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PARTICLE SIZE MEASUREMENT WITH CASCADE IMPACTORS

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PROCEDURES MANUAL FOR THE RECOMMENDED ARB PARTICLE SIZE DISTRIBUTION METHOD (Cascade Impactors)

May 1986

Prepared for
THE CALIFORNIA AIR RESOURCES BOARD

ARB Contrct A3-092-32

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PROCEDURES MANUAL FOR THE RECOMMENDED ARB PARTICLE SIZE DISTRIBUTION METHOD

(Cascade Impactors)

Attachment No. 1 to the Final Report for
ARB Contract A3-092-32
"Recommended Methodology for The Determination of
Particle Size Distribution in Ducted Sources",
October 1984

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FOREWORD

Broadly speaking, one can divide the ARB current or potential needs with respect to particle sizing into three classes: (1) regulatory, including setting of emission standards and compliance testing; (2) control strategy development (emission inventories) and permitting (control device selection, etc.); and (3) basic research and development. Of course, considerable overlap exists in the types of information needed for each of these activities.

As currently foreseen, possible regulatory action on emissions may take place based on one or both of two particle size classes. The first, and more likely, of these possible regulatory actions is related to the PM_{10} class (particles having aerodynamic diameters smaller than 10 μm) for which a state ambient air regulatory standard has already been set. The second class for possible action concerns fine particles, those particles having aerodynamic diameters smaller than 2.5 μm. In either case, the regulations may be chemical species and/or industry or process specific as well as particle size specific. If particle size specific regulations are set, compliance test methods would be a concomitant necessity. Development of an emissions inventory would be a preliminary activity prior to such regulatory action - such an inventory is currently being constructed within the ARB for the PM_{10} class based on such information as is now available. The number of size classes (and the resolution) required for these activities is obviously limited - only one or two size cuts are needed and relatively simple and inexpensive techniques are desirable if they are to be used as compliance tools.

Greater resolution than that needed for compliance testing is desirable for activities related to permitting. The performance of many (or most) particulate control devices can be predicted for a given source from a broad base of experimental data and models provided that the gas stream conditions and the particle size distribution of the material to be collected are known. In most cases, the critical size range for estimating the probability of achieving a required level of control in this fashion is from about 0.1 μm to 20 μm. Resolution into about eight size classes, evenly spaced in terms of the logarithm of particle diameter, over the latter range is generally sufficient. In some instances specific target chemical species are of interest which may not be homogeneously distributed with respect to particle size. In those cases, size segregated samples suitable for chemical analysis may be needed in addition to data for overall size distribution. Three to five size fractions may be adequate for this application.

The needs of the agency with respect to basic research presently fall into three areas. The first is providing support for the activities previously described; the second is the development of a data base characterizing the principal types of industrial emissions in the state; and the third is concerned with particulate chemistry. At present the main concerns in the area of

particulate chemistry are primarily emissions of toxic substances and substances which act as catalysts in secondary aerosol formation.

This document describes detailed procedures for measuring particle size distributions of emissions from stationary sources with moderate to high resolution. This method is not intended for use as a possible compliance method nor is it well suited for obtaining samples for chemical analysis. Although it might be used for either of those purposes in some situations, alternative methods which are specific to those purposes are described in companion reports (other attachments to the project final report).

ABSTRACT

This report concerns the use of cascade impactors to measure the particle-size distributions of particulate matter at stationary industrial sources, and is an attachment to the Project Final Report. The Project Final Report describes the evaluation process used to select the instrumentation described herein. This report describes basic principles of cascade impactor performance and discusses the non-ideal behavior and interferences associated with the instruments. It also provides a detailed field protocol for the use of cascade impactors at stationary industrial sources and describes the details of data analysis and quality assurance/quality control. Commercially available hardware is described and documentation is given for a microcomputer program used to perform all the calculations associated with instrument setup, operation, data reduction, analysis, and graphical presentation of the size distribution information. All programs have been written for the Apple II personal computer.

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ACKNOWLEDGEMENTS

This report was submitted in partial fulfillment of ARB Contract No. A3-092-32, "Recommended Methodology for the Determination of Particle Size Distributions in Ducted Sources" by Southern Research Institute under the sponsorship of the California Air Resources Board. Work was completed as of February 28, 1986.

SECTION 1

INTRODUCTION

Moderate to high resolution particle size distribution information is needed for research applications and for control device selection and permitting in that this information provides a basis for estimating expected efficiencies of control devices. Experience has shown that for most applications the critical range over which size distribution data is needed is from about 0.2 μm to 10 μm, together with total concentrations for the ranges smaller than 0.2 μm and larger than 10 μm. Sufficient resolution for modeling the effects of control devices, estimating overall control device efficiencies, predicting stack opacities (for noncondensing stacks), and characterizing the fractional collection efficiencies of operating control devices can be provided by separating the aerosol particles into about six to eight size classes within the 0.2 μm to 10 μm size range. The range also includes "respirable" particles and consequently is of special importance in health effects.

1.1 Specifications for the Selected Particulate Sizing Method

In order to select a method as a standard means of measuring particle size distributions of effluents from stationary sources, a set of specifications for the method was developed. These specifications were based on anticipated data needs together with a number of practical considerations related to field usage. The specifications on which the method, devices, and protocols were based are presented in the following paragraph:

The actual size distributions of most natural and industrial aerosols are such that they can best be described by distribution functions in which the logarithm of the diameter is the argument (for instance the log-normal distribution). Thus the resolution specification for the method can best be given in terms of log(diameter). Size fractionation at steps of 0.25 to 0.333 in log(diameter) over the 0.2 to 10 μm range is expected to be adequate for most foreseeable needs of potential users of the method. The sharpness of cut provided by the classifier(s) should result in separation efficiency curves having geometric standard deviations of less than 1.5. The size fractionations must be well characterized with respect to performance changes produced by changes in operating conditions. Other specifications are as follows:

1. Provide a measure of total particulate loading.

2. Provide usable samples (data) from sources having any concentration within the range from 0.005 to 50 grains per cubic foot.

3. Provide measurement of the weight fraction of particles smaller than any (the) specified size to within 10 percent of the stated size, with 95 percent confidence.

4. Be applicable in stacks having -5 to +20 inches of water pressure differential to ambient.

5. Be applicable at sources having stack gas temperatures in the range of 0 to 450° Celsius.

6. Be capable of obtaining a representative sample from stacks having gas velocities in the range from 10 to 100 feet per second.

7. Have a maximum single component weight of 50 pounds.

8. Be resistant to corrosion by acids and alkalis.

9. Require port dimensions no larger than four inches in diameter. (Three inches preferably.)

10. Be capable of traversing the stack.

11. Require no greater electrical service than that needed for EPA Method 5.

12. The maximum length of any single component should be six feet or less (probe excluded).

Devices meeting these specifications are man-portable, amenable to use in the normal physical environment under which source tests must be carried out, and capable of withstanding exposure to hot, corrosive stack gases. The velocity and traversing requirements are necessary in order to insure that representative samples can be obtained, even when the particulate matter is stratified within the duct or stack.

1.2 Size Basis

A number of conventions are used as bases for the presentation of particle size distributions with respect to both the definition of particle size and the property of the distribution presented. Particle size is most often defined in terms of a "diameter" implying that the particles are being treated as spheres - this may be rigorously true or only a useful approximation depending upon the circumstances. The most frequently used diameter bases in air pollution work are as follows:

True diameter - the actual diameter of the particle. This diameter is useful only if the particles are spherical.

Stokes diameter - the diameter of a sphere having the same density and settling velocity in air as the particle in question. For spherical particles the Stokes diameter is equal to the true diameter. This

definition is often used as an approximation for estimating the volume or surface area of irregular particles.

Aerodynamic diameter - the diameter of a unit density sphere which has the same settling velocity in air as the particle in question.

Volume equivalent diameter - the diameter of a sphere which has the same internal volume as the particle in question.

Surface equivalent diameter - the diameter of a sphere which has the same total surface area as the particle in question.

Area equivalent diameter - the diameter of a sphere which has the same projected area as the particle in question.

No set conventions exist for selecting the diameter basis for data presentation, however, certain bases are favored for use in particular applications. For instance, the aerodynamic basis is the preferred choice in work related to inhalation and health effects as well as wet scrubber technology; while the Stokes diameter is favored for work related to light scattering (opacity) and in electrostatic precipitation. In most cases, convenient transformations exist for changing from one basis to another; however, this may not be the case if the particles are highly irregular in shape. Because of their widespread use in research related to health effects, visibility, and control device technology, the method best suited to ARB's purposes is one for which the natural diameter bases are either aerodynamic or Stokes. In order to prevent misunderstanding and erroneous conclusions being drawn from data, the diameter basis on which data are presented should be made clear in any data presentations.

1.3 Selection of the Standard Method

After reviewing all available methods for measuring particle size distributions, the method of inertial separation using cascade inertial impactors was selected as the recommended technique (standard method) for measuring particle size distributions of effluent from stationary sources. This method, of all those available, most nearly met all of the specifications set forth above.

For years inertial impactors have been commonly used to determine the particle size distribution of particulate matter suspended in industrial process gases, especially those emitted to the atmosphere. Impactors have several advantages over competing equipment: they are compact, they can be inserted directly into gas ducts (avoiding the problems associated with extractive sampling), they are fairly accurate, and they produce information which has been widely used and understood. The majority of the particle-size distribution data available on industrial process streams have been taken using cascade impactors covering a diameter range of 0.3 to 20 μm. These devices consist of serial configurations of several impaction stages. Each stage of the impactor removes particles of a characteristic diameter, starting with the largest and progressing to smaller diameters. The popularity of these devices

is due not only to their simplicity of design and operation but also to their portability and adaptability to a large variety of aerosol streams.

When used properly, cascade impactors are capable of providing particle size distribution measurements extending from below 0.5 µm to diameters of 10 µm and above.

1.4 Purpose and Scope of This Document

This document has several purposes. Above all, the ARB wishes to ensure the comparability of data gathered by different sampling organizations: that is, that they use equipment whose characteristics are known, follow sound sampling procedures, and reduce the data by the use of accepted and defined techniques. This document is also intended to help users of impactors avoid some of the problems which others have experienced. Finally, this manual is intended to serve as a resource document for use by state and district environmental enforcement agencies in developing PM_{10} attainment strategies.

The procedures presented are expected to yield valid data at most sampling sites. Situations will occur in which the information presented in this document will not be completely applicable and suitable modifications to the procedures will have to be developed. In such situations professional judgment is still an important element in successfully determining particle-size distribution information and fractional collection efficiencies of air pollution control devices.

The scope of this report includes an introduction to the basic principles of impactor operation, sampling apparatus, collection substrate preparation and use, the preliminary survey, testing procedures, data analysis, calibration procedures, quality assurance, and report requirements. The information herein is applicable to cascade impactors in general. Specific illustrations are given using the instrumentation and configuration recommended in the Equipment Selection chapter of the project final report. Specific commercially available impactors are discussed in Appendix B.

SECTION 2

BASIC PRINCIPLES OF CASCADE IMPACTOR PERFORMANCE

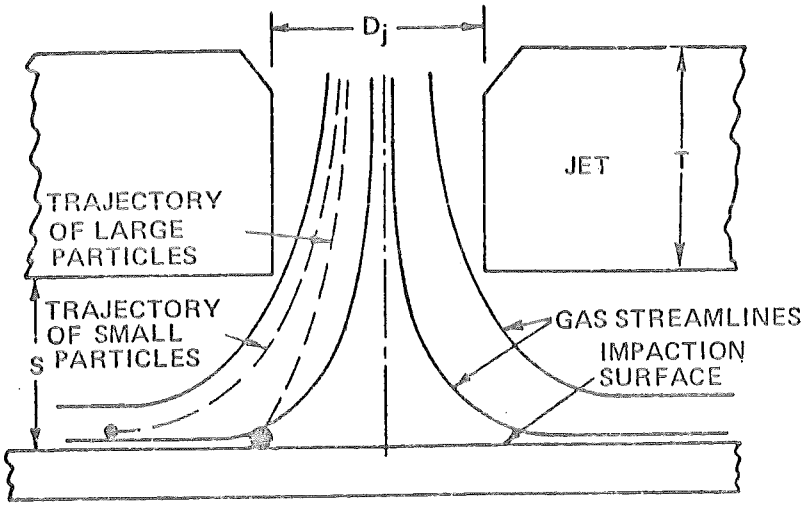
Figure 2-1A is a schematic diagram illustrating the principles of particle collection common to all inertial impactors. The sample aerosol is constrained to pass through a circular hole or rectangular slit to form a jet that is directed toward an impaction surface. Large particles will possess sufficient inertia to cross the gas streamlines and impact on the collection surface. Particles having lower momentum will follow the gas stream past the collection plate. In a cascade impactor the gas stream passes sequentially through several impaction stages designed to remove successively smaller particles, thus collecting the airborne particulate matter in a series of discrete size fractions.

The probability of collection in an impactor stage typically varies with particle size as shown in Figure 2-1B. Ideally, an impaction stage would provide complete collection of all particles larger than a known size and pass all smaller particles. In other words, the ideal collection efficiency curve would be a step function. In practice, the real stage collection efficiency curves such as the one schematically illustrated have sharp enough transitions to be useful for aerosol size distribution measurements. The behavior of a real stage in operation is then described in terms of a characteristic particle diameter (D_{50}) which is collected with 50 percent efficiency for the operating conditions used.

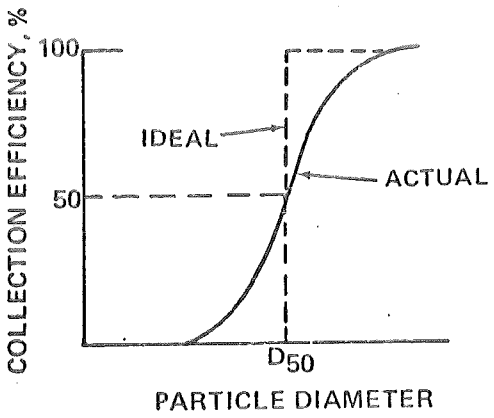
Impactors with a wide variety of geometrical configurations have been observed to have the qualitative behavior described above. Impactor stages have been constructed with one to several hundred holes or rectangular jets, depending on the desired jet velocity and volumetric flow rate. The number of jet stages ranges from one to about 20 for various impactor geometries reported in the literature; most commercially available impactors use 5 to 10 stages.

2.1 Scaling Relationships

Parameters which determine the collection efficiency for a given geometry are particle density, gas viscosity, gas velocity throughout the jet, jet diameter for circular jets or jet width and length for rectangular jets, jet-to-plate spacing, and thickness of the jet orifice. Certain dimensionless factors can be defined which allow scaling relationships in stage efficiency to be predicted. Gas flow in the impactor jet can be scaled in the typical manner by using Reynolds number (Re) of the gas referenced to the jet dimension as a dimensionless gas velocity. For circular jets, the relation is



A TYPICAL IMPACTOR JET AND COLLECTION PLATE



B GENERALIZED STAGE COLLECTION EFFICIENCY CURVE

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Figure 2-1. Operating principle and typical performance for a cascade impactor.

$$Re = \frac{\rho_g v_j D_j}{\mu} \qquad (2\text{-}1)$$

where

ρ_g = gas density (g/cm^3),

v_j = mean jet velocity (cm/s),

D_j = jet diameter (cm),

and μ = gas viscosity (g/cm sec).

Other geometric parameters can likewise be referenced to the jet width. For round jets, the important dimensionless ratios are relative jet to plate spacing (S_j/D_j) and relative jet thickness (T_j/D_j). Where D, T, and S are dimensions as shown in Figure 2-1A. These dimensionless ratios and the jet Reynolds number are sufficient to define the gas flow field for a given impactor geometry.

Similar scaling relationships can be developed for particle motion in the impactor. Since particle motion relative to the gas stream is assumed to obey Stokes' law, a dimensionless inertial parameter related to particle size can be defined in terms relating to particle motion in a continuous viscous medium. This inertial size parameter (the impaction parameter), ψ, is defined as

$$\psi = D_p^2 \frac{C\rho_p v_0}{18\mu D_j} \qquad (2\text{-}2)$$

where

D_p = Stokes diameter of a spherical particle (cm),

ρ_p = particle density (g/cm^3),

C = Cunningham slip correction factor (dimensionless), defined by Equation 2-3,

v_0 = initial particle velocity in the jet (cm/s).

The remaining quantities are as defined previously.

As defined above, ψ is the ratio of an inertial characteristic length (the stopping distance of a particle injected with initial velocity v_0 into still air) to the diameter of the impactor jet. Alternately, ψ is equal to the ratio of an inertial characteristic time (the particle relaxation time in the fluid) to a transit time characteristic of the system (the ratio of the particle's

initial velocity to the jet diameter). Inspection of equation (2-2) reveals that $\sqrt{\psi}$ has the form of a dimensionless particle diameter. Alternate dimensionless inertial constants can also be defined. Another such constant frequently used is the Stokes number (STK), defined as the ratio of the particle stopping distance of a particle injected with initial velocity V_0 into still air to the radius or half-width of the jet, so that STK = 2ψ. In this document we will use STK in many of the discussions but will use ψ as defined by equation (2-2) when reducing data.

The quantities in equation (2-2) which are dependent on the particle enter as the product $C\rho_p D_p^2$, which only has meaning for spherical particles of known density. Since impactors are also used to characterize particles which are not spherical or are of unknown density, it is useful to define certain equivalent diameters on the basis of aerodynamic behavior of the particles. The three common equivalent diameters used in this text are the Stokes, classical aerodynamic, and aerodynamic impaction diameters. The Stokes diameter of a particle is defined as the diameter of a spherical particle having the same density and the same aerodynamic characteristics (e.g., terminal settling velocity in air) as the particle in question.

In this document, the Stokes equivalent diameter is typically used unless otherwise explicitly stated; in particular, D_p in equation (2-2) is the Stokes diameter. The classical aerodynamic diameter of a particle is the physical diameter of a particle with density of 1.0 g/cm^3 which has the same aerodynamic behavior as the particle in question. This equivalent diameter is useful when the particle density is unknown or irrelevant. The aerodynamic impaction diameter of a particle is defined as the quantity $D_p\sqrt{C\rho_p}$, where D_p is the Stokes diameter. This equivalent diameter (Mercer et al., 1968), has the useful feature that it incorporates the size-dependent correction C. It thus eliminates iterative calculations otherwise required to determine particle diameter from aerodynamic measurements.

The Cunningham factor, C, in equation (2-2) is an empirical correction for the breakdown of the assumption that the fluid medium is a continuum. For particle diameters on the order of the mean free path of molecules in the gas, the net drag force seen by a moving particle is decreased by the ratio 1/C. Within the Stokes model, this behavior can be visualized as a gas medium which is continuous, but which "slips" past the particle surface. This model is reflected in the alternate name "slip correction factor". The numerical value of C is given (Fuchs, 1964) by equation (2-3),

$$C = 1 + \frac{2\ell}{D}\left[1.23 + 0.41 \exp\left(\frac{-0.44D}{\ell}\right)\right] \qquad (2\text{-}3)$$

where

ℓ = mean free path of the gas medium (cm),

D = Stokes diameter of the particle (cm).

Other empirical equations with slightly different constants but having the same form as (2-3) are also found in the literature. Under conditions where the particle diameter is smaller than the gas mean free path, the Cunningham correction becomes large enough to be a controlling factor in the aerodynamic behavior of the particle. These conditions are observed in impactors designed to operate at reduced pressure. In these devices, the large Cunningham factors due to the increased gas mean free path allow inertial impaction of particles with diameters less than 0.05 μm, extending the potential range of size distribution measurements by over an order of magnitude. While this effect is mentioned here for completeness, low pressure impactors are beyond the scope of this manual. For typical gas conditions and particle diameters above 0.5 μm, the Cunningham correction factor provides a significant but relatively small (<35%) correction to the effective aerodynamic diameter of the particle.

In reducing cascade impactor data, the assumption is made that the impaction parameter ψ completely specifies the aerodynamic behavior of particles passing into a given impactor stage. In particular, it is assumed that a stage has a single characteristic value of ψ which defines the particle D_{50} over a wide range of operating conditions. This value, usually expressed as its square root $\sqrt{\psi_{50}}$, is typically determined by calibration at a single set of operating conditions. The validity of the assumption that $\sqrt{\psi_{50}}$ is truly constant even for a specific geometry will be explored in the following subsection.

2.2 Theory of Impactor Behavior

Although various attempts have been made to predict the behavior of particles in an impactor stage, the most comprehensive theoretical treatment was performed by Marple (Marple, 1970; Marple and Liu, 1974). Marple numerically solved the two-dimensional Navier-Stokes equations for the laminar flow of an incompressible viscous fluid within a single-jet impactor stage. Having obtained the gas flow field for a given gas Reynolds number and stage geometry (defined by S_j/W_j, T_j/W_j, and the choice of round or rectangular jets), numerical integration of the equations of motion of particles in the flow field is possible. Marple generated theoretical impaction efficiency curves by generating trajectories for particles of selected initial conditions and different size (Marple chose to use the square root of the Stokes number, $\sqrt{STK}$, as his dimensionless inertial size parameter).

Figure 2-2 illustrates the model. Assuming incompressible fluid flow, the flow field for the stage geometry shown is calculated by numerically solving

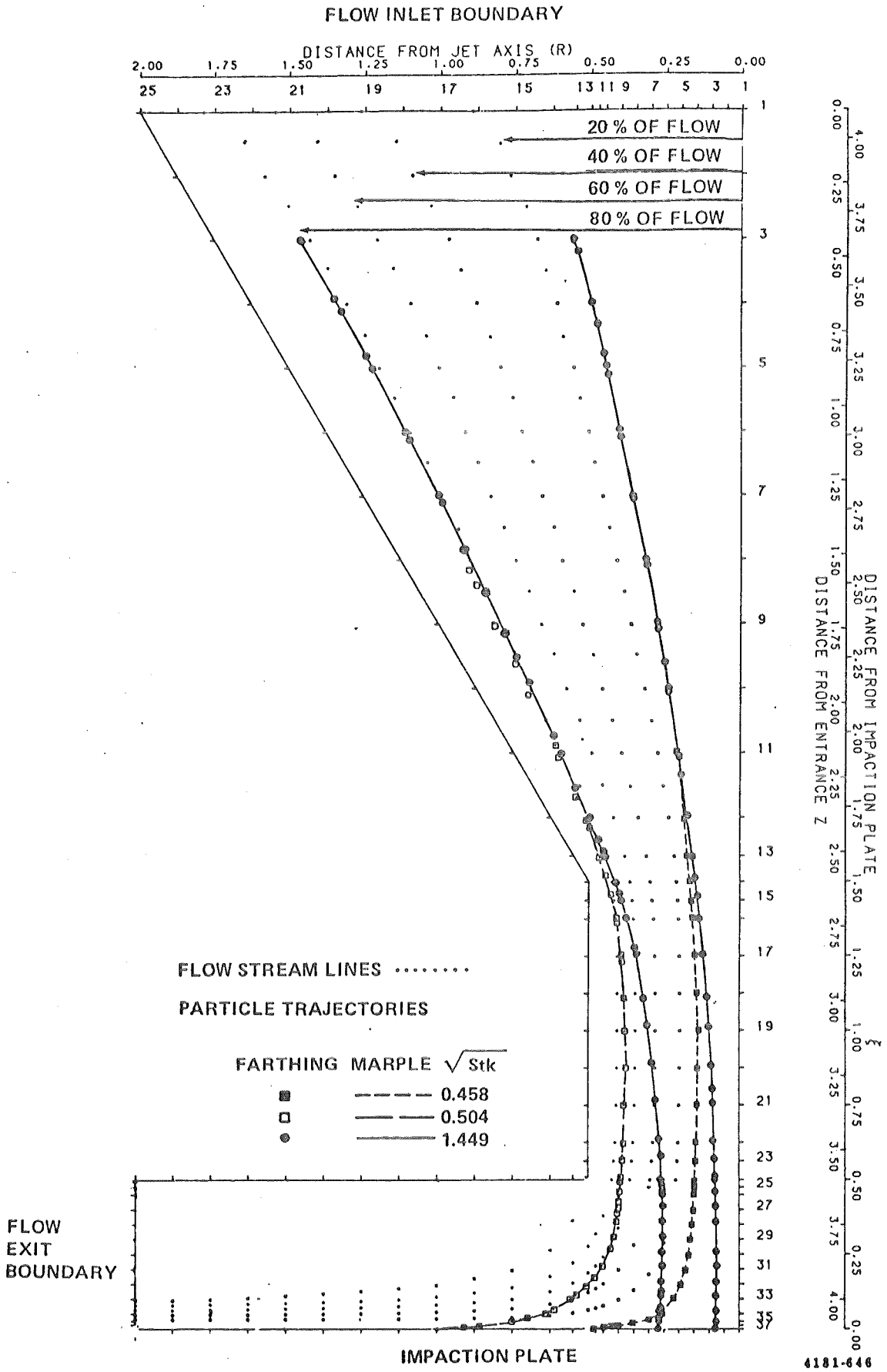


Figure 2-2. Marple's Impactor Model showing calculated flow lines and particle trajectories (Farthing, 1983).

the Navier-Stokes equation for many points in the model. Radial and axial positions of these points are indicated in Figure 2-2. Flow lines are illustrated by the dotted lines. After the flow field is known, stage collection efficiency is obtained by calculating particle trajectories for many assumed starting positions across the stage inlet.

Trajectories are obtained by numerical integration of the equations of motion for particle in the gas flow field. Particles are initially assumed to have the same velocity as the fluid stream. Figure 2-2 shows a few typical trajectories calculated using different $\sqrt{STK}$. For each starting position, trajectories are calculated for enough values of $\sqrt{STK}$ so that the critical value of $\sqrt{STK}$ is determined, above which particles impact upon the collection plate and below which particles reach the exit boundary of the model. The collection efficiency of the stage is readily calculated from a set of critical values of $\sqrt{STK}$ versus starting position at the stage inlet, assuming that the particle concentration is uniform across the stage inlet.

The variables of the model are jet throat T relative to the jet diameter W (T/W), jet-to-plate-distance S relative to W (S/W), and Reynolds number, Re. Marple (1970) investigated a range of geometries and Reynolds numbers by varying each of the three parameters while leaving the other two fixed at reference values. For round jet impactors, these reference values were Re = 3000, S_j/W_j = 1/2, and T_j/W_j = 1. Marple's efficiency curves for this range of parameters are shown in Figure 2-3. As can be seen in the figure, variation of S_j/W_j above about 1/2 and variation of T_j/W_j above about 1/4 did not seem to affect the efficiency curves for the reference Reynolds number of 3000. As seen in Figure 2-4, the $\sqrt{STK_{50}}$ value for the reference geometry was not a strong function of Reynolds number in the range 100 - 1000. Thus, Marple's calculations tended to reinforce the conclusion that a single calibration constant $\sqrt{STK_{50}}$ (or $\sqrt{\psi_{50}}$) could be used to characterize an impactor stage over a broad range of temperature and flow rate.

Table 2-1 describes the stages of several impactors commonly used for stack sampling and representative values of Re at three operating temperatures, assuming a nominal flow rate and air as the fluid. It is seen that S/W values range between 1 and 12 and Re values range between 20 and 2000. Thus it appeared that theoretical data were needed for higher values of S/W and lower values of Re in order to characterize impactors over conditions commonly encountered in process stream sampling.

Recently, calculations using Marple's formalism have been repeated for impactor geometries more typical of commercially available cascade impactors (Farthing, 1983). Specifically, larger values of S_j/W_j (up to 11) were used in these calculations. Trajectories were calculated to obtain stage collection efficiencies. These are illustrated in Figures 2-5 to 2-8, where efficiency is plotted versus $\sqrt{STK}$ for various values of S/W and Re over the ranges of interest. It is seen that at S/W = 1/2, changes in Re cause small changes in impactor behavior. At larger values of S/W, changes in Re cause substantial changes in $\sqrt{STK_{50}}$ as well as minor changes in the slope of the curves (in log $(\sqrt{STK_{50}})$. As shown in Figure 2-9, $\sqrt{STK_{50}}$ becomes a much stronger function of stage Reynolds number for larger jet-to-plate spacings than at Marple's

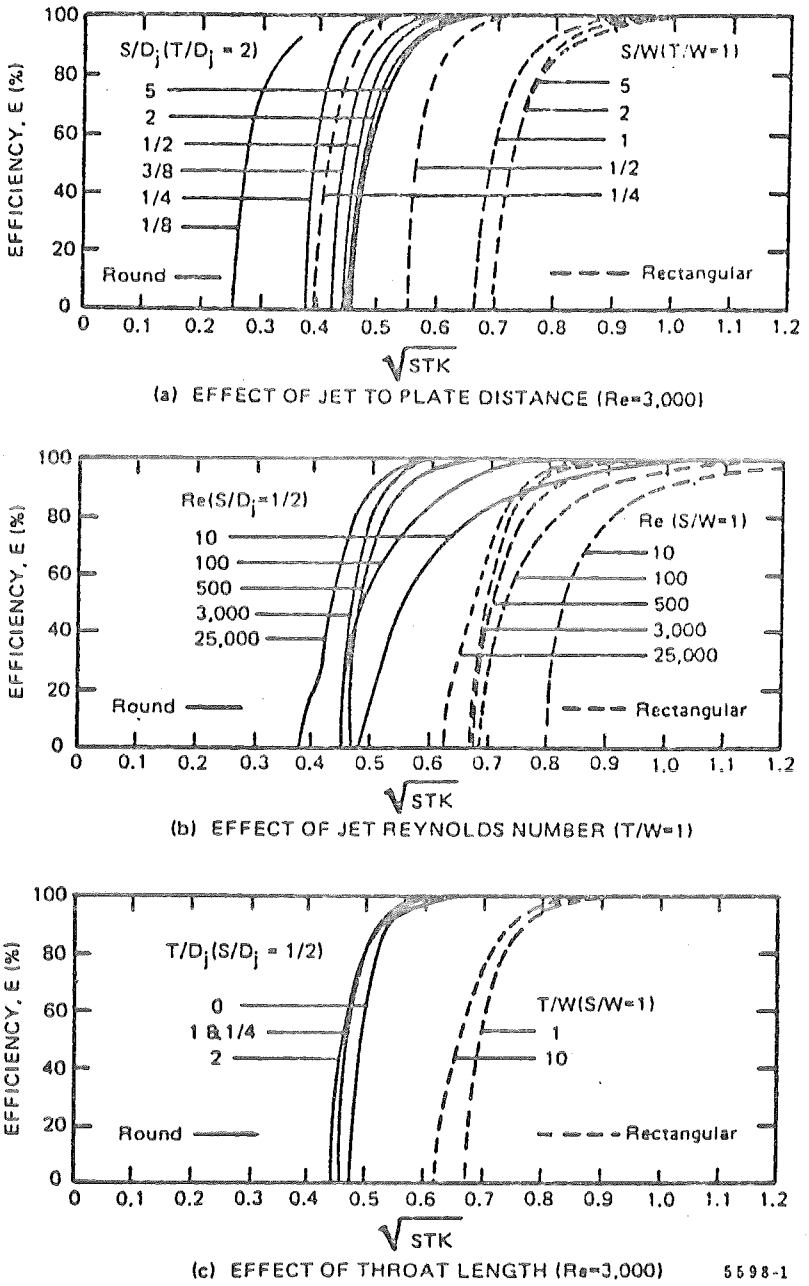


Figure 2-3. Theoretical impactor efficiency curves for rectangular and round jet impactors showing the effect of jet-to-plate distance S, Reynolds number Re, and throat length T (Marple, 1970).

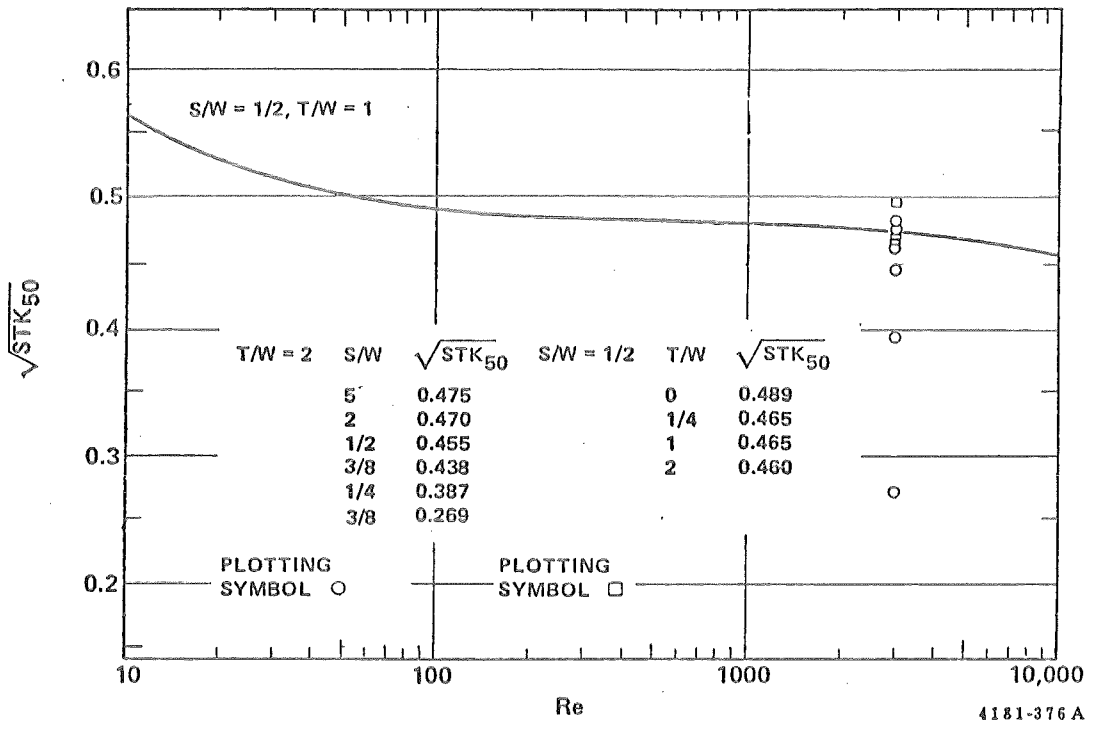


Figure 2-4. Variation of $\sqrt{STK_{50}}$ with Reynold's number from Marple (1970). Points shown are from calculations done at SoRI.

Table 2-1

Impactor Stage Parameters for Commercially Available Cascade Impactors

Stage No	No. of Jets	Jet Diameter D_j, cm	S/W	T/W	Re (Nominal) Flow Rate at Nozzle 14 ALPM) 20°	121°C	232°C
Pollution Control Systems (U of W) Mark III/V Cascade Impactor:							
1	1	1.8237	0.772	2.07	1065	628	409
2	6	0.5791	0.983	0.52	564	333	216
3	12	0.2438	1.2	1.31	653	385	251
4	90	0.0790	3.75	4.06	276	163	106
5	110	0.0508	5.66	6.00	336	198	129
6	110	0.0390	2.317	1.90	434	256	167
7	110	0.0343	8.824	2.47	519	306	199
8	105	0.0300	9.677	2.52	622	367	239
9	105	0.0262	11.111	3.00	691	408	265
10	78	0.0262	11.111	2.81	930	549	357
11	56	0.0262	11.538	3.04	1351	797	518
12	40	0.0262	10.714	2.75	1749	1032	671
13	36	0.0262	10.714	2.75	1944	1146	746
Belfort (MRI) Model 1502 Cascade Impactor:							
1	8	0.8700	1.5	6.9	258	153	100
2	12	0.4760	1.5	1.2	314	186	122
3	24	0.1984	1.5	1.6	365	216	141
4	24	0.1191	2.5	1.3	639	379	247
5	24	0.0838	3.5	1.2	879	521	340
6	24	0.0533	5.7	1.9	1411	836	546
7	12	0.0533	5.7	1.9	2821	1673	1093
Andersen Mark III Cascade Impactor:							
1	264	0.1638	1.550	0.966	47	28	18
2	264	0.1253	2.027	0.706	62	36	24
3	264	0.0948	2.679	0.962	81	48	31
4	264	0.0759	3.347	1.202	101	60	39
5	264	0.0533	4.480	1.608	136	80	52
6	264	0.0343	7.086	1.301	215	127	82
7	264	0.0254	9.732	1.789	296	174	113
8	156	0.0254	10.120	1.861	494	292	190
Brink Model C Cascade Impactor:							
Cyc	Cyclone	(Catch assigned to Jet No. 0)					
0	1	0.3607	2.82	0.22	326	198	125
1	1	0.2490	3.06	0.49	482	284	185
2	1	0.1775	3.04	0.29	670	395	257
3	1	0.1396	3.05	0.37	855	504	328
4	1	0.0946	3.03	0.55	1264	746	485
5	1	0.0731	3.03	0.70	1620	955	621
6	1	0.0559	3.10	0.89	2050	1210	787

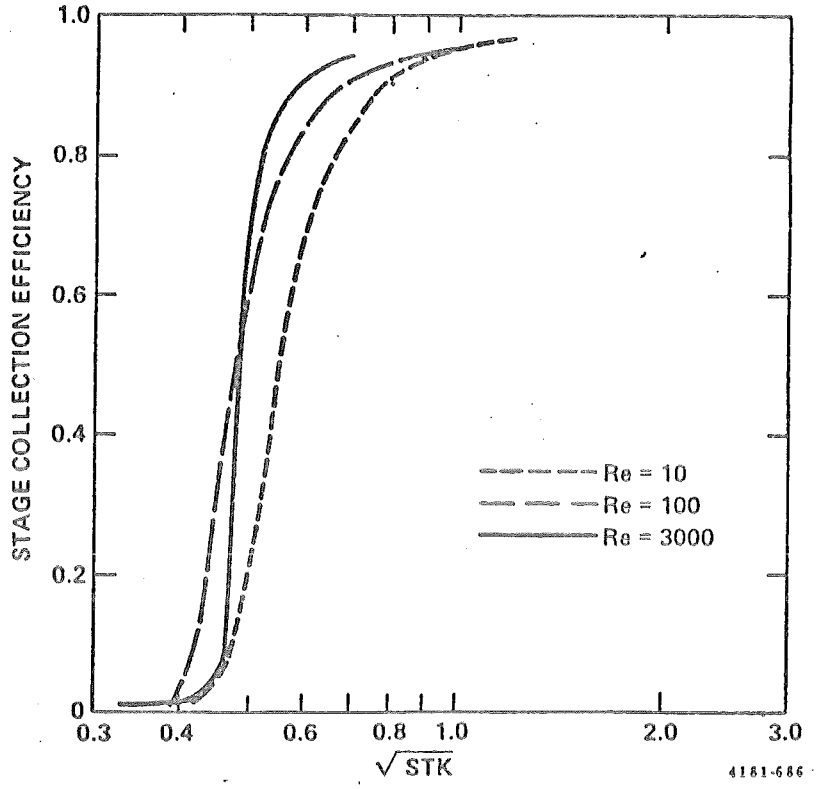


Figure 2-5. Impactor collection efficiency calculated from Marple's Theory (Farthing, 1983). S/W = 1/2 and T/W = 2.

