APCA Paper No. 67-119

STACK GAS SAMPLING IMPROVED AND SIMPLIFIED WITH NEW EQUIPMENT

by

W.S. Smith, R.M. Martin, D.E. Durst, R.G. Hyland,
T.J. Logan, and C.B. Hager
Engineering Control Section
Control Development Program
National Center for Air Pollution Control
Cincinnati, Ohio

Public Health Service
Bureau of Disease Prevention and Environmental Control
U.S. Department of Health, Education, and Welfare

ABSTRACT

Commercially available equipment necessary for isokinetic sampling of process gases proved cumbersome and inadequate for recent atmospheric emission studies of chemical and combustion processes. The Public Health Service has therefore designed a compact, portable, sturdy stack sampling train capable of collecting solids, mists, and gaseous pollutants from most chemical and combustion processes.

This paper presents the theory, design, and operation of the stack sampling apparatus and a discussion of its application to date.

KEY WORDS: Source testing, particulate, design, equipment, air pollution

To be presented at the 60th Annual Meeting of the Air Pollution Control Association, June 11-16, 1967, Cleveland, Ohio.

STACK GAS SAMPLING IMPROVED

AND SIMPLIFIED WITH NEW EQUIPMENT

by

W.S. Smith, R.M. Martin, D.E. Durst, R.G. Hyland
T.J. Logan, and C.B. Hager
Engineering Control Section
Control Development Program
National Center for Air Pollution Control
Cincinnati, Ohio

Public Health Service
Bureau of Disease Prevention and Environmental Control
U.S. Departement of Health, Education, and Welfare

INTRODUCTION

The United States Public Health Service entrusted to the Control Development Program the task of measuring air pollutant emissions at their sources. This work required a highly mobile test team, which had to travel to distant parts of the country to conduct source tests for a variety of emissions. Basic measurements taken by the test team were particulate, gaseous pollutants, and effluent flow. Because the equipment needed for this work was not commercially available, it had to be built.

Briefly, described in this paper is the sampling train designed and built by the Control Development Program.* The sampling train has demonstrated, over more than a year of use, the following advantages:

1. Accuracy within 5 percent for isokinetic sampling.
2. Adaptability to most chemical and combustion processes.
3. Portability and compactness for frequent and rapid transportation.
4. Durability to withstand frequent shipping.
5. Reliability to avoid the high cost and difficulties of making field repairs.

*This paper is not intended as a manual on the construction or use of the sampling train as brevity has resulted in the omission of pertinent details. A more detailed paper suitable for constructing and operating the sampling trains will be published at a later date.

6. Interchangeability of parts to simplify maintenance.
7. Rapid setup and disassembly.
8. Simple operation for routine testing.
9. Low cost per sample.

A nomograph, alignment charts, and a computer program developed along with the sampling train have greatly facilitated calculations and data handling.

EQUIPMENT DESCRIPTION

The primary purpose of particulate sampling is to determine the weight of solids, and sometimes liquids and condensable vapors, in a specific volume of stack gas. The sampling must be isokinetic, and the stack gas velocity must be measured if the emission rate is to be determined.

The equipment used by the Control Development Program is shown in action in Figure 1.

The apparatus is divided into five major components:

1. Pitobe- combination sampling probe and pitot tube.
2. Sample box - contains the glass sampling equipment.
3. Duorail - supports the pitob and sample box on the stack.
4. Umbilical cord - connects sample box with the meter box.
5. Meter box - contains volumetric flow meters, manometers, vacuum pump, and electrical controls for sampling.

Pitobe

The pitobe* consists of: a sample nozzle, heated probe, and pitot tube (see Figure 2). The sample nozzle is made of stainless steel tubing formed

*Pitobe - derived from combining the words pitot and probe.

so as to be directed into the gas stream without any sharp bends in the tubing. The tip is beveled 15 degrees on the outside to provide a knife edge to minimize stream turbulence. A range of nozzles is required to give flexibility in sampling gas streams of different velocity. The inside diameters of the nozzles range from 1/8 to 1 inch. A sample port of 2-1/2-inch diameter was chosen as a practical minimum size, and all nozzles are designed to fit this opening. The shank end of the nozzle is attached to the probe through a Swagelock* union (Figure 2).

The probe is a 1/2-inch-diameter Kimax tube wrapped with the nickel-chromium wire. A high-termperature resistant tape is wrapped over the wire. The wrapped Kimax tube is then inserted into a 1-inch-diameter stainless steel tube, or sheath. The Kimax tube has a butt joint on the nozzle end (Figure 2). The Kimax tube is held in the stainless steel tube at the nozzle by an O-ring inside a 1/2-inch Swagelock fitting welded to the stainless steel tube. The sample box end of the tube is equipped with a ball joint for easy connection to the sample box glassware. The Kimax tube is held within a 1/2-inch bored No. 7 rubber stopper. The stopper also has a 1-inch-diameter dado, 1/4 inch deep, for insertion over the end of the steel tube. The nickel-chromium wire is connected to 2 feet of stranded 16-gauge insulated copper wire for connection to the sample box. The wire exits through a slit in the steel tube. The probes, which can be of any length suitable for the job, are stacked in several different lengths for flexibility of sampling.

*Mention of company or product names does not constitute endorsement by the U.S. Department of Health, Education, and Welfare or the Public Health Service.

The stainless steel tube is welded longitudinally to a pitometer (S-type pitot tube) so situated that its openings are adjacent to the sample nozzle. The pitometer is made from 3/8-inch outside-diameter, thin-walled, stainless-steel tubing. Quick-disconnect fittings soldered on the end permit rapid connection to manometer lines.

