

## SECTION 4

### RECOMMENDED METHOD FOR OBTAINING SIZE FRACTIONATED SAMPLES FOR CHEMICAL ANALYSIS

#### 4.1 INTRODUCTION

The environmental effects of particulate emissions from stationary sources depend on both the composition and particle size distributions of the emissions. Although composition information obtained from bulk samples can be used in estimating potential effects, the possibility - indeed, probability in many cases - of the composition of emissions being inhomogeneous with respect to particle size makes it desirable to have the capability of determining composition by particle size. Redispersion and separation of bulk samples might be used for this purpose; however, if all or part of the aerosol material were capable of coalescing it would be impossible to reconstitute the original size and composition distributions. Further, even in the case of dry solids, it becomes difficult or impossible to remove submicron particles from the surfaces of larger ones once contact has been made. Therefore, redispersion and subsequent partitioning by size of a bulk sample is a poor choice for the purpose. A method in which the particles are separated by size as they are collected is needed.

Two forms of inertial particle size separators are commonly used in source sampling - cascade impactors and cyclones. Impactors have a number of advantages for use in measuring particle size distributions and have been recommended to the CARB for that purpose. But they are not well suited for providing samples for chemical analysis. The quantities of material that can be collected on an impactor stage are limited to a few milligrams at most and many stages in an impactor sample will have catches of only fractions of a milligram. (The fact that only small amounts of material can be collected is no problem in a size distribution measurement. In fact, the need to collect only small amounts can be advantageous because it reduces the time required to do the sampling.) Omission of stages in impactors frequently results in operational failures because of particle bounce so that approach cannot be used to reduce the number of fractions and increase catch sizes. Moreover, the adhesives or surface coatings used for particle retention in impactors can result in intolerably high backgrounds and/or interferences. Cyclones, on the other hand, do not suffer problems from particle bounce or retention, have capacities of the order of grams, and require no surface coatings which might lead to interferences. Therefore, they were selected as the recommended means to obtain size fractionated samples for chemical analysis. Cyclones may also be used to good advantage for measuring particle size distributions when the particulate concentration in the stream to be sampled is very high. In such circumstances cascade impactors which are normally used for size distribution measurement may be impractical for the application because of too rapid overloading.

The use of cyclones is not without drawbacks. First, particulate catches are frequently distributed over rather large surface areas within the cyclone, making sample recovery difficult, especially if the recovery is to be sufficiently complete that the data can be used reliably for concentration

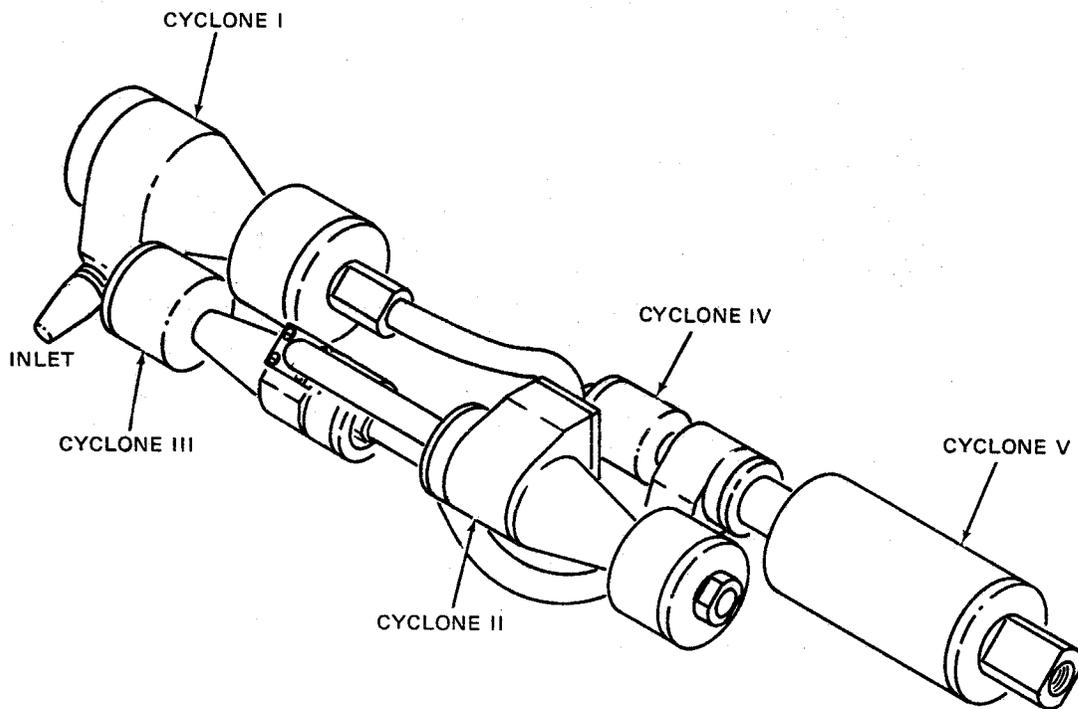
measurement. This is not a problem if the catches are large, but long sampling durations may be required to obtain them. Second, current theories on cyclone operation are rudimentary at best, and none do well in predicting cyclone performance from geometrical and flow considerations. Therefore, extensive calibrations are needed so that good empirical relationships can be developed for use in calculating the sizes of the collected particles. This results in less flexibility in construction and operation being available to the user than is the case with impactors.

Target cutoffs for particle size fractions for chemical analysis were set as follows: A cut at or near a diameter of ten (10) micrometers was desired to provide samples which conform to the PM<sub>10</sub> ambient air standard. Isolation of the fraction commonly designated as respirable suggests that a cut near 2.5 to 3 micrometers is desirable. Isolation of the one (1) micron and smaller fraction was desired by researchers working in the field of catalytic effects in the atmosphere, and finally, a cut near 0.25 micrometers was suggested since many combustion aerosols contain a sub-micron mode in their distributions which is known to differ chemically from the remainder of the material and which almost always falls below that size. The sampler which most nearly met these specifications was the SoRI/EPA designed Five Series Cyclone. These cyclones are available commercially from a number of manufacturers both in and out of the United States.

#### 4.2 DESCRIPTION OF THE SAMPLER

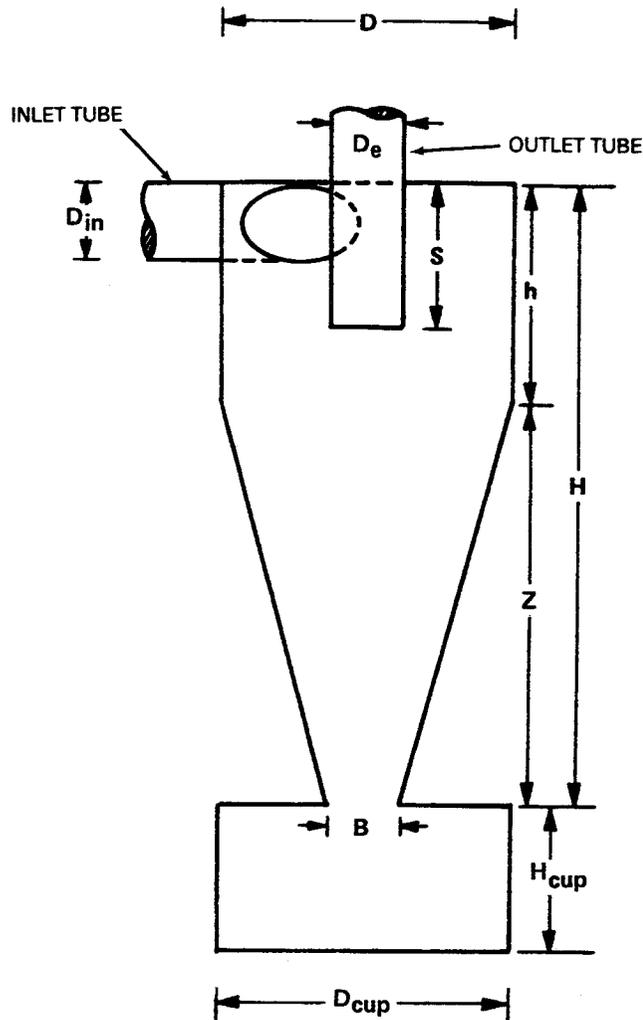
The design goal for the SoRI/EPA Five-Stage Cyclone Sampler (Smith and Wilson, 1978) shown in Figure 4-1 was five equally spaced particle size cuts ( $D_{50}$ ) on a logarithmic scale within the range of 0.1-10  $\mu\text{m}$ . This in situ sampling system operates at a nominal sample flowrate of 28.3 L/min (1 ACFM), and is compact enough to fit through a 10 cm (4 inch) diameter port. The sampler consists of five cyclones and a backup filter connected in series. Since the backup filter is a separate unit, either a flat filter mat can be used or, in the case where there is a large percentage of fine particulate present, a thimble filter. The first of the five cyclones, Cyclone SRI-I (which separates the large fraction of particulate matter from the gas stream), accepts a range of nozzles to facilitate isokinetic sampling.

The critical, internal dimensions of a cyclone are illustrated in Figure 4-2. These are critical because a change in any one of them may affect the operational characteristics of the cyclone (with the exception of  $H_{\text{cup}}$  and  $D_{\text{cup}}$  for some designs). Since there is no cyclone theory that analytically describes the performance of a small cyclone as a function of the critical dimensions, it is necessary to hold close tolerances during manufacture.



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*Figure 4-1. Environmental Protection Agency-Southern Research Institute  
Five-Stage Cyclone.*



- $D$  = DIAMETER OF THE CYLINDER PORTION OF THE CYCLONE,  
 ALSO CALLED THE DIAMETER OF THE CYCLONE  
 $D_{in}$  = DIAMETER OF THE INLET  
 $D_e$  = DIAMETER OF THE GAS EXIT  
 $B$  = DIAMETER OF THE DUST EXIT  
 $H$  = HEIGHT OF THE CYCLONE  
 $h$  = HEIGHT OF THE CYLINDER  
 $Z$  = HEIGHT OF THE CONE  
 $s$  = INSIDE LENGTH OF THE GAS EXIT TUBE  
 $H_{cup}$  = HEIGHT OF THE COLLECTION CUP  
 $D_{cup}$  = DIAMETER OF THE COLLECTION CUP

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Figure 4-2. The critical, internal dimensions of a cyclone.

### 4.3 OPERATING PRINCIPLES, CALIBRATION, AND EMPIRICAL MODELS

Cyclones are forms of centrifugal particle collectors in which the circulation of a particle laden gas stream about a central axis is induced by conversion of forward motion through the cyclone inlet. The gas enters through the inlet tube from whence it passes into the cylindrical body of the device. Here it acquires a spiral motion, descending along an outer spiral toward the base of the cyclone for some distance; it then undergoes an abrupt change of direction and continues upward to and through the exit tube. The length of the exit tube is made great enough that the gas does not simply "short-circuit" the intended flow path and flow directly from the inlet to the outlet tube. The flow in the central core of the cyclone, after the gas has turned upward, may proceed in a tighter inner spiral, or may flow in a rectilinear path to the outlet tube. The latter is believed to be the case when the Reynolds number of the flow in the outlet tube is low (Ayer and Hochstrasser, 1979). Large particles, because of their inertia, will tend to cross the curving flow streamlines and thus drift towards the wall of the cyclone body where they become disentrained upon contact. Additional separation may take place by impaction on the wall opposite the inlet and at the bottom of the outer spiral where the reversal in flow direction takes place (Fuchs, 1964) and by impaction on the wall opposite the inlet.

#### 4.3.1 Theoretical models

The flow field within a cyclone is highly complex and cannot be modeled in two dimensions as has been done for impactors. Generally, the flow consists of a double spiral with the outer spiral moving down and the inner moving up to the exit tube. The flow pattern within a cyclone can, under some conditions, be unstable; resulting in two possible operating pressure drops and efficiency curves for a given flow rate (Hochstrasser, 1976). This may be indicative of transitions from operation with the core flow forming an inner spiral to a mode in which the core flow becomes laminar and rectilinear (Ayer and Hochstrasser, 1979). There is also evidence that the particle collection characteristics can be significantly influenced by flow perturbations located downstream of the exit tube (Knight, 1976). The lack of a complete understanding of the flow fields within cyclones makes it very difficult to accurately predict their performance on the sole basis of information concerning geometry, flow rate, and gas properties. A number of theories have been developed based upon simplified models (Rosin et al., 1932; Davies, 1952; Lapple, 1951; Leith and Licht, 1972; Soo, 1973; Dietz, 1981). Some of these models could be made to reproduce the shape of measured cyclone efficiency curves reasonably well, but these all relied upon the adjustment of empirical constants to make the calculated curves match the measured data. For small sampling cyclones the agreement between predicted and measured performance was never very good for theoretical models which did not use adjustable constants.

Typically the theories are based on the classical equations for centripetal force and include additional terms to account for viscous drag on the particles, turbulence, and particle exchange between the outer and inner vortices. The models then usually attempt to relate the cyclone efficiency to

cyclone dimensions, flow rate and aerosol properties. The behavior is normally expressed in terms of the  $D_{50}$ , the diameter for which the collection efficiency is 50%. One of the more widely used equations, that of Lapple, is

$$D_{50} = \left( \frac{9H_c B_c^2 \mu}{2\pi N e \rho Q} \right)^{1/2} \quad (4-1)$$

where

$H_c$  = height of the cyclone inlet,

$B_c$  = width of the cyclone inlet,

$D_{50}$  = the particle diameter at which the efficiency is 50%,

$\mu$  = the gas viscosity,

$N e$  = the number of turns made by the gas stream in the outer spiral,

$\rho$  = the particle density,

and  $Q$  = the volumetric flow rate.

The gas viscosity is a function of the gas composition and temperature so that, with the exception of  $N e$ , the  $D_{50}$  is given in terms of easily measured variables: gas composition, gas temperature, flow rate, particle density, and cyclone dimensions. Unfortunately, the number of turns made by the gas stream within the cyclone is difficult to measure, may not be a constant for a given cyclone, and, at present, is impossible to predict (with sufficient accuracy to be useful), from the cyclone geometry and flow.

Leith and Licht's theory results in the following equation for cyclone  $D_{50}$ s:

$$D_{50} = \left[ \left( \frac{18 D B_c H_c}{E (1+n)} \right) \left( \frac{\mu}{\rho Q} \right) (\ln \sqrt{2})^{2n+2} \right]^{1/2} \quad (4-2)$$

where

$D$  = the cyclone diameter,

$E$  = a coefficient which depends solely on the cyclone geometry, and

$$n = 1 - \left( 1 - \frac{(0.394 D_c)^{0.14}}{2.5} \right) \left( \frac{T}{283} \right)^{0.3} \quad (4-3)$$

where

$T$  = the gas temperature in degrees Kelvin.

This equation includes the same  $\sqrt{\mu/\rho Q}$  term as did Lapple's equation, but has another temperature dependent term,  $n$ , in addition to the gas viscosity.

The  $\sqrt{\mu/\rho Q}$  term results in the predicted  $D_{50}$  increasing as the square-root of viscosity, which itself increases with temperature. The effect of  $n$  is to cause a further increase in the  $D_{50}$  with increasing temperature above that which would result from the increased viscosity alone. For cyclones of the sizes of interest here, the effect of  $n$  is to cause an additional increase in the calculated  $D_{50}$  by amounts ranging from zero to about twenty percent as the temperature is increased from 10 to 250 degrees Celsius.

All of the theoretical models developed to date result in the term  $\sqrt{\mu/\rho Q}$  being the dominant factor in calculating the cyclone performance. Thus all models result in the  $D_{50}$  having an inverse square-root of flow rate dependency. Chan and Lippmann (1977) showed that this flow rate dependency did not hold for many small sampling cyclones. In fitting an equation of the form  $D_{50} = kQ^n$  to experimental data, they found  $n$  to lie between  $-.636$  and  $-2.13$  for several cyclones. Similarly Smith and Wilson (1977) reported values of ranging from  $-.63$  to  $-1.11$  for the SoRI/EPA Five-Stage Cyclone set. Figure 4-3 illustrates the  $D_{50}$ -flow rate relationships reported by Chan and Lippmann and Smith and Wilson. Based on data taken with air in the temperature range from 20 to 200 degrees Celsius, the latter authors found the cyclone  $D_{50}$  exhibited a more nearly linear than square-root dependence on viscosity. Thus the theoretical models are found to be deficient in predicting the forms of the dependencies on the gas conditions and flow rates.

#### 4.3.2 Empirical Models

As a consequence of the inadequacies of current theories, empirical models based on fits to measured behavior have become the basis for calculation of cyclone performance. Beeckmans (1979) concluded that the collection efficiency (by particle size) of a cyclone is related to the particle Stokes number,  $Stk$ , and the Reynolds number,  $Re$ , of the flow. For the cyclones which he studied, he found that the collection efficiency, expressed in transfer units, could be well represented by an equation of the form

$$N_t = a_0 + a_1 \ln Re + a_2 \ln Stk \quad (4-4)$$

where

$$N_t = \begin{aligned} &\text{the number of transfer units,} \\ &= -\ln(\text{penetration}) \end{aligned}$$

and

$a_0$ ,  $a_1$ , and  $a_2$ , are regression constants and the penetration is the fraction of the particles passed by the cyclone.