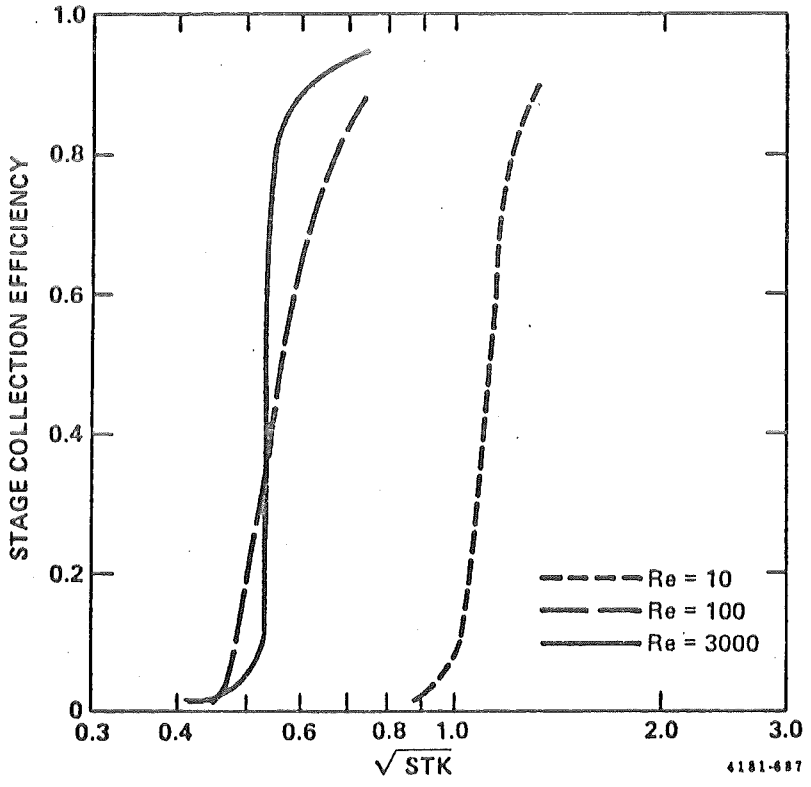


Figure 2-6. Impactor collection efficiency calculated from Marple's Theory (Farthing, 1983). S/W = 2 and T/W = 2.

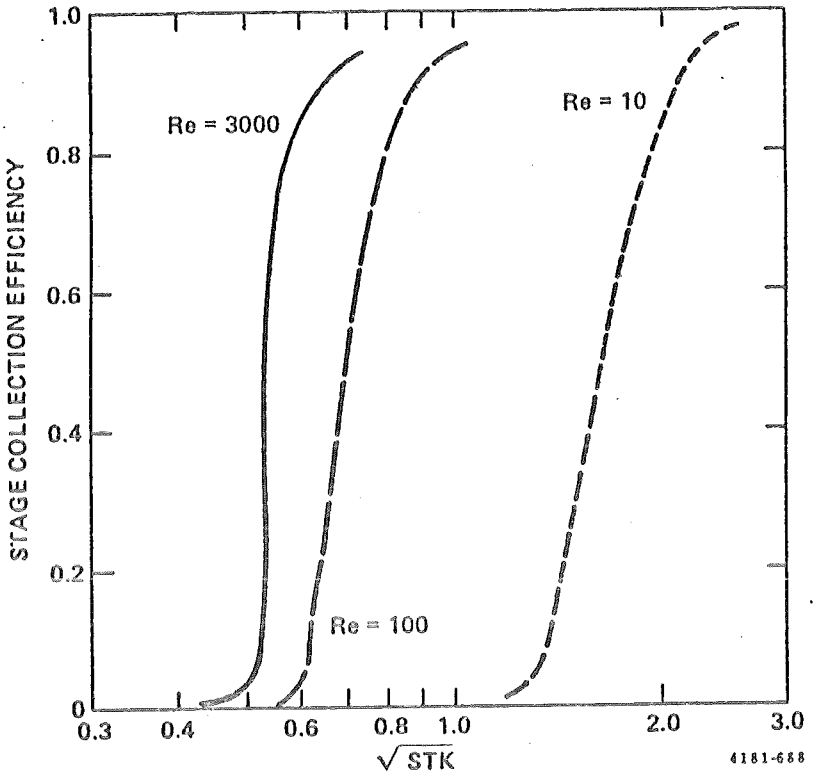


Figure 2-7. Impactor collection efficiency calculated from Marple's Theory (Farthing, 1983). S/W = 5 and T/W =2.

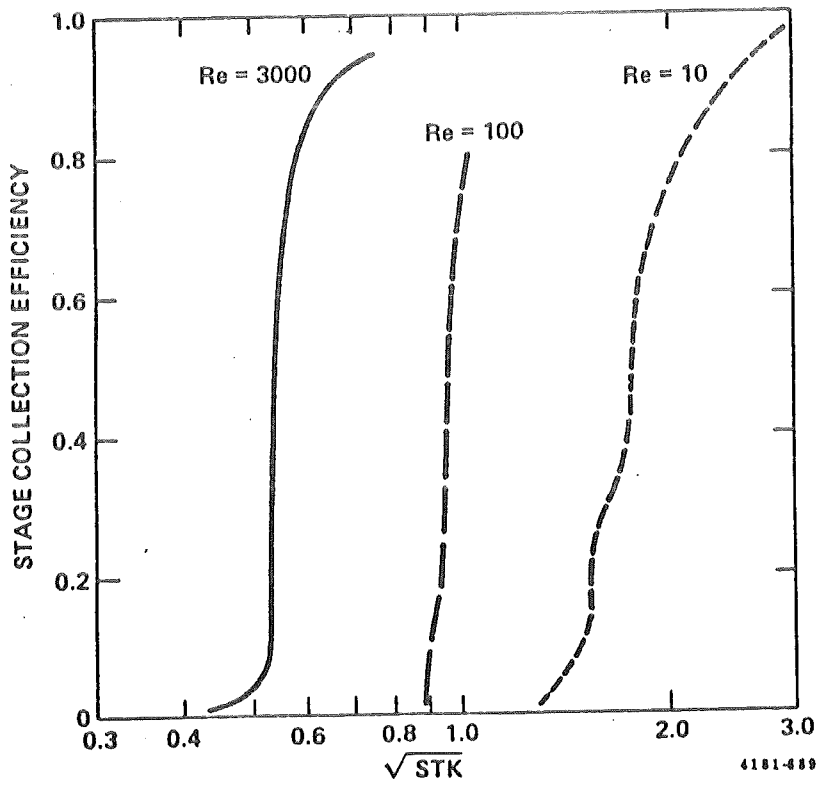


Figure 2-8. Impactor collection efficiency calculated from Marple's Theory (Farthing, 1983). S/W =11 and T/W = 2.

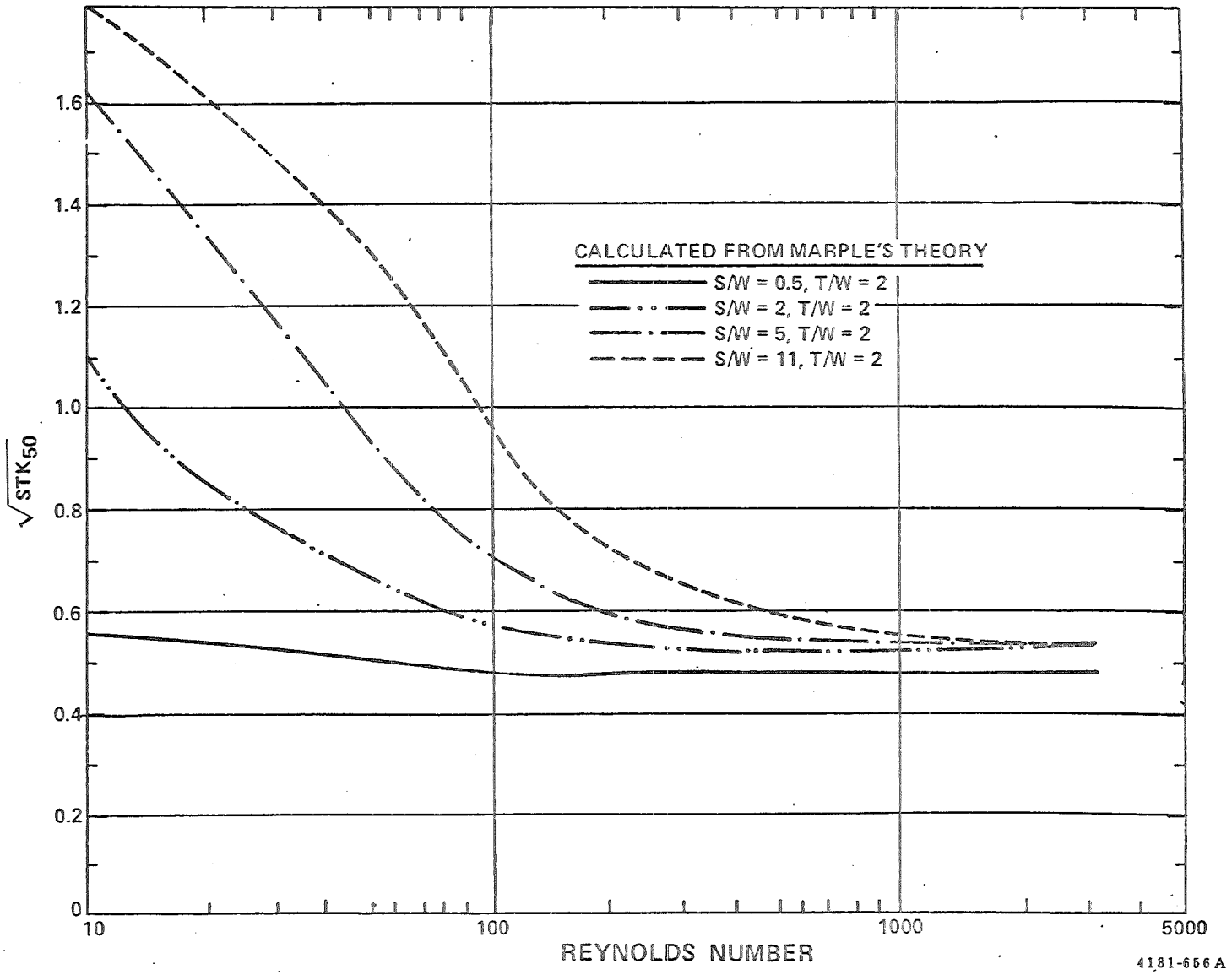


Figure 2-9. Theoretical variations (Farthing, 1983) with jet Reynolds number of impactor stage cut-diameter parameters ($\sqrt{STK_{50}}$).

reference value of $S_j/D_j = .5$. In extreme limits of low Reynolds number and large S_j/D_j, $\sqrt{STK_{50}}$ may be higher than the value predicted from Marple's early calculations (Marple, 1970) by as much as 200% to 300%. In this publication we will continue to use the assumption that a single calibration constant can characterize the behavior of an impactor stage over its recommended operating range. However, the user must be cautioned that actual field conditions must not represent a range of stage Reynolds number greatly different from those over which calibration data has been obtained. It is this reason that we suggest the use of impactor flow rates and stage configurations such that Re $\geq$ 200. If operation at lower Re is required, the effect of the low Re should be accounted for when the data are reduced.

2.3 Effect of Gas Compressibility

The pressure drop across some impactor stages can be appreciable, several inches of mercury in some cases. Even when individual stage pressure drops are low, the cumulative drop through a complete impactor is usually too great to ignore. The stage pressure drops lead to two problems. First, the volumetric gas flow at succeeding stages increases as the pressure is reduced and this increase must be accounted for in the calculation of jet velocities, etc. Second, because the upstream and downstream pressure can be significantly different the question arises as to what are the proper conditions to use in calculating the jet velocity, slip correction factor, etc. for any one jet. That is, should the jet inlet (upstream) or outlet (downstream) conditions be used?

Accounting for the gas expansion to obtain the correct volumetric flow rates at the inlet to each stage is a fairly simple matter. Individual pressure taps for each stage could be used to measure the pressures but implementing such a scheme would be quite cumbersome. Fortunately, stage pressure drops can be estimated with sufficient accuracy using orifice or nozzle flow equations providing that the Mach numbers are not too high. This condition is normally met in source test cascade impactor operations.

Even though the jet inlet and outlet pressures can be estimated with sufficient accuracy by standard flow equations, we are still left with the question of whether to use upstream or downstream conditions in the calculations of the parameters related to the stage D_{50}'s. Flagan (1981) modeled the behavior of impactor stages operating at high pressure drops in a manner similar to that used by Marple (1970), but using the assumption of inviscid, compressible flow matter than viscous, incompressible flow. In this work, pressure drops including values substantially larger than those needed to produce sonic jets were investigated. The results of the flow field calculations indicated that the pressure in the jet impingement region is very near the upstream stagnation pressure. Even at conditions under which the downstream pressure was less than 20% of the upstream pressure, the pressure in the impingement region was greater than 75% that of the upstream stagnation pressure. Pressure recovery in the impingement region was found to be almost complete for subsonic flows. Modeling of particle trajectories and stage efficiencies showed that when the impaction parameter was defined in terms of the upstream stagnation conditions, it was only weakly dependent on the pressure ratio or jet Mach number and the value of the impaction parameter for 50% collection efficiency agreed with the results from the incompressible flow model. This was not the case if downstream conditions were used.

2.4 Verification of Impactor Theory

Before the theoretical models of impactor behavior can be used in the treatment of data they must be verified experimentally. Verification of the models require laboratory calibrations of impactor stages whose designs span a wide range of variation in each of the important parameters in the model. Several such studies have been carried out by a number of researchers and the more important results of these investigations are summarized in the following paragraphs.

One of the most difficult tasks in the calibration of particle sizing devices is the generation of suitable test aerosols. Primary calibration standards should be uniform spheres of precisely known diameters and densities. Detailed treatment of the generation of such particles is beyond the scope of this document but brief descriptions of the two most common techniques will be provided.

Polymerization of certain plastics in liquid suspensions can be controlled to produce particles having a very narrow range of sizes. Under proper conditions it is possible to form hydrosols (particles in liquid suspensions) in which the standard deviation in particle diameter is on the order of one percent. Hydrosols of this type are manufactured and marketed in a large number of sizes from below one tenth of a micrometer to several micrometers by the Seragen Diagnostics Division of Seragen, Inc. Aerosols (particles in gaseous suspension) can be made from the hydrosols by nebulizing the liquid suspensions. (Nebulization is commonly called "atomization".)

Another technique commonly used to generate uniform particles is based on the manner in which a liquid jet breaks up into small droplets. The droplets formed by the breakup of a liquid jet issuing from a small opening tend to be fairly uniform in size as a result of wave phenomena in the jet. If an oscillator and piezo-electric crystal is used to induce pressure perturbations in fluid at the jet at a frequency near that of the natural breakup wave, the jet can be made to form very uniformly sized droplets. Such particle generators are known as vibrating orifice aerosol generators. The geometric standard deviation of the aerosols produced by these devices is typically about 1.04 (or 68% of the liquid is contained in droplets whose sizes are within four percent of the median). The size of the droplets made in this fashion is set by the properties of the liquid used, the size of the orifice used to produce the jet, and the oscillator frequency. Typically the droplet diameters will be about twice the orifice diameter. By dissolving a suitable solid or liquid aerosol material in a volatile solvent, uniform particles of the solute can be made over a broad continuum of sizes. This is accomplished by adjusting the concentration of the solute in the solution, thus altering the size of the residual particle after evaporation of the solvent from the initial droplet.

Impactor stage collection efficiencies are measured by establishing the desired operating conditions (e.g., flow rate, temperature, etc.) and then introducing the test particles. Online particle counters may be used to directly measure particle concentrations upstream and downstream of the jet/collection plate combination (impactor stage) from which collection efficiencies may be calculated. Alternatively, the aerosol passed by the stage

may be collected by a filter after which the amounts collected and passed by the stage can be measured gravimetrically or by other means such as solvent washing of the surfaces followed by chemical or spectroscopic analyses of the washes.

Detailed studies of impactor stage efficiency curves and comparisons with the predictions from theoretical models have been carried out by Mercer and Stafford (1969), Rao (1975), Cushing et.al. (1976, 1979) and Farthing (1984). Results of experiments by Mercer and Stafford are shown in Figures 2-10 together with Marple's theoretical curves. The results of similar experiments by Rao are shown in Figures 2-11 and 2-12. The impactors used in each of these sets of experiments were single jet, round hole impactors operating at relatively small jet-to-plate separations and relatively high Reynolds numbers. In these figures the uncertainties in the measured efficiencies are on the order of seven percent and the uncertainties in the square roots of the particle Stokes numbers are on the order of three percent. Measured stage collection efficiencies for a rectangular slit type impaction jet operated at an intermediate jet-to-plate spacing and high Reynolds number were reported by Felix et.al. (1982). These are compared to the model predictions in Figure 2-13. In all of the foregoing examples the measured and theoretical curves were found to be very similar qualitatively and to differ by only a few percent - typically two to three percent - in the value of the square root of the Stokes number at 50% collection efficiency. Figures 2-14 through 2-17 show results obtained by Farthing for round jet impactors operated at greater jet-to-plate spacings and lower Reynolds numbers than were tested by Mercer and Stafford or Rao. Again, the results are in good agreement with the theoretical predictions, both qualitatively and quantitatively, to Reynolds numbers of about 50. At lower Reynolds numbers the theoretical model appears to underpredict the measured values of Stokes numbers for 50% collection efficiency.

Verification of the appropriateness of using upstream rather than downstream conditions to define the impaction parameter was obtained by Flagan (1982) using data from Hering et.al. (1978). Figure 2-18 illustrates the behavior of the value of the impaction parameter for 50% collection efficiency versus the stage pressure ratio as predicted from theory compared to measured values obtained by Hering et.al. McCain and Ragland (1982) reached similar conclusions in a calibration study of a low pressure impactor designed for sizing submicron particles.

The results discussed in the preceding paragraph all pertain to experiments for which the geometry of the actual test impactor somewhat resembled that of the model. Cushing et.al. (1976) noted that for the first stages of some impactors the value of the Stokes number for 50% collection was considerably lower than the value predicted by Marple's theory. In others, the stage in question would be located immediately following a long, often tapered, flow expansion zone. In most of these cases, the impaction jets were the sampling nozzles which were diverging tapers with moderate angles of divergence (approximately 15°). The deviations for the latter cases probably resulted from the inlet jet failing to expand fully to the exit dimensions of the nozzle or cone. We thus find that the actual geometry of the jet must at least approximate that used in developing the theory for the theoretical predictions

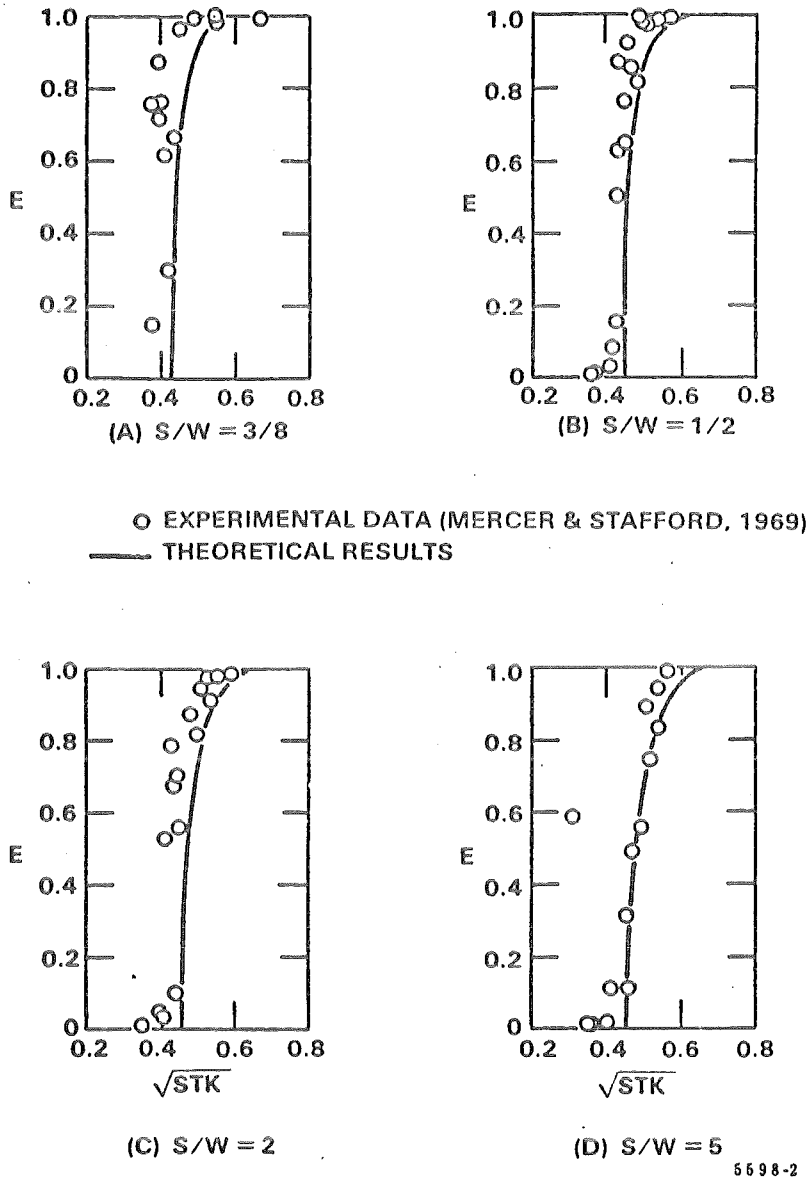


Figure 2-10. Comparisons of theoretical and experimental efficiencies of the round impactor (Marple, 1970).

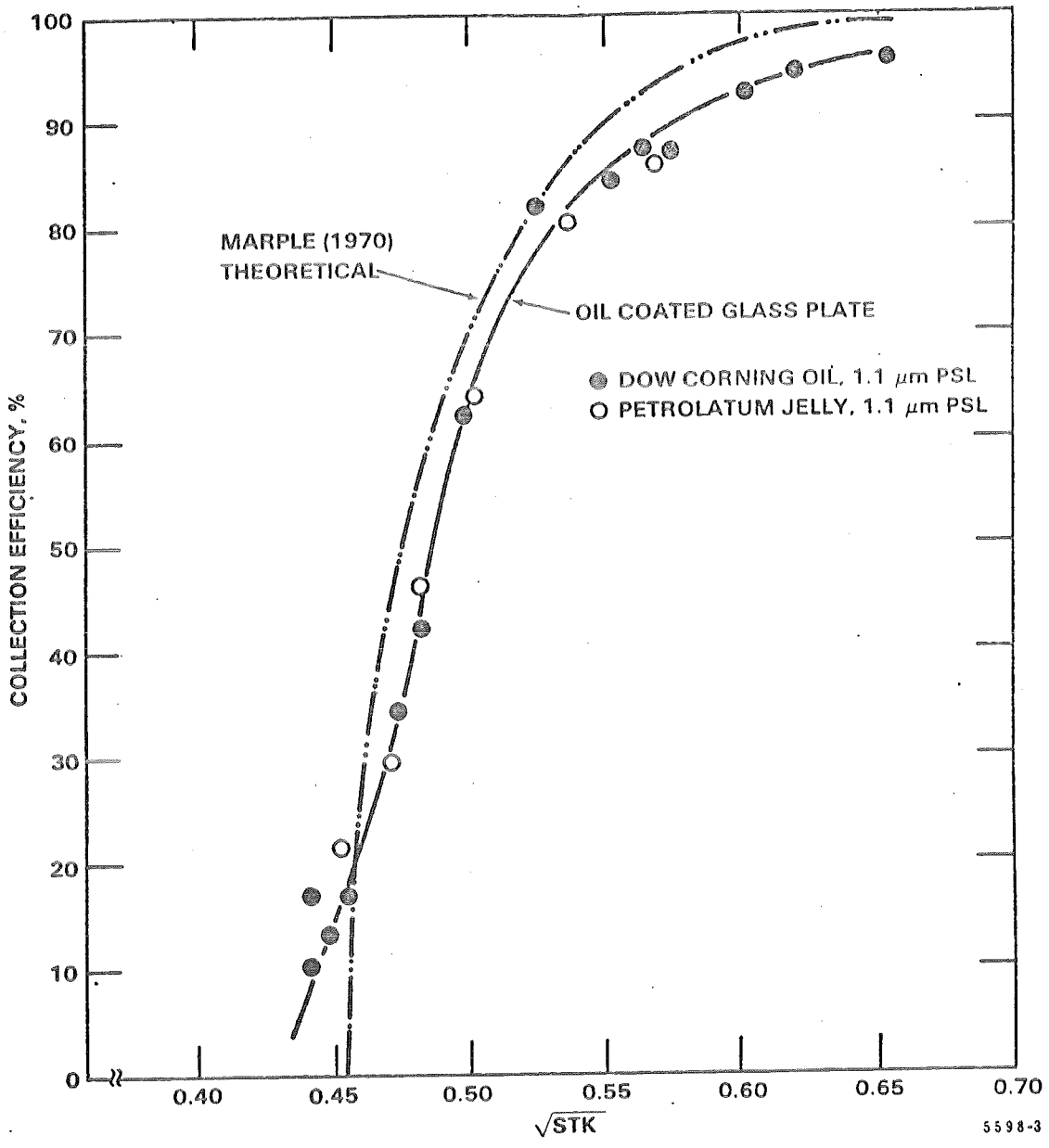


Figure 2-11. Measured and theoretical impactor collection efficiency with oil coated glass plate. S/W = 1.7 and T/W = 2.0 (Rao, 1975).

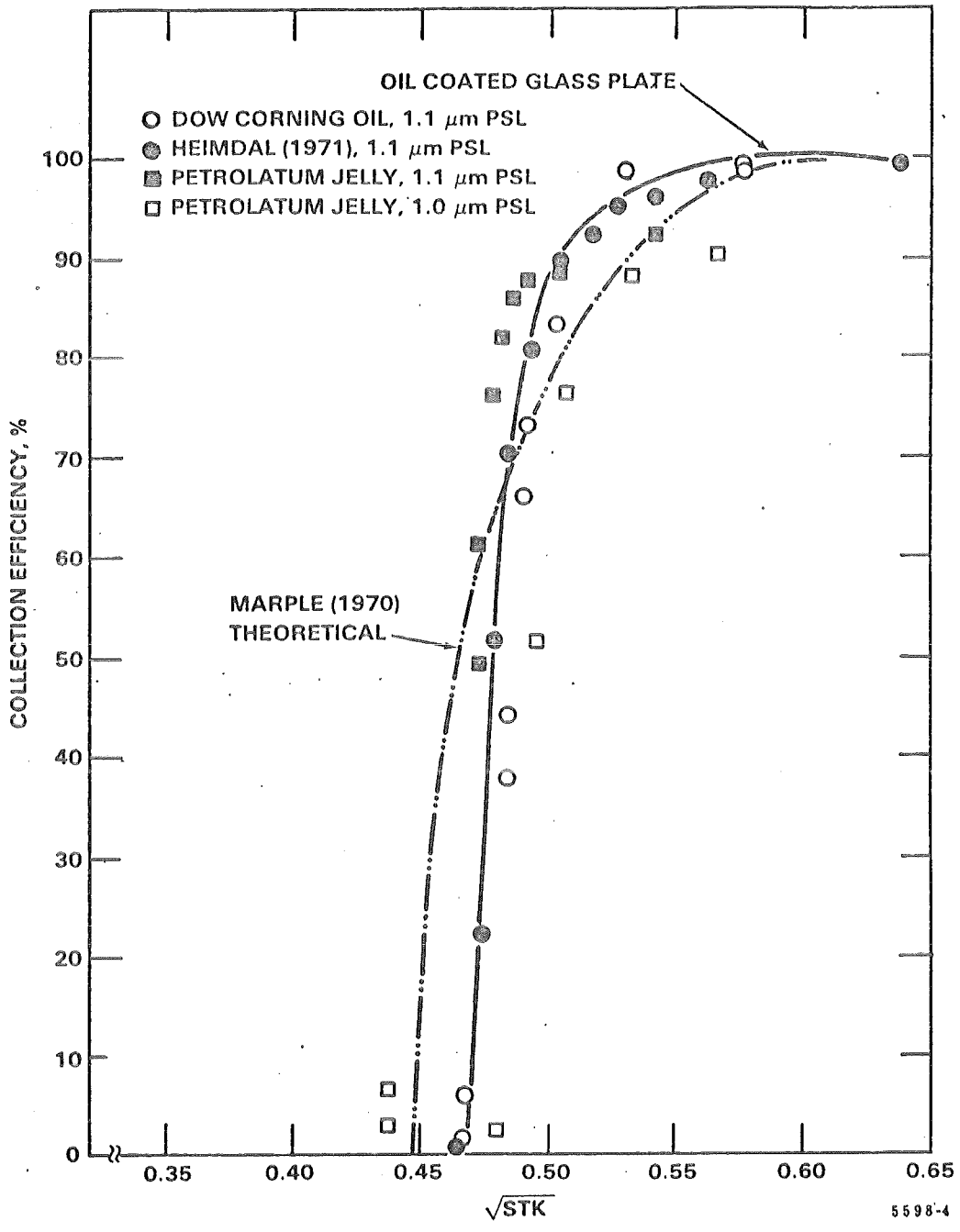


Figure 2-12. Measured and theoretical impactor collection efficiency with oil coated glass plate. S/W = 0.94 and T/W = 1.0 (Rao, 1975).

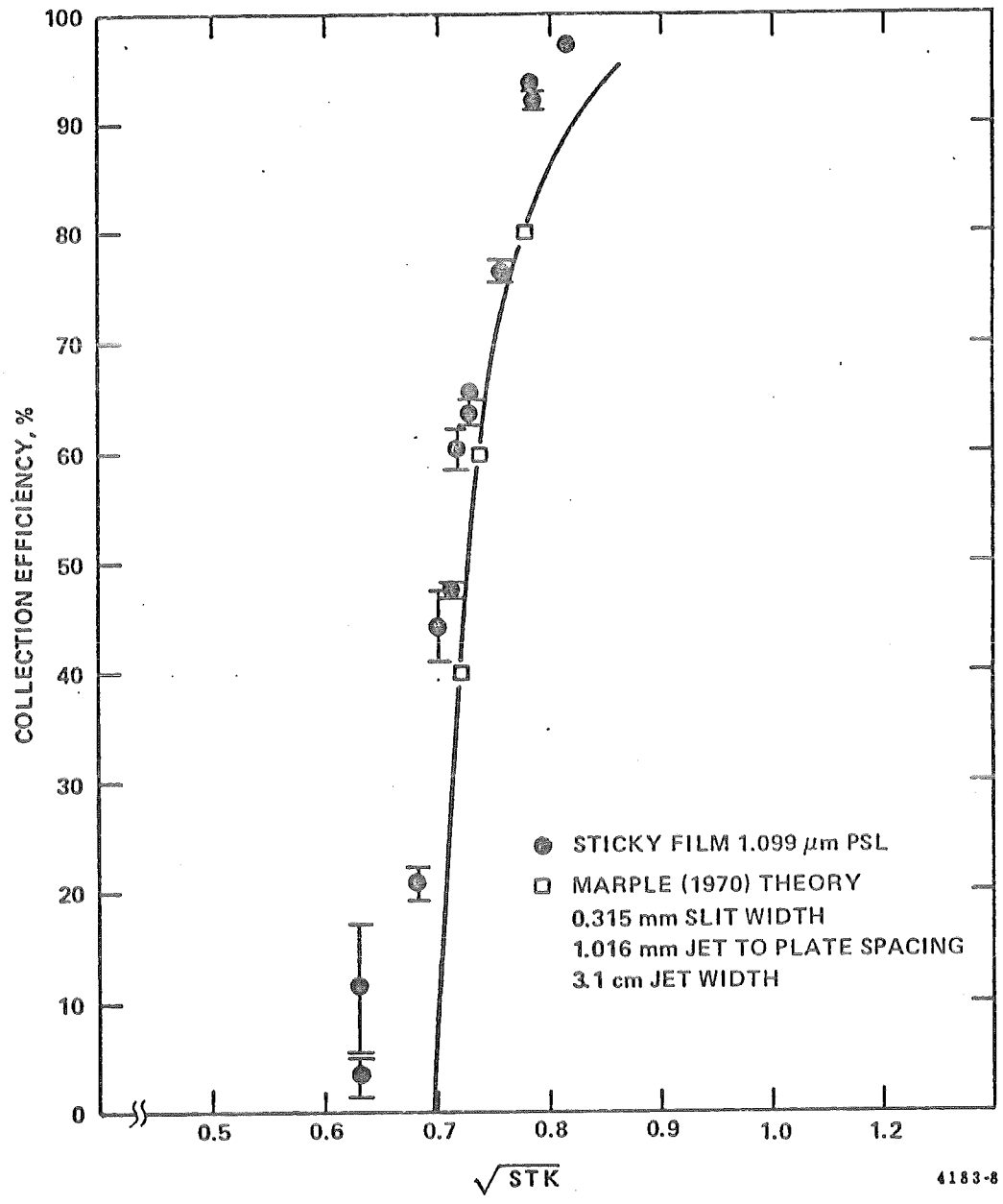


Figure 2-13. Measured and theoretical impactor collection efficiency for a slit type impactor (Felix, et al., 1982).

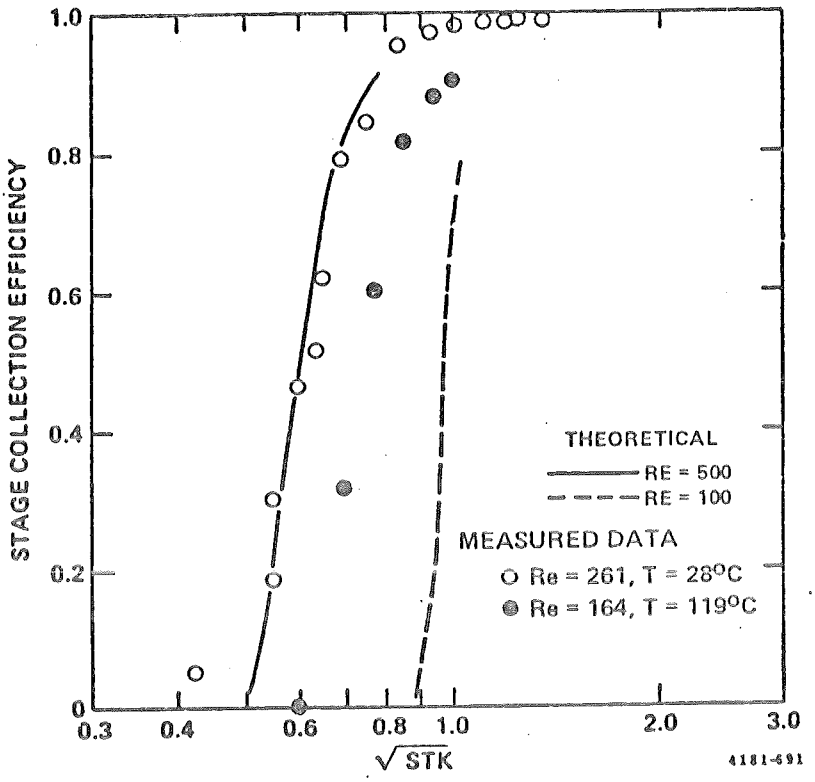


Figure 2-14. Measured and theoretical impactor collection efficiency. For theoretical curves, S/W = 11 and T/W = 2; for measured data S/W = 9 and T/W = 2.5 (Farthing, 1983).

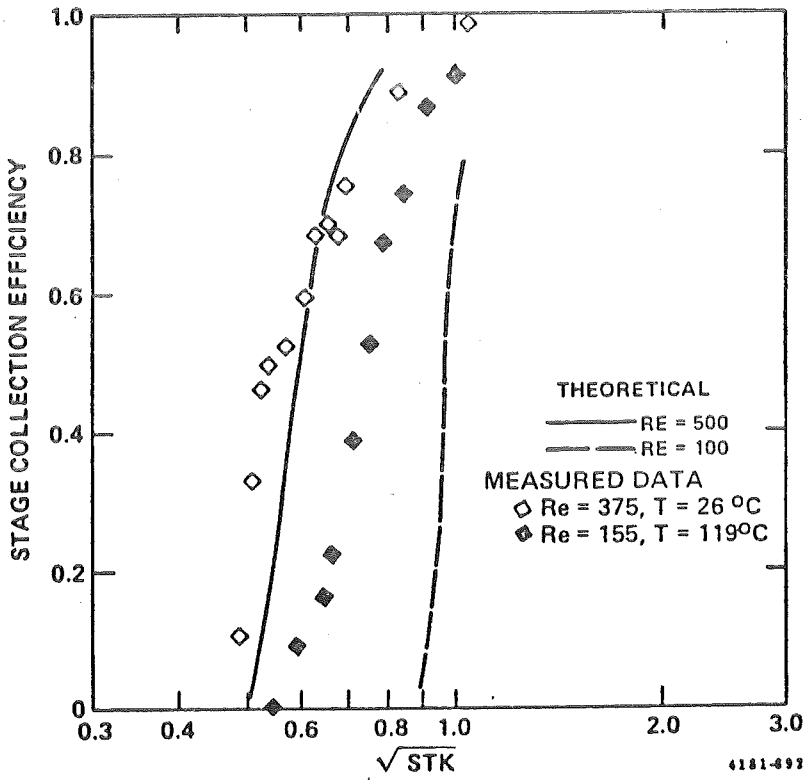


Figure 2-15. Measured and theoretical impactor collection efficiency. For theoretical curves, S/W = 11 and T/W = 2; for measured data S/W = 11 and T/W = 3 (Farthing, 1983).

