CONF-791015--1

MASTER

LA-UR-79-2421

TITLE: A PROTOTYPE PARTICULATE STACK SAMPLER WITH SINGLE-CUT NOZZLE AND MICROCOMPUTER CALCULATING/DISPLAY SYSTEM*

AUTHOR(S): John C. Elder, H-5
Larry G. Littlefield, H-5
Marvin I. Tillery, H-5

SUBMITTED TO: To be presented at the EPA-sponsored symposium entitled "Advances in Particulate Sampling and Measurement," October 7-10, 1979 at Daytona Beach, FL.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

By acceptance of this article for publication, the publisher recognizes the Government's (license) rights in any copyright and the Government and its authorized representatives have unrestricted right to reproduce in whole or in part said article under any copyright secured by the publisher.

The Los Alamos Scientific Laboratory requests that the publisher identify this article as work performed under the auspices of the USERDA.

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

An Affirmative Action/Equal Opportunity Employer

*This work was supported by the Environmental Protection Agency and performed at the Los Alamos Scientific Laboratory operated under the auspices of the US Department of Energy, Contract No. W-7405-ENG-36.

Form No. 836
St. No. 2629
1/75

UNITED STATES
ENERGY RESEARCH AND
DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 36

A PROTOTYPE PARTICULATE STACK SAMPLER WITH SINGLE-CUT NOZZLE AND MICROCOMPUTER CALCULATING/DISPLAY SYSTEM*

by

John C. Elder, Larry G. Littlefield, and Marvin I. Tillery
Industrial Hygiene Group
Health Division
Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87545

ABSTRACT

A prototype particulate stack sampler (PPSS) has been developed to improve on the existing EPA Method 5 sampling apparatus. Its primary features are (1) higher sampling rate (56 l/min); (2) display (on demand) of all required variables and calculated values by a microcomputer-based calculating and display system; (3) continuous stack gas moisture determination; (4) a virtual impactor nozzle with 3 μm mass median diameter cutpoint which collects fine and coarse particle fractions on separate glass fiber filters; (5) a variable-area inlet to maintain isokinetic sampling conditions; and (6) conversion to stainless steel components from the glass specified by EPA Method 5. The basic sampling techniques of EPA Method 5 have been retained; however, versatility in the form of optional in-stack filters and general modernization of the stack sampler have been provided in the prototype design. Laboratory testing with monodisperse dye aerosols has shown the present variable inlet, virtual impactor nozzle to have a collection efficiency which is less than 77% and significant wall losses. This is primarily due to lack of symmetry in this rectangular jet impactor and short transition lengths dictated by physical design constraints (required passage of the nozzle through a 7.6 cm (3 in) diameter stack port). Electronic components have shown acceptable service in laboratory testing although no field testing of the prototype under a broad range of temperature, humidity, and SO_2 concentration has been undertaken.

---

*This work was supported by the Environmental Protection Agency and performed at the Los Alamos Scientific Laboratory operated under the auspices of the U. S. Department of Energy, Contract No. W-7405-ENG-36.

Reference to a company or product name in this paper does not imply approval or recommendation of the product by the University of California or the U. S. Department of Energy to the exclusion of others that may be suitable.

INTRODUCTION

The standard manual stack sampling method for particulates, EPA Method 5,[1] was reviewed to identify needed improvements.[2] A prototype particulate stack sampler (PPSS) incorporating the more desirable improvements into a general purpose particulate stack sampler has been developed. Increasing the flow rate (double the 28 l/min of most Method 5 samplers commercially available) permits either shorter sampling time, collection of a larger sample, or greater sensitivity. Other major improvements include: electronic calculating/display of calculated variables such as stack velocity, sample volume, and per cent of isokinetic sampling conditions; electronic continuous readout instrumentation for temperature, pressure, flow, and humidity; reduced weight in individual packages; stainless steel surfaces contacting the gas stream; improved structural strength to reduce breakage; single-point particle size classification (3 μm aerodynamic diameter) in the nozzle; and optional in-stack particulate filter sampler to simplify sampling at low stack moisture conditions. Development of a null-probe device that would greatly simplify stack sampling was discontinued due to technical problems.

It was not our intention to provide an all-purpose sampler capable of particulate sampling under all environmental conditions. Design specifications that the PPSS will meet are compared with typical Method 5 capabilities in Table 1. Our experience in the early stages of the study and experience of others has shown that not all the conditions encountered in particulate stack sampling can be accommodated by a single sampler. It was therefore decided that the design specifications should accommodate the most common ranges of stack temperatures, pressures, and humidities found in actual use. Several options could also be provided to allow sampling under special conditions outside these design limits. The PPSS will not, for example, be applicable to high-temperature conditions in the typical incinerator stack, or to the high-temperature, nearly saturated conditions of the power plant stack at the outlet of a scrubber where droplets interfere with particle size classification in the nozzle.

SI or metric units have been incorporated into the PPSS to replace the British system of engineering units commonly used in existing samplers. Consistency of units is observed within the PPSS, and external data, such as barometric pressure, are entered into the calculating/display system in the proper units.

Table 1

EPA Method 5 and the PPSS Compared

Feature	Method 5	PPSS
Nozzle cutpoint	None	2.5-3.5 μm
Max. port dia.	7.6 cm (3 in)	7.6 cm (3 in)
Max. weight/pkg.	Approx 27 kg	24 kg[a]
Sample flowrate	28 l/min	56 l/min
Material	Pyrex glass	Stainless steel
Stack velocity measurement	S-type pitot	S-type pitot
Max. stack temp:		
with cooling	1000 °C	Not applicable
without cooling	320 °C	320 °C
Max. stack dia.	9 m (30 ft)	6 m (20 ft)
Max. stack gas velocity	>22 m/s	22 m/s
Max. stack gas humidity	Saturated	Nearly saturated
Particulate filters	Note b	Note b
Number of samples	5[c]	3[c]
Calculation/display	Nomograph calculation; display by dials, incline gage	Digital display on demand (by microcomputer)
Probe washing	Required	Not required after nozzle characteristics are known.

