVE GAS FLOW DETERMINATIONS

Test no.	Type of train	Location	Date	Time start	Gas flow				Gas Composition		
					Standard		Actual		H_2O	O_2	CO_2
					DNCMM	DSCFM	ACMM	ACFM	%	%	%
1	U.S.-5	Inlet	3/12	1425	5,061	178,737	11,658	411,708	8.0	3.5	14.4
1	U.S.-5	Outlet	3/12	1405	5,700	201,310	12,757	450,500	7.4	4.0	13.9
1	U.S.S.R.	Inlet	3/12	1425	5,859	206,913	13,089	460,480	8.0	3.4	14.7
1	U.S.S.R.	Outlet	3/12	1405	6,002	211,973	13,221	466,889	7.4	4.0	13.8
2	U.S.-5	Inlet	3/13	1030	4,950	174,793	11,548	407,796	8.2	3.3	14.7
2	U.S.-5	Outlet	3/13	1030	5,902	208,424	13,374	472,280	7.2	3.8	14.1
2	U.S.S.R.	Inlet	3/13	1030	5,376	189,854	12,548	443,120	8.2	3.3	14.7
2	U.S.S.R.	Outlet	3/13	1030	5,945	209,945	13,477	475,928	7.2	3.7	14.1
3	U.S.-5	Inlet	3/15	1000	4,982	175,923	11,355	401,009	7.2	2.9	15.2
3	U.S.-5	Outlet	3/15	1004	5,690	200,928	12,953	457,430	7.8	3.7	14.0
3	U.S.S.R.	Inlet	3/15	1000	5,200	183,642	11,683	412,594	7.2	2.9	15.2
3	U.S.S.R.	Outlet	3/15	1004	5,502	194,319	12,510	441,796	7.8	3.7	14.0
4	U.S.-5	Inlet	3/16	0950	4,749	167,717	11,133	393,142	7.6	3.2	15.1
4	U.S.-5	Outlet	3/16	0948	5,520	194,936	12,841	453,467	8.6	3.7	14.5
4	U.S.S.R.	Inlet	3/16	0950	5,292	186,883	12,226	431,754	7.6	3.2	15.1
4	U.S.S.R.	Outlet	3/16	0948	5,469	193,144	12,758	450,547	8.6	3.7	14.5
5	U.S.-5	Inlet	3/17	0934	4,905	173,217	11,375	401,685	7.7	3.5	15.0
5	U.S.-5	Outlet	3/17	0918	5,722	202,086	12,958	457,615	7.1	3.9	13.5
5	U.S.S.R.	Inlet	3/17	0934	5,257	185,643	12,147	428,988	7.7	3.5	15.0
5	U.S.S.R.	Outlet	3/17	0918	5,778	204,055	13,081	461,954	7.1	3.9	13.5
6	U.S.-5	Inlet	3/18	1115	5,084	179,529	11,572	408,660	6.7	2.8	14.9
6	U.S.-5	Outlet	3/18	1046	5,743	202,794	12,979	458,330	7.9	3.7	14.1
6	U.S.S.R.	Inlet	3/18	1115	5,335	188,420	12,214	431,823	-	2.8	14.9
6	U.S.S.R.	Outlet	3/18	1046	5,688	200,865	12,886	455,065	-	3.7	14.1
7	U.S.-5	Inlet	3/19	1009	2,685	94,529	6,191	218,633	8.3	3.3	15.5
7	U.S.-5	Outlet	3/19	1010	3,322	117,314	7,444	262,894	8.0	3.8	14.0
7	U.S.S.R.	Inlet	3/19	1009	2,601	91,866	5,964	210,632	-	3.3	15.4
7	U.S.S.R.	Outlet	3/19	1010	3,306	116,735	7,467	263,696	-	3.9	13.8
8	U.S.-5	Inlet	3/19	1400	2,592	91,520	6,041	213,332	8.0	3.2	15.2
8	U.S.-5	Outlet	3/19	1405	2,459	86,821	5,555	196,156	7.6	3.9	13.6
8	U.S.S.R.	Inlet	3/19	1400	2,390	84,404	5,479	193,485	-	3.3	15.4
8	U.S.S.R.	Outlet	3/19	1405	2,329	82,233	5,253	185,526	-	3.9	13.8

TABLE 5. SUMMARY OF COMPARATIVE TOTAL MASS CONCENTRATION DETERMINATIONS

Test no.	Type of train	Location	Date	Time start	Total mass concentration				Mass Rate		Precipitator efficiency %
					Standard		Actual				
					mg/NCM	gr/SCF	mg/ACM	gr/ACF	kg/hr	lb/hr	
1	U.S.-5	Inlet	3/12	1425	11,325	4.949	4,917	2.148	3,439	7,582	
1	U.S.-5	Outlet	3/12	1405	44.98	.0197	20.10	.0088	15.38	33.91	99.59
1	U.S.S.R.	Inlet	3/12	1425	5,883	2.571	2,643	1.155	2,068	4,559	
1	U.S.S.R.	Outlet	3/12	1405	64.75	.0283	29.40	.0128	23.32	51.41	98.87
2	U.S.-5	Inlet	3/13	1030	12,172	5.319	5,217	2.280	3,615	7,969	
2	U.S.-5	Outlet	3/13	1030	33.92	.0148	14.97	.0065	12.01	26.48	99.71
2	U.S.S.R.	Inlet	3/13	1030	6,341	2.771	2,717	1.187	2,045	4,509	
2	U.S.S.R.	Outlet	3/13	1030	127.16	.0556	56.10	.0245	45.36	100.00	97.78
3	U.S.-5	Inlet	3/15	1000	10,792	4.716	4,734	2.069	3,226	7,111	
3	U.S.-5	Outlet	3/15	1004	49.33	.0216	21.67	.0095	16.84	37.13	99.54
3	U.S.S.R.	Inlet	3/15	1000	6,936	3.031	3,087	1.349	2,164	4,771	
3	U.S.S.R.	Outlet	3/15	1004	73.87	.0323	32.49	.0142	24.39	53.77	98.86
4	U.S.-5	Inlet	3/16	0950	10,943	4.782	4,668	2.040	3,118	6,875	
4	U.S.-5	Outlet	3/16	0998	28.84	.0126	12.40	.0054	9.55	21.06	99.74
4	U.S.S.R.	Inlet	3/16	0950	7,697	3.364	3,332	1.456	2,444	5,388	
4	U.S.S.R.	Outlet	3/16	0998	53.60	.0234	22.98	.0100	17.59	38.78	99.28
5	U.S.-5	Inlet	3/17	0934	12,063	5.271	5,202	2.273	3,550	7,827	
5	U.S.-5	Outlet	3/17	0918	33.31	.0145	14.71	.0064	11.44	25.21	99.72
5	U.S.S.R.	Inlet	3/17	0934	6,223	2.720	2,693	1.177	1,963	4,327	
5	U.S.S.R.	Outlet	3/17	0918	54.69	.0239	24.16	.0106	18.96	41.80	99.03
6	U.S.-5	Inlet	3/18	1115	10,858	4.745	4,770	2.084	3,312	7,301	
6	U.S.-5	Outlet	3/18	1046	25.23	.0110	11.16	.0049	8.69	19.17	99.76
6	U.S.S.R.	Inlet	3/18	1116	11,005	4.809	4,508	2.101	3,523	7,767	
6	U.S.S.R.	Outlet	3/18	1046	46.29	.0202	20.43	.0089	15.80	34.83	99.55
7	U.S.-5	Inlet	3/19	1009	12,598	5.505	5,464	2.388	2,030	4,475	
7	U.S.-5	Outlet	3/19	1010	26.61	.0116	11.88	.0052	5.30	11.69	99.78
7	U.S.S.R.	Inlet	3/19	1009	13,560	5.926	5,914	2.584	2,117	4,666	
7	U.S.S.R.	Outlet	3/19	1010	60.40	.0264	26.74	.0117	11.98	26.41	99.43
8	U.S.-5	Inlet	3/19	1400	10,630	4.645	4,560	1.993	1,653	3,644	
8	U.S.-5	Outlet	3/19	1405	30.74	.0134	13.61	.0060	4.53	10.00	99.70
8	U.S.S.R.	Inlet	3/19	1400	12,890	5.633	5,623	2.457	1,848	4,075	
8	U.S.S.R.	Outlet	3/19	1405	78.01	.0341	34.58	.0151	10.90	24.03	99.41