$Stk$  and  $Re$  in the equation are given by:

$$Stk = \frac{\rho_p C u d^2}{9 \mu D} = 2\psi \quad (4-5)$$

and

$$Re = \frac{4 \rho_g Q}{\pi \mu D} \quad (4-6)$$

$\rho_p$  = the density of the particle,

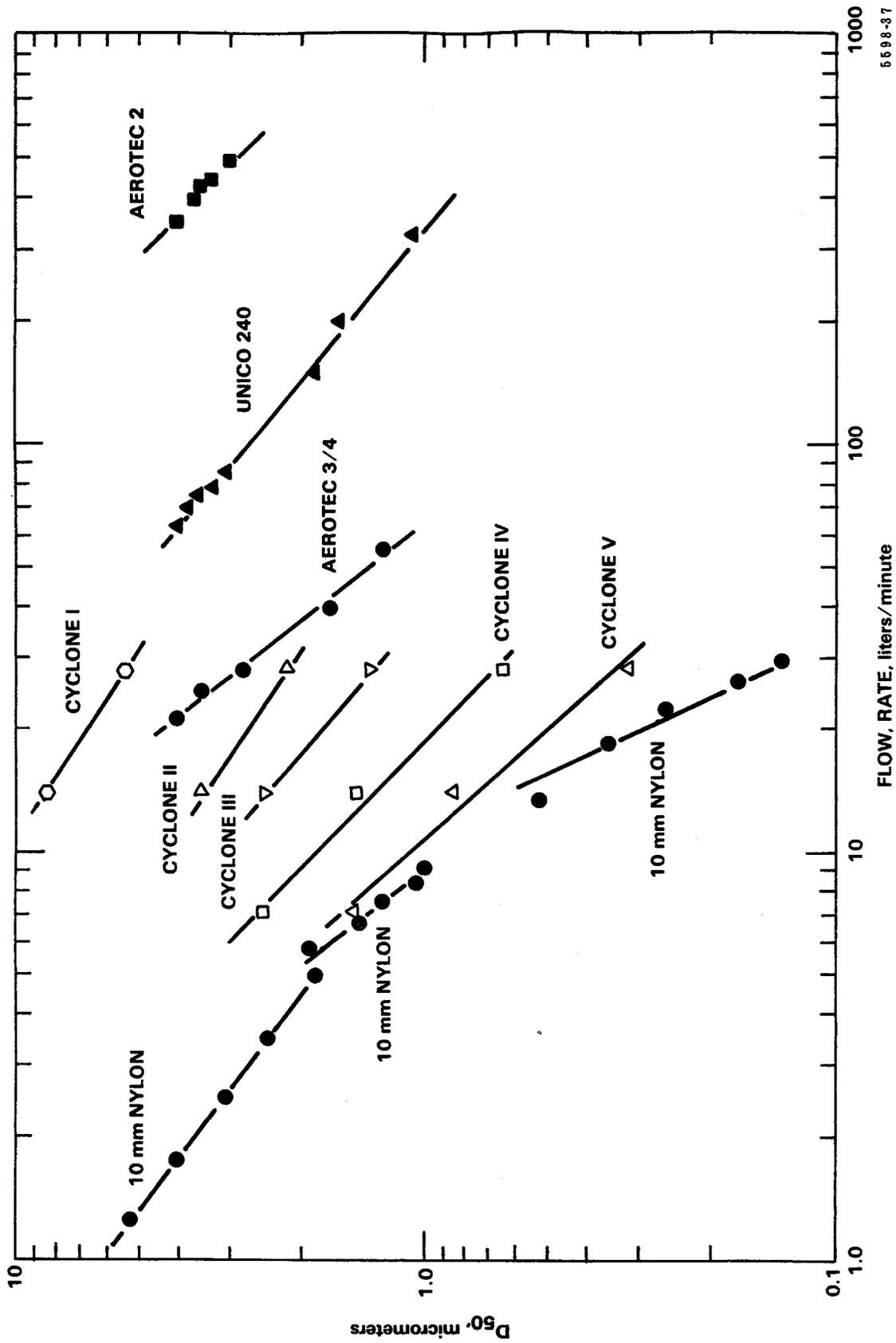
$C$  = the Cunningham slip correction (which is dependent of the size of the particle relative to the mean free path of the gas molecules),

$u$  = the gas velocity at the cyclone inlet,

$d$  = the particle diameter,

$D$  = the cyclone inlet diameter,

$\mu$  = the gas viscosity,



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Figure 4-3.  $D_{50}$  vs. flow rate for Cyclones I through V at flow rates of 7.1, 14.2, and 28.3 L/min, a temperature of 25 °C, and for a particle density of 1.00 g/cm<sup>3</sup> (Smith and Wilson, 1979). Other cyclone data from Chan and Lippman (1977).

$\rho_g$  = the gas density,

$Q$  = the total volumetric flow rate.

and

$\psi$  = inertial parameter used in describing impactor behavior.

Thus the value of  $Stk$  for a collection efficiency of 50% becomes a function of  $Re$ . Note,  $Stk$  and  $Re$  can also be defined in terms of the exit tube diameter and in some contexts it may be more appropriate to do so.

Similarly, Saltzman and Hochstrasser (1983) found that the  $D_{50}$ s of eighteen small cyclones could be calculated from an equation of the form

$$\log (D_{50}/D_e) = \log K_d + m \log \left( \frac{Re}{1000} \right) \quad (4-7)$$

where

$D_e$  = the diameter of the cyclone exit tube,

$K_d$  = a dimensionless constant characterizing each cyclone

and

$m$  = an empirical constant.

In this study, the performance measurements were made using air at laboratory conditions. Saltzman and Hochstrasser concluded that a single value of  $m$ ,  $-0.713$ , could be used to describe the behavior of all eighteen cyclones studied. The values of  $K_d$  for seventeen of the eighteen cyclones were quite close to one another, falling in the range  $0.0002$  to  $0.00026$ .

#### 4.3.3 Calibration

A laboratory study conducted by Lee et al. (1985) revealed that the  $D_{50}$ s of four other small sampling cyclones were highly correlated with  $Re$ . On the other hand, they found that with Argon as the carrier gas, the  $D_{50}$ s of the cyclones decreased as compared to  $D_{50}$ s for air in spite of the higher viscosity of Argon, as shown in Figure 4-4. This behavior was contrary to the increase in  $D_{50}$  attributed by Smith and Wilson to increased viscosity in air at elevated temperature. Three of these cyclones were from the SoRI/EPA Five-Stage Cyclone set. In the study by Lee et al., the  $D_{50}$ s of the cyclones were measured over a range of flow rates using both air and argon as carrier gases. By using different gases, variations in viscosity and Reynolds numbers could be achieved independently of variations in flow rate. The results of the study indicated that gas density as well as viscosity has a strong influence on cyclone  $D_{50}$ s.

Additional calibrations of the Five-Stage Cyclone Sampler have been carried out at Southern Research Institute (Farthing, 1985). These calibrations were carried out over a wide range of flow rates with air, helium, carbon dioxide, and argon as carrier gases. Again, the use of gases other than air permitted independent variation of flow rate and Reynolds number. The results of these calibrations for two of the cyclones are shown in Figures 4-5 and 4-6. The earlier calibrations reported by Smith and Wilson (1979) have also been incorporated in these figures. From these figures one can see that the particle Stokes number for 50% collection can be determined for each cyclone from the Reynolds number of the inlet flow. It is worth noting that

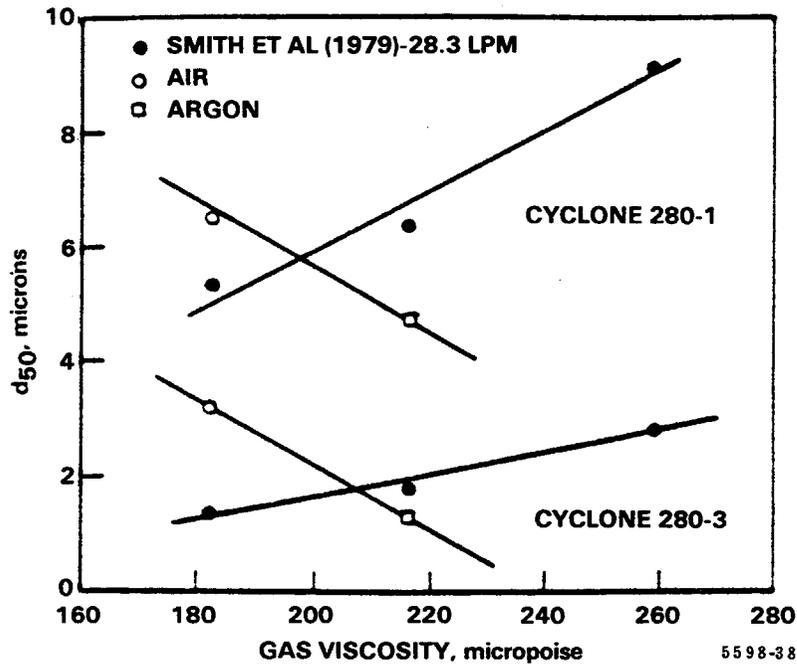


Figure 4-4. Particle cut diameter vs gas viscosity. (Lee, et al., 1985)

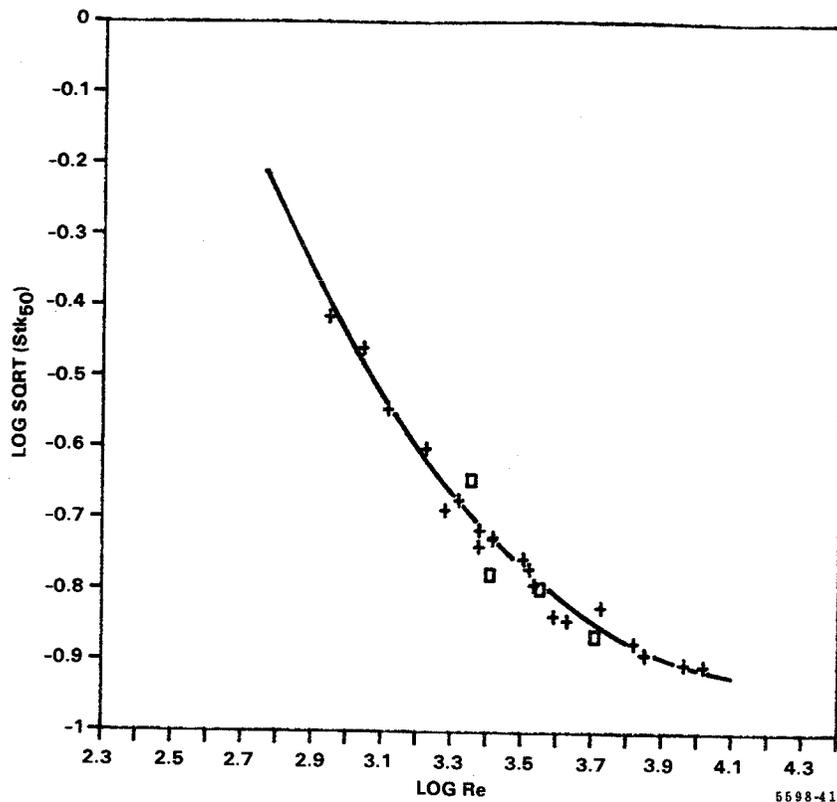


Figure 4-5. Calibration data for Cyclone III of the five-stage cyclone sampler.  $\square$ —data from Smith and Wilson (1979), air only, variable temperature and flow rate.  $+$ —data from Farthing (1985), air, CO<sub>2</sub>, Argon, and Helium, laboratory conditions, variable flowrate.

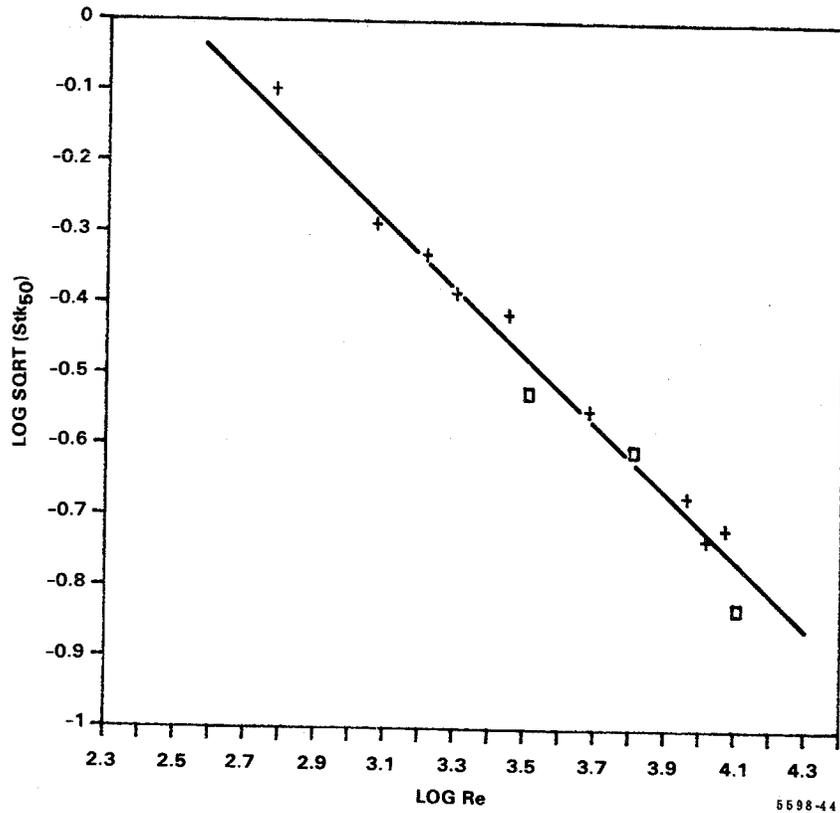


Figure 4-6. Calibration data for Cyclone V of the five-stage cyclone sampler.  $\square$ —data from Smith and Wilson (1979), air only, variable temperature and flow rate.  $+$ —data from Farthing (1985), air, CO<sub>2</sub>, Argon, and Helium, laboratory conditions, variable flowrate.

the data for each cyclone can be represented by a smooth continuous curve or, almost equally well, by two straight line segments. If two line segments are used, the transition point between the two would be located at a Reynolds number near 2000. The location of the break point is thus consistent with the change in the behavior of the core flow postulated by Hochstrasser.

In order to make use of the calibration data in the analysis of field samples, a mathematical relationship must be established between  $Stk_{50}$  and  $Re$ . A satisfactory fit to the calibration data was obtained for each cyclone using an equation of the form:

$$\ln\sqrt{Stk_{50}} = C + A (\ln Re) + B(\ln Re)^{1/2} \quad (4-8)$$

where A, B, and C are empirically determined constants. The values, obtained by least squares fits to calibration data, are as follows:

Cyclone	A	B	C
I	0.197	0.0	0.156
II	1.982	-13.596	20.894
III	4.732	-29.370	43.462
IV	2.841	-18.929	29.494
V	0.472	0.0	2.707

These values are based on calibrations obtained over a wide range of flowrates (2 to 55 lpm) with air at temperatures from ambient to 200°C and carbon dioxide, helium, and argon at ambient conditions (Farthing, 1985). The equations generally reproduce the calibration values of  $\sqrt{Stk_{50}}$  to an accuracy of 10% or better.

#### 4.4 PRETEST OPERATIONS

Before using the sampler, it should be cleaned with a mild detergent in an ultrasonic bath, rinsed with distilled or dionized water, and dried. All the internal surfaces must be cleaned. Any surface which comes in contact with the sample gas is considered an internal surface. If analysis for organic compounds is to be done, additional rinses of all the internal surfaces with an organic solvent such as methylene chloride should be made. Teflon wash bottles should be used to hold the solvent during the wash procedure. All glassware to be used during the wash should be thoroughly cleaned and rinsed with the solvent.

A complete second rinse of each cyclone with the chosen solvent is recommended prior to taking the cyclone set into the field. An analysis of this rinse should be made to insure the absence of contaminants in the cyclones. At the same time, this preliminary rinse analysis serves as a check that appropriate cyclone cleaning procedures were used. This rinse should be performed enough in advance of the field test so that any action dictated by the results of the analysis may be carried out.

The internal surfaces of each cyclone (i.e., the body underneath the cap, the outside of the gas exit tube, the inside walls, and the underside of the body) should be rinsed with the solvent and the wash collected in a clean glass beaker. For each cyclone the inside of the gas exit tube and the connecting tubing should be rinsed together with the downstream cyclone. Metal or viton o-rings should be washed and rinsed as described above but their solvent rinse should not be included with the cyclone rinse. The collected rinse should be stored in glass bottles with teflon caps and labeled with the appropriate cyclone I.D. After completion of the rinse procedure, the cyclone set should be assembled and sealed with Saran wrap or aluminum foil to prevent contamination during transport to the field site.

The sampler should be assembled as shown in the assembly drawing shown in Figure 4-1. The proper nozzle and filter holder should be selected and attached to the sampler at the appropriate places. Threads should not be coated with anything (such as thread lubricant) which could contaminate the sample. Before the sampler is used in the field, the threads can be silver or chromium plated to prevent galling. Sealant is not needed for the threads on the nozzle; the metal-to-metal seal is sufficient. Teflon tape may be used, if temperatures permit, as a sealant and thread lubricant on any tapered pipe threads and screw-together parts.

Once the cyclone set has arrived at the field test site, a blank wash of the set should be performed using the desired solvent prior to any test runs. This blank wash should be performed in the same manner as the wash procedure described previously.

#### 4.4.1 GAS VELOCITY AND COMPOSITION

The results of a velocity traverse, stack gas temperature measurement, and gas analysis are used to determine testing parameters such as flow rate and nozzle size.