Notes

a. Production model weight can probably be reduced approximately 20%.

b. Both methods can be provided with either in-stack or out-of-stack particulate filters.

c. Number includes samples requiring preweigh, handling, and analysis by some method; i.e., filter containing solid material washed from probe, main gas filter, bleed gas filter, impinger volume, or dessicant weight.

PROTOTYPE PARTICULATE STACK SAMPLER (PPSS) COMPONENTS

The PPSS is shown schematically in Figure 1 and photographically in Figure 2. The primary components are (1) an in-stack variable-inlet, virtual impactor nozzle capable of inertially separating the particle size distribution into two fractions (single cut-point capability), (2) a straight, heated, stainless steel probe with smooth internal surfaces and an extension to provide up to 3-m inside-stack length, (3) an insulated 200-mm-diam filter holder, (4) a wet-bulb, dry-bulb psychrometer, (5) air-cooled or-water-cooled-desiccant dryer, (6) electronic flow meters, (7) carbon vane rotary pump, and (8) electronic temperature and pressure instrumentation.

Variable-Inlet, Virtual Impactor Nozzle

The variable-inlet, virtual impactor nozzle, shown in Figure 3, was designed to pass through a 7.6 cm (3 in) stack port. The rectangular virtual impactor was originally proposed as a versatile single cut-point sampler by Forney.[3] Virtual impaction was expected to provide the advantage of low particle rebound and minimal wall losses. Further, the rectangular shape of the jet was compatible with the proposed rectangular variable area inlet.

The nozzle was designed to separate gas borne particles as follows: the larger particles in the gas stream intrude into a volume of relatively stagnant air and, being unable to negotiate a sharp turn at that point, proceed to a collection filter within the nozzle; the smaller particles successfully negotiate the turn and proceed along the probe to the main sample filter. By selection of appropriate length of the jet (L), width of the jet (W), separation between jet and virtual surface (S), virtual chamber width (H), main flow (Q_m) and bleed flow (Q_b), the nozzle should provide separation of particles at the desired aerodynamic diameter cutpoint. The dimensions L, W, and S and the two flowrates are maintained constant during a sampling run. Isokinetic conditions are maintained by adjusting the nozzle opening N during the run by mechanical linkage from outside the stack.

Four versions of the variable-inlet, virtual impactor nozzle were tested by sampling monodisperse dye aerosol produced using the Berglund-Liu vibrating orifice aerosol generator. The version shown in Figure 3 was the final version. Although it was adjusted to optimum ratios of S/W and H/W recommended by Forney et al.[4], the nozzle displayed the relatively low collection efficiencies and high wall losses, as shown in Figure 4. Peak efficiency did not exceed 77% and exhibited an even lower efficiency for aerosols as large as 14 μm mass median diameter. This efficiency is total aerosol mass collected in the virtual chamber (thimble filter plus chamber wall losses) as a per cent of total aerosol mass entering the nozzle. Wall losses in the nozzle, probe, and filter holder ranged from 34-72% with particles near the cutpoint size showing the highest losses. Figure 4 shows, in less detail, the designs of the previous three virtual impactor