U.S. Test Results

The inlet total mass concentration as measured by the U.S. train averaged 4,941 milligrams per actual cubic meter (mg/ACM) with a standard deviation of 319 mg/ACM. The outlet concentration as measured by the U.S. train averaged 15.06 mg/ACM with a standard deviation of 3.85 mg/ACM. These results show very good reproducibility with the standard deviation being less than 10 percent of the mean at the inlet and about 25 percent of the mean at the outlet.

The high-volume sampling train used at the outlet during the first two tests was designed for use with metric measurement units. Since the computer interface used in calculating the results was not compatible with metric units, an alternate sample train designed for English units was used for the remainder of the tests.

A structural steel brace in front of port 4 on inlet duct B1 prohibited that port from being tested with U.S. equipment. For the purpose of calculations the assumption was made that the mass concentration at that port was equal to the average concentration of the particulate mass in the entire duct. However, there were two other ports in inlet duct B1 with zero gas velocity; hence the center ports including port 4 might have had velocities somewhat higher than the average velocity; and, hence mass flow rates of dust somewhat higher than the average. In fact, the preliminary velocity traverses, which did include port 4, showed it to have a velocity 22 percent higher than the average duct velocity. It is, therefore, possible that the inlet results are biased to the low side because of the uncertainty concerning port 4 in duct B1.

For the first six tests, which involved both ducts, the average inlet gas flow measured using the U.S. train was 11,440 actual cubic meters per minute (ACMM) with a standard deviation of 191 ACMM. The outlet gas flow measured by the U.S. train averaged 12,977 ACMM with a standard deviation of 212 ACMM. These results yield a consistent increase of gas flow at the outlet averaging 13 percent more than the inlet. One possible reason for this discrepancy is air leakage into the inlet ports or into some other openings between the inlet and outlet test ports. This hypothesis is supported by the consistently higher oxygen readings measured at the outlet. Leakage from outside would also tend to dilute the particulate concentration at the outlet.

The one exception to the higher outlet flows occurred in Test 8. Test 7 utilizing duct B2 follows the previous data of higher outlet versus inlet gas flow; however, Test 8 utilizing duct B1 indicates lower outlet than inlet gas flow. This result indicates the possibility of flue gas leakage from one duct to the other.

An alternate explanation of the higher flow rates observed at the outlet is the error introduced by not sampling port 4 on inlet duct B1. Since this port is known to have had a velocity higher than the duct average, the calculated gas flow of the entire inlet was reduced by the simplifying assumption made concerning port 4.

U.S.S.R. Test Results

The inlet mass concentration determined by the U.S.S.R. train averaged 3,815 mg/ACM with a standard deviation of 1350 mg/ACM. The outlet mass concentration determined by the U.S.S.R. train was 30.86 mg/ACM with a standard deviation of 11.27 mg/ACM. The standard deviation expressed as a percentage of the mean, is approximately 36 percent for both of these determinations. At the inlet the deviation between these results and the U.S. test results is understandable since the tests were performed with the nozzle facing down, and no precautions were taken until Test 6 to prevent loss of particulate catch during port changes. Commencing with Test 6, an extension was added to the balanced tube apparatus, which transported sample gas higher inside the thimble and made the loss of dust less probable. Also, prior to Test 6, a leak was found in one static tube of the U.S.S.R. balanced tube apparatus at the outlet. The leaking apparatus was replaced with a new unit at that time, and Tests 6, 7, and 8 were performed with the new unit.

After the first four tests, when poor agreement between the U.S. results and the U.S.S.R. results was apparent, the Soviet delegation suggested operating the test equipment at a higher sample rate, i.e., 0.1 in. of water above zero on the null manometer. When the balanced tube apparatus is calibrated for the particular gas stream, adjustment of the sampling rate is sometimes required. The Soviet delegation had hoped to spend more time calibrating the instruments during the initial phase of the test program; however, the scheduling of the program did not permit more time. The only calibrations performed during the initial phase of the program were pitot tube calibrations, and the balanced tube apparatus was operated but not calibrated. The results of the last three

tests, which were performed after the equipment modification discussed previously and with the higher sampling rate, show particulate mass concentrations which are considerably higher than the first five Soviet tests and also higher than the corresponding U.S. tests. At the inlet the last three Soviet tests averaged 5,348 mg/ACM with a standard deviation of 742 mg/ACM. At the outlet the average was 27.25 mg/ACM with a standard deviation of 7.09 mg/ACM. Part of the reason that the Soviet results are higher than the U.S. results is probably that the balanced tube apparatus was operated at the higher sampling rate, and therefore, more gas volume was pulled through the train, resulting in a higher net filter weight. Since the U.S.S.R. calculations involve a simple relationship between the net thimble weight and test time, a superisokinetic sample rate can result in high test results.

The inlet Tests 1 through 4 were performed without testing port 5 on duct B1. This port was obstructed by a structural steel brace, which prevented turning the probe to insert it into the port. It was agreed by the Soviet delegation to calculate the results using the test time as if that port had been tested, and by modifying the filter weight as if the port had been tested. The following is an adjustment equation for the net filter weight and was used for calculation of results from Tests 1 through 4:

$$gm_c = gm_a \times \left(1 + \frac{1}{N_p}\right)$$

where:

gm_c = grams of catch corrected,

gm_a = grams of catch actual,

N_p = number of ports tested.

During each of Tests 5 through 8 the sample time of each of the two test ports adjacent to the inaccessible test port was increased by 50 percent, compensating for not testing the inaccessible port.

According to the Soviet delegation, normal cleanup procedure for the balanced tube apparatus is to turn the apparatus with the nozzle opening pointing upward. The apparatus is allowed to cool in this position. The inside surface of the nozzle is brushed with a soft brush and adhering particulate is allowed to fall down into the filter. The filter is then removed carefully.

