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SAMPLING INTERFACE FOR THE QUANTITATIVE TRANSPORT OF AEROSOLS

Field Prototype

by

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ABSTRACT

Deposition of particles in conventional sampling probes precludes their use with continuous monitors. The transpiration of air through the probe wall has been shown to be effective in significantly reducing deposition during the quantitative transport of particles up to 50 μm. The purpose of the present contract was to develop the transpiration concept into a field-usable prototype.

A sampling nozzle with a 90° bend and incorporating a porous wall tube through which clean air could be transpired was designed, fabricated, and tested in the laboratory with model aerosols. A coordinated testing program for the nozzle and the experimental probe was also conducted.

Based on the laboratory test results, the final prototype was designed and fabricated. The prototype consisted of a sampling probe and a control box housing necessary air supply and auxiliary instrumentation.

The prototype was evaluated in the field at two sites at the Will County Power Station of Commonwealth Edison. The first site represented a coal-fired power plant emissions following a hot electrostatic precipitator. The second site represented a coal-fired power plant emissions following a wet scrubber. The test results show that the prorotype is efficient in transporting

the particles in these effluents. Transport efficiencies greater than 95% were obtained with transpiration air to sample flow ratio of 2 to 1 for the front section of the probe.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

SAMPLING INTERFACE FOR THE QUANTITATIVE TRANSPORT OF AEROSOLS

INTRODUCTION

In the sampling of particulate emissions, the aerosol must be transported from the source to the sensor with a minimum of deposition, agglomeration, and reentrainment enroute. Particle losses to and reentrainment from conventional probe walls can be excessive.

The Fine Particles Research Section of IIT Research Institute developed a sampling interface which permits transport of aerosols without modification of the total mass rate and size distribution of the source aerosols. This program was sponsored by EPA under Contract No. 68-02-0579. The probe consists of a porous metal tube encased in a manifold through which transpiration air is passed inward to provide a moving clean air sheath that minimized particle deposition on the walls. The efficiency of the probe to transport an aerosol ranging in size from 0.05 to 50 μm was demonstrated in a statistically designed test program. The results of this program are available in the final report.[1]

The purpose of the present program was to apply the knowledge gained in the development of the experimental probe to a field operable sampling interface. The experimental probe consisted of only a straight run of the encased porous

1. Sampling Interface for Quantitative Transport of Aerosols. Prepared by IITRI for EPA, #EPA-650/2-74-016 (1973).

tube. In order to sample out of a stack, the probe must include a 90° bend. The standard gooseneck nozzle used with conventional probes suffers from deposition like the conventional probes. Extending the porous tube and transpiration idea to the bend was considered to be most effective in preventing deposition. Under this program, a 90° bend using the porous internal tube was designed and fabricated. It was then tested to determine its efficiency in transporting the particles in the range 0 to 10 μm. The bend was tested separately, as well as attached to the experimental probe.

A final design of the prototype sampling interface containing the probe, an air supply system for transpiration, and a control box was developed to meet the specifications listed in Table 1. The bend was fabricated and the experimental probe was modified to withstand temperatures upto 700°F and to meet the other specifications in Table 1.

The probe was tested in laboratory and in the field. The sampling sites consisted of two stacks of a coal-fired power plant. One of the stacks followed a hot electrostatic precipitator; and the other stack followed a wet scrubber.

The laboratory and field tests showed that the sampling probe could be used for several hours with insignificant deposition of particles in the lines.

Table 1. PERFORMANCE SPECIFICATIONS FOR SAMPLING INTERFACE

Aerosol concentration range	10^2-10^8 particles/cm^3
Aerosol size range	0.05-10 μm
Sampling rate	7.1-28.3 lpm (0.25-1.0 cfm)
Sampling temperature	Ambient to 300°C (572°F)
Sampling probe	1.29 cm I.D. (1/2 in. I.D.) x ∿180 cm (6 ft) long
Sampling nozzles	0.63, 0.95, and 1.29 cm I.D. (1/4, 3/8, and 1/2 in. I.D.)
Sampling requirements	Isokinetic sampling
	90° bend
	Minimum diameter of sampling port compatible with the probe -- 10 cm (4 in.)
	Probe to be heated to at least 150°C (300°F) to prevent water condensation
Transpiration rate	Up to 142 lpm (5 cfm)

CONCLUSIONS

The concept of the transpiration probe was extended to design and fabricate a sampling interface that could be used to transport particulate matter from stacks to a measuring device with minimal deposition. In this program, the following significant results were obtained.

1. The transpiration concept was extended to form a sampling nozzle with a 90° bend. This design significantly reduced the loss of particles compared to the standard goose-neck nozzle. The extent of deposition was dependent on the transpiration rate in the nozzle section and was reduced as the transpiration rate was increased.

2. Due to the high transpiration rate in the front section, deposition in the rear section was significantly reduced. Consequently, less transpiration rate was required in the rear section.

3. The laboratory interface was developed into an interface usable in actual stacks having temperatures of up to 371°C (700°F).

4. The field prototype was evaluated at two sites and showed that it can be used to efficiencly transport the particles uptp 60 μm in size.

5. The tests with the scrubber effluent showed that the interface could be used for sampling in the presence of water droplets.

RECOMMENDATIONS

Further testing of the sampling interface should be aimed at adapting the interface with continuous monitors. In addition, the interface has a potential for conditioning of the particulate samples in a controlled manner to study the interaction of the particulate matter with the atmospheric components.

Development of a flow measurement device that can be placed inside the sampling nozzle will avoid errors in calculating the sample flow rate by difference in the transpiration and the total flow rates. Such a flow measurement device should not hinder the flow of the sample. Use of a null type sampling nozzle should also be investigated to achieve the accuracy in the sample flow calculations.

DESIGN OF THE 90° BEND

In conventional sampling situations, the sampling probe is inserted into the stack through ports in the wall. The ports are usually 10 cm (4 in.) diameter circular openings. The sample flow must be in the direction of the stack flow. he sample stream, therefore, must be turned by 90° in the sampling probe. Many conventional probes use a gooseneck nozzle shown in Figure 1. Considerable loss of the particulate sample occurs in this type of nozzle. Minimizing the deposition losses in the nozzle should result by extending the idea of the internal porous tube to the 90° bend.

Fabrication of the 90° bend with the porous inner tube, such that the entire front end of the probe would pass through a 10 cm (4 in.) port, was a challenging problem. Attempts at bending the porous tube were unsuccessful even for a large radius bend. One approach for obtaining the bend was to join tube pieces to form an arc. The 90° bend would be formed by welding the pieces together. This may result in some blind areas around the joins where the transpiration air would not reach. However, this arrangement would certainly be an improvement over the present conventional gooseneck bends. The number of pieces used to make the bend is also important. If only a few pieces were used, the aerosol flowing in the bend would have rather sharp turns. On the other hand, if too many pieces were used, the area available for the transpiration flow would be greatly reduced.

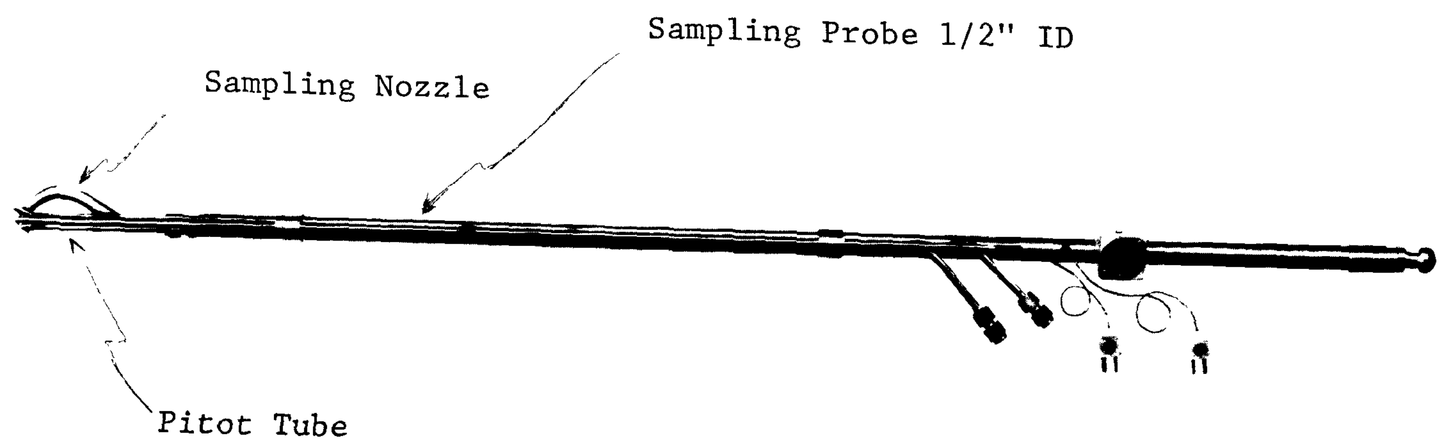


Figure 1

CONVENTIONAL SAMPLING PROBE

We decided to use 10° segments for making the bend as shown in Figure 2. For preliminary experiments, the sections could be joined by gluing them. For final prototype, the sections were welded.

The 90° bend section was designed to have an independent transpiration air supply. In the earlier program[1] a higher rate of transpiration in the rapidly established the air sheath around the sample, and reduced the deposition at the entrance. To achieve this feature, the separateness of the front and back section transpiration air was essential. In addition, the nominal pore size of the porous tube used for the 90° bend was chosen 5 μm instead of the 2 μm nominal pore size of the back section porous tube. The assembly of the front section is shown in Figure 3. The sampling nozzles were interchangable. Coupling the front section to the rear section was achieved with minimum loss of transpiration air, so the clean air sheath around the sample stream would be preserved.