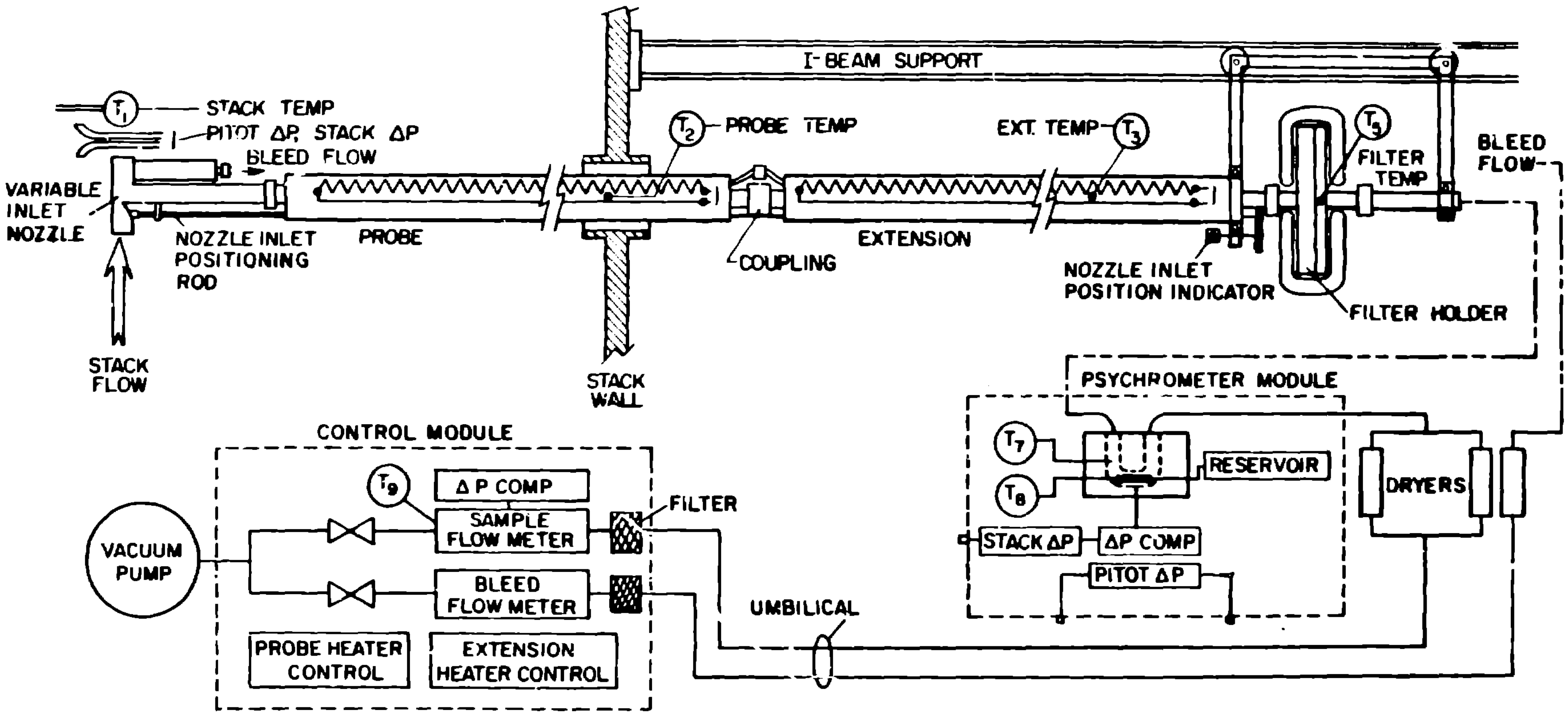

Figure 1. Schematic Diagram of the PPSS

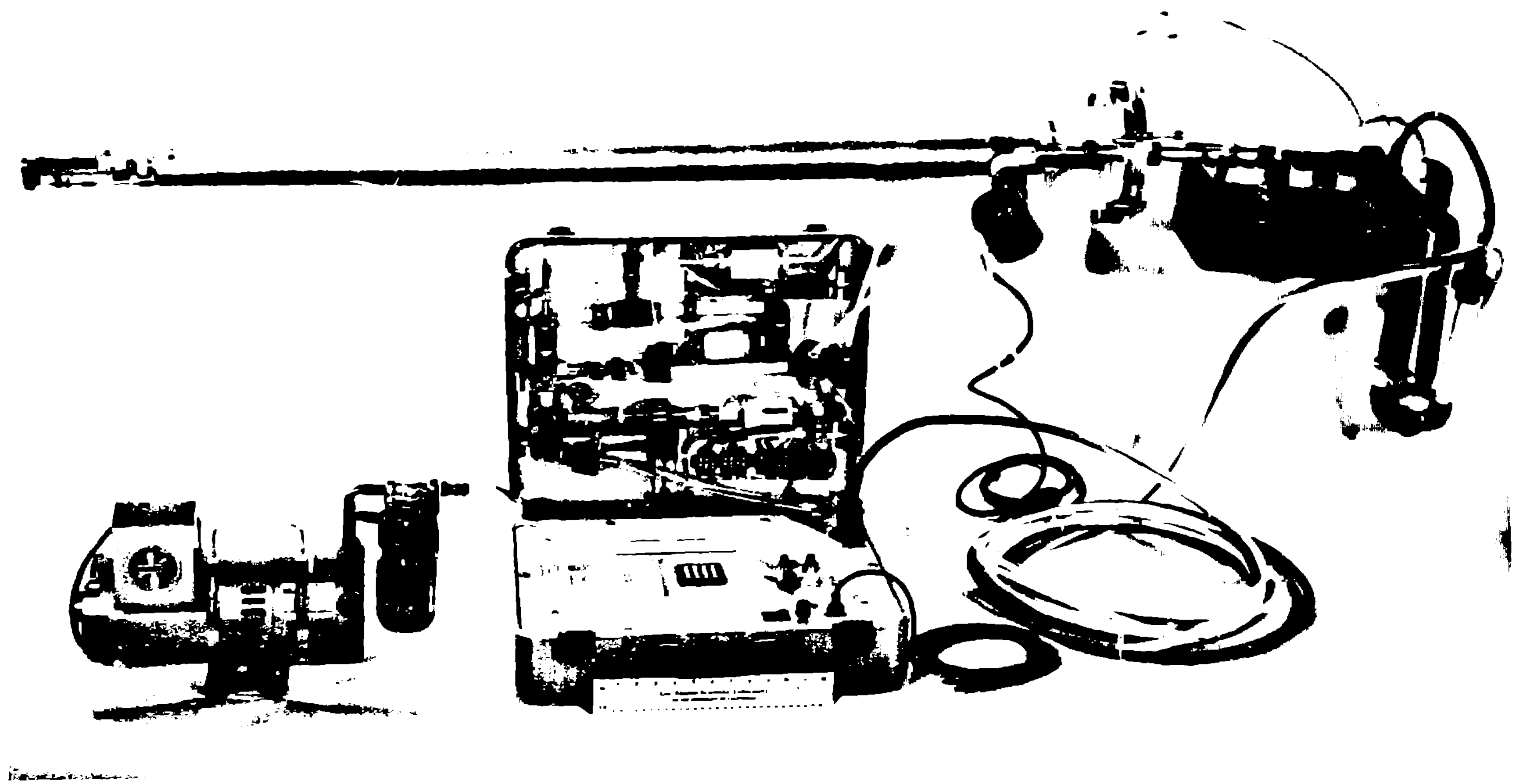

Figure 2. Overall Arrangement of the PPSS Modules

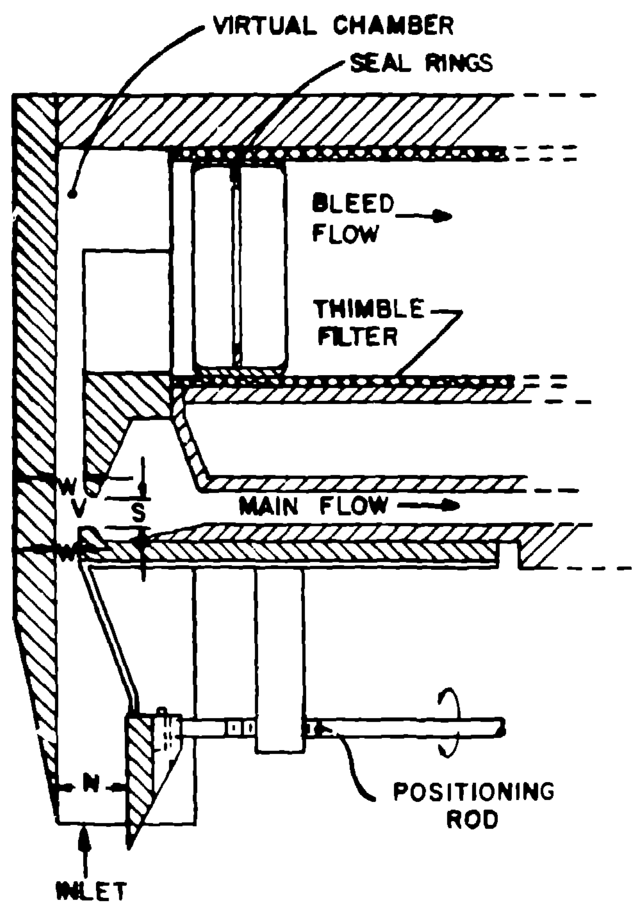

Figure 3. Section of Variable-Inlet, Virtual Impactor Nozzle (Mod 3)

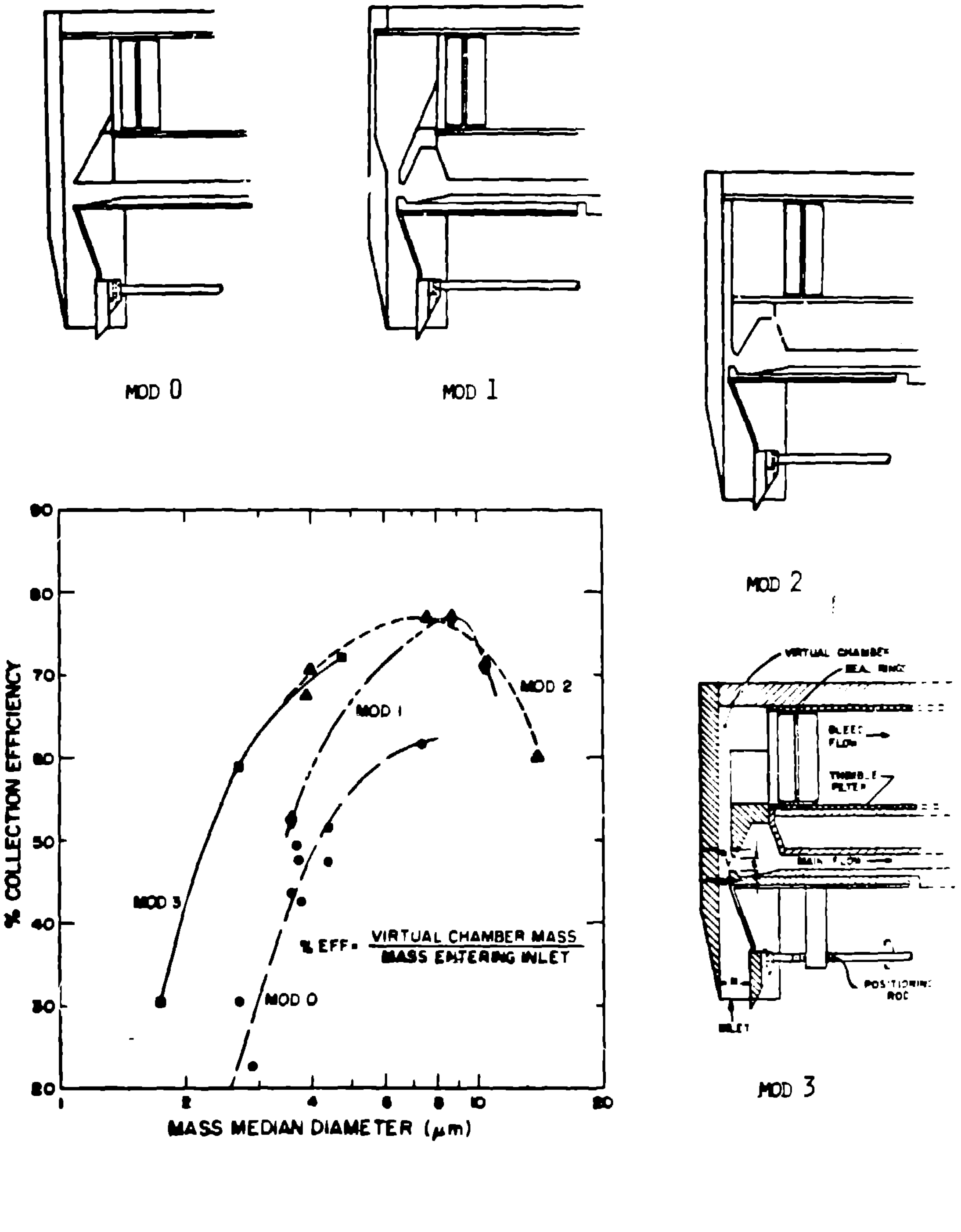

Figure 4. Test Results of Virtual Impactor Nozzle

nozzles and the performance characteristics of each of these designs. Mod 2 displayed performance characteristics comparable to those previously noted for Mod 3. Figure 5 shows a photograph, provided by Professors Ravenhall and Forney, detailing flow patterns within a water model geometrically similar to our Mod 3 nozzle. Breakup of streamlines starting before the exit of the jet illustrates nonuniformity of flow which would promote loss to the walls, particularly at a point opposite the small particle exit. Further work on this particular version is not anticipated at this time. However, if additional work is planned, it is recommended that a symmetrical nozzle (circular or annular in shape) without the constraint of fitting through a 7.6 cm port be considered. Larger port clearance will allow adequate length for smooth transitions within the inlet and nozzle and greater separation between the inlet and the flow disturbances caused by the broad body of the nozzle. Symmetry will allow the main flow stream to exit in all directions, thereby eliminating crossover and end effects inherent in rectangular impactors.