It was decided during the field testing to determine whether any particulate adhered to the inside nozzle surface after brushing. Tests 5 through 8 ended with cleaning the nozzle surface with acetone. The acetone was then evaporated in a tared beaker and weighed. Although these results were not used in calculation of the mass rate, they are presented in Table 6.

An additional study was undertaken to determine how much dust leaked through the thimble holder cases and adhered to the inside surface of the probe. Before and after Tests 4, 5, and 6, the probe was rinsed with acetone, and the final rinse was evaporated in a tared beaker and weighed. These results are also reported in Table 6. The flow of gas leaking through the thimble holder cases was not monitored by the static pressure taps and, therefore, should not have affected the test results.

For the first six tests, which involved both ducts, the inlet gas flow as measured by the U.S.S.R. train averaged 12,317 ACMM with a standard deviation of 469 ACMM. The outlet gas flow as measured by the U.S.S.R. train averaged 12,984 ACMM with a standard deviation of 336 ACMM. Like the results obtained with the U.S. train, the outlet gas flows were consistently higher than the inlet gas flows, although the difference between inlet and outlet was not as great with the U.S.S.R. train. The average difference of 5 percent between the outlet and the inlet gas flow as measured by the U.S.S.R. train was probably caused by air inleakage through the inlet ports or elsewhere between the

TABLE 6. RESULTS OF SOVIET NOZZLE AND PROBE WASHES

Test no.	Location	Date	Nozzle wash g	Probe wash g	Net filter weight g
4	Inlet	3/16	-	2.71665	23.39200
4	Outlet	3/16	-	.03436	.18237
5	Inlet	3/17	.00820	.20444	20.35294
5	Outlet	3/17	.02382	.02980	.19663
6	Inlet	3/18	.10725	.38368	36.53119
6	Outlet	3/18	.01109	.12777	.16382
7	Inlet	3/19	.03667	-	21.94611
7	Outlet	3/19	.02186	-	.12424
8	Inlet	3/19	.02693	-	19.16634
8	Outlet	3/19	.00951	-	.11305

inlet and outlet sample ports. One significant difference existed between the U.S. and U.S.S.R. procedures. Although an inaccessible center port on duct B1 was omitted from particulate mass testing by both the U.S. and the U.S.S.R. train, the U.S.S.R. pitot tube traverse, which was a separate part of the Soviet test, included all ports. Since both center ports had significantly higher than average velocity, the U.S.-determined gas flows had a tendency to be biased to the low side.

DETERMINATION OF PARTICLE SIZE DISTRIBUTION

As explained in Section 3, three U.S.S.R. and two U.S. devices were used to determine the particle size distribution. At the precipitator inlet both Soviet cascade impactors (designated as Model I and Model II) and the Soviet series cyclones were used. The Brink impactor was used for U.S. inlet testing. At the outlet the Soviet Model I and the U.S. Andersen impactor were used.

Comparative results of the three devices used at the inlet are presented in Table 7. The mass median diameter (MMD) and geometric standard deviation (σg) estimates were obtained from best judgment fits of the data to log-normal cumulative distributions. Note that the inlet data are categorized by sampling location because port-to-port traverses were not possible in each day's test. Agreement between the Brink and the Soviet Model II is reasonably good in most cases, but the Soviet Model I deviates considerably. Cumulative and differential distribution plots of all of the inlet data are categorized by sample location and presented in Appendix J.

Figures 16, 17, and 18 are differential distribution plots of the inlet data by device. These plots give an indication of the variability of separate measurements, which is a function of both variability of true size distribution in the ducts with time and position and variability of individual tests with the same device.

Table 7 also presents a comparison of the results obtained at the outlet with the Andersen impactor and the Soviet Model I. With both devices the last four tests are reasonably consistent, but the Soviet device indicates a higher mass median diameter. This is probably a result of differences in the methods of calibrating the impactors and may be resolved at a future date when comparable calibrations for the two sets of equipment become available. Differential distribution plots of the outlet data by device are presented in Figures 19 and 20. Cumulative and differential distribution plots of all of the outlet data are categorized by date and presented in Appendix J.

TABLE 7. COMPARATIVE RESULTS OF PARTICLE SIZING DEVICES

Inlet tests

Date	Location	Brink		Soviet Model I		Soviet Model II	
		MMD,μm	σg	MMD,μm	σg	MMD,μm	σg
March 13	B1, Port 7	17	3.4	70	11	54	3.2
March 15	B2, Port 4	28	3.7	-	-	24	2.4
March 15	B1, Port 3	28	3.3	35	2.9	31	2.8
March 16	B1, Port 5	17	4.1	-	-	23	2.3
March 17	B2, Port 2	18	3.8	18	2.8	22	2.4
March 19	B2, Port 6	26	3.6	45	5.6	23	3.1

Outlet tests

Date	Andersen		Soviet Model I	
	MMD,μm	σg	MMD,μm	σg
March 12	4.1	4.0	4.0	4.0
March 13	6.4	2.6	17	5.5
March 15	30	20	9.4	7.8
March 16	11	3.1	22	2.9
March 17	10	2.5	17	2.8
March 18	11	3.7	18	4.2
March 19	9.4	3.9	14	2.7