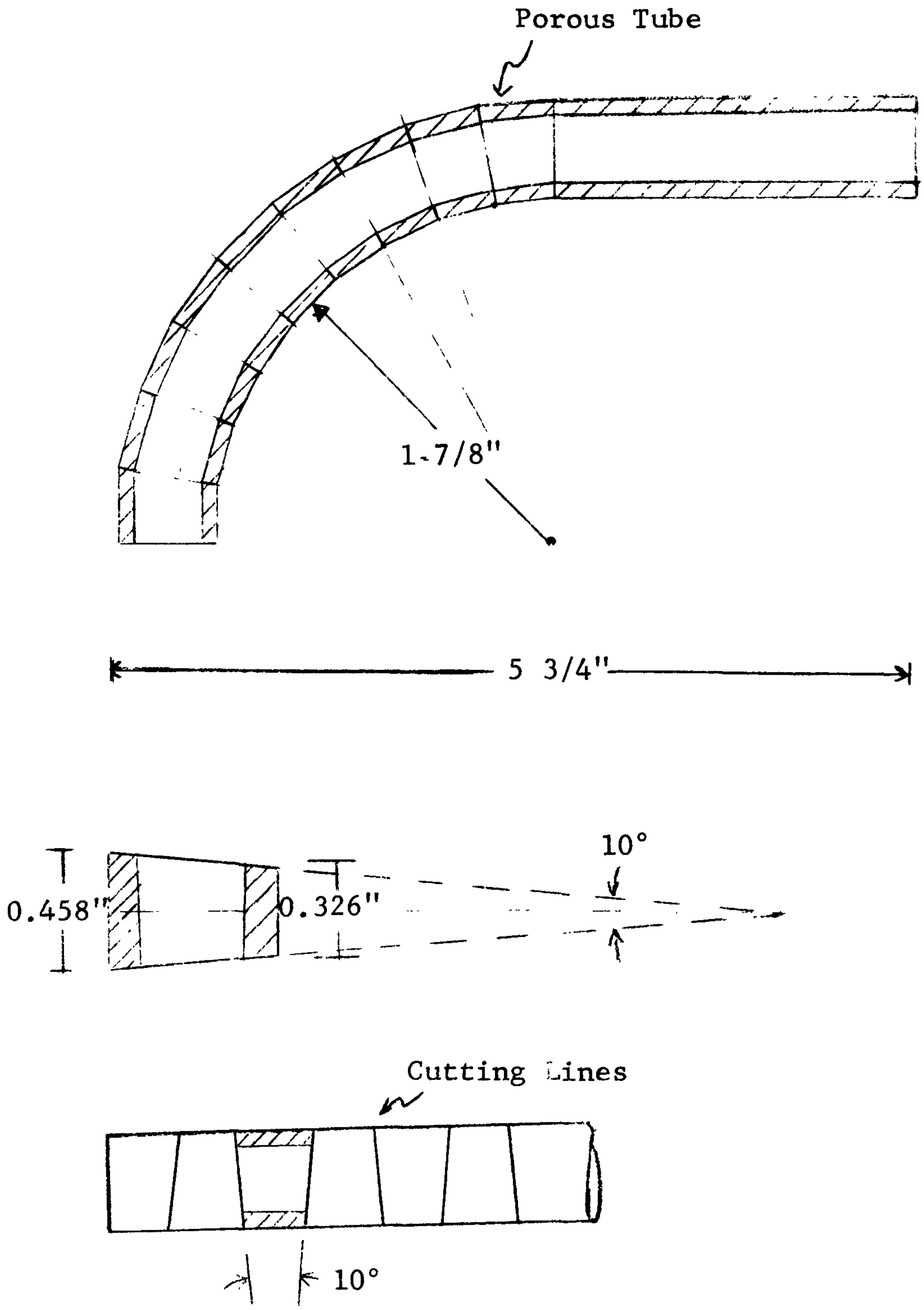


Figure 2

CONSTRUCTION DETAILS OF THE POROUS BEND

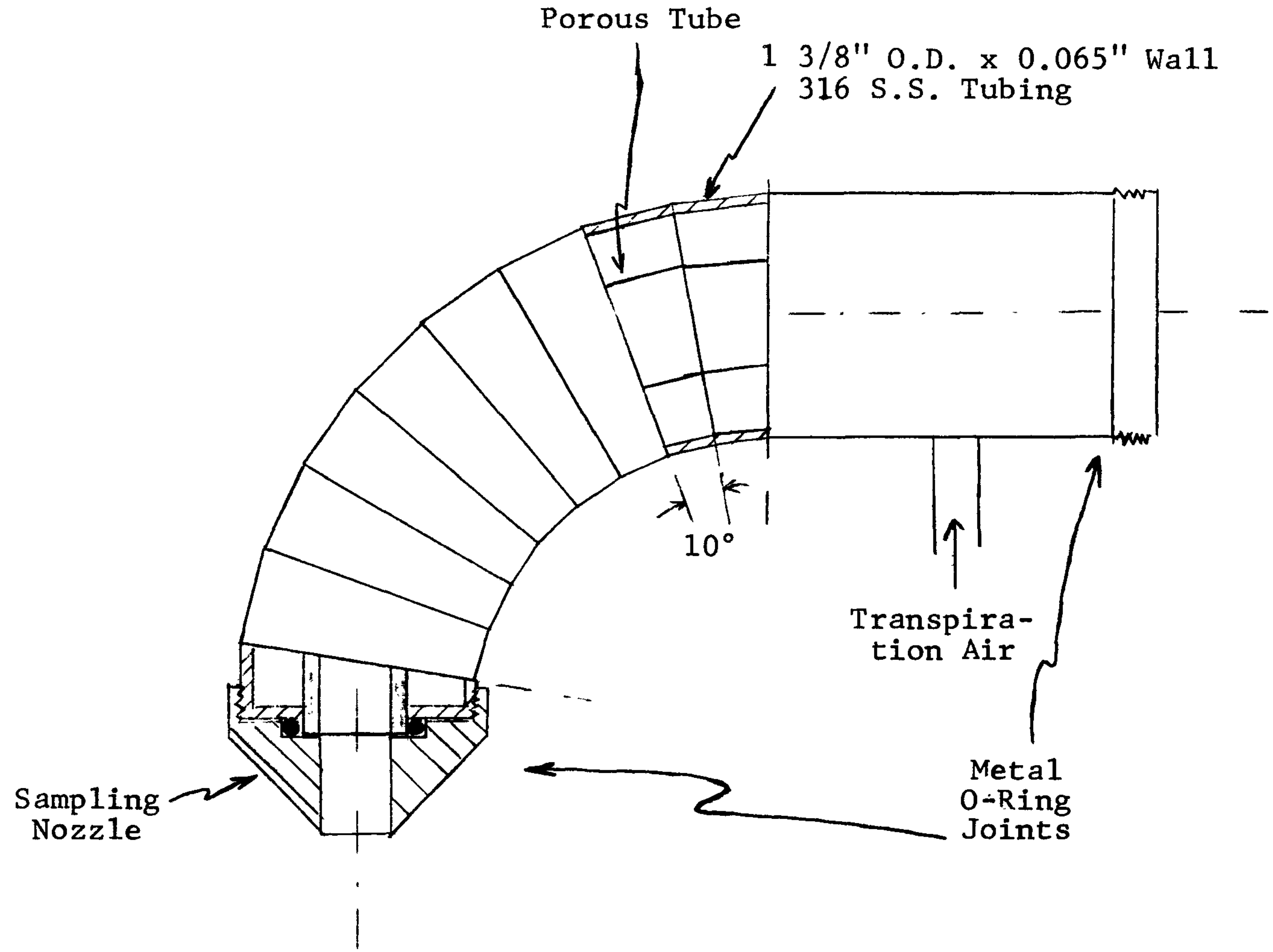


Figure 3

FRONT SECTION WITH 90° BEND

LABORATORY TESTING

The sampling probe was tested in the laboratory with a uranine aerosol. The uranine aerosol was generated according to the procedure described in the previous final report.[1] Uranine powder in the 5-50 μm size range was dispersed in an aerosol form from the generator shown in Figure 4.. Part of the aerosol was sampled by the probe section in the test set-up sketched in Figure 5.

For some of the tests, the upper size of the aerosol was limited to 10 μm with a small cyclone used to remove larger particles before sampling by the probe section.

As described in the previous final report,[1] the effects of the particle size and the transpiration air on the deposition of particles in a 1.29 cm (1/2 in.) I.D. and 176 cm (70 in.) long porous tube (2 μm nominal pore size) were studied extensively. However, the main areas where further experimental verification was needed were the deposition and effect of transpiration air in the 90° bend front section; and the effect of varied transpiration rates in the front and rear sections.

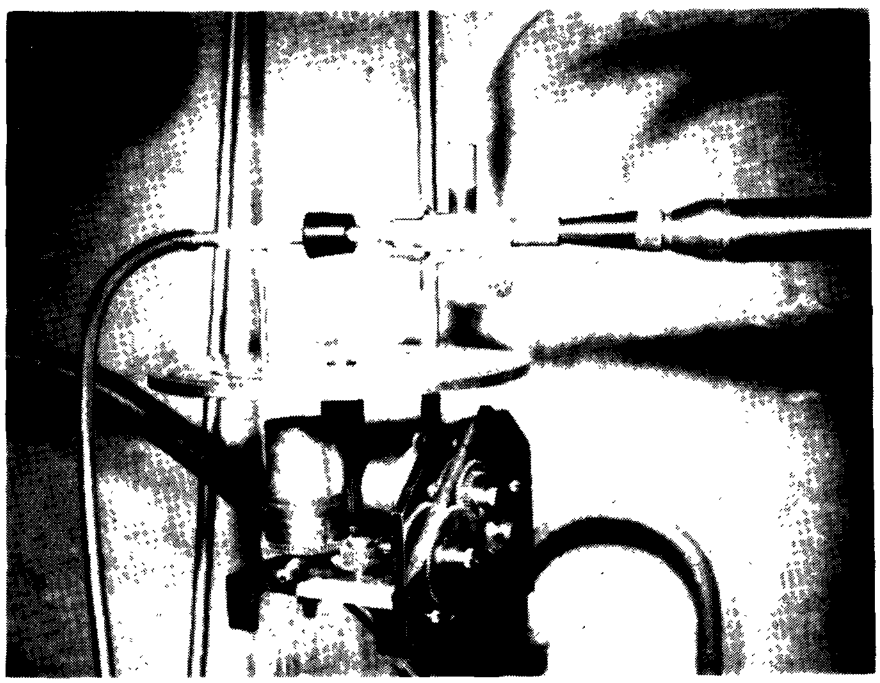


Figure 4

PHOTOGRAPH OF THE AEROSOL GENERATOR

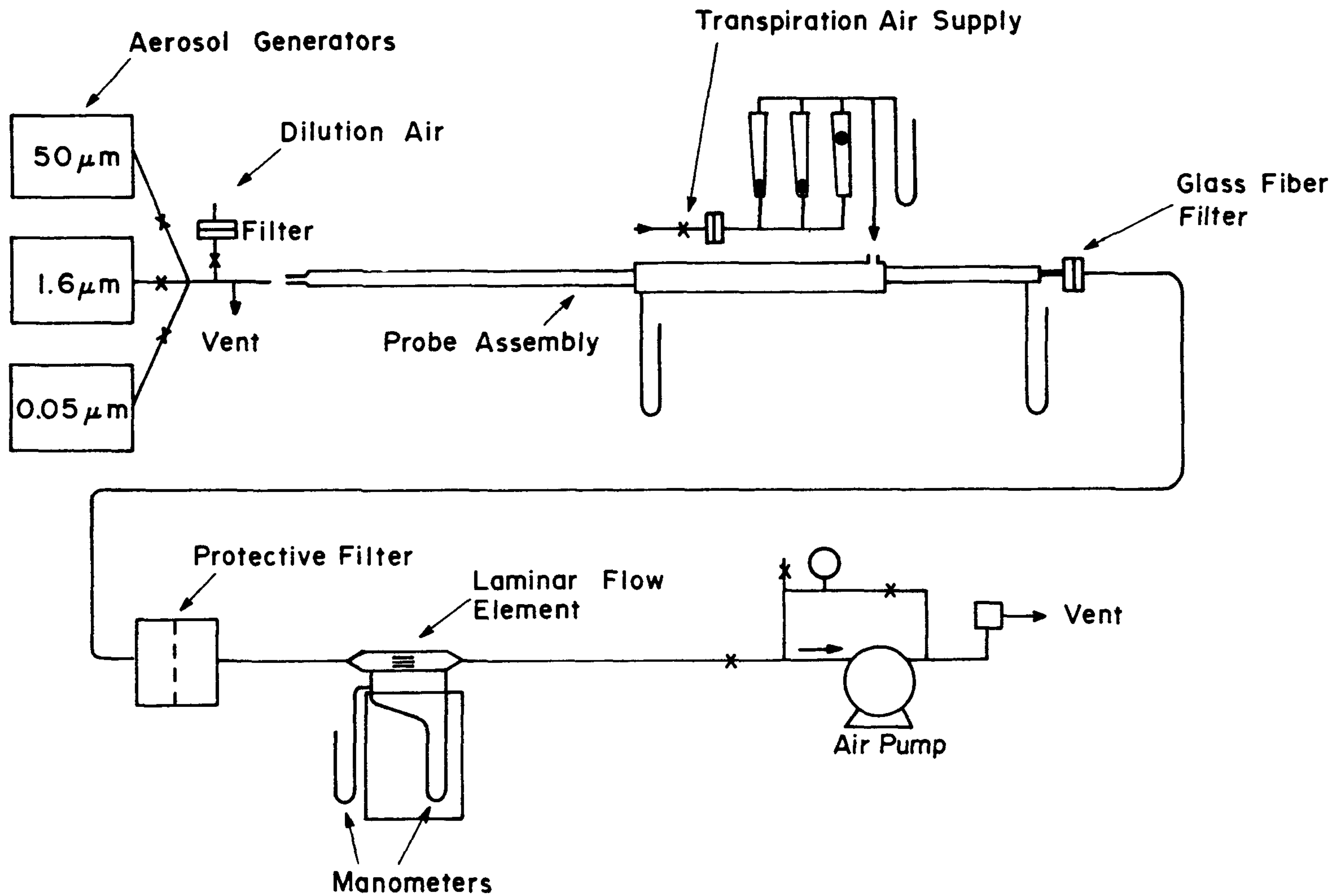


Figure 5

LABORATORY TEST FACILITY

TESTING OF THE 90° BEND

The set-up for the tests is shown in Figure 6. The test section was followed by a 10 cm (4 in.) glass fiber filter. The transpiration air was supplied through rotameters (Figure 5). The total flow rate through the section was monitored by noting the pressure drop across the laminar flow element. The details of the test procedure are described in the previous report.[1]

To begin the test, the transpiration flow was first established at the desired level. The aerosol generator was truned on. Flow through the laminar flow element was adjusted so that

Total flow rate = transpiration air flow rate
+ sample flow rate

The sample flow rate was checked at the beginning of the experiment with a wet test meter. The aerosol was sampled for a period sufficient to obtain a sample for analysis. The probe section and the filter were washed and the amount of uranine deposited was determined by a colorimetric method.[1]

The percent deposition values were calculated by the relation

$$\%\ \text{Deposition} = \frac{\text{mass of uranine in probe wash}}{\text{mass of uranine in (probe wash+filter)}}$$

For comparison, tests were also made to determine the extent of deposition in a standard 1.29 cm (1/2 in.) gooseneck nozzle and a bent impervious copper tube having the same

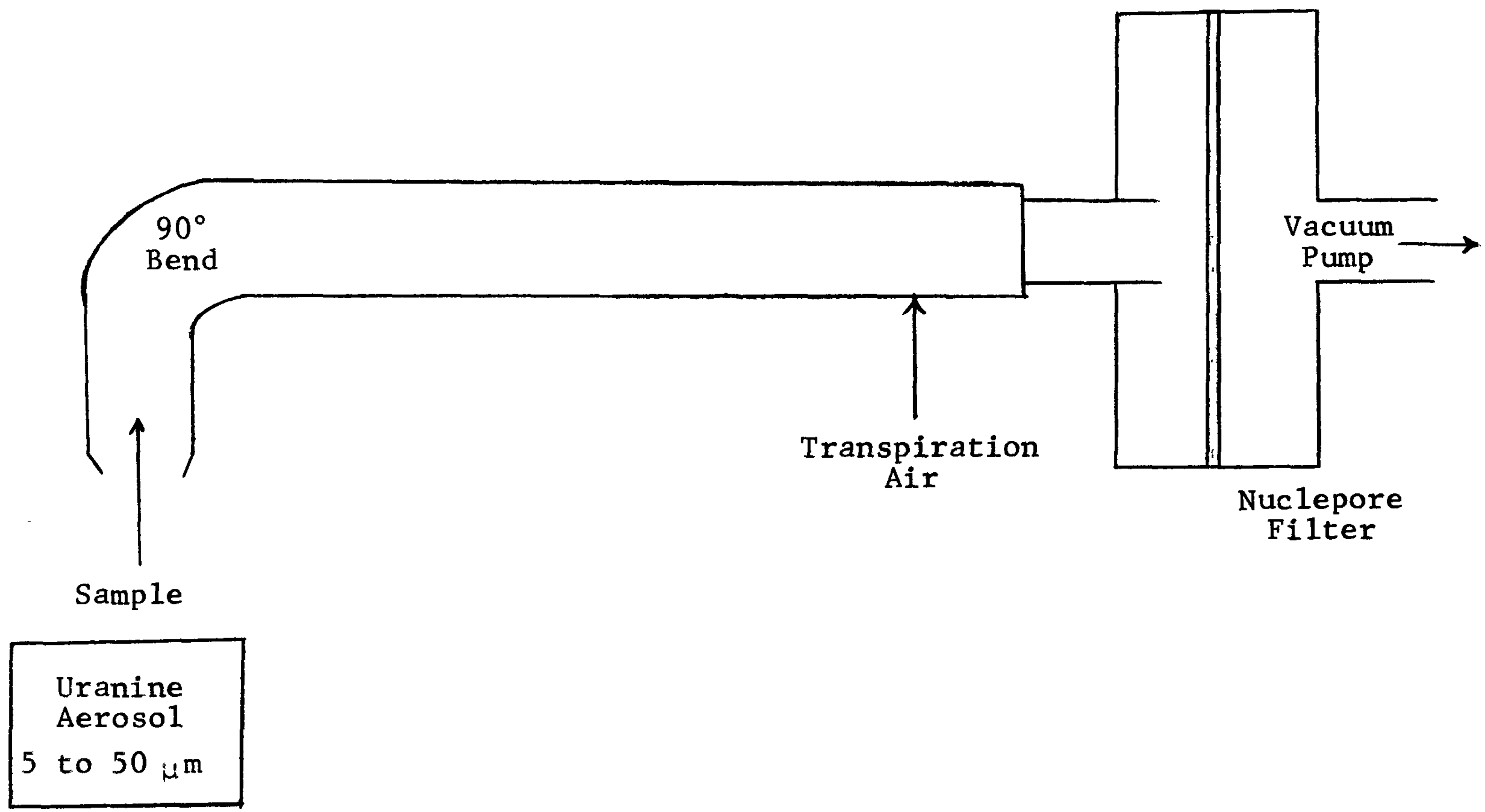


Figure 6

FACILITY FOR TESTING THE 90° BEND

internal diameter of 1.29 cm (1/2 in.) and having the same radius of curvature and length as the 90° bend with the porous tube. The results are summarized in Table 2.

The 90° bend, based on the transpiration principle, was effective in reducing the deposition significantly compared to both the impervious 90° bend of the same curvature and the standard gooseneck nozzle.

The extent of deposition of large particles is controlled by gravity and, as expected, the deposition increases with increasing sample velocity for the impervious bend and the gooseneck nozzle. In the porous bend at low levels of transpiration velocity, deposition was fairly high. At higher levels of transpiration velocity, the deposition was significantly reduced at the sample rates of 14.2 and 28.3 lpm (0.5 and 1 cfm, respectively). However, deposition was still high at the low sample rate of 7.1 lpm (0.25 cfm), indicating that the gravitational settling was not completely overcome.