Stack Velocity Measurement

Stack velocity is determined from S-type pitot differential pressure as measured by an electronic pressure transducer with $\pm$ 25 mm H_2O range. A null-probe device (Figure 6) which provided static pressure taps internal and external to the nozzle was evaluated. The small differential pressure induced by velocity imbalance was sensed by a $\pm$ 25 mm H_2O differential pressure transducer and was minimized to achieve isokinetic conditions. The difficulty with this technique is sensing the low differential pressure required to achieve $0.9 < V_{nozzle}/V_{stack} < 1.1$. This ΔP was approximately 50 Pa (5mm H_2O) at 9.1 m/s, which was easily detectable, but was not measured with acceptable stability owing to pressure fluctuations near the large body of the variable inlet nozzle. The usefulness of a null-probe sensor was suggested by these tests, and may warrant further development.

In-Stack Filter Holder

Placement of a filter holder in the stack gas stream is not novel and is an EPA-approved procedure (Method 17).[5] The advantages of an in-stack filter are reduced deposition on extraneous surfaces and no further need for probe and filter heating. A major disadvantage appears when entrained droplets in the stack gas stream blind the filter. The PPSS provides optional capability for sampling with an in-stack filter connected to the variable-slit nozzle.

Instrumentation to Monitor Sampling Conditions

Instrumentation in the PPSS is capable of transmitting continuous voltage signals for calculating and display purposes, which replace the mechanical and manual methods of flow, pressure, and moisture measurement now part of Method 5. These instruments were selected to perform with accuracy and precision at least equivalent to that provided by Method 5 instrumentation. Field testing to establish their ruggedness has not been accomplished. Instrumentation channels are listed in Table 2 and discussed in the following sections.

Figure 5. Dye Trace in Water Model of Nozzle(Inlet at Bottom)

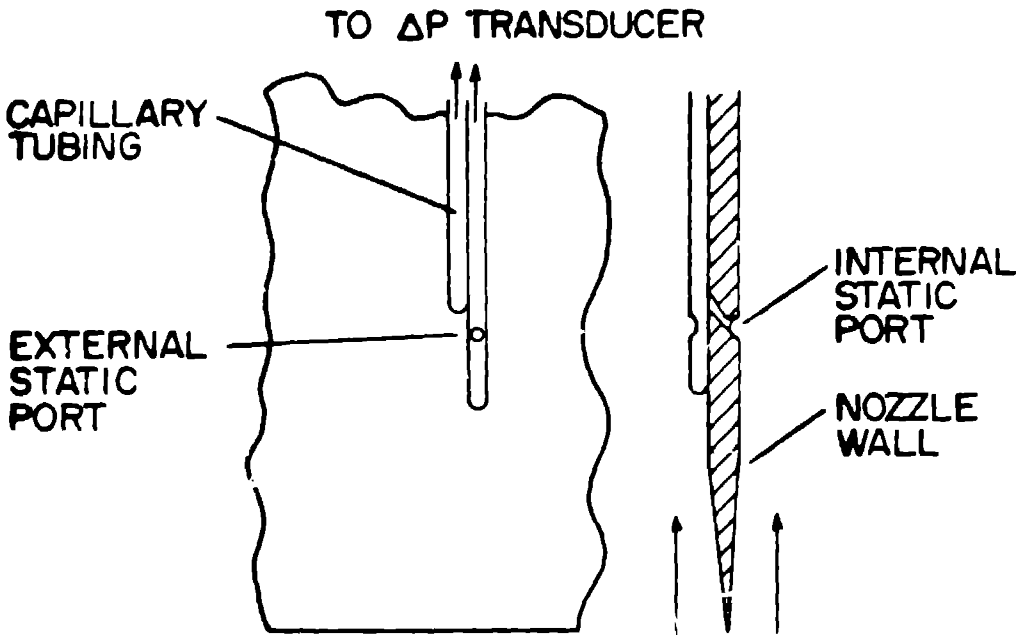

Figure 6. Static Pressure Null Probe Device

Table 2

PPSS Instrumentation Channels

Sensors	Range or Max	Type	Signal	Overall Precision
Stack temp	20-325°C	RTD*	0-5Vdc	±5°C
Probe temp	20-325°C	RTD*	0-5Vdc	±5°C
Extension temp	20-150°C	RTD*	0-5Vdc	±5°C
Holder temp	20-150°C	Thermistor	0-5Vdc	±1°C
Dry-bulb temp	20-150°C	Thermistor	0-5Vdc	±0.5°C
Wet-bulb temp	20-150°C	Thermistor	0-5Vdc	±0.5°C
Sample flow temp compensation	20-150°C	Thermistor	0-5Vdc	±1°C
Stack velocity (pitot)	±34 mb	Variable reluctance	±5Vdc	±0.05 mb
Flow meter press. correc.	±340 mb	Variable reluctance	±5Vdc	±5 mb
Psychrometer press. correc.	±340 mb	Variable reluctance	±5Vdc	±5 mb
Sample flow rate	$7\text{-}12\times10^{-4}$ m^3/s	Turbine	0-5Vdc	$\pm0.2\times10^{-4}$ m^3/s
Bleed flow rate	$1\text{-}3\times10^{-4}$ m^3/s	Hot-wire	0-5Vdc	$\pm0.1\times10^{-4}$ m^3/s
Elapsed time	0-99 min: 0-60s	Digital		
Interval time	0-99 min: 0-60s	Digital		