The velocities and temperature in the flue, as well as the static pressure in the flue, should be measured. An extra effort should be made to obtain the point velocities at the proposed sampling points if those suggested in Section 4.5 are to be used. If possible, velocity fluctuations at those points should also be noted. If the velocity fluctuations are so large that  $\pm 20\%$  isokineticity cannot be maintained, alternate sampling positions should be selected, if possible, where the velocity is more stable. It should be noted that the flow rate through the sampler must be constant.

A gas analysis should be performed to determine the composition (molecular weight) of the gas, including the amount of water vapor. The molecular weight of the gas can then be accurately determined for viscosity and flowrate calculations. Supplemental heating of the sampler may be needed if the gas temperature is near the dewpoint or if the gas is saturated. It may be acceptable to use an estimation of the flue gas composition based on previous tests. This is especially true if this particular source has been tested often. In such a situation, an estimate of the gas composition for the purpose of determining the gas viscosity is appropriate.

#### 4.4.2 SAMPLING TIME

The length of time required to collect an adequate sample is dependent upon the mass loading of the aerosol, the size distribution of the particles, the flow rate of the sampler and the amount of material needed for the analyses to be performed. If the results of a mass test are available, the mass loading can be obtained from them. If not, an estimate should be made based on the pre-test survey or other available information. Given the mass concentration, an estimate of the sampling time for initial tests can be obtained from Figure 4-7. Results from the initial tests can then be used to more accurately establish the optimum sampling time. The curves in the figure are based on collecting a one-gram sample. If more or less material is needed, the user should adjust the sampling time as appropriate.

#### 4.5 SAMPLING

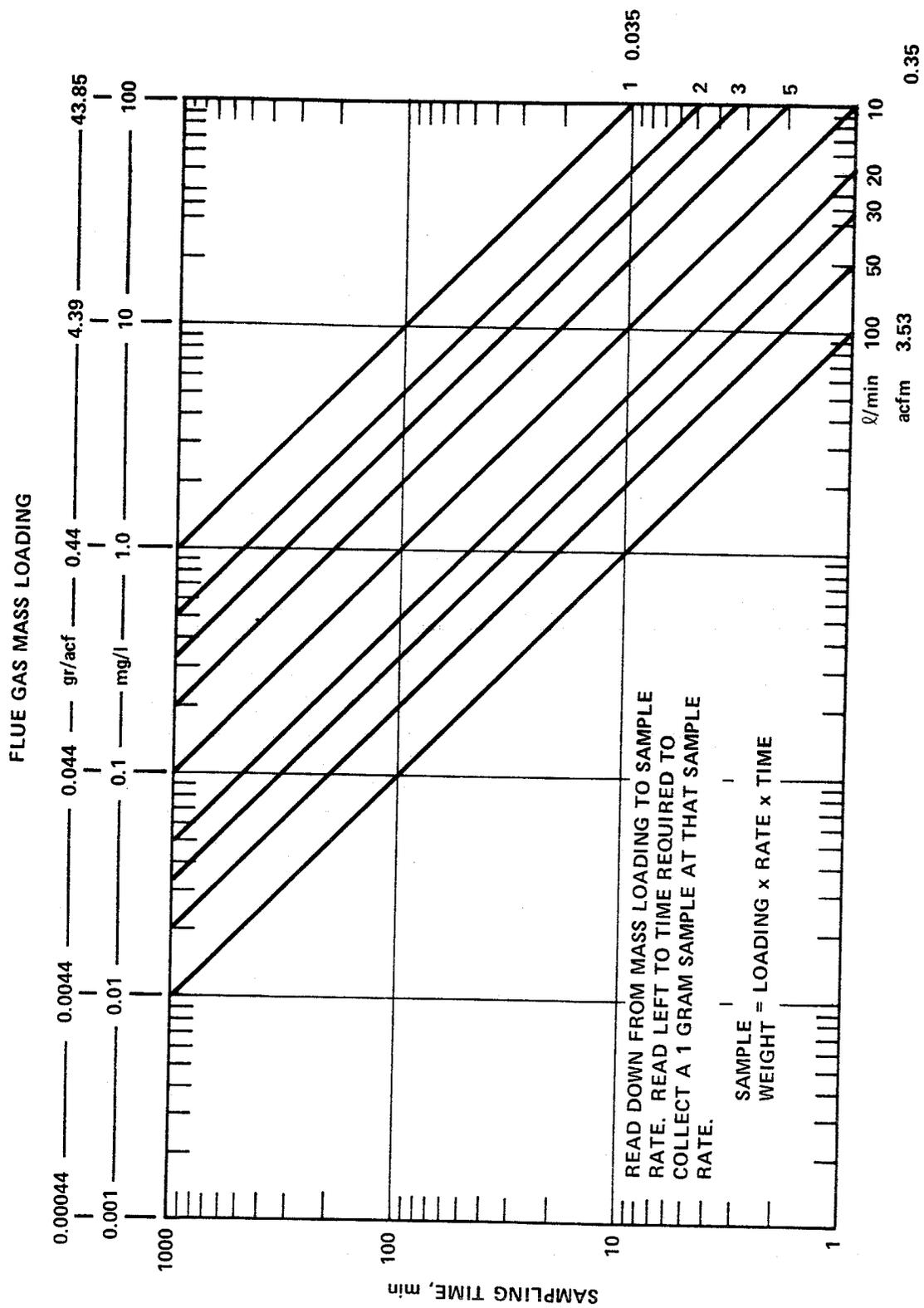
Figure 4-8 shows the locations of the sampling points that are recommended. After a measurement of the velocity profile has been made and the nozzle has been selected, samples should be taken at the locations shown. In sampling the effluents from variable or cyclical processes, the test should extend through several process cycles to insure that a representative sample is obtained.

Regardless of the velocity distribution in the flue, the flowrate through the sampler must remain essentially constant. It is desirable to maintain sampling within  $\pm 20\%$  of isokinetic throughout the sampling period, but the sampling rate should not be altered to accomplish this. If a zone of the duct has a velocity that would result in a large deviation from isokinetic, it simply should be avoided.

##### 4.5.1 SELECTING THE SAMPLE FLOWRATE AND NOZZLE

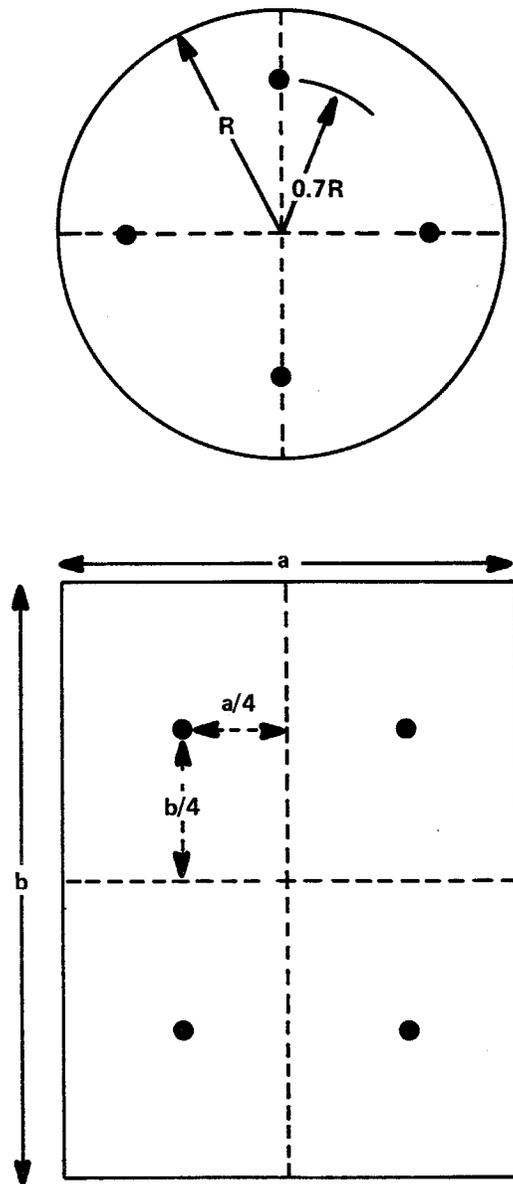
The  $D_{50}$  of a cyclone is dependent on gas density, gas viscosity, and flow rate. Of these variables, only the flow rate can be set by the user. Therefore, if a specified size cut off must be obtained in a particular sampling application, the required sampler flow rate must be determined. Plots of the  $D_{50}$ s of the five cyclones versus flow rate are shown in Figures 4-9 through 4-13. In these figures, curves are shown for operation at 25, 100, 150, and 200 degrees Celsius. A gas composition typical of many industrial flue gases was used in generating these curves (10% CO<sub>2</sub>, 8% O<sub>2</sub>, 82% N<sub>2</sub> on a dry basis and 10% moisture). Estimates of the required flow rate needed to obtain a particular  $D_{50}$  can be obtained from these curves for most cases. However, if the gas temperature is much higher than 200°C or if the composition is radically different from that used here, the required flow rate should be obtained by back calculation from the  $D_{50}$  equations. The computer program provided for data reduction can be used to facilitate these calculations. Note that the flow rate selection can be made to obtain a specified cut with any one, but only one, of the five cyclones. After a flow rate is selected, the cuts of the remaining four can be estimated from the figures.

Once the desired flow rate is known, the appropriate nozzle can be selected using Figure 4-14. Only straight nozzles should be used.



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Figure 4-7. Nomograph for selecting proper sampling duration.



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Figure 4-8. Recommended sampling points for circular and square or rectangular ducts.

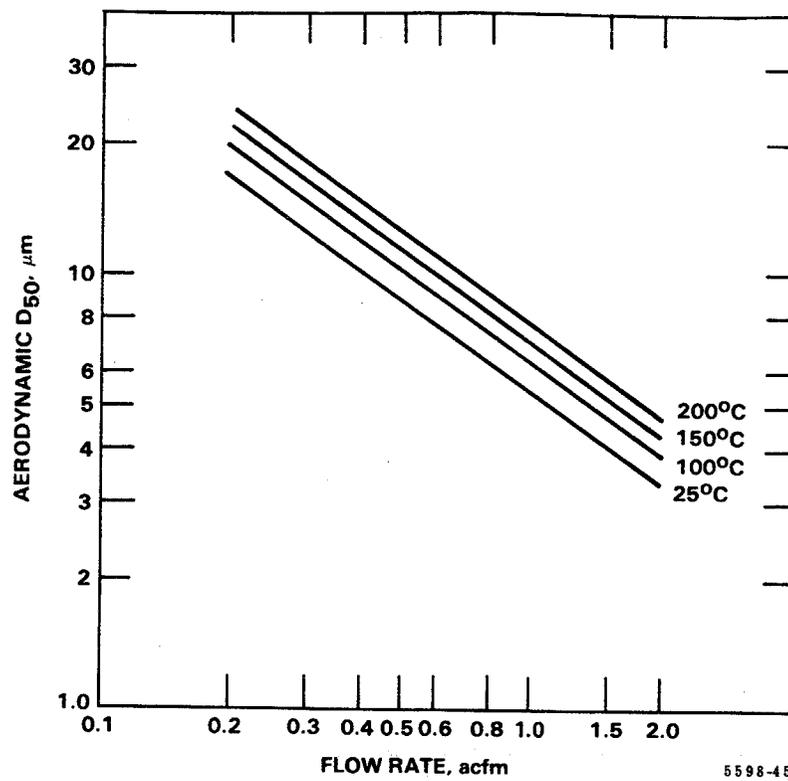


Figure 4-9.  $D_{50}$  versus flow rate for Cyclone I of the five-stage cyclone sampler.

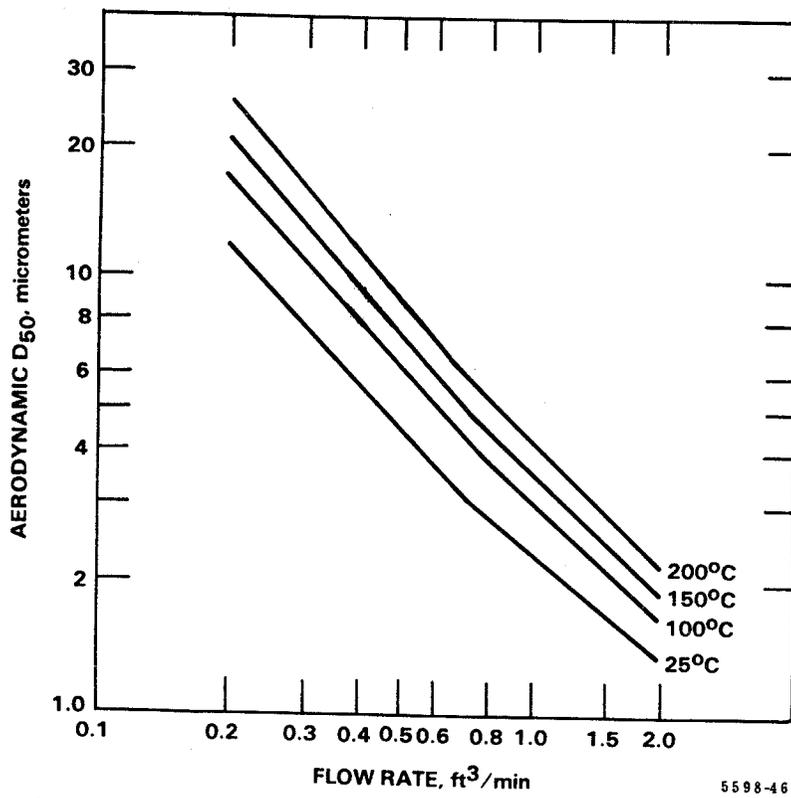


Figure 4-10.  $D_{50}$  versus flow rate for Cyclone II of the five-stage cyclone sampler.

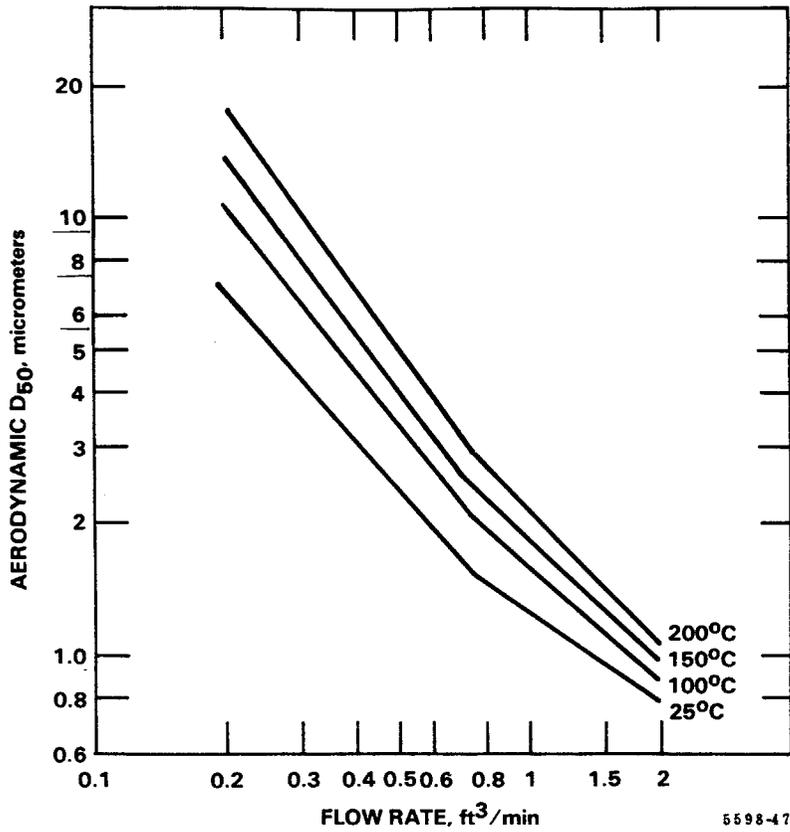


Figure 4-11.  $D_{50}$  versus flow rate for Cyclone III of the five stage cyclone sampler.

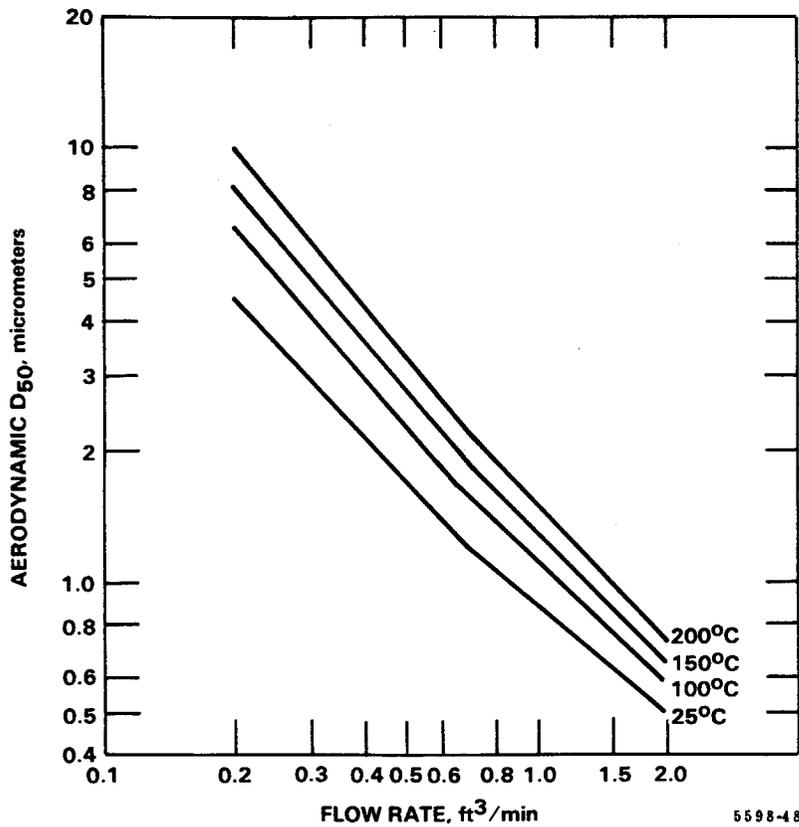


Figure 4-12.  $D_{50}$  versus flow rate for Cyclone IV of the five-stage cyclone sampler.