COORDINATED TESTING

Deposition in the entire probe (with both the front and rear sections) was also experimentally studied. This was necessary to assess the effect of the varied transpiration rates in each section on deposition. The tests were conducted with 0-10 μm uranine powder. Since the data on the straight section, as obtained in the previous program,[1] were based on 50 μm particles, few tests with 0-10 μm particles were conducted with the straight probe only for comparison. The

Table 2. RESULTS OF MASS PRESERVATION TESTS WITH THE 90° BEND[a]

Sample flow rate, lpm (cfm)	Sample velocity, cm/sec	Transpiration flow rate, lpm (cfm)	Transpiration velocity, cm/sec	% Deposition in porous bend	% Deposition in impervious bend[b]	% Deposition in gooseneck nozzle[b]
7.1 (0.25)	93	2.83 (0.1)	47	26.4	81.5	72.0
7.1 (0.25)	93	14.2 (0.5)	233	7.0		
14.2 (0.5)	186	2.83 (0.1)	47	27.0	46.0	42.0
14.2 (0.5)	186	14.2 (0.5)	233	1.0		
28.3 (1.0)	372	2.83 (0.1)	47	23.6	9.8	2.2
28.3 (1.0)	372	14.2 (0.5)	233	1.0		

a) 0-50 μm uranine aerosol (concentration range -- 1-10 mg/lit).

b) No transpiration air.

results are presented in Table 3.

The results for the straight probe show that the deposition of 0-10 μm particles is low even with a very low transpiration air. At all sample rates, the results showed a similar trend of deposition in the two probe sections. Deposition in the front section was not affected when the front transpiration air was increased from 14.2 to 28.3 lpm (0.5 to 1.0 cfm). Deposition in the rear section was also similar for transpiration rates of 142 and 283 lpm (5 and 10 cfm).

The particle size of the aerosol in the coordinated tests were 0-10 μm, as compared to 0-50 μm for the tests with bend alone. The deposition in the front section at a flow rate of 14.2 lpm (0.5 cfm) was higher than corresponding results for the bend alone (Table 2). These results are consistent with the findings of the previous program.[1] Deposition of 50 μm particles was controlled by gravity and entrainment effects, and decreased as the sample and transpiration rates were increased. Deposition of intermediate size particles first decreased and then increased slightly as the transpiration rate was increased.

The results of the tests with 90° bend are informative for mostly the large particles, which contribute to the mass in the samples. In other words, at 14.2 lpm (0.5 cfm) and higher transpiration rates, the large particles are transported better than the intermediate sized particles. As pointed out from the size distribution data in the previous

Table 3. COORDINATED TESTINGS

Sample, lpm (cfm)	Transpiration Front, lpm (cfm)	Transpiration Back, lpm (cfm)	Deposition, % 90° Bend	Deposition, % Straight	Filter
0-10 μm Particles (1-10 mg/lit):					
7.1 (0.25)	14.2 (0.5)	142 (5)	4.2	0.5	95.3
7.1 (0.25)	14.2 (0.5)	283 (10)	5.1	0.8	94.1
7.1 (0.25)	28.3 (1.0)	142 (5)	4.4	0.4	95.2
14.2 (0.5)	14.2 (0.5)	142 (5)	6.2	2.4	91.4
14.2 (0.5)	14.2 (0.5)	283 (10)	2.3	1.1	96.6
14.2 (0.5)	28.3 (1.0)	142 (5)	5.6	4.3	90.1
28.3 (1.0)	14.2 (0.5)	142 (5)	4.6	0.4	95.0
28.3 (1.0)	28.3 (1.0)	142 (5)	5.0	1.2	93.8
Test with Straight Probe Only:					
14.2 (0.5)		142 (5)	---	0.86	99.14
28.3 (1.0)		142 (5)	---	0.64	99.36
28.3 (1.0)		28.3 (1)	---	0.83	99.17

program,[1] even this level of deposition for the intermediate sized particles does not affect the size distribution of the sample in a significant manner. Moreover, if only intermediate sized particles are present, the effect on size distribution will be minimal.

DESIGN OF THE SAMPLING INTERFACE

Based on the results of experiments under the present and the previous programs, the sampling interface was designed to meet the specifications listed in Table 1. In addition, the design specifications for larger aerosols (up to 50 μm) to be transported were also developed so that the fabricated prototype could be used at higher particle size ranges without substantial modifications.

In the design of the prototype, attention was given to simplicity of operation, ease of handling, and adaptability to coarser aerosols. The sampling interface consists of a sampling probe and the self-contained control box. A schematic drawing of the interface is shown in Figure 7. These components are described below.

SAMPLING PROBE

The sampling probe consists of a 1.9 cm (3/4 in.) O.D. porous walled tube encased in another solid tube through which the transpiration air is distributed. The probe consists of three parts: sampling nozzle, a front section with a 90° bend, and a straight section. Transpiration air in the 90° bend and the straight section is supplied independently. A discussion of the components is given below.

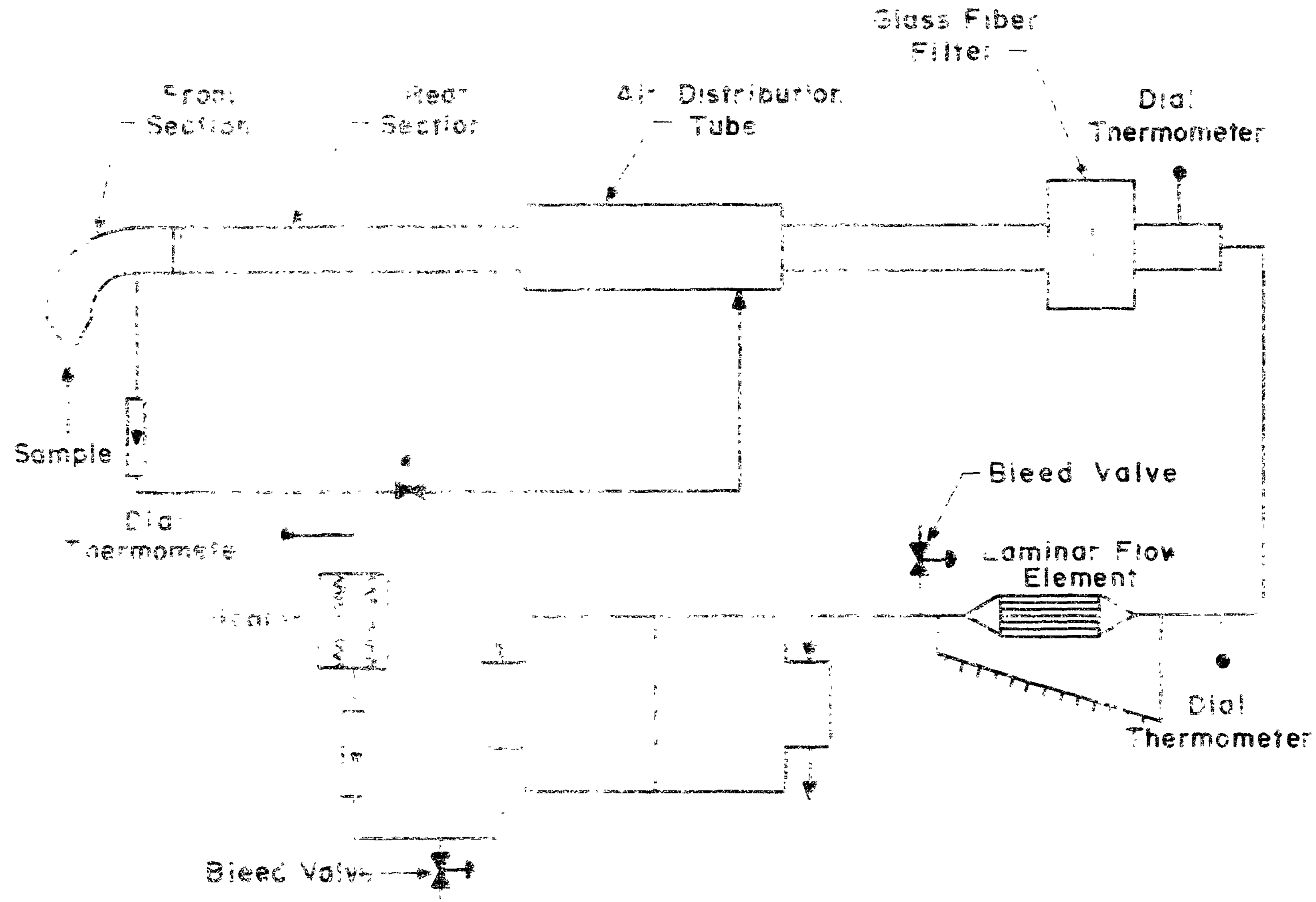


Figure 7

FLOW DIAGRAM OF PROTOTYPE SAMPLING INTERFACE

Sampling Nozzles

Three 316 S.S. nozzles shown in Figure 8 were fabricated. Nozzles with 0.65, 0.97, and 1.29 cm (1/4, 3/8, and 1/2 in., respectively) diameter openings were chosen for allowing isokinetic conditions in most stack sampling operations. The nozzles were designed with a blunt taper so that the probe assembly could be inserted into a 10 cm (4 in.) diameter opening. Nozzles with gentler taper may be fabricated for situations where the opening is considerably larger. However, the shortness of the nozzle has the advantage that only a small area of the probe assembly is without the transpiring air.

90° Bend Based on Transpiration Principle

The porous stainless steel tube could not be bent in a single piece. In addition, the bend had to be of such a curvature that the bend and the attached nozzle could be inserted through a 10 cm (4 in.) diameter opening. The 90° bend was accomplished by joining 10° segments of straight tube, as shown in Figure 9. The assembly of the porous tube and the outer tube is also shown in Figure 9. Transpiration air is supplied through a 0.63 cm (1/4 in.) diameter tube. The individual segments were welded together. The outer case was welded to the inner tube, as shown in Figure 9. The sampling nozzle with 0.62, 0.95, and 1.27 cm (1/2, 3/8, and 1/2 in., respectively) openings could be attached simply, as shown in Figure 9. A metal gasket is used to seal the nozzle-bend joint. A screw-on socket joint is used to connect the front and the back section.