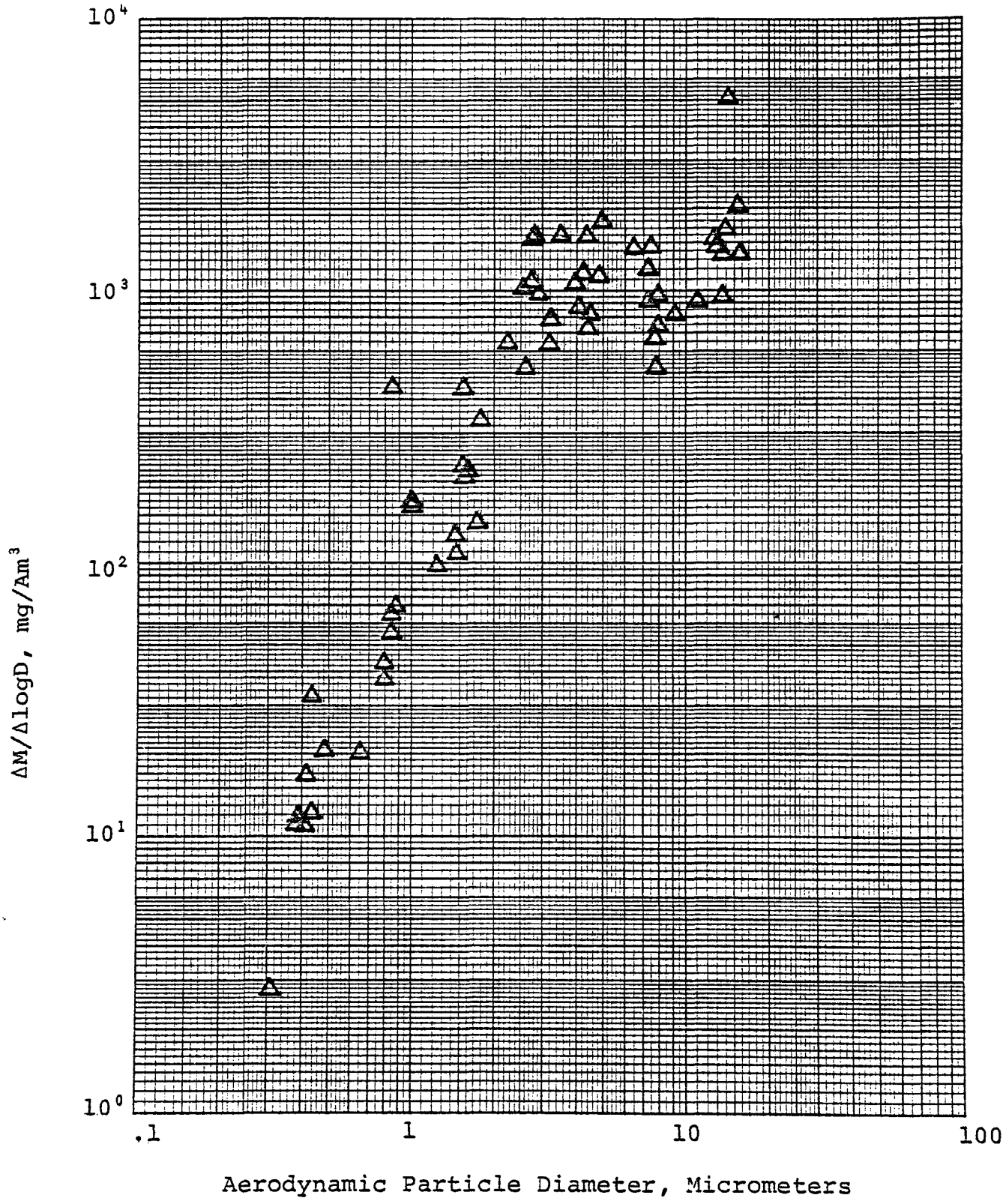

Figure 16. Inlet size distribution on a differential mass distribution basis - Brink data.

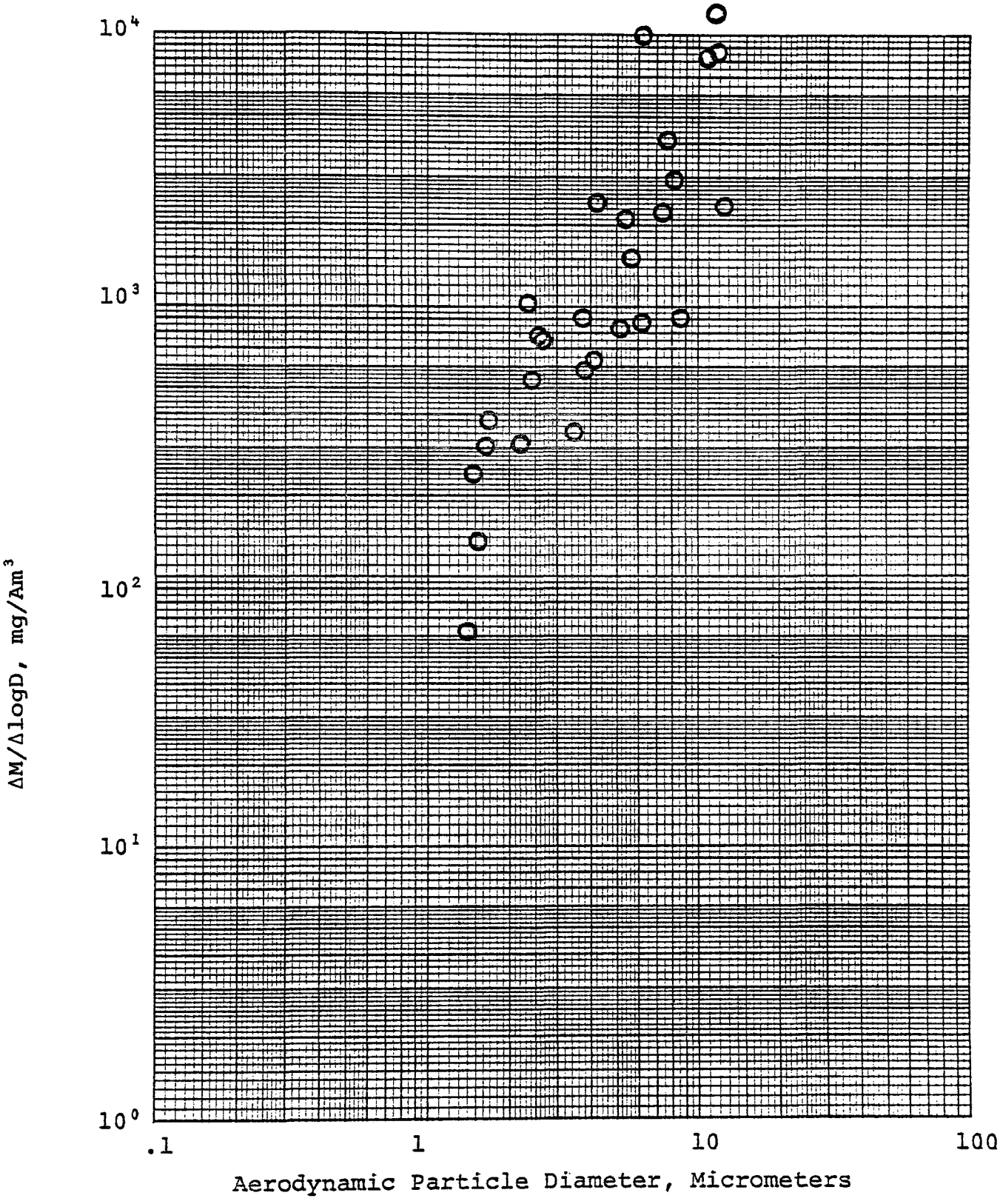

Figure 17. Inlet size distribution on a differential mass distribution basis - Soviet Model I data.