*Resistance temperature detector

<u>Flow Metering.</u> Since the particulate mass concentration is desired in terms of dry gas volume at standard temperature and pressure, dry gas volume is measured and automatically converted to standard conditions according to perfect gas laws. The gas stream is dried and filtered prior to entering the flow meter. Additional correction are required if constituents of the gas change from the calibration gas or if temperature or pressure of the gas stream varies from calibration conditions. Gas analysis prior to each particulate sampling run is required to provide gas constants to determine mass flow meter correction.

Two flow meter types, hot-wire and turbine, were included in the prototype to permit evaluation under field conditions since laboratory testing did not show a clear advantage of one type over the other. Datametrics hot-wire mass flow meter Model 1000.5B was used to meter the bleed flow. It is compact and lightweight and has been used successfully in other areas of our laboratory. The instrument is supplied with linearizing signal conditioning. A turbine flowmeter (Flow Technology Model FTC-8) was used to meter sample flow rate. The advantage of the turbine flowmeter over a hot-wire flow sensor is its direct indication of flow volume in the presence of gases other than the components of air. Its output does, however, require compensation for temperature and pressure changes.

Flow control is performed by manual adjustment of needle valves in the main flow stream and the bleed flow stream. This adjustment is made infrequently since normal operation with the virtual impactor nozzle requires constant flow.

Moisture Measurement. The PPSS contains a wet-bulb, dry-bulb psychrometer for measuring water vapor content of the sample gas stream. Total moisture can also be determined by measuring total weight change in the dryers. The volume occupied by water vapor is required in the isokinetic calculation to correct nozzle inlet velocity, which is volumetric flowrate of wet gas divided by probe nozzle cross-sectional area. The psychrometer, shown in Figure 7, is located immediately behind the sample filter where temperature of the gas stream is maintained above dew point. The wick material is polyester, which is resistant to the acids (primarily dilute H_2SO_4) encountered in some sampling situations. The wick is fed from a water reservoir through a stainless steel tube approaching within 3 mm of the thermistor thermometer from the downstream side. Covering the feed tube with the wick adjusts the temperature of the feedwater to approximately that of the wet bulb temperature and prevents cooling or heating of the wet bulb thermistor by the feedwater.

The wet-bulb, dry-bulb psychrometer may be used up to dew points of 100°C with reasonable accuracy (less than 5% maximum error). Other methods of moisture measurement such as cooled-mirror dew-point devices, hygroscopic salt devices and semiconductor devices are limited by maximum ambient temperature, usually about 50°C.

Pressure Measurement. Three pressure channels are required in the PPSS: pitot tube differential pressure (stack gas velocity); pressure at the psychrometer; and pressure at the flow measurement section to allow pressure compensation of flow rates. Pressure within the stack to allow calculation of total stack volumetric or mass discharge is measured occasionally by connecting one leg of the pitot tube to one of the existing transducers. The operating ranges of these instruments are listed in Table 2. Datametrics variable-reluctance, differential-pressure transducers with miniaturized carrier demodulators which supply dc voltage to the calculating/display system were used to monitor pressure. These transducers are lightweight and have displayed good stability.