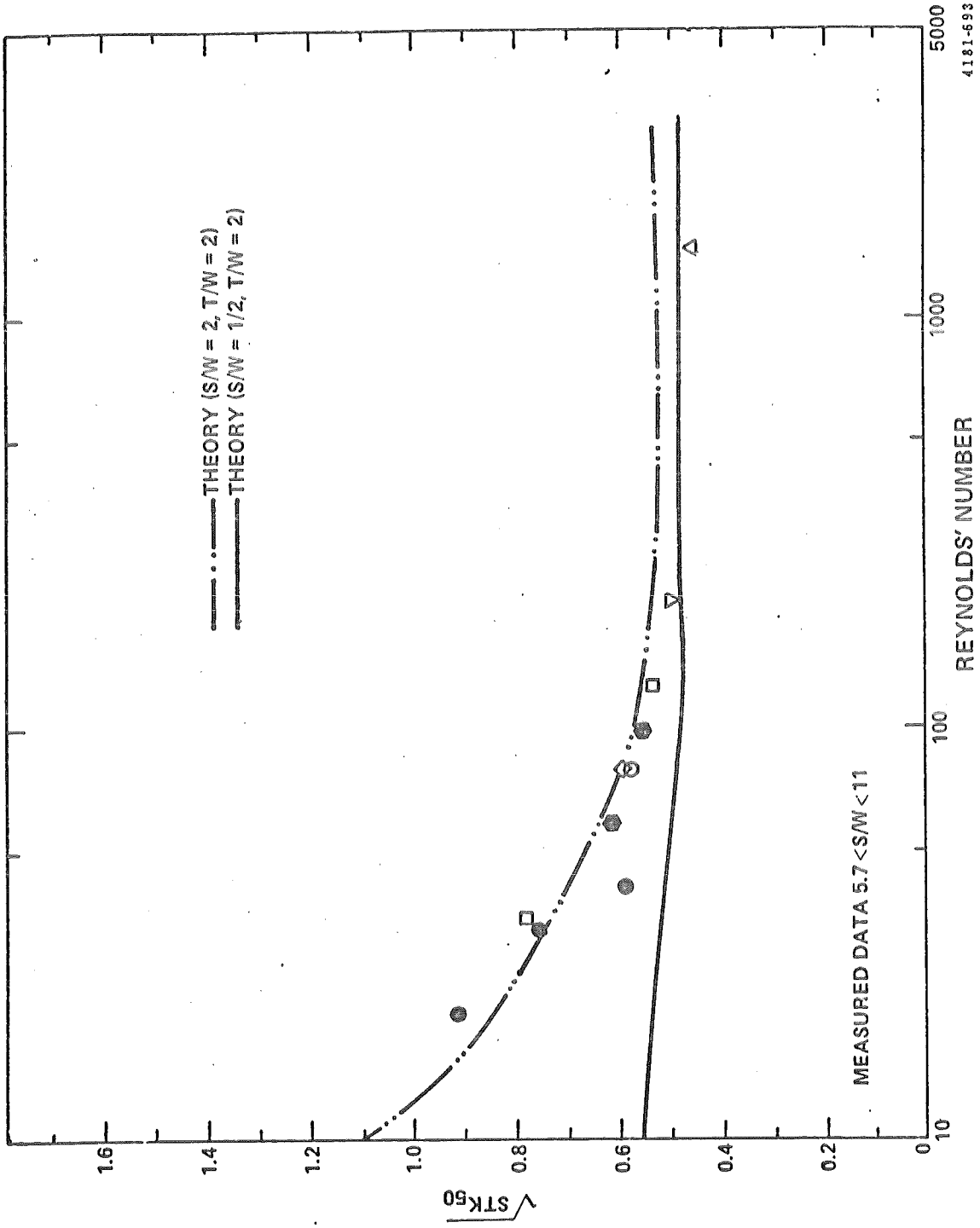


Figure 2-16. Measured and theoretical $\sqrt{STK_{50}}$ versus impactor jet Re. Measured data is from stages with S/W between 2 to 3.5 (Farthing, 1983).

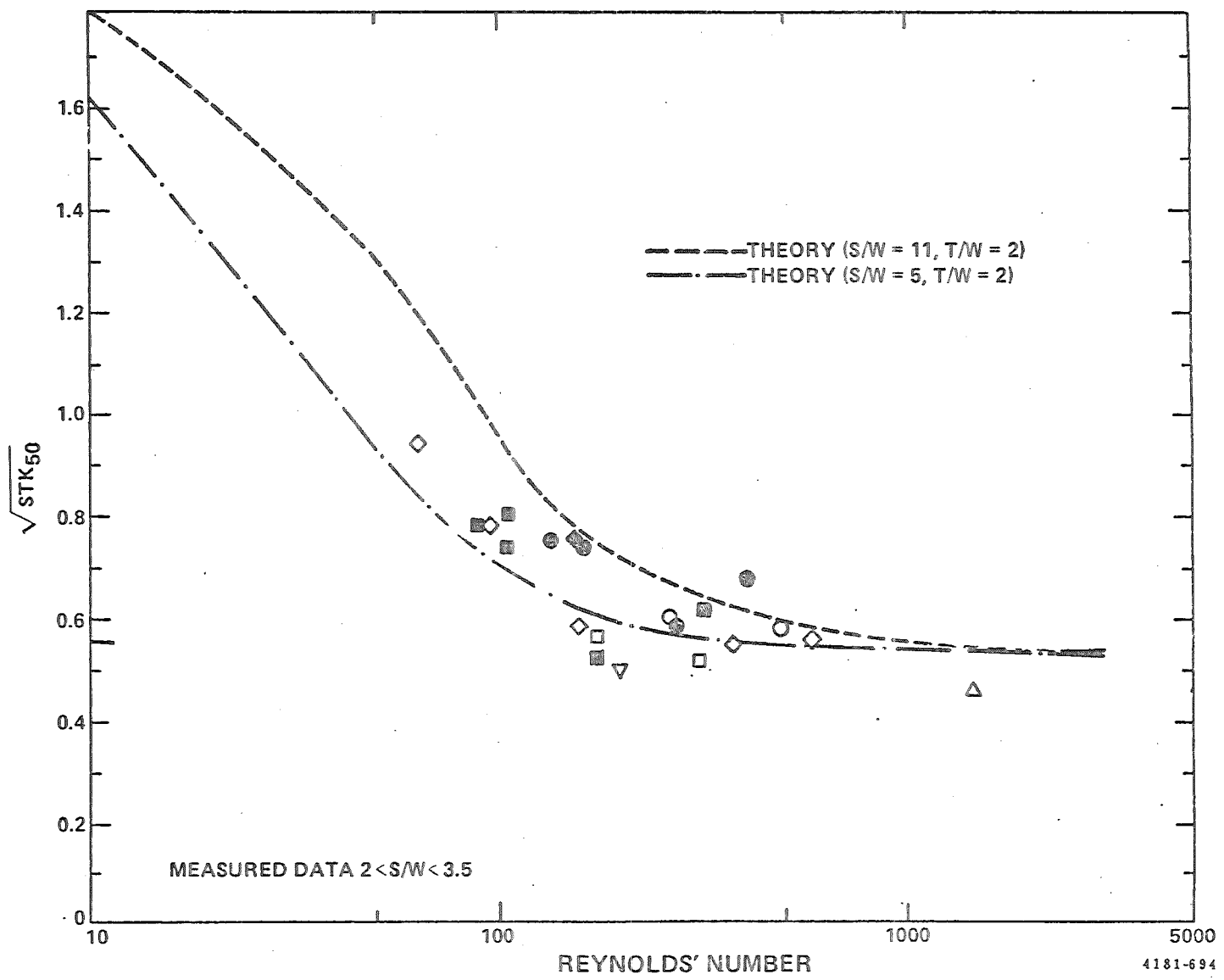
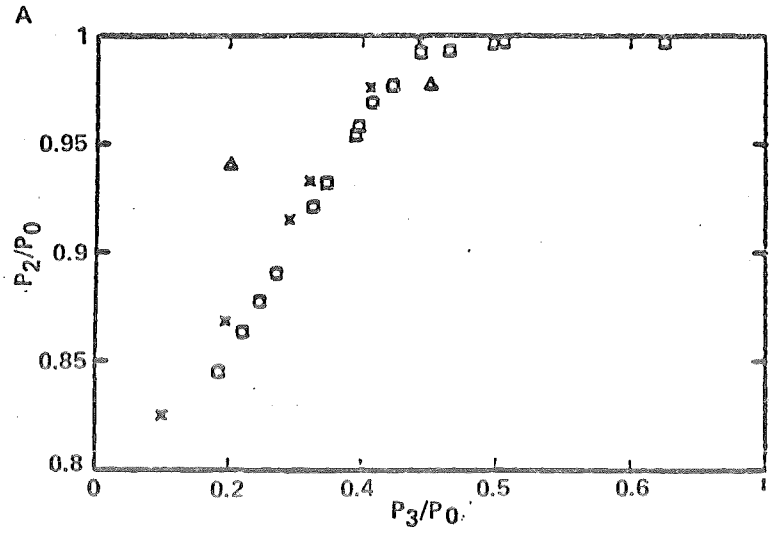
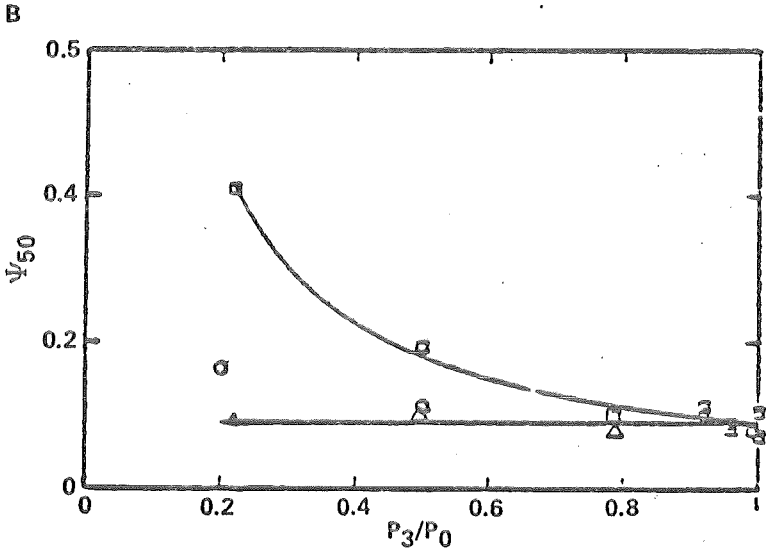


Figure 2-17. Measured and theoretical $\sqrt{STK_{50}}$ versus impactor jet Re. Measured data is from stages with S/W between 5.7 to 11 (Farthing, 1983).



DIMENTIONLESS STAGNATION POINT PRESSURE VERSUS OVERALL PRESSURE RATIO. EXPERIMENTAL MEASUREMENTS MADE ON CALTECH LOW-PRESSURE IMPACTOR (× AND □ ARE EXPERIMENTAL MEASUREMENTS; △ IS THEORY).



IMPACTION PARAMETER VERSUS PRESSURE RATIO FOR THE CALTECH LOW-PRESSURE IMPACTOR. (□ - Ψ_{50} CALCULATED BASED ON DOWNSTREAM PRESSURE, △ - Ψ_{50} CALCULATED BASED ON STAGNATION PRESSURE - BOTH FROM MEASUREMENTS. O - Ψ_{50} CALCULATED FROM THEORY BASED ON STAGNATION PRESSURE.

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Figure 2-18. Impaction zone pressure versus upstream/downstream pressure ratio and variation of Ψ_{50} with pressure ratio. (P_2 = stagnation pressure, P_0 = inlet pressure, P_3 = downstream pressure.) (Flagan, 1982).

to be valid. On the other hand, many of the jets tested for which good agreement was obtained had converging tapers that differed from the inlet tapers of the model by considerable amounts, or were simply flat orifice plates with no inlet taper at all. Thus it appears that the theoretical predictions of impactor performance can be relied upon with confidence without great concern about details of the jet construction, provided a diverging taper is not used.

SECTION 3

NON-IDEAL BEHAVIOR AND INTERFERENCES

Although the performance of actual impactor stages can be well described and predicted by the theoretical model described in the last sections, certain elements of the model are incomplete and some physical phenomena are not treated. Among these missing elements are the effects of gravity, electrostatics, particle charge, turbulence, the compressibility of gases, and particle rebound. The potential magnitude of errors arising from these items and, in some cases, means of ameliorating them are discussed in the following paragraphs.

3.1 Particle Bounce

In the theoretical model of impactor performance, it is assumed that any particle which contacts the collection surface will be retained by the surface. However, as is commonly observed in sand-blasting operations, this assumption is frequently invalid. In the case of impactors, beyond the qualitative information that particles stick when striking a surface at low speeds and bounce at high speeds, little is known about the bouncing or sticking of particles (Rao, 1975). If a particle strikes the collection surface and bounces, it remains entrained in the gas stream and will be collected in a subsequent part of the sampler, resulting in bias and error in the measured size distribution.

For particles smaller than 10 μm, it has been found that although Van der Waals forces, electrostatic forces, and capillary forces in liquid bridges can all play a role in particle adhesion, the dominant force is almost always the Van der Waals force (Jordan, 1954; Löffler, 1968). Even for a 10 μm particle possessing a relatively high charge of 1000 elementary units, the Van der Waals forces are about 100 times as great as the electrostatic forces when the particle is in contact with a surface.

According to Dahneke (1971) particles will bounce if the incident velocity, v_p, is great enough that

$$v_p > \left[\frac{2G}{m}\,\frac{1 - e^2}{e^2}\right]^{1/2} \qquad (3\text{-}1)$$

where

G = particle-surface interaction energy or the depth of the potential well as seen by the incoming particle,

m = mass of the particle,

e = coefficient of restitution.

The depth of the potential well for a sphere of diameter D_p adhering to a flat surface is

$$G = \frac{A\ D_p}{12\ z_o} \qquad (3\text{-}2)$$

where

A = Hamaker-Van der Waals constant, generally of the order of 10^{-12} ergs

z_o = distance between adhesion partners, typically 4 Å

From Equations (3-1) and (3-2) we find that the critical velocity is inversely proportional to the particle diameter.

It should be noted here, of course, that this theory applies only to ideally smooth surfaces of adherents. In case of elastic flattening of the sphere and/or indentation of the flat surface, the adhesion energy, G increases substantially.

The magnitude of the potential problem introduced by particle bounce is illustrated in Figures 3-1 and 3-2 which show calibration results obtained by Rao (1975). The test particles used in generating these data were dry solids (polystyrene latex beads). In each figure we find that the experimental curves of collection efficiency versus $\sqrt{STK}$ fall very close to the theoretical curves if the collection surface was coated with a material that could absorb the impact energy and act as an adhesive to retain particles which struck it. On the other hand, collection efficiencies using uncoated glass plates fell close to those for the coated plates at the lower Stokes numbers (lower jet velocities) but for values above some critical jet velocity (or Stokes number) the curves broke away from those for the coated plates. For Stokes numbers above the break collection efficiencies failed to reach even 50%.

Cheng and Yeh (1979) proposed a guideline for impactor operation intended to eliminate particle bounce problems. Based on numerous experiments with a number of types of dry "bouncy" particles they suggested that if the product of the jet velocity and aerodynamic diameter, υD_{50}, of the particles impacting on each stage were kept to values below about 5 μm-m/s, the assumption that particles adhere to the collecting surface on contact would be valid. In practice it is impossible to adhere to this guideline without forcing operation at very low Reynolds numbers by using very large numbers of quite small jets. As previously discussed, impactor performance becomes less well predicted at very low Reynolds numbers than is desirable; moreover, the manufacturing costs for making impactors would rise considerably, if this option were taken.

The close agreement between the theoretical and experimental performance curves shown in the two previous figures, when oil coated impaction plates were

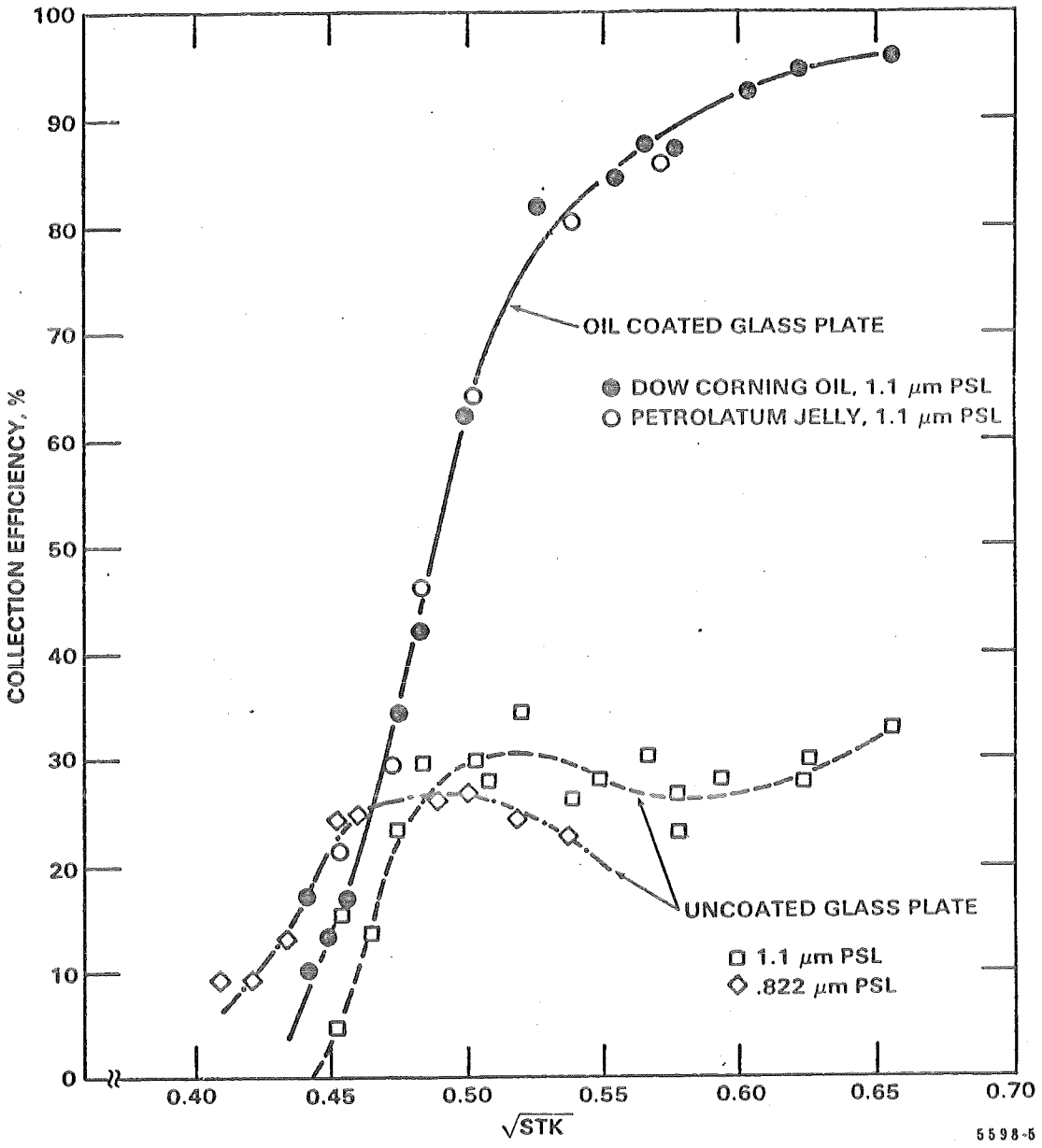


Figure 3-1. Collection efficiency of impactor with oil coated glass plate, and uncoated glass plate. S/W = 1.7 and T/W = 2.0 (Rao, 1975).

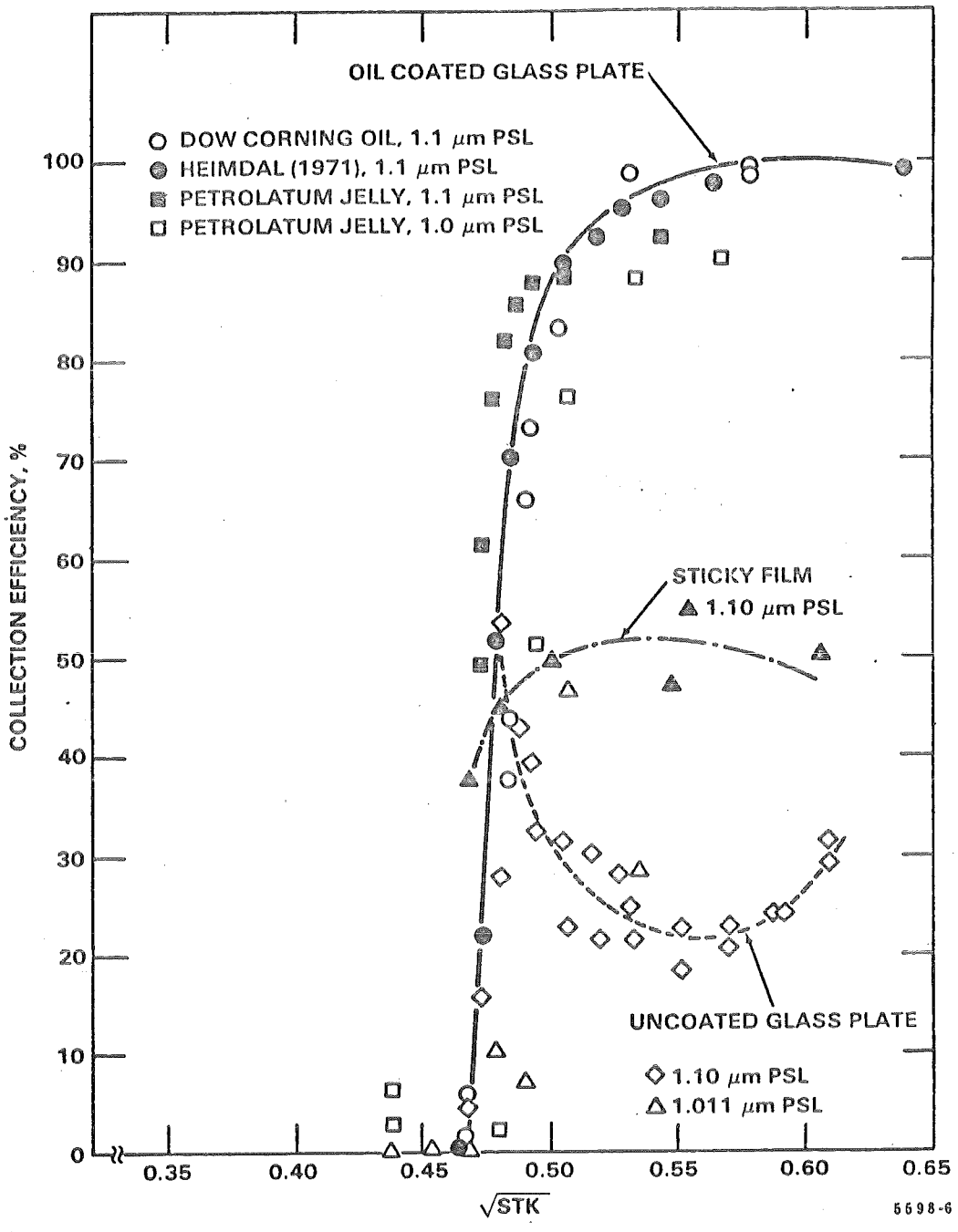


Figure 3-2. Collection efficiency of impactor with oil coated glass plate, uncoated glass plate, and sticky film. S/W = 0.94 and T/W = 1.0 (Rao, 1975).

used, lies at the heart of the most widely used technique for eliminating particle bounce problems. That is the use of surface coatings to absorb the impact energy and retain the particles. Various silicone and hydrocarbon-based oils, greases, polymers, and rubbers have been used successfully as coatings by one or another group of impactor users. A material which wets and that will wick up through the collected particles to maintain a fresh surface coating is desirable. However, the coating must not be able to flow or it will be subject to loss to other surfaces of the impactor while being transported or used. This results in the use of coating materials which are selected for a compromise in particle wetting, wicking, and retention with enough stiffness to remain in place on the collection substrate in use, limiting the υD_{50} products for the impactor stages even when coatings are used; albeit at higher values than for bare surfaces. (The jet velocities must also be kept low enough to insure that the coating is not eroded by the jet.) The key requirements are the ability of the coating to simultaneously maintain stability in weight and the needed physical properties for particle adhesion. A number of coating materials and the approximate limits of temperature for each are given in the field applications section of this document.

It is important that a coating material be used only within its specified temperature range. There are several reasons for restricting the temperature range. Among these are weight loss and/or degradation of the needed physical properties at excessively high temperatures and the fact that many materials become too hard at temperatures below the recommended limit. An example of the latter effect is shown in Figure 3-3. This figure illustrates the measured collection efficiency by particle size for the same impactor stage and sampling conditions using two different coatings. The measurements were made at laboratory temperatures. Under these circumstances, the first coating petroleum jelly was soft and "sticky", while the other (Apiezon H) was too hard at low temperatures. Apiezon H is commonly used in flue gas sampling for temperatures in the range from 150 to 200°C.

To date, no coating materials have been identified which can be used at temperatures above about 230°C. Thus, alternate solutions to the bounce problem were sought to avoid the necessity of limiting the υD_{50} product to very low values. The use of fiber mat surfaces has been the most successful of these to date. If a fiber mat such as a glass or quartz fiber filter is used as a collection surface, particles which do bounce have a reasonable probability of being deflected into the depths of the mat and being retained rather than rebounding directly back into the gas stream. This technique has been demonstrated to reduce particle bounce sufficiently to permit useful data to be obtained. Figure 3-4 shows actual stage collection efficiency curves for an Andersen cascade impactor sampling dry solid particles in ambient air (Rao, 1975). Three sets of curves are shown in the figure: one for which oil-coated collection surfaces were used; one for which bare metal surfaces were used; and one for which glass fiber filter surfaces were used. It is quite apparent that the performance with bare metal surfaces is totally unacceptable. However, the performance with glass fiber substrates is adequate, even though the measured efficiencies did not quite reach 100% for any size at any stage. As the υD_{50} product for an impactor stage is increased, the maximum collection

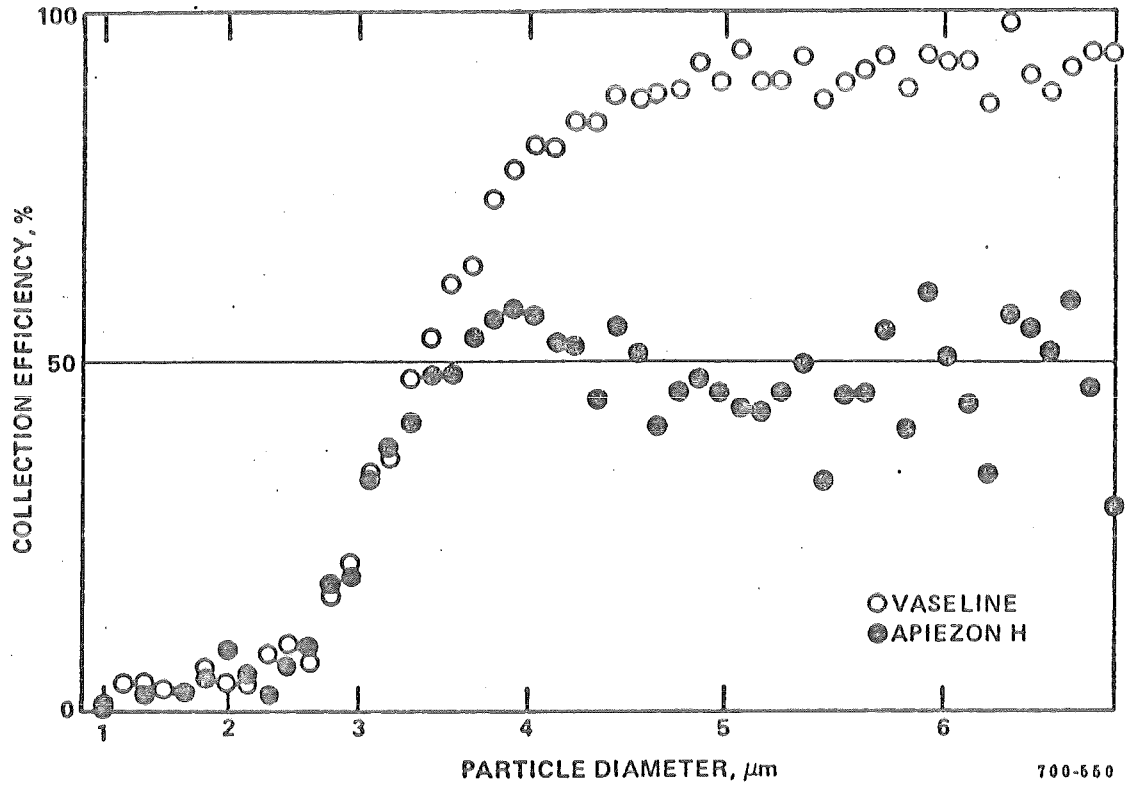


Figure 3-3. Measured collection efficiency at room temperature of an impactor stage with two substrate greases. Significant particle bounce effects are seen with Apiezon H, which at room temperature is far below the softening point (McCain, et al, 1985).

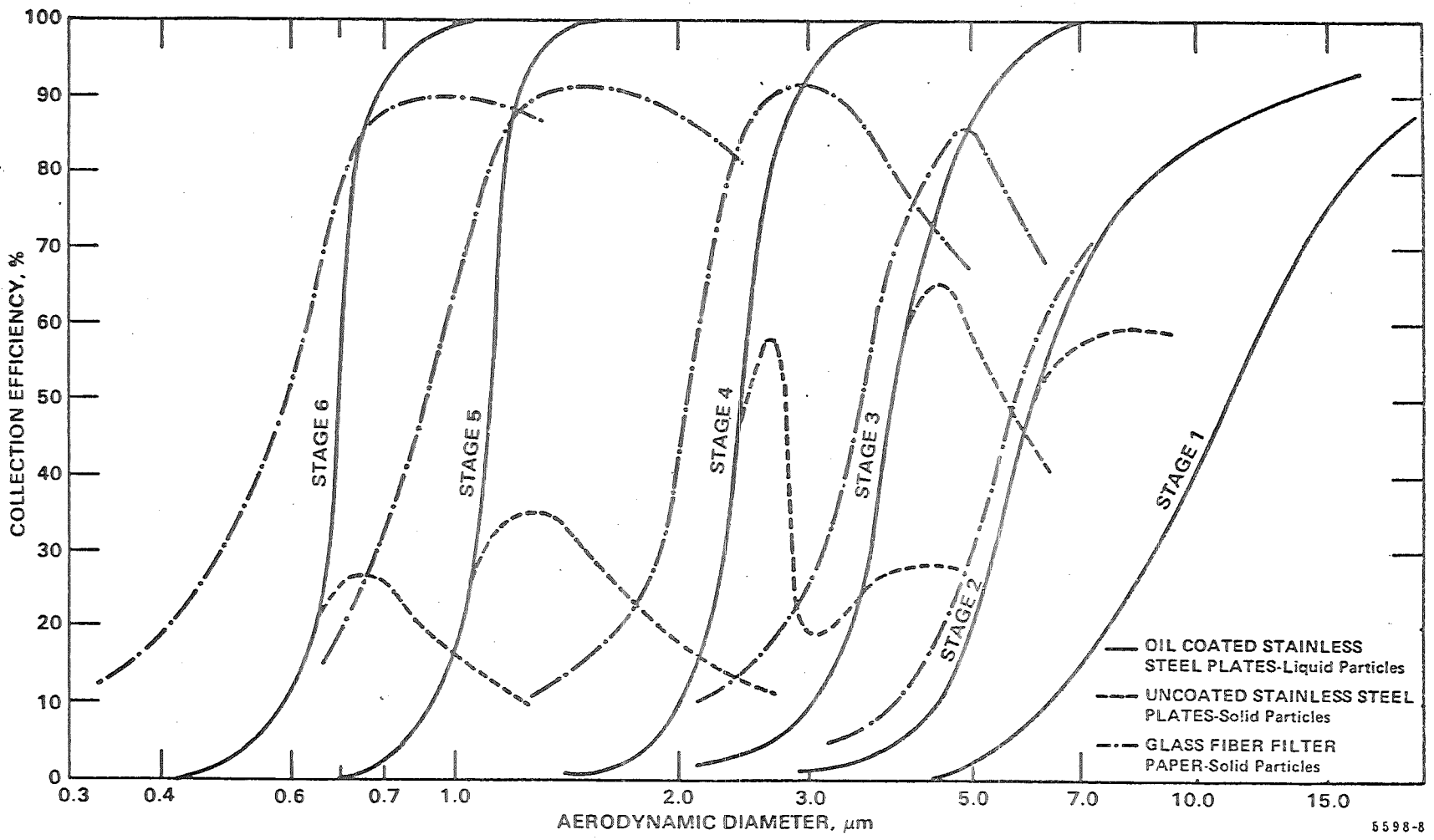


Figure 3-4. Collection characteristics of the Andersen sampler (Rao, 1975).

efficiencies obtainable with fibrous substrates decreases, thus limits must also be set on υD_{50} products for operation with fiber substrates. It should be noted that the stage D_{50}'s in Rao's data shifted to smaller diameters and the sharpness of the cut was reduced when the glass fiber surfaces were used. The relative shift in D_{50} was not constant from stage to stage and cannot be predicted by any currently available theory. Thus if fibrous substrates are to be used, the impactor should be calibrated with these substrates at conditions similar to those under which the sampling will take place.

Aerodynamic D_{50}'s are plotted versus stage jet velocities in Figure 3-5 for a number of cascade impactors. These velocities and D_{50}'s represent the values that would result if the impactors were operated at their respective design flow rates at laboratory conditions. The shaded area in the figure represents the range in which the υD_{50} products would meet the criterion set by Cheng and Yeh for operation with bare collection surfaces. As can be seen, none of the impactors meet the criterion for all stages and some do not meet it for any of their stages. Extensive laboratory calibrations were performed by Southern Research Institute of each of these impactors. Calibrations of the Andersen, Flow Sensor, and Sierra impactors were done with glass fiber substrates. The results of this work revealed that the performance of the Sierra impactor was unsatisfactory because of excessive particle bounce when it was operated at a flow rate of 14 lpm. The performance of the Flow Sensor and Andersen impactors at that flow rate was satisfactory, and when the flow rate of the Sierra impactor was reduced to 7 lpm its performance became satisfactory. The Brink, Pilat Mark III, and MRI impactors were all tested with grease-coated substrates as was an experimental impactor designed by Southern Research Institute. For the Brink and MRI, performance was marginal with respect to particle bounce at the conditions of the tests. The experimental SRI impactor had excessive bounce even when a normally effective grease was used. As a result of these experiments, general guidelines were developed for impactor operation that are based on the υD_{50} products for the individual stages. For bare metal as a collection surface, the υD_{50} product should not exceed 10 μm-m/s at any stage and should probably be kept to values below 5 μm-m/s. For fibrous collection surfaces, the υD_{50} products should not exceed 15 μm-m/s. For grease-coated substrates, the product should not exceed 25 μm-m/s. Adherence to these guidelines should result in acceptable control of particle bounce under virtually all circumstances. In instances in which the particulate matter is sticky, these limits may be unduly restrictive and operation at conditions which result in larger υD_{50} products may still produce acceptable performance.

3.2 Catch Limits

The quantity of particulate matter which can be collected on a single stage is limited by factors which depend on the detailed geometry of the stage, the properties of the particles being sampled, and the properties of the collection surfaces. If the deposits of collected particles become too large they become subject to being reentrained, resulting in the transfer of particles from the proper collection stage to one or more subsequent stages. Such reentrainment will obviously bias the results and, if severe, will totally invalidate them. Limits to stage loadings that will insure that reentrainment poses no problem are difficult to quantify as they depend on the adhesion and cohesion properties of the particles, as well as the properties of the

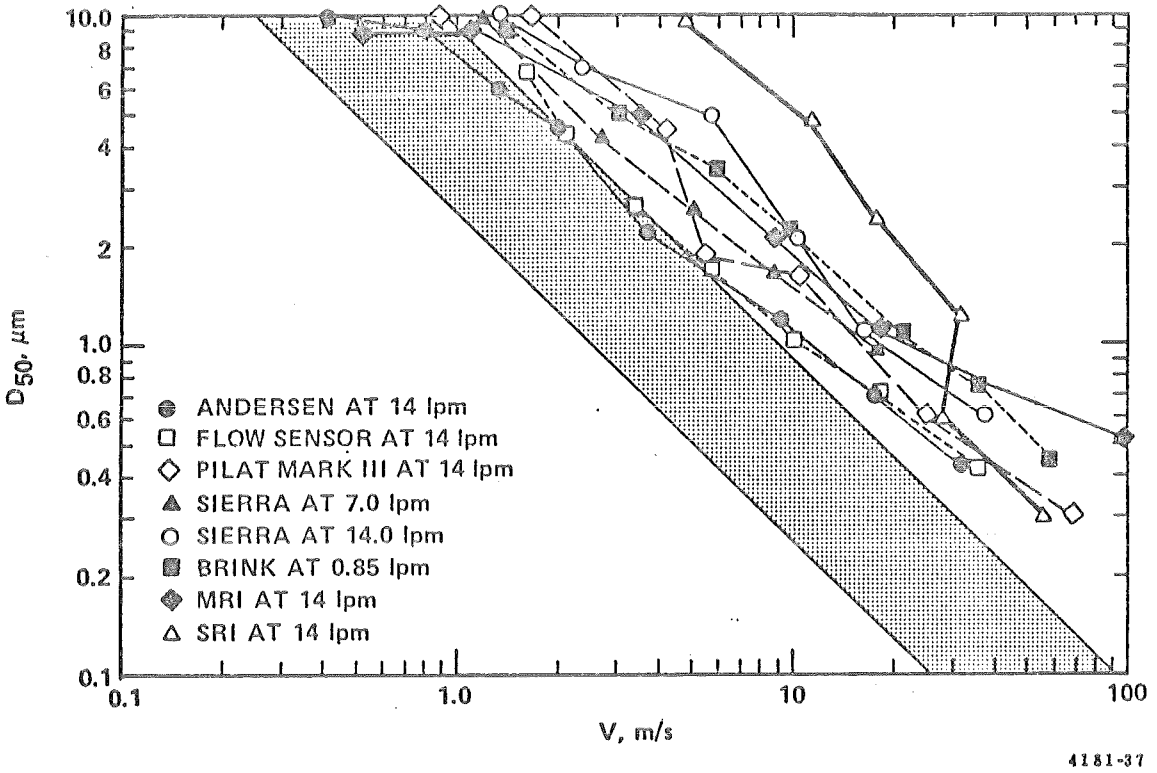


Figure 3-5. Stage D_{50} versus stage jet velocity for various round jet cascade impactors. Grayed area satisfies no bounce criterion of Cheng and Yeh (1979).

collection media and particle/media interactions. However, extensive laboratory and field experience has resulted in the use of the figure of 15 mg as a good guideline target for the maximum load to be collected by any one impactor stage.

A further limitation in stage loading is set by the fact that as material collects under a jet the effective jet-to-plate spacing is reduced. This can result in an unacceptably large shift in the stage D_{50} as the sample collection takes place, depending on the initial spacing and the jet Reynolds number. Figure 3-6 illustrates a measured shift in stage collection efficiency resulting from such particle buildup on the collection surface. In extreme cases when sampling very sticky particles, the impacted particles collect in a rod-like structure which can bridge the gap between the collection plate and jet and actually plug the jet.