Sample Box

The pitobe is attached to the sample box that houses the glassware for particulate collection (see Figure 3). The ball joint from the pitobe connects directly to a glass cyclone designed to remove particles greater than 5 microns in diameter. The cyclone is followed by a glass holder with a coarse-porosity fritted-glass filter. Both the cyclone and filter are maintained between 240° and 280°F. Next in line are four Greenberg-Smith impingers in an ice bath. Only the second impinger has the original impinger tip, the other three have had the tip removed to decrease the pressure drop through them. The first and second impingers are filled with 250 and 150 milliliters of deionized water, respectively. The third impinger is left dry to remove entrained water. The last impinger contains silica gel to remove any remaining water.

The sample box is made of plywood (Figure 3). The front left compartment (viewing the sample box from the pitob) houses a blower and electrical circuitry. The blower circulates air through a thermostatically controlled heating element in the left rear compartment. The right side contains the ice bath and four impingers connected to the filter through a hole in the side of the enclosed heated compartment.

The box is fiberglassed and varnished to make it more durable and imprevious to water. Polyethylene foam insulates the ice bath from the heated compartment and supports the impingers.

Duorail

Angled aluminum is attached to the sides of the sample box so that it may be moved either horizontally or vertically along two aluminum rails attached to the sides of the duct. The "duorail" is a long rectangle, the front of which is mechanically clamped to the sample port. The rear is supported by an angled aluminum brace, which is placed at an angle against the stack and held there by nylon cord tied around the duct and/or up to the front of the duorail. That is, the duorail is one leg of a right triangle, the nylon cord (paralleling the stack) is the second leg, and the brace forms the hypotenuse. The duorail has proved very versatile in fastening the sampling equipment to the stack, and the sampling equipment can usually be attached to any stack without scaffolding.

Umbilical Cord

The umbilical cord (Figure 4) connects the last modified Greenberg-Smith impinger, the pitot tube, and the heating elements to the meter box. It consists of four parts:

1. A 3/8-inch vacuum hose with a ball-joint connection to the sample box and a quick disconnect connection to the meter box (connects impinger to meter box vacuum pump). A thermometer and check valve are built into the ball-joint connector.

2. Two 1/4-inch lines made of Tygon tubing with quick disconnects on both ends of the tubing (connects pitot tube to the meter box manometer).
3. Four multistrand insulated conductors with Amphenol connectors on both ends (connects sample box circuit to meter box power supply).
4. Ground wire.

Meter Box

The umbilical cord attaches to the meter box, which contains a vacuum pump, regulating valves, instantaneous and intergrating flow meters, pitot tube manometers, vacuum gauge, and electrical controls. Figure 5 is a photograph of the meter box control panel.

The pitot tube lines of the umbilical cord connect through a quick-disconnect fitting to an inclined/vertical manometer. A U-tube mercury manometer is also connected to one leg of the pitot line; the other leg is open to the atmosphere. This manometer is used to measure the static duct pressure when the pitot tube is turned perpendicular to the flow stream. A schematic of the meter box plumbing is shown in Figure 6. The umbilical cord sample line connects through a quick-disconnect valve to the vacuum pump.

The pump intake vacuum, and indirectly the pressure drop across the collection apparatus, is monitored with a vacuum gauge just after the quick disconnect. The pressure drop across the sample apparatus is the gauge vacuum less the stack draft. The vacuum pump has a quick disconnect immediately before and after the pump. An auxiliary pump

may be connected if additional pumping capacity is required. A bypass valve is in parallel with the vacuum pump to give fine flow control and to permit recirculation of gases at low sample rate so that the pump motor is not overloaded. Downstream of the pump and bypass valve are a thermometer, dry gas meter, another thermometer, and a calibrated orifice with an inclined/vertical manometer in parallel. The calibrated orifice and inclined/vertical water manometer are used to indicate the instantaneous sampling rate. The dry gas meter gives an integrated gas-sample volume. The average of the two temperatures on each side of the dry gas meter gives the temperature at which the volume is sampled. The meter pressure is the atmospheric pressure plus the orifice pressure drop.

The electrical circuitry for the meter box is shown schematically in Figure 7. Many of the electrical controls are shown in Figure 5. The meter box has a pilot light to indicate when the meter box is energized and a 110-volt outlet to provide power for accessories. Four toggle switches are located on the front of the meter box to control:

1. Vacuum pump, auxiliary pump outlet, timer with buzzer, and a pilot light.
2. Fan in the sample box and a pilot light on the meter box.
3. Heating element in the sample box and a pilot light on the meter box, all in series with the toggle switch for the sample box fan. This prevents the heating element from operating without the fan; however, the fan can operate without the heating element.

4. Probe heating element controlled by a variable transformer and a pilot light.

The sample box fan and heating element, and the probe heating element along with a common ground are connected to a four-pronged female Amphenol for ready connection to the umbilical cord.

SAMPLING TRAIN OPERATION

The most difficult part of sampling is frequently installation of the sampling equipment in a position to sample. Occasionally, the sample port is not near a catwalk or other structure to accommodate the sample box. On the spot ingenuity is required to determine how to get the sampling equipment to the sample port. The duorail described previously has proved very versatile in solving this problem.

A preliminary traverse is made with a pitot tube. In a rectangular duct a pitot traverse, or sample traverse, is made by dividing the duct into equal areas and sampling at the center of each area. In a circular duct a traverse is made by dividing the duct into equal concentric areas and sampling in the center of each area on both sides of the center. The number of equal areas chosen depends on the size of the duct and accuracy desired. From a nomograph (described in the next section) the nozzle that will give isokinetic sampling at approximately 3/4 cubic foot per minute is selected.

The cyclone, flask, and coarse-porosity fritted filter are placed in the heated portion of the sample box, which is maintained between

240° and 280°F. The fritted filter is usually used as a filter holder for a 934 AH Unico glass fiber filter. The four impingers are filled and placed in the ice bath in the following order.

1. Modified Greenberg-Smith impinger filled with 250 milliliters of deionized water.
2. Greenberg-Smith impinger filled with 150 milliliters of deionized water.
3. Modified Greenberg-Smith impinger left dry to remove entrained water.
4. Modified Greenberg-Smith impinger containing approximately 175 grams of precisely weighed dry silica gel.