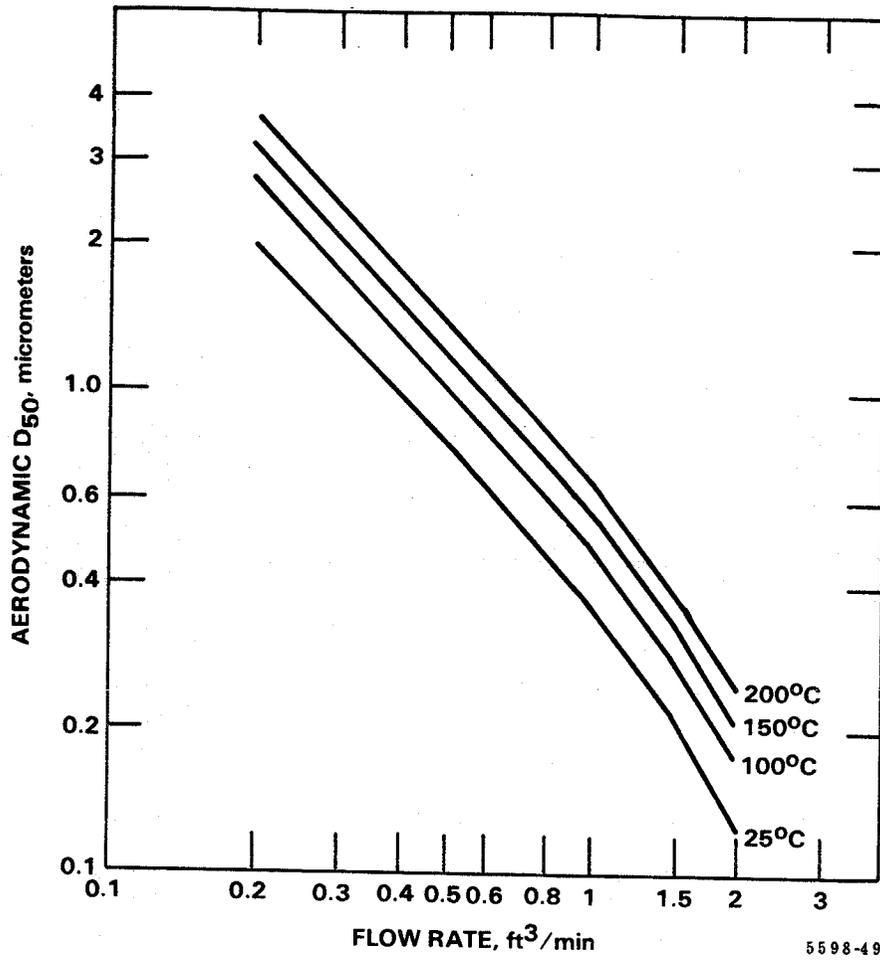


Figure 4-13. D<sub>50</sub> versus flow rate for Cyclone V of the five-stage cyclone sampler.

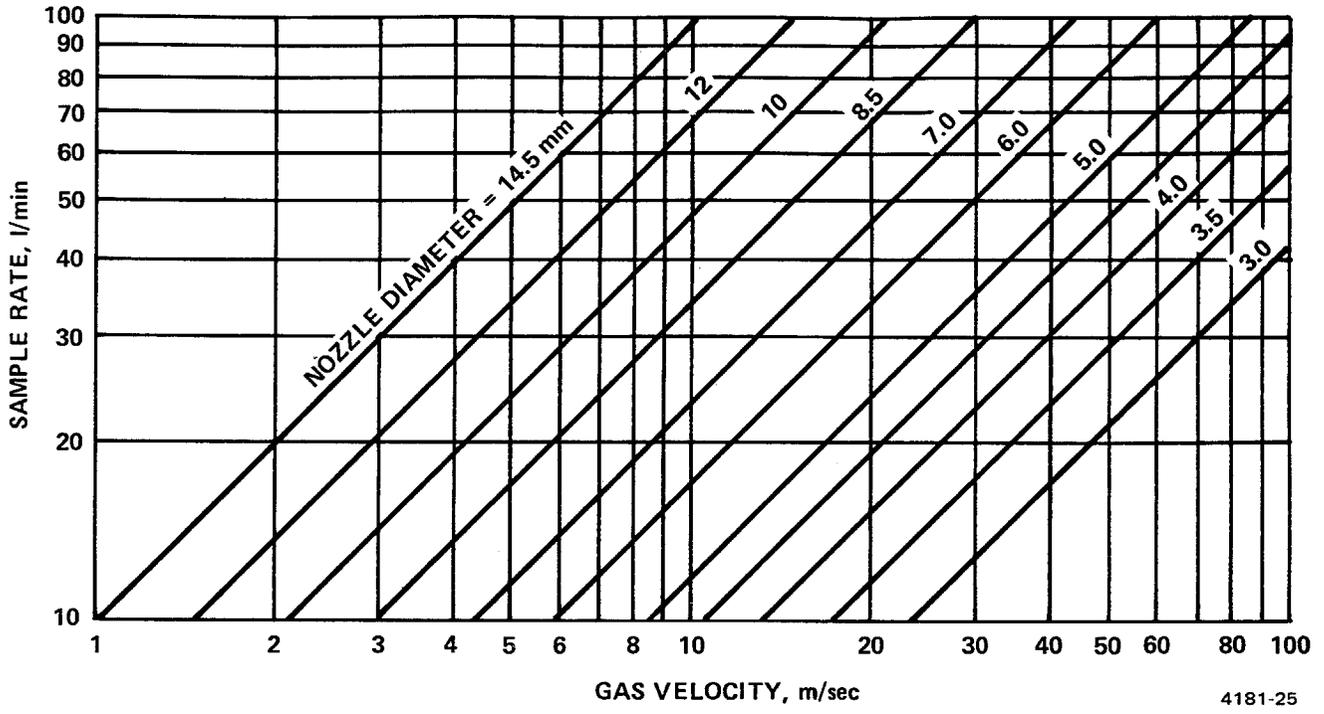


Figure 4-14. Nomograph for selecting nozzles for isokinetic sampling.

#### 4.5.2 LEAK TESTING

Before use, the sampler should be leak tested. The first test should be made immediately after assembly. This test can be performed in the field lab with a minimum amount of equipment. A leak check should also be made after the cyclones have reached the sampling temperature. Some slight leakage is expected, especially if metallic o-rings are used, and the sampler should not be expected to meet the Method 5 leak check criterion. The probe and the remainder of the sampling system should, however, meet the Method 5 criterion.

#### 4.5.3 FLOW RATE

During the run, the predetermined flowrate must be maintained to ensure stable cut points. Any attempt to modulate flow to provide isokinetic sampling will destroy the utility of the data by changing the cut points of the cyclones.

As the final filter collects particulate, the pressure drop across it will increase, lowering the sample flowrate. The flowrate should be monitored and adjusted as necessary to compensate for this filter loading effect. Filter changes or removal may be necessary if the pressure drop becomes excessive.

#### 4.5.4 TRAVERSING

During traversing (moving to a new point or new port), all motion should be smooth and brief to avoid bumping or vibrating the sampler. When removing or inserting the sampler, care must be taken not to scrape the nozzle on the port wall. Also, the sampler should not be allowed to bump against the far inside wall of the flue.

#### 4.5.5. ORIENTATION

The Five-Stage Cyclone Sampler is designed to operate in any orientation with equal results. However, the flow should not be terminated until the run is complete and the sampler is in a horizontal position. Otherwise, some material might fall from one stage of the sample to another and thus be measured where it is not collected. After the flow has been terminated, the sampler can be transported to the lab. It should be kept in a horizontal position with the nozzle plugged or covered to avoid contamination or loss of sample.

#### 4.5.6 DATA LOGGING

In addition to the sampling parameters and process information normally recorded such as gas composition and temperatures, pressures, gas volumes, etc., the operator of the Five-Stage Cyclone Sampler should also record the sampler identification, orientation, filter identification, gas velocity, flowrate and the run time.

#### 4.6 SAMPLE RECOVERY

After the sampler has cooled to nearly ambient temperature and brought into the lab, it should be carefully "unloaded." Unloading consists of removing all of the particulate matter retained in the sampler. Great care is required in this procedure to insure that all of the particulate is recovered and placed in the proper sample containers.

The sample collected in cyclone SRI-I should be removed first, followed by the samples collected in cyclone SRI-II, SRI-III, SRI-IV, and SRI-V, respectively. The particles adhering to the internal surfaces of the cyclone, i.e., the body underneath the cap, the outside of the gas exit tube, inside the nozzle, the inside walls, and the underside of the body, should be brushed, scraped, or rinsed into a pre-weighed sample container along with the material from the collection cup. If the particulate matter is a dry powder, a No. 7 camel's hair brush is suggested for this operation. Material deposited inside a gas exit tube and the connecting tubing to the next cyclone should be included in the sample for the downstream cyclone. Material collected on the inside of the gas exit tube and connecting tubing to the filter should be brushed onto the filter or washed into the filter containers. When all internal surfaces directly upstream of the filter have been cleaned, remove the filter and place it in its proper sample container.

In some cases, it may also be necessary to wash the internal surfaces of the nozzle and cyclone with a solvent, such as methylene chloride, into preweighed bottles. If organic analyses are to be performed, glass bottles with teflon caps should be used. If the material is hard and dry, the particles can be brushed off into the container; if the particles are sticky or wet, a washdown procedure should be followed. The solvent must be considerably more volatile than the particles (Methylene chloride is recommended, but other solvents may be needed for some compounds.)

#### 4.7 DATA ANALYSIS

After obtaining a sample, the data must be reduced to obtain the desired size distribution from the stage weights, sampling information, and hardware specifics. Data taken in various studies of particulate emissions should be readily comparable, regardless of the sampling team. The data should therefore be presented in a uniform format. Data reduction for the cyclones is accomplished using the same  $D_{50}$  method described for impactors. The only difference being that the values of  $STK_{50}$  be used in reducing the cyclone data must be found from the empirical fitting equations of  $STK_{50}$  vs  $Re$  described in paragraph 4.2 rather than being calculated from theory as was the case for impactors. A set of data reduction programs for the cyclones were developed from the impactor programs (CIDRS) and is provided as an appendix to the cyclone procedures document.

Data reduction is described fully in the cyclone procedures document and a sample set of results is worked through in detail there.

## SECTION 5

### PROPOSED PM<sub>10</sub> MEASUREMENT METHOD

#### 5.1 Introduction

Procedures for measurement of size-specific particulate emissions (such as PM<sub>10</sub>) are more complex, but similar to, those for total particulate sampling by EPA Reference Methods 5 or 17. Potential sampling biases exist due to variations in the spatial distribution of particulate concentrations across the sampling plane defined by the duct cross-section. Likewise, temporal variations in particulate concentrations due to process variations can cause inaccurate or unrepresentative results. Also, if the gas velocity entering the sampling nozzle is not the same as the local duct velocity, particulate matter will be selectively depleted or enriched in the sample gas stream due to inertial separation at the nozzle entrance. EPA Reference Methods 5 and 17 deal with these problems by specifications on the sampling location to minimize stratification and by sampling isokinetically at an array of points spanning the sample plane. Isokinetic sampling is accomplished by measurement of duct velocity at each point and adjustment of the sample train flowrate so that it is proportional to velocity.

Size-specific emission measurements are accomplished by sampling through an inertial size-separation device. The procedure and equipment must deal with the same problems described above while, in addition, maintaining a constant flowrate through the separator to provide the desired size cut (10 $\mu$ m for the present purpose). This constraint on flowrate causes there to be substantial differences between sampling methods for PM<sub>10</sub> and those for total particulate matter. The constraints of isokinetic sampling and a specified flowrate for the size cut directly conflict, resulting in a requirement for additional hardware.

The method described here is under development by the USEPA as a PM<sub>10</sub> source method. It uses a special sampling nozzle which allows isokinetic sampling while maintaining the specified flowrate for a 10 $\mu$ m size cut provided by an instack particle classifier. The sampling train incorporates the principle of emission gas recycle (EGR). It allows a variable fraction of conditioned and filtered exhaust gas from the sampler to be added to the sample stream between the sample nozzle and the inertial classifier. This allows a preselected constant flowrate to be maintained through the inertial classifier while the gas flowrate into the sampling nozzle is adjusted to remain isokinetic with the local duct velocity. Although the method might, in principle, be applied with any type of inertial classifier, it has been tested only with a single stage cyclone for PM<sub>10</sub> measurement to date. Therefore its use in other applications is not currently recommended.

The emission gas recycle concept was originally developed into a prototype sampling train at the U.S. Environmental Protection Agency facilities at Research Triangle Park by making modifications to a commercially available Method 5 sampling system<sup>1</sup>. This system was subsequently evaluated, in laboratory and field situations, at Southern Research Institute (SoRI) and

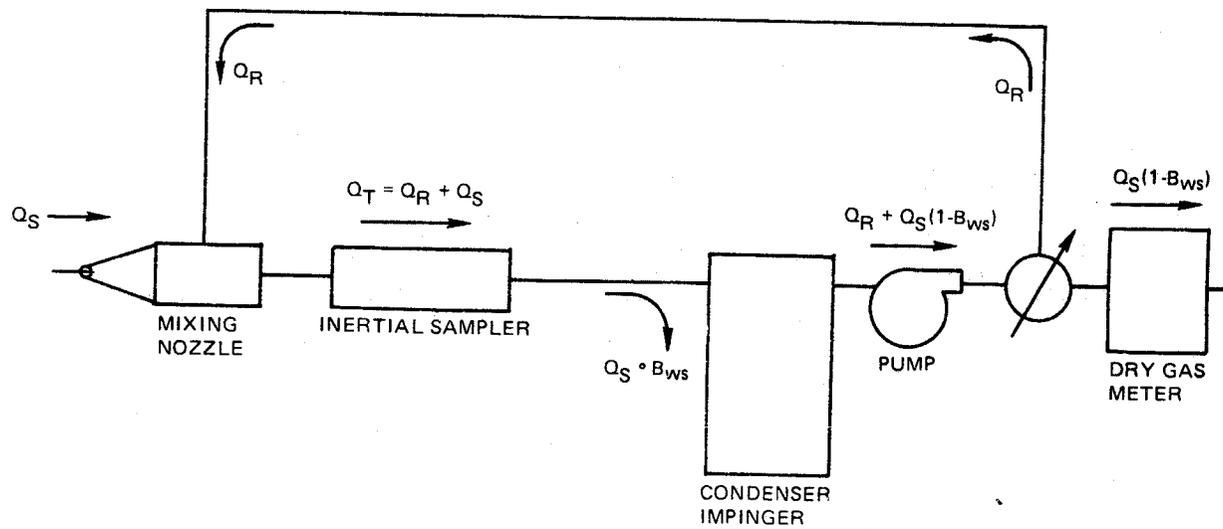
improved prototype systems were designed and constructed under EPA contract. (Williamson et al., 1984. Williamson et al., 1985).

The principle of operation of the EGR train is illustrated in Figure 5-1. Stack gas is extracted isokinetically at volumetric flowrate  $Q_s$ . If the stack moisture fraction is  $B_{ws}$ , the sample flow consists of  $Q_s \cdot B_{ws}$  moisture and  $Q_s(1 - B_{ws})$  dry gas flow. At the mixing point a flow,  $Q_r$ , of dry recycle gas is added to the sample stream to bring the total flowrate to the predetermined constant level,  $Q_t$ . In the impingers or condenser, the moisture content  $B_{ws} \cdot Q_s$  is removed. After the pump and total flow metering element, the recycle flow  $Q_r$  is diverted by means of adjustable valves. By mass balance, in a leak-free system, the remaining flow which passes through the dry gas meter and orifice will simply be  $Q_s(1 - B_{ws})$ , exactly as would occur in an isokinetic sampling train without gas recycle.

A block diagram of the prototype train is shown in Figure 5-2. The gas sample which contains particulate matter enters through the sample inlet of the mixing nozzle. Oversize particles are removed by the classifier, after which the desired particulate sample is collected on the sample filter. The gas then passes through an impinger train or ice-cooled condenser, followed by a sealed pump controlled by valves  $V_1$  and  $V_2$  for coarse and fine flow adjustment, respectively. From this point in a standard isokinetic sampling train the gas would pass directly to the dry gas meter and sample orifice and finally be exhausted. In the train as modified for EGR, after the gas exits the pump (sealed, oilless) it passes through an absolute (HEPA) filter and the first of two laminar flow elements where the total flow is measured. The gas stream is then split into the recycle and sample lines. The recycle gas flow is controlled by valves  $V_3$  and  $V_4$ , and measured by a second laminar flow element. The sample flow is monitored in the usual manner, using a dry gas meter and a calibrated orifice. Valve  $V_5$ , at the inlet to the dry gas meter, was added to the system to extend the range of control to higher recycle percentages by adding back pressure to the sample flow line.