In sampling sources at which the particle size distribution is dominated by particles whose diameters are larger than the cutoff diameter of the first impactor stage, a method is needed to provide a means to avoid overloading the first stage before sufficient material for measurement can be collected on succeeding stages. Several forms of high capacity precollectors are available for this purpose. Some of these are small cyclonic separators while others are impaction devices which are designed to utilize gravity and baffling for retention of large particles. All of the devices made for this application have load capacities of several hundred milligrams or more.

3.3 Interferences

Both grease and fibrous impaction surfaces are subject to chemical and/or physical changes when exposed to industrial flue gases. These can be in the form of weight gains or losses which may be comparable to or larger than the gains caused by the collected sample or they may, in the case of greases, alter the surface properties so that the impacted particles are not retained.

In the case of fibrous media, reactions with vapor phase components of the sample stream can result in weight losses or gains. Most commonly, such reactions result in weight gains; however, some may result in losses (e.g. reactions with low concentrations of HF in some process exhausts). SO_2 is a common constituent of flue gases from combustion processes which can react with glass fiber materials to form sulfates on the fiber surface. Such reactions can lead to weight changes of several milligrams while the weight of the sample collected on an impactor stage is typically only a fraction of a milligram to a few milligrams. Because of its ubiquitous nature and the severity of the problem, special treatments have been devised to deal with SO_2 reactions with glass fiber media. These are detailed in the field procedures section of this document. Many of the reactive properties of glasses are related to impurities and non-silica components contained in them. Barium oxide is one such component that is especially susceptible to reaction with SO_2. Quartz fiber materials are far less subject to problems resulting from chemical reactions but are not as mechanically strong as borosilicate glasses and consequently may not be useful in some applications. In addition, mechanical loss of fibers, if permitted to occur, can lead to unacceptably

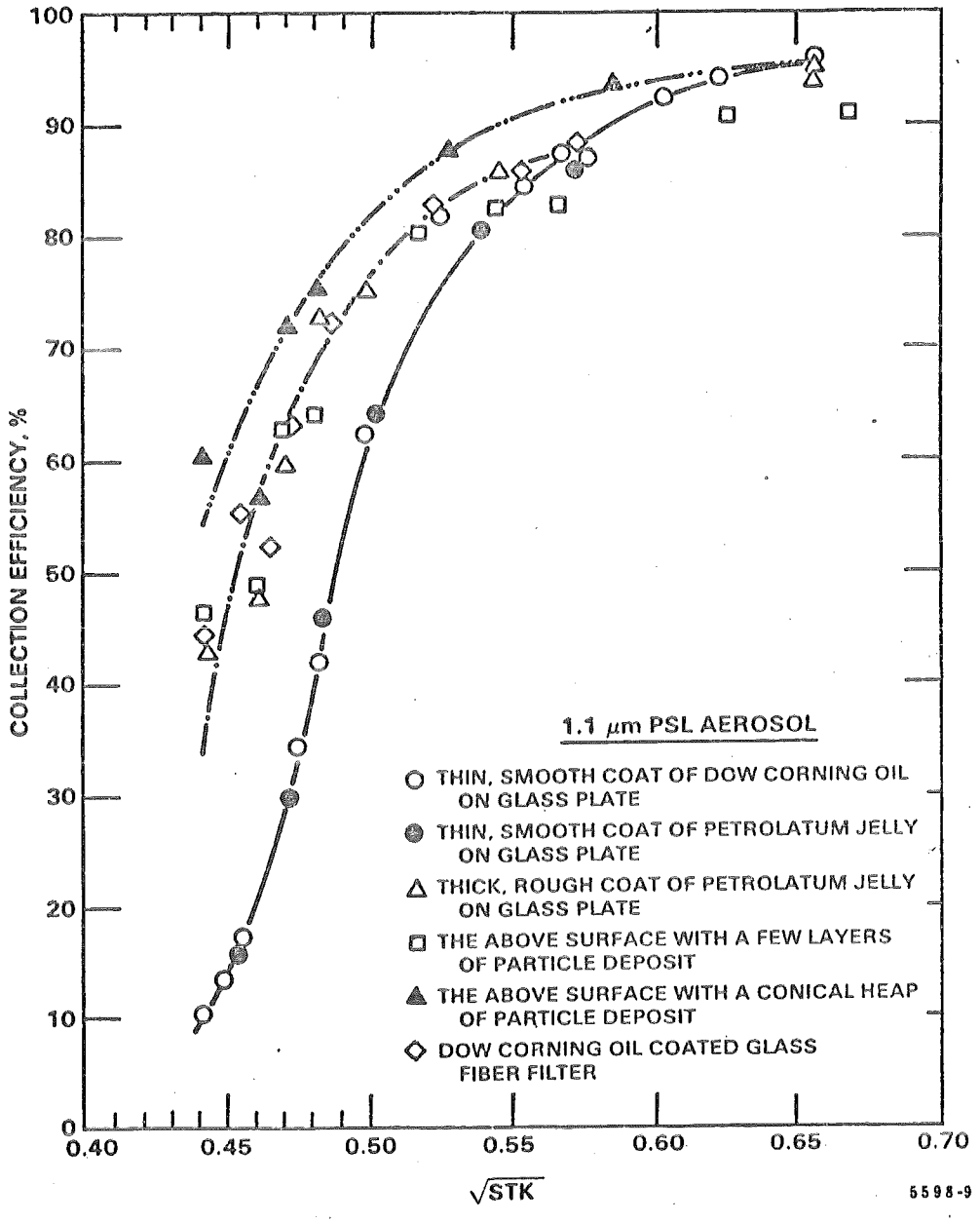


Figure 3-6. Effect of particle loading on the collection efficiency (Rao, 1975).

large errors due to weight loss or transfer from one stage to another downstream.

Greases and similar coatings are subject to weight changes from several mechanisms. If the grease flows too freely at the operating temperature, some can be blown off a stage from excessive jet velocities or be transferred to other surfaces simply by flowing off of the impaction substrate. Evaporation of volatile constituents can also lead to weight loss. On the other hand, chemical reactions with gas phase constituents of the sample stream can result in weight gains that are unrelated to collected particulate matter. In addition, temperature and chemically induced changes in the physical properties of the coating can make it unsuitable for its intended purpose of particle retention.

Because of the effects discussed above, it is imperative that the collection media to be used in a sampling program be tested for suitability for the particular application before the actual sampling is begun. It is also advisable to periodically recheck the selected impaction substrate materials during extended sampling programs at a single source. Details on methods for these checks are given in the Protocol Section of this document.

3.4 Sampling Nozzle and Inlet Effects

Particle size dependent effects in the sampling nozzles and inlet transforms used to withdraw the sample from the gas stream to be measured and deliver it to the impactor stages must be accounted for in the measurement process. Losses in bends, expansion zones, interconnecting tubing, and housings can arise from inertial deposition, turbulent deposition, and gravitational settling - none of which are accounted for in the theoretical treatments of impactors.

First of all, settling losses are excessive in horizontal probes of the lengths required for stationary source sampling, so impactors must be operated in situ. Even when impactors are operated in stack, losses in the inlet sections of the sampler can be significant and must be accounted for in impactor measurements. Perhaps the most common error here lies in the easily overlooked fact that the sampling nozzle always acts as an impaction jet. Some, but not all, impactors are designed to make use of this. But in all cases, the nozzle, whose tip size must be correct for isokinetic sampling conditions, becomes the first impaction jet - whether by design or not. (Note: isokinetic sampling is a requirement for obtaining a sample which is unbiased with respect to particle size.)

Historically, the recommended practice for sampling with cascade impactors has been to attach the impactor to the probe with a 90° bend between the impactor and probe axis allowing the impactor axis to be aligned with the gas stream being sampled. In many instances, the geometry of the sampling ports would not permit insertion of such a configuration thus a "gooseneck" nozzle was used so that the impactor could be aligned with the probe. However, it has been found that the trajectory of the sample into the first size separating stage must be parallel to the flow stream from which the sample is being taken. The use of "gooseneck" or similar 90° bend nozzles to turn the sample flow into

the probe in the fashion used with Method 5 cannot be permitted for size distribution measurements. If such a 90° bend nozzle is used, it effectively becomes a poorly-behaved impaction stage preceding the particle separator and can cause large changes in the apparent size distribution (Felix and McCain, 1981; Knapp, 1980). Figure 3-7 illustrates the predicted separation diameters for 90° bend nozzles over the range of sampling conditions that are commonly encountered in industrial source sampling. Cutoff diameters for such nozzles under typical conditions range from about 2 to 7 μm. Results obtained using such nozzles are not valid for diameters larger than the cutoff diameter of the nozzle. Recently, manufacturers have begun to offer samplers with the first stage oriented at a right angle to the main body of the sampler or add-on precollectors with a right angle orientation. These arrangements permit the impactor assembly to be mounted co-axially with the probe while maintaining the direction of flow parallel to the sampled stream up to the first inspection stage.

Even when 90° bend nozzles are not used, impaction losses in impactor inlet stage can be a problem. The nozzle tip sizes required for isokinetic sampling are typically small enough that the effective stage D_{50} of the nozzle is only a few microns as was illustrated in Figure 3-7. To allow size fractionation at larger particle diameters, the standard practice in the design of impactors for source testing is to gradually expand the nozzle and/or transform to the first "standard" collection stage. By permitting the sample to decelerate before reaching that stage these designs attempt to raise the effective D_{50} of the inlet to a value that does not undercut the first stage or stages. In some cases the nozzle itself is flared over a short enough distance to make settling losses acceptable and the nozzle exit is used as the first jet. This approach is used in the Pilat impactors and in several of the "Right Angle" precollectors which are on the market. However, the expanding jet geometry has not been modeled and calibrations of this geometry show that the cuts are not predicted at all well by current theory. In other devices, such as the Andersen Mark III Stack Sampler and the Sierra stack sampling impactors, long expansion transforms are used. But even though the effective jet-to-plate distances are large, impaction still occurs on the inlet surface to the first jet stage. Moreover, settling losses become quite significant when the devices are operated in a horizontal position. Likewise, the multijet inlet transform of the MRI 1501 impactor is subject to significant impaction losses. Figure 3-8 illustrates typical first stage efficiency curves for geometries using both long transforms and others for which the nozzle is designed to act as the first impaction jet. As can be seen, the effective value of the impaction parameter is much smaller than predicted by theory in all cases. Therefore, calibrations must be used to determine empirical relationships for obtaining the first stage D_{50}'s. The end result of all these effects is to make it very difficult (or virtually impossible) to size particles larger than about 10 to 15 μm with cascade impactors.

3.5 Electrostatic Effects

The effect of particle charge on particle deposition in impactors is of potential concern, especially when sampling aerosols that are known or are expected to carry significant unipolar charge levels. Particles exiting a high efficiency electrostatic precipitator (ESP) would fall into this class.

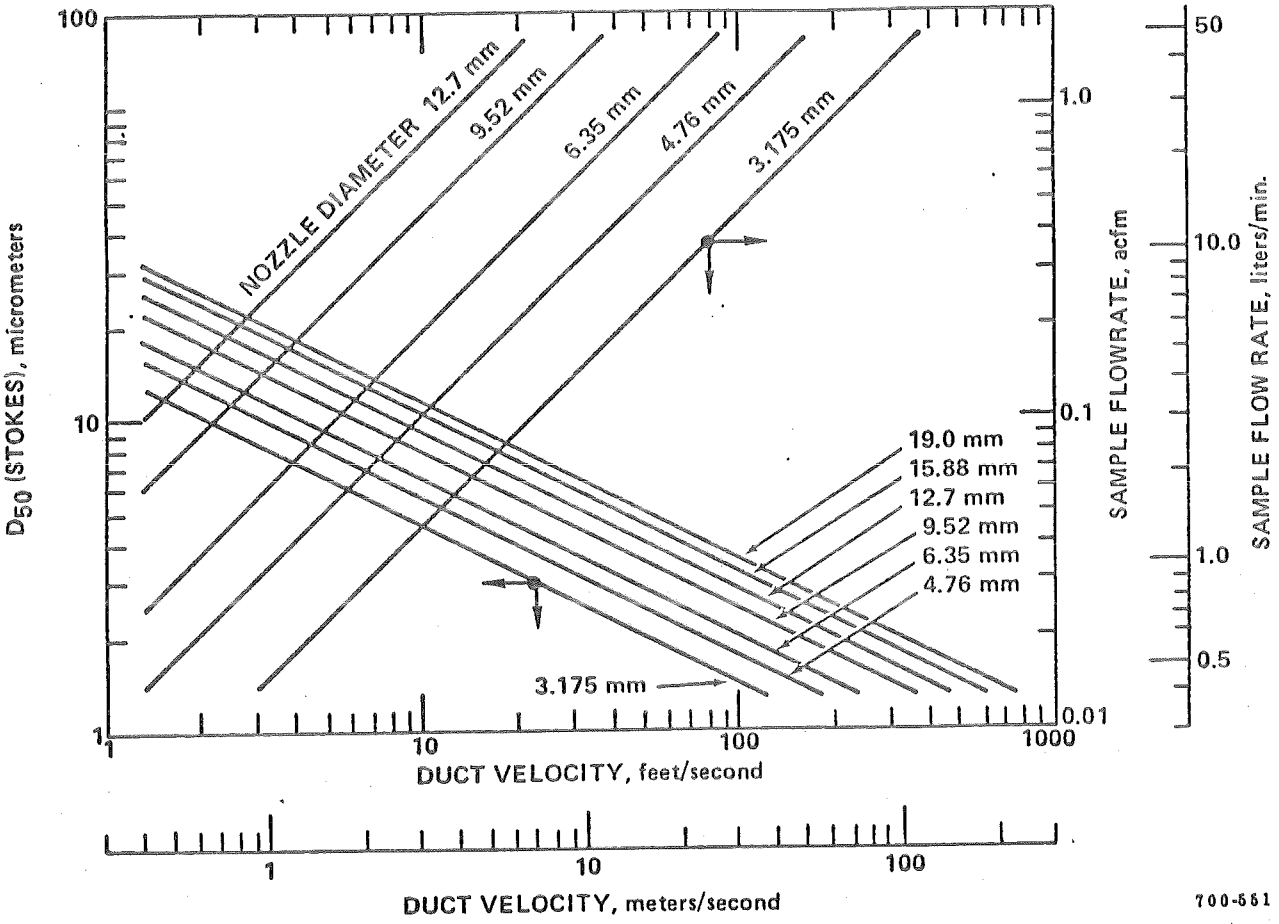


Figure 3-7. Curves to predict the physical cut-diameters (Stokes D_{50}) of 90° sampling nozzles for various nozzle sizes and sampling conditions. Calculated for 150°C and 2.4 g/cm^3 particle density; for aerodynamic cut-diameter multiply Stokes D_{50} by 1.55 (McCain, et al., 1985).

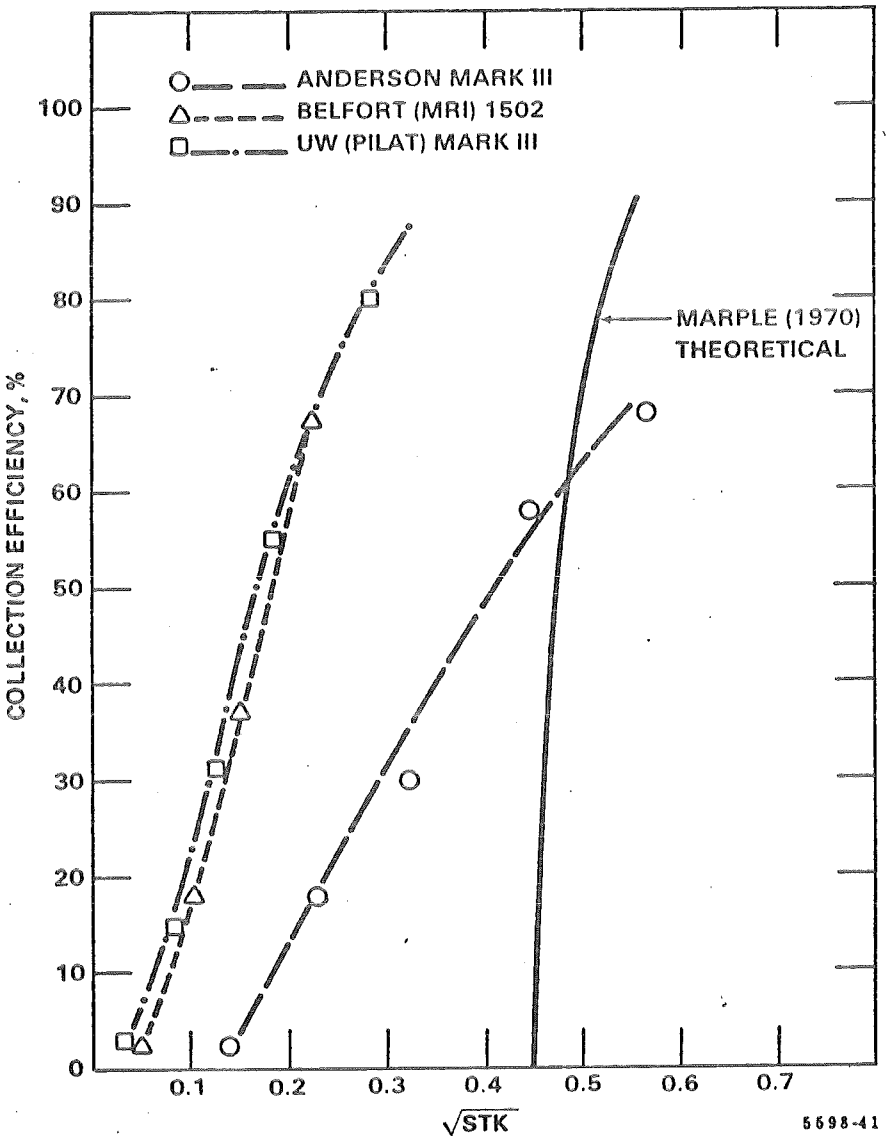


Figure 3-8. Measured first stage collection efficiencies for three commerical impactors compared to Marple's theoretical curve.

Experiments to quantify the effect of particle charge on particle collection in impactors have been carried out using both monodisperse and polydisperse aerosols (Farthing et.al., 1979). A range of charge levels from neutral to levels about five times greater than would be expected on particles exiting an ESP were used in these experiments. The results showed the following:

1. At moderate charge levels there was no shift in stage D_{50}'s.

2. At high charge levels (5x typical ESP exit charges) there were large effects, primarily in the form of increased wall losses.

3. Grounding the impactor and collection surfaces made the effect of charge greater.

4. The measured size distributions of the same polydisperse aerosol with neutral particles and with moderate charge (comparable to ESP exit charges) were virtually identical.

5. The measured size distributions of polydisperse aerosols showed apparently higher concentrations of large particles and correspondingly reduced concentrations of small particles than the true distribution when the particles were highly charged.

Examples of the effects of particle charge are shown in Figures 3-9, 3-10, and 3-11.

In conclusion, particle charge is not believed to cause serious errors in cascade impactor data under the conditions which might be expected to be found in sampling industrial sources, although errors can be expected if charge levels a great deal higher than those encountered at ESP outlets are met.

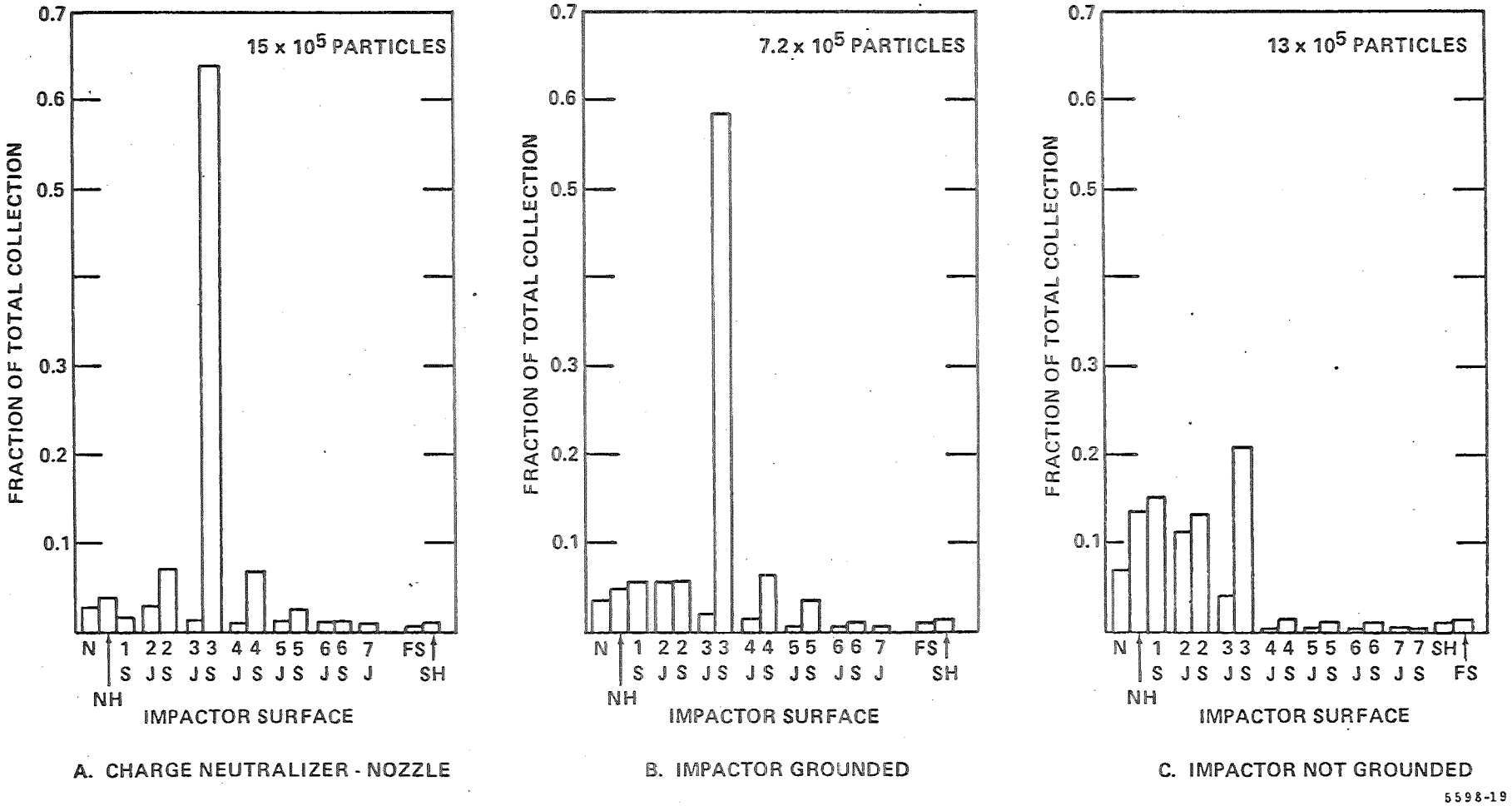


Figure 3-9. Sampling 5.2 μm charged particles using U. of W. Mark III Impactor. Comparison of sampling with charge-neutralized particles, high particle charge with grounding wire on impactor, high particle charge with no grounding wire or impactor (Farthing et al., 1979).

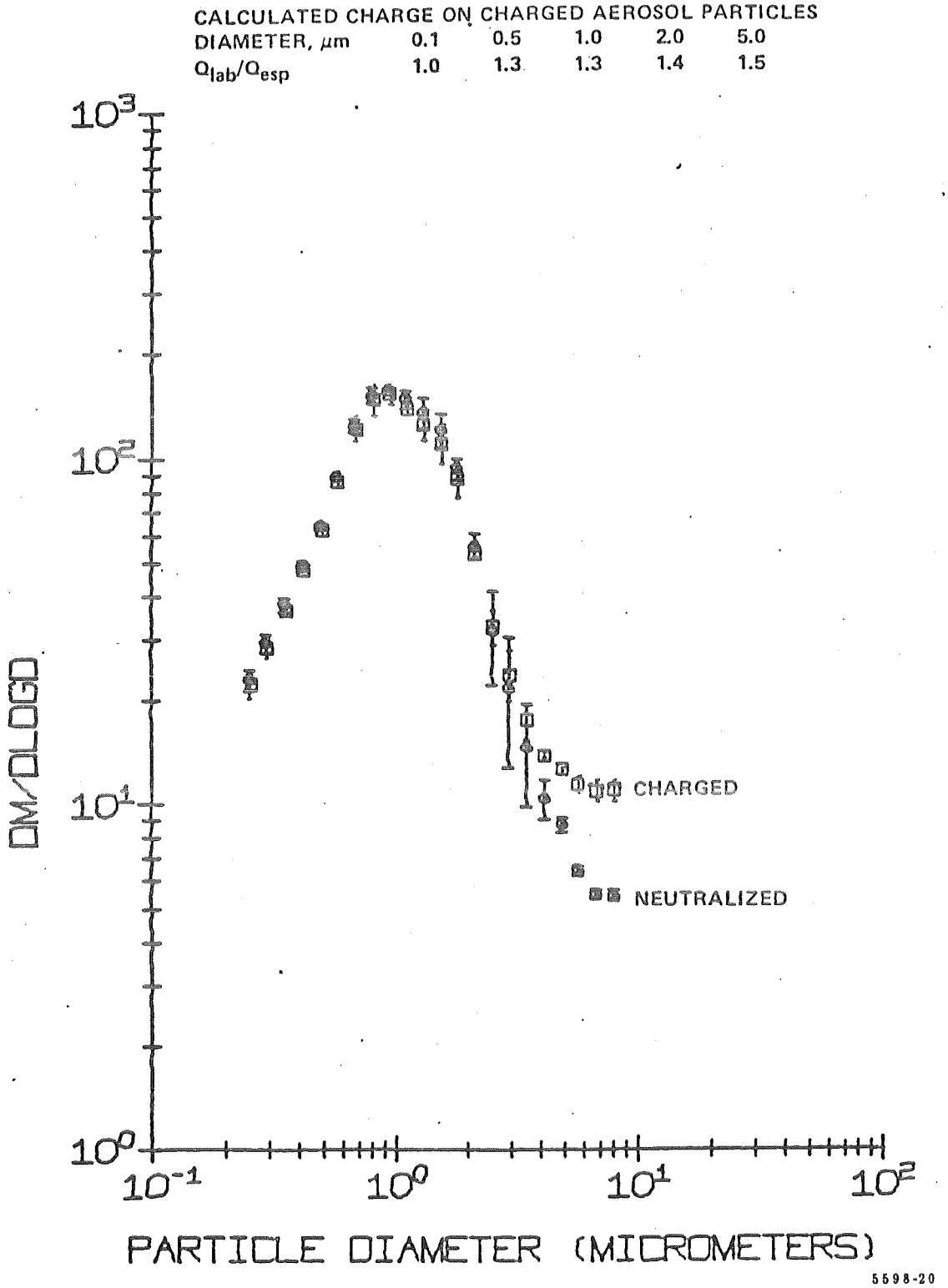


Figure 3-10. Particle size distribution for moderate charging condition for a mass median diameter of 1.02 micrometers (Farthing et al., 1979).

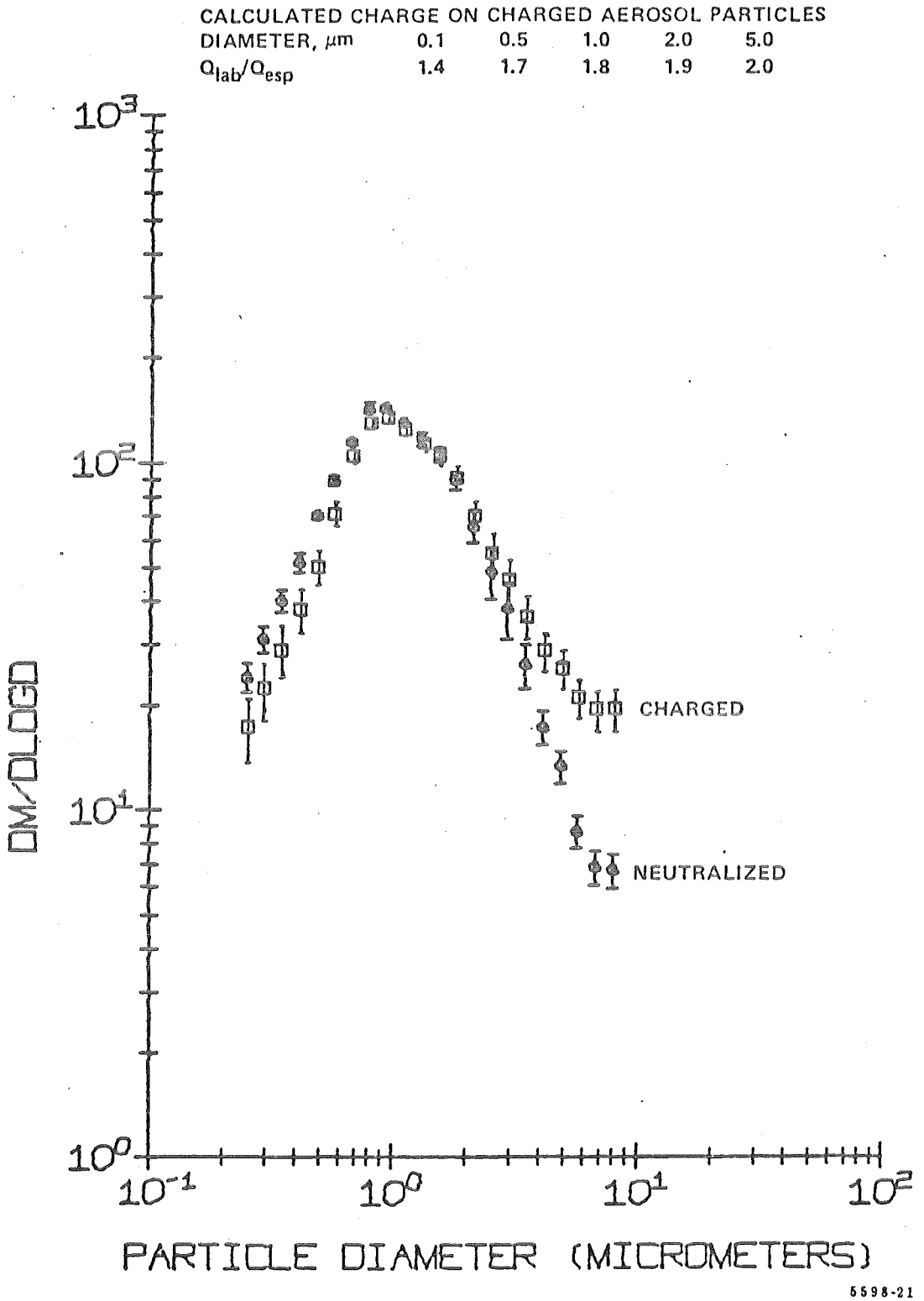


Figure 3-11. Particle size distribution for high charging conditions for a mass median diameter of 1.01 micrometers (Farthing, et al., 1979).

SECTION 4.

FIELD PROTOCOL

4.1 Introduction

The following paragraphs provide step by step instructions for the determination of particle size distributions at stationary industrial sources by using cascade impactors. This protocol may be used for any of the cascade impactors listed in Appendix B (Commercially Available Hardware) within the stated operational limitations for the respective impactors as given in the appendix. The Pollution Control Systems (University of Washington) Mark V Cascade Impactor with right angle precollector was recommended to ARB as the preferred instrumentation for the Size Distribution Method and this Protocol is specifically aimed at the special features of that device. Little modification is needed to adapt the protocol to the other instrumentation listed in the appendix and where such adaptation is necessary appropriate comments have been included. Selection of the preferred instrumentation has been described in detail in the project final report in a section entitled "Equipment Selection for ARB Particle Sizing Methods (Stationary Source PM_{10} Method, Size Distribution Method, and Sized Chemical Sample Method)". Appendix A documents computer programs that perform all the calculations associated with the operation of cascade impactors and the analysis of the data obtained, and provide graphical presentations of the data (particle size distributions of grouped data and control device fractional efficiencies). The complete algorithms used in the analysis of impactor data are described in Section 5 (Data Reduction and Analysis Procedures) and herein the protocol makes reference to Section 5 rather than repeat that documentation. Where the equations are more straight forward and do not involve iterative techniques or laborious spline curve fitting techniques, the equations are given in the protocol so that they can be performed by hand calculation if desired. Quality Control procedures have been integrated into the Protocol and are summarized in Section 6 (Quality Assurance/Quality Control).

Inlet and Outlet Sampling Situations:

Most industrial sources utilize a control device to remove particulate matter from the sample stream before discharge to the atmosphere. Sampling at points upstream of the control device is frequently referred to as the inlet sampling environment and sampling at points downstream of the control device is referred to as the outlet sampling environment. With today's high efficiency control devices, collection efficiencies of 99.9% are common. At such a facility the particulate concentration at the outlet is $^{1}/_{10}$ of one percent of that at the inlet, a difference of 1,000 to 1. Differences of 10,000 to 1 are not uncommon. As one might suspect this can pose a formidable problem when the

same sampler is to be used for both sampling environments. The same 50% collection diameters are desired for both environments, so the impactor flow rate must be approximately the same if the same stages are used. Consequently the only remaining control variables that can be adjusted to obtain the same D_{50} for both environments are stage weight gains (loadings) and the run time (θ). If any one of the stages of the impactor overloads, particulate matter is transferred down to lower stages (reentrainment) causing the data to be invalidated. The dynamic range between minimum stage loading which can be reliably measured (weight change 0.2 mg) and the maximum stage loading prior to reentrainment occurring (about 15 mg, dependent on aerosol characteristics, jet velocities, and substrate material) is at best about 75 to 1. This leaves only the run time as the adjusting factor. If a five minute run time at the inlet of a high efficiency control device (99.99%) resulted in weight gains of less than 15 mg on the most heavily loaded stage, outlet run times would need to be 667 min (11.1 hours) to obtain a weight gain of 0.2 mg on the most heavily loaded stage. Note that this would lead to unreliable weights for all other stages. Most impactors have been designed to require a sample time of about two hours on high efficiency control devices. Consequently the same impactor would commonly overload in less than one minute at the inlet to this same control device. For this reason, some impactors have been designed for inlet situations by using stages which give the desired D_{50} at lower flow rates. The need to sample isokinetically together with a practical minimum nozzle diameter of about 1/8 to 1/16 inch, places a lower limit on the impactor flow rate. These low flow rate impactors would require very very long run times if used at the outlet of a high efficiency control device. One solution is to use different impactors, another solution is to use an impactor with multiple stages, some of which will be used for inlet situations (low sampling flowrate) and others which may be used to give the same D_{50}'s for outlet sampling situations (high sampling flowrate). The preferred impactor is one which will permit the selection of stages to obtain the desired D_{50}'s at either high flow rates or low flow rates. Where differences between inlet sampling and outlet sampling procedures occur they will be identified as such in this protocol.

4.2 Measurement Principle and Applicability

This protocol addresses the application of cascade impactors to industrial source sampling situations. Cascade impactors use the principle of inertial separation to size segregate particles sampled from a particulate laden gas stream. Particles are collected on various substrates through the impactor by virtue of their size. The amounts of collected particulate are then quantified gravimetrically by measurement of substrate weight changes. The technique is valid when the equipment configuration, operational flow rate, and total gas volume sampled are properly selected such that measurable quantities are collected (without overloading) and operational regime limits for Reynolds number and jet velocities are observed. Skilled operators are needed for proper operation of cascade impactors and for carrying out the subsequent analysis of the data. This protocol attempts to set forth procedures which are workable and valid for most commonly encountered sampling situations but it is impossible to address all possible sampling situations. Consequently these procedures are to be considered as recommendations rather than compliance procedures. The skill, experience, and judgment of the user are still important factors in the successful application of the method.

4.3 Apparatus

The following paragraphs describe the apparatus used with cascade impactors.

4.3.1 Sampling Train

A schematic of the sampling train is shown in Figure 4-1. The right angle precollector and cascade impactor are mounted on the modified probe of a standard Method 5 sampling train. The pitot head normally used on a standard Method 5 sampling train is not used with impactors. The flow metering orifice on the dry gas meter may need to be changed to an appropriate size for the desired impactor flow rate. Since the impactor is operated in-situ, the filter/oven section of the Method 5 train is not used. This is analogous to using Method 5 sampling equipment to run Method 17 Emission Tests. The reader is referred to U.S.E.P.A. publication APTD-0581 (Construction Details of Isokinetic Source - Sampling Equipment) (Martin, 1971) for a more detailed equipment description. All in-situ components should be constructed of stainless steel for purposes of temperature tolerance, ruggedness, and resistance to corrosive flue gases. High temperature heating tapes permit the same probe to be used in hot side (>400°F) as well as cold side sampling situations. Method 5 Sampling Trains are available from numerous commercial vendors. The following paragraphs describe the various components of the sampling train.

4.3.1.A Right Angle Precollector

In most situations the use of a right angle precollector is essential. The precollector serves to (1) turn the sample stream through a 90° angle and (2) help prevent overloading of first impactor stage. If the port arrangement is such that the impactor can be rotated into flow and the loading and size distribution of the sample stream does not cause overloading problems with the first impactor stage, then the precollector is not necessary. Such is seldom the case, however.

Most industrial sources only have four inch diameter sampling ports and use thick, insulated walls so that clearance is not adequate to permit rotation of the impactor into the flow stream. The curved nozzles (90° Bend and Buttonhook) used with Methods 5 and 17 are unacceptable for use with particle sizing devices because of high particulate losses in the nozzle. At moderate to high duct velocities it is quite possible for such a nozzle to have a 50% collection efficiency diameter, D_{50}, smaller than the D_{50}'s of the first several stages of the impactor with which they are used (see Section 3).

At most sources the mass is concentrated in the larger particles thus overloading of the first stage may occur before minimum detectable weights are obtained on some of the lower stages. The capacity of the upper stage needs to be increased to permit collection of weighable quantities at the lower stages. The precollector provides a means of accomplishing this.