The pitobe is attached to the sample box. The meter box is located in a convenient place within 100 feet of the sample port. The umbilical cord is connected to the meter box and sample box. The pitob of the sample box is inserted into the sampling port. Sampling is begun as soon as the sample box temperature reaches 250°F. The number of traverse points made of the stack depends on its configuration and the accuracy desired. The sampling time at each traverse point depends upon the loading and moisture of the stack. The limiting factor here is the amount of particulate the cyclone and filter can hold, the amount of condensate the impingers can accommodate, and the pressure drop that develops across the sampling equipment. Generally, 5 or 10 minutes per traverse point is adequate. The pitobe is moved quickly from traverse point to traverse point without turning off the vacuum pump. The sample rate is maintained isokinetic at the meter box by observing the pitot tube manometer reading, performing the necessary

computations on the nomograph, and correcting the sampling rate to comply. Recordings of temperatures, manometer pressure, and dry gas meter volumes are made at the start and the end of each traverse point, and whenever a change occurs while at a traverse point.

FIELD CALCULATIONS

Isokinetic sampling requires that the sampling velocity through the nozzle be equal to the effluent velocity in the stack. The nozzle velocity is determined from the volumetric sampling rate. Both stack velocity (measured by the pitometer) and volumetric sampling rate (measured by the calibrated orifice) are indicated by manometer pressure differentials. For isokinetic sampling, the calibrated orifice manometer is made dependent on the pitometer manometer by combining the pitometer equation,

$$V_p = C_p \sqrt{\frac{2 g_c \Delta P R T_s}{P_s M_s}} \qquad (1)$$

with an equation relating volumetric sampling rate to effluent velocity through the nozzle,

$$Q_m = \frac{\pi}{4} D^2 V_p \frac{T_m}{T_s} \frac{P_s}{P_m} M_c \qquad (2)$$

where: C_p = pitometer calibration factor, dimensionless

g_c = gravitational constant, 32.17 (lb_{mass}) (ft)/(lb_{force}) (sec^2)

ΔP = pitometer pressure differential, $(lb_{force})/(ft^2)$

R = gas-law constant, 1545 (ft)(lb_{force})/(°R) (lb-mole)

T_s = stack gas temperature, °R

P_s = stack gas pressure, $(lb_{force})/(ft^2)$

M_s = effluent molecular weight, $(lb_{mass})/(lb\text{-}mole)$

Q_m = volumetric flow rate, ft^3/sec

D = nozzle diameter, ft

V_p = stack velocity at traverse point, ft/sec

T_m = effluent temperature at the meter, °R

P_m = meter pressure, $(lb_{force})/(ft^2)$

M_c = mole fraction of dry gas in stack effluent, dimensionless.

When a calibrated orifice is used to measure Q_m,

$$Q_m = JA \sqrt{\frac{T_m \, \Delta H \, 2 \, g_c \, R}{P_m \, M_m}} \qquad (3)$$

where: J = orifice coefficient, dimensionless

A = orifice area, ft^2

ΔH = orifice pressure differential, $(lb_{force})/(ft^2)$

M_m = dry effluent molecular weight, $(lb_{mass})/(lb\text{-}mole)$

Combining and rearranging Equations 1, 2, and 3 give the dependency of the calibrated orifice manometer on the pitometer manometer,

$$\Delta H = K \, (\Delta P) \, D^4 \, T_s^{-1} \qquad (4)$$

where: $$K = \left(\frac{\pi C_p M_c}{4JA}\right)^2 \quad \frac{M_m}{M_s} \quad \frac{P_s}{P_m} \quad T_m \qquad (5)$$

Stack velocities not only change between different traverse points, but also vary at a point because of variable flow conditions. The calculation of Equation 4 presents an undesirable time lag between changes

in stack velocity and sampling rate. In addition, too frequently errors are made when calculations are attempted under the stress of field sampling conditions. The net result is deviation from isokinetic sampling.

A three-independent-variable nomograph constructed to represent Equation 5 reduces calculation time to a few seconds (Figure 8). The K term in Equation 4 is usually a constant during sampling, but it may change for different sampling locations or processes. A four-independent-variable nomograph could be used; but, because this would make the nomograph that much larger and unwieldy and because K does not frequently vary, K is incorporated into the T scale. This is done by making the T scale movable and setting its position with a C scale. The C scale is a ratio of the true value of K to an assumed value. If the values for K vary from the assumed values, then a new value for C is obtained from a second nomograph (Figure 9). The nomograph of Figure 8 is based on the assumption that there is 5 percent water in the stack gas and 0 percent water passing through the orifice. It assumes a dry gas molecular weight of 29, atmospheric and stack pressures of 29.92 in. Hg, a meter temperature of 70°F and a $\Delta H_@$ (the orifice pressure differential that gives 0.75 cubic feet per minute for dry air at 70°F and 29.92 in.Hg) of 1.84. The nomograph of Figure 9 corrects for different stack and atmospheric pressures, different stack gas moistures, and different gas temperatures at the orifice. Figure 9 does not correct for moisture in the gas passing through the orifice nor molecular weight changes other than those due to water in the stack gas.

The construction of the nomographs will not be detailed. Instead, the reader is referred to other references that describe nomograph construction.[3]

Use of the nomograph (Figure 8) is as follows:

Prior to sampling:

1. Obtain C from Figure 9, and set the T scale.
2. Make a rough preliminary pitot traverse, and determine the minimum, average, and maximum ΔP.
3. Measure approximately the stack temperature, T.
4. Align T and the ΔP's from step 1, and choose a convenient nozzle diameter, D.
5. Align T and D to obtain a ΔP.
6. Align the ΔP from step 5 and the reference point on the ΔH line to obtain a K factor setting.
7. Keep this K factor setting as a pivot.