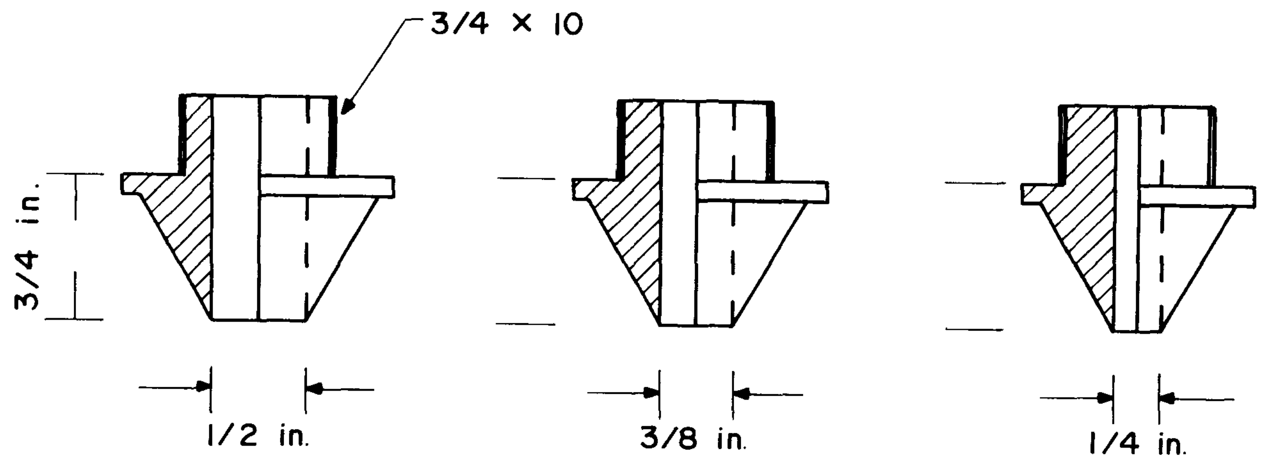


Figure 8

SAMPLING NOZZLES

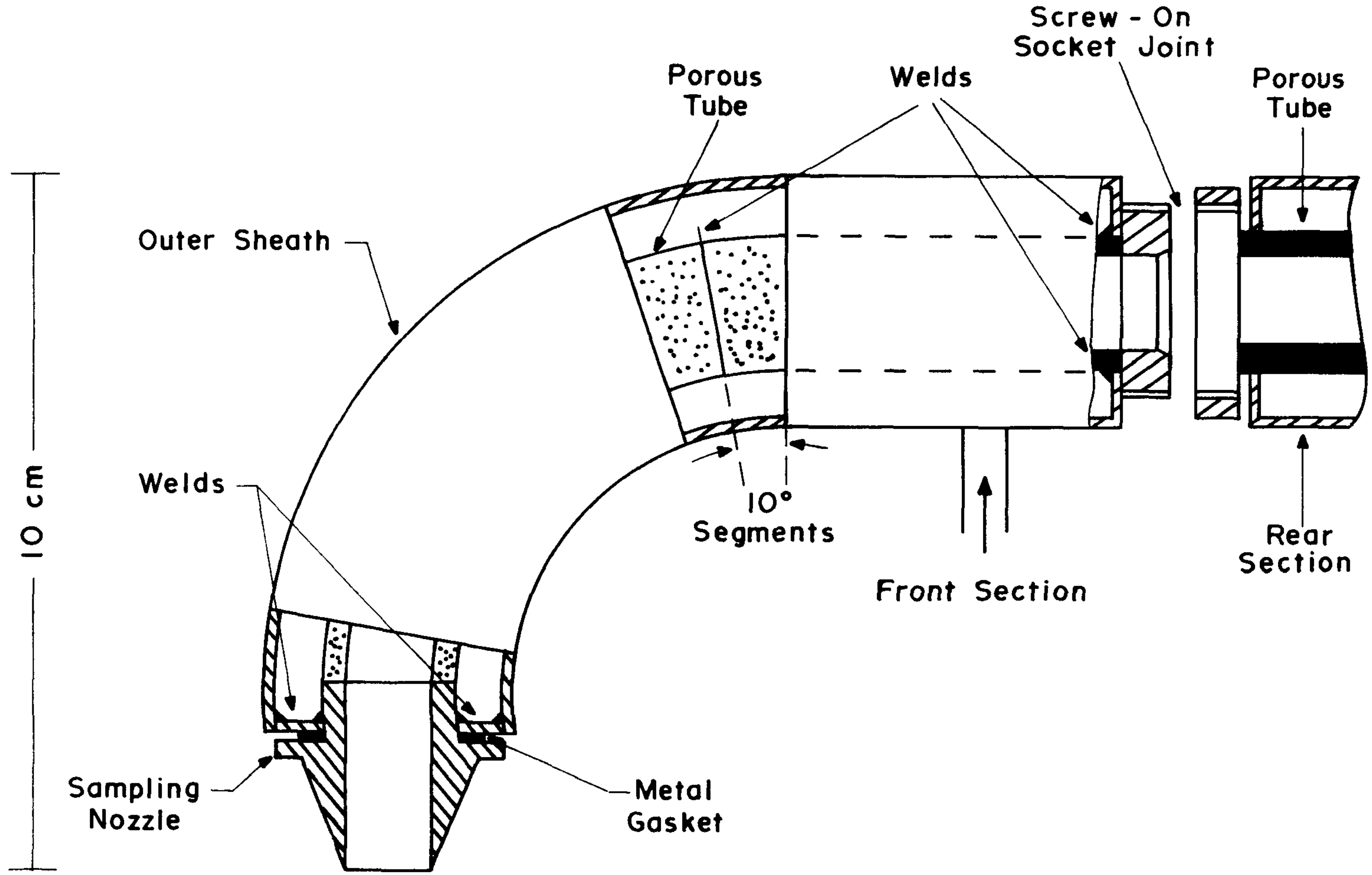


Figure 9

DETAILS OF THE FRONT SECTION

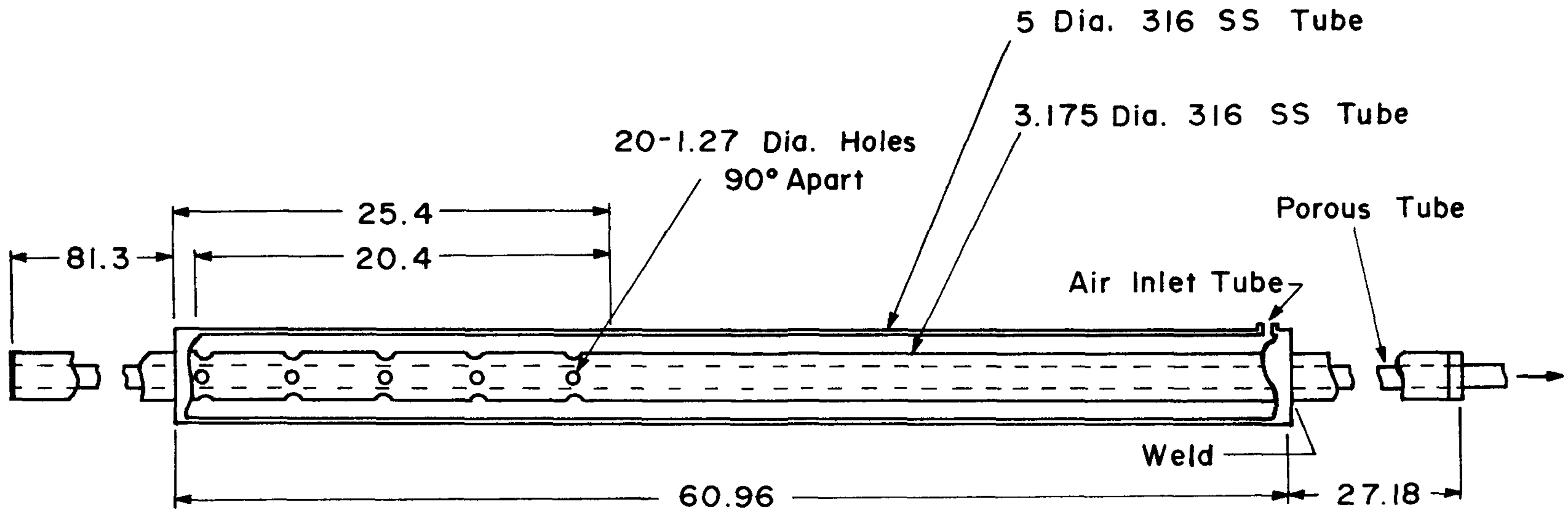
Straight Section of the Probe

The straight section consists of a 1.9 cm (3/4 in.) diameter and 178 cm (70 in.) long porous tube encased in a 3.2 cm (1-1/4 in.) O.D. tube. At the middle of the section, a 5 cm (2 in.) diameter by 61 cm (24 in.) long tube is used for distribution of transpiration air, as shown in Figure 10. A mating screw-type joint is used to join the front and the back sections.

CONTROL BOX

A control box for housing the auxiliary components and controls was designed. A flow drawing is shown in Figure 11. A combination vacuum pump and compressor unit was chosen to provide both the supply of the transpiration air and the suction for sampling.

Transpiration air is filtered at the pump intake. The air is pumped through a rotameter with a capacity of 0-470 lpm (0-1000 cfh). A bleed line before the rotameter is used for varying the flow through the rotameter. The air from the rotameter flows through an in-line heater. The air leaving the heater is divided into two transpiration air streams for the front and the rear sections. Tha air for the front section flows through another flowmeter and in supplied to the front section through Teflon® lined flexible hoses with a glass wool filter at the end. The air for the rear section is routed through a ball valve and is supplied to the rear section through another Teflon® lined hose.



All Dimensions In Centimeters

Figure 10

DISTRIBUTION OF TRANSPIRATION AIR FOR REAR SECTION

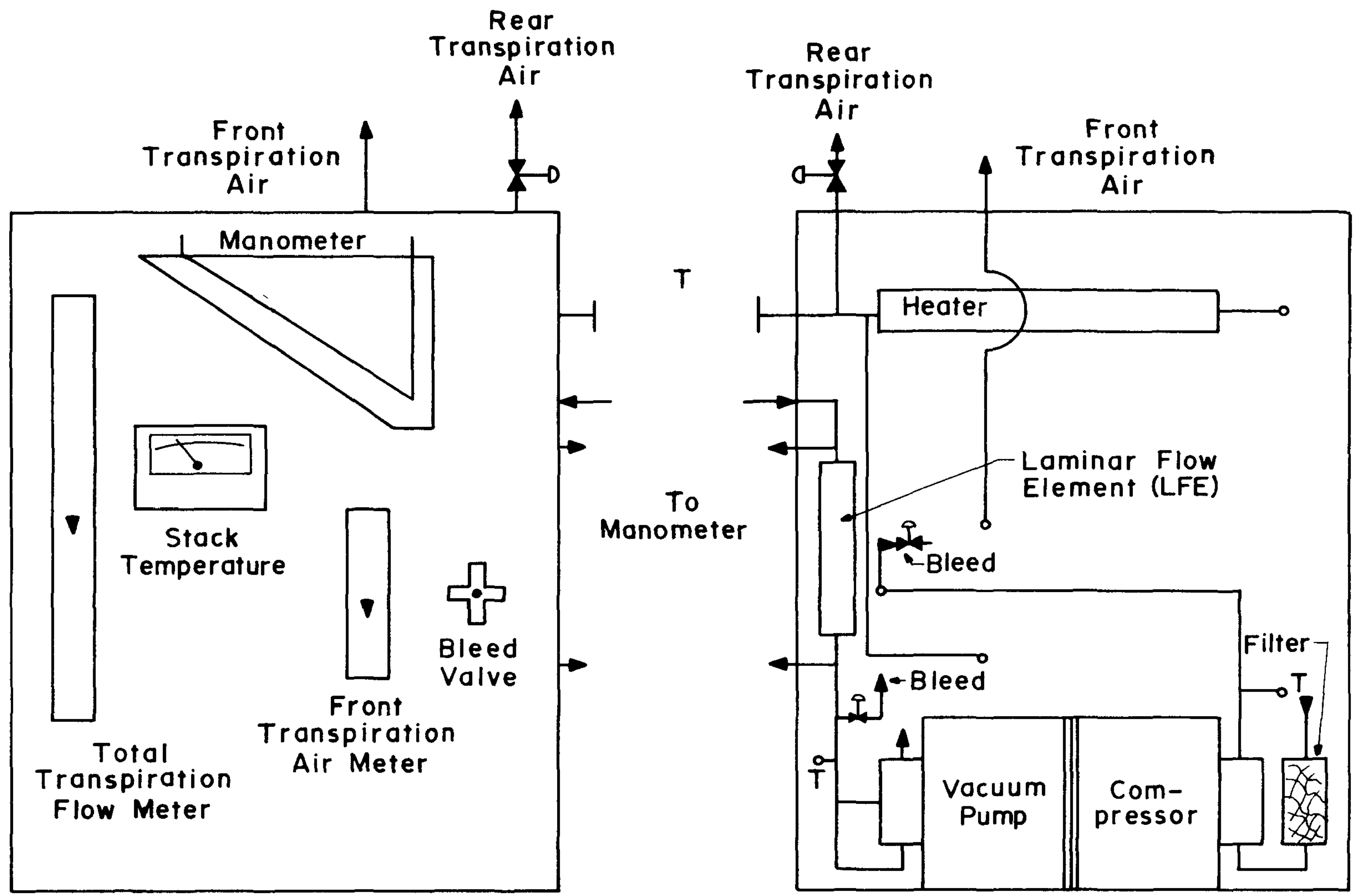


Figure 11

SCHEMATIC DIAGRAM OF THE CONTROL BOX

The combined sample and transpiration air is pulled by the vacuum pump through a laminar flow element. An inclined oil manometer is used to measure the pressure drop across the laminar flow element, which is calibrated for volumetric flow rate against the pressure drop. A protective glass wool filter is used to keep the laminar flow element clean. The total flow rate of the sample and the transpiration air is variable by means of a needle breed valve.

Dial thermometers and pressure gauges are used at appropriate points to characterize the air flow. Details of the components are discussed in the manual, which is enclosed as Appendix A to this report.

OPERATION OF THE PROBE

The operating procedure of the probe for fixed rate and isokinetic sampling is given in Appendix A. In general, the sample flow rate should be chosen first. Experimental results show that a higher sampling rate is generally preferable. While sampling isokinetically, the sampling nozzle should be chosen such that the volumetric flow rate is the highest possible. A sampling rate of 28.3 lpm (1 cfm) gave good results in our experimental program. A sample flow rate should be above 7.1 lpm (0.25 cfm) is recommended whenever possible.

The transpiration flow rate to be used is determined by the particle size and the sample flow rate. When the particles are below 10 μm the front transpiration air rate should be above 14. 2 lpm (0.5 cfm) and the rear transpiration air rates should be at least 28.3 lpm (1 cfm). For larger particles upto 50 μm, the transpiration air rates may be above 14.2 lpm (0.5 cfm) for the front and above 142 lpm (5 cfm) for the rear. As the sample rate is increased from 7.1 to 28.3 lpm (0.25 to 1 cfm), the amount of transpiration air required is reduced. However, the front transpiration air should always be kept above 14.2 lpm (0.5 cfm).

Recommended sets of sample and transpiration rates are listed in Table 4. The total flows are kept below 142 lpm (5 cfm) whenever possible so that the pump in the prototype can handle the flow. For larger particles (50 μm), a larger pump may be used. The laminar flow element may be used for measuring the total flow rates upto 710 lpm (25 cfm). If the sample flow rate is kept above 14.2 lpm (0.5 cfm), a front transpiration rate of 28.3 lpm (1 cfm) and a back transpiration rate of 85 lpm (3 cfm) will be satisfactory for any stack sampling situation. It is also convenient to use fixed values of transpiration rates, thus minimizing manipulation.

Table 4. RECOMMENDED TRANSPIRATION RATES

Sample flow rates, lpm (cfm)	Particle size, μm	Transpiration air rate	
		Front, lpm (cfm)	Back, lpm (cfm)
<7.1 (0.25)	upto 10	28.3 (1.0)	85 (3.0)
	upto 50	56.6 (2.0)	283 (10)
7.1 - 14.2 (0.25-0.5)	upto 10	28.3 (1.0)	85 (3.0)
	upto 50	56.6 (2.0)	142 (5.0)
14.2 - 28.3 (0.5-1.0)	upto 10	28.3 (1.0)	85 (3.0)
	upto 50	56.6 (2.0)	85 (3.0)

FIELD TESTING OF THE SAMPLING INTERFACE

The prototype sampling interface was tested at a coal-fired power plant. Two sites were selected for sampling. The first site was located at an exhaust duct following a hot electrostatic precipitator and leading to a stack. The second site was the exhaust duct following a wet scrubber and leading to a stack. Both sites were located at the Will County Power Station* of Commonwealth Edison, who provided cooperation in the evaluation program. The objective of the field sampling program was to compare the Method 5 train and the prototype interface and to study the variation of operating parameters of the prototype.

SAMPLING OPERATION

Site No. 1 -- Hot Precipitator Exhaust

The No. 3 boiler unit at the plant is equipped with a Research Cottrell® hot electrostatic precipitator. The precipitator handles 42000 m^3/min (1,400,000 cfm). The operating temperature is 288°C (550°F). The sampling was conducted on a 1.2 meter x 4 8 meter (4 ft x 16 ft) duct through a 10 cm ID (4 in. nominal pipe) port shown in Figure 12. The sampling set-up is illustrated in Figure 13. The first series of tests

* Located in Romeoville, Illinois.