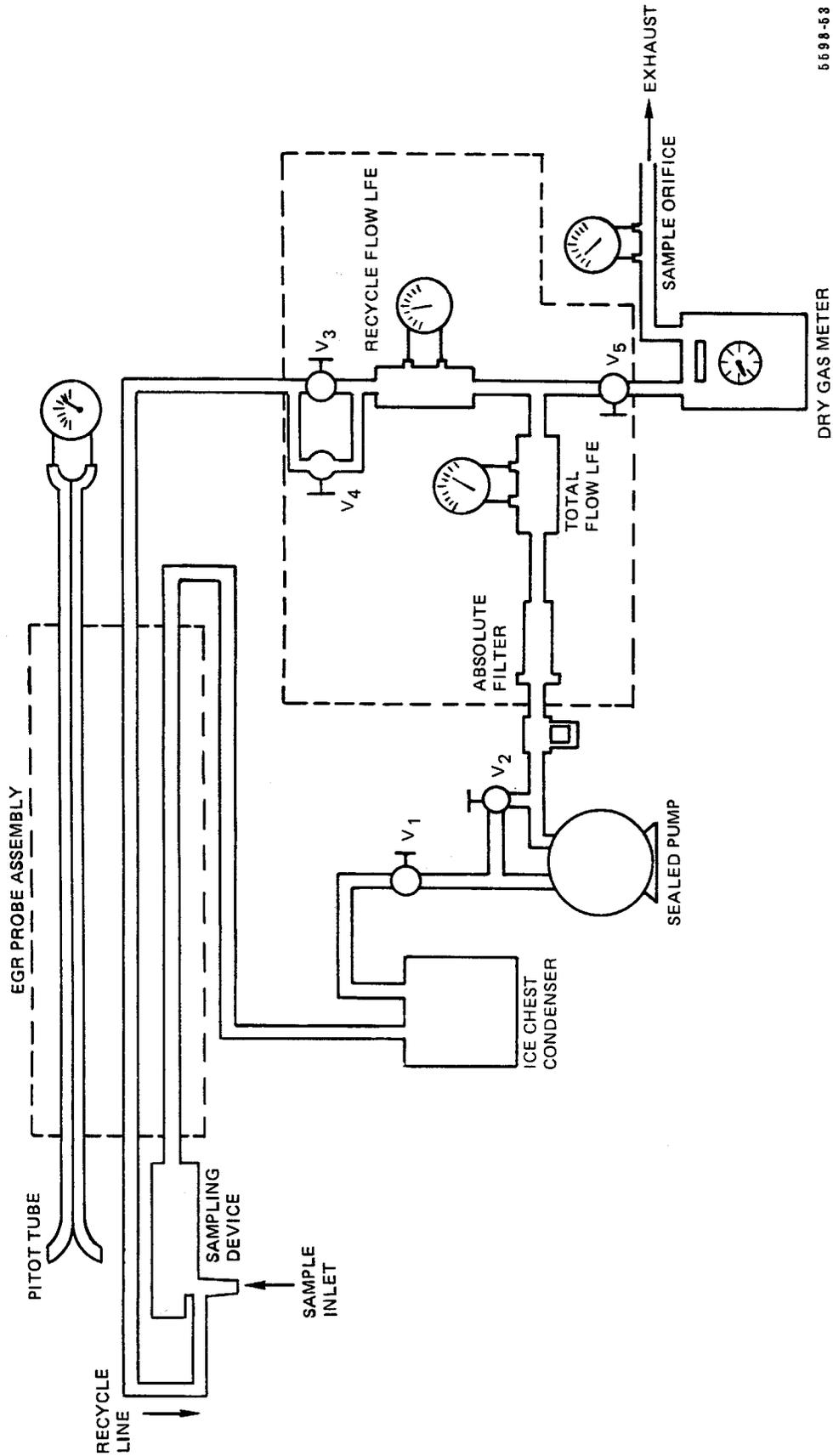
Figures 5-3 and 5-4 show the control module for the USEPA prototype EGR system. As can be seen, the appearance of the module is similar to that of a standard Method 5 sampling box, with the exception of the total, inlet, and recycle magnehelics, the recycle and sample (back pressure) control valves, and the recycle gas outlet. The  $PM_{10}$  size-fractioning cyclone used in conjunction with the EGR system is shown in Figures 5-5 and 5-6. The cyclone chosen as the  $PM_{10}$  sizing device was the commercially available version of SoRI/EPA's Cyclone I (of the 5-Stage Series Cyclone). The particular cyclone used was of the Flow Sensor type, currently marketed by Andersen Samplers, Inc. Potential problems which were considered in design and selection of hardware for the EGR train, were deposition of particles smaller than  $10\mu m$ , upstream of the sizing device, bounce and reentrainment of particles larger than  $10\mu m$ , and inaccuracy in the cutoff diameter due to error in setting the total flowrate.

The EGR sampling system as described above consists of an in-stack classifier and filter combination. In this configuration, its operation is analogous to Method 17 for total particulate emissions measurement. It should be noted, however, that system could be assembled to operate in a geometry



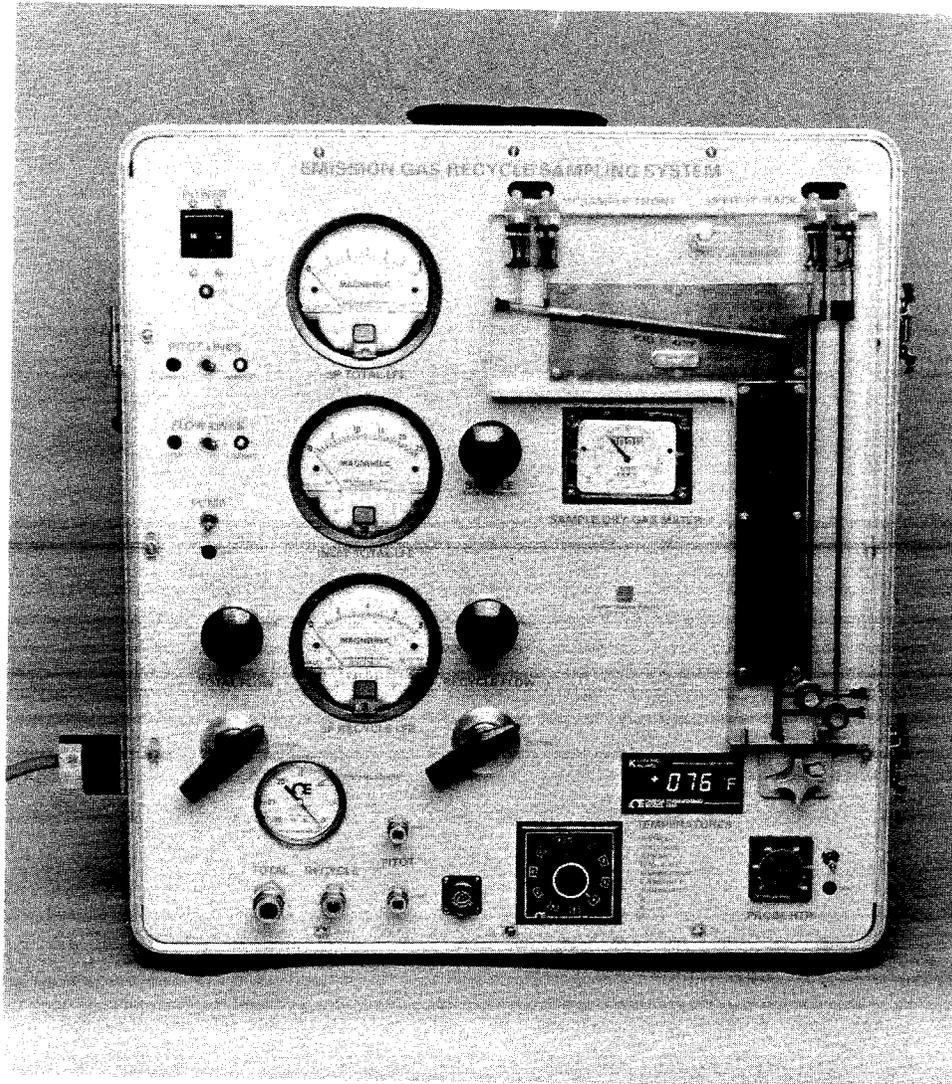
5050-409

Figure 5-1. Gas flow in emission gas recycle (EGR) train (Harris, et al., 1981).



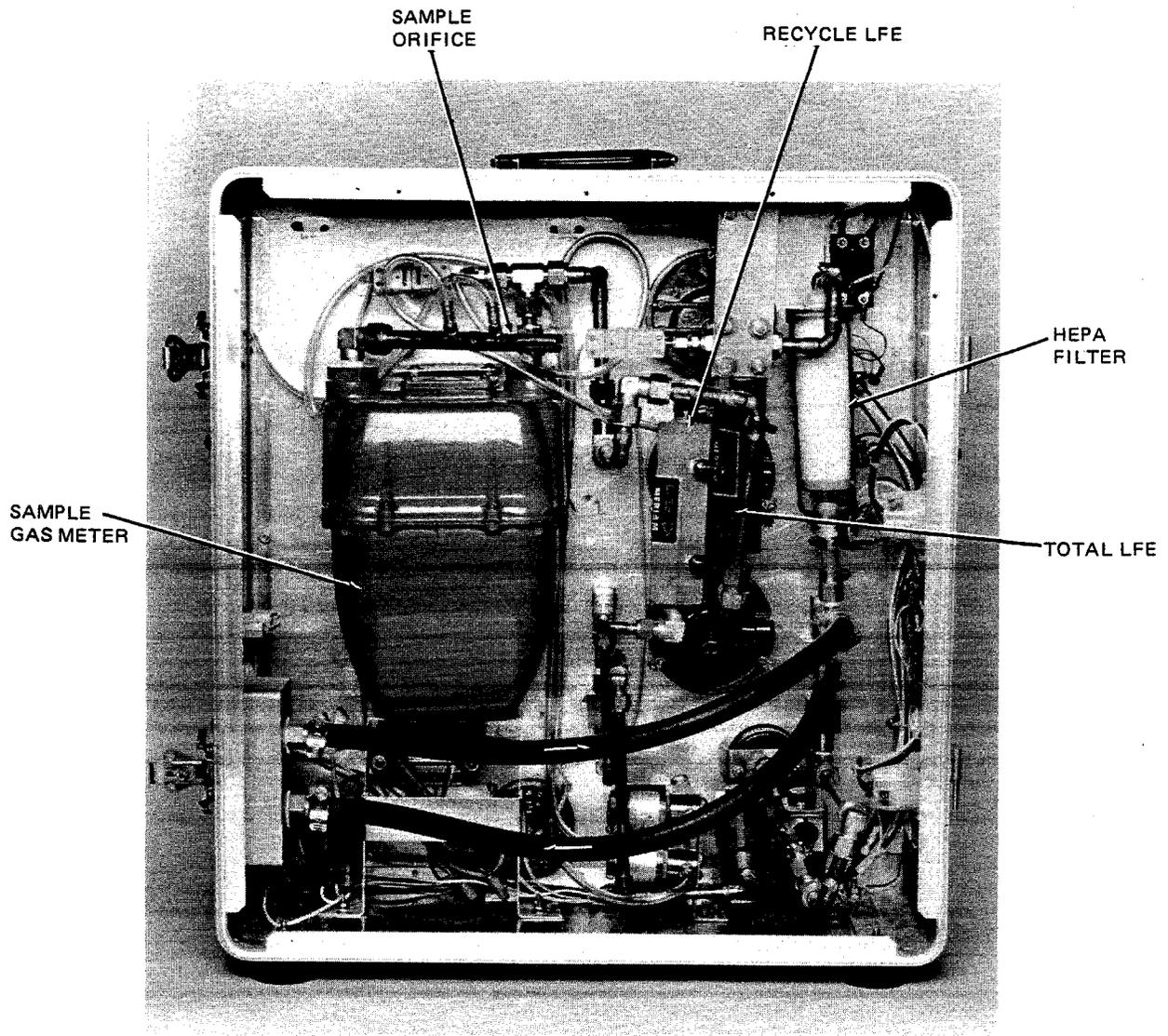
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Figure 5-2. Schematic of the emission gas recycle train (Williamson, et al., 1984).



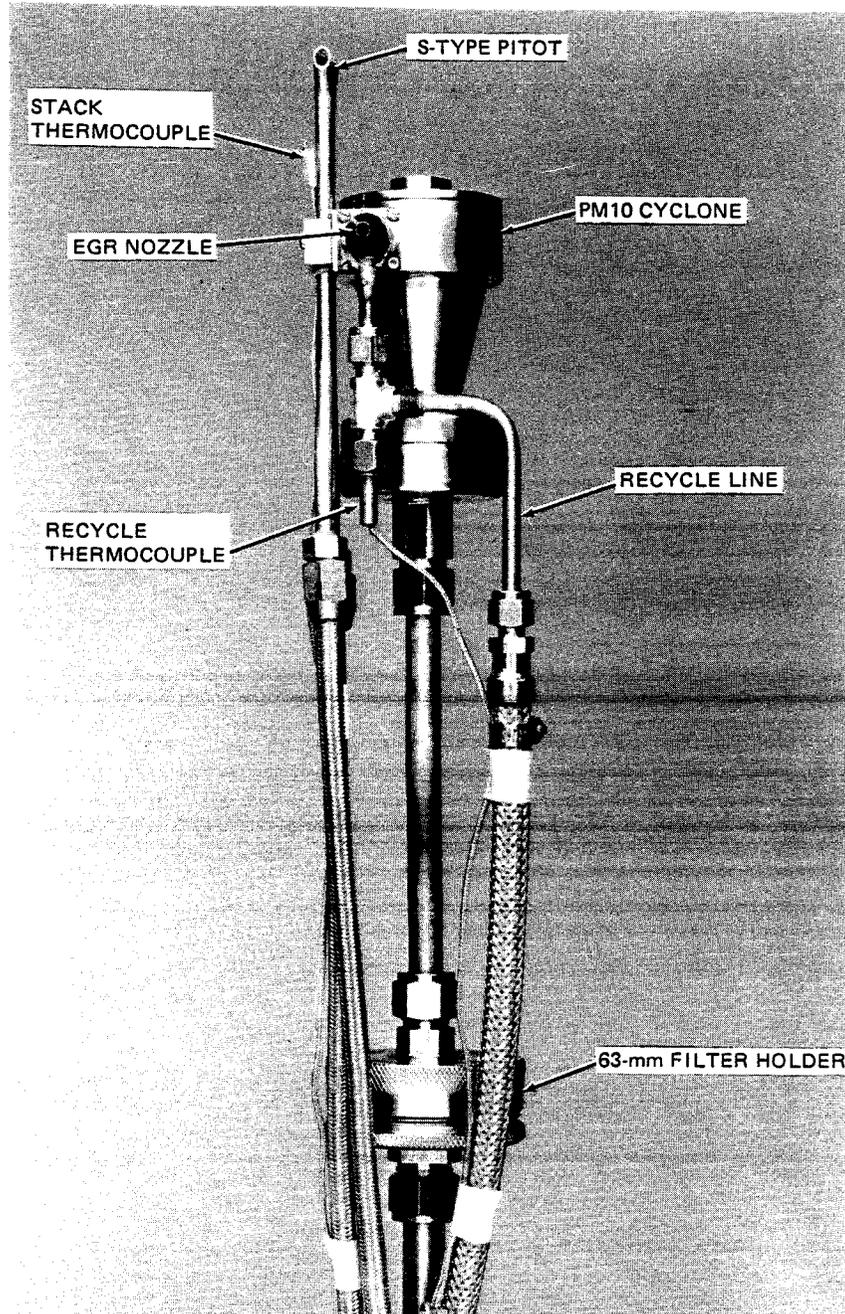
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Figure 5-3. EGR Sampling System Control Module (front view).