During sampling:

8. Determine ΔH for the ΔP's of the pitot traverse.
9. If T changes, repeat steps 3 through 8.

CALCULATIONS

The samples obtained in the field are returned to the laboratory for particulate analysis. Impinger solutions can be analyzed for soluble gaseous emissions. In some instances it may be desirable to replace the water used in the impingers with a solution to react with, or absorb, the gaseous constituents of the sample. The water content of the sampled gas is calculated from the vapor removed in the impingers. The stack gas velocity is calculated from the pitot traverse data. The particulate in the stack gas is expressed as weight per standard cubic foot or weight per unit time. Gaseous emissions are expressed in the units of parts per million (volume ratio) or weight per unit time. For combustion processes a measurement of carbon dioxide is usually made with an Orsat analyzer. The particulate and gaseous emissions are frequently corrected to a base of 12 percent carbon dioxide.

CONCLUSION

The Control Development Program's sampling train can be used for measuring particulate and gases in ducts and stacks of most chemical and combustion processes. Thus far it has been used to take measurements in the following processes: wet phosphoric acid, furnace phosphoric acid, phosphate fertilizer, chlorine, titanium, incineration, and coal combustion. In every case it has proved successful. Extreme conditions, such as high stack gas temperature (>1500°F), requires slight modification of the equipment. One feature that makes the Control Development Program's sampling train more accurate than other particulate sampling trains is the simultaneous pitot traverse with the sampling to insure isokinetic conditions. (The null balance particulate sampling technique also accomplishes isokinetic sampling; however, the static pressure taps plug easily, and stack velocity is not measured directly with the null balance technique.)

The use of sampling trains in module form and the elimination of calculations have greatly simplified stack sampling. This approach has reduced manpower requirements, the skill needed by operators, cost, and has improved the accuracy of measurements. For example, a team of two men can enter a chemical plant, sample a stack in triplicate, and leave the plant within an 8-hour work day.

The equipment developed by the Control Development Program is not the final word on particulate sampling equipment, but there does not appear to be any currently available equipment that will answer the need as well.

NOMENCLATURE

A = orifice area, ft^2

C = $(K_{actual})/(K_{assumed})$, dimensionless

C_p = pitometer calibration factor, dimensionless

D = nozzle diameter, ft

g_c = gravitational constant, 32.17 $(lb_{mass})(ft)/lb_{force})(sec^2)$

ΔH = orifice pressure differential, $(lb_{force})/(ft^2)$

$\Delta H_@$ = orifice pressure differential that gives 0.75 cfm of air at 70°F and 29.92 in. Hg, $(lb_{force})/(ft^2)$