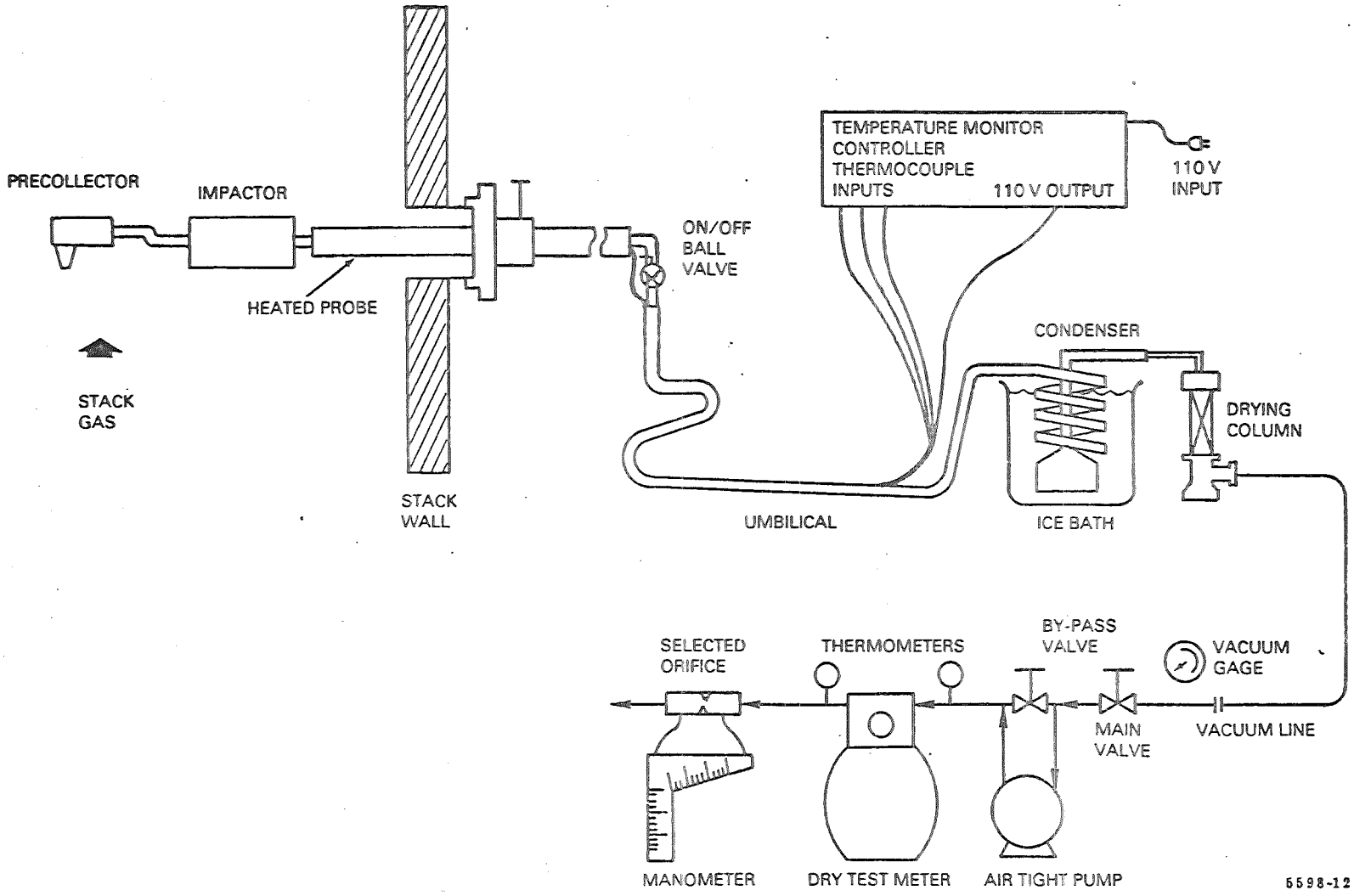


Figure 4-1. Cascade Impactor particulate sampling train for noncondensible particulate (modified EPA Method 5 Train).

The right angle precollector is separate from the impactor and as such can be attached to almost any impactor which is operable at a compatible flow rate. The Zoltec Brink Model C Cascade Impactor has a built-in cyclone that serves as a right angle precollector to this low flow rate sampler. The Brink is especially designed for inlet sampling situations.

4.3.1.B Nozzles

When attached to the right angle precollector, the nozzle should not inhibit entry through a four inch diameter port. However, if the impactor can be rotated into flow it may not be necessary to use a precollector. As discussed earlier, the curved nozzles (90° Bend and Buttonhook) used with Methods 5 and 17 are unacceptable for use with particle sizing devices because of high particulate losses in the nozzle. The nozzles should have a sharp leading edge. The inside of the nozzle should have an even taper from the inlet diameter to a correct exit diameter for the particular precollector. It is important that all nozzles have the same exit diameter since this is one of the critical dimensions in the aerodynamic performance of the precollector (inlet jet diameter).

A range of nozzle sizes is needed for isokinetic sampling. The recommended range is from 1/8 to 1/2 inch (3.2 to 12.7 mm) diameter in increments of 1/16 inch (1.6 mm). For inlet sampling with a low flow rate impactor, it may be necessary to use smaller diameter nozzles and smaller increments in nozzle diameter. Problems with nozzle pluggage establish a minimum diameter of about 0.0550 inches (1.4 mm, wire gauge drill size No. 54). Note that a 1400 µm particle will plug this nozzle. Because of the high probability of a nozzle being damaged while the impactor is being inserted and removed from the sampling ports it is recommended that at least one spare set of calibrated nozzles be on hand for quick replacement. Nozzles should be calibrated as described in Section 4.6.2 (Calibration: Precollector Nozzle). Emergency field repairs can be made using a sharp round tapered metal tool such as an awl or a scribe. Care should be taken to avoid flaring the thin metal edges of the nozzle when performing the emergency repair. Repaired nozzles must be so noted in equipment log books and recalibrated before use. A Dial Caliper (0.001 inch) as described in Section 4.6.2 should be on hand for this calibration.

4.3.1.C Cascade Impactor

Appendix B gives a list of current commercially available cascade impactors suitable for use as in-situ stack samplers. All of these impactors are designed with an internal filter holder. The calibration of the impactor type used must have been verified as described in Section 4.6.9 (Impactor Stage Calibration Constants) for the configuration to be used (choice of substrate material and stages used). The Pollution Control Systems (University of Washington) Mark V Cascade Impactor is the ARB preferred instrumentation, together with an accessory right angle precollector and nozzle set (EPA/SoRI design). The Mark V impactor is of an in-line design permitting the user to choose appropriate stages for a given sampling situation (inlet, outlet, stack velocity, temperature, etc.). The right angle precollector's connecting tube serves as a single jet first stage (zero stage) for the impactor and uses a

solid disk-shaped collection substrate rather than the donut-shaped collection substrates used with the multi-jet stages. The impactor design requires that the solid disk must be used to direct the air flow to the subsequent multi-jet stages. Up to ten of these multi-jet stages may be selected as desired from the twelve multi-jet stages furnished with the Mark V (i.e. we have two extra jet plates). Spacers may be used to permit operation with fewer than eleven stages. The preferred configuration is to use the single jet inlet followed by six multi-jet stages with one disk-shaped collection plate, seven donut-shaped collection plates respectively and two filters. The second filter serves as a quality control check. The extra donut-shaped collection plate is loaded with the selected substrate material and inserted upside down directly behind the collection plate of the last stage. This extra substrate is out of the gas flow path and thus never subjected to particulate matter. It serves as a quality control blank for the individual run and quantifies handling losses, balance changes, flue gas interaction, etc. Spacers may be used in the Mark V shell or a shorter Mark III shell may be used to make the impactor lighter and easier to traverse in and out of small ports with long probes. Viton o-rings and Teflon inserts (at the filter) are normally used with this impactor. For high temperature applications metal o-rings and Kapton inserts may be substituted for the Viton and Teflon.

A filter holder and filter is needed to perform the "Blank Impactor Run" described in Section 4.5.3.B. The filter is attached to the impactor inlet in place of the precollector and prevents particulate from entering the impactor, thus providing a quantitative measure of substrate flue gas interactions. Method 17, Section 2.1.2 describes a suitable filter. Nozzles are not required. Filter sizes commonly used are 47 mm or 63 mm.

4.3.1.D Pitot Tube

A pitot tube may be used as part of the sampling train if desired but is not required. Velocity profile information is obtained prior to the sampling run by performing a velocity traverse as per Method 2. The sampling flow rate, nozzle, and sampling points are selected based on this velocity traverse.

4.3.1.E Sampling Probe and Umbilical Lines

The sampling probe and umbilical lines are the same as those for a Method 5 Train as described by Martin (1971). The internal tubing of the probe should be stainless steel. The probe should be heated and if an external jacket is used the jacket may be constructed of aluminum for weight purposes. The probe length should be sufficient to reach all traverse points. Generally, at least two separate probes need to be on hand, one 8 foot length for the most frequently encountered sampling situations and a second, longer, probe (12 foot or longer) for unusual ducts where the 8 foot probe is not long enough to reach all of the traverse points. The long probes are very difficult to handle and are thus undesirable for general use. An umbilical cord is used to connect the probe to the condensers and metering/control system. Experience has shown that it can be advantageous to have a large ball valve mounted at 90° to the out-of-stack end of the probe immediately upstream of the umbilical attachment. As explained in Section 4.5.3.D.4 (Leak Check Procedures) this can reduce the

turnaround time between runs and even permit one to untangle sampling line when multiple units are operating at the same location in congested sampling areas.

The umbilical connects the probe to the condensers and metering/control system. It is often subjected to harsh treatment from sharp objects, hot metal, the feet of people in a congested area, and the strain of its own weight at the end of the sampling probe. It is best if all lines are bundled together and protected by an external sheath. The umbilical provides connections for the thermocouple stack temperature sensor, probe heater power and temperature control thermocouple as well as the sample line itself. If instack heating of the impactor is required, the umbilical must provide power and a temperature control thermocouple for the impactor heater. In very cold, windy weather, condensed water can freeze in the umbilical, shutting off flow to the impactor. In such cases measures must be taken to insulate and heat the umbilical itself.

4.3.1.F Condenser

The impinger system described in Method 5 may be used to remove the moisture from the sample stream and to determine the moisture content of the stack gas. Alternatively, any system that allows measurement of both the water condensed and the moisture leaving the condenser, each to within 1 mL or 1 g may be used. The moisture leaving the condenser can be measured either by (1) monitoring the temperature and pressure at the exit of the condenser and using Dalton's law of partial pressures; or (2) passing the sample gas stream through a silica gel trap with exit gases kept below 20°C (68°F) and determining the weight gain gravimetrically.

If means other than silica gel are used to determine the amount of moisture leaving the condenser, it is recommended that silica gel still be used between the condenser system and pump to prevent moisture condensation in the pump and metering devices and to avoid the need to make corrections for moisture in the metered volume. When sampling high particulate concentration gas streams, the condensers/impingers may not be needed because of the small amount of gas sampled. In such cases the silica gel drying column is usually sufficient by itself to protect the pump and metering devices. If the gas volume sampled is small, independent measurement of the moisture content may be required.

The standard Method 5 glass impingers may be used or a stainless steel condenser and plexiglass silica gel holder may be used. The stainless steel condenser is subject to corrosive action by condensed acids from the stack gases and is frequently found to be the cause of a failed leak test. Such a leak may manifest itself as abnormally high moisture content readings.

4.3.1.G Metering System

The metering system is the same as that for a Method 5 Sampling Train with the exception that in sampling situations requiring low impactor flow rates it may be necessary to use a smaller orifice than the standard 0.180 inch ID orifice. Construction of such smaller orifices is the same as for the standard Method 5 orifice except that a smaller diameter (e.g. 0.130, 0.093, and 0.059

in. i.D.) is used to obtain a higher pressure drop reading for the lower flows. These orifices should be calibrated as described in Section 4.6.4.

Inlets: The 0.059 inch I.D. orifice is used for low flow inlet impactor runs. The nominal flow rate for the Zoltec Brink Cascade Impactor is 0.03 cfm resulting in a ΔH value of approximately 0.4 inches on the 0.059 inch ID orifice. The dry gas meter in a Method 5 Meter Box registers 1/10 ft^3/revolution and has a rated flow capacity of approximately 130 CFH (2.17 cfm). Most diaphram type dry gas meters are cited at about 99% accuracy down to 1% of the rated capacity (i.e. 0.02 cfm). The 0.03 cfm of the Brink is above this limit but it is important that any dry gas meter used for these low flows be calibrated specifically for this flow range (i.e. low flow Y). A quality control check is to calculate the total sample volume by using the average actual ΔH and the total run time θ, then compare this to the dry gas meter reading. A second potential problem when using the 0.059 orifice is possible partial pluggage by excess pump oil. This should be monitored closely. Empty the oil trap on the pump exhaust and visually inspect the orifice before and after each run.

The metering system is described in detail by Martin (1971). Some of the major components are discussed below. A four cfm oil-lubricated pump is used with a recirculating loop control valve arrangement for flow control. Most oil-lubricated pumps will meet the leak test criteria when warm but may not satisfy the criteria before the oil warms up. For this reason it is recommended that the pump be running with the flow control valve in the closed position while the train is being serviced (impactor mounted to the probe, new condensers and silica gel are being connected into the system, etc.). By observing the dial on the dry gas meter one can tell when the pump is sufficiently warm and the metering system (with Flow Valve closed) meets the leak test criteria.

EPA approved Method 5 metering systems are available from many different vendors. To meet the ARB 50 lb. single component weight limit the metering system should be designed so that the pump is detachable from the main unit.

The dry gas meter should be capable of measuring volumes to within 2% of true volume.

The metering system also contains differential pressure meters for monitoring (1) orifice ΔH, (2) velocity pitot Δp, and (3) stack differential pressure. These meters must be leveled, leak checked and zeroed as per Section 4.5.3.D.3 and must be calibrated as described in Section 4.6.5.

Temperature measuring systems and temperature controllers should be calibrated as per Section 4.6.6. Temperatures should be determined to within 3°C (5.4°F) of actual. (See also Method 2, Section 2.3).

In some situations where the pump will not pass a leak test or where very low flow rates are required, it may be necessary to modify the connecting lines so that the dry gas meter and orifice are on the negative pressure side of the pump. Doing so gives the advantage that any pump leaks become

inconsequential and lower flows may be obtained with the same pump without necessitating the substitution of a lower flow capacity pump. The disadvantage is that the pressure at the dry gas meter changes throughout the run as the impactor backup filter loads, thus a cubic foot measured at the beginning of the run is different from a cubic foot measured at the end of the run. Likewise, we must refer to a table of ΔH versus vacuum gauge reading rather than a single target ΔH value because the flow rate at the orifice depends on both ΔH and absolute pressure (ambient pressure minus gauge pressure). For these reasons, negative pressure configurations should be avoided when possible. The table of ΔH versus vacuum gauge values needed for such an arrangement is provided by the set up programs given in Appendix A. For a vacuum gauge reading equal to zero the corresponding ΔH value is the normal Target ΔH value given by Equation 4-40. The negative pressure configuration is defined as follows: vacuum gauge, orifice, dry gas meter, main valve, then pump with one leg of the by-pass valve and the exhaust side of the pump open to ambient. Special hardware is often required to connect the exhaust side of the orifice to the inlet of the dry gas meter. When configured in this manner the vacuum gauge allows one to determine the absolute pressure at the orifice and the dry gas meter, and the by-pass valve becomes an adjustable inleak for pump flow control. The amount of air being pulled through the sampler is controlled by the main valve and the in-bleed (by-pass). Closing down on the in-bleed increases the sample flow for any given setting of the main valve. When negative pressure configurations are used the dry gas meter indication of actual sample volume must be corrected to compensate for the pressure change occurring during the course of the run.

4.3.1.H Barometer

A Mercury, aneroid, or other barometer capable of measuring atmospheric pressure to within 2.5 mm Hg (0.1 in.Hg) may be used. In many cases, the barometric reading may be obtained from a nearby national weather service station, in which case the station value (which should be the absolute barometric pressure, not corrected to sea level) shall be requested and an adjustment for elevation differences between the weather station and sampling point shall be applied at a rate of minus 2.5 mm Hg (0.1 in.Hg) per 30 m (100 ft) elevation increase.

4.3.1.I Gas Density Determination Equipment

Temperature sensor and pressure gauges, are described in Sections 2.3 and 2.4 of Method 2, and gas analysis equipment is described in Method 3.

4.3.1.J Safety Equipment

The sampling location often poses many safety hazards. The following items are frequently needed but may well depend on the particular circumstances at a given sampling location. A portable fire extinguisher and first-aid kit are often needed at remote locations such as smoke stacks where such equipment is not normally readily available. Sheet plywood is often cut and used in the immediate work area to prevent hand tools, etc. from falling through open metal grating. A screwdriver falling sixty feet could seriously injure a worker below. Safety ropes, flags, and signs (Danger Falling Objects, Men Working

Above) should close off any areas immediately below a sampling platform. If sampling is performed after dark, portable trouble lights may be needed to illuminate the sampling area and access stairs or ladders commonly used to travel from the sampling platform to the laboratory area. Temporary guard rails may need to be installed at the sampling platform and tarps may be desirable for protection from the rain, wind, and sun. If testing is performed in the rain all circuits should be protected by Ground Fault Interrupter (GFI) circuits. Electrical storms can be especially dangerous since tall smoke stacks attract lightning. Two-way radios are desirable in any situation and are essential in some, such as when an elevator is used to access a sampling platform on a smoke stack. Were the elevator to break or a person be injured on the stack, the radio could be used to call for help. If there is a plant paging phone at the sampling area it should be tested to be sure it is in working order. Many plants provide two-way radios and require that anyone going to the stack check in and out with the control room. A safety check list is given in Appendix C.

Personal safety items would include hard hat, hearing protection, safety glasses, goggles, and steel-toed boots. Leather gloves are needed to prevent burns and cuts and insulated gloves are desirable for handling hot probes and impactors. Rain suits and insulated cold weather gear are often needed. In some situations respiratory equipment (gas masks) may be necessary for control of particulate and SO_2 and in other situations a safety harness and ropes may be called for. Sometimes the test plan requires that sampling be performed at top entry ports on hot metal ductwork. In such situations, it may be necessary to provide some form of nonflammable insulator between the test crew and the hot ductwork. Wooden pallets are not usually acceptable for this purpose. Additional specialty safety equipment may be called for in particular situations.

4.3.1.K Other Support Items

A Method 2 Pitot Probe is used to perform velocity traverses. This equipment is described in Method 2. Additional equipment might include ropes and pulleys for hoisting long probes and meter boxes to and from the sampling platform, long extension cords for bringing additional electrical power to the sampling area, and tarps to cover equipment for protection from rain and snow. Elastic bungie cords and spring clamps are convenient for securing the tarps. Covering equipment at night provides rain protection and can discourage pilferage. Chains for locking tool boxes to metal grating also help discourage pilferage. Polyethylene Shipping Containers seal watertight and can provide protection from rain as well as unitize and protect equipment during shipment.

In very cold weather propane heaters are very welcome and heater tapes with insulation may be needed to prevent condensate from freezing in the umbilicals.

An ultrasonic cleaner and cleaning solution should be used to clean the nozzles and jet plates prior to the field test. During the field test these items should be visually inspected and recleaned as necessary between runs.

4.3.2 Sample Recovery

Various items are used in the sample recovery process. A polyethylene wash bottle may be used to washdown the nozzle with acetone after cleaning the exterior and dry brushing the larger particles onto the precollector substrate with a small camel hair or nylon bristle brush. Note that acetone should not be stored in polyethylene bottles for longer than one month. A clean nozzle brush is used with the acetone washdown. The nozzle brush should have nylon bristles, a stainless steel wire handle and be properly sized for the probe nozzle. For small nozzles ultrasonic cleaning may be used. If the probe wash is to be evaporated on site glass sample storage containers will not be needed. If post-test evaporation is to be done in the laboratory (where a vented hood is available) the wash should be stored in properly labeled glass sample bottles. These bottles should be chemically resistant, borosilicate glass, 500 mL or 1000 mL, with screw cap liners. The liners should be either rubber-backed Teflon or constructed so as to be leak-free and resistant to chemical attack by acetone. The acetone rinse is then carefully evaporated in a preweighed aluminum evaporation dish placed on a hot plate. Use extreme care as acetone is highly flammable and has a low flash point. A ring stand and funnel are helpful during washdown.

A graduated cylinder (rugged plastic is recommended) is used to measure the volume of water removed during the sample run by the ice bath condenser or impingers. The cylinders should not have graduations larger than 2 mL. This will permit determinations to the nearest 1 mL. The condensers are followed by silica gel drying columns. Gravimetric determinations of water uptake by the silica gel may be made using a lab balance capable of weighing to the nearest $^1/_2$ g or less. The conversion factor 1 g H_2O = 1 mL H_2O is then used to obtain moisture volumes.

Petri dishes (plastic is recommended) are used to protect the substrates. Each petri dish should be clearly labeled with the substrate identification number. Prior to the initial prerun weighings and the postrun weighings the petri dishes are placed in airtight desiccators (plastic food storage containers work well) containing silica gel.

4.3.3 Analysis

Various analytical equipment is needed for the on-site laboratory where the impactors are loaded and unloaded and the substrates are weighed. The most important of these items is the analytical balance. Accurate weighing of the particulate matter collected on the impactor substrates requires a balance having a sensitivity of 0.01 mg or better. Several electrobalances marketed in the United States (Cahn, Mettler, Sartorius, etc.) have the portability and insensitivity to vibration required for field use, as well as weighing chambers and pans large enough to accommodate flat unfolded substrates. Some may require modification if abnormally large substrates are to be weighed. Various items are used with the analytical balance. These include tare weights, Class S standard calibration weights, smooth tweezers for handling the calibration weights, tweezers for handling the substrates, control weights (for QC), thread for securing balance hang downs during transport, static charge neutralizer strips, special large sample pans, and tape for bundling petri dishes with substrates from the same run.

If at all possible, the substrates should be weighed in the on-site laboratory rather than being transporting back to the home laboratory for weighing. The collected particulate matter is laying on an open substrate, protected only by the petri dish. Handling and transporting over long distances can easily cause some material to be spilled over to the petri dish. Because the weight changes are so small (less than 15 mg per stage) any losses during transport can represent a large percentage of the total weight change.

Other on-site lab items include plastic desiccators with silica gel, a triple beam lab balance for determining silica gel drying column weight gains, 50 g Class P calibration weight for this balance, and equipment for leak checking samplers before sending them to the sampling location. High temperature fiberglass tape and permanent markers should be used to label the loaded sampler with its run number and substrate set identifier. Data is recorded on the run sheet bearing these numbers and all prerun calculations (ΔH, etc.) are attached to this sheet. A hygrometer and thermometer are used to determine the relative humidity in the on-site laboratory. The portable barometer described in Section 4.3.1.H may be located in the lab and elevation connections used to obtain the pressure at sampling sites. This barometer can be carried into the control room and checked against control room barometer (provided it reads room pressure and not the pressure at some point in the process).

4.3.3.A Computers and Calculators

If used, the computer would normally be located in the on-site lab. It would be used to perform the prerun calculations using the equations given in Section 4.5.3.D.1 (Preliminary Calculations) and Section 5 (Data Reduction and Analysis Procedures). Operating instructions and documentation for computer programs used to calculate these prerun parameters are given in Appendix A (Computer Programs). The computer programs are written for the Apple II series, or compatible, microcomputer with two disk drives. A "Grappler +" or a similar graphics card is required to obtain graphics hardcopy without program modification. A graphics capable dot matrix printer is used for hard copy output of plotted data.

One option to having the computer on site is to perform the data reduction and analysis post-test in the home laboratory. In this situation D_{50} calculations associated with stage selection could be performed during the test by a crew member in the home lab with telephone inputs from the on-site test crew. Set up calculations could be done with nomograms or programable calculators. Such a situation is workable but cumbersome. The preferred arrangement is to have a computer on site and perform all data reduction and preliminary analysis during the test so that any bad runs can be redone while the test crew is still on-site.

4.3.3.B Supplemental Analysis by Commercial Testing Labs

In order to calculate stage D_{50}s on a Stokes Diameter basis, if the latter are needed, one must determine the average particle density (gm/cm^3). This value is determined from Helium Pycnometer measurements on screened hopper samples. The hopper ash is screened with a No. 60 Sieve (ASTM E 11 Sieve Designation, 250 μm openings) to remove rust, aglomerates, etc. which would not have been captured by the control device but may be found in hopper samples. This type of testing is performed by numerous commercial testing laboratories.

4.3.4 Laboratory Calibration

Calibration procedures are described in Section 4.6. Laboratory calibration equipment used includes a wet test meter for calibration of the dry gas meter and orifice and a reference DGM to determine when recalibration (by wet test meter) is required. Other calibration equipment may be used either pretest in the lab or on-site. These include a precision glass thermometer with ice water bath and hot plate for thermocouple/controller calibration, dial calipers as listed above for nozzle calibrations, mercury barometer, standard pitot or reference pitot, slant tube manometer for magnehelic differential pressure meters, and Class S Calibration Weights for the analytical balance.

4.4 Reagents

Various reagents are used in connection with cascade impactor sampling. These include substrate materials and filters as well as any chemicals used to prepare them, desiccants, water, ice, acetone and stopcock grease. The water is used for priming the condensers and the ice for chilling the condensers in an ice bath. If Method 5 glassware is used in place of the condenser and drying column, acetone-insoluble, heat-stable silicone grease (stopcock grease) may be needed to form an airtight seal at the ground ball and socket joints. Alternate designs which eliminate the ball and socket joints do not require the stopcock grease. Indicating type silica gel (6 to 16 mesh) may be used as a desiccant in the drying column and desiccators. Previously used silica gel may be rejuvenated by heating at 175°C (350°F) for two hours. A change in color indicates that the desiccant has been depleted. Acetone is used for washing down the nozzles, etc. The wash is evaporated and weighed to determine the total amount of particulate present. Consequently the acetone should be reagent grade with no more than 00.001% residue. Acetone should only be stored in glass bottles (or temporarily in polyethylene bottles) since metal containers can greatly increase the residue content. Acetone blanks are run prior to the field test and only acetone with low blank values (≤00.001%) may be used.

The filters and substrate material used depend on the sampling situations and the type of impactor to be used. High temperatures can prohibit the use of greased inserts. High flue gas sulfur levels can cause significant weight changes in the filter due to reactions with flue gas constituents. For these reasons blank impactor runs are mandated as described in Section 4.5.3.B. Selection of substrate materials is discussed in Section 4.5.2.B. In most cases only four to ten impactor runs will be made during a field test. When this is the case one can arrive on site with sufficient quantities of two or

more types of substrates so that if a blank run shows unacceptable weight changes with, for example, greased substrates, preweighed quartz would be on hand for use. If numerous runs are to be performed and it is impractical to have preweighed substrates of multiple types, blanks should be run during the pretest site survey to select the substrate material to be used. Acid washing of fiberglass substrates to minimize reactions with SO_2 is described in Section 4.5.2.B.3 along with a detailed discussion of substrate options. Any filters used should be certified as 99.95% efficient on 0.3 μm dioctyl phthalate smoke particles. This filter test is described in ASTM Standard Method D2986-71. Test data from the supplier's quality control program are sufficient for this purpose.

4.5 Procedures

The following paragraph summarizes the general sequence followed to determine the particle size distribution of an industrial source. Subsequent paragraphs describe each aspect in detail. The initial step in any field test is to define the test objectives. Test objectives can range from relative simple to very complicated, involving the coordinated efforts of several sampling teams. The second step is to develop an initial Test Plan tailored to accomplishing the test objectives at the given test site. Usually these general steps are performed during the funding request process but are continuously refined as decisions are made and more specific information becomes available. The next step is coordination with plant personnel and any other groups or organizations who are to be on-site during the test. Plant access must be obtained, the test date must be coordinated, and either a Pretest Site Survey must be scheduled or the preliminary information listed in Section 4.5.1 must be obtained through dialogue with plant personnel. At this point the Test Plan is revised using the information obtained from the Pretest Survey and Pretest Laboratory Preparation can be scheduled. These preparations would typically include substrate preparation and pretest weighing, equipment preparation and calibrations, and preparation/acquisition of any special equipment identified during the Pretest Survey. Upon arriving on-site the sampling equipment would be assembled at the test site and the on-site lab established after any in-briefings by plant management (tour of Control Room, etc.). Once the equipment is in place and the site prepared (safety equipment erected, ports opened and cleaned, etc.) the velocity distribution and flue gas composition measurements would be performed. Based on this information the traversing strategy, flow rate, nozzle selections, and impactor configuration decisions would be made so as to obtain the desired stage D_{50}'s while sampling at near isokinetic velocities. A blank impactor should be run to verify that flue gas-substrate interactions are acceptable for the substrate material selected and an initial impactor run performed to determine the suitability of the initial guess at sampling flow rate and run time. This initial run is examined and adjustments made to the sample time, flow rate, or stage configuration as appropriate. At this point the preliminaries would be complete and one would be ready to obtain real data. A sufficient number of runs should be performed to obtain the degree of completeness called for in the test plan. Post-test weighings should be performed in the on-site lab and data reduction for the individual runs is generally performed on-site using the computer programs described in Appendix A.

4.5.1 Pretest Site Survey

A pretest site survey is usually advisable but not always necessary. The purpose of the survey is to coordinate with plant personnel and obtain specific information that is important to the planning of an efficient field test. Some coordination and information can be provided by telephone conversations with plant personnel. If reports of previous Particulate Compliance Tests are available, most of the information can be obtained without the need for a pretest site visit. The major question that usually necessitates a site visit relates to substrate-flue gas interactions that can result in unacceptable weight changes. Blank impactor runs (Section 4.5.3.B) must be made to verify the suitability of any given substrate material. The other situation commonly necessitating a pretest site visit is one in which a large crew will be required to conduct the test. It is then cost effective to verify that preparations have been completed before the full crew arrives. Sometimes this can be accomplished by sending a small advance party to open and clean ports, erect scaffolding, connect extra power, etc. In some situations these preparations would be performed by plant personnel upon request, in others they may be performed by test crew personnel (labor union craft restrictions not withstanding).

If only a small number of impactor runs are to be made and these will be done by a two or three man crew, it may be more cost effective to coordinate with the plant personnel by telephone, verify that a sufficient number of four inch or larger ports are available at the required location, and use the first day or so of the field test to open and clean ports, etc. Since only a few impactor runs will be made, it may be practical to have on hand a sufficient number of preweighed substrates of each different type or coating which might be used. The unused substrates would be available for subsequent field tests. One would need sufficient quantities of preweighed grease, and quartz substrates (Section 4.5.2) to complete all required runs with whichever material proved acceptable. If blanks from each of these showed unacceptable weight changes then the fiber glass or quartz substrates could be conditioned in-situ, dessicated, weighed, and then run.

If the test plan calls for coordinated testing with other contractors (compliance test crew, special plant conditions not normally available, etc.) then questions related to these potential problems need to be answered before the first day of coordinated testing. The purpose of any pretest survey is to cost effectively expedite sampling by addressing the Preliminary Determinations listed in Section 4.5.3.A so that either a coordinated test schedule can be maintained or a large expensive test crew won't have to sit around helplessly watching a few people work. The decision to conduct a pretest site visit depends on the particulars of a given test plan. Table C-1 (Preliminary Survey for Particulate Sizing) and Table C-2 (Safety Checklist) in Appendix C are checklists of information to be answered before actual sampling can begin. It is anticipated that the normal situation for ARB would be a two man test crew with two sampling trains performing perhaps eight or nine impactor runs (including blanks and one preliminary run). As such a presite visit would not normally be required since the important information (port suitability, size, type, orientation, particulate loading, etc.) could be obtained through telephone conversations with plant personnel. If a situation

occurred where the two man crew arrived on site only to find that ports needed to be installed, etc. the cost of the initial trip would only be slightly more than that of a presite visit. Generally, the best plan for a small crew is to arrive on site prepared to do the actual test if circumstances permit.

4.5.2 Pretest Laboratory Preparations

Pretest laboratory preparations include equipment maintenance, equipment calibration, and substrate preparation and weighing. As mentioned above, a pretest site survey may or may not be necessary. If one is deemed necessary then the pretest laboratory preparations would focus on the conclusions and recommendations of the site survey. The survey would determine what preliminary work must be performed by both plant personnel and by the field test crew. It should identify situations where special sampling equipment must be prepared such as extra long probes, equipment to heat the impactors in-situ, special port adaptors, and show what kind of substrate materials should be used. The suitability of any given type of substrate material is verified by the blank impactor run (Section 4.5.3.B). If a pretest site visit is not performed then the field test crew must carry sufficient equipment to meet a wide variety of frequently encountered situations and adequate numbers of preweighed substrates of different kinds of material. Equipment calibration procedures are described in Section 4.6. Equipment maintenance, substrate material preparations, backup filters and Analytical Balance Weight Record are discussed in the following paragraphs.

4.5.2.A Equipment Maintenance

The right angle precollector and impactor do not require any special maintenance other than simple cleaning and ultrasonic cleaning of the impactor jet plates (to prevent any buildups that could change the hole sizes). All internal parts must be spotlessly clean before a run so that any particulate on the substrates can accurately be attributed to the stack gases. From time to time it may be necessary to use a laping compound between threaded surfaces to repair rough threads and prevent gauling. Some impactors have silver plating on their threads to prevent gauling. Silver plating is highly recommended for temperatures above 425°F. The threads should be loose and smooth, not tight or rough. Teflon tape may be used to prevent gauling when the temperature is less than 425°F. It should be noted that some liquid base thread lubricants can contaminate the substrates and should be avoided. When needed, use them sparingly. The blank impactor run should reveal problems of this type. When nozzles are damaged they usually require repair by a machine shop. Frequently, this requires being bored out to a larger diameter.

The sampling train itself is a standard Method 5 train and should be maintained as described in APTD-0576. The most common problems are low fluid levels in the pump oiler and condensation in the dry gas meter (DGM). Oil should be replenished and old oil (in the exhaust side trap) discarded. Dry, clean air can be pumped through the DGM by connecting the desiccator and a filter in line and pulling ambient air through the system. This will help purge any buildup of moisture in the DGM. Oil lubricated pumps should not be flushed with chemical solvents. From time to time the vanes may need to be changed. The worst enemy of the sampling system is rain. Water can rust the

electric motor in the pump, short circuit electrical wires and otherwise cause problems. Calibration should reveal any problems with the differential pressure meters. Fluid may need to be added. Damaged pitot heads should be repaired and recalibrated.

The flue gas composition equipment (Orsat analyzer or Fyrite-type combustion gas analyzer) contains corrosive chemicals and should be maintained as directed in the manufacturer's literature.

4.5.2.B Substrate Materials and Preparation

Cascade Impactors use lightweight inserts for the collection plate below each jet stage. These inserts must be light in weight to permit the detection of very small weight changes (0 to 15 mg) and must hold the captured particulate in place. As discussed in Section 3 (Deviations from Theory) particle bounce can present problems. Some aerosols are wet and sticky and can be satisfactorily collected with bare metal inserts, but such is not generally the case. Hence, most aerosols require the use of something to absorb the particle momentum and keep particles from bouncing to surfaces where they don't belong. Various substrate material options are available for this purpose. Each has its advantages and disadvantages. Certain impactor designs, however, exclude or make it difficult to use of some of these options. The main options are bare metal, greased metal, polypropylene coated metal, fiberglass, and quartz. Bare metal is restricted to sticky aerosols that do not exhibit bounce problems.

4.5.2.B.1 Coated Metal Foil

Greased metal foils are generally the preferred substrate choices. Felix et.al. (1977) tested 19 different greases for possible use at typical stack temperatures. Many were found to be unstable at stack temperatures. Some hardened and others flowed too freely. Only one was found to be sufficiently stable at 177°C (350°F), Apiezon H. This particular brand of grease is commonly used in Gas Chromatography (GC) and is available through several laboratory supply vendors. The manufacturer is James G. Biddle Co., Plymouth Meeting, PA 19462. The company offers a second version formulated for temperatures near ambient, Apiezon L (L for low temperature and H for high temperature). Apiezon H was found to be too hard a coating at low temperatures (<125°C) but the L formulation worked well at some sources at these temperatures.

Other greases or polymers have been used successfully under conditions of flue gas composition and temperature which are hostile to Apiezon H. Specifically, low-molecular-weight amorphous polypropylenes have been found to perform well with little weight change in gases containing high levels of sulfur oxides. Unpublished results of research by J.D. McCain at Southern Research Institute showed that Hercules AFAX 800 and 500 (HL1) amorphous polypropylenes have suitable viscosities to be used, respectively, at ambient and stack (up to 165°C) temperatures. Another compound which has been found not to degrade at stack temperatures up to 230°C is Exxon 065 butyl rubber. An additional benefit of these polymers is that they contain sufficiently low levels of trace metals to be used as collection surfaces for samples intended

for elemental analysis by such techniques as Neutron Activation Analysis (NAA).

It is probable that other greases or compounds may perform as well as those mentioned above for particular conditions. In general, any material is suitable if it has the consistency of a tacky fluid at the sampling temperature and if it does not show a significant change in weight or other physical properties due to interaction with the hot flue gases.

The greases are normally applied as suspensions or solutions of 10-20% grease in a solvent. Toluene is a suitable solvent for Apiezon H and L. Cyclohexane has been used for the polypropylene and butyl rubber polymers. The mixture is placed on the cut foil substrate with a brush or medicine dropper, or sprayed onto the foil with an air brush. Approximately the same amount of coating (same number of drops) should be applied to each substrate. This can be very significant in situations where a flue gas interaction is occurring. The reproducibility of any weight changes is discussed in Section 4.7.17, but different amounts of coating on different substrates can prevent weight change from being uniform. The coated foil is baked at 150°C (300°F) for 1 to 2 hours and then dried 12-14 hours over Silica Gel in a desiccator at ambient temperature prior to weighing. It is important to avoid an excess of grease. Too much grease, or one with too low a viscosity, causes "blow off" problems—the physical removal, spreading, or creep, of the grease off the impactor stage. The dry greased surface of the substrate should be tacky, but not slippery, with a film thickness equal to or greater than the diameter of the particles which are to be captured. Typically, the amount of grease on a suitably coated substrate will be about 10 to 25 milligrams.

4.5.2.B.2 Fiber Mats

Glass or quartz fiber mats are used routinely in some commercial impactors and in all impactors for sampling at temperatures above the limits of greases. In addition to providing a light-weight impaction surface, such fiber mats reduce reentrainment due to particle bounce. As mentioned in Section 3, fibrous substrates have different collection characteristics from those of flat surfaces, so calibrations performed with fiber mats must be used for reduction of data taken with fiber mat substrates.

Glass fiber mats and in some instances, quartz mats, cut to the required shape can usually be obtained from the impactor manufacturer. Mats of other fibers can usually be cut to shape upon request to the manufacturer, if the mats are sent to him. In particular, quartz fiber mats may be preferable for substrates for use at higher temperatures or where sulfur oxides are a problem, as mentioned below. The quartz mats must be handled carefully to avoid loss of fibers.