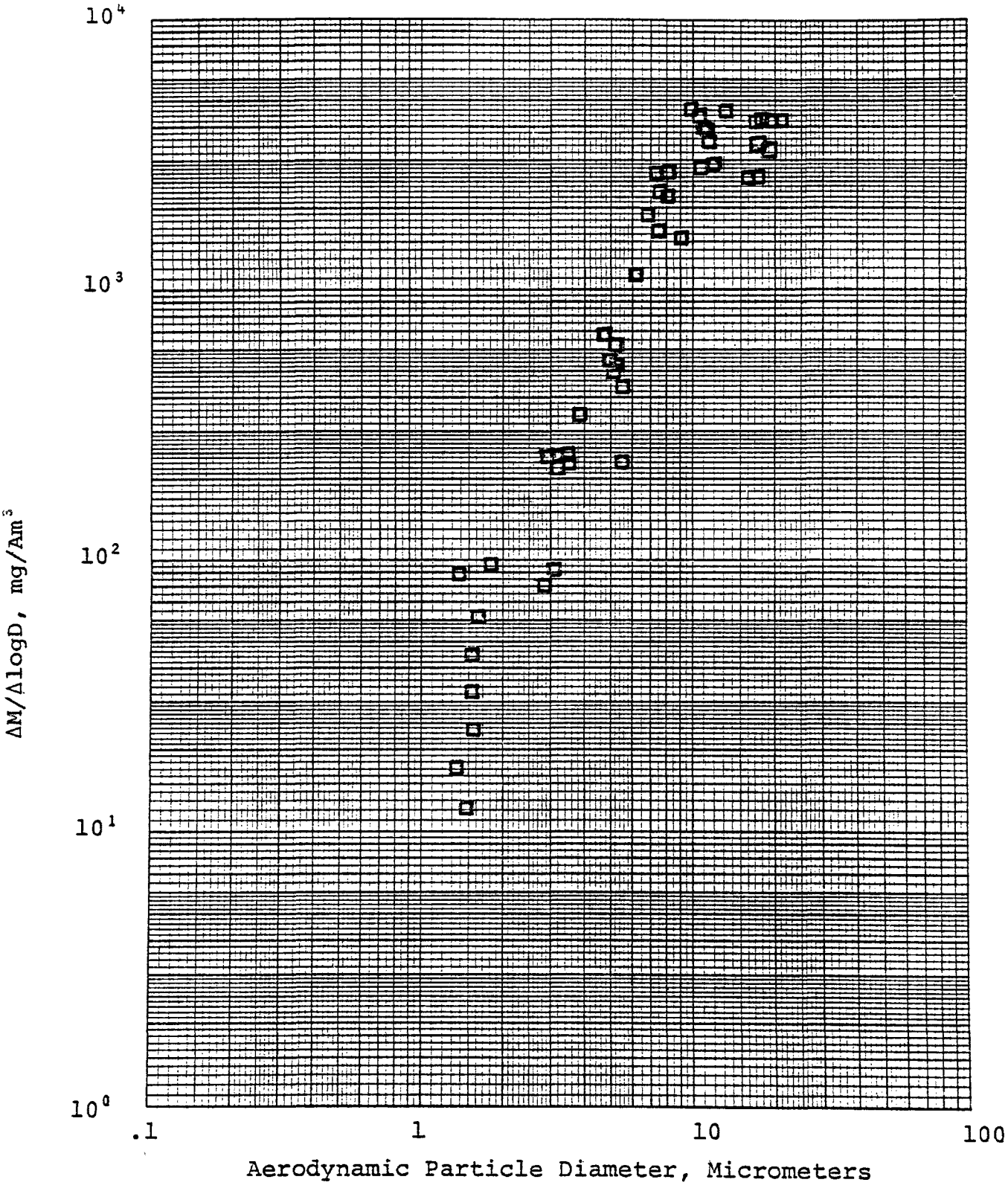

Figure 18. Inlet size distribution on a differential mass distribution basis - Soviet Model II data.

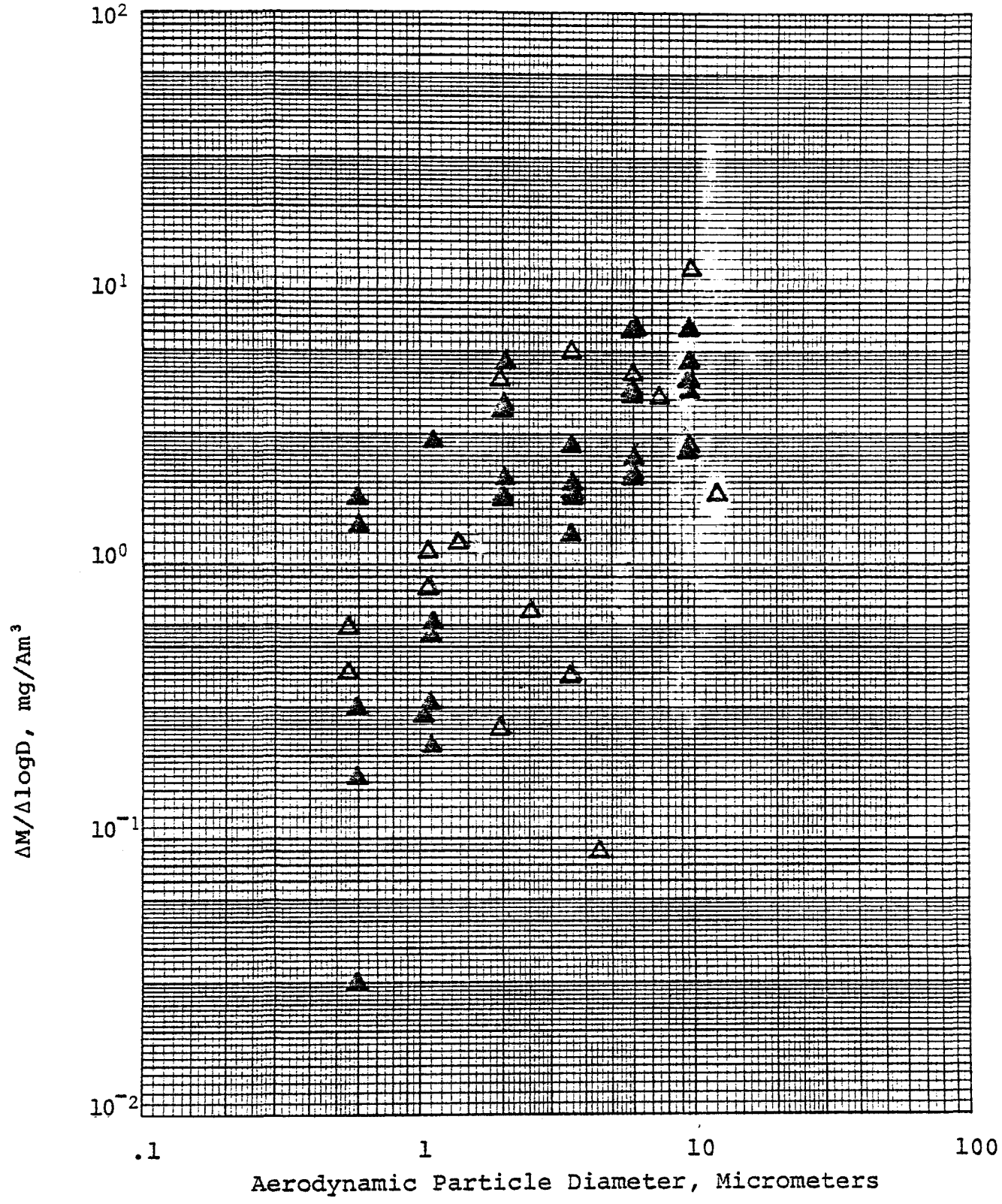

Figure 19. Outlet size distribution on a differential mass distribution basis - Andersen data. (Open symbols - 120 minute samples, solid symbols - 288 and 360 minute samples).