J = orifice coefficient, dimensionless

K = defined by Equation 5

M_c = mole fraction of dry gas in stack effluent, dimensionless

M_m = dry effluent molecular weight, $(lb_{mass})/(lb\text{-mole})$

M_s = effluent molecular weight, $(lb_{mass})/(lb\text{-mole})$

P_m = meter pressure, $(lb_{force})/(ft^2)$

P_s = stack pressure, $(lb_{force})/(ft^2)$

ΔP = pitometer pressure differential, $(lb_{force})/(ft^2)$

Q_m = volumetric flow rate, $(ft^3)/(sec)$

R = gas-law constant, 1545 $(ft)(lb_{force})/(°R)(lb\text{-mole})$

T_m = effluent temperature at the meter, °R

T_s = stack gas temperature, °R

V_p = stack velocity at a traverse point, ft/sec

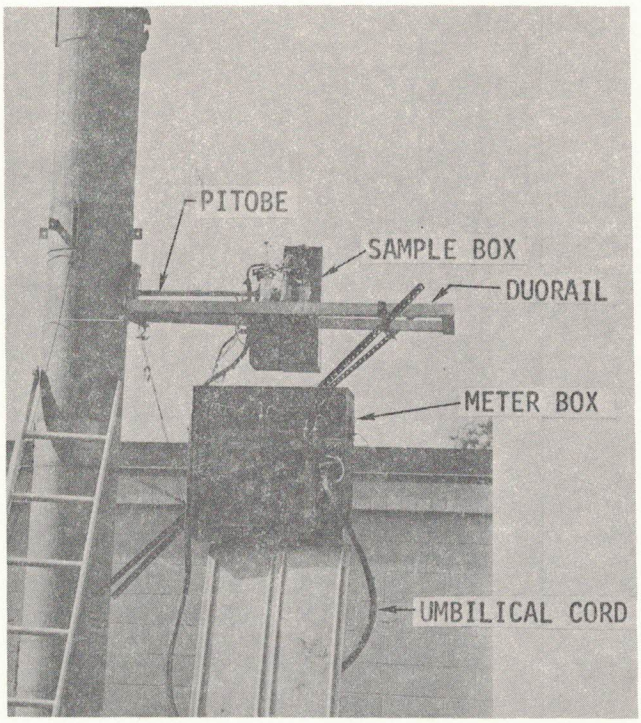
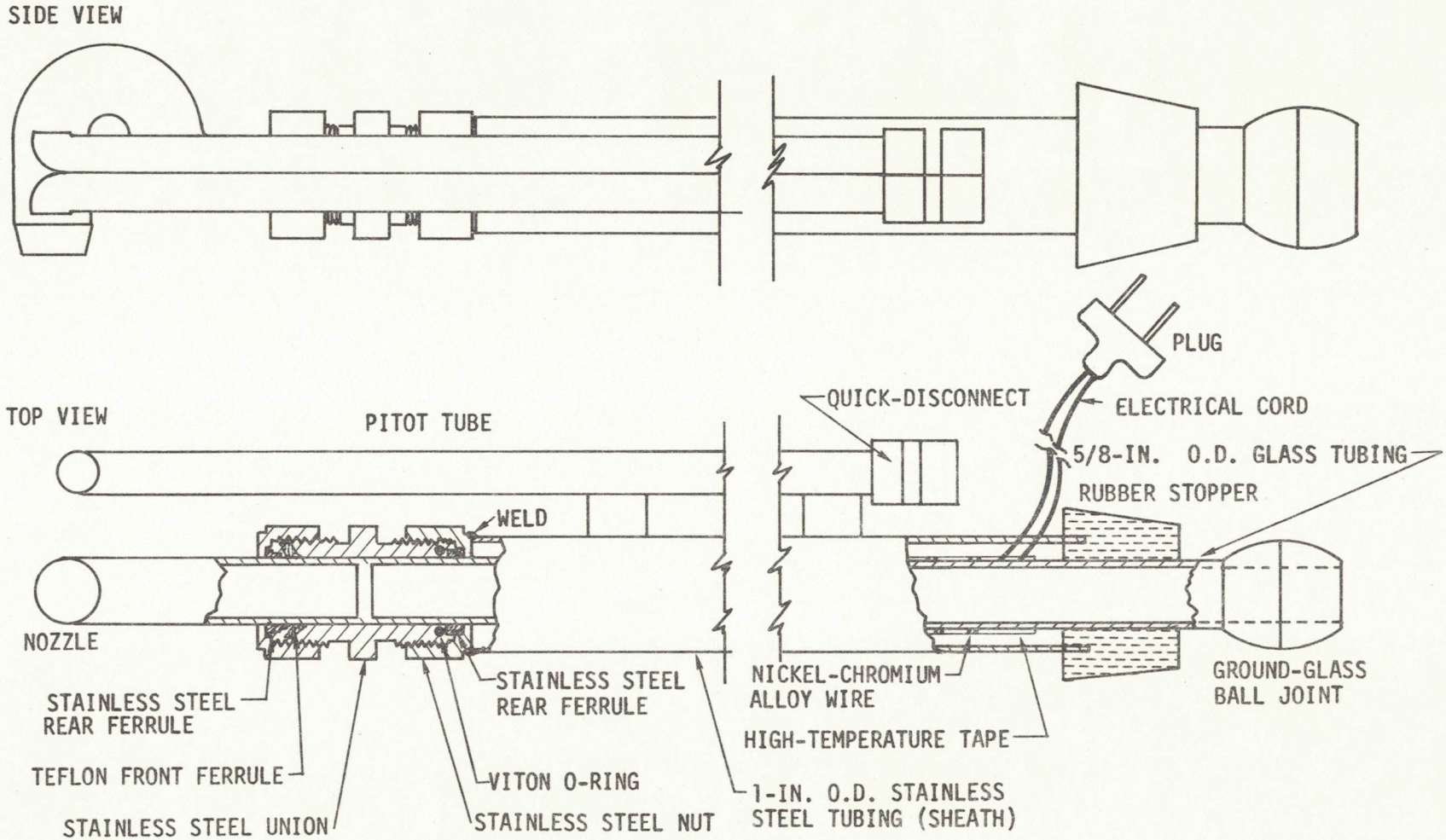


Figure 1. Sampling train.



NOTE: 1. PITOBE LENGTH CAN BE ANY SUITABLE SIZE.

2. NOZZLE DIAMETER AND CONFIGURATION CAN BE A VARIETY OF SIZES, BUT IT MUST HAVE A 5/8-IN. SHANK.

Figure 2. Pitobe.

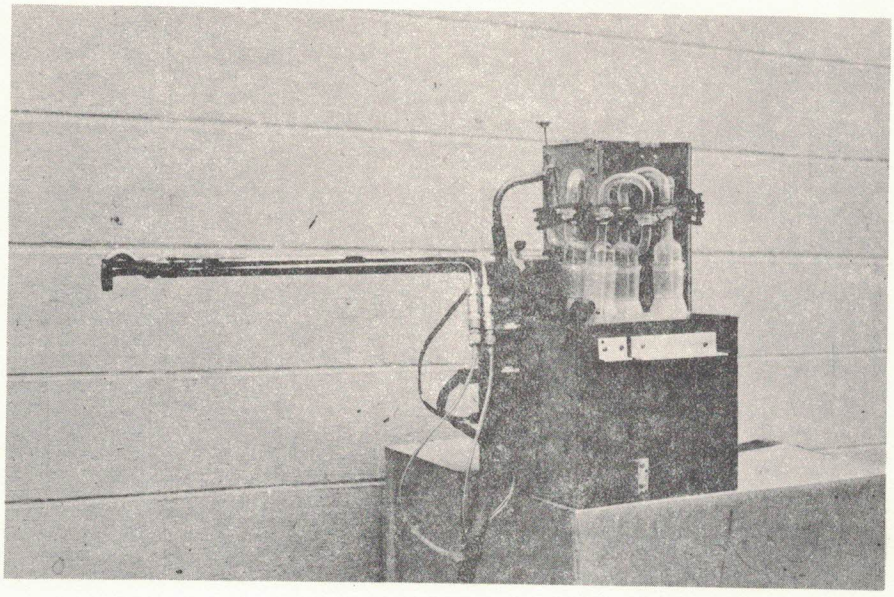


Figure 3. Sample box with pitobe, impingers, and umbilical cord.

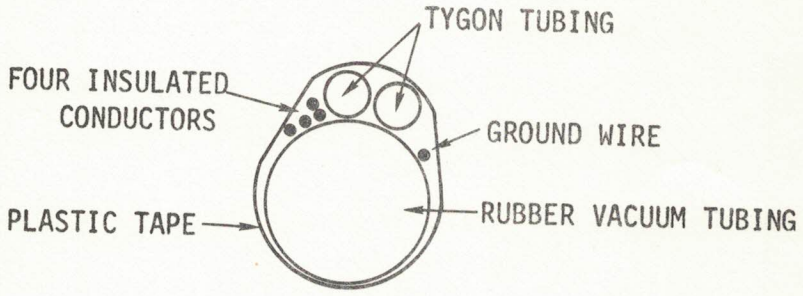


Figure 4. Umbilical cord.