In hot gases containing sulfur oxides, glass fiber mats often exhibit anomalous gains in weight due to reaction with sulfur oxides and the formation of sulfates. After extensive laboratory and field experiments on a number of glass fiber mats (Felix et al., 1977; Cushing, 1978; Peters and Adams, 1978), the only mats that have to date been found suitable for use as impactor substrates are Whatman 934AH (formerly Reeve Angel 934AH) and Schleicher and

Schuell No. 30. Both are available from Whatman, Inc., 9 Bridewell Place, Clifton, NJ 07014. When these materials are treated with sulfuric acid by the procedure outlined below, gains in weight caused by reaction with flue gas constituents can be kept acceptably low. Glass fiber backup filters exhibit the same behavior and should be treated in the same manner.

In the studies mentioned above, quartz fibers were found to have negligible weight changes in the presence of sulfur oxides, but most pure quartz fiber mats were also found to be too fragile for use as substrates. Since the time of these studies, Pallflex 2500 QAST quartz fiber filters have been introduced. While still more fragile than glass fiber mats, these quartz mats have proven to be sufficiently strong for use as substrates for several impactors. As appears general for quartz fiber materials, 2500 QAST mats were found to exhibit low blank weight gains at stack conditions, even without the acid washing treatments recommended below for glass fiber mats. These limited results suggest that the Pallflex 2500 QAST quartz fibers should be considered when the use of a fibrous mat substrate or filter is indicated. However, it should be noted that quartz fiber mat substrates are not generally available from impactor manufacturers, and the mats may not be suitable for all impactors. For example, quartz fiber mats would probably not be strong enough to be cut for Andersen Mark III substrates.

4.5.2.B.3 Procedure for Acid-Washing Glass Fiber Mats

1. The mats should be submerged in a 1:1 mixture (by volume) of distilled water and reagent-grade concentrated sulfuric acid at 100-115°C (210-240°F). Maintain the mixture at this temperature for 2 hours. This operation should be conducted in a fume hood using clean glassware and a temperature controlled laboratory hot plate. If the fiber mats need to be weighted down to keep them submerged in the acid bath, Teflon disks may be placed on the top and bottom of the stack and a glass or Teflon weight placed on top of this disk.

2. After removing the mats from the acid bath, they should be allowed to cool to room temperature and then be placed in a bath of distilled water and rinsed continuously with a water flow of 10-20 mL/min. until the pH value of the rinse water, after a few minutes in contact with the mats, is nearly the same as that of distilled water. The importance of thorough washing cannot be over-emphasized.

3. After rinsing in the distilled water, the mats should be rinsed in reagent-grade 2-propanol (isopropanol, isopropyl alcohol) by submerging them for several minutes. Repeat this step four or five times using fresh 2-propanol each time.

4. Allow the mats to drain and dry. After they are dry enough to handle, spread them out in a clean place to dry.

5. When the mats are dry to the touch, they should be baked in a laboratory oven at 100°C (212°F) for about 2 hours, to vaporize residual water and alcohol, then raise the oven temperature to 370°C (700°F) for 3 hours. This vaporizes any residual sulfuric acid. The mats may become discolored unless the water and alcohol are driven off prior to vaporizing the sulfuric acid.

6. To verify that the acid has been removed, one can tear two mats into small pieces, immerse them in about 50 mL of distilled water, stir the water for about 10 minutes and measure the pH with a meter. If the pH is significantly lower than that of the distilled water, the remaining mats may be baked at 370°C (700°F) for several additional hours to remove any residual acid. The 370°C (700°F) temperature is necessary because of the high boiling point of sulfuric acid, 340°C (640°F).

4.5.2.B.4 Procedure for In-situ Conditioning of Acid Washed Glass Fiber Mats

Even after being washed with sulfuric acid, glass fiber mats have still shown anomalously high gains in weight in some process streams, particularly those at extremely high temperatures and those containing relatively large concentra- tions of sulfur oxides. If blank runs with acid-washed substrates reveal problems, they can be minimized by conditioning the glass fiber mats in the process gas stream prior to use. Place the mats, loosely packed, in a suitable container preceded by a filter; insert the container into the gas stream, and draw filtered flue gas through the container for 6-24 hours before the initial desiccation and weighing. Blanks should be run with these in-situ conditioned and washed glass fiber mats. These will be used to verify the magnitude and reproducibility of any remaining weight changes.

4.5.2.C Backup Filters

Backup filters are used on all impactors to collect the material that passes the last impactor stage. Binderless glass fiber filter mats are normally used for this purpose in all impactors, although the shape and size of the filter varies according to the impactor design.

Glass fiber backup filters have the same reactivity problems as glass fiber impaction substrates and may also require acid washing or conditioning. Quartz fiber filters should not require this treatment, and are available in many standard sizes. At temperatures below 150°C, Teflon fiber or membrane on fiber filters have also been found to perform well. Teflon inserts (washers) may be used to prevent the filter from sticking to the metal surfaces and a foil pouch is used to prevent the loss of particulate collected on the filter. In high temperature situations where Teflon is unacceptable, Kapton inserts may be substituted. A second filter is frequently used as a quality assurance check as described in the latter part of Section 4.5.3.D.2 (Preparation of the Cascade Impactor).

4.5.2.D Weight Records

A normal part of the pretest laboratory preparations is to both prepare the substrates to be used during the test and then obtain their dry prerun weights. This weighing function may be performed on-site if desired but is generally performed before hand so that the on-site time can be more effectively utilized. Calibration procedures and control weights are used to insure that no errors are introduced by moving the weighing laboratory between

weighings (pre and post). The balance procedures and weight records used are described in Section 4.5.3.H (on-site procedures) because the postrun desiccation and weighing should be done on-site to avoid particulate losses from occurring during transport back to the home laboratory.

4.5.3 On-site Procedures

The following paragraphs describe the procedures that must be performed on-site in order to characterize the particle size distribution of a stationary industrial source using cascade impactors. Some of the functions may be performed during a pretest site visit and some may be performed prior to the test in the home laboratory rather than on-site. The first section describes preliminary determinations that must be made or at least estimated prior to making the initial impactor run and the blank impactor run. Other sections describe flow rate calculations, leak check procedures, operation and data recording procedures, sample recovery and inspection, weighing procedures and quality assurance/quality control. Calibrations and calculations are discussed in Section 4.6 and 4.7 respectively.

4.5.3.A Preliminary Determinations

Table C-1 (Preliminary Survey for Particulate Sizing) and Table C-2 (Safety Checklist) list preliminary information that is needed prior to any field test. In situations where a Pretest Site Survey is performed (as described in Section 4.5.1) most of this information would be obtained at that time. As described in Section 4.5.1, however, the normal situation would not require that a pretest site survey be conducted since most testing would be performed with a small 2 or 3 man crew at a familiar site. Most of the information in Table C-1 and Table C-2 could be obtained through dialogue with plant personnel and examination of previous compliance test reports. Any information not yet obtained should be gathered immediately upon arrival at the test site. For this reason, these two tables have been listed in Appendix C rather than Section 4.5.1 (Pretest Site Survey). Most of the missing information will be obtained during the initial inspection of the sampling site.

4.5.3.A.1 Plant Operational Mode

At most industrial sites the plant can operate in a variety of modes (peak load, normal load, base line, equipment upset, etc.) and for some processes the operation is cyclic (charging, stoking, cooking, pouring, etc.). For this reason, it is important that plant management familiarize the test crew with the control room operator and/or monitors to be used to identify the operational mode occurring prior to and during the sampling run. This is necessary to verify that sampling represents the "desired operational mode" as specified by the Test Plan. Plant upsets during a run (load changes, etc.) can invalidate an otherwise good sample.

4.5.3.A.2 Site Inspection

After the management in-briefing and control room visit the actual sampling site will be inspected. At this time, any necessary preparations

would be performed and the sampling equipment would be positioned at both the sampling site and on-site laboratory. As described in Section 4.3 (Apparatus), the preparations might include such activities as installing safety equipment, roping off any traffic areas beneath the sampling platform with flags and signs (Danger Falling Objects, Men Working Overhead), opening and cleaning ports, running extension power cords, installing additional lighting, erecting rain tarps, setting up the on-site laboratory (balance, computer, etc.), locating circuit breakers, water fountain, toilet, fire extinguishers, break room, and other such actions as called for by Table C-2 (Safety Checklist) or as deemed necessary.

4.5.3.A.3 Flue Gas Composition and Velocity Profile (P_s, B_{ws}, M_s, υ_s)

Once the sampling site is prepared and the equipment is in place, the first action is to determine the Flue Gas Composition using Method 3 (Gas Analysis for Carbon Dioxide, Oxygen, Excess Air, and Dry Molecular Weight) or Grab Sampling Techniques (Fyrite type Analysis) and Approximation Method 4 (Determination of Moisture Content in Stack Gas, Section 3). It is not necessary to determine the excess air. The average value (three runs as specified) for the dry Molecular Weight (M_d) should be calculated from the Fyrite or Orsat data and an approximate value should be obtained for the stack moisture (B_{ws}). At this point, an average moisture value may be obtained from interviews with plant personnel or values based on experience may be used rather than running a Method 4 sample since subsequent impactor runs will usually provide accurate measurements of the stack moisture. A pitot traverse (Method 2) must be made in order to determine gas temperatures and velocities over the sampling plane. The gas fractions for O_2, CO_2, and B_{ws}, the molecular weight (M_s), absolute stack pressure (P_s), point velocity distribution $\upsilon_{s_{i,j}}$, average velocity (υ_s) and an initial guess at the flue gas mass loading (c_s, gr/acf), will be used in the following sections to determine stage configuration, sampling flow rate, nozzle selection, and traversing protocol. Note: The symbol υ has been used for both jet velocity (υD_{50}) and stack velocity (υ_i). The context will clarify which usage is intended.

4.5.3.A.4 Traversing Protocol

In order to obtain a representative measurement one must obtain samples at representative points across the duct (stack) at isokinetic rates. In the case of conventional total particulate testing (e.g., EPA Methods 5 and 17), this is accomplished by dividing the duct into a large number of equal area segments (per EPA Method 1) and obtaining an isokinetic sample at the centroid of each of these areas. Isokinetic sampling is achieved by selecting a nozzle which is appropriate for the combination of the nominal flow rate at which the sampler is intended to operate and the average duct velocity. Compensation for duct velocity variations is then achieved by adjusting the sampling rate. This procedure cannot be used with inertial particle size classifiers because changes in sampling rates result in shifts in the diameter(s) at which size fractionation takes place.

With a fixed flow rate sampler the following procedure is recommended: establish anisokinetic limits and divide the sample plane (Method 1 Traverse

Points) into multiple regions such that all points within a given region may be sampled at a fixed flowrate with a single nozzle and satisfy the anisokinetic limits. Separate runs are then performed for each region. The runs are averaged using a weighting proportional to the total volumetric flow of each region, this average synthesizes a complete traverse. Method 1 procedures are used to define the complete traverse and Method 2 procedures are used to determine the velocity at each point.

The recommended isokinetic error limit for the above procedure is that each point sampled by an impactor should have a point velocity that is within ±20% of the impactor inlet velocity. We must sample at each of the traverse points which would be used in a standard Method 5 run; thus if the ratio of the minimum velocity to maximum velocity is greater than 1.5, multiple impactor runs are required. In this case, two or more regions would be selected such that for each region the velocity at every point within the region satisfied the 20% requirement.

Thus for any point i within a given region, the velocity at that point (υ_i) meets the criteria $.8V \leq \upsilon_i \leq 1.2V$ where V is the sampling velocity into the impactor nozzle (fixed by the choice of Nozzle Diameter and Impactor Flow Rate).

The following is a suggested technique for selecting the regions and respective sampling velocities when more than one region is required (i.e., $\upsilon_{max}/\upsilon_{min} > 1.5$):

Order the point velocities from lowest (υ_{min}) to highest (υ_{max}) then determine the 20% limits associated with each of the regions as follows:

For Region A:

$$\upsilon_{min} = \upsilon_{A_{min}} = 0.8\ V_A$$

$$\text{thus } V_A = 1.25\ \upsilon_{min}$$

$$\text{and } \upsilon_{A_{max}} \leq 1.2\ V_A$$

For Region B

$$\upsilon_{max} = \upsilon_{B_{max}} = 1.2\ V_B$$

$$\text{thus } V_B = 0.833\ \upsilon_{max}$$

$$\upsilon_{B_{min}} \geq 0.8\ V_B$$

if $\upsilon_{A_{max}} < \upsilon_{B_{min}}$ it may be necessary to assign a third Region (Region C) since there are some point velocities which are not covered by Regions A and B. It should be noted that it is very possible to have a skewed velocity distribution where there are two tight groupings of low velocity points and high velocity

points such that although $\upsilon_{A_{max}}$ is less than $\upsilon_{B_{min}}$, all the points are either less than $\upsilon_{A_{max}}$ (Region A) or greater than $\upsilon_{B_{min}}$ (Region B). If there are points that lie between these two limits

$$\upsilon_{A_{max}} < \upsilon_i < \upsilon_{B_{min}}$$

then a third region, Region C, (or possibly more than one additional region) would be required. Denote these points as υ_i' and repeat our previous approach as follows:

For Region C:

$$\upsilon'_{min} = \upsilon_{C_{min}} = 0.8\ V_C$$

$$\text{thus } V_C = 1.25\ \upsilon'_{min}$$

$$\text{and } \upsilon_{C_{max}} \leq 1.2\ V_C$$

If there are still some points remaining which do not fall within Region C then additional Regions would be called for as follows:

$$\upsilon'_{max} = \upsilon_{D_{max}} = 1.2\ V_D$$

$$\text{thus } V_D = 0.833\ \upsilon'_{max}$$

$$\upsilon_{D_{min}} \geq 0.8\ V_D$$

In the unlikely event that additional points remained then yet more regions could be constructed by repeating the process above using "υ" to designate all remaining points. Two regions will usually be sufficient. In some cases additional regions may be required. These cases would generally be situations where major flow obstructions existed close to the sampling ports.

If a 10% anisokinetic limit is desired rather than the 20% limit used above, then one may substitute $\upsilon_{min} = \upsilon_{A_{min}} = 0.9\ V_A$ and $\upsilon_{A_{max}} = 1.1\ V_A$, etc.

To be rigorous, one should adjust the dwell time at each point within a region so that the sample time at each point is velocity weighted and rounded to the nearest half minute. Although this is valid in that emissions factors are velocity dependent, the use of variable dwell times at each sample point can cause confusion on the part of the operator. Since total emission rates are normally based on Method 5/17 Runs, which are isokinetic, the suggested procedure is that equal dwell times be used.

It should be noted that use of different nozzles with the same impactor flow rate will produce different sampling velocities (V). The actual sampling velocity will depend on the choice of nozzle diameter and impactor flow rate as described in Section 4.5.3.A.5. It may be necessary to reassign points from

one Region to another if it is not possible to obtain V_A, etc. (as calculated above) in light the constraints of Section 4.5.3.A.5.

4.5.3.A.5 Impactor Stage Configuration, Sampling Flow Rate, and Nozzle Selection

The general process is as follows: (1) measure/calculate the flue gas temperature, pressure, moisture, mean molecular weight, and required sampling velocity for a given traverse region then estimate the mass loading; (2) make an initial guess at the impactor flow rate that will give a reasonable sample time to collect weighable quantities on each stage; (3) select a nozzle and adjust the initial guess at the impactor flow rate so as to obtain the required sampling velocity for this traverse region; and (4) select stages that will give the desired stage cuts at this flow rate without resulting in particle bounce (υD_{50} product guidelines) or unacceptably low Reynold's numbers. The following paragraphs elaborate on these four steps. Steps 3 and 4 must be repeated for each of the traverse regions since different regions may require different flow rates, nozzles, and/or stage configurations. The following paragraphs illustrate the selection process for region A.

Step 1 - Preliminary Calculations:

Sections 4.5.3.A.3 and 4.5.3.A.4 discuss the calculation of flue gas temperature, pressure, moisture, mean molecular weight, and required sampling velocity for traverse region A. Plant personnel are generally able to provide approximate particulate concentration information (mass loading, gr/acf). If this information is not available, it may be necessary to run an instack filter to obtain a "good guess" at the particulate concentration so that $t_{50\,mg}$ may be determined as described below.

Step 2 - $t_{50\,mg}$:

An initial guess for the impactor flow rate is made by calculating the time to collect a total sample of 50 mg particulate ($t_{50\,mg}$). Equation 4-30 may be used to calculate this value for various flow rates or the nomogram shown in Figure 4-2 may be used to estimate $t_{50\,mg}$ as described in Section 4.5.3.A.6. In this manner a flow rate may be found that will result in an acceptable run time as described in Section 4.5.3.A.6. Note: It may be necessary to select a different flow rate and repeat Steps 3 and 4 if the criteria of Step 4 are not satisfied.

Step 3 - Nozzle Selection and Impactor Flow Rate:

In Step 2 we determined the impactor flow rate which would produce an acceptable run time ($t_{50\,mg}$). We may now use Equation 4-32 to calculate the ideal nozzle diameter that would yield the required sampling velocity (V_A) for this traverse region when the sampler is operated at the flow rate determined in Step 2 above. From the set of available nozzles one would now select the real nozzle (D_{nA}) closest to this ideal size and use Equation 4-12 to calculate the corrected flow rate (Q_A) for this real nozzle. This flow rate is isokinetic to V_A, the mean velocity of Region A.

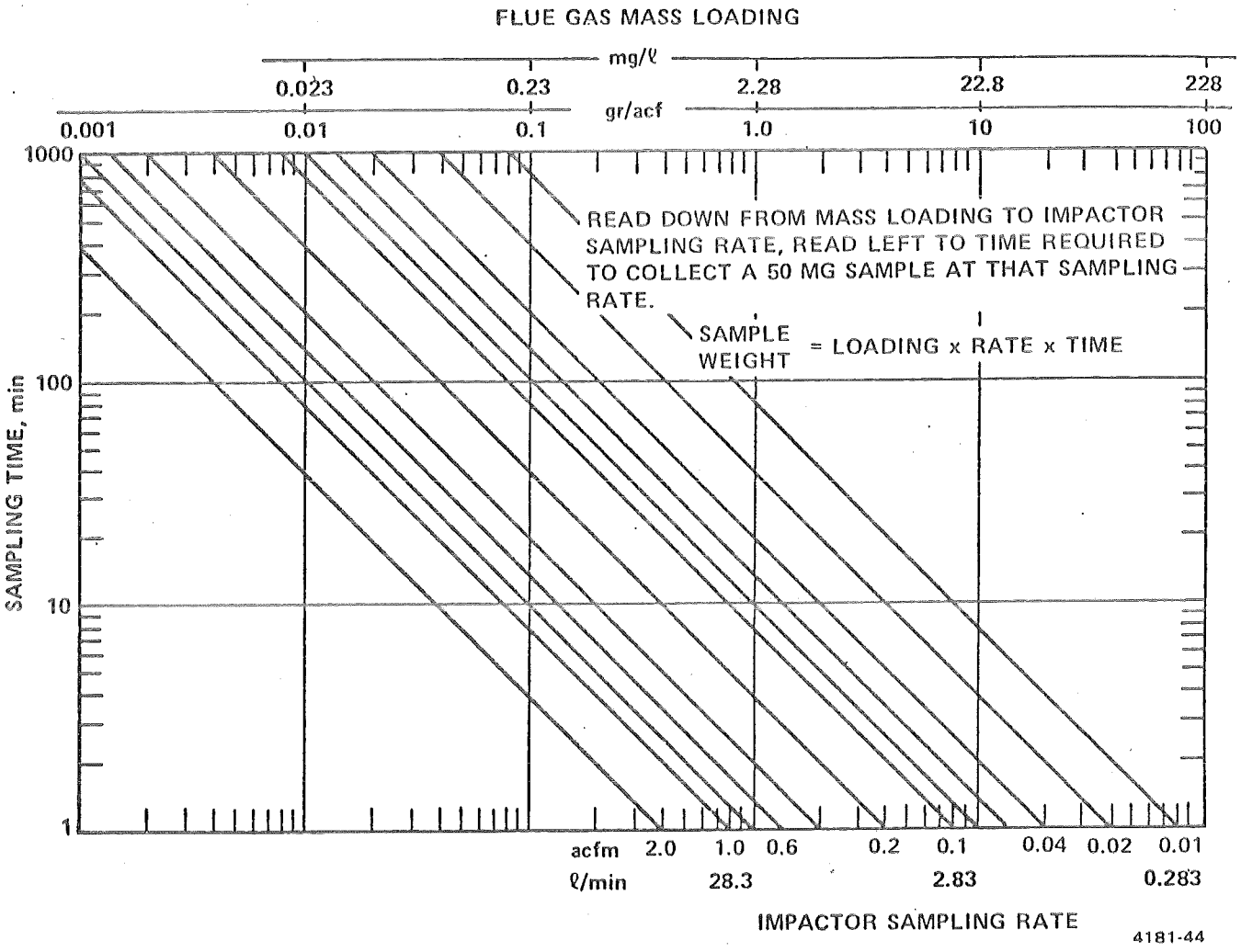


Figure 4-2. Nomograph for determining sampling time (50 mg sample).

Figure 4-3 (Nomograph for selecting nozzles for isokinetic sampling) is used to determine this corrected flow rate. Note: In inlet sampling situations the nozzle must be very small to permit isokinetic sampling at low impactor flow rates. The minimum useful nozzle size is 1.4 mm (0.0550 inches, wire gauge drill size No. 54) because smaller nozzles tend to plug during the run. The 1.0 mm nozzle size shown on Figure 4-3 is for information purposes only and is not recommended for normal use. If feasible, nozzle sizes should be 1/8 inch or larger.

Step 4 - Stage Configuration:

Using the corrected flow rate (Q_A) determined in Step 3, one would now select the stages which would give the desired size cuts without resulting in (1) particle bounce or (2) unacceptably low Reynold's numbers. Note: It may be necessary to choose a different flow rate and repeat Step 3 if the criteria are not satisfied. If the design of the impactor used does not permit stages to be selected/deleted then one must continue to try different flow rates until one is found for which all the stages satisfy the two criteria given above. In such cases, one may be forced to compromise on either the desired stage cuts or to tolerate undesirably short or long run times. Data is suspect and may need to be rejected if any one of the stages are operated in a bounce mode or at very low Reynold's numbers. The preferred impactor design is one that permits the selection of stages to optimize the configuration used.

The desired size range and resolution is 0.25→ 10 μm with 5 to 8 cuts evenly spaced on a log scale (constant ratio of 2.52 to 1.69) as shown in Figure 4-4. Thus we want the precollector to cut at or above about 10 μm and the last stage to cut at or below about 0.25 μm.

It should be noted that any stages having a D_{50} comparable to or larger than the D_{50} of the precollector will have little if any particulate catch and these catches will have no significance as sizing data. If possible, such stages should not be used. For data analysis purposes, (if they must be included) the weights of the material collected on such stages should be combined with the catch of the first stage having a D_{50} smaller than that of the precollector and the intermediate stages should be omitted in the D_{50} calculations, etc.

One must verify that each stage selected meets the two criteria given below for the specified flow rate (Q_A). Note: "υ" has been previously used to represent the stack gas velocity. In the following paragraphs, we are using "υ_i" to represent the jet velocity for any one of the jets on impactor stage i.

The criteria are (1) υD_{50} product be less than a critical value, CV, to prevent bounce and scouring and (2) the jet Reynolds Number, Re be greater than 50. These two considerations compete against each other. For a given jet size as the flow rate is increased the D_{50} decreases, but the Re and υD_{50} increase. As the velocity is decreased one can stay below the υD_{50} limits but the run time increases and Re may approach values where the impactor calibration data ceases to be valid. The υD_{50} product guideline, CV, depends on the type of substrate material used, and has the following values: Bare Metal - 5 μm-m/s,

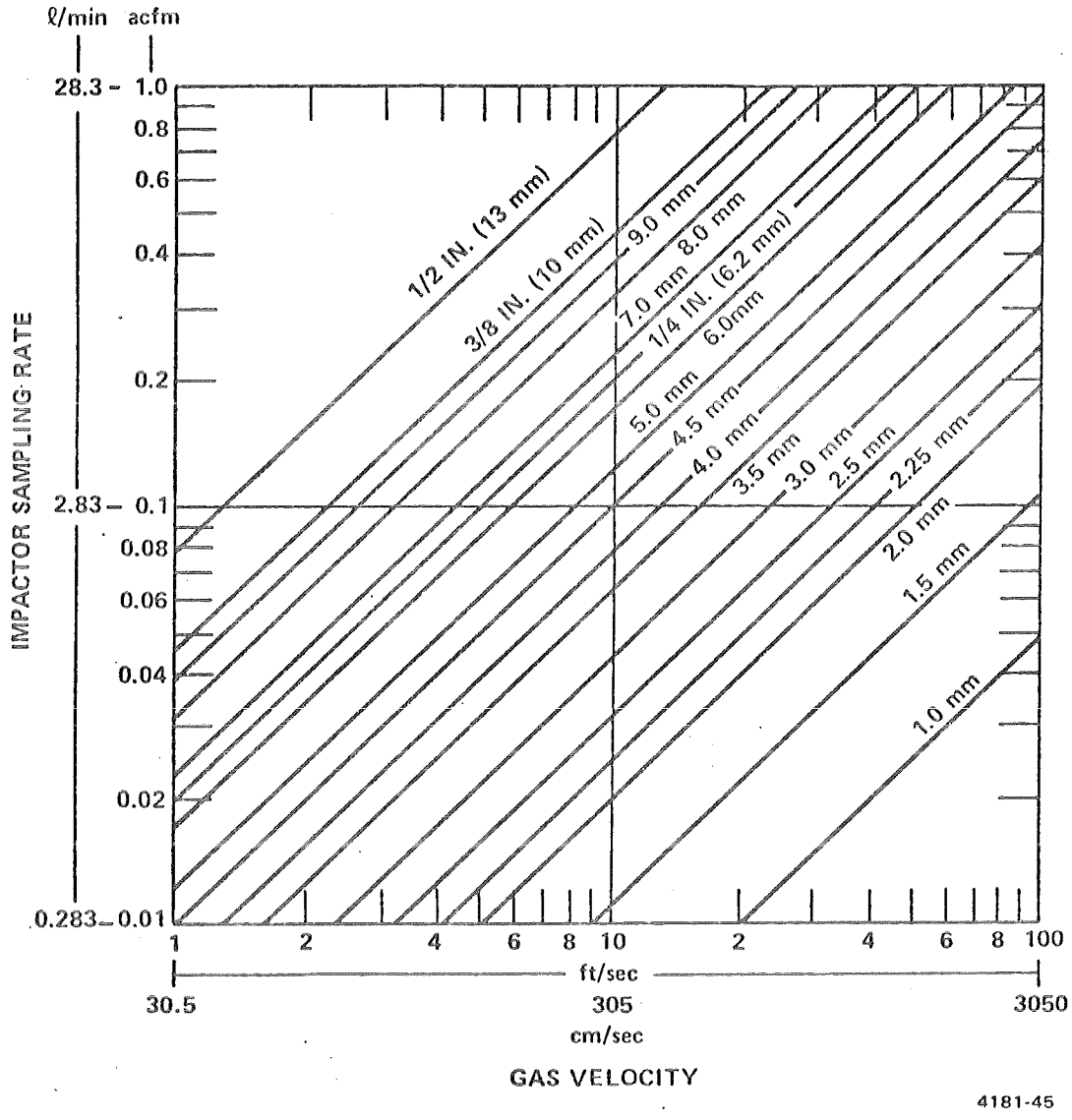


Figure 4-3. Nomograph for selecting nozzles for isokinetic sampling.

NUMBER OF CUTS	9	8	7	6	5
RATIO OF CUTS	1.585	1.694	1.849	2.089	2.518
CONSTANT Δlog D	0.200	0.229	0.267	0.320	0.401
PRECOLLECTOR D_{50} (μm)	≥10	≥10	≥10	≥10	≥10
FIRST STAGE D_{50}(μm)	6.3	5.9	5.4	4.8	4.0
SECOND STAGE D_{50}(μm)	4.0	3.5	2.9	2.3	1.6
THIRD STAGE D_{50}(μm)	2.5	2.1	1.6	1.1	.63
FOURTH STAGE D_{50}(μm)	1.6	1.22	.85	.52	.25
FIFTH STAGE D_{50}(μm)	1.0	7.2	.46	.25	—
SIXTH STAGE D_{50}(μm)	.63	.42	.25	—	—
SEVENTH STAGE D_{50}(μm)	.40	.25	—	—	—
EIGHTH STAGE D_{50}(μm)	.25	—	—	—	—
PLOT DESIGNATION	A	B	C	D	E

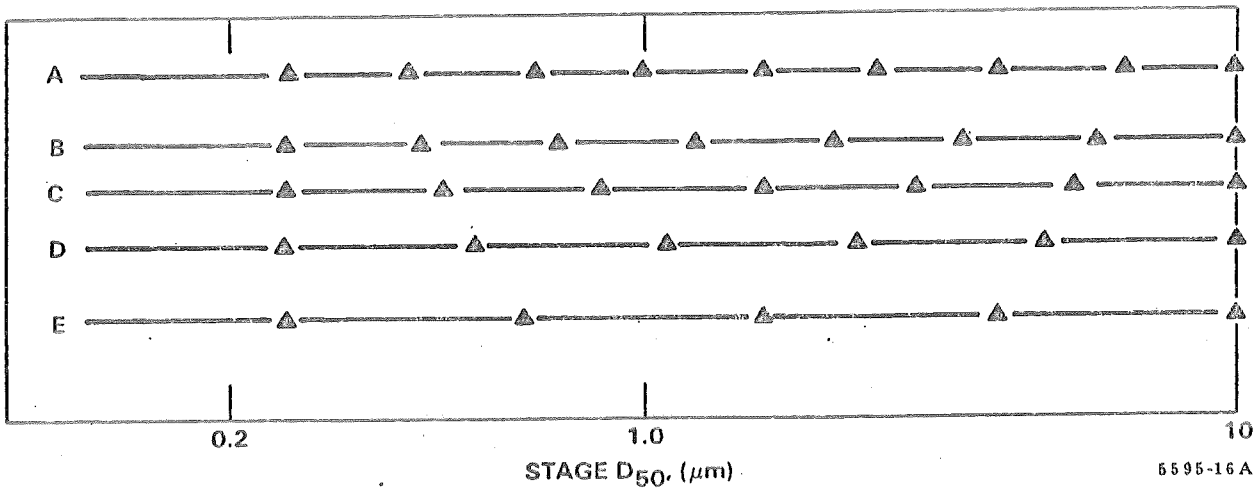


Figure 4-4. Desired size cuts range of interest: 0.25 μm to 10 μm.

Fiberglass - 15 μm-m/s and Grease - 25 μm-m/s. The desired Re value is greater than 100. It is possible to operate at lower values, but the desired range is at least 100 or higher. If a run results in Re values of 50 or less it should be considered suspect because the theory has not been proven in this regime. The other considerations in selecting a flow rate are the desired maximum and minimum D_{50}'s. The higher the flow rate the smaller the D_{50} for the same stage. This is illustrated for the Pollution Control Systems Mark V impactor (U of W) in Figure 4-5 for the stated conditions of temperature, pressure, and flue gas composition. Equations for calculating stage D_{50}'s are given in Section 4.7.21 and Computer Programs for performing these calculations are described in Appendix A.

4.5.3.A.6 Run Time (θ)

As mentioned above, Figure 4-2 is a nomograph for determining the sample time to collect 50 mg ($t_{50\,mg}$) of particulate given the Flue Gas Mass Loading and sample flow rate. The equations used to calculate run time are given in Section 4.7.8. Figure 4-2 should be used to make an initial guess at the run time for the initial impactor run. Adjustments for subsequent runs are then made after examining the substrates from the initial run.

To use Figure 4-2, one must make an initial guess at the flue gas mass loading, (G_A, gr/acf) then read down to the appropriate impactor sampling rate curve (2 ACFM to 0.01 ACFM). Reading to the left from the intersection of the mass loading and sampling flow rate one will find the time required to collect a 50 mg total sample (sum of all stage weights plus filter). The 50 mg total sample is a rule of thumb, the actual constraints are that no stage with the exception of the filter or precollector should collect more than 15 mg. At the outlet to a high efficiency control device, long run times may be unavoidable. Two hour outlet samples are desirable but six hour run times are common, and even longer runs are sometimes required. For inlet situations the concentration is typically very high and run times generally need to be very short to prevent overloading. The recommended minimum run time is 90 sec. If possible run times should be at least three minutes.

4.5.3.A.7 Blank Run and Initial Impactor Run

After an initial selection is made of sampling flow rate, stage configuration and nozzle diameter, two impactors are assembled as described in Section 4.5.3.D.2 with the selected components. These will be the Blank Run and Initial Run. The initial run is usually performed concurrently with the blank impactor run described below. The purpose of the blank is to verify the suitability of the selected substrate material. As described below, the Initial Run is an exploratory run used to determine the optimum the run time, θ. At this point, the preliminary calculations remaining are the same as those for any impactor run and are described in Section 4.5.3.D. For simplicity, both the Blank Run and the Initial run are usually single point runs rather then following the traversing protocol given in Section 4.5.3.A.4. If large concentration gradients are expected, the Initial Run should traverse the entire area to be sampled.

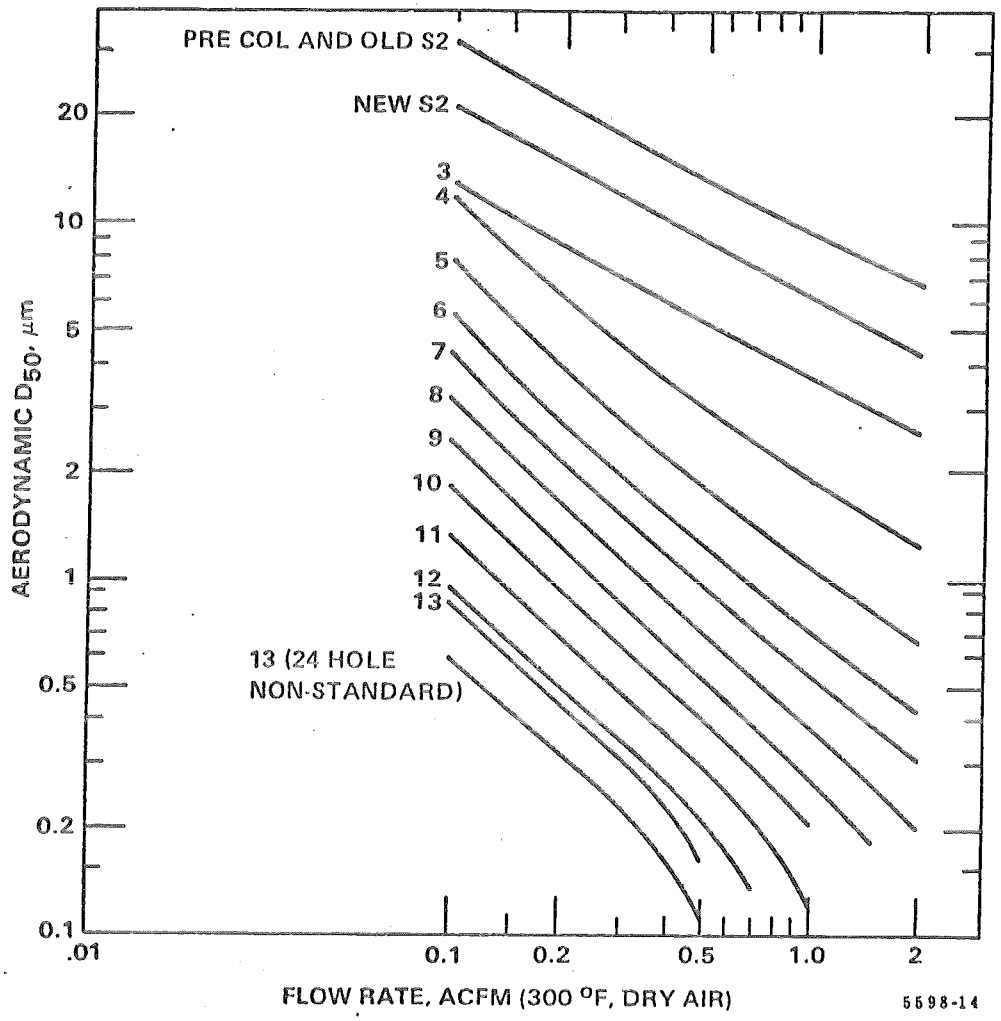


Figure 4-5. Pollution Control System Mark V Impactor stage cuts (at 300 °F, 29.00 Hg, dry air) for multiple flow rates.

After the selected orifice has been installed on the dry gas meter the initial setup leak check of the meter box backhalf should be performed as described in Section 4.5.3.D.4 (Leak Check Procedures). The initial check does not need to be repeated unless the meter box is moved or a different orifice is installed.

4.5.3.B Blank Impactor Run

It has been shown that some substrate materials can change weight by simple exposure to particulate free stack gases. When such substrate-flue gas interactions occur, it is important to determine the magnitude and reproducibility of these extraneous weight changes so that the true particulate loadings can be determined. The problem usually relates to sulfur oxides in the flue gas and the chemistry of the particular type of substrate material being used. When greased metal foils are used as substrates, temperature can also be a problem. Proper selection of substrate material and, in some cases in-situ conditioning of the material, can eliminate or minimize the problem. Section 4.5.2.B gives guidance for the judicious selection of substrate materials for various sampling situations. As a quality control check the precollector is replaced by a filter holder containing one or more unweighed filters and attached to the inlet of a impactor loaded with preweighed substrates of the selected material (greased metal, fiberglass, etc.). This configuration is referred to as a "Blank" impactor. This assembly is then inserted in the stack and, after warmup, stack gas is pulled through the impactor at approximately the same flow rate and for the same duration as a real run. The objective is to expose the substrates to flue gas under the same conditions as those of the real runs. With the filter preceding the impactor, all the particulate should have been removed so that any weight changes can be ascribed to flue gas-substrate interactions. The blank weight change for any given substrate should not exceed 0.25 mg or 10% of the stage catch of the most lightly loaded substrate in the real runs, whichever figure is smaller. The impactor filter blank weight change should not exceed 0.25 mg. Larger blank weight changes can be tolerated if they are reproducible. An average change of 1.5 mg which is reproducible to ±0.1 mg is preferable to an average change of 0.1 mg with a range of ±0.25 mg since corrections can be applied if the change are reproducible. If these limits are exceeded, alternate substrate materials should be tested until one is found which does satisfy the above criteria.

If no substrate material appears to be satisfactory, one last technique is to use in-situ conditioning as discussed in Section 4.5.2.B.4. If in-situ conditioned substrates are used, a blank must still be run to verify that weight changes are now acceptable.