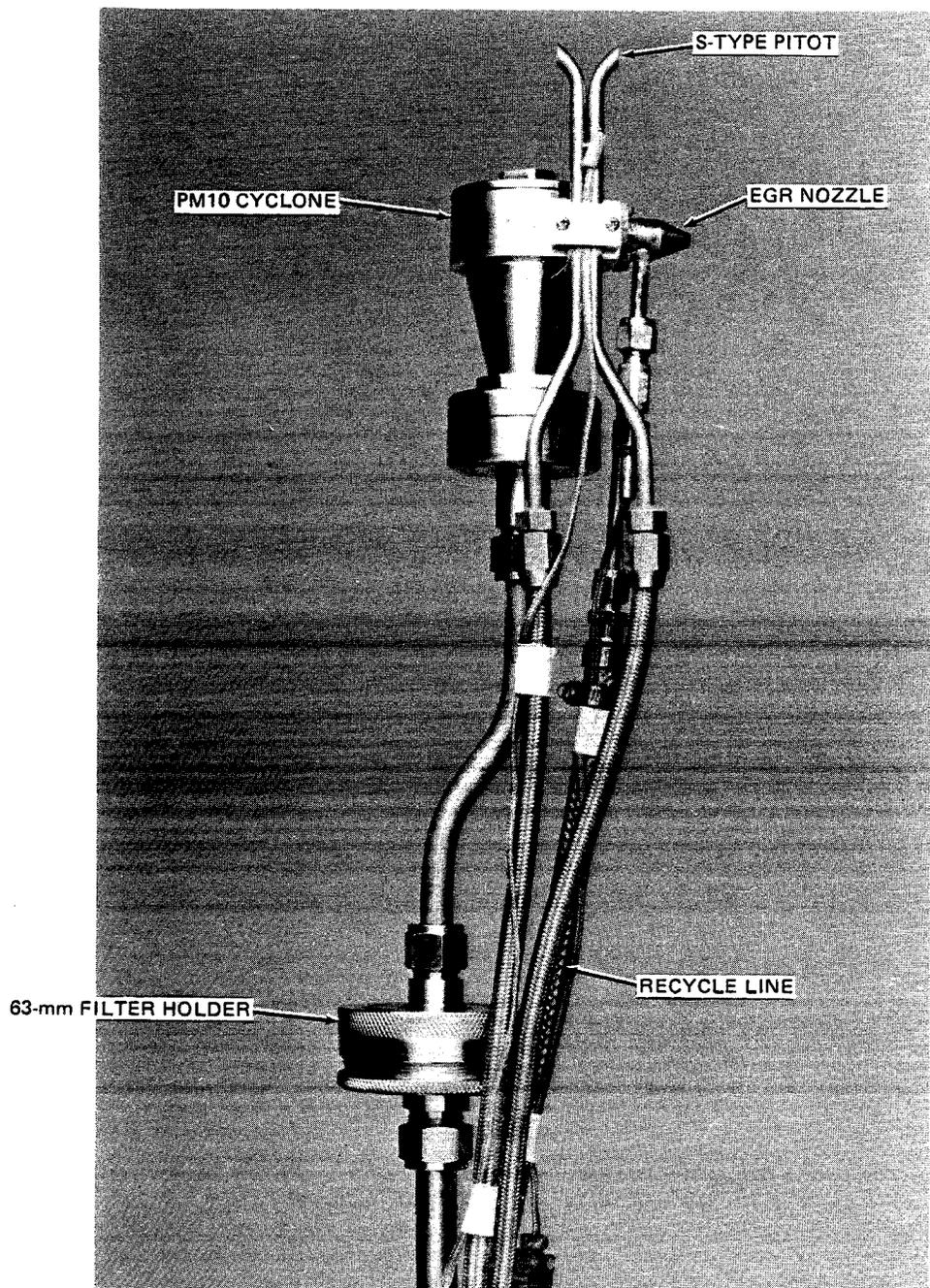
5598-32

*Figure 5-4. EGR Sampling System Control Module (rear view) showing internal components.*



5598-35

Figure 5-5. EGR-PM10 Cyclone Sampling Device (front view).



5598-36

Figure 5-6. EGR PM10 Cyclone Sampling Device (front view).

similar to that of Method 5 sampling with the  $PM_{10}$  cyclone mounted directly onto the sampling probe and the filter mounted on the opposite end of the probe contained within an exterior oven. This mode would make it possible to maintain maximum similarity between the EGR sampling procedures and Method 5.

## 5.2 Field Operation Preliminary Activities

During a sample traverse, the operator must be able to convert the velocity pressure at a given point into the pressure differentials required across the flow orifice and recycle LFE to maintain isokinetic sampling and constant total flowrate,  $Q_t$ . With this goal in mind, the first step is the performance of a traverse to determine flue gas velocity, composition and temperature. Once the composition of the gas is known, molecular weight and viscosity can be determined. The viscosity of the gas is then used to calculate the relationship between flowrate and pressure drop for each LFE and orifice. With the velocity values obtained from the traverse, the operator can decide upon the remaining sampling parameters, such as inlet nozzle diameter and sampling time.

### 5.2.1 Gas Velocity and Analysis

A velocity traverse should be performed in accordance with EPA Reference Method 2. The velocities, temperatures, and the static pressure in the flue should be measured. A gas analysis to determine the composition (molecular weight) of the flue gas, including the amount of water vapor, should be performed using the guidelines in EPA Reference Methods 3, 4, and others as necessary. For example, if there is a large amount of sulfuric acid in the flue, one would want to determine the percentage of  $H_2SO_4$  present in the gas as vapor and the acid dew point by using EPA Reference Method 8.

The wet and dry mean molecular weights of the stack gas are needed for orifice, laminar flow element, and pitot calculations. For the accuracy needed in these calculations, the approximation is made that the only significant components of stack gas are  $O_2$ ,  $CO_2$ ,  $H_2O$ ,  $N_2$ , and  $CO$ . Further, since  $CO$  has essentially the same molecular weight and approximately the same viscosity as  $N_2$ , the two gases are lumped together. Typically, oxygen and carbon dioxide concentrations are determined by Orsat or continuous monitors, and the balance of the dry gas composition is assumed to be nitrogen (or a combination of nitrogen and carbon monoxide). The dry gas mean molecular weight  $M_d$  is given by

$$M_d = 32 f_{O_2} + 44 f_{CO_2} + 28 (1 - f_{O_2} - f_{CO_2}) \quad (5-1)$$

where  $f_A$  is the volumetric or mole fraction of molecular species A.

The relative molecular weight of the wet stack gas is then given by

$$M_w = (M_d (1 - f_{H_2O}) + 18 f_{H_2O}) / 28.95 \quad (5-2)$$

The ambient pressure ( $P_a$ , in. Hg) and stack pressure differential relative to ambient ( $\Delta P_s$ , in. w.g.) are combined to calculate stack absolute pressure by the relation:

$$P_s = P_a + \Delta P_s / 13.6, \quad (5-3)$$

where  $P_s$  is expressed in inches of mercury.

The viscosity of the flue gas can be determined by the equation (Williamson et al., 1983):

$$\eta = C_1 + C_2 T + C_3 T^2 + C_4 f_{H_2O} + C_5 f_{O_2} \quad (5-4)$$

where  $\eta$  is in micropoise,  $T$  in °C, and

$$\begin{aligned} C_1 &= 160.62 \\ C_2 &= 0.42952 \\ C_3 &= 1.0483 \times 10^{-4} \\ C_4 &= -74.143 \\ C_5 &= 53.147 \end{aligned}$$

or for  $T$  in °R

$$\begin{aligned} C_1 &= 51.05 \\ C_2 &= 0.207 \\ C_3 &= 3.24 \times 10^{-5} \\ C_4 &= -74.143 \\ C_5 &= 53.147 \end{aligned}$$

This equation fits data (with a standard error of 0.98 micropoise) for a combustion gas of arbitrary composition in the range 0-350°C, 0-70% moisture. This equation was generated by SoRI personnel (Williamson, 1983) from large "data banks" of viscosities calculated by the more rigorous algorithm of Wilke (1950).

### 5.2.2 SAMPLING TIME

The sampling time required is set by the goals of the measurement effort. If the goal is to generate emissions factor data, then sufficient particulate matter in the  $PM_{10}$  fraction must be collected for accurate gravimetric analysis. If the goal is to obtain a  $PM_{10}$  sample for chemical analysis, the minimum amount of material to be collected is set by the requirements of the analytical laboratory. If the method is to be used as a compliance technique, a minimum sampled gas volume and/or dwell time per traverse point may be the determining factors.

The length of time required to collect an adequate sample is dependent upon the mass loading of the aerosol, the size distribution of the particles, and the sample flowrate. If the results of a previous total mass test (Method 5 or 17) are available, the mass loading can be obtained from them. If not, an estimate should be made on the basis of the pre-test survey or other information. The nomograph in Figure 4-7 estimates the sampling time for a high capacity sampler, such as a  $PM_{10}$  cyclone, given a mass loading estimate. Results from an initial test can be used to more accurately establish the optimum sampling time. Cyclones can inherently collect a large amount of material without fear of bounce and re-entrainment. Cyclone catches may easily

exceed 1 gm; the determining factor concerning loading limitations is whether or not re-entrainment occurs. In compliance or emissions factor measurement situations it is unlikely that a PM<sub>10</sub> cyclone will ever be overloaded at controlled sources if reasonable sampling durations are used.

### 5.2.3 SAMPLING TRAVERSE

The number and placement of traverse points should be selected according to EPA Reference Method 1. In order to adequately characterize a given source, the complete traverse protocol should be successfully performed a minimum of three separate times, as is similarly called for by Method 5. If a sampling run is interrupted or declared invalid, the sampler should be cleaned, reassembled, and the test repeated.

It should be noted that when sampling the effluents from variable or cyclical processes, the test at each sampling point should extend through a complete cycle to insure that a representative sample is taken. This may not be practical and is commonly ignored in conventional source sampling procedures.

### 5.2.4 EGR SAMPLING FLOWRATES

The sample flowrate through the nozzle is determined from the nozzle diameter and the local stack velocity V:

$$Q_S = 0.3242 d^2 V \quad (5-5)$$

where V is expressed in ft/sec, d in inches, and Q<sub>S</sub> in acfm.

This basic relationship assures an isokinetic target sample flowrate. Alternatively, the value of Q<sub>S</sub> needed for isokinetic sampling can be determined from Method 5 nomographs once the nozzle diameter is known.

Unless the velocity distribution is very flat, and constant, the nozzle flow will have to be changed to maintain isokinetic sampling conditions. Because of the viscosity changes which take place with changes in the balance between the nozzle and recycle flow components of the total flow, the required total flow needed to maintain a fixed D<sub>50</sub> will change somewhat as the flow balance changes. Therefore the required total flow (and recycle flow) must be found by an iterative process as a function of the nozzle flow. The latter in turn is a function of the local flue gas velocity (or pitot ΔP).

Since the flow through the particle sizing device is the sum of the sample and recycle flows, the relationship can be expressed showing the recycle flowrate as a function of the sample flowrate. This is given by the equation

$$Q_T = X Q_S \quad (5-6)$$

where Q<sub>T</sub> is the total flow through the particle sizing device (acfm),  
Q<sub>S</sub> is the nozzle sample flowrate (acfm), and

X is a variable representing the relationship between the recycle gas and sample flowrates (at  $x=1$ ,  $Q_T=Q_S$  and  $Q_{RECYCLE}=0$ ).

The percent of the total gas mixture which is composed of the recycle gas can then be given by

$$PR = [(X-1)Q_S/Q_T] (100\%) \quad (5-7)$$

It has been concluded from laboratory experiments that if the recycle gas percentage exceeds 80%, the ability to obtain stable samples flows degenerates. Therefore, if the recycle gas flow exceeds this limit, the chosen sample nozzle is too small and should be replaced with a larger one.

The addition of dry recycle gas to the sample gas in the EGR system decreases the moisture content of the gas mixture to the particle sizing device. This in turn changes the gas viscosity. With an initial value of percent recycle (PR) estimated, the water fraction of the mixture can be determined by

$$f_{H_2O} = B_{WO} (1 - \frac{PR}{100}) \quad (5-8)$$

where  $B_{WO}$  is the volumetric or mole fraction of water in the stack gas, and  $f_{H_2O}$  is the water fraction of the mixture.

The viscosity of the mixture must now be calculated, using the previous viscosity equation, before the desired flowrate through the chosen particle-sizing device can be determined for a specific "cut-point".

The total flow through the sampler can be set at any desired rate by the operator. Normally, a  $10\mu\text{m}$  cut will be desired and the required total sampler flowrate to obtain that cut will be found by using empirically determined calibration equations for the specific sampler. For example, if Cyclone I (of SORI's Five-Stage Series Cyclone) is used as an initial particle separator, the required equation, based on currently available data, is

$$Q_{cyc\ 1} = .072962 \left(\frac{M_w P}{T}\right)^{-0.2949} \mu(D_{50})^{-1.4102} \quad (5-9)$$

where  $D_{50}$  is the desired "cut-point" particle diameter in microns,  
 $\mu$  is the viscosity of the gas mixture in micropoise, and  
 $Q_{cyc1}$  is the flow through the cyclone in acfm.  
 $T$  is the cyclone gas temperature in °R,  
 $M_w$  is the wet molecular weight of mixed gas, and  
 $P$  is the absolute stack pressure in inches of mercury.

The Cunningham correction was assumed to have a constant value of 1.015 in generating this equation. The assumption is accurate to within 0.5% at any likely sampling condition which might be encountered.

If the desired sampler flowrate,  $Q_t$ , is less than the predetermined sample (through the nozzle) flowrate,  $Q_s$ , the sampling nozzle is too large and a

nozzle with a smaller diameter must be used. If the total flowrate desired after recalculating the gas viscosity differs from the initial estimate calculated for a given sample flow by more than 1% the equations must be reiterated. The variable "X" in equation 5-6

$$Q_T = XQ_S$$

is then changed to the ratio

$$X = Q_T/Q_S$$

The equations are then recalculated until the desired tolerance (1%) between successive values for the total flowrate is attained. The 1% tolerance means that the  $D_{50}$  actually achieved will differ from the target  $D_{50}$  by less than 1%. If a greater relative deviation from the target  $D_{50}$  can be permitted, the 1% tolerance can be relaxed somewhat. This will greatly reduce the computational time required for the setup calculations.

Since the recycle gas flowrate has been calculated as a percentage of the total sampler flowrate, it can be expressed by the equation

$$Q_R = Q_T(PR/100) \quad (5-10)$$

where  $Q_R$  is the recycle gas flowrate (acfm),  
 $Q_T$  is the total flowrate through the sampler (acfm), and  
 PR is the percent recycle gas as compared to the total sampler flowrate.

After the three target flowrates ( $Q_S$ ,  $Q_t$ , and  $Q_R$ ) have been calculated, the settings for the flow metering devices must be determined. For the purpose of these calculations the sample flow meter is assumed to be an orifice meter for which the flow is governed by the equation.

$$Q = (.9615/\sqrt{\Delta H@}) * (\Delta HT/P(M_w))^{0.5} \quad (5-11)$$

The calibration factor  $\Delta H@$  is defined as the pressure drop across an orifice which produces a flowrate of 0.75 cubic feet per minute at standard conditions (528°R and 29.92 in Hg). Because of the lower flowrate at which the  $PM_{10}$  sampler operates as compared to Method 5, the orifice meter used for Method 5 train is not appropriately sized for  $PM_{10}$  sampling. The  $\Delta H@$  value of the  $PM_{10}$  orifice is found as outlined in Method 5. For the present calculations,  $Q$  is expressed in actual cubic feet per minute,  $T$  in °R,  $P$  in inches of mercury, and  $\Delta H$  in inches water gauge.  $M_w$  is inherently dimensionless, and equals 28.97 for standard air.

Using the above formalism and typical ideal gas law calculations, the desired readings at the sample flow orifice can be calculated. For the equations that follow, variables subscripted with "s" refer to stack conditions, and the subscripts "a" and "m" refer to ambient and meter conditions, respectively. The  $\Delta H_m$  target for the desired flows is given by

$$\Delta H_m = \frac{M_w T_m \Delta H_0}{P_m} \left( \frac{Q_s P_s (1 - B_{wo})}{.9615 T_s} \right)^2 \quad (5-12)$$

In this equation, correction has been made for the uptake of moisture in the condenser or impinger train and drying column.

The flow behavior of the laminar flow elements (for total and recycle flowrates) can be found by an equation of the form:

$$Q_{LFE} = M \Delta P (\mu_{STD}/\mu_{LFE}) + B \quad (5-13)$$

where  $Q_{LFE}$  = flowrate at LFE (acfm),  
 $M, B$  = linear fit calibration coefficients,  $y = MX+B$   
 $\Delta P_m$  = LFE pressure differential (in. H<sub>2</sub>O),  
 $\mu_{STD}$  = viscosity of standard air (180.1<sup>2</sup> micropoise), and  
 $\mu_{LFE}$  = viscosity of gas through LFE (micropoise).

Since the absolute pressure at the inlets to the recycle and total flow LFE's is typically higher than zero it cannot be ignored when converting from meter flowrates to flowrates at stack conditions. Laboratory and field testing have indicated an average difference to ambient of eight inches water gauge at the inlet to these devices. For the purpose of setup equations, the absolute pressure at these devices is assumed to be given by the equation:

$$P_m = P_a + (8.0/13.6) \quad (5-14)$$

$$P_m = P_a + 0.588$$

Therefore, the target pressure differential for the total flow LFE can be found from the equation

$$\Delta P_t = (\mu_{LFE}/\mu_{STD}) \left( (Q_s P_s T_m / P_m T_s (1 - f_{H_2O})) - B_t \right) / M_t \quad (5-15)$$

It should be noted that  $f_{H_2O}$  represents the water content of the mixed (cyclone) gas and not the stack<sup>2</sup> gas.

Since the recycle gas theoretically contains no moisture at either the LFE or the cyclone (stack) the equation for the target  $\Delta P$  recycle becomes:

$$\Delta P_R = (\mu_{LFE}/\mu_{STD}) \left( (Q_s P_s T_m / P_m T_s) - B_R \right) / M_R \quad (5-16)$$

If desired, the time per revolution of the EGR sample dry gas meter (for a 0.1 cubic foot per revolution gas meter) is given by:

$$t(\text{sec/rev}) = 6 / (Q_{DGM} \times \gamma)$$

where

$$Q_{DGM} = (Q_s P_s / T_s) (1 - f_{H_2O}) (T_m / P_a), \text{ and} \quad (5-17)$$

$\gamma$  = is the dry gas meter correction factor.