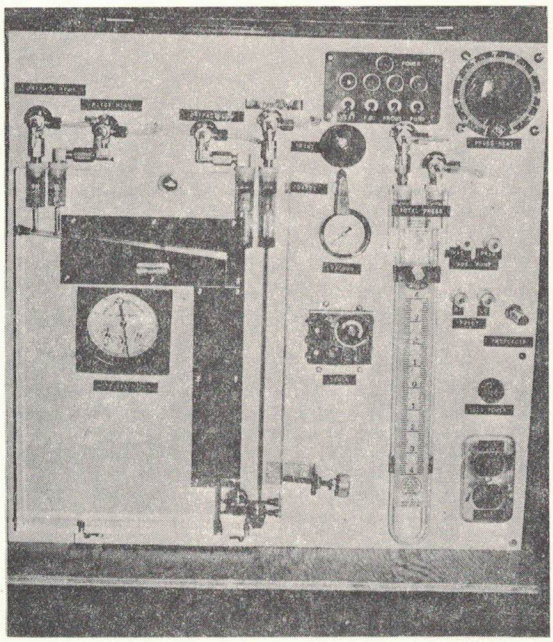


Figure 5. Meter box controls.

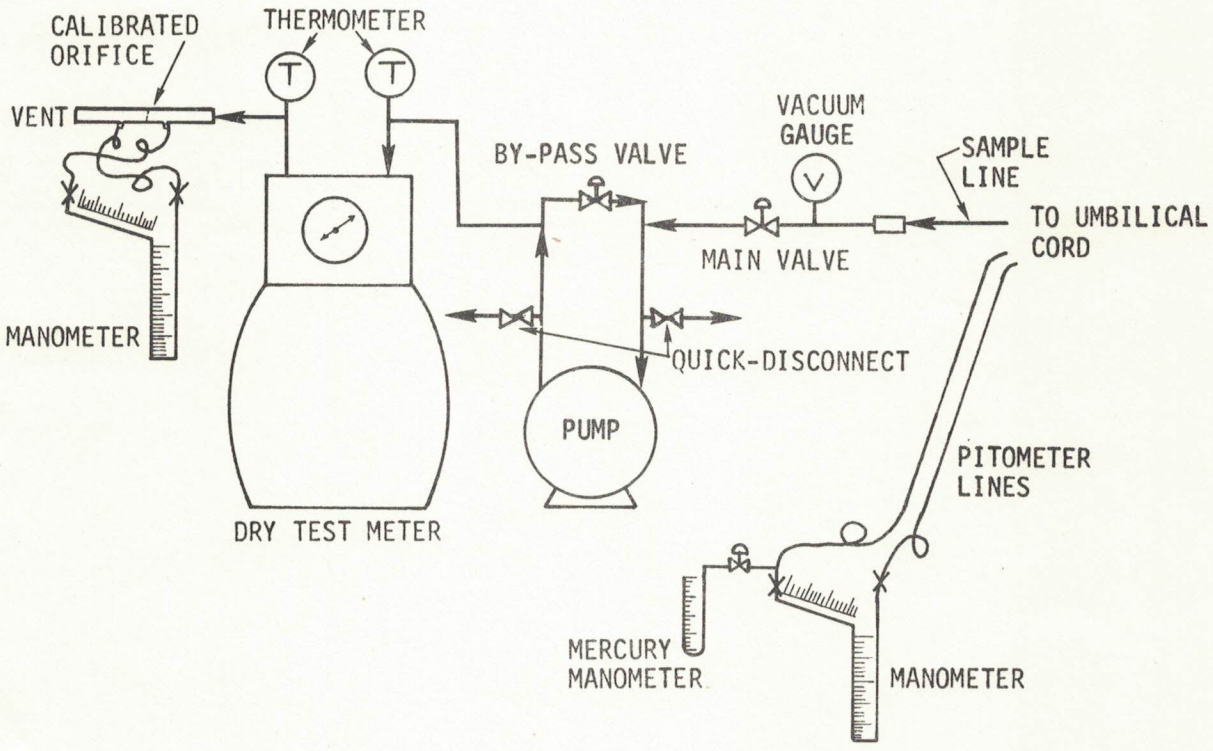


Figure 6. Meter box piping schematic.