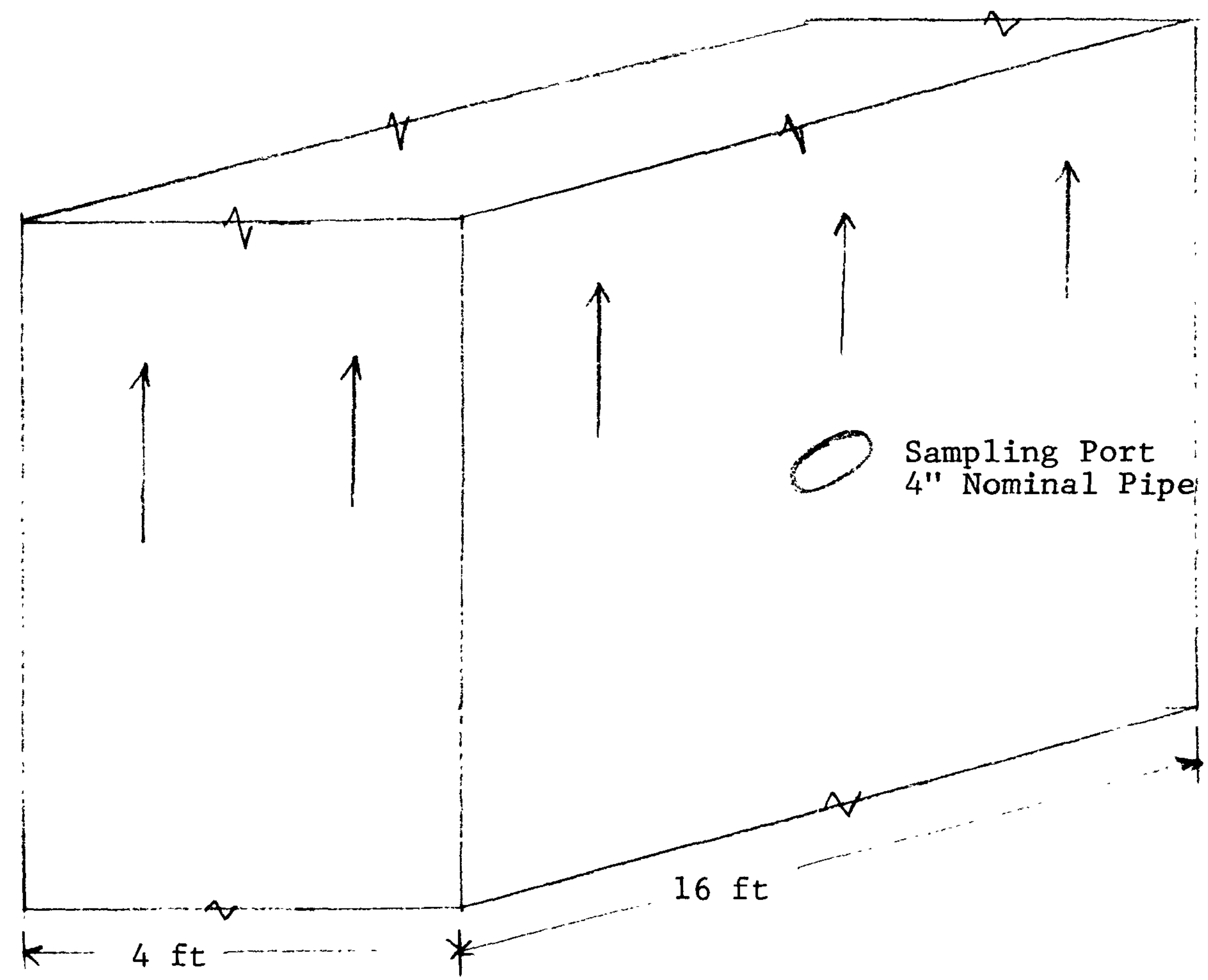


Figure 12

SAMPLING PORT AT SITE NO. 1

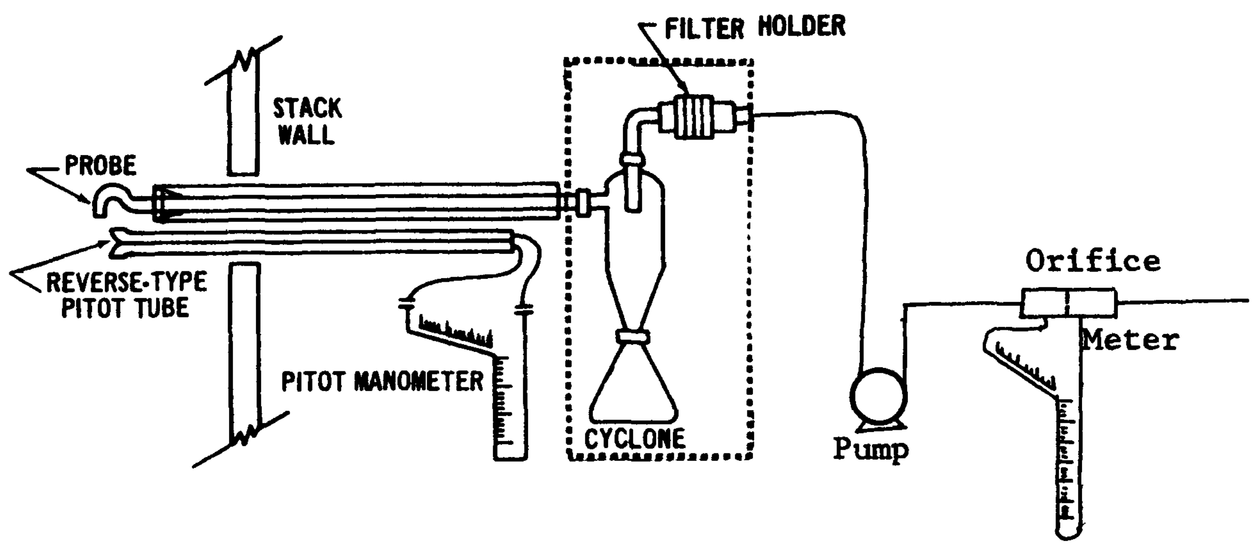


Figure 13

SAMPLING ARRAGEMENT

consisted of a velocity traverse and a single point isokinetic sampling by a Method 5 train Since the objective of the evaluation was only to compare the method 5 train and the prototype interface, single point sampling was considered to be adequate

After the velocity traverse was made, appropriate sampling conditions were determined by the standard nomograph for the Method 5 train. The sampling point was so chosen that it reflected the average conditions in the stack Sample was taken for half an hour. At the end of the sampling period, the probe sections were washed with acetone. The deposit in the probe tip (1/2 in. gooseneck nozzle) and the probe were determined separately by weighing the washings after drying in an oven The deposit on the 10 cm (4 in.) glass fiber filter was weighed on a microbalance. Results are shown in Table 5. Parts of the collected samples were dispersed and mounted on slides for size distribution determination by optical microscopy

The second series of sampling consisted of sampling with the prototype sampling interface. For the first test, the sampling point and rate were the same as with the EPA Method 5 tests A transpiration rate of 193.2 lpm (4 cfm) was chosen The test layout is shown schematically in Figure 14.

To begin the test, the transpiration flow was started and maintained at 193.2 lpm (4 cfm) The transpiration air flow divided equally between the front and the rear sections. The probe was inserted into the stack and kept with the nozzle pointing in the reverse direction to the flow for 10-15 minutes.

Table 5. SAMPLING CONDITIONS AT SITE NO. 1

Test No.	Sampling device	Sampling rate, lpm (cfm)	Sampling time, min	Transpiration rates, lpm (cfm)		Deposit, g		
				Front	Rear	Probe tip	Straight probe	Filter
1	EPA (1/4 in. nozzle)	22.6 (0.8)	30	0	0	0.0242 (13.1%)	0.0520 (28.2%)	0.1082 (58.7%)
2	Prototype Interface	22.6 (0.8)	60	28.3 (1.0)	84.9 (3.0)	0.0081 (11.1%)	0.0005 (0.7%)	0.0642 (88.2%)
3	Prototype Interface	22.6 (0.8)	30	28.3 (1.0)	84.9 (3.0)	0.0023 (9.1%)	0.0001 (0.4%)	0.0227 (90.5%)
4	Prototype Interface	28.3 (1.0)	60	56.6 (2.0)	56.6 (2.0)	0.0007 (4.0%)	0.0001 (0.6%)	0.0166 (95.4%)
5	Prototype Interface	28.3 (1.0)	240	28.3 (1.0)	84.9 (3.0)	0.0185 (11.0%)	0.0073 (4.2%)	0.1462 (84.8%)

Particulate loading -- 0.1-0.2 (mg/lit)

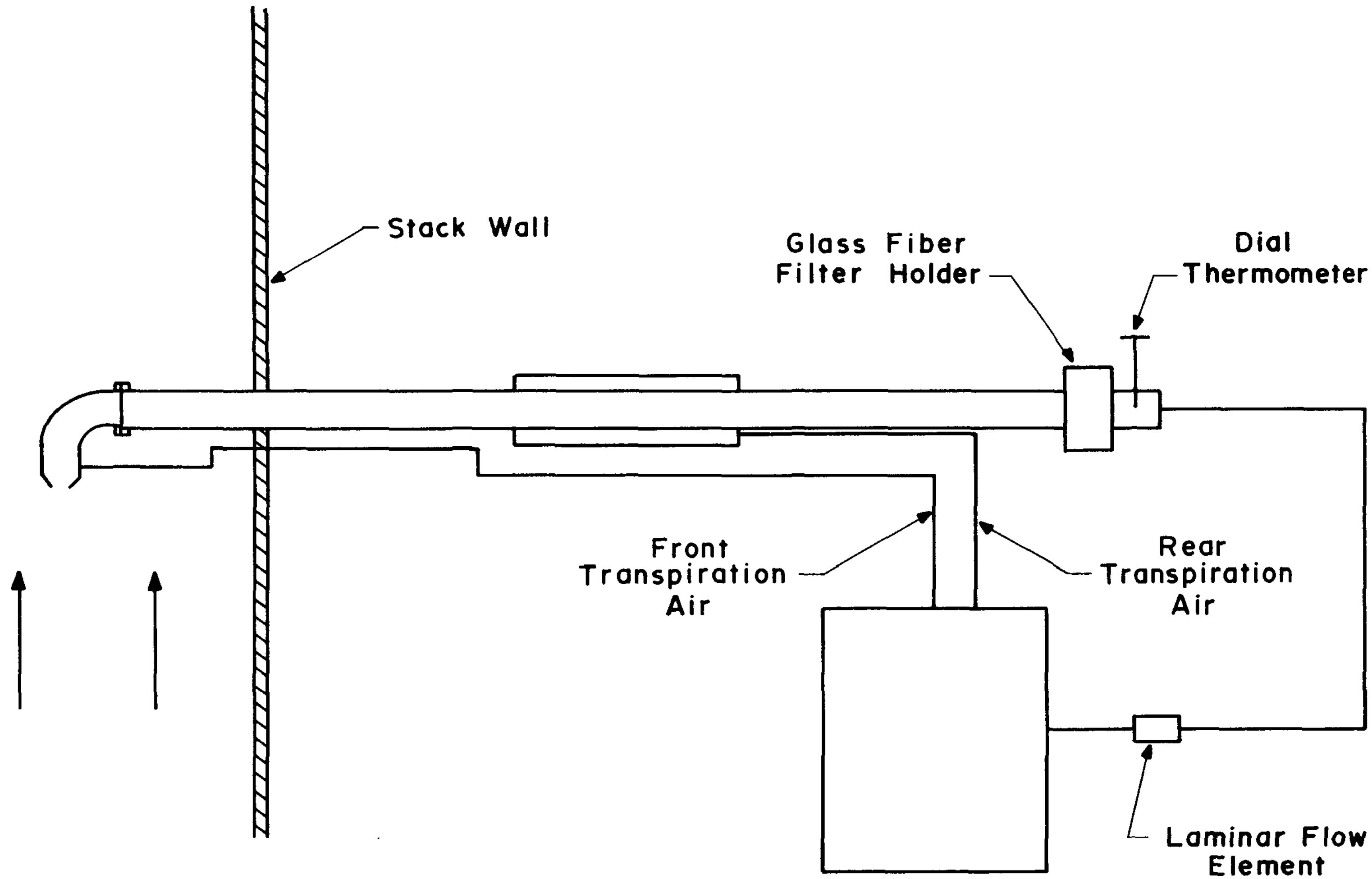


Figure 14

SAMPLING ARRANGEMENT USING TRANSPIRATION PROBE

The heater was operated so that the transpiration air temperature leaving the control box was 204°C (400°F). The probe was straightened, so that it was in line with the flow, and sampling started. The sampling rate was adjusted to the desired level and sampling continued for 30 minutes.

For the second test, the sampling conditions were kept the same, but the sampling period was extended to four hours to evaluate continuous operation. For the remaining tests, a sampling rate of 28.3 lpm (1 cfm) was chosen and the transpiration rate was varied.

The deposits on the front section (with 90° bend) and the rear section were washed separately by acetone and weighed after drying. The deposit on the 10 cm (4 in.) filter was also determined by weighing. Part of each deposit sample was used for size distribution determination by optical microscopy. The sampling conditions and results are given in Table 5.

Site No. 2 -- Wet Scrubber Exhaust

The No. 1 boiler unit at the plant is equipped with two Babcock and Wilcox limestone slurry scrubbers for SO_2 and particulate removal. The scrubber handles 21,000 m^3/min (770,000 cfm); and the temperature is 82°C (180°F).

The scrubber represented a different type of source from the hot precipitator due to the expected larger particle size and presence of water. The transpiration air could be used to evaporate the water by lowering the partial pressure of water, thereby preventing condensation in the sampling equipment.

Two tests were performed with the prototype interface. The same conditions were used for each run. The samples were handled in the same manner as in the other tests. No evidence of condensation was found on the sampling line or the filter. The results are summarized in Table 6.

DISCUSSION OF RESULTS

The results of the sampling operations are given in Tables 5, 6, and 7. Tables 5 and 6 represent the efficiency of particle transport by mass, while Table 7 reflects the size selectivity of the sampling operation.

Effluent Characteristics

The samples collected on the glass fiber filter at both sites were examined by optical microscopy (using polarized light and ∿ 65-600X magnification). At site No. 1, which followed an electrostatic precipitator, the filter deposit consisted of glass spheres upto 10 μm, Fe_2O_3 particles upto 20 μm, magnetite spheres upto 10 μm, coal particles upto 24 μm, and metal shavings upto 40 μm. A typical sample is shown in Figure 15. At site No. 2, which followed a wet scrubber, the particle size was usually high. The effluent consisted of coal particles upto 100 μm, partially burnt coal upto 370 μm, mineral particles upto 90 μm, Fe_2O_3 upto 40 μm, magnetite and glassy spheres upto 30 μm, and small glass spheres less than 1 μm (< 30% by weight).

Sampling Efficiency

The results of the sampling operations show that the prototype interface can be used for sampling from stacks with

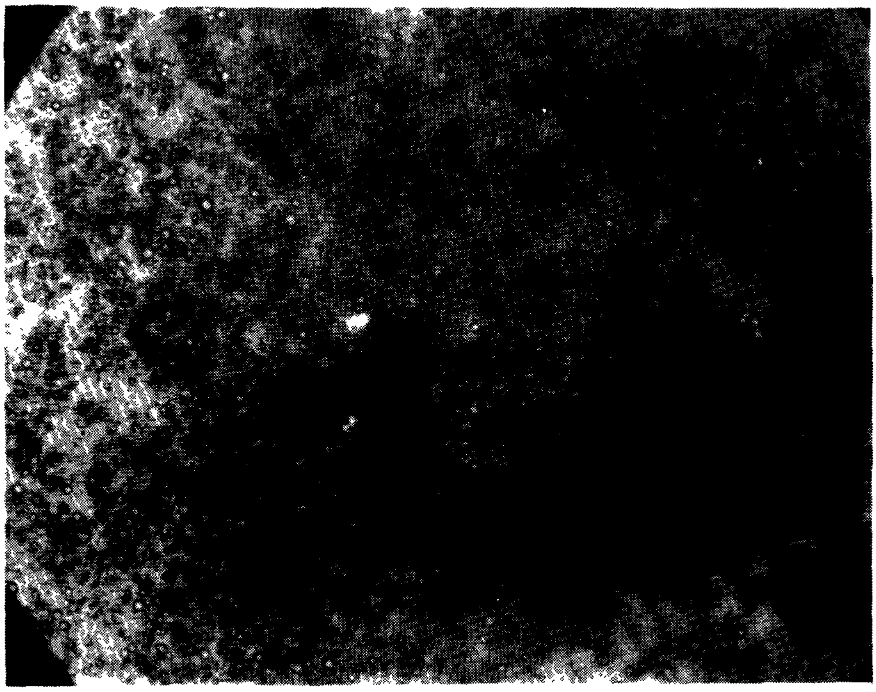
Table 6. SAMPLING CONDITIONS AT SITE NO. 2

Test No.	Sampling device	Sampling rate, lpm (cfm)	Sampling time, min	Transpiration rates, lpm (cfm)		Deposit, g		
				Front	Rear	Probe tip	Straight probe	Filter
6	Prototype Interface	28.3 (1.0)	60	56.6 (2.0)	56.6 (2.0)	0.0024 (2.5%)	0.0010 (1.0%)	0.0925 (96.5%)
7	Prototype Interface	28.3 (1.0)	60	56.6 (2.0)	56.6 (2.0)	0.0030 (2.9%)	0.0005 (0.5%)	0.0969 (96.6%)