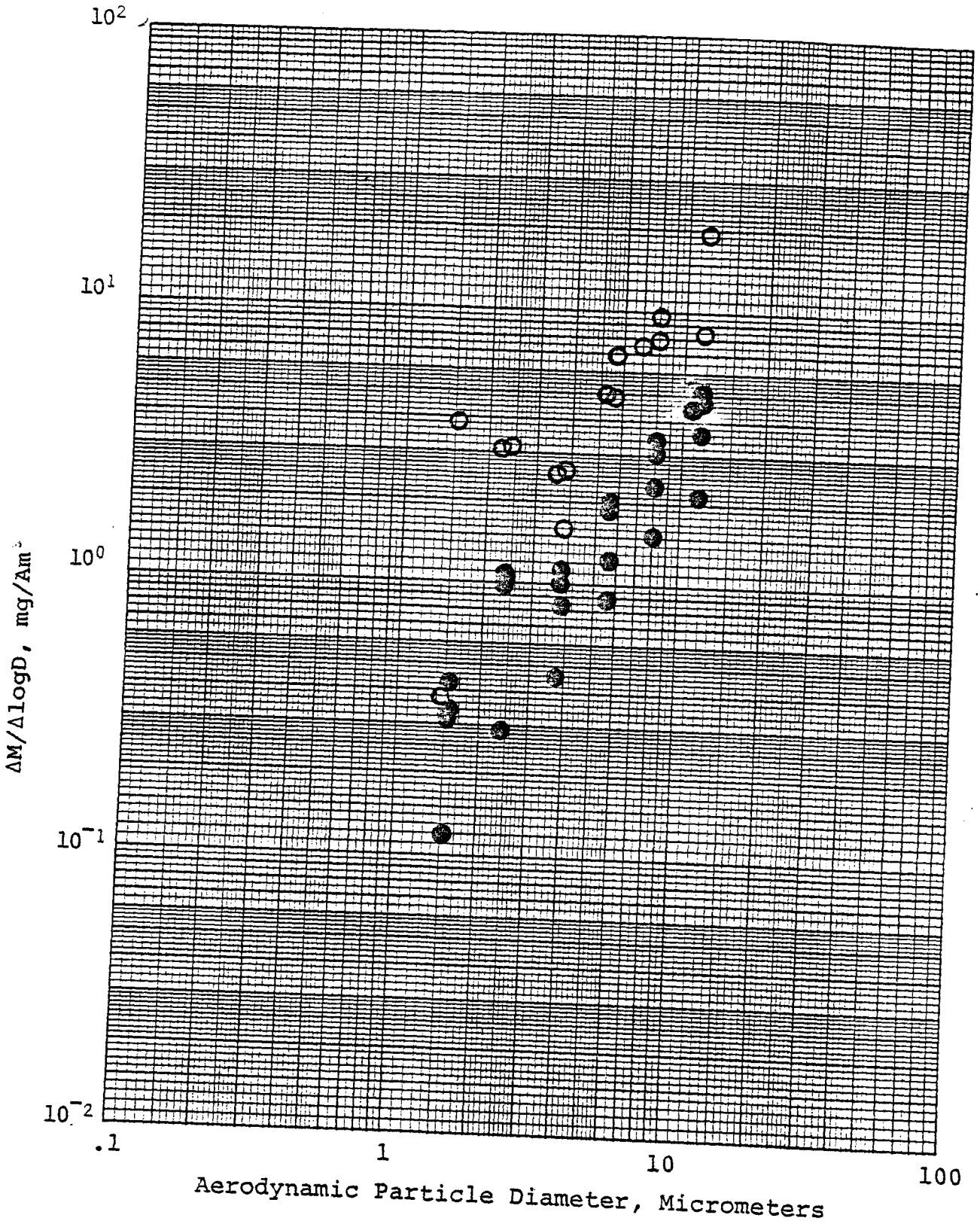

Figure 20. Outlet size distribution on a differential mass distribution basis - Soviet Model I data. (Open symbols - 120 minute samples, solid symbols - 288 and 360 samples).

The sample entry nozzles for all the Soviet samplers and for the Brink impactors were straight while "buttonhook" nozzles were used with the Andersen impactors. The particulate which was recovered from the sampling nozzles was added to the cyclone or first-stage collection in all cases. Filter catches and cyclone or first-stage catches were omitted in all the differential size-distribution data plots because of the difficulty in assigning a representative particle size to them.

Sampling rates and gas volumes sampled were determined with orifice meters and stopwatches for the Soviet equipment and the Brink impactors, while orifice meters and dry gas meters were used with the Andersen impactors. Calibrations of the Soviet orifice meters with a dry gas meter at the test site subsequent to the actual testing determined that the Soviet orifice meter used at the inlet indicated 9 percent less than the true flow, and the outlet orifice meter, as used, indicated 19 percent less than the true flow. The flow rates and all concentrations and size cuts reported herein have been adjusted to account for this discrepancy.

In addition to the complete set of plotted data, Appendix J contains a tabulation of data and results by run after all corrections for flow rate, temperature, and other physical parameters were made. Corrections were also made for gas phase interferences by subtracting the appropriate blank or control correction from each stage weight. Appendix J reports the average weight changes and standard deviations for the blank, or control, runs. Unfortunately, a single homogeneous batch of impaction substrates was not available from the manufacturer for use with the Andersen impactors. As a result, the data for the last 2 days of testing with these impactors were somewhat confused by intermixing of two different substrate sets, one of which was much more reactive with the flue gas than the other. This can readily be seen in the data from the final Andersen blank runs in Appendix J. Correction of the Andersen data for the final 2 days of testing was difficult because of this mixing of the materials, and the proper corrections may not have been applied for all stages for these runs although best judgment was used to correct for gas phase interference as accurately as possible.

The stage cut sizes (diameters for 50 percent collection) were based on Southern Research Institute calibrations for the Andersen and Brink impactors and on Soviet calibrations for the Soviet devices. All cut sizes were calcu-

lated on the basis of unit density spheres, thus the reported values are aerodynamic diameters. Calibration of the Andersen has shown that cut sizes of the first and second stages are much closer than theory predicts. This feature results in an anomalous spike in the differential mass distribution plot if normal calculation methods are used. To avoid this anomaly, the second and third stages were lumped together to calculate the differential mass distribution. In Appendix J, the lumped geometric mean diameter and resulting differential mass distribution value are shown adjacent to the uncorrected result. The lumped values were used in all differential mass distribution plots.

Data obtained with the Soviet series cyclones are included in Appendix J. However, because the data are not amenable to the same treatment as impactor data and no data reduction techniques were provided, the cyclone results are not shown on the figures in this section. Preliminary analysis of some of the cyclone data indicated general agreement between that data and the data obtained from the impactors.

A summary of total particulate mass concentrations as determined with the various particle sizing devices and with the total mass devices is given in Table 8. Fractional efficiencies derived from the Brink and Andersen impactor data (excluding anomalous extreme values) are shown in Figure 21. The outlet data, especially the high concentrations of large particles obtained with both the Soviet and U.S. devices, indicate that rapping reentrainment losses in this precipitator contribute significantly to the overall emissions.

FLY ASH RESISTIVITY DETERMINATION

The results of the fly ash resistivity tests conducted with the Southern Research Institute point-to-plane probe are presented in Table 9. The average value of the resistivity during the test period was 1.9×10^{10} ohm-centimeters.