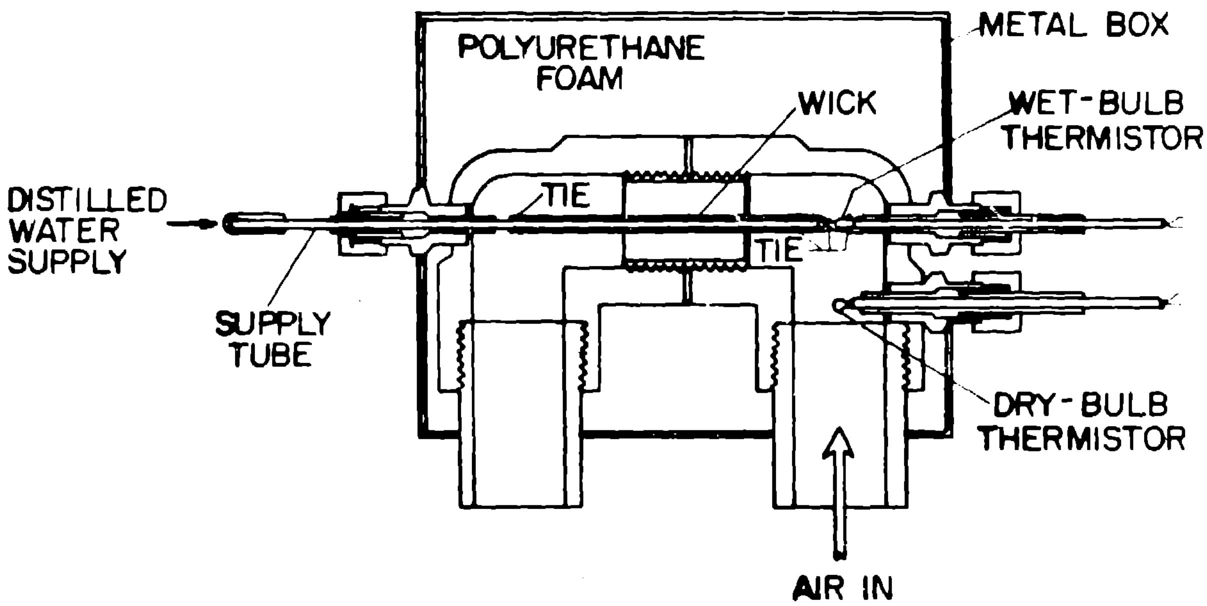

Figure 7. Arrangement of Wet-Bulb, Dry-Bulb Psychrometer

Temperature Measurement. All temperatures except stack temperature, probe temperature, and extension temperature are sensed by Yellow Springs Thermilinear thermistors which show good linearity and response. They are delicate and must be potted with epoxy to make them more rugged and resistant to acid. The accuracy of the measuring circuit is generally within $\pm 0.2^{o}C$ over the range 0-93°C. Stability appears adequate, showing standard deviation of 0.05°C on the difference between two thermistors in an oil bath. This order of stability is required by psychrometric calculation which is based on wet-bulb, dry-bulb depression. Sensitivity of the thermistor circuit is set at 0.1 V/°C, far exceeding response of any thermocouple.

Stack temperature, probe temperature, and extension temperature sensors are resistance thermometers (RTD) (Yellow Springs Platinum RTD 0-138 AX), which provide the additional range required at these locations.

Calculating/Display System

A calculating/display system is an integral part of the PPSS.[6] The system incorporates a microcomputer and microprocessor to calculate stack volumeric flow rate, sample flow rate, isokinetic ratio, and various temperature and pressure compensation factors. A block diagram of the system is shown in Figure 8.

The system operates on 115-Vac, 60-Hz line power and retains read-only (program) memory in the event of power loss. It displays data in large (1.3-cm) liquid crystal displays (LCD) visible in strong sunlight. Isokinetic ratio is updated and displayed whenever other values are not demanded. All other variables are displayed on demand through the keyboard. Separate clocks provide elapsed time and interval time capabilitiy (interval time prompts move to new sampling location).

The National Semiconductor MM 57109 MOS/LSI number-oriented microprocessor performs the number processing/calculation. This 28-pin dual in-line package provides scientific calculator instructions (key level language) with reverse polish notation entry. The capabilities of this device include all of the functions available on the Hewlett Packard HP-21 hand calculator. The Intel ASM 48 single-component microcomputer performs data sequencing computation processing and display updating.

The microcomputer is programmed in assembly language and allows operation in the following selected modes:

a. Load constants - allows loading of all constants specific to the run (i.e., barometric pressure, gas constants, etc.);

b. Profile - allows velocity traverse across the stack while calculating stack velocity.