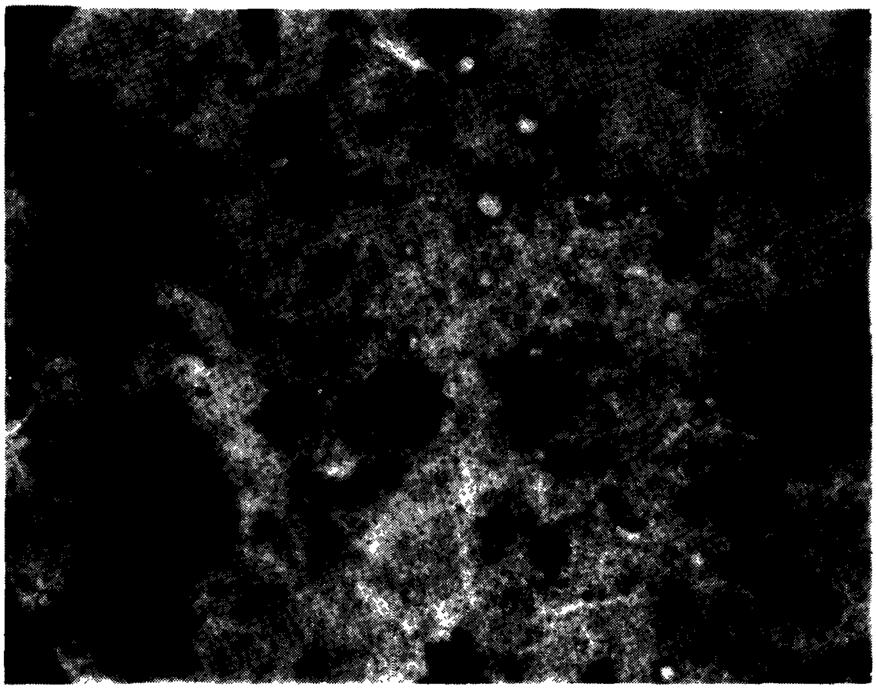
Particulate loading ∿0.1 (mg/lit)

Table 7. SIZE DISTRIBUTIONS OF COLLECTED SAMPLES

Interface	Sample flow rate, lpm (cfm)	Transpiration flow rate, lpm (cfm)		Sample location	Cumulative % smaller than size, μm							
		Front	Rear		3	6	12	18	24	30	45	60
Method 5 (Test #1)	22.6 (0.8)	0	0	Nozzle	63.3	85.7	94.5	97.2	98.2	99.1	99.7	100.0
				Probe	60.8	81.0	88.7	92.9	96.0	98.1	99.4	100.0
				Filter	100.0							
Prototype (Test #2)	22.6 (0.8)	28.3 (1.0)	84.9 (3.0)	Nozzle	46.3	78.2	89.6	95.0	97.8	99.0	99.6	100.0
				Probe	58.6	85.6	93.2	96.8	98.3	99.1	99.6	100.0
				Filter	88.2	96.2	98.0	98.9	99.4	99.6	99.8	100.0
Prototype (Test #3)	22.6 (0.8)	28.3 (1.0)	84.9 (3.0)	Nozzle	53.8	76.6	88.5	94.0	97.1	99.1	99.8	100.0
				Probe	45.2	76.6	89.1	95.0	98.0	99.3	99.8	100.0
				Filter	80.1	91.5	96.2	98.2	99.0	99.6	99.9	100.0
Prototype (Test #4)	28.3 (1.0)	56.6 (2.0)	56.6 (2.0)	Nozzle	71.4	89.6	96.8	97.8	98.6	99.3	99.9	100.0
				Probe	69.3	88.2	93.5	96.2	98.2	99.6	100.0	100.0
				Filter	77.5	90.4	95.5	97.8	98.8	99.6	99.9	100.0



Site No. 1



Site No. 2

Figure 15

PHOTOMICROGRAPHS OF EFFLUENT PARTICULATES (420X) very little deposition. The Method 5 train transported only 58.7% of the particles to the glass fiber filter at the site No. 1. The particles that were transported to the glass fiber filter were extremely fine (less than 3 μm), indicating that the larger particles were lost in the nozzle and the probe. Size distributions of the nozzle and probe deposit show that the larger particles were deposited on the probe wall and the nozzle.

In test No. 1, with the Method 5 train, the level of deposition in the sampling nozzle and the probe were 13.1 and 28.2%, respectively. As seen in Table 5, for the same sample flow rate in test No. 2, the deposition in the nozzle section was 11.1% and the deposition in the straight probe was only 0.7%. Test No. 3 showed a similar pattern of deposition. When the front transpiration flow was increased to 56.6 lpm (2.0 cfm), the deposition in the front nozzle section was reduced significantly, while the deposition in the rear section remained low. The test No. 5 showed comparable results to tests No. 2 and No. 3 while sampling for a longer time at about the same sampling conditions.

Results from site No. 2 (Table 6) showed that sampling could be performed in the presence of a considerable amount of liquid water in the effluent of the scrubber. Comparable results to test No. 4 at site No. 1 were obtained even though the sample consisted of several large particles. The two tests showed good reproducibility of the amount of samples.

The size distribution results of the samples are consistant with the mass sampling efficiency. For test No. 1, with the Method 5 train, the glass fiber filter deposit consisted only of particles smaller than a few microns. The size distributions of the nozzle and probe deposit were comparable.

For tests No. 2 and No. 3, the nozzle and probe deposits contained greater proportions of larger particles than the glass fiber filter. At a higher transpiration rate in the front section for test No. 4, the size distributions of the nozzle, probe, and filter deposits were comparable to each other.

APPENDIX A

OPERATING MANUAL

Transpiration Sampling Interface

OPERATING MANUAL

Transpiration Sampling Interface

1. INTRODUCTION

The transpiration sampling interface is based on the use of transpiring air to prevent the deposition of the particulates on the walls of the sampling tube. The interface was developed at IIT Research Institute on two projects under contracts from the Environmental Protection Agency. Test results and design principles are reported in the following final reports for these projects:

1. Sampling Interface for Quantitative Transport of Aerosols. Prepared by IIT Research Institute, Chicago, for Environmental Protection Agency, Research Triangle Park, Contract No. 68-02-0579, Final Report #EPA 650-2-A016 (December 1973).

2. Sampling Interface for Quantitative Transport of Aerosols. Prepared by IIT Research Institute, Chicago, for Environmental Protection Agency, Research Triangle Park, Contract No. 68-02-1295, (July 1975).

2. DESCRIPTION

The sampling interface consists of two major components: the sampling probe, and a control box for the sampling operation.

The sampling probe is shown in Figure A. It consists of a front section (FS) with a 90° bend and a rear section (RS). Each section has an inner tube of 1.27 cm (1/2 in.) I.D. and 1.9 cm (3/4 in.) O.D. 316 stainless steel porous tube. The inner tube is encased in an outer 316 stainless steel tube (3.5 cm [1-3/8 in.] O.D.). The two sections are joined by a screw-on type ball joint. The front section has a provision to screw on any of the three interchangeable sampling nozzles. Air is supplied to the front and the back section through the 0.95 cm (3/8 in.) tubes with Swagelok fittings.

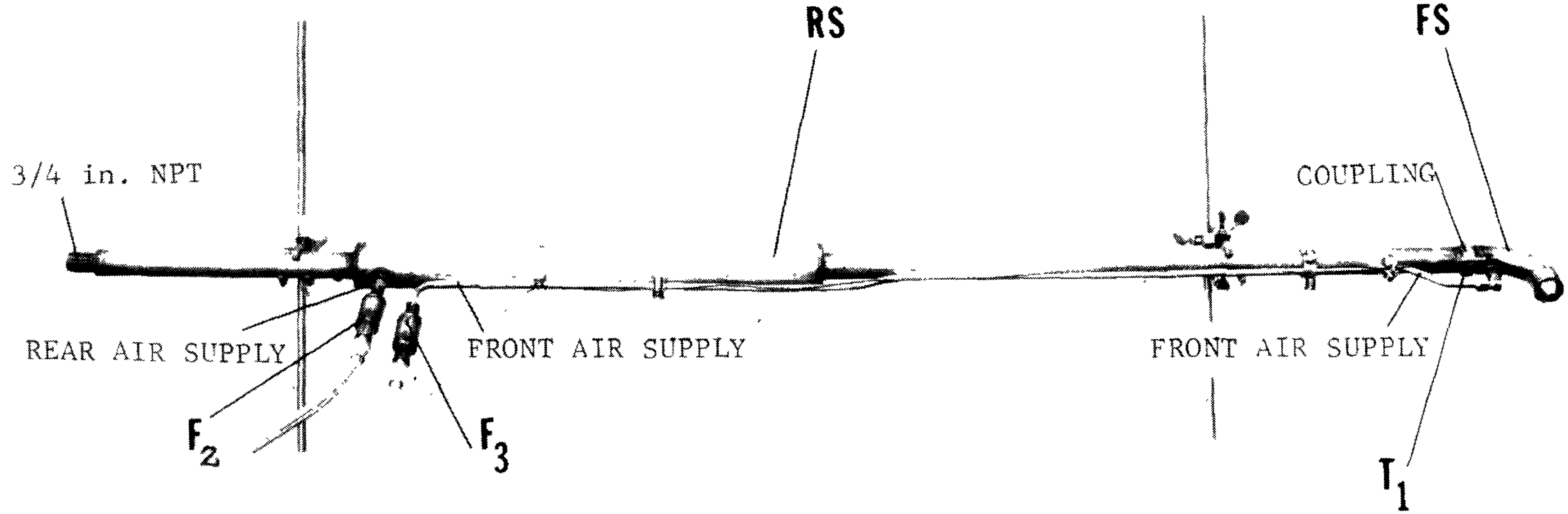


Figure A

TRANSPIRATION SAMPLING PROBE

The probe can be joined to a sampling device through a 3/4 in. NPT male connection or to a 12/25 ball joint through an adapter.

The control box is shown in Figures B and C. It contains a combination vacuum and pressure pump rated at 7 cfm air output and 7 cfm intake capacities. The air from the pump flows through a flowmeter R_1 and a heater H, and is divided into two streams in order to supply air to the front and the rear sections of the probe. On the vacuum side, the flow is monitored by observing the pressure drop across a Meriam laminar flow element (LFE) as measured by a 0 to 3 in. water inclined tube manometer (M_1). The output of the pump and the intake are adjusted by the use of two bleed valves (V_1 and V_4, respectively). The relative amounts of the transpiration air to the front and the back sections of the probe are adjusted by manipulation of the bleed valve (V_1) and a ball valve (V_3). Valve V_2 should not be used for flow control. Full adjustment is possible with the help of the bleed valve (V_1); thus keeping the output of the pump constant for an even operation.

Three Teflon® lined flexible hoses are provided to connect the sampling probe to the control box. A thermocouple is used to monitor stack temperature. The heater with a variac is used for preheating the transpiration air to temperatures up to 400°F. Dial thermometers are used to monitor the temperature of the airstream.

The transpiration air is filtered by a coarse filter, F_1, before it enters the pump. The heated transpiration air flows through two glass wool filters, F_2 and F_3, before entering the front and back sections.

A list of parts and their sources is given in Table A.