SULFUR DIOXIDE AND SULFUR TRIOXIDE DETERMINATIONS

Sulfur oxide tests were performed at the precipitator inlet ducts using the U.S. EPA Method 8 test apparatus. Six tests were performed, coinciding with the first six particulate mass tests performed on the precipitator. On a dry basis the sulfur trioxide results averaged 2.38 ppm by volume with a standard deviation of 1.91 ppm, and the sulfur dioxide concentration averaged

TABLE 8. AVERAGE PARTICULATE MASS LOADINGS BY SAMPLING DEVICE

Inlet

Device	U.S. mass train		U.S.S.R. mass train		Brink	Soviet Model I	Soviet Model II	Soviet cyclone
	All runs	Runs 6,7,8	All runs	Runs 6,7,8				
Grand average (mg/ACM)	4,942	4,931	3,815	5,348	3,244	10,491	4,794	4,596
Standard deviation (mg/ACM)	319	473	1,350	742	828	11,336	1,635	1,613
Average omitting extremes (mg/ACM)*	4,918	-	3,660	-	3,254	5,832	4,424	4,136

Outlet

Device	U.S. mass train		U.S.S.R. mass train		Andersen	Soviet Model I
	All runs	Runs 6,7,8	All runs	Runs 6,7,8		
Grand average (mg/ACM)	15.06	12.22	30.86	27.25	5.47	6.90
Standard deviation (mg/ACM)	3.85	1.26	11.27	7.09	1.88	5.02
Average omitting extremes (mg/ACM)*	14.61	-	28.39	-	5.49	6.09

*The single highest and single lowest values omitted in each case.

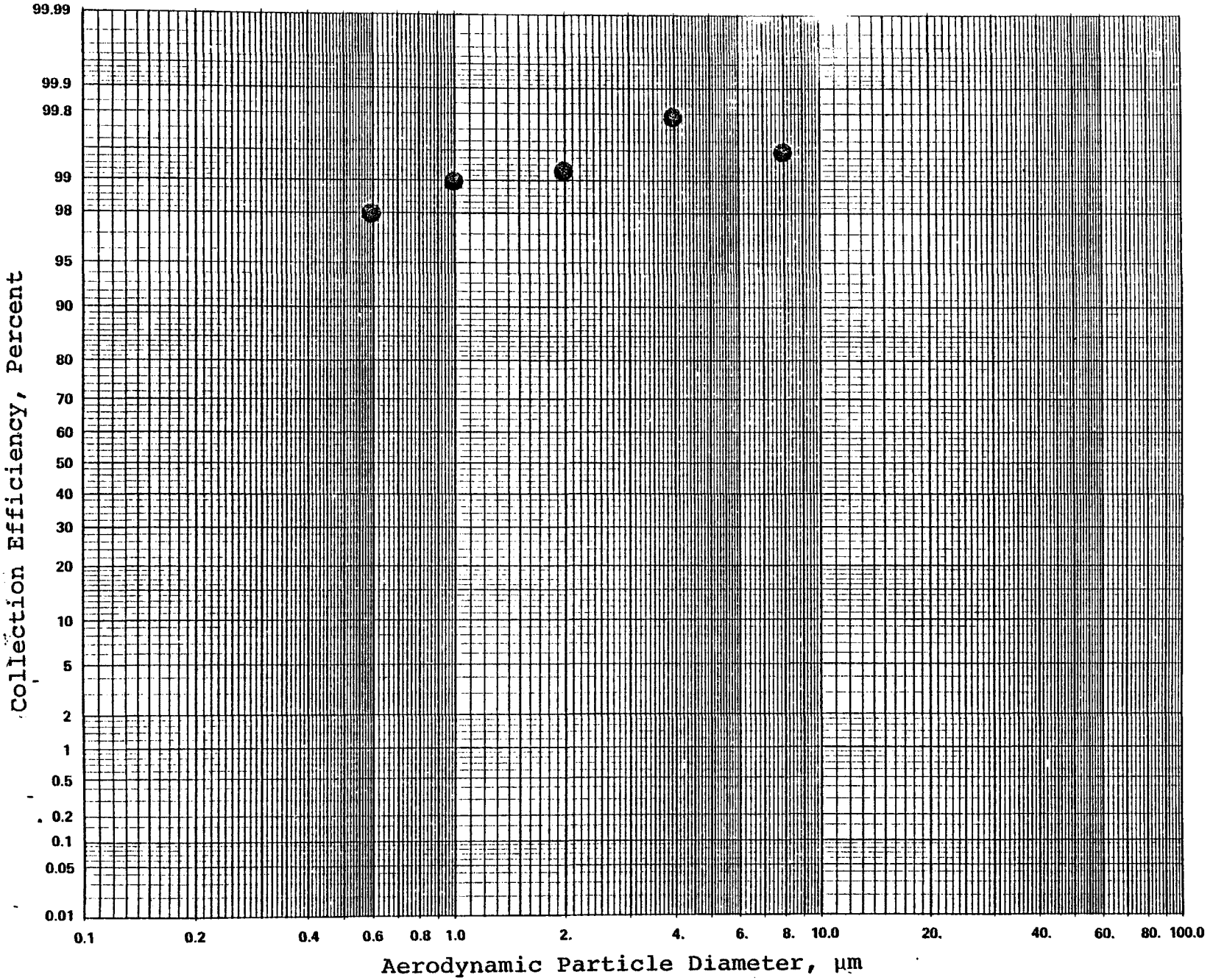

Figure 21. Precipitator fractional efficiency from Brink and Andersen data.

TABLE 9. FLY ASH RESISTIVITY RESULTS

Date	Time	Gas Temperature (°C)	Resistivity (Ω-cm)
3/13	0900-1000	347	3.5×10^{10}
	1000-1100	349	1.2×10^{10}
3/16	1445-1545	342	1.5×10^{10}
3/17	1030-1130	344	3.6×10^{10}
3/18	1030-1130	346	1.5×10^{10}
	1230-1330	345	1.4×10^{10}
	1430-1530	343	1.3×10^{10}
	1645-1745	343	1.2×10^{10}

818.2 ppm with a standard deviation of 124.0 ppm. Table 10 reports the results of each test.

RESULTS OF BASIC CORONA TESTING

The Soviet method of evaluating the effects of back corona by studying the voltage/current relationship of the precipitator produced no evidence of back corona at Allen Unit 3. The V-I data are shown for reference in Appendix Q.

GAS AND COAL ANALYSES - THEORETICAL GAS VOLUME

Theoretical gas volumes (TGV) were calculated from the ultimate and proximal coal analysis, gas composition (Orsat) data, and coal flow rate. The coal analyses are presented in Table 11. The moisture of the coal is reported as received by York Research Corporation after preparation at Plant Allen. TGV calculations assumed that the moisture of the coal entering the burners of Unit 3 on a given day was the same as the moisture of the corresponding sample.