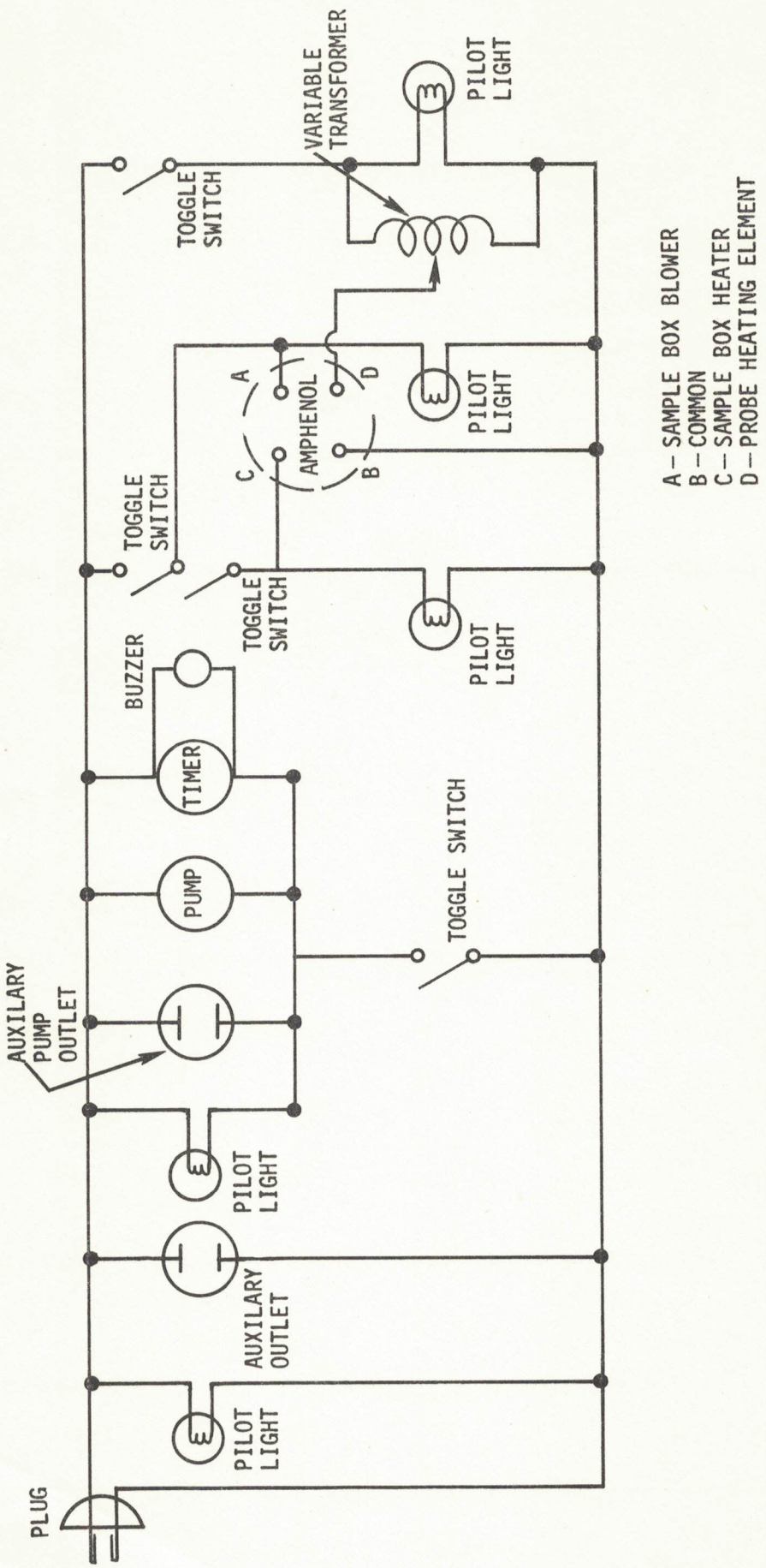


Figure 7. Schematic of meter box electrical circuit.