It should be noted that the precollector substrate was not included in the blank run. If the same substrate coating material is used on both the precollector substrate and the impactor collection plate substrates, the same correction factor may be used for both if approximately the same amount of coating material was applied to both surfaces. Frequently, the precollector catch is very large and the correction factor would be less than 1% of the total catch. In cases where the catch is low and the correction factor is significant, one may choose to scale the correction factor to the relative amount of coating material used on the two different surfaces or to construct

special hardware that would permit the precollector to be included in the blank run.

Some precollectors permit the optional use of a fiberglass (or quartz) insert. If such inserts are used and loadings are low it may be desirable to construct the special hardware mentioned above. If the filter is constructed of the same material, one can obtain an estimate of any weight change by scaling the filter correction factor. Where the change seems to be significant, one should use coated foil inserts in the precollector rather than fiberglass inserts.

In situations where testing has been performed at similar sampling sites, experience will aide one in the substrate selection process. In other situations, one must simply run numerous blanks until an acceptable substrate material is found. Sometimes this is done during a pretest site or as described in Section 4.5.1 the crew may carry sufficient quantities of substrates of multiple kinds of material so that when the blank run shows a given material to be acceptable, testing can proceed without delay. If the test program is complex and involves a large number of people, it will usually pay to run blanks well beforehand to avoid lengthy delays should a problem with substrates be found.

4.5.3.C Initial Impactor Run

The initial impactor run is used to gather information that can be used to adjust the sampling time for subsequent runs. The initial run itself is seldom useful as data, often being run only half as long as the rest of the runs. For this reason, it is often referred to as an exploratory run or "trash" run. It is usually a single point run rather than a full traverse and is normally run concurrently with the blank run. If the blank run indicates that a different substrate material must be used, it is at the discretion of the operator to run a second "trash" run concurrently with the second blank or run only the second blank. The normal case would be to assume the second choice of substrate material will prove to be acceptable and use the results of the initial run to adjust the run time so that this run (with the new material) will hopefully provide real data. If this second trash run is traversed and is deemed acceptable (examination shows that minimum/maximum stage loadings were obtained, scouring and bounce did not occur, etc.) then it may be counted as real data. Each successive run is adjusted based on information gained from the previous runs. For a run to be counted as data, it must satisfy all the criteria listed in Section 4.11 (Acceptable Results).

4.5.3.D Performing the Individual Sampling Runs

After making the preliminary determinations described in Section 4.5.3.A and completing the Blank Impactor Run and Initial Impactor Run as described above, we are ready to make the individual sampling runs for data purposes. The following paragraphs detail this process. Note: At this time all ports should have been opened, cleaned, and any needed port adapters installed.

4.5.3.D.1 Preliminary Calculations

Once decisions have been made as to stage configuration, nozzle selection, and sampling flow rate, it becomes necessary to calculate the target ΔH needed to obtain the desired sampling flow rate at the given set of stack conditions. This calculation is the same as that used for Method 5 sampling except that it is not necessary to generate the table of ΔH vs. Δp_{pto} used to maintain isokinetic sampling. Once the run is started, the flow rate is not changed. As explained earlier, changing the flow rate changes the stage D_{50}'s. For this reason, a constant ΔH setting is maintained throughout the entire run. The only flow adjustments made are those necessary to compensate for the filter loading. The traversing protocol described in Section 4.5.3.A.4 may be used to select a subset of the Method 1 traverse points such that the constant flow rate is always ±20% of isokinetic for each point sampled. Multiple runs may be needed (each at a different flow rate or with a different nozzle) in order to traverse the full stack.

Equations for the calculation of ΔH are given in Section 4.7.10 (Target ΔH Control Parameter) and calculations are performed by the computer programs of Appendix A. As described above, the run time Θ is determined from examination of the initial impactor run after using the nomograph (Figure 4-2) to obtain an initial guess for Θ. Future run times should be adjusted as indicated by examination of completed runs.

4.5.3.D.2 Preparation of the Cascade Impactor

On-site laboratory preparation of the impactor includes loading the impactor with the selected jet plates and with preweighed, numbered substrates (same material as used with the blank impactor run), loading the precollector, attaching the calibrated nozzle, and attaching the precollector to the impactor, then leak testing the impactor/precollector combination. This lab leak test is optional because the mandatory QA postrun leak test will show if leaks have occurred and will either accept or reject the run as valid with respect to leaks. The purpose of this Quality Control laboratory leak test is to catch and correct any leaks (missing o-rings, loose fittings, etc.) before the run is made. For this reason, a simple quick untimed procedure may be used. Once the impactor and precollector are loaded they are labeled with the Run Code (Run Identification Number) shown on the Run Sheet. All data related to this run is recorded on the run sheet with the exception of the weight records. The Substrate Weight Records are maintained in a separate log book that never leaves the on-site laboratory. Section 4.5.3.D.5 outlines the instructions for preparing the Run Sheet (shown in Figures 4-6 and 4-7). The velocity traverses are recorded on Method 2 Velocity Traverse Forms and are maintained separately from the run sheets. The following paragraphs describe the procedures for loading the impactor.

Before loading the substrates in the impactors, the impactor and precollector parts should be inspected to ensure that they are free of loose dirt, lubricants, or liquids. An ultrasonic cleaner is useful for removing contamination from small crevices (e.g. the inside of an Andersen impactor o-ring and the small jet holes of the last stages of the impactor). The jets of each impactor stage should be inspected by holding the plate between a light

LAB LOAD/UNLOAD SHEET FOR UNIVERSITY OF WASHINGTON IMPACTOR (SIX JET PLATES)

RUN CODE

L1

SUBSTRATE SET IDENTIFICATION NO.

L2

PERSON LOADING IMPACTOR AND DATE LOADED

L3

- LOAD IMPACTOR
- MARK SHELL AND PRECOLLECTOR WITH RUN CODE
- LEAK TEST

UNIVERSITY OF WASHINGTON MARK V IMPACTOR

SHELL ID NO. L4

JET PLATE SET ID NO. _____

STAGE CONFIGURATION _____

PRECOLLECTOR ID NO. _____

NOZZLE ID NO. _____

NOZZLE DIAMETER _____ (INCHES)

LAB LEAK CHECK (60 SEC PRESSURE CHANGE)
CHECK UNDER VACUUM (~ 8 IN. Hg)

WITH PRECOLLECTOR: L6

INITIAL _____ (IN. Hg)

FINAL _____ (IN. Hg)

WITHOUT PRECOLLECTOR (ONLY IF LEAKS FOUND ABOVE)

INITIAL _____ (IN. Hg)

FINAL _____ (IN. Hg)

NOTES AND OBSERVATIONS

U3

PERSON UNLOADING IMPACTOR AND DATE UNLOADED

U4

NOTE YOUR OBSERVATIONS ON THE APPEARANCE OF EACH STAGE, SUBSTRATE, OR CYCLONE UPON DISASSEMBLY

U5

PRECUTTER
I P

U5

STAGE ZERO (DISK)
I D

U5

STAGE ONE (FIRST PLATE, NO. L5A)
I -1

U5

STAGE TWO (SECOND PLATE, NO. _____)
I -2

U5

STAGE THREE (THIRD PLATE, NO. _____)
I -3

U5

STAGE FOUR (FOURTH PLATE, NO. _____)
I -4

U5

STAGE FIVE (FIFTH PLATE, NO. _____)
I -5

U5

STAGE SIX (SIXTH PLATE, NO. _____)
I -6

U5

BLANK OR BEHIND DISK (CIRCLE ONE)
I -BX

U5 L5B

BACK UP FILTER
I -F

U5

5598-26

Figure 4-6. Run Sheet - Lab Side.

RUN SHEET FOR CARB SIZE DISTRIBUTION METHOD
USING A CASCADE IMPACTOR SAMPLING TRAIN

L7
REAL BLANK

RUN CODE L8	DATE 1	DIFFERENTIAL STACK PRESSURE 2 (IN. H_2O)
CONTROL BOX ID L9	START TIME 11	AMBIENT PRESSURE (LAB BAROMETER) 3 (IN. Hg)
GAS METER ID L10	END TIME 28	AMBIENT TEMPERATURE 4 (F)
THE CALCULATED TARGET ΔH VALUES REQUIRES THE OPERATOR TO USE ORIFICE ID L11	SAMPLING DURATION 12 (MIN.)	—60 SEC LEAK TEST— PRE HOT A. 15 IN. Hg W/SAMPLER 5 FT^3
SAMPLING ASSIGNMENT INLET, OUTLET, OTHER: L12	GAS METER-START 13 (FT^3)	B. 5 IN. Hg W/SAMPLER FT^3
TARGET ΔH L13	GAS METER-FINISH 29 (FT^3)	C. 15 IN. Hg W/O SAMPLER FT^3 POST HOT 30
	TOTAL VOLUME BY GAS METER U6 (ACF)	NOTE: RELEASE VACUUM AT NOZZLE TO AVOID RUPTURING FILTER. PASS ≤ 0.02 FT^3 FOR A OR B OR C VISUAL CHECK OF NOZZLE ☐

	RUN TIME (MIN)	PORT NO. TRAVERSE POINT	GAS METER READING	GAS METER TEMP. (F)	FLUE GAS TEMP. (F)	19	ORIFICE ΔH IN. (H_2O)	PUMP VACUUM (IN. Hg)	PROBE TEMP. (F)
	Pre	15	16	17	18				20
1	14	21	22	23	24		25	26	27
2	↓	↓	↓	↓	↓	↓	↓	↓	↓
3	↓	↓	↓	↓	↓	↓	↓	↓	↓
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									
21									
22									
23									
24									
25									
26									
27									
28									
29									
30									
	POST TEST CALCULATIONS:								
	U7	TOTAL	U8						
		AVG.		U9	U10	U11	U12		

—WATER—
CONDENSER ID NO. 6
CONDENSER H_2O CATCH 31 (ml)

DRYING COLUMN WEIGHT CHANGE
ID NO. L14 INITIAL WT. L15 (gm)
FINAL WT. U1 (gm)
(1 gm = 1 ml) H_2O GAIN U1 (ml)

TOTAL VOLUME H_2O U2 (ml)

NOTES AND OBSERVATIONS
32

7 SAMPLING LOCATION
INLET OUTLET

IN THE SPACE BELOW GIVE THE UNIT, CHAMBER, DUCT PANTLEG, ETC. WHERE THE SAMPLER WAS RUN.

PORT NUMBER(S)

SAMPLER ORIENTATION (CIRCLE ONE)
8
HORIZONTAL
TOP ENTRY VERTICAL
W/ TURN AROUND
W/O TURN AROUND
BOTTOM ENTRY VERTICAL
OTHER

OPERATORS
(1) 9 (2)

5598-25

Figure 4-7. Run Sheet - Run Side.

and the eye and using a 10 X occular. Metal gaskets should be checked for warpage or nicks and pliable gaskets checked for hardening, cracking, tears, slits, or imbedded dirt which could cause leaks. If there is any doubt about a gasket it should be replaced. The nozzle should be clean and the edges sharp and free of nicks.

During loading, handle the precollector, impactor, and nozzles with clean fingers and the substrates with tweezers or clean fingers by the edges. Make a final inspection of the substrates during loading. The substrates should have been inspected prior to the prerun weighings but this is a second check. If a substrate must be replaced, the replacement should be pulled from an "extra" set and the weight records and the run sheet annotated accordingly.

Where mating threads are both stainless steel, chrome or silver plating of one or both mating surfaces will greatly reduce the potential for galling. Teflon thread sealant tape can be used on any threads that are not otherwise protected. Antiseize compounds should be used sparingly or not at all because of the possibility of contaminating the substrates.

After the nozzle, precollector, and impactor have been assembled they should be checked for leaks as mentioned above. Leaks at this point in the procedure can be easily found and corrected. Checking the pressure drop across the assembly for various flows of filtered air against predetermined values will indicate deviations from the norm resulting from both external and internal leaks and plugged jets.

When the impactor has been loaded and leak checked and the Target ΔH value calculated as per the Traversing Protocol, the Sampler, Run Sheet, and preweighed drying column are ready to be carried to the sampling area. Section 4.5.3.D.5 provides a step-by-step guide to the preparation and operation of a sampling run. At this point, Items L1 through L15 of Section 4.5.3.D.5 have been completed.

The following example illustrates the Pollution Control Systems (University of Washington) Mark III impactor which might be used. The case illustrated in Figures 4-8 and 4-9 is substrate set number I23 ("I" for impactor). The substrate set numbering code permits any set to be loaded into any impactor configuration (Inlet or Outlet). The designation of sampler hardware description and assignment is made on the Run Sheet not in the substrate set coding.

LAB LOAD/UNLOAD SHEET FOR UNIVERSITY OF WASHINGTON IMPACTOR (SIX JET PLATES)

RUN CODE: SAMPLE CALC

SUBSTRATE SET IDENTIFICATION NO.: I 23

PERSON LOADING IMPACTOR AND DATE LOADED: SSD 4-20-84

- ✓ LOAD IMPACTOR
- ✓ MARK SHELL AND PRECOLLECTOR WITH RUN CODE
- ✓ LEAK TEST

UNIVERSITY OF WASHINGTON MARK ~~IMPACTOR~~ MARK III

- SHELL ID NO. III Z
- JET PLATE SET ID NO. III Z
- STAGE CONFIGURATION P,2,3,4,5,6,7,B,F,BF
- PRECOLLECTOR ID NO. Z
- NOZZLE ID NO. Z-3
- NOZZLE DIAMETER 3/16 (0.188) (INCHES)

LAB LEAK CHECK (60 SEC PRESSURE CHANGE)
CHECK UNDER VACUUM (~ 8 IN. Hg)

WITH PRECOLLECTOR:
- INITIAL 7.8 (IN. Hg)
- FINAL 6.0 (IN. Hg)

WITHOUT PRECOLLECTOR (ONLY IF LEAKS FOUND ABOVE)
- INITIAL 7.8 (IN. Hg)
- FINAL 7.8 (IN. Hg)

NOTES AND OBSERVATIONS

$\bar{v}$ = 50 fps

PRE

LEAK AT PRECOLLECTOR NOZZLE, SMALL

POST

BF STICKING TO F. COMBINE THESE WEIGHTS FOR DATA ENTRY.

NOZZLE GOOD, NO NICKS.

PERSON UNLOADING IMPACTOR AND DATE UNLOADED: SSD 4-21-84

NOTE YOUR OBSERVATIONS ON THE APPEARANCE OF EACH STAGE, SUBSTRATE, OR CYCLONE UPON DISASSEMBLY

PRECUTTER (I P 23): GOOD LOADING, NO SIGN OF NOZZLE SCRAPINGS IN CATCH.

STAGE ZERO (DISK) (I D 23): LIGHT LOADING

STAGE ONE (FIRST PLATE, NO. 2 (OLD)) (I -1 23): GOOD PEAKS, NO INDICATION OF BOUNCE FROM SOLID DISK

STAGE TWO (SECOND PLATE, NO. 3) (I -2 23): GOOD PEAKS

STAGE THREE (THIRD PLATE, NO. 4) (I -3 23): GP

STAGE FOUR (FOURTH PLATE, NO. 5) (I -4 23): GP

STAGE FIVE (FIFTH PLATE, NO. 6) (I -5 23): GP

STAGE SIX (SIXTH PLATE, NO. 7) (I -6 23): GP

BLANK OR BEHIND DISK (CIRCLE ONE) (I -BX 23)

BACK UP FILTER (I -F 23): AND I 23 BF BLANK FILTER IS STICKING TO THE DIRTY FILTER. MUST COMBINE AND WEIGH AS ONE PACKAGE

5050-481C

Figure 4-8. Example of a completed Run Sheet - Lab Side.

RUN SHEET FOR CARB SIZE DISTRIBUTION METHOD USING A CASCADE IMPACTOR SAMPLING TRAIN

(REAL) BLANK

RUN CODE: SAMPLE CALC
DATE: 4-20-84
DIFFERENTIAL STACK PRESSURE: −0.3 (IN. H_2O)

CONTROL BOX ID: RAC # 1
START TIME: 0900
AMBIENT PRESSURE (LAB BAROMETER): 29.60 (IN. Hg)

GAS METER ID: RAC # 1
END TIME: 1110
AMBIENT TEMPERATURE: 74 (F)

THE CALCULATED TARGET ΔH VALUES REQUIRES THE OPERATOR TO USE
ORIFICE ID: 12 0 5
SAMPLING DURATION: 120 (MIN.)
—60 SEC LEAK TEST— PRE HOT
A. 15 IN. Hg W/SAMPLER: .016 FT^3
B. 5 IN. Hg W/SAMPLER: .007 FT^3

SAMPLING ASSIGNMENT
INLET (OUTLET) OTHER:
GAS METER-START: 321.450 (FT^3)
GAS METER-FINISH: 361.640 (FT^3)
C. 15 IN. Hg W/O SAMPLER: — FT^3 POST HOT 0.017

TARGET ΔH: 5.44
TOTAL VOLUME BY GAS METER: 40.190 (ACF)

NOTE: RELEASE VACUUM AT NOZZLE TO AVOID RUPTURING FILTER.
PASS ≤ 0.02 FT^3 FOR A OR B OR C
VISUAL CHECK OF NOZZLE OK

—WATER—
CONDENSER ID NO. RAC #1
CONDENSER H_2O CATCH: 39 (ml)

DRYING COLUMN WEIGHT CHANGE
ID NO. E — INITIAL WT. T+478.0 (gm)
W/O HOSE — FINAL WT. T+482.0 (gm)
(1 gm = 1 ml) H_2O GAIN: 4.0 (ml)

TOTAL VOLUME H_2O: 43.0 (ml)

	RUN TIME (MIN)	PORT NO. TRAVERSE POINT	GAS METER READING	GAS METER TEMP. (F)	FLUE GAS TEMP. (F)		ORIFICE ΔH IN. (H_2O)	PUMP VACUUM (IN. Hg)	PROBE TEMP. (F)
	Pre	A1	321.450	72	300				310
1	5	A1	23.12	74	300		.44	2	
2	10	A2	24.80	74	301		.44		
3	15	A3	26.47	74	300		.44		
4	20	A4	28.15	74	301		.44		
5	25	A5	29.82	74	301		.44		
6	30	A6	31.50	74	301		.44	3.3	300
7			MOVE						
8	5	B1	33.17	74	298		.44		
9	10	B2	34.85	74	300		.44		
10	15	B3	36.52	74	300		.44		
11	20	B4	28.20	74	298		.44		
12	25	B5	39.87	74	302		.44		
13	30	B6	41.54	74	300		.44	4.5	305
14			MOVE						
15	5	C1	43.22	74	300		.44		
16	10	C2	44.89	74	300		.44		
17	15	C3	46.57	74	298		.44		
18	20	C4	48.24	74	299		.44		
19	25	C5	49.92	74	300		.44		
20	30	C6	51.59	74	301		.44	6.0	300
21			MOVE						
22	5	D1	53.27	74	299		.44		
23	10	D2	54.94	74	302		.44		
24	15	D3	56.62	74	300		.44		
25	20	D4	58.29	74	298		.44		
26	25	D5	59.97	74	301		.44		
27	30	D6	61.64	74	300		.44	7.2	305
28			END	RUN			361.640 AT 1110 hrs.		
29							120 MIN. TOTAL SAMPLE TIME		
30									
	POST TEST CALCULATIONS:								
	120	TOTAL	40.190						
		AVG.		74	300		.44		

NOTES AND OBSERVATIONS
CO_2 = 0.22 % dry
O_2 = 19.75 % dry
NO PLANT UPSETS DURING RUN.

SAMPLING LOCATION
INLET (OUTLET)
IN THE SPACE BELOW GIVE THE UNIT, CHAMBER, DUCT PANTLEG, ETC. WHERE THE SAMPLER WAS RUN.
UNIT 3 ESP OUTLET

PORT NUMBER(S)
ALL
A, B, C, D

SAMPLER ORIENTATION (CIRCLE ONE)
(HORIZONTAL)
TOP ENTRY VERTICAL
W/ TURN AROUND
W/O TURN AROUND
BOTTOM ENTRY VERTICAL
OTHER

OPERATORS
(1) JWR (2) SJG

5050-482C

Figure 4-9. Example of a completed Run Sheet - Run Side.

Description	Number on Petri Dish
Precollector	
Precollector Substrate Foil	I23P
Zero Stage (Impactor Inlet Throat)	
Collection Disk and Substrate (Solid Disk)	I23D
First Jet Plate (No.2)	
Collection Disk and Substrate (Donut)	I23-1
Second Jet Plate (No.3)	
Collection Disk and Substrate	I23-2
Third Jet Plate (No.4)	
Collection Disk and Substrate	I23-3
Fourth Jet Plate (No.5)	
Collection Disk and Substrate	I23-4
Fifth Jet Plate (No.6)	
Collection Disk and Substrate	I23-5
Sixth Jet Plate (No.7)	
Collection Disk and Substrate	I23-6
Blank Collection Disk (Inverted)* and Substrate	I23-BX
Teflon Insert Ring**	
Filter	I23F***
Teflon Insert Ring**	
Teflon Insert Ring (BF)**	
Blank Filter	I23BF***
Teflon Insert Ring (BF)**	
Support Screen	

Notes:

*The Extra Collection Stage can be used in either of two different locations. If this is an outlet run the extra collection stage is used as a blank. The blank is a collection stage (loaded with a numbered substrate) that has been inserted upside down (out of flow) directly behind the collection plate of the last jet. It is referred to as a blank because it is not preceded by a jet stage and is oriented out of flow. It is intended to act as a check in weighing and for any flue gas-substrate interactions. It is treated the same as all the other substrates as far as conditioning and handling go. Because of high loadings at an inlet sampling location, it may be placed directly beneath the solid disk which precedes the first multijet stage to catch any overload or blow-by from the zero stage (impactor inlet and solid disk). Usually at inlets the run time is so short and the flow rate so low that no problems are encountered from flue gas-substrate interactions. Outlet loadings are typically low enough that zero stage overloading is not normally a problem, thus this collection substrate is used as a blank rather than a safety.

**Thin light weight Teflon may be cut in a donut shape and placed in front of and behind a filter to prevent the filter from sticking to the metal. The Teflon rings should be weighed with their respective filters. Kapton plastic film can be used if the flue temperatures are too high for Teflon.

***The petri dish with the filter also contains the filter's pouch (aluminum foil envelope) and the Teflon inserts. All of these pieces are weighed as a package rather than separately. The envelope remains in the petri dish while the inserts and filter are loaded into the impactor. The purpose of the envelope is to prevent particles falling off the filter prior to and during the post-test weighing. Note: the pouch must be open during desiccation in order to permit moisture to escape from the filter.

The filter package (I23F) consists of one filter, one pouch, and two Teflon inserts. The total weight of these four pieces is assigned to I23F in the weight records. The blank filter package (I23BF) consists of one filter and two Teflon inserts. The pouch is not necessary but may be desirable. The total weight of these three or four pieces is assigned to I23BF in the weight records. The third and fourth Teflon inserts are marked BF to avoid confusion between them and the other two during unloading.

4.5.3.D.3 Preparation of the Sampling Train

Preparation of the sampling train is basically the same as that for a Method 17 run. The one major difference is that the equipment is modified to permit the use of smaller orifices when lower flow rates are required. The other difference is that a metal condenser and preweighed drying column (Figure 4-1) is commonly used in lieu of the glass impingers. All manometers should be leveled, leak checked, and zeroed. Then the backhalf of the sampling train should be leak checked as described in Section 4.5.3.D.4 below.

4.5.3.D.4 Leak Check Procedures (Prerun and Postrun)

In general the backhalf of the sampling train must be tested at the beginning and end of each field test (and again if components are changed or the equipment is moved). Each impactor will be checked at least twice, and possibly four times. The last two tests are acceptance tests and the first two may be thought of as screening tests aimed at finding and correcting leaks in an advantagious manner. The first test (optional) is performed in the lab before the impactor is carried to the stack. The second (optional) is made before the impactor is warmed up. If leaks are found during the prerun hot leak checks they must be corrected before the run may proceed. Since the impactor may cool down during this time, one may be forced to repeat the 45 min. to 1 hr. warmup time.

The significance of a leak and the acceptance limits assigned to a leak depend on where it occurs. For example, a leak around a nozzle attachment means that all the gas does pass through the precollector and impactor thus impactor performance is not affected. Likewise, a leak between the precollector and impactor inlet flange means the gas passed through the impactor but bypassed the precollector. A leak downstream of the impactor would not be acceptable because the dry gas meter reading is greater than the actual amount of gas sampled by the impactor. Once the impactor run has been completed it could compromise the data to disassemble the unit and try to isolate the location of a leak. Leaks affect not only the indicated amount of gas sampled but also the calculated D_{50}'s, thus data cannot be salvaged by making leak rate corrections.

Many different techniques are available for leak checking a sampler. The particular techniques used to perform any pretest cold checks are optional since these are all aimed at finding leaks before the run is performed. Although the pretest cold leak checks are optional, it is highly recommended that some form of check be made prior to warmup. Such checks can locate leaks early and prevent unnecessary delays. The pretest hot leak test and the post-test hot leak test are mandatory. It is these tests which accept or reject a run with respect to leaks. The techniques used for these tests are spelled out in detail in the following paragraphs.

Initial Set-Up Check of Meter Box Backhalf: Each time the sampling train is set up (desired orifice installed on the dry gas meter) the meter box should be checked as described below. The normal leak check procedure will not detect leaks on the positive pressure side of the pump since such leaks are discharged to ambient, never reach the dry gas meter, and thus less volume is recorded than sampled. Once this check has been performed it need not be repeated until the meter box is moved or the orifice is changed. If this initial check (and any equipment change checks) is not made, all subsequent leak checks are subject to question. The results of this check should be recorded in a field test log book (a chronological record of what took place during the field test). The procedure (see Figure 4-10) is as follows (the same as used with a Method 5 train): Close the main valve on the meter box. Insert a one-hole rubber stopper with rubber tubing attached into the orifice exhaust pipe. Disconnect and vent the low side of the orifice manometer. Close off the low side orifice tap. Pressurize the system to 5 to 7 in. water column by blowing into the rubber tubing. Pinch off the tubing and observe the manometer for one minute. A loss of pressure on the manometer indicates a leak in the meter box. Leaks, if present, must be corrected. (A soap solution is helpful for locating the source of leaks in a pressurized system.)

Lab Leak Check:

A simple vacuum check is sufficient. Assemble the impactor and precollector. Connect a vacuum source to the impactor outlet (pump off). Plug the nozzle and turn the pump on, adjusting the pump valves to about 8 inches Hg negative differential to ambient. Then close off the line between the impactor exit and pump and see if the system holds this vacuum. If it falls a leak is present. The rate at which it falls indicates the size of the leak. If leaks are present, one may switch to a slightly positive pressure (~6 in. of water) and use a soap solution to locate the source(s) of the leak(s). Usually these will be due to missing o-rings, loose fittings, etc. These should be corrected before the sample is sent to the sampling platform. Note: Release the vacuum at the nozzle to avoid damage to the filter.

Cold Leak Check:

At the sampling platform the sampler is connected to the probe and a cold leak check is performed (optional). As shown on the Run Sheet, the criteria is a leakage rate $\leq$ 0.02 ACFM. The test is first done at -15 in. Hg with the precollector and sampler attached. If the system fails this test, the operator should attempt to fix the leak by checking the most common problem areas such as loose connections, etc. The test may then be repeated at the -5 in. Hg level (line B on the Run Sheet). If it still fails to meet specs, one needs to isolate the source as to the sampler or the train. Line C may be used for this purpose. Any leaks should be located and corrected before warming the

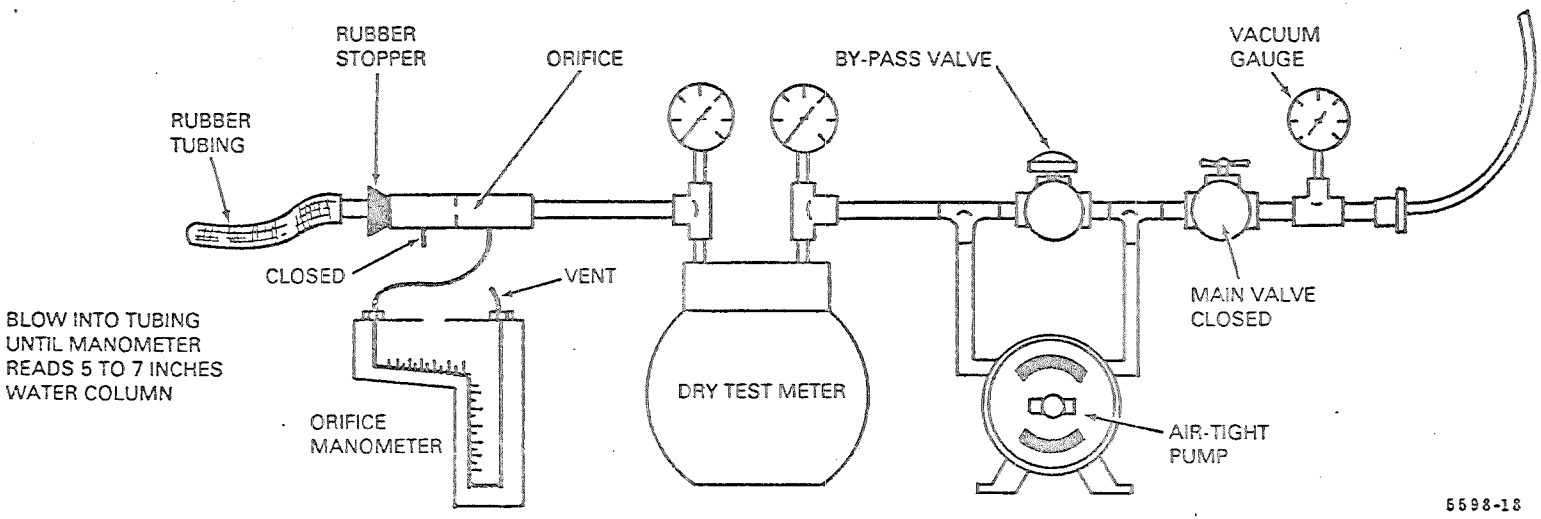


Figure 4-10. Leak check of meter box.

impactor, otherwise the pretest hot leak test may prohibit the run from being started. Wrapping the entire impactor assembly with aluminum foil at this time is advantageous. This prevents the outer surfaces and joints from accumulating particulate matter during warmup and sampling. Such an accumulation can make disassembly difficult or even result in the loss of a run if any of the material is dislodged onto a substrate when one impactor is unloaded.

Hot Prerun Leak Check:

After the warmup is completed, the hot sampler is removed from the port, the cover is removed from the nozzle and the hot prerun leak check is performed. Plug the nozzle with a material that will be able to withstand the nozzle's high temperature then turn on the pump and draw a vacuum in the system equal to or greater than the maximum value reached during the previous sampling run. Record this rate as L_N. Table 4-1 (Leak Test Criteria) gives instructions and criteria in a flow chart form. One will note that unlike Method 5, flow rate corrections are not permitted because such corrections affect the D_{50} as well as the total volume sampled.

Hot Postrun Leak Check:

After the run is completed and the hot sampler is removed from the last port, the hot postrun leak check is performed to verify that no leaks developed during the run. The criteria of Table 4-1 is used for this purpose. One must not attempt to remove the nozzle or disassemble the sampler at this time in order to isolate a leak. The only permissible leak is at the nozzle and a comparison is made between prerun and postrun leak rates. The sampler is removed and the train is checked to verify that all measured gas went through the sampler.

The following leak-check instructions for the sampling train described in APTD-0576 and APTD-0581 may be helpful. Start the pump with the by-pass valve fully open and coarse adjust valve completely closed. Partially open the coarse adjust valve and slowly close the by-pass valve until the desired vacuum is reached. Do not reverse direction of the by-pass valve. If the desired vacuum is exceeded, either leak-check at this higher vacuum or end the leak-check as shown below and start over. When the leak-check is completed, first slowly remove the plug from the inlet to the sample nozzle and immediately turn off the vacuum pump. This prevents water from being forced backward and keeps silica gel from being entrained backward.

4.5.3.D.5 Instructions For Using the Run Sheet

The run sheet accompanies the impactor at all times. All information and comments relating to the run are recorded on this document. Figure 4-6 shows side of the run sheet used by lab personnel to record identifying equipment numbers and to record observations made while unloading the impactor. This data form is specific to the University of Washington impactor configured with precollector, six jet plates, control blank, and filter, since this is the recommended ARB preferred instrumentation and configuration. Use of other impactors or configurations will require minor alteration of this form. Figure 4-7 shows the other side of the run sheet. This side is used by the testing personnel during the run, example data is shown in Figures 4-8 and 4-9. Appendix A shows a an alternate version of the run sheet prepared by the

Table 4-1 Leak Test Criteria

Definitions:

L_N = leak rate with Nozzle, Precollector, Impactor, and Train
L_T = leak rate, assembly removed from probe (Train only)
L_a = 0.02 cfm or 4% Q_I whichever is smaller (acceptable leak rate criteria)
L_M = 10% Q_I (maximum acceptable leak rate), 10% Trash Point

All Prerun testing is performed at the highest pressure drop obtained in most previous runs. The Postrun testing is performed at the highest pressure drop obtained in the actual run.

For Hot Prerun Test, the term "Reject Run" means that the leaks must be corrected before the run may proceed. This will usually mean the unit must be returned to the lab and reassembled.

Pretest Hot

Plug Nozzle, Test (Record L_N)

$L_N < L_a$?	Yes:	Acceptable
	No:	Attempt to correct leaks, retest
$L'_N < L_a$?	Yes:	Acceptable
	No:	Continue
$L'_N > L_M$?	Yes:	Reject Run
	No:	Remove Impactor Assembly, Retest (Record L_T)
$L_T < L_a$?	Yes:	Acceptable
	No:	Reject Run

Post-Test Hot

Plug Nozzle, Test (Record $L_{N_{Post}}$)

$\left\lvert L_{N_{Post}} - L_{N_{Pre}} \right\rvert > L_M$?	Yes:	Reject Run or tighten Nozzle and retest
	No:	Continue, do not attempt to correct leaks. Do Not remove nozzle. Remove Assembly (Precollector/Impactor) from Probe, Plug Probe, Test (Record $L_{T_{Post}}$)
$L_{T_{Post}} < L_a$?	Yes:	Acceptable
	No:	Reject Run

Computer Programs. Entries to the alternate form are similar to those described herein for the "manual" version shown in Figure 4-7. The circled numbers relate to additional information given below. The prefixes L and U are used to identify information recorded by laboratory personnel during loading (L) and unloading (U). Unprefixed numbers identify information recorded by testing personnel at the sampling location before, during, and after the run. The number sequence represents the normal sequence one would use in recording the information. One major difference between impactors and a Method 5 mass train is the use of a constant flow rate. On a Method 5 run the operator monitors point velocities and adjusts the sampler flow rate to maintain isokinetic sampling at each traverse point but impactors require a constant flow rate. With impactors a Method 2 velocity traverse is performed before the run and the techniques described in Section 4.5.3.A.4. are used to select the traversing procedures for one or more runs, each of which is made at constant but possibly differing flow rates. The desired flow rate for a run will be obtained for stack conditions when the train is operated at the Target ΔH (pressure drop across for the orifice) listed on the run sheet.

Lab Prerun Entries:

(L1) Run Code: This key number is usually assigned in the written test plan and will generally include abbreviations for the plant name, sampling location (inlet, outlet) and sequence number at this location (see Appendix A). This same code is also listed at (L8) on the Run Side.

(L2) Substrate Set Identification No.: This is the number assigned in the Weight Book to the substrate set. This set includes one or two filters and substrates for the precollector, zero jet (solid disk), six jet plates (donuts), and one blank collection plate (donut) as listed on the right side of the form. This set number together with the sequence information (P, D, 1-6, BX, F, and BF) is marked on the petri dish for each member of the set (Example: I26F, Impactor substrate set No. 26, filter).

(L3) Person loading impactor and date loaded: With a small test crew many of these items are not important but on a larger test where eight to ten runs are made per day this can avoid a lot of confusion in answering questions related to the run.

(L4) Hardware Identification: When a substrate set is loaded in an impactor, this information must be completed and the run number marked on the impactor shell. This information identifies which jet plates were loaded in the impactor during the run. The Nozzle Diameter is the calibration value for the nozzle and is used in the calculation of the Target ΔH valve. Nominal Diameters are also shown as fractions.

(L5) First Jet Plate No.: This information has already been recorded on the stage configuration line in the Hardware Identification section. As such these blanks are optional and are simply for added clarity. These numbers are read from the back side of the plates. (The plates should have been permanent permanently marked when the hole verifications were made.) At (L5B) one of the two choices "Blank" or "Behind Disk" should be circled to indicate where the extra collection plate was loaded, upside down and directly behind the collection plate of the last jet stage or right side up and directly behind the

zero stage (entrance jet) solid disk collection plate to catch any overloading from the disk.

(L6) Lab Leak Check: The first check is performed with the precollector mounted on the impactor. If a leak is present which cannot be corrected by inspecting and tightening fittings, then the impactor should be checked without the precollector in order to determine if the leak is in the precollector or the impactor. Small leaks in the precollector are acceptable. Leaks in the impactor should be located and corrected before sending the assembly to the sampling site. Use of a slightly positive pressure (less than 8" H_2O) and a foaming leak detector liquid can be helpful in locating the leaks. Be careful not to rupture the filter by causing air to rush through it in the wrong direction. Always release the vacuum slowly at the precollector inlet, not by turning the pump off.

(L7) Real or Blank: The lab personnel should circle the appropriate description. Although the presence of a filter (in place of the precollector) at the inlet of the impactor obviously identifies the run as a blank rather than a real, the circles are used to facilitate identification during data processing. Frequently this will be redundant since the Run Code would normally identify the run as being a blank.

(L8) Run Code: Same as (L1), listed on both sides of the form.

(L9) Control Box ID: This is the assignment of the impactor to a specific sampling train. This is necessary because the orifices in the different sampling trains generally have different calibration constants. Consequently, an assignment must be made before the Target ΔH value can be calculated.

(L10) Gas Meter ID: When the Control Box ID is specified, this selects the gas meter since it is an integral part of the Control Box. The gas meter must be identified so that the appropriate dry gas meter calibration factor (Y) can be used for data reduction.

(L11) Orifice ID: Since impactors may require the use of orifices of different diameters to cover the broad range of flow rates which may be used, it is necessary to identify which specific orifice is to be installed by the testing personnel. The orifice calibration factor ($\Delta H@$) of the specified orifice is used in the calculation of the Target ΔH value.

(L12) Sampling Assignment: The test plan will frequently identify the areas where sampling is to be performed and distinguish between these different areas by the abbreviations used in the Run Code. In that respect, this line is redundant. It has been included for the purpose of clarity. Frequently different stage configurations and flow rates will be used in the different sampling areas (inlet, outlet zone to be traversed, etc.) and the loaded impactor (stage configuration used) and calculated Target ΔH will only be appropriate for one of these areas. Thus the need to clearly identify the sampling assignment.