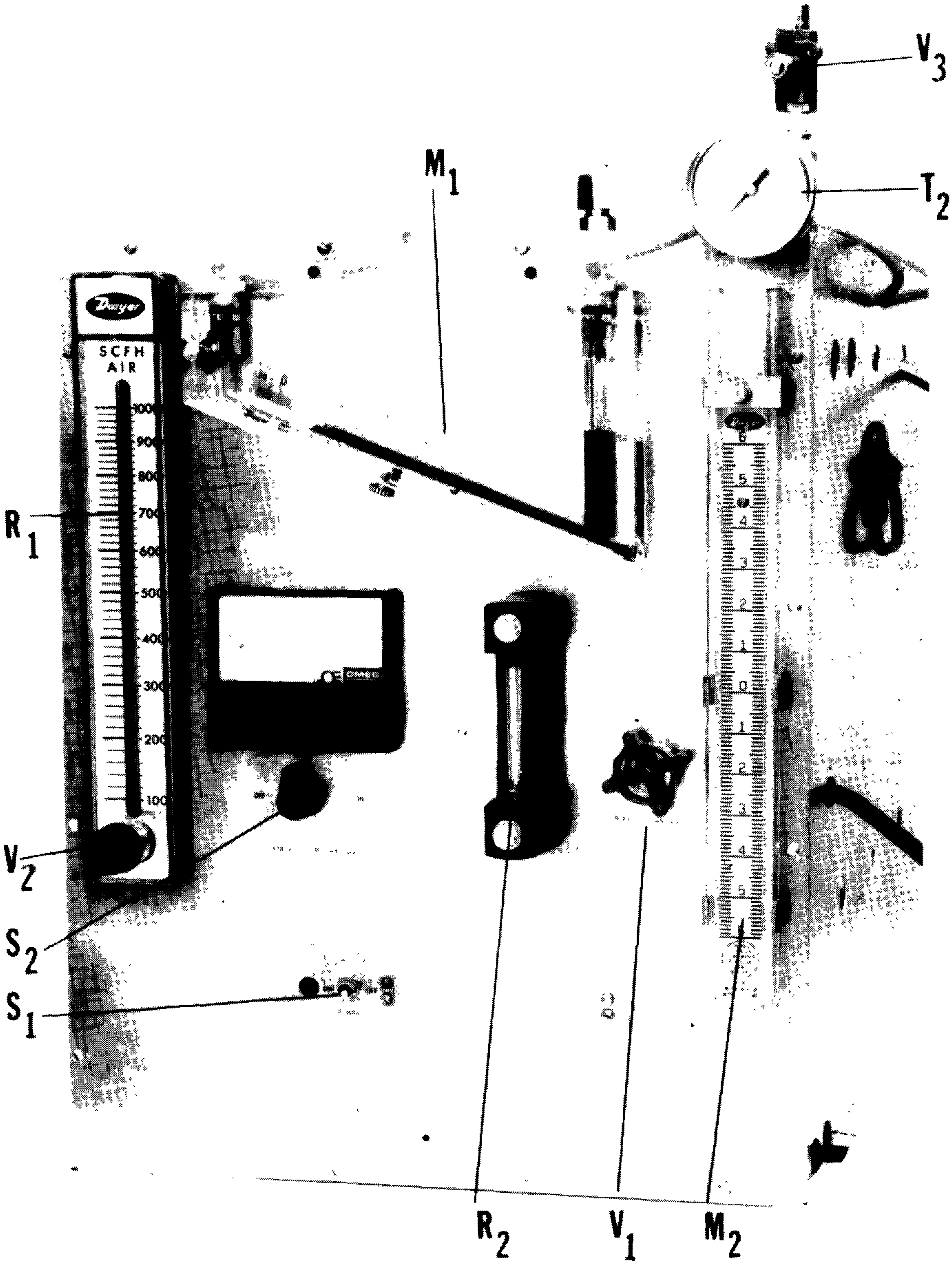


Figure B

FRONT VIEW OF CONTROL BOX

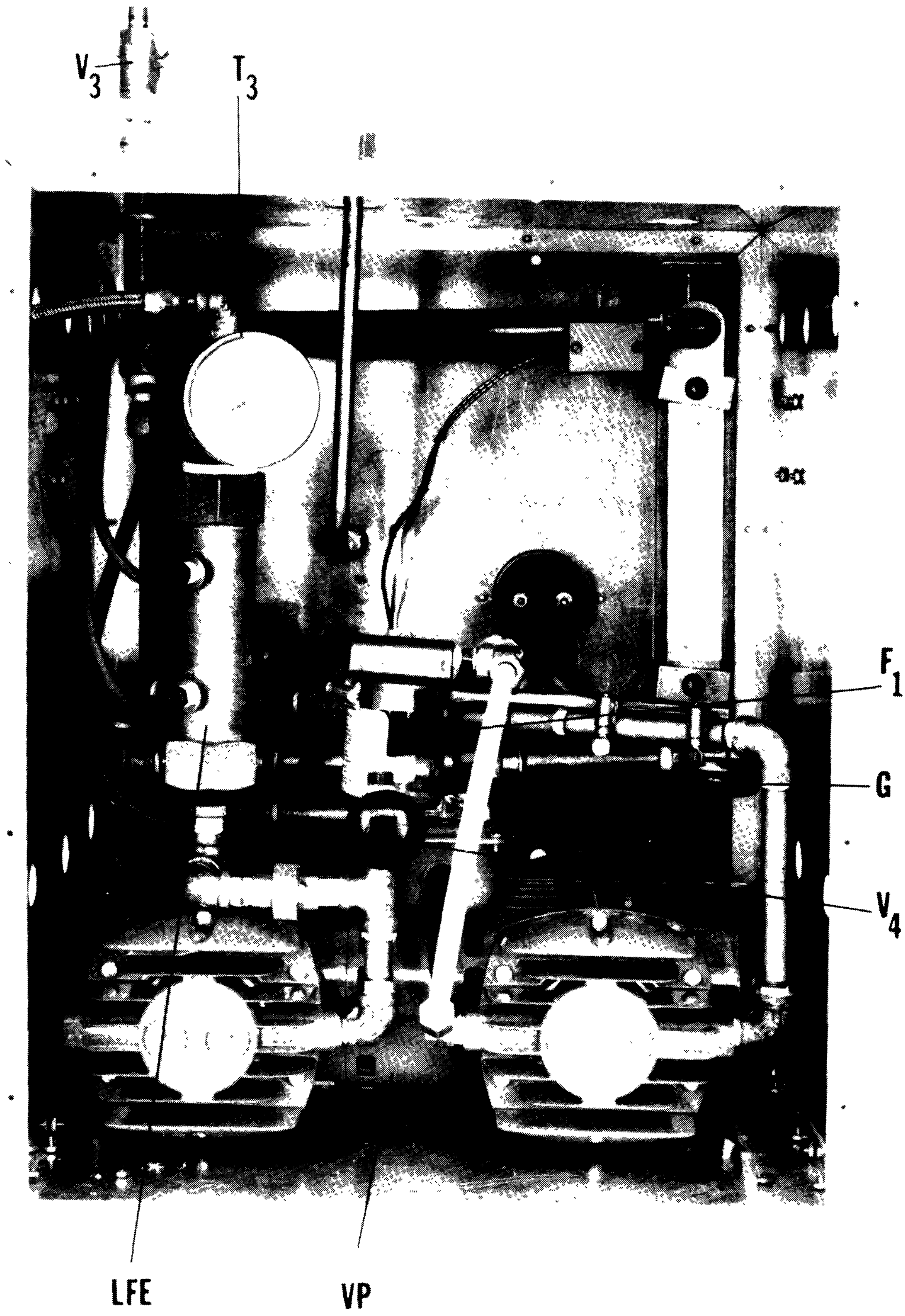


Figure C

REAR VIEW OF CONTROL BOX

Table A

COMPONENTS OF THE SAMPLING INTERFACE

Symbol	Description	Manufacturer and Model	Capacity and Specification
F_1	Coarse Filter	Gast	
F_2	Glass Wool Filters	--	10 cfm
F_3	Glass Wool Filters	--	10 cfm
G	Pressure Guage	--	0-15 psi
H	Heater	Vulcan, Model No. AH-3	1500 watts
LFE	Laminar Flow Element	Meriam, Model No. 50MW20-1½	0-24 cfm air
M_1	Inclined Tube Manometer	Dwyer	0-3 in. water
M_2	U-Tube Manometer	--	0-12 in. Hg
N_1	Sampling Nozzle	--	1/4 in. I.D.
N_2	Sampling Nozzle	--	3/8 in. I.D.
N_3	Sampling Nozzle	--	1/2 in. I.D.
PS	Powerstat	--	115 V, 10-15 Amps
R_1	Rotameter	Dwyer, Ratemaster	100-1000 cfh
R_2	Rotameter	Fischer and Porter	0-1.8 cfm
S_1	Switch for Pump	--	115 vac
S_2	Switch for Thermocouple	--	--
T_1	Stack Thermocouple	--	Iron-Constantine (10 Ω resistance)
T_2	Heater Thermometer	--	0-400°F
T_3	LFE Thermometer	--	0-400°F
T.I.M.	Temperature Indicator Meter	Omega, Model	0-800°F
V_1	Bleed Valve for Transp. Air	Globe Type	--
V_2	Metering Valve	Needle Valve 1/4 in. NPT	--
V_3	Proportionaling Valve	Ball Valve 3/8" NPT Female	--
V_4	Vacuum Bleed-Off	Needle Type 1/4" NPT	--
VP	Combination Vacuum and Compressed Air Pump	Thomas Model 2727	0-7 cfm air pump 0-7 cfm vacuum pump
W	Washer for Nozzle	--	15/16" O.D. x 3/4" I.D. x 1/16" Thick

3. PREPARATION OF THE PROBE

1. Select sampling nozzle. Suggested nozzles:

	Velocity (FPM)
N_1 - 1/4" I.D.	> 3,000
N_2 - 3/8" I.D.	1,000 - 3,000
N_3 - 1/2" I.D.	< 1,000

2. Screw the nozzle and washer W on the FS section (as in Figure A).

3. Connect the 90° FS section to the RS section (Figure 1) at the coupling by hand tightening. Loosen the clamps to align and connect the FS air supply tube with the Swagelok® fitting. Tighten the coupling between FS and RS sections with a wrench. Tighten the clamps.

4. Connect the air hoses to the front and back transpiration air supply (3/8" NPT pipe).

5. Connect the glass wool filters to the other ends of the hoses.

6. Connect the hoses and filters to the Swagelok® fittings for front and rear transpiration sections (Figure A).

7. Connect the pump cord to a standard 3 prong 115 volt outlet.

8. Connect the heater (H) to the powerstat (PS).

9. The probe and the hoses may be preheated to 300°F by wrapping them with heating tape.

10. Connect the probe to the measuring device or a sample collector (GF filter holder).

11. If using the pump VP for pulling the flow through the measurement device or sample collector, it may be connected using the third hose to the inlet of the laminar flow element.

12. Level and zero manometer M_1.

4. OPERATION OF THE PROBE

1. Fixed rate sampling:

A. Convert the desired sample rate to standard conditions

$$\text{SFR (scfm)} = \text{SFR (acfm)} \times \frac{530\ P_s}{T_s \times 29.92}$$

where SFR = sample flow rate, P_s = stack pressure (in Hg), T_s = stack temperature °R (460 + °F).

B. Choose the transpiration flow rate and convert it to standard conditions

$$\text{TFR (scfm)} = \text{TFR (acfm)} \times \frac{530\ P_a}{T_a \times 29.92}$$

where TFR = transpiration flow rate, P_a = ambient pressure (in Hg), and T_a = ambient temperature °R (460 + °F).

C. Calculate total flow

$$Q_t\ \text{(scfm)} = \text{SFR (scfm)} + \text{TFR (scfm)}$$

D. Start the transpiration air flow through the probe and place the probe tip in the stack with the nozzle tip in the opposite direction to the flow (see calibration curves: Figures D & E).

E. Read ΔP' across the laminar flow element from the curve in Figure F corresponding to $1.1 \times Q_t$.

F. Adjust vacuum bleed valve V_4 until the ΔP on manometer M_1 across the laminar flow element is equal to ΔP as determined in step E.