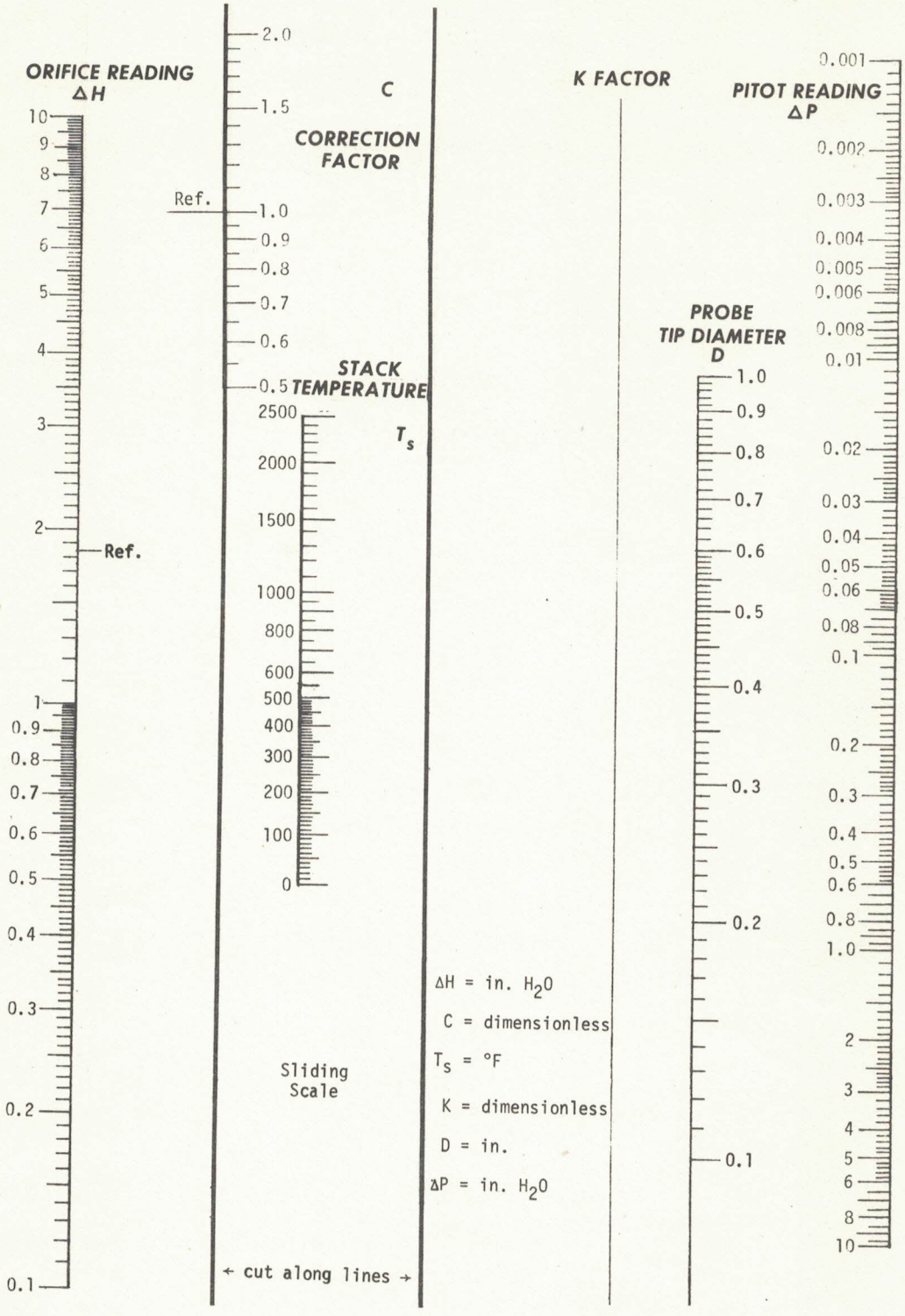
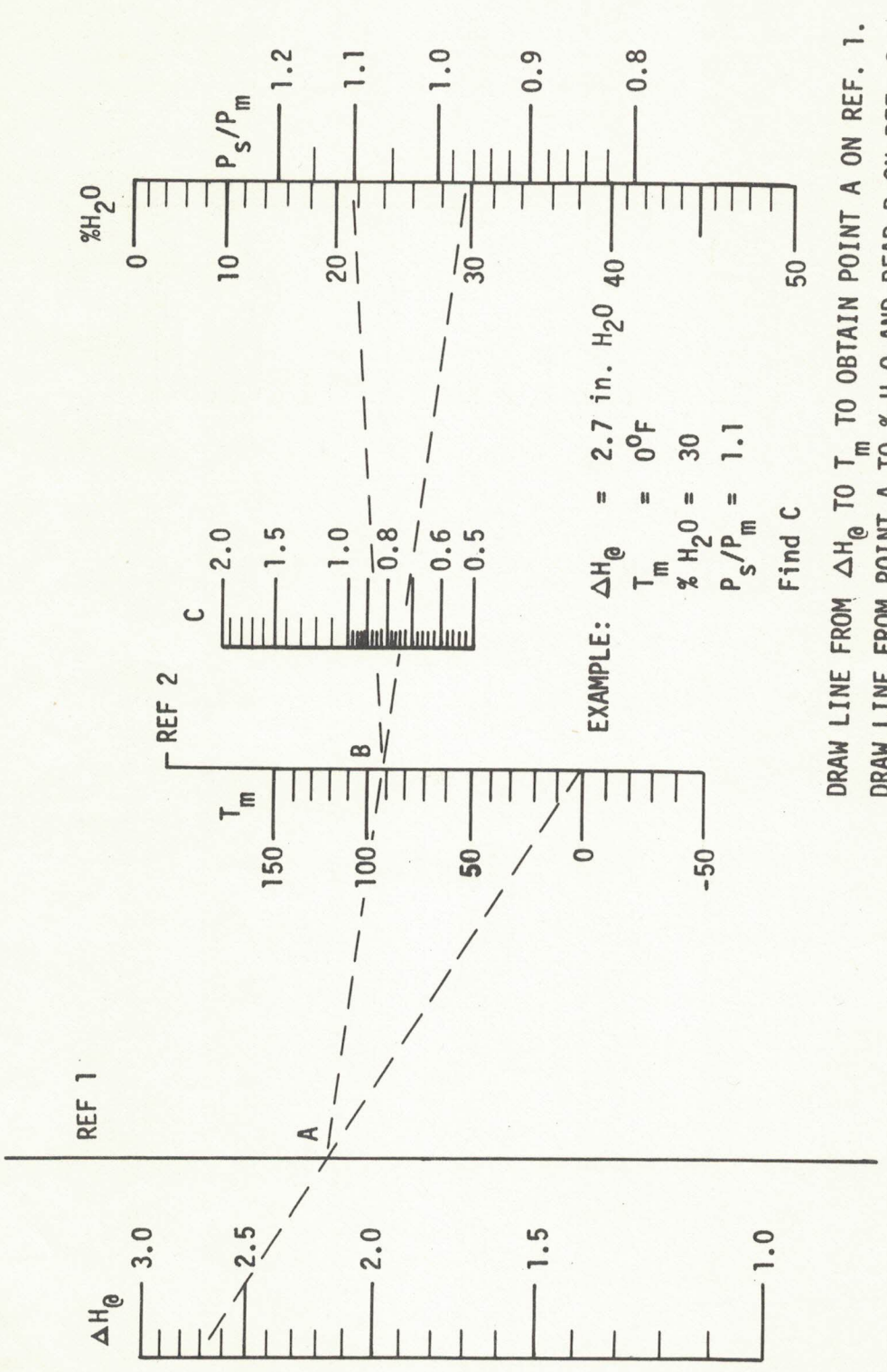


Figure 8. Operating nomograph.



DRAW LINE FROM $\Delta H_@$ TO T_m TO OBTAIN POINT A ON REF. 1.
DRAW LINE FROM POINT A TO $\%\ H_2O$ AND READ B ON REF. 2.
DRAW LINE FROM POINT B TO P_s/P_m, AND OBTAIN ANSWER OF 0.85 FOR C.

Figure 9. Correction factor C for Figure 8.

BIBLIOGRAPHY

1. H. Devorkin, et al; "Air Pollution Source Testing Manual." Los Angeles County, Cal.: Air Pollution Control District, 1963, Western Precipitation Corp., "Methods for Determination of Velocity, Volume, Dust and Mist Content of Gases," Bulletin WP-50 (5th ed.). Los Angeles.

2. W. F. Patton and J. A. Brink, Jr., "New Equipment and Techniques for Sampling Chemical Process Gases." Air Poll. Control Assoc.

3. J. H. Perry, "Chemical Engineers' Handbook," New York: McGraw-Hill Book Co., Inc., 1950.

4. U. S. Department of Health, Education, and Welfare, Public Health Service, Bureau of Disease Prevention and Environmental Control, National Center for Air Pollution Control, Training Program. "Source Sampling for Atmospheric Pollutants," Cincinnati, January, 1967.

5. A. B. Whitelely and L. E. Reed; "The Effect of Probe Shape on the Accuracy of Sampling Flue Gases for Dust Content." Institute of Fuel, Vol. 32,