Results of the TGV calculations are presented in Table 12 and compared with measured gas volumes. The tests were performed on ducts B1 and B2, which comprise 50 percent of the total duct cross-sectional area at the test location. The calculated gas volume is 50 percent of the total volume of flue gas entering the Unit 3 precipitators. The TGV's are also based on an assumed coal flow rate which was calculated using an average heat rate supplied by Duke Power. The assumption was necessary because there were no coal feed

TABLE 10. SULFUR OXIDES TEST RESULTS

Test no.	Date	Time start	Gas Flow Standard DNCMM	Gas Flow Standard DSCFM	Gas Flow Actual ACMM	Gas Flow Actual ACFM	SO_3 Emission ppm	SO_3 Emission kg/hr	SO_3 Emission lb/hr	SO_2 Emission ppm	SO_2 Emission kg/hr	SO_2 Emission lb/hr
1	3/12	1405	6,074	214,494	13,927	491,831	4.16	5.06	11.15	819.8	796.65	1,756.28
2	3/13	1053	5,093	179,849	11,488	405,710	1.77	1.80	3.98	627.3	511.11	1,126.79
3	3/15	1027	4,741	167,428	10,896	384,779	5.37	5.09	11.23	991.5	752.09	1,658.05
4	3/16	1018	5,052	178,413	11,698	413,097	.933	.94	2.08	906.4	732.58	1,615.04
5	3/17	0950	4,883	172,451	11,324	399,915	.942	.92	2.03	780.5	609.78	1,344.32
6	3/18	1137	4,782	168,887	10,931	386,029	1.10	1.06	2.33	783.6	599.53	1,321.72

TABLE 11. COAL ANALYSIS

Test no.	Btu/lb Dry	Btu/lb As rec'd	% Ash Dry	% Ash As rec'd	%S Dry	%S As rec'd	%N Dry	%N As rec'd	%C Dry	%C As rec'd	%H Dry	%H As rec'd	$\%H_2O$
1	12,535	12,344	14.67	14.45	1.04	1.02	1.39	1.37	72.61	71.51	4.83	4.76	1.52
2	12,627	12,473	13.64	13.47	1.01	1.00	1.32	1.30	72.68	71.79	4.85	4.77	1.22
3	12,559	12,338	13.41	13.23	0.98	0.97	1.30	1.28	73.13	72.14	4.85	4.78	1.36
4	12,540	12,397	14.05	13.89	0.99	0.98	1.42	1.40	72.02	71.20	4.76	4.71	1.14
5	12,429	12,296	14.09	13.94	0.98	0.97	1.37	1.36	72.45	71.67	4.85	4.80	1.07
6	12,650	12,502	13.56	13.40	0.97	0.96	1.38	1.36	72.78	71.93	4.93	4.87	1.17
7 & 8	12,453	12,315	13.17	13.02	0.94	0.93	1.37	1.35	73.35	72.53	4.93	4.88	1.11

TABLE 12. MEASURED AND THEORETICAL GAS VOLUMES

Test no.	Date	Time start	Measured gas flow* Soviet DNCMM	Measured gas flow* Soviet ACMM	Measured gas flow* EPA Method 5 DNCMM	Measured gas flow* EPA Method 5 ACMM	TGV calculation's† DNCMM	TGV calculation's† ACMM
1	3/12	1405	5,859	13,089	5,061	11,658	6,947	16,034
2	3/13	1030	5,376	12,548	4,950	11,548	6,940	16,038
3	3/15	1000	5,200	11,683	4,982	11,355	6,846	15,635
4	3/16	0948	5,292	12,226	4,749	11,133	7,185	16,785
5	3/17	0918	5,257	12,147	4,905	11,375	7,054	16,277
6	3/18	1046	5,335	12,214	5,084	11,572	6,668	15,310
7 & 8	3/19	1009	4,991	11,443	5,277	12,232	7,031	16,126

*Measured flow through inlet ducts B1 and B2 which comprise 50 percent of the total cross-sectional duct area entering the precipitator.

†Fifty percent of total calculated gas flow entering the precipitator.

scales located at the Allen Steam Plant. The TGV calculations indicate that the total gas flow might not be equally distributed to the four ducts entering the precipitator. Complete computer summary sheets of each test can be found in Appendix O.

FLY ASH ANALYSIS

Results from the chemical analysis of the combined fly ash samples are presented in Table 13. As stated in Section 3, each test sample was made up of a composite of fly ash collected from the two boilers associated with Unit 3. There is no assurance that the collected fly ash was identical in size distribution to the ash entering the precipitator. Since chemical analysis of fly ash is known to depend to some extent on the particle size, the results may not be precisely indicative of the composition of ash collected by the precipitator or of the small quantity of ash contained in the stack gas.

TABLE 13. FLY ASH CHEMICAL ANALYSES (all results in percent of total mass)

Test no.	1	2	3	4	5	6	7	8
Loss on ignition	2.64	2.18	5.11	2.80	2.84	2.25	2.48	5.21
SiO_2	55.91	55.89	54.30	55.56	55.92	55.63	56.37	54.77
Al_2O_3	27.20	28.95	28.85	28.63	28.68	27.69	28.53	29.87
Fe_2O_3	8.41	7.90	7.21	7.60	7.77	9.17	7.67	6.23
TiO_2	1.51	1.05	0.92	1.34	1.13	1.05	0.78	0.94
CaO	1.16	1.05	0.92	1.17	1.08	1.26	1.11	1.16
MgO	0.92	0.77	0.74	0.74	0.73	0.92	0.95	0.87
Na_2O	0.46	0.49	0.45	0.50	0.47	0.52	0.51	0.47
K_2O	1.09	1.28	1.08	1.06	0.78	1.06	1.07	0.84
Li_2O	0.032	0.033	0.034	0.032	0.029	0.030	0.028	0.026
SO_3	0.40	0.15	0.16	0.20	0.25	0.14	0.20	0.26
P_2O_5	0.34	0.33	0.30	0.37	0.36	0.38	0.35	0.33
Total	100.07	100.07	100.07	100.00	100.04	100.10	100.05	100.98

TECHNICAL REPORT DATA
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16. ABSTRACT The report describes a U.S./USSR cooperative test program to quantify and characterize particulate emissions from a U.S. coal-burning power plant boiler, equipped with a hot-side electrostatic precipitator, at Duke Power Co.'s Allen Steam Station in March 1976. U.S. and Soviet equipment and procedures were used to determine flue gas composition and velocity, total particulate mass concentration of the gas stream, particle size distribution, electrical resistivity of the particulate entering the precipitator, evidence of back corona in the precipitator, SO2 and SO3 concentrations in the flue gas, and chemical composition of the fuel and fly ash. The test site and test procedures are described. Results of the comparative tests are presented and discussed. In 1972, the U.S. and the USSR signed a bilateral agreement pledging cooperation on environmental protection. As part of this agreement, the Working Group on Stationary Source Air Pollution Control was subsequently formed by the U.S. EPA and the USSR Research Institute of Industrial and Sanitary Gas Cleaning to conduct cooperative programs in several areas of air pollution control technology, including particulate emission control. This is one of those cooperative programs.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Boilers	Air Pollution Control	13B	13A
Electrostatic Precipitators	Electric Power Plants	Stationary Sources Particulates		10B
Flue Gases	Sulfur Oxides	Back Corona	21B	07B
Dust	Electrical Resistivity		11G	
Coal	Fly Ash		21D	20C
Coronas				

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