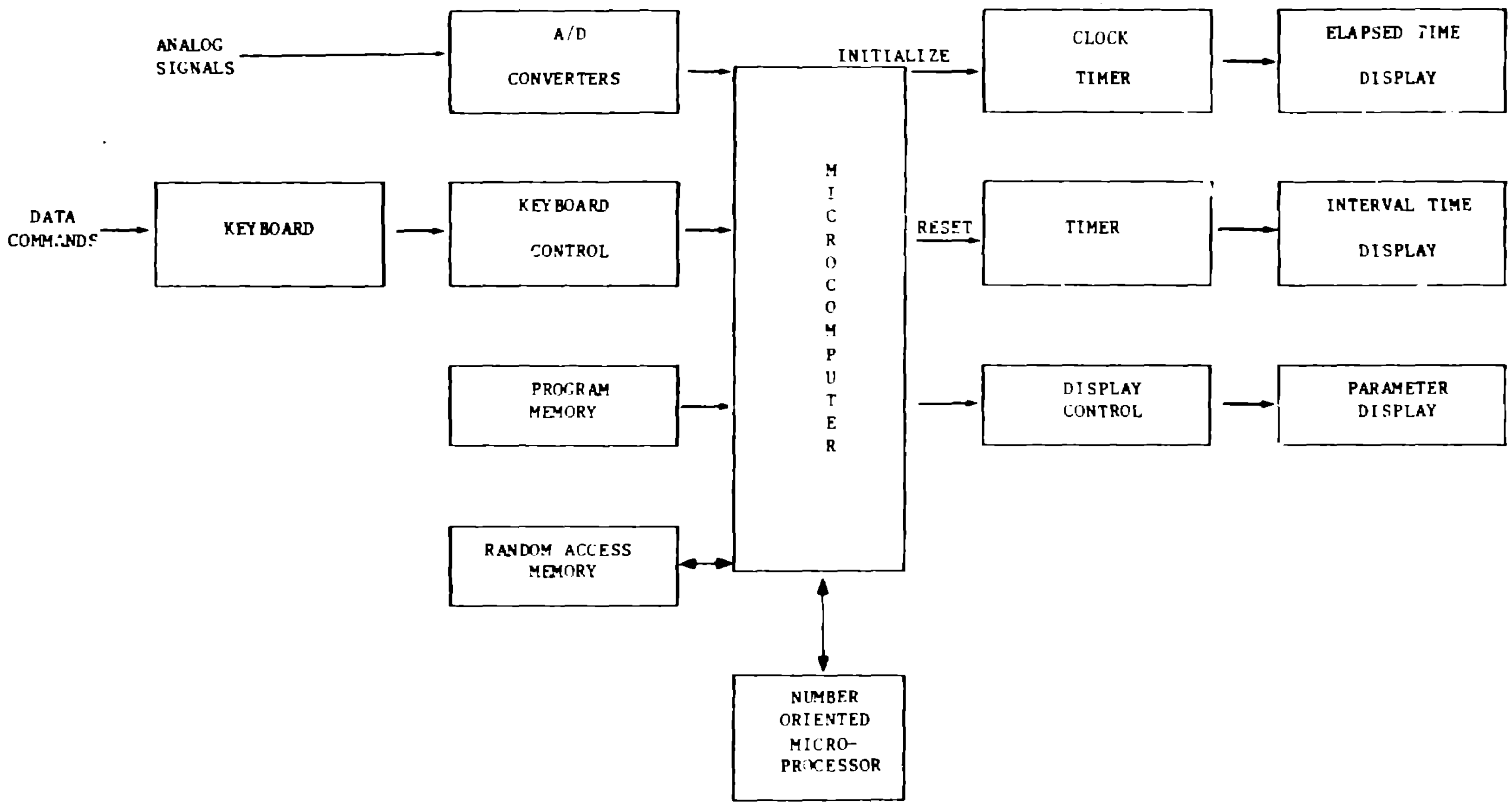

Figure 8. Block Diagram of PPSS Calculating/Display System

c. Static pressure - allows stack pressure to be measured using the transducer usually assigned to monitoring psychrometer pressure;

d. Main - starts the clocks and updating of all calculated variables;

e. Main pause - allows temporary interruption of the run to relocate the sampler to another port; also accommodates mid-run delays for any other reason.

Although interfacing the microcomputer with all analog signals has been completed and all calculations checked for accuracy, overall system errors over typical ranges of operation remain to be determined. The microcomputer has functioned without failure since original debugging of its software. Its operation is rapid, with maximum calculating time 7.5 sec for updating stack velocity.

Equipment and Structural Arrangement

The vacuum pump selected for the PPSS is a Gast 1022 carbon vane rotary pump, which provides 280 l/min at 0 mmHg and 68 l/min at -500 mmHg. Maximum pressure drop in the PPSS is 415 mmHg (100 mmHg occurring in the nozzle, 115 mmHg in the 200-mm filter holder, and 200 mmHg in the dryer). The Model 1022 pump weighs 23.6 kg (52 lb) and is the heaviest component in the PPSS. In general, weight of any other major component is limited to about 14 kg (31 lb).

The probe of the PPSS will be supported by an I-beam cantilevered outward from the stack. This arrangement, shown in its basic form in Figure 1, will be similar to Method 5 arrangement. The probe is clamped in two places by a trolley device which straddles the filter holder.

The sampling probe is a straight 2.32 cm ID tube of type 304 stainless steel. Total heated length is 130 cm. The probe is heated in the manner of EPA Method 5, controlled by separate automatic controller, and is provided with a cooling air blower for temperature reduction to 120°C when sampling intermediate temperature stacks. The probe extension is about the same weight and length as the sampling probe and allows 3m total length.

Lightweight dryers containing silica gel desiccant are provided for both the main and bleed streams. The dryer is designed for either air or ice bath cooling. Silica gel crystals are packed within stainless steel bellows tubing. A change in mass of the dryer can be used as a measure of total moisture in the sample gas stream. Recharging is accomplished by replacement of desiccant or drying in a warm oven (70°C).

SUMMARY AND CONCLUSIONS

A prototype particulate stack sampler has been developed with the following primary features: (1) nominal 56 l/min sampling flow rate, (2) electronic transducers for pressure, temperature, flow, and humidity ratio, (3) stainless steel surfaces and components not subject to breakage, (4) electronic calculating/display system providing direct display of updated data such as stack velocity, sample volume, and isokinetic ratio, (5) single-point particle size classification in the nozzle, (6) continuous adjustability of nozzle inlet area, and (7) manageable weight of individual components. A wet-bulb, dry-bulb psychrometer provides continuous indication of moisture content of the gas stream. The psychrometer is a particularly promising device in the severe conditions of high temperature (95 to 100°C) and high humidity in which the device must operate.

The variable inlet, virtual impactor nozzle has potential for well-characterized separation of fine and coarse particulate, although versions tested to date have shown collection efficiencies which do not exceed 77%, and high wall losses. A new design with symmetry in flow passages and less dimensional constraint is recommended.

In general, the PPSS has the operating capability of the existing Method 5 sampling train, has modernized its design, and has eliminated the obvious problem areas. However, field demonstration of the prototype might reveal other problems in the novel areas of the PPSS design. The effect of acid on the psychrometer wick and of presence of CO_2, SO_2, and other contaminants on behavior of the psychrometer is not known. Also, stainless steel surfaces in the PPSS may provide greater potential for formation of sulfate aerosols than in the glass components of the Method 5 train. Component ruggedness remains to be proven by field testing.

ACKNOWLEDGEMENTS

We would like to acknowledge the assistance of the following personnel in developing the PPSS design: Dwayne C. Ethridge, LASL, and Professors Forney and Ravenhall of the University of Illinois, Urbana-Champaign.

REFERENCES

1. Federal Register 36 (247): (December 23, 1971).

2. J. C. Elder, M. I. Tillery, and H. J. Ettinger, "Evaluation of EPA Method 5 Probe Deposition and Filter Media Efficiency," Los Alamos Scientific Laboratory report LA-6899 PR (August, 1977).

3. L. J. Forney, "Aerosol Fractionator for Large-Scale Sampling," Rev. Sci. Instrum. 47, No. 10, 1264-1269 (October, 1976).

4. L. J. Forney, D. G. Ravenhall, and D. S. Winn, "Aerosol Impactors: A Study of a Fluid Jet Impinging on a Void," J. App. Phys., 49, No. 4 (April, 1978).

5. Federal Register 41 (187): (September 24, 1976).

6. C. D. Ethridge and L. G. Littlefield, "Microcontroller for Exhaust-Stack Environmental Measurements," Los Alamos Scientific Laboratory report LA-UR-79-968 (June, 1979).