G. Read P_f (in Hg) on manometer M_2 and T_f on the dial thermometer.

H. Read P_{cf} and T_{cf} from Tables B and C.

I. Divide Q_t by P_{cf} and T_{cf}.

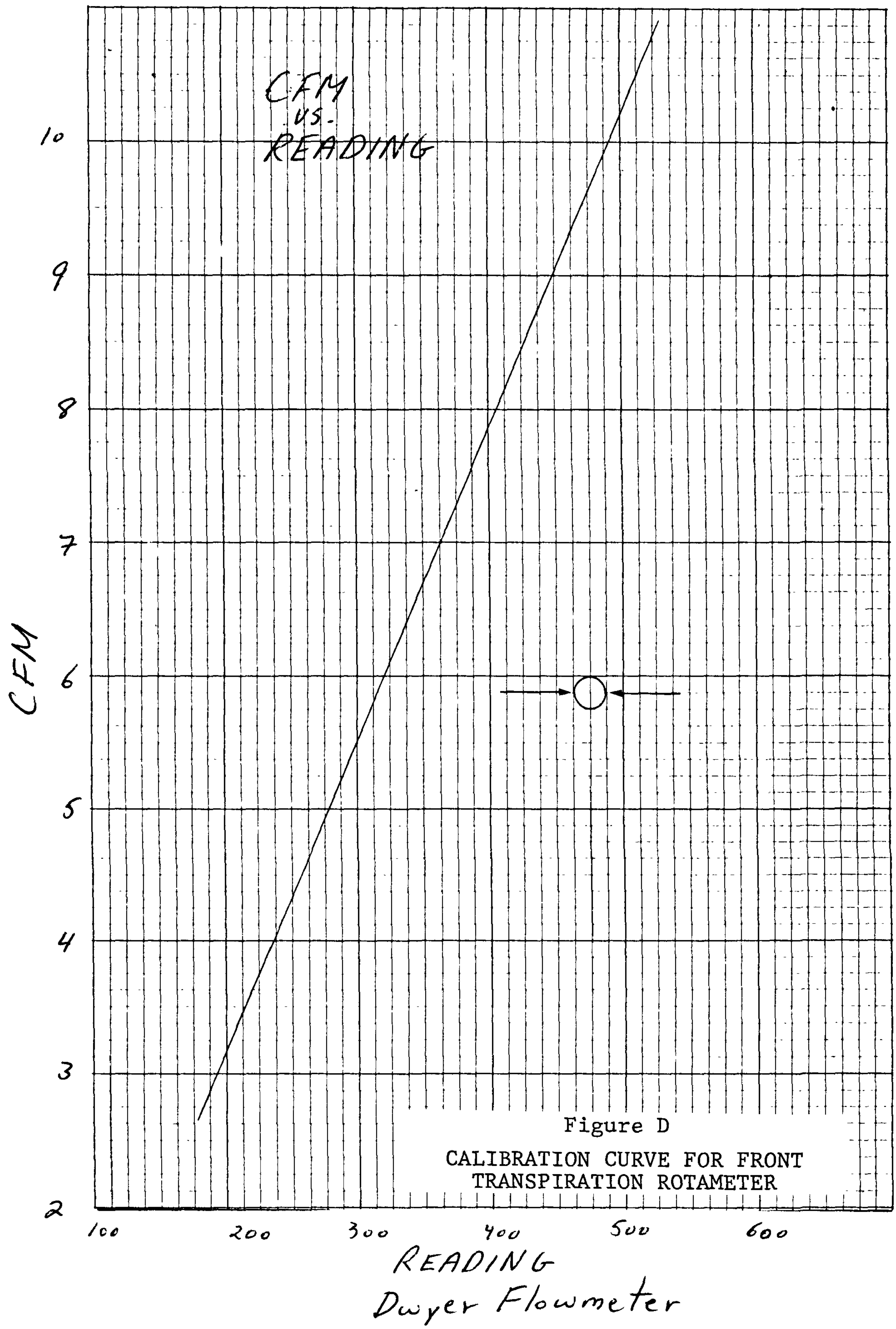


Figure D

CALIBRATION CURVE FOR FRONT TRANSPIRATION ROTAMETER

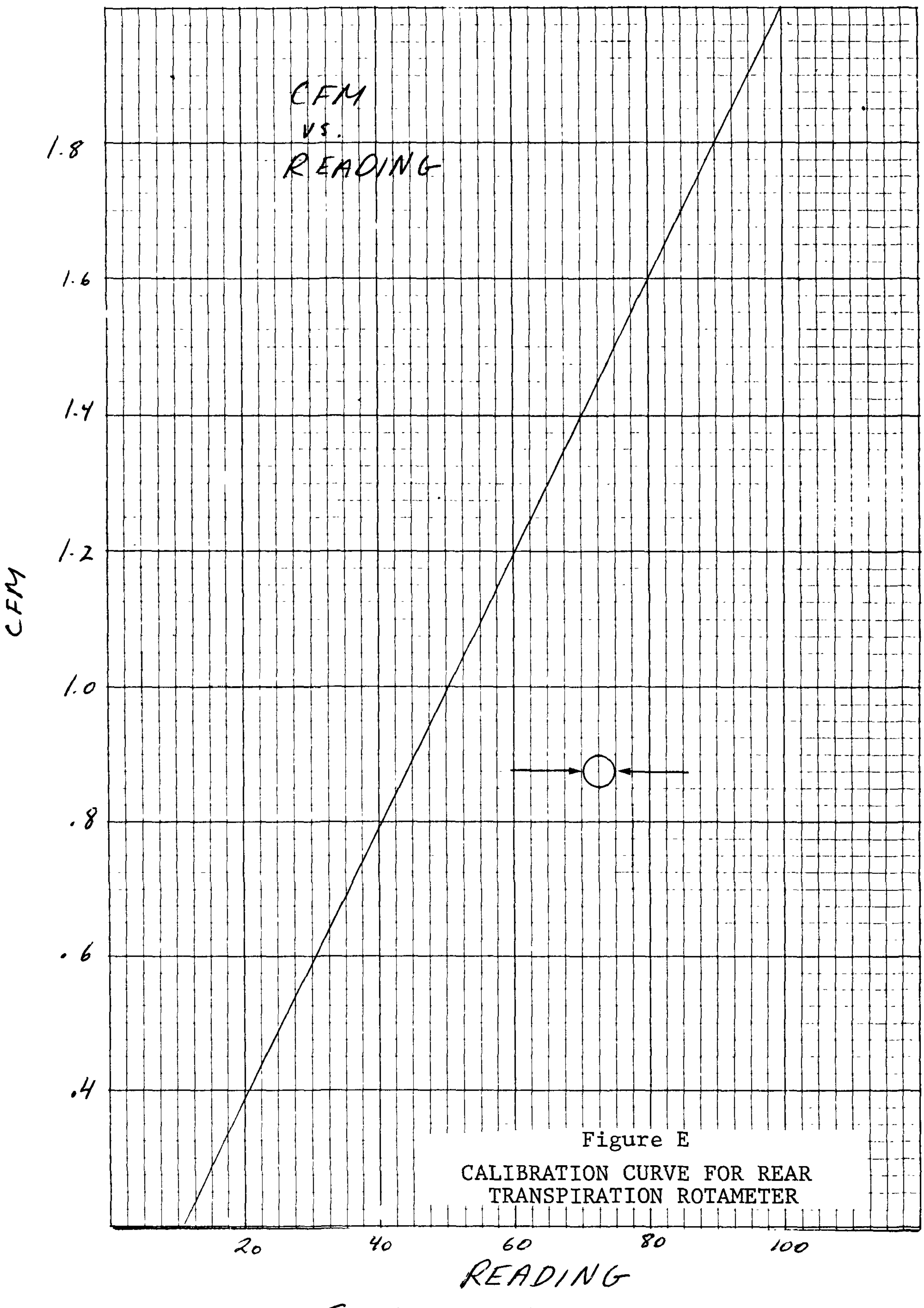


Figure E

CALIBRATION CURVE FOR REAR TRANSPIRATION ROTAMETER

Fischer-Porter Flowmeter

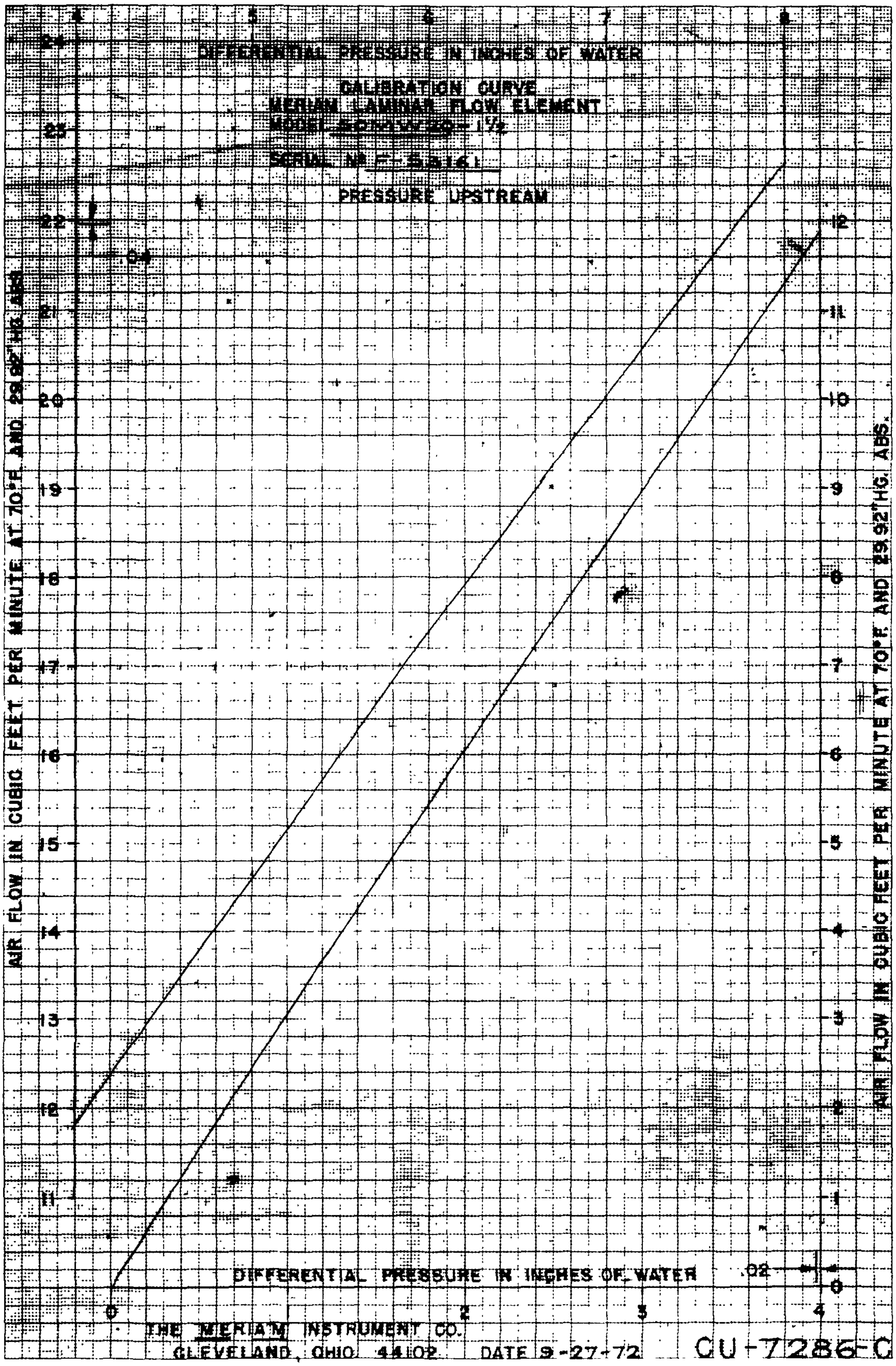


Figure F
CALIBRATION CURVE FOR LAMINAR FLOW ELEMENT

Table B

MERIAM LAMINAR FLOW ELEMENT
AIR OR GAS PRESSURE CONVERSION MULTIPLICATION FACTOR
BASE PRESSURE (ASSIGNED STANDARD) 29.92 INCHES MERCURY ABSOLUTE

LAMINAR INLET PRESS. INCHES HG. ABS.	C.F.	LAMINAR INLET PRESS. INCHES HG. ABS.	C.F.	LAMINAR INLET PRESS. INCHES HG. ABS.	C.F.	LAMINAR INLET PRESS. INCHES HG. ABS.	C.F.
26.00	.8689	28.20	.9425	30.35	1.0143	32.55	1.0879
26.05	.8706	28.25	.9441	30.40	1.0160	32.60	1.0895
26.10	.8723	28.30	.9458	30.45	1.0177	32.65	1.0912
26.15	.8739	28.35	.9475	30.50	1.0193	32.70	1.0929
26.20	.8756	28.40	.9491	30.55	1.0210	32.75	1.0945
26.25	.8773	28.45	.9508	30.60	1.0227	32.80	1.0962
26.30	.8790	28.50	.9525	30.65	1.0243	32.85	1.0979
26.35	.8806	28.55	.9542	30.70	1.0260	32.90	1.0995
26.40	.8823	28.60	.9558	30.75	1.0277	32.95	1.1012
26.45	.8840	28.65	.9575	30.80	1.0294	33.00	1.1029
26.50	.8856	28.70	.9592	30.85	1.0310	33.05	1.1046
26.55	.8873	28.75	.9608	30.90	1.0327	33.10	1.1062
26.60	.8890	28.80	.9625	30.95	1.0344	33.15	1.1079
26.65	.8907	28.85	.9642	31.00	1.0360	33.20	1.1096
26.70	.8923	28.90	.9659	31.05	1.0377	33.25	1.1112
26.75	.8940	28.95	.9675	31.10	1.0394	33.30	1.1129
26.80	.8957	29.00	.9692	31.15	1.0411	33.35	1.1146
26.85	.8973	29.05	.9709	31.20	1.0427	33.40	1.1163
26.90	.8990	29.10	.9725	31.25	1.0444	33.45	1.1179
26.95	.9007	29.15	.9742	31.30	1.0461	33.50	1.1196
27.00	.9024	29.20	.9759	31.35	1.0477	33.55	1.1213
27.05	.9040	29.25	.9776	31.40	1.0494	33.60	1.1229
27.10	.9057	29.30	.9792	31.45	1.0511	33.65	1.1246
27.15	.9074	29.35	.9809	31.50	1.0528	33.70	1.1263
27.20	.9090	29.40	.9826	31.55	1.0544	33.75	1.1280
27.25	.9107	29.45	.9842	31.60	1.0561	33.80	1.1296
27.30	.9124	29.50	.9859	31.65	1.0578	33.85	1.1313
27.35	.9141	29.55	.9876	31.70	1.0594	33.90	1.1330
27.40	.9157	29.60	.9893	31.75	1.0611	33.95	1.1346
27.45	.9174	29.65	.9909	31.80	1.0628	34.00	1.1363
27.50	.9191	29.70	.9926	31.85	1.0645	34.05	1.1380
27.55	.9207	29.75	.9943	31.90	1.0661	34.10	1.1397
27.60	.9224	29.80	.9959	31.95	1.0678	34.15	1.1413
27.65	.9241	29.85	.9976	32.00	1.0695	34.20	1.1430
27.70	.9258	29.90	.9993	32.05	1.0711	34.25	1.1447
27.75	.9274	29.92	1.0000	32.10	1.0728	34.30	1.1463
27.80	.9291	29.95	1.0010	32.15	1.0745	34.35	1.1480
27.85	.9308	30.00	1.0026	32.20	1.0762	34.40	1.1497
27.90	.9324	30.05	1.0043	32.25	1.0778	34.45	1.1514
27.95	.9341	30.10	1.0060	32.30	1.0795	34.50	1.1530
28.00	.9358	30.15	1.0076	32.35	1.0812	34.55	1.1547
28.05	.9375	30.20	1.0093	32.40	1.0828	34.60	1.1564
28.10	.9391	30.25	1.0110	32.45	1.0845	34.65	1.1580
28.15	.9408	30.30	1.0127	32.50	1.0862	34.70	1.1597

THE MERIAM INSTRUMENT COMPANY
10920 Madison Avenue
Cleveland, Ohio 44102

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SHEET 1 OF 2

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Table B (continued)

MERIAM LAMINAR FLOW ELEMENT
AIR OR GAS PRESSURE CONVERSION MULTIPLICATION FACTOR
BASE PRESSURE (ASSIGNED STANDARD) 29.92 INCHES MERCURY ABSOLUTE

PRESS INCHES HG. ABS	C.F.	PRESS INCHES HG. ABS	C.F.	PRESS INCHES HG. ABS	C.F.	PRESS INCHES HG. ABS	C.F
34.75	1.1614	35.10	1.1731	35.45	1.1848	35.80	1.1965
34.80	1.1631	35.15	1.1747	35.50	1.1864	35.85	1.1981
34.85	1.1647	35.20	1.1764	35.55	1.1881	35.90	1.1998
34.90	1.1664	35.25	1.1781	35.60	1.1898	35.95	1.2015
34.95	1.1681	35.30	1.1798	35.65	1.1915	36.00	1.2032
35.00	1.1697	35.35	1.1814	35.70	1.1931		
35.05	1.1714	35.40	1.1831	35.75	1.1948		

For values not shown in table, interpolate or use equation.

$$Po.f. = \frac{P\ flow}{P\ Base} = \frac{P\ flow}{29.92}$$

Po.f. = Pressure Conversion Factor
P base = Assigned Base Pressure of 29.92 inches mercury absolute
P flow = Laminar Inlet Pressure, inches mercury absolute

Above equation can be used up to and including two atmoshperes absolute. It will be necessary to calibrate laminars for pressure exceeding above.

To use: Take the flow value from the flow vs differential pressure curve and multiply by the pressure conversion multiplication in the table above. This gives the flow in standard cubic feet per minute referenced to a pressure base of 29.92 inches mercury absolute.

Table C

AIR TEMPERATURE CORRECTION FACTORS FOR LAMINAR UNIT

Base Temperature = 70°F

$$\text{CORRECTION FACTOR} = \frac{530}{460+°F} \times \frac{181.87}{\mu_g}$$

TEMP. °F.	+0	+1	+2	+3	+4	+5	+6	+7	+8	+9
50	1.0714	1.0677	1.0640	1.0603	1.0566	1.0529	1.0493	1.0457	1.0421	1.0385
60	1.0350	1.0315	1.0280	1.0245	1.0210	1.0175	1.0141	1.0107	1.0073	1.0039
70	1.0006	.9972	.9939	.9906	.9873	.9841	.9808	.9776	.9744	.9712
80	.9680	.9648	.9617	.9585	.9554	.9523	.9492	.9462	.9431	.9401
90	.9371	.9341	.9311	.9281	.9251	.9222	.9193	.9164	.9135	.9106
100	.9077	.9049	.9020	.8992	.8964	.8936	.8908	.8881	.8853	.8826
110	.8799	.8772	.8745	.8718	.8691	.8665	.8638	.8612	.8586	.8560
120	.8534	.8508	.8482	.8457	.8431	.8406	.8381	.8356	.8331	.8306
130	.8282	.8257	.8233	.8208	.8184	.8160	.8136	.8112	.8088	.8065
140	.8041	.8018	.7995	.7971	.7948	.7925	.7903	.7880	.7857	.7835
150	.7812	.7790	.7768	.7746	.7724	.7702	.7680	.7658	.7637	.7615

TEMPERATURE CORRECTION FOR SCFM

MERIAM INSTRUMENT, CLEVELAND, OHIO. 44102

A-31882

J. Read $\Delta P''$ corresponding to $Q_t/P_{cf}T_{cf}$ if different than $\Delta P'$ adjust to $\Delta P'$ by means of valve V_4.

K. If the P_f and T_f change significantly, i.e., temperature by more than 10° and pressure by more than 1 in. Hg, adjust the flow again repeating steps I and J.

NOTE: If sampling near 70°F the total flow may be set prior to insertion in the sample stream by connecting a wet test meter to the inlet of the sampling nozzle.

2. Isokinetic sampling (single point):

A. Determine the velocity (ft/min) at the sampling point with a pitot tube.

B. Calculate the sample flow rate in acfm

$$SFR\ (acfm) = V_s \times \text{Area of Nozzle}$$

Nozzle	Diameter (in.)	Area (ft^2)
N-1	1/4	0.000347
N-2	3/8	0.000767
N-3	1/2	0.001363

C. Follow procedures described in steps 1A to 1K.

3. Isokinetic sampling (multipoint):

A. Make a velocity traverse with a pitot tube.

B. Find the stack velocity at the sampling points.

C. Choose appropriate nozzle (see Section 3).

D. Calculate SFR.

E. Choose TFR and keep it constant for the entire sampling operation.

F. Obtain total sample flow rate at each point Q_1, Q_2 ...

G. Set the ΔP across M_1 to $1.1Q_1$.

H. Adjust for P_{cf} and T_{cf}.

I. Set $\Delta P''$ again.

J. Use the same P_{cf} and T_{cf} for all of the points.

K. Sample at each point adjusting the flow through the laminar flow element.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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16. ABSTRACT

A sampling interface for the quantitative transport of aerosols was designed, fabricated and evaluated. The interface may be used for transporting particles (up to 50 μm on diameter) from industrial stacks to a collection device or a monitoring instrument. The interface consists of a porous wall probe with clean air transpiring inwards to prevent deposition of particles. Laboratory and field testing of the interface has shown it to be efficient in transporting particles encountered in industrial stacks.

17. KEY WORDS AND DOCUMENT ANALYSIS

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