### 5.3 TAKING THE SAMPLE

#### 5.3.1 LEAK TEST

The sampler, probe, condensers, and sampling lines should have been leak-checked prior to final assembly by pressurization and testing for holding a positive pressure in the devices. This can be achieved by plugging one end of the line to be tested and applying a positive pressure at the opposite end. By placing a pressure gauge in parallel with the test line the pressure within the system can be monitored. If the system fails to maintain pressure after it is sealed, a soap solution can be used to locate leaks.

Leaks within the sampling device, probe, or condensers may be found using the EGR control console pump as in a Method 5 leak check. Plug the sampling nozzle, turn the recycle gas valves completely off, and turn on the EGR pump to produce a vacuum across the desired test section. Use the total flow fine adjust valve to set the system vacuum to 15 inches of mercury. If the required vacuum reading on the console mounted vacuum gauge cannot be achieved or if the gas meter indicates a flowrate greater than 0.02 cubic feet per minute, the system is not sealed and the leak(s) must be located and fixed.

The positive pressure portion of the control console can be tested for leaks in a similar manner or using the procedure in Method 5. Using an auxillary pump/DGM system (or spare sampling system), attach the recycle output of the EGR system, using latex or similar tubing, to the input of the auxillary system. Completely open the recycle valves and close the total flow and sample back-pressure valves. Continue the procedure as outlined above. The same limits (leak rate  $\leq 0.02$  cfm) apply to the positive side of system as the negative side. An alternate method for the positive side of the EGR system would be to completely close the recycle valve, plug the sample inlet, and attach a short section of tubing to the outlet of the flow orifice. Vent the low side of the orifice manometer to ambient pressure and plug the corresponding pressure tap on the orifice. Pressurize the system to 5 to 10 inches of water, then pinch off the tubing. If the manometer fails to hold pressure, a leak is present in the system. Parts to check are the pump, tube fittings, valves, and tubing.

#### 5.3.2 PRETEST EQUIPMENT WARMUP

Since most flue streams to be tested are not at ambient temperatures, the EGR sampling train must be heated to stack conditions. This helps insure isokinetic sampling, significantly reduces the chance of acid deposition within the sample line, and allows isothermal introduction of recycle gas at the inlet of the particle sizing device. This is accomplished through the use of the heated EGR probe and in-the-flue-heating of the sampler.

The sampler should be heated in the flue long enough to equilibrate. Typically, the PM<sub>10</sub> Cyclone I/Filter combination should remain in the flue at least 15-20 minutes to insure thermal equilibrium. The nozzle, if uncapped, should not point into the flow field during preheating. If possible, the nozzle should be capped or plugged during preheating, and the cap or plug

removed immediately before sampling. The probe temperature is regulated by a proportional temperature controller set approximately equal to the stack temperature. While the sampling device is heating in the flue, the probe heater controller should be adjusted to heat the recycle line to stack temperature. When condensible vapors are present, the probe should be heated to and maintained above the dew point. Care should be taken to insure that vapor does not condense in the portion of the probe extending outside the flue and flow back into the sampler.

### 5.3.3 FLOWRATES

As stated previously, the flowrate through the sampling nozzle is directly dependent on the stack gas velocity at the sample point. In operation, therefore, the pressure differential,  $\Delta H$ , of the sample orifice meter is adjusted according to the previously determined run calculations with shifts in the  $\Delta P_{\text{pitot}}$  readings. This insures continued isokinetic sampling. This in turn means the flowrate of the recycle gas must also be adjusted to maintain the proper total flow through the particle sizing device. During startup the operator initially sets the total sampler flowrate using valves  $V_1$  and  $V_2$ . After setting the approximate total flowrate, the sample flowrate is set by adjusting the recycle valves  $V_3$  and  $V_4$ . If high recycle ratios are required,  $V_5$  may need to be adjusted. The operator should check to be sure the recycle flowrate is now properly set. Because there is some interaction between flowrates, a few minor repeat adjustments may be required between the total and sample flowrates. Typically, when traversing to another sampling point, only the fine recycle adjust ( $V_4$ ) or the sample back pressure valve ( $V_5$ ) will need adjustment. These point-to-point adjustments may require slight adjustment to the total flow. If so, repeat the iterative process outlined above until the target  $\Delta P_t$  and  $\Delta H$  sample values are achieved. Again, the recycle flowrate should be used as a "check" of the other flowrates. The practiced operator can usually obtain the target values within one or two iterations at each new point.

### 5.3.4 SHUTDOWN ORIENTATION

Depending on the orientation of the sampler, it may be advisable to maintain an appreciable flowrate while removing the sampler from the flue. The flowrate should be maintained until the sampler can be placed in a favorable orientation (usually horizontal). This is particularly true when operating a cyclone in a vertical orientation. Otherwise some dust might fall from one stage of the sampler to another and thus be measured where it was not collected. After the flow has been terminated, the sampler can be transported to the lab. It should be kept in a horizontal position with the nozzle plugged or covered to avoid contamination or loss of sample.

### 5.3.5 DATA LOGGING

The parameters of the test should be recorded in a clear, concise format. Parameters that are likely to change, such as sample and recycle gas flowrates, should be recorded periodically. Other examples are port number, traverse

point, gas meter temperature, gas meter volume, metering orifice and LFE pressure drops, atmospheric pressure, stack gas temperature, etc.

#### 5.4 SAMPLE RECOVERY AND WEIGHING

##### 5.4.1 UNLOADING THE SAMPLER

After the sampler has cooled down to nearly ambient temperature and been brought into the lab, it should be carefully "unloaded." Unloading consists of removing the particulate mass caught in the sampler. Great care is needed in this procedure to insure that all of the particulate matter is recovered and placed in the proper sample containers. The sample can be effectively recovered using a combination of brushing and washing. The particulate should be brushed into a uniquely identified, preweighed sample container for each stage of the sampler. A No. 7 camels hair brush or small nylon bristle brush is suggested for this operation. After the brushing is completed the same surface should be washed with a reagent grade solvent, such as methylene chloride, into a preweighed bottle or aluminum cup. The sample wash should be allowed to completely evaporate before desiccation and weighing. The mass gained for each stage (PM<sub>10</sub> cyclone and filter) is the sum of the appropriate brushed recovery and wash residue.

Particulate matter collected from the inner surfaces of the EGR nozzle, the cyclone body, collection cup and cap are to be considered as collected by the cyclone. Furthermore, any matter brushed or rinsed from the outside of the cyclone exit tube is also to be considered part of the cyclone catch. The PM<sub>10</sub> fraction, if that was the size fractionation achieved, consists of particulate matter collected from the inner surface of the "turn-around" on the cyclone cap, the inside wall of the exit tube, the inner walls of the filter holder (upstream of the filter), and the surface of the filter. Also, if the system was operated in a Method 5 geometry, the wash from the probe is to be included in the PM<sub>10</sub> fraction. In some circumstances, the residue from the condensers or impingers may be considered to be PM<sub>10</sub> condensables.

##### 5.4.2 DRYING AND WEIGHING

Each of the particulate containers must be dried to a constant weight, with two hour checks used to establish the uniformity of the weights. Hard, non-volatile particles are often dried in a convection oven at a temperature of 212°F, desiccated until cooled to room temperature, weighed, and then check-weighed two hours later. Volatile particles present special problems which have to be dealt with according to the particulate characteristics and sampling goals. One technique for particles which are volatile at elevated temperatures is to desiccate them 24 hours before weighing. Whatever the technique used, constant weight of the samples after further drying is the criterion to be met. The results of the weighings and any notes should be recorded in a notebook with which the run sheets are kept.

#### 5.5 DATA ANALYSIS

### 5.5.1 Average Run Parameters

In order to calculate the resultant values from a test run the average values of the recorded temperatures and pressure drops must be calculated. The pressure drop across the pitot tube, however, requires special attention. The stack velocity is a function of the square root of the pitot  $\Delta P$ ; therefore, a straight average of the  $\Delta P$ 's over a given run would not result in the true average velocity. Because of this, the value used for calculating the average velocity must be the square of the average square root of the velocity heads. This will result in a  $\Delta P$  value which will allow calculation of the true average velocity.

#### Dry Gas (Sample) Volume

The sample volume measured by the EGR dry gas meter can be corrected to standard conditions (68°F, 29.92 inches Hg) by using the following equation:

$$V_{m_{STD}} = (V_m \gamma) \left( \frac{T_{STD}}{T_m} \right) \left( \frac{P_{BAR} + \frac{\Delta H}{13.6}}{P_{STD}} \right)$$

$$= \left( 17.65 \frac{^{\circ}R}{\text{in. Hg}} \right) (V_m \gamma) \left( \frac{P_{BAR} + \frac{\Delta H}{13.6}}{T_m} \right) \quad (5-18)$$

where  $V_{m_{STD}}$  = Volume of gas sample through the dry gas meter (standard conditions), cu. ft.

$V_m$  = Volume of gas sample through the dry gas meter (meter conditions), cu. ft.

$\gamma$  = Gas meter calibration constant.

$T_{STD}$  = Absolute temperature at standard conditions, 528°R

$T_m$  = Average dry gas meter temperature, °R.

$P_{BAR}$  = Barometric pressure, inches of Hg.

$\Delta H$  = Average pressure drop across the orifice meter, inches of H<sub>2</sub>O.

13.6 = Specific gravity of mercury.

$P_{STD}$  = Absolute pressure at standard conditions, 29.92 inches Hg.

#### Recycle and Total Gas Flowrates

The recycle and total gas flowrates are monitored by laminar flow elements (LFE). Therefore, the average flowrates through these respective devices can be determined using the manufacturers calibration charts or an empirically determined calibration equation in the form:

$$Q_{STD} = (M \Delta P \left( \frac{\mu_{STD}}{\mu_{LFE}} \right) + B) \left( \frac{T_{STD}}{T_m} \right) \left( \frac{P_I}{P_{STD}} \right)$$

$$= 17.65 \left( M \Delta P \left( \frac{\mu_{STD}}{\mu_{LFE}} \right) + B \right) \left( \frac{P_I}{T_m} \right) \quad (5-19)$$

where  $Q_{STD}$  = Flowrate through laminar flow element (standard conditions), cu. ft./min.

M and B = Empirically determined calibration constants.

$\Delta P$  = Average pressure drop across LFE, inches  $H_2O$ .

$\mu_{STD}$  = viscosity of STD gas (180.1  $\mu$ poise).

$\mu_{LFE}$  = viscosity of LFE gas, refer to cyclone  $D_{50}$  ( $\mu$ poise).

$T_m$  = Average temperature at LFE,  $^{\circ}R$ .

$T_{STD}$  = Absolute temperature at standard conditions,  $528^{\circ}R$ .

$P_I$  = Absolute pressure at inlet to LFE, inches Hg.

$P_{STD}$  = Absolute pressure at standard conditions, 29.92 inches Hg.

### Percent Recycle

The amount of recycle gas, expressed as a percentage of total flow through the particle-sizing device is given by the equation:

$$PR = [Q_R/Q_T] \times 100\% \quad (5-20)$$

where PR = Percent of total gas flow contributed by recycle gas, percent.

$Q_R$  = Recycle gas flowrates (standard conditions), cu. ft./min.

$Q_T$  = Total gas flowrate (standard conditions), cu. ft./min.

### Volume of Water Vapor

The volume of the water vapor collected from flue gas is calculated as follows:

$$\begin{aligned} V_{W_{STD}} &= V_{l_c} \left( \frac{\rho_{H_2O}}{M_{H_2O}} \right) \left( \frac{RT_{STD}}{P_{STD}} \right) \\ &= 0.04707 \frac{\text{cu. ft.}}{\text{ml}} V_{l_c} \end{aligned} \quad (5-21)$$

where  $V_{W_{STD}}$  = Volume of water vapor in the gas sample (standard conditions), cu. ft.

$V_{l_c}$  = Total volume of liquid collected in impingers and/or silica gel, ml.

$\rho_{H_2O}$  = Density of water, 1 g/ml.

$M_{H_2O}$  = Molecular weight of water, 18 lb./lb.-mole.

R = Ideal gas constant, 21.83 inches Hg-cu. ft./lb.-mole- $^{\circ}R$ .

$T_{STD}$  = Absolute temperature at standard conditions,  $528^{\circ}R$ .

$P_{STD}$  = Absolute pressure at standard conditions, 29.92 inches Hg.

## Moisture Content

The moisture content of the stack gas or sample gas is calculated by the equation:

$$B_{wo} = \frac{V_{wSTD}}{V_{mSTD} + V_{wSTD}} \quad (5-22)$$

where  $B_{wo}$  = Proportion by volume of water vapor in the gas stream, dimensionless.  
 $V_{wSTD}$  = Volume of water in the gas sample (standard conditions), cu. ft.  
 $V_{mSTD}$  = Volume of gas sample through dry gas meter (standard conditions) cu. ft.

The addition of a known amount of dried recycle gas to the measured sample gas upstream of the particle-sizing device changes the moisture content of the gas mixture. This new moisture content is determined by the equation below:

$$f_{H_2O} = B_{wo} \left(1 - \frac{PR}{100}\right) \quad (5-23)$$

where  $f_{H_2O}$  = Fraction of water vapor (by volume) in the gas mixture, dimensionless.  
 $B_{wo}$  = Proportion by volume of water vapor in the gas stream, dimensionless.  
PR = Percent recycle gas as compared to the total gas mixture flowrate.

## Flowrates (Actual Conditions)

In order to calculate the particle cut diameter of the inertial classifier, it is necessary to know the flowrate through the sampler at the actual sampler conditions. This can be accomplished using the following equation:

$$\begin{aligned} Q_A &= Q_{STD} \left(\frac{1}{1 - f_{H_2O}}\right) \left(\frac{T_s}{T_{STD}}\right) \left(\frac{P_{STD}}{P_s}\right) \\ &= Q_{STD} \left(\frac{1}{1 - f_{H_2O}}\right) \left(\frac{T_s}{P_s}\right) \left(0.0567 \frac{\text{in. Hg}}{^\circ\text{R}}\right) \end{aligned} \quad (5-24)$$

where  $Q_A$  = Flowrate through sampler (sampler conditions), acfm.  
 $Q_{STD}$  = Flowrate through sampler (standard conditions), scfm, dry basis.  
 $f_{H_2O}$  = Fraction (by volume) of water vapor in gas mixture, dimensionless.  
 $T_s$  = Average temperature of sampler ( $\approx$ stack),  $^\circ\text{R}$ .  
 $T_{STD}$  = Absolute temperature at standard conditions,  $528^\circ\text{R}$ .  
 $P_s$  = Absolute stack pressure, inches Hg.  
 $P_{STD}$  = Absolute barometric pressure, 29.92 inches Hg.

### 5.5.2 Stack Gas Velocity

The average stack gas velocity or the gas velocity at any one point within the stack can be found using the following equation:

$$V_s = K_p C_p (\Delta P)^{1/2} \left( \frac{T_s}{P_s M_s} \right)^{1/2} \quad (5-25)$$

where  $V_s$  = Stack gas velocity, ft/sec.

$K_p$  = 85.48 ft/sec  $\frac{\text{lb.}}{\text{lb. mole} \cdot ^\circ\text{R}}$  when these units are used.  
 $C_p$  = Pitot tube coefficient, dimensionless.  
 $T_s$  = Absolute stack gas temperature,  $^\circ\text{R}$ .

$\Delta P$  = Square of the average square root of the velocity heads, inches  $\text{H}_2\text{O}$ .

$P_s$  = Absolute stack gas pressure, inches Hg.

$M_s$  = Molecular weight of stack gas (wet basis), lb./lb.-mole,  
 $= M_d (1 - B_{wo}) + 18 B_{wo}$

$B_{wo}$  = Proportion by volume of water vapor in the gas stream.

$M_d$  = Dry molecular weight of stack gas,  
 $= 32 f_{\text{O}_2} + 44 f_{\text{CO}_2} + 28 (1 - f_{\text{O}_2} - f_{\text{CO}_2})$ .

$f_A$  = Volumetric or mole fraction of molecular species A.

### 5.5.3 Concentration

The concentration of the particulate matter caught by each stage and the total particulate concentration in the stack gas can be calculated by the equation below:

$$C' = 0.0154 \text{ gr/mg} \left( \frac{M_p}{V_{m\text{STD}}} \right) \quad (5-26)$$

where  $C'$  = Concentration of particulate matter for a given stage or in stack gas, gr./scf, dry basis.

$M_p$  = Mass of collected particulate (either per stage or total), mg.

$V_{m\text{STD}}$  = Volume of gas sample through dry gas meter (standard conditions) cu. ft.

The units of gr./scf can be converted to  $\text{mg/dnm}^3$  by using the following:

$$C = 2293.2 C'$$

where  $C$  = Concentration of particulate,  $\text{mg/dnm}^3$ .

#### 5.5.4 Sampler D<sub>50</sub>

The D<sub>50</sub> or cut-point of each stage of the chosen particle-sizing device should be calculated for accurate determination of the particle size distribution. The cut-point is primarily a function of the actual flowrate through the sampler and the viscosity of the gas mixture. The procedure for calculating the actual flowrate (acfm) was described previously, therefore, the viscosity of the mixture must be calculated. It can be determined from equation 5-4.

The currently available data concerning the calibration of Cyclone I, used to obtain the 10μm cut for PM<sub>10</sub> measurement, shows the behavior to be described by the equation

$$D_{50} = 0.15625 \left( \frac{M_w P}{T} \right)^{-0.2091} Q_T^{-0.7091} \mu^{0.7091} \quad (5-27)$$

where  
 D<sub>50</sub> = Diameter of particles having a 50 percent probability of penetration, microns (μm);  
 μ = gas viscosity at conditions through cyclone system, micropoise;  
 Q<sub>T</sub> = gas flowrate the cyclone system, acfm  
 M<sub>w</sub> = molecular weight of mixed gas,  
 P = absolute stack pressure (in Hg) and  
 T = cyclone gas (stack) temperature (°R).