(L13) Target ΔH: Calculated using the computer program in Appendix A and the equations given in Section 4.7.10 for the equipment arrangement shown in

Figure 4-1. This pressure drop across the orifice (as specified in (L11)) should be maintained throughout the run.

(L14) Drying Column ID No.: Both an ice bath condenser and silica gel drying column are used. The triple beam balance (1/10 g) is usually maintained in the lab and to avoid confusion, the drying columns are numbered. This number shows which drying column was used with which impactor.

(L15) Drying Column Initial weight: The weight of the drying column specified above is recorded on the Run Sheet. The weight gain of the drying column is used in the determination of the stack moisture value (B_{ws}). Note: 1 gm = 1 mL, 1 mL liquid = 0.04707 ft^3 vapor at standard conditions (68°F, 29.92 in. Hg).

Stack Entries:

At this point the Run Sheet, Drying Column, and Impactor are ready to be given to the testing personnel and carried to the appropriate sampling site. The following entries are made by the testing personnel.

1) Date: This is the date the run was performed. It may be different from the date it was loaded.

2) Differential Stack Pressure: This reading was made during the Method 2 pitot traverse performed prior to the impactor run.

3) Ambient Pressure: This may be read directly if a barometer is at the sampling site (mark through LAB) or, if the barometer is in the LAB (and the lab is at ambient pressure), altitude corrections can be made, 0.1 in. Hg/100 ft. If a reading is taken from the plant control room, be sure the reading is measuring ambient pressure and not absolute pressure at some point in the plant process.

4) Ambient Temperature: Temperature at the start of the test.

5) Prerun Leak Test: This is described in Section 4.5.3.D.4. The COLD is optional but recommended. The HOT Prerun and Postrun are required. To end a leak test and avoid rupturing the filter, the vacuum should always be released at the nozzle with the pump running. This sets the direction of flow through the filter so that the filter will be supported. Look at L6 to see if the precollector leaks. Even if the lab test indicates a leak, the stack test is a different kind of test (a quantitative measure) and may prove to be acceptable. If the system fails Test A (15 in. Hg) then Test B should be performed. If B fails and the lab test showed a leaking precollector, the precollector should be removed and Test B repeated. If it still fails then Test C should be performed to see if the leak is in the impactor or the train.

6) Condenser ID No: List the ID No. Some condenser designs do not permit all the water to be removed. Residual amounts are trapped. Before using such a condenser add some water to the condenser then pour it out using the same technique that will be used after the run is completed. This preloads the entrapment areas to permit an accurate reading of the subsequent catch.

7) Sampling Location: This describes where the sample was run. To avoid replicate detailed drawings reference is often made to figures, and descriptions in the test plan. This should agree with the Sampling Assignment. Space is provided to permit a detailed description.

8) Sampler Orientation: This is somewhat an extention of (7). It is important to know if the sampler was operated horizontal, right side up, or upside down. If a sampler is operated upside down, flow must be maintained while the sampler is moved from port to port while traversing. The sampler must be right side up or horizontal before flow is stopped. Any gas sampled while moving from port to port should be discounted in data analysis. A written record of the orientation may be useful later if problems are encountered in interpreting the data.

9) Operator: The test personnel must identify themselves so that they can be called upon at a future time to answer questions, receive praise, or be chastised as appropriate. This is also needed to maintain chain-of-custody records.

10) Blank Space: This may be used as desired. Frequently the time at which the impactor was inserted for warm-up will be listed (Example: start warm-up at 1322).

11) Start Time: This is the time the run actually started. Since a stop watch is normally used for the traversing dwell times, this and Item #28 will generally be the only recorded clock times (unless item #10) is used as above). Sufficient warm up must have been completed by this time. Usually this entry is made shortly after insertion for in-situ warm-up and indicates the scheduled start time. If something prevents the run from being started at this time, simply mark through the entry and write the correct actual start time. Note: during the end of the warm-up time the pump should be running with the shut-off valve closed.

12) Sampling Duration: This is the actual run time (θ). Usually this entry is made before the run is started and indicates the scheduled run time. If something happens to change it during the run, it should be properly noted on the bottom portion of the run sheet. The operator should then mark through this entry and write in the correct actual run time. Lab personnel will verify this after the run and make the same entry in U7.

13) Gas Meter-Start: This is recorded here and in (16) after the probe has been leak checked and inserted for warm-up. This is recorded to the nearest 1/1000 ft^3 (see example). Pump is running with shut off closed. This is one of the most important entries on the page.

14) Run Time Column: As shown in the example, this column and column 15 are usually completed before the run is started and show the scheduled dwell time at each traverse point. If the schedule is altered one can mark through the entry and either write the correct entry to the left or use the blank column (19). Note: the implied meaning is that the listed time marks the end of the dwell (not the beginning) and the gas meter reading was recorded on the fly at the indicated time. Immediately after this indicated time, the probe is

positioned to the next traverse point. In the example on line 3 the implied meaning is that from stop watch time 10 to time 15 the probe was at position A3 and the DGM reading at time 15 was 795.64 (approximate, since the needle was moving). If desired, clock times may be used for very long runs. For a run of around two hours or less, use of stop watch time as shown in the example are recommended. Clock times may be entered to the left of the appropriate line number (or in the blank column) if so desired.

15) Port No./Traverse Point Column: See explanation in (14) above. The entry on the "Pre" line and on line "1" are the same. "Pre" implies at or near start.

16) Gas Meter Reading Column: "Pre" is same as (13). During the run (22) this is the approximate reading (moving) at the indicated stop watch time. See also (14).

17) Gas Meter Temp, Pre: The pump is not sampling stack gas at this time so this temperature will be lower than the run temperature. During the run (23) the operator should record the temp at some point during the dwell at this traverse point.

18) Flue Gas Temp, Pre: The purpose of this entry and (20) is to remind the operator that the probe heater should be working. Probe heat prevents the accumulation of water (in the probe) which could back wash the filter and substrates.

19) Blank Column: May be used as desired (see (14)).

20) Probe Temp, Pre: Entry is to remind the operator to turn on the probe heater (see 18).

21) See (14) and (15).

22) See (14) and (16).

23) Gas Meter Temperature Column: This is the temperature of the dry gas meter, read shortly before the dry gas meter reading is taken.

24) Flue Gas Temperature Column: This is a reading of the temperature of the flue gas at this traverse point, read sometime during the dwell at this point.

25) Orifice ΔH Column: The Target ΔH value (L13) is the desired value. This column is intended to be a record of the actual ΔH as well as a reminder to adjust the valves as necessary to maintain the flow at the Target ΔH value (compensate for filter loading).

26) Pump Vacuum Column: This is a pump inlet vacuum read toward the end of the dwell at this traverse point.

27) Probe Temperature Column: This is a probe temperature read sometime during the dwell at this traverse point. This is a reminder to verify that the

probe heaters are working to prevent condensate from draining back to the filter. This information is not used during data reduction.

28) End Time: This is the 24 hr. clock time when the run was actually ended. The interval between start and stop will generally be longer than the sampling duration because the flow is normally cut off and the timer stopped when the probe is moved from one port to the next.

29) Gas Meter-Finish: This is the reading of the gas meter when the run is stopped by closing the shut-off valve with the pump still running.

30) Postrun Leak Test and Visual Check of Nozzle: After the run has been stopped (with pump running) and the final gas meter reading recorded, the probe is removed from the stack and the Postrun Leak Test described in Section 4.5.3.D.4 is performed. This is similar to the test described in (5) except that it is performed post-test. This test is mandatory and is used to accept or reject the run with respect to leaks. At this time the operator should also visually check the nozzle to verify it was not damaged (banged, scraped, etc.) during the course of the run. If the nozzle appears undamaged place a check mark in the box. If the nozzle is damaged write in the words Damaged and make appropriate entries in the Notes and Observations section.

31) Condenser H_2O Catch: After the hot leak test has been completed, the sampler is removed from the probe. The operator will then shake the umbilical to drain water in the line into the condenser. The line to the drying column may also contain some water droplets and should be drained into the condenser. At this time the condenser is removed and a graduated cylinder is used to measure the amount of water that was captured by the condenser. This value is recorded here. The length of tubing connecting the drying column to the control box inlet should be disconnected at the drying column and the short length of tubing connecting the drying column to the condenser should be re-connected where the other tube was removed. This loop will close off the drying column to prevent any loss or gain of water. The drying column, with tubing, is ready to be returned to the lab for weighing.

32) Notes and Observations: Any notes or observations not yet recorded should be entered at this time.

Lab Postrun Entries:

At this point the SAMPLER, RUN SHEET, and DRYING COLUMN are ready to be returned to the lab for analysis and turn around. The following entries are made by the lab personnel.

(U1) Drying Column Final Weight: The drying column is weighed and the value recorded here. Note: If the initial weight was done with a tube connected to the two ends, the final weight must be done with the same tube attached. The weight gain is calculated and recorded.

(U2) Total Volume H_2O: This is the sum of the condenser catch and the drying column weight gain.

(U3) Notes and Observations: This space may be used as desired.

(U4) Person Unloading Impactor and Date Unloaded: Used to identify the person unloading the impactor and when it was unloaded (see also L3).

(U5) Observations: If you wish to record any observations made while unloading the precollector and impactor, this is the place to make the notes. Such observations as obvious indications of bounce or overloading, hunks of rust (from nozzle scrapings) in the precollector, ruptured or wet filter, damaged o-ring, dramatic color changes from stage to stage, etc. are listed on the appropriate line.

(U6) Total Gas Meter Volume: This is the value obtained by subtracting the START reading from the FINISH reading. The readings in the gas meter column (22) should be examined to verify that this is the actual start and finish values. This is the most important number on the Run Sheet.

(U7) Post-Test Calculations-Run Time: This is the same as (12) and is optional. The common usage is to examine the column to determine the total run time and be sure that the "planned" duration and the "actual" duration are the same.

(U8) Post-Test Calculations-Gas Meter Reading: This is the same as (U6), total volume sampled, and is optional.

(U9) Post-Test Calculations-Gas Meter Temperature: This is the simple average of the values listed in the column. Data reduction equations assume the gas meter was operated at a constant temperature. The average value is used as that value.

(U10) Post-Test Calculations-Flue Gas Temperature: This is the simple average of the values listed in the column. The data reduction procedures assume that the flue gas temperature was constant. The average value is used as that value.

(U11) Post-Test Calculations-Blank Column: If the blank column is used and and if an average value is desired it is recorded here.

(U12) Post-Test Calculations-Orifice ΔH: This is the simple average of the values listed in the column. This value is not used in the data reduction but if it differs from the Target ΔH value the calculation of % isokinetic value (%I) will probably be different from 100%.

Summary: All written comments and data related to a given impactor run should be recorded on the run sheet. Only the substrate weight records and velocity traverse information are recorded on other forms. The three most important data elements recorded are the Sample Duration (θ), Total Volume Measured by Gas Meter (V_m), and Total Volume H_2O collected (V_{lc}). All entries are important but these are essential.

4.5.3.D.6 Particulate Train Operation and Data Recording

Once preliminary velocity traverses, selection of stage configurations and nozzle diameters, and pretest cold leak checks are completed, the nozzle is covered securely and the sampler is inserted into the flue gas and rotated out of flow for warm up. Aluminum foil and high temperature fiberglass tape serve well for covering the nozzle. Once the impactor is at the desired operating temperature the probe may be withdrawn from the stack, the cover removed and the pretest hot leak check performed. Once the leak test is completed the assembly is reinserted in the stack. The sampler must be at stack temperature when sampling begins. Depending on how long the leak check required, the second warmup may be as short as 5-10 minutes. The first warmup time will

generally be about 45 minutes to one hour. Probe heaters are turned on at the start of the warmup time. This will insure that vapor does not condense in the portion of the probe outside the flue and drain back into the impactor backwashing the filter and lower collection plates during sampling.

Section 4.5.3.D.5 (Instructions for Using the Run Sheet) lists the various entries made to the run sheet before, during, and after the run. This run sheet serves as both a record and a guide. The most important data to be recorded before the run starts is the initial gas meter reading. The pump may be running during warmup with the cut off valve closed since the pump oil needs to be warm for the pump to be leak free. Using the Traversing Protocol described in Section 4.5.3.A.4, the impactor is positioned to the first sampling point and rotated into flow. The cut off valve is opened (with the pump running) and the flow adjusted to the Target ΔH value. The impactor is then moved to the second traverse point at the appropriate time. Valves are adjusted as necessary throughout the run to maintain the Target ΔH value and data is recorded on the run sheet as outlined in Section 4.5.3.D.5. Flow is maintained while the impactor is moved from one traverse point to another in the same port but the flow is stopped ($\Delta H=0.00$) as the impactor is removed from one port and inserted into the new port. Flow is resumed at the first traverse point in the new port. [If, however, the impactor is operated in an upside down orientation (rather than a horizontal or upright orientation) the flow is maintained without interruption throughout the run until the impactor has been removed from the last port and oriented to a horizontal or upright position. Only then can the flow be stopped.] During traversing, move the impactor as smoothly and as quickly as possible without bumping or vibrating the sampler. When removing or inserting the sampler, take care not to scrape the nozzle on the port wall. Also, take care not to bump the sampler against the far inside wall of the flue.

When all the traverse points have been sampled for the desired dwell time the sample run is completed. Flow is then stopped and the sampler is removed from the stack. The post-test hot leak check is performed and the impactor/precollector assembly is then gently disconnected from the probe using as little motion as possible and allowed to cool before being transported to the lab. If the assembly was wrapped with foil, then foil should be removed at this time. The nozzle should be covered and the impactor oriented in an upright position. The condenser catch is measured and the drying column is removed for transport to the lab together with the sampler and run sheet. A wooden carrier made especially for transporting hot impactors in an upright position is convenient for this purpose.

4.5.3.D.7 Calculation of Percent Isokinetic

At this point the % Isokinetic should be calculated as described in Section 4.7.17 using the computer programs described in Appendix A. Acceptable results are: $80\ \% < I < 120\ \%$. If "I" exceeds these limits, the run may be rejected.

It should be noted that only the large particles are affected by nonisokinetic sampling. Consequently, the information on the lower stages may be valid even if the Isokinetic check is not met. Where multiple runs are made

and only one has poor isokinetics, the outlier test used in the averaging of multiple runs (Section 4.5.3.G) will probably reject the bad data from the run and retain the data in the unaffected smaller sizes.

4.5.3.E Sample Recovery (Nozzle Wash and Unloading the Impactor)

Unloading the Sampler

After the sampler has cooled down enough to be handled without gloves, it should be brought into the laboratory and carefully unloaded (to remove the particulate matter caught). Great care is needed in this procedure to ensure that all the particulate matter is recovered and transferred to the appropriate containers.

If a cyclone precollector was used, remove the sample collected in the cyclone. With a small brush (a small nylon brush made for cleaning electric shavers is suggested), push the particles caught inside the nozzle down into the cyclone. Then, holding the cyclone upright on a table (or in a vise), carefully remove the cap and, holding the cap over the cyclone, brush the particles adhering to the bottom of the cap and to the outside of the gas exit tube into the cyclone body. (A No. 7 camel's hair artist's brush is convenient here.) Then, lay the cap aside, being careful not to dislodge any of the particles inside the gas exit tube. Using a downward, pushing motion, brush the particles on the inside walls of the body of the cyclone down into the collection cup. Carefully detach the collection cup from the body and, holding the body over the cup, brush the particles adhering to the underside of the body into the cup. (At this point, all the particles caught by the cyclone should be in the cup.) If a cup insert was used, remove it with a pair of forceps for desiccation and weighing. If not, transfer the particles to a preweighed container. Wash the internal nozzle and cyclone surfaces with a solvent, such as acetone, into a preweighed bottle or aluminum cup. Cover the wash container loosely and allow the solvent to evaporate completely before desiccation and weighing.

If an impactor precollector was used, carefully remove the substrate with forceps as is done with impactor substrates. Brush the residue from the nozzle, body and outside of the gas exit tube onto the substrate or weighing container using the same techniques as for a cyclone precollector.

For either type of precollector, collect and weigh the particles adhering to the inside of the gas exit tube and to the connecting tubing from the precollector to the impactor as part of the catch for the first impactor stage. This may be done by washing and/or brushing this tube.

Carefully disassemble the impactor, and sequentially remove the substrates, inspecting each stage before it is placed in the weighing or storage container. Handle substrates sparingly with forceps, spatula, or clean dry fingers. Teflon o-rings are also used with the filter. Place the first filter in a thin aluminum foil envelope before and after the run to help prevent loss during handling. The envelope should be part of the initial and final weighings and should be labeled according to the filter it contains. The second filter is a control and is placed directly beneath the first filter,

separated only by a set of Teflon o-rings. The second filter is clean and does not require an envelope.

Typically, some of the material that is deposited in an impactor is collected on surfaces other than the substrates, accumulating on interior surfaces such as gaskets or jet plates. Collecting this "misdirected" particulate matter is often troublesome. If the material is hard and dry, one may brush off the particles on to the appropriate substrate or into the weighing container. If the particles are sticky or wet, some type of washdown procedure should be used. Use a solvent that is considerably more volatile than the particles. Also remove and weigh (with the sample) any pieces of substrate that stick to the stage. Generally, recovering material collected on the impactor walls is difficult, frustrating, and perhaps successful only on the inlet sections, where there may be a significant amount of material. By convention, all of the particulate matter collected between two consecutive primary collection surfaces is assigned to the second of the two stages. That is, all the material collected on surfaces between one substrate and another is considered to be a part of the catch of the second, or lower, substrate. Material collected in the impactor inlet assembly is added to the first stage catch, (as is the nozzle catch if no precollector is used).

As the impactor is unloaded note the appearance of each stage, substrate, or cyclone in a notebook or run sheet such as was shown in Figure 4-9. Use a magnifying glass or low-power microscope to examine the deposits. The deposits below impactor jets should appear as compact cones or spikes with little or no material appearing as streaks across the surfaces or "halos," i.e., concentric rings around the main deposit.

A SOP for loading and unloading the U of W impactor (Mark V-III) is given in Table 4-2 and Table 4-3. Section 4.5.3.H describes Procedures for Operating the Analytical Balance.

4.5.3.F Inspection of the Run

Section 3 and 4 discussed deviations from theory and practical problems. The purpose of this inspection is to verify that these problems have been successfully avoided or limited. This analysis consists of a visual examination of a completed impactor run and a study of the postrun dry weights. The analysis is summarized in the following paragraphs which give qualitive and quantitative guidelines. The problems discussed cover nozzle scraping, bounce, overloading, underloading and negative weight changes. Additional inspection information is given in Section 6.2.

Nozzle Scraping

It is extremely easy to scrape a nozzle when inserting or removing the impactor from a port. If this happens, the results can be devastating. If the nozzle is significantly damaged as determined by the visual inspection made at the time of the postrun hot leak check it may be necessary to reject the run. Even if the nozzle is not damaged, scrapings from the port well may invalidate the precollector catch. For this reason the precollector catch and zero stage collection plate (solid disk) should be inspected for particles that are

Table 4-2

Impactor Loading Procedure for the
University of Washington Mark III/V Cascade Impactor

Note: All parts must be cleaned prior to assembly

A. Outlet Section

1. Secure outlet section of impactor in vise.
2. Place o-ring in groove at base of threads.
3. Teflon tape threads, approximately 1 1/2 wraps.
4. Place filter support plate and fine screen in outlet section, support plate first, fine screen second.
5. When using a second (blank) filter for QA purposes one Teflon ring (marked BF) and blank filter are placed on top of the fine screen. The second Teflon ring marked BF is then placed over the filter. The filter assembly is then placed on top of the blank assembly as follows: Teflon ring, filter, Teflon ring. If stack temperatures exceed 425°F, Kapton may be substituted for the Teflon.
6. Check to insure that the Teflon rings and filters are lying flat. Place the filter collar onto the outlet section and turn gently until the alignment pin on the top of the outlet section matches up with the hole in the filter collar. The Filter collar should now be properly seated.
7. The inside edge of the top Teflon ring should be visible along the inside edge of the collar. If not, it should be replaced since the collar will cut the filter when the impactor is tightened.
8. Place an o-ring in the groove at the top edge of the filter collar.

B. Impactor Substrates

1. If a blank collection plate is to be included in the run, place the proper foil substrate in a collection plate. Place the collection plate on the filter collar with the substrate facing the impactor outlet (upside down).
2. Starting with the foil designated as the last collection substrate, place the foil in a collection plate and put it on top of the blank with the substrate surface facing up. If a blank is not used, this plate is placed directly on the filter collar with the substrate surface up.
3. The last jet plate (smallest flow area) is then placed on top of the collection plate. The jet plate should be oriented so that the jets are at the bottom, closest to the collection plate.
4. Place o-ring in groove at top of jet plate.
5. The remainder of the donut-shaped substrates should be loaded in the same way and added to the stack, alternating collection plates with jet plates.
6. When the last of the donut-shaped substrates and the corresponding jet stages have been placed in the stack, the zero stage collection plate

should be loaded with the disk-shaped substrate and placed on top of the stack.

7. Align the stack, then slide the impactor cylinder (outer shell) over it. Tighten the cylinder onto the outlet section until it seals against the outlet section o-ring.

C. Inlet Section

1. Wrap Teflon tape approximately 1 1/2 times around the threads of the inlet section.
2. Screw the inlet section (with connecting tube attached) into the impactor shell. Hand tighten only. Excessive tightening of the inlet section into the shell can cut the back up filter.

D. Precollector

1. Wrap threads of top and bottom sections and the nozzle 1 1/2 times with Teflon tape.
2. Screw bottom section and nozzle into precollector body.
3. Remove foil from petri dish and curl slightly.
4. Insert foil into precollector body, greased side facing nozzle inlet.
5. Screw top onto precollector body.
6. Tighten precollector onto connecting tube (impactor body). Make sure the precollector is aligned such that the bend in the connector tube offsets the nozzle.

E. Leak Check

1. Connect the inlet of the precollector/impactor assembly to the suction end of a pump by attaching a hose to the nozzle. Cap the outlet.
2. Pull a vacuum of approximately 10 inches of mercury on the assembly and observe the vacuum pressure for about a minute.
3. After this observation period is over, release the vacuum at the inlet, not at the outlet. Opening the outlet to ambient can rupture the filter.
4. Pressure losses of approximately four to five inches should be expected. Drastic leaks indicate loose fittings or missing o-rings. Attempt to correct any leaks. Use of a slightly positive pressure (~6 inches of water) and a soap solution may help to locate the source(s) of the leak(s).
5. If small leaks are present which can not be corrected, a leak check should be performed without the precollector.
6. Enter leak check data in appropriate space on impactor lab sheet.

F. Wrapping

1. On two small pieces of high temperature tape, write the impactor run code. Place one on the impactor and the other on the precollector.
2. Wrap impactor body and precollector with aluminum foil and secure with tape.
3. Rewrite impactor run code on the wrapped impactor body.

Table 4-3

Impactor Unloading Procedure for
University of Washington Mark III/V Cascade Impactor

A. Preliminary

1. Hold impactor upright at all times.
2. Remove foil wrapping and blow off any loose dust from the impactor/precollector assembly with compressed air or gas (Effaduster). Cover nozzle with thumb to prevent blowing into precollector. Exterior surfaces should be clean to prevent contamination during unloading.
3. Secure outlet section in vise for disassembly.
4. Remove impactor lab sheet from run sheet notebook. As substrates are unloaded, observations such as broken peaks or loose particulate should be noted on the lab sheet.

B. Precollector and Impactor Inlet Section

1. Separate precollector from impactor where precollector attaches to the connector tube.
2. Unscrew top of precollector and remove foil from body, placing in petri dish.
3. Remove nozzle from precollector body and using clean dry brush, brush any loose particulate on the inside of the nozzle or the top section of the precollector onto the foil. Place nozzle to the side so that it can be washed in Step 7.
4. Separate body from bottom section and (using the same brush) brush any loose particulate in either section onto the foil. Place the brush to the side so that it can be washed in Step 7. Note: particulate on the inside of the exit tube (bottom section) should be transferred to the first substrate of the impactor.
5. Carefully fold foil in half twice and then loosely fold a small ridge on each side to prevent loss of particulate. The fold must be loose to permit drying during desiccation.
6. The tube connecting the precollector to the impactor should remain connected to the inlet section of the impactor. Any particulate in this tube should be brushed (using a second clean brush) onto the first substrate in the impactor. This is best done by tapping the sides of the tube over the substrate, then brushing the interior of the tube with a small nylon bristle brush. The interior surface of the precollector exit tube (bottom section) should also be brushed onto the first substrate in the impactor. Set tube/inlet assembly, precollector exit tube, and brush, to the side so that they can be washed in Step 8.
7. Washdown techniques as described in Section 4.2 of Method 17 may be used to rinse the nozzle and brush with acetone. The collected rinse must then be evaporated, desiccated, and weighed on a precision balance. Note: It is important that the brushes used were previously cleaned by an acetone rinse and allowed to dry before being used to

brush the particulate. Since short straight nozzles are used, it may not be necessary to perform this nozzle washdown.

8. The precollector exit tube and the connecting tube between the precollector and impactor should also be washed into a second sample bottle. The evaporated dry weight gain from this washdown is assigned to the impactor's zero stage as shown in Figure 4-11 (Example Weight Sheet).

C. Impactor Substrates

1. Loosen and remove the shell of the impactor. The impactor inlet section with attached connecting tube was removed in Step B8 above.
2. Inspect the interior of the shell for any evidence of internal leakages. If any such evidence is found, make a notation and try to identify the stage(s) with which it was associated.
3. Remove the zero stage collection plate from the stack. If the o-ring of the jet plate directly beneath the collection plate sticks, remove both plates from the stack.
4. Remove the disk-shaped substrate from the collection plate and place in its labeled petri dish. This is best accomplished by grasping the edge of the substrate with tweezers and rotating the disk gently.
5. If the jet and collection plates are stuck together, gently push the collection plate horizontally until the o-ring seal releases.
6. Each donut-shaped substrate should be removed in the same way and placed in its respective labeled petri dish.
7. Any particulate present on the surface of a jet plate should be brushed onto the substrate directly beneath it unless it is obvious that the material was removed or reentrained from the preceeding substrate.

D. Outlet Section

1. Gently lift the filter collar and brush any part of the filter adhering to it into the foil envelope.
2. Removing the outlet section from the vise, insert the handle of the brush into the outlet neck and gently lift the filter support plates.
3. Remove filters and Teflon rings from the plates and place respectively, dirty filter and two Teflon rings into the foil envelope and clean filter with two Teflon rings (labeled "BF") into its labeled petri dish.

E. Reloading Preparation

1. All parts of impactor and precollector should be blown off with compressed air or gas (Effaduster) before being reloaded as described in Table 4-2.

obviously too large to have been suspended in the gas stream during sampling, or which appear from their shape, coloration, etc. to be foreign material.

Bounce

The "UD_{50} product" guidelines discussed in Section 4.5.3.A.5 are intended to prevent a situation where bounce could be a problem. The visual inspection however is still necessary. Bounce can occur even when stages are not overloaded. Bounce occurs when the collection plate substrate material fails to capture and hold a particle that strikes its surface. If bounce has occurred the most direct indication is the filter. The filter loading will be very high and observation with a 10x occular will show the presence of particles much larger than the D_{50} of previous stages. When bounce occurs it is usually a substrate problem, meaning that a different substrate material must be used or the UD_{50} products of the stages must be reduced by sampling at a lower flow rate. Sometimes the same end result can occur from scouring due to excessive jet velocities. The UD_{50} product guideline used in the impactor flow rate/stage selection section will indicate those cases where a different jet stage or impactor flow rate should be selected.

Overloading

The maximum individual stage loading which should be permitted (excluding the precollector and filter) is 15 mg. The impactor is normally operated in a horizontal mode, consequently captured particulate may fall away from the substrate and migrate to some other part of the impactor unless the substrate material holds the particulate in place. Greased substrates normally work well for this purpose. Matted materials such as quartz or fiberglass will trap the particulate in the fiber mat. Visual observations can provide some indication of whether the "capture" ability of the substrate material has been exceeded. If so, this run is in question and subsequent runs should sample for shorter durations.

4.5.3.G Multiple Sampling Runs

Multiple impactor runs are required to characterize a given test condition (inlet, outlet, etc.). Cascade Impactors are labor intensive instruments with typical run times of two to six hours (at the outlet of a high efficiency control device). The cost per run is quite high, yet if results are to be believable, multiple runs must be performed. The absolute minimum number of "good" runs is three. This does not include the mandatory Blank Run or the exploratory Initial Run. The recommended minimum number of good runs is five since these two additional runs decrease the width of the confidence interval at the 95% confidence level to about 1/2 the interval for three readings (a 50% gain in confidence). To obtain an additional 50% gain over the three run confidence interval (50% decrease in the width of the confidence interval associated with the five runs) one would need to make a total of about 14 runs. Admittedly 14 runs is impractical. Seven runs is reasonable and yields roughly one-half the benefit of increasing the number of runs from 5 to 14. For this reason five good runs is the recommended minimum, seven is desirable, while three is the absolute minimum requirement. If, as described in Section 5.5.3.A.4, a skewed velocity profile requires multiple regions (multiple runs)

Table 4-4

Desiccation of Substrate Sets
(Pretest and Post-Test)

1. Substrate sets should desiccate for approximately 6 to 12 hours immediately prior to the first weighing (Pretest and Post-Test).

2. A small tray of fresh desiccant should be placed in the weighing compartment of the balance (to prevent moisture uptake during weighing) and the exposure of the substrate (filter) to undesiccated air should be minimized unless a moisture uptake test shows that exposure to room air does not result in significant weight changes. This test is made by performing multiple weighings on the same substrate after different amounts of exposure time to room air. Weighing procedures are given in Table 4-5.

3. The substrate set should desiccate for a second 6-12 hour period before the second weighing. This second weighing may be a spot check unless the difference between the two weighings is greater than 0.05 mg. Second weighings should always be performed on the filters and on post-test weighings of the precollect and most heavily loaded substrates.

4. If the difference between the first and second weighings is greater than 0.05 mg, a third weighing should be performed after further desiccation.

Each sample to be weighed should be desiccated to a constant weight, with periodic checks being used to establish constancy. Hard, nonvolatile particles may be dried in a convection oven at 100°C (212°F), then stored in a desiccator until they cool to room temperature. Weigh them, then check-weigh them 2 hours later. Volatile particles present special problems which have to be dealt with according to the characteristics of the particulate matter and the sampling goals. One technique that has been used for particles which are volatile at elevated temperatures is to dry them in a desiccator 24 hours at room temperature before weighing. Whatever the technique, constant weight of the samples after further drying is the criteria which is normally to be used. Record the results of the weighings (Figure 4-11, Example Weight Sheets) and any notes in a notebook.

Occasionally samples are collected which are inherently unstable in weight. This can occur if the collected particulate matter is reactive, if it is so hygroscopic that it continues to absorb water even in a conventional desiccator, or if it contains a component sufficiently volatile at room temperature to evaporate during the desiccation period. For these situations special weighing protocols may have to be devised using insight into the nature of the offending process. For example, one may deal with steady loss of volatile components by immediate "warm" weighing of real and blank substrates followed by periodic reweighings to establish an estimate of the dry, "time zero" weight. Similar techniques or improved desiccation techniques may be used with hygroscopic weight gains. Occasionally it has proven useful to chemically alter a hygroscopic component. In particular, neutralization of sulfuric acid by exposure to trace amounts of ammonia vapor may allow otherwise intractable substrates to be dried to a stable weight.

Table 4-5 is an SOP for operating the balance. Section 4.5.3.D.2 gives a recommended configuration for use with the UW Mark V/III. This configuration is used in the example weight sheet (Figure 4-11).

On some impactors such as the UW Mark 5, the inlet throat serves as the first jet stage. The D_{50} of the precollector is frequently close to, or perhaps smaller than, that of the first stage. The minimum stage D_{50} ratio should be 4:3 (x 1.3 or Δlog D=0.124). For stage D_{50}'s more closely spaced, the weight change on the lower stage tends to be affected too much by the lack of sharpness in the collection efficiency of the upper stage (see Section 2 - Theoretical and Empirical Basis for Cascade Impactors). For this reason if the D_{50} of a stage is too close to that of an adjacent stage its weight is combined with that of the next lower stage and it is omitted from the analysis. If the D_{50} of the precollector is less than that of the first stage, the weight change of the first stage provides a measure of the reentrainment from the precollector. The weight sheet records record the individual weights, these are combined by the computer program options described in Appendix A.

As shown in Figure 4-11 and discussed in Section 4.5.3.D.2 the filter, foil pouch, and two Teflon insert rings are weighed as an assembly rather than individually. The blank filter and two Teflon insert rings marked "BF" are also weighed as an assembly. The weight sheet (Figure 4-11) provides a section for recording washdown weights and a description of the tare weights used. The check marks on Figure 4-11 indicate that the reproducibility criteria was satisfied for the control weight, blank substrate, and blank filter as specified in Section 4.11 (Acceptable Results).

WEIGHT SHEET

University of Washington Impactors (Pilot)
Mark V Stages in a Mark III Type Shell

SUBSTANCE SET NO. I 23
☐ APIEZON H
☐ FIBERGLASS ☐ BARE
☐ HERC. POLY. ☐ OTHER

DATE OF INITIAL WEIGHING 1: 4 - 10 - 84
DATE OF INITAL WEIGHING 2: 4 - 11 - 84
DATE OF FINAL WEIGHING 1: 4 - 21 - 84
DATE OF FINAL WEIGHING 2: 4 - 22 - 84

WASH DOWN

$C_a = 5 \times 10^{-6}$ mg/ml

SOLVENT ☐ ACETONE ☐ DISTILLED WATER

PRECOLLECTOR NOZZLE AND BODY: EVAPORATOR DISH:	
ID	I 23 N
INITIAL Wt (mg)	416.72
FINAL Wt (mg)	420.16
Δ (mg)	3.44
WASH VOLUME (mL)	156 ml
RESIDUE, W_{aN}	0.0008
CORRECTED WASH WEIGHT	3.44 mg

PRECOLLECTOR EXIT TUBE AND SOLID DISK: EVAPORATOR DISH:	
ID	I 23 T
INITIAL Wt (mg)	418.53
FINAL Wt (mg)	419.23
Δ (mg)	0.70
WASH VOLUME (mL)	161 ml
RESIDUE, W_{aT}	0.0008
CORRECTED WASH WEIGHT	0.70 mg

(ADD THESE WEIGHTS TO THE DRY WEIGHTS TO GET TOTAL WT GAIN)*

DESCRIPTION	ID NO.	INITIAL TARE (mg)	INITIAL 1 (mg)	INITIAL 2 (mg)	FINAL TARE (mg)	FINAL 1 (mg)	FINAL 2 (mg)	TOTAL WT. GAIN (mg)
PRECOLLECTOR	I23P	100	30.66	30.69	100	48.79	48.81	21.57*
SOLID DISK	I23D	700	4.31	4.29	700	5.16	5.17	1.55*
	ZERO		00.00	00.01		-00.01	00.00	
DISK DONUT:								
CONTROL	CTRL	1050	57.14	57.15	1050	57.14	57.14	✓
S1	I23-1	↓	58.32		↓	59.88		1.56
S2	I23-2		53.03			57.87		4.84
S3	I23-3		65.07	65.05		66.67		1.60
S4	I23-4		64.06			64.95		0.89
S5	I23-5		56.87			56.96		0.09
S6	I23-6	↓	56.02		↓	55.89		-0.13
BLANK	I23-B	1050	64.91		1050	64.73		(-0.18) ***
FILTER 1 *	I23-F	600	53.03	53.01	600	54.06		1.36 ***
FILTER 2 * *	I23-BF	500	62.01	62.00	500	62.34		N/A
	ZERO		00.01	-00.01		00.00	00.01	

7 → 3.11

SEE ALSO: (1) LAB LOAD/UNLOAD SHEET
(2) OPERATOR'S RUN SHEET

RUN NO. SAMPLE CALC
DATE 4-20-84

COMMENTS:

FILTER TYPE: ☐ 2500 QAS QUARTZ
☐ REEVE ANGEL 934AH FIBERGLASS ☐ ACID WASHED ONLY
☐ GEIAH TEFLON ☐ ACID WASHED AND STACK CONDITIONED
☐ OTHER ☐ STACK CONDITIONED ONLY

DESCRIPTION OF TARES USED:

* FILTER + 2 TEF. RINGS + POUCH
** BLANK FILTER + 2 TEF. RINGS (BF)
*** COMBINED WEIGHTS SINCE BF STUCK TO F DURING RUN

100 → 100
700 → 500 + 200
1050 → 500 + 500 ss + 50
600 → 500ss + 100
500 → 500

6698-11C

18.13 + 3.44 = 21.57
0.85 + 0.70 = 1.55
1.03 + 0.33 = 1.36

Figure 4-11. Example of a completed Weigh Sheet.

Table 4-5

Balance Procedures for 1/100 mg Analytical Balance
(See also Figure 4-11 Example Weight Sheet)

Note: The procedures listed in this table are generic and should be considered minimal. Modifications should be made as appropriate for a specific vendor's model number.

A. Precautions

1. Calibration and tare weights should be handled with smooth edged tweezers. These tweezers should not be used on substrates.
2. When substrates are weighed, check to make sure the substrate is not touching the side of the weighing chamber.
3. Door to weighing chamber should be kept closed except when changing substrates or weights.
4. To protect tare weights, the boxes containing these weights should be closed. Tare weights must be protected from dust and lint.
5. Balance and weighing chamber should be equilibrated in temperature with their surroundings to avoid thermal drift of the zero and scale factor (calibration dial). Room temperature in the weighing room should be regulated to less than 85°F and maintained at this temperature ±5°F throughout the weighing session. Wide swings in temperature can be devastating.
6. Adequate warmup time must be allowed to assure electrical stability (10-30 min.) and thermal stability. It is best to allow the balance to remain in a power on (standby) mode 24 hr. days during a test. Be sure that sunlight does not shine directly on the balance weighing chamber.
7. Place a small dish filled with indicating type silica gel (desiccant) inside the weighing chamber. Be sure this dish does not interfere with the pan movement.

B. Weighing Procedure

1. Check to make sure electrical tare indicator is off.
2. Range dial should be set to 200 mg range.
3. Check zero. If readout does not indicate 00.00, adjust coarse and fine zero dials until the readout is 00.00.
4. Remove 200 milligram calibration weight from container with smooth edged tweezers and place on weighing pan.
5. Allow balance sufficient time to equilibrate. If readout is not 199.99 adjust with calibration dial. This adjustment sets the scaling factor.
6. Record calibration and zero data