Since the proposed PM<sub>10</sub> Cyclone is actually part of a 5-stage series cyclone system, it may at some point be desirable to operate the full cyclone set with the EGR system. If such is the case, the D<sub>50</sub>'s for each of the remaining cyclones should be calculated as described in the vendor supplied operator's manual.

#### 5.5.5 Percent Isokinetic

In order to insure non-biased particulate sampling, the following equation should be used to determine the percentage of isokinetic sampling:

$$I\% = \left( \frac{1.677 T_s \left[ 0.00267 V_{l_c} + \frac{V_m Y_{cal}}{T_m} \left( P_{bar} + \frac{\Delta H}{13.6} \right) \right]}{\theta V_s P_s A_n} \right) 100\% \quad (5-28)$$

where  
 I% = Percent of isokinetic sampling.  
 V<sub>l<sub>c</sub></sub> = Total volume of liquid collected in impingers and/or silica gel, ml.  
 V<sub>m</sub> = Volume of gas sample through dry gas meter (meter conditions), cu. ft.  
 Y<sub>cal</sub> = Gas meter calibration constant, dimensionless.  
 T<sub>m</sub> = Absolute average dry gas meter temperature, °R.  
 P<sub>bar</sub> = Barometric pressure at sampling site, inches Hg.

$\Delta H$  = Average pressure drop across the orifice, inches  $H_2O$ .

$T_s$  = Absolute average stack temperature, °R.

$\theta$  = Total sampling time, min.

$V_s$  = Stack gas velocity, ft/sec.

$P_s$  = Absolute stack gas pressure, inches Hg.

$A_n$  = Cross-sectional area of sampling nozzle, sq. ft.

If  $90\% \leq I\% \leq 110\%$ , the results are acceptable; otherwise, reject the results and repeat the test.

#### 5.5.6 Computer Programs

Programs have been written in Apple basic computer language which perform the setup and data reduction calculations for the EGR train. The setup program calculates and prints a table of the necessary target readings for a range of flue gas temperatures and pitot  $\Delta P$  readings based on expected minimum and maximum values of each parameter. The data reduction programs calculate the appropriate run parameters and particulate concentrations.

### 5.6 INTERNAL QUALITY CONTROL CHECKS

Field use of the Exhaust Gas Recirculation (EGR) Sampling System is a difficult task. The accuracy required is more nearly that for a laboratory program than for a conventional source test. There are many places in the operational sequence where errors can occur in spite of a conscientious effort to do a good job. A quality assurance program attempts to discover inaccuracies before they are propagated throughout the test program. A conscientious operator will be aware of the problems unique to each sampler and to the total EGR sampling system itself and will take steps to avoid them.

Problems associated with the particle classifier, such as particle bounce and reentrainment, and effective sample recovery techniques should be addressed in the operator's manual. Other quality assurance checks, such as system leaks, flow checks, meter calibrations, weighing techniques, etc. should be carefully monitored by the EGR operator.

#### 5.6.1 SYSTEM LEAKS

Conscientious leak testing will preclude any sampling errors due to leaks. However, if a leak occurs during testing it may be noticed by a sudden change in the pressure readings of the system. If a leak goes unnoticed during testing, it will adversely affect the final test results. Leak checks made at the operating temperature will identify leaks not found at ambient conditions. Besides loosened fittings, internal sampler leaks may be caused by nicked or warped metal or hardened rubber "O"-rings. It is recommended that a quick leak check be performed after warmup.

### 5.6.2 FLOW CHECKS

By definition the total flow through the EGR sampling system is the sum of the recycle and sample gas flow. Since the EGR system uses differential pressure monitoring devices (manometers and magnehelics) to monitor the above three flowrates, any deviation from the expected value can be immediately noticed. For example, if the total flow magnehelic reading relates to 1.0 cfm and the sample flow manometer relates to 0.6 cfm, the reading on the recycle magnehelic must relate to 0.4 cfm. During operation the total flowrate through the system is held constant; therefore, if the sample flowrate changes to remain isokinetic, the recycle flowrate must change by an equal, but opposite amount.

If the flows are fairly constant, the EGR dry gas meter may also be used as a quality assurance check. By measuring the time per revolution of the gas meter rotation needle, the sample flowrate can be determined. This, by definition, should equal the difference of the total and recycle gas flowrates.

### 5.6.3 CALIBRATION

Calibration of the chosen particle-sizing device should be performed according to procedures outlined in the particular operator's manual specific to each sampler. The calibration of the metering devices, nozzles, pitots, etc. to be used in conjunction with the EGR sampling system should be performed at approximate run conditions. In order to assure the validity of the field test, a spot calibration of the EGR equipment is recommended upon completion of the field test. This would help eliminate possible errors in final data analysis.

### 5.6.4 WEIGHING TECHNIQUES

The manufacturer's directions should be followed when operating the balance. The balance should be calibrated at least once a day. Several times throughout the day the repeatability of measurements should be checked by weighing a sample and a control weight. A control or test weight is a small piece of material (ceramic or metallic) whose weight does not change with changes in temperature or humidity or through repeated handling. Small pieces of stainless-steel or platinum are proven control weights. Dry weight checks are made by desiccating the samples, weighing, then desiccating again and reweighing. When the agreement is within the repeatability of the balance, dry weight has been achieved.

### 5.6.5 DATA REVIEW

After the data have been collected, they should be examined for any inconsistencies or weak points. Careful decisions should be made concerning "outliers"--data points which are not compatible with the bulk of the data.

## 5.7 CALIBRATION DATA FOR SoRI/EPA CYCLONE I

EGR nozzles have been designed for Cyclone I of the SoRI/EPA Five Stage Series Cyclones (Smith, et al., 1979) and the commercial version of it

(Andersen Samplers, Inc., Atlanta, GA). The calibration data available for Cyclone I originates from the work of Smith, et al. (1979) and Farthing, et al (1985), and recent work concerned directly with  $PM_{10}$ . All of these calibrations were performed with monodisperse dye aerosols produced using a vibrating orifice aerosol generator (VOAG).

In each series of calibrations, the cyclone was backed up by an absolute filter which collected the test particles that were not removed by the cyclone. After each run, solvent washes of the internal surfaces of the cyclone, connecting tubing, and filter were then made using measured amounts of solvent. The quantities of the particulate matter collected by the various surfaces were then determined by photometric analysis of the dye concentrations in the washes. From these data the deposition pattern in the cyclone could be determined together with the total particulate mass which entered it and the fraction of the mass which it collected.

In the original data reported by Smith et al., the aerosol stream flowed into the cyclone through a tube which had the same diameter as the cyclone inlet (0.5 inch). During these calibrations two types of experiments were performed. In the first type, the cyclone flowrate was held constant and the particle size was varied from one run to the next so as to define the shape of the collection efficiency curve of the cyclone. The collection efficiency curve as measured in these experiments can be described by a log-normal function with a Sigma-g of about 1.18. In the second type of experiment, the flowrate required to obtain a 50% collection efficiency was found for a number of particle diameters and operating temperatures. These latter data permitted the generation of equations for predicting the cyclone  $D_{50}$  for different operating conditions. Smith et al. used the sample flowrate and gas viscosity to characterize the behavior of the cyclone in terms of its  $D_{50}$  at different operating conditions. Farthing et al. (1985) reported the results of calibrations of Cyclone I which were carried out in a manner similar to that used by Smith et al. Subsequent to the work reported by Smith et al. the Reynolds number of the flow in cyclone outlets was found to be the governing factor in their performance through the particle Stokes number for 50% collection efficiency (Beeckmans, 1979). Figure 5-7 presents the data obtained by Smith et al. and Farthing et al. in terms of the Stokes number for 50% collection and the Reynolds number of the flow in the cyclone inlet tube. (The Reynolds number in the outlet tube is approximately equal to that in the inlet, but difficult to define because of the reversed exit.) A more detailed discussion of cyclone behavior as related to particle Stokes number and cyclone Reynolds number is given in Section 4.3.

These calibration results are used to determine the appropriate flowrate for  $PM_{10}$  sampling by first generating an equation relating the particle Stokes number for 50% collection efficiency,  $Stk_{50}$  and  $Re$  are given by the expressions:

$$\sqrt{Stk_{50}} = D_{50} \sqrt{2Q/\rho\pi\mu d^3}, \quad (5-29)$$

and

$$Re = 4\rho Q/\pi\mu d$$

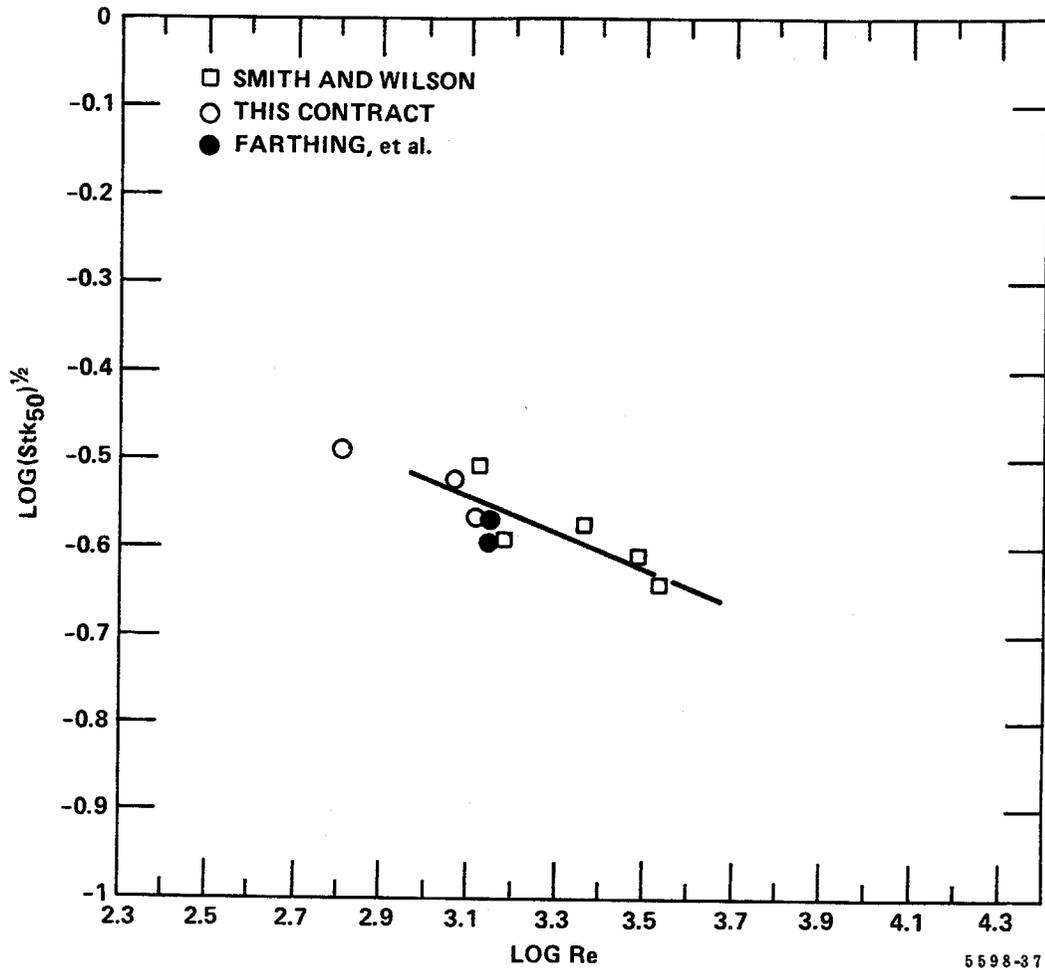


Figure 5-7. Calibration data for Cyclone I of the five-stage cyclone sampler. Data from Smith and Wilson (1979), Farthing, et al. (1985) and unpublished data from this contract. (Air only, variable temperature and flow rate).

where

$Q$  = cyclone flowrate in actual  $\text{cm}^3/\text{sec}$ ,  
 $\mu$  = gas viscosity in poise,  
 $d$  = cyclone inlet diameter (1.27cm),  
 $\rho$  = gas density in  $\text{gm}/\text{cm}^3$ .

The solid line in Figure 5-8 is the empirical function:

$$\sqrt{\text{Stk}_{50}} = 1.285 \text{Re}^{-0.2091} \quad (5-30)$$

obtained by a least squares fit to the data. It is used for  $\text{PM}_{10}$  sampling by setting  $D_{50} = 10\mu\text{m}$  and solving for  $Q$  in terms of the gas conditions of the source being tested. This equation is used in different forms in paragraph 5.2.4 in describing the setup calculations for sampling and paragraph 5.5.4 concerning data reduction.

The aerosol entry into Cyclone I in the experiments described above was not realistic in terms of field operation. In actual applications, the sample stream is withdrawn isokinetically through a nozzle whose tip size is substantially smaller in diameter than the cyclone inlet. The sample stream must then expand in a rather short distance to the inlet diameter and the question of whether it can do so or what the effect on the cyclone cut diameter might be if it does not is problematical. The modification of the nozzle that is required for operation in the EGR mode poses additional questions regarding the performance of the cyclone for  $\text{PM}_{10}$  applications. Therefore, a new series of experiments were begun to resolve these questions. In this recent set of calibrations, the aerosol was introduced to the sampler in a manner which more realistically simulated isokinetic sampling in the field. For the larger nozzles, which are used for low velocities, the aerosol flowed through a 3" pipe and for the smaller nozzles the aerosol flowed through a 1.5" pipe. For each experiment the nozzle mounted on Cyclone I was located at the center of the pipe exit. The gas flowrate through the pipe was adjusted so that measured gas velocity matched the nozzle velocity. The results of these experiments to date were also included in Figure 5-7.

Figure 5-8 presents the results of these calibrations as aerodynamic  $D_{50}$  versus Cyclone I flowrate. The close agreement between the EGR 0.25" nozzle and the 0.5" standard inlets with one another and with the older data suggests that the EGR nozzle has little if any effect upon behavior of the cyclone. There is substantial scatter in the data,  $\pm 10\%$ , and the range of conditions (Reynold's number) tested is limited. The assumed functional dependence may not be appropriate for values of the inlet Reynolds number outside the range of the calibrations. Substantially more data at more conditions, other nozzle sizes and varying EGR recycle rates, are needed to verify the influence of the nozzle geometry and cover a wider range of Reynolds number to provide for all expected field operation. There is substantial scatter in the data,  $\pm 10\%$ , and the range of conditions (Reynold's number) tested is limited. The assumed functional dependence may not be appropriate for values of the inlet Reynolds number outside the range of the calibrations.

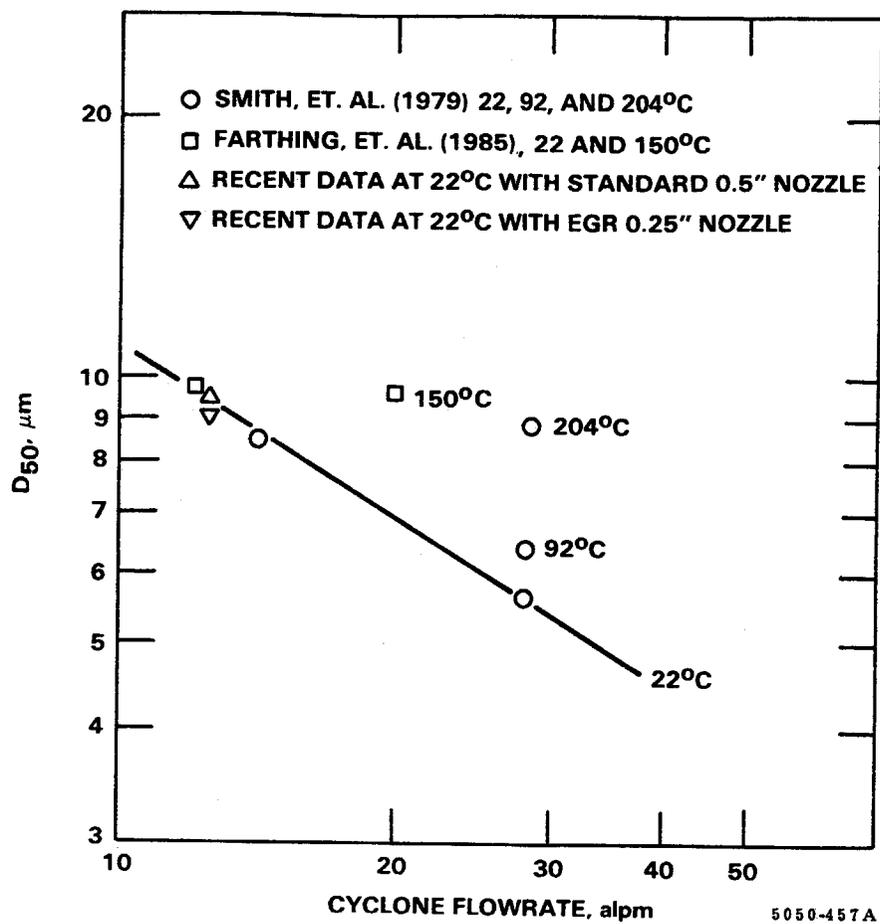


Figure 5-8. Cyclone I Aerodynamic D<sub>50</sub> versus flowrate at various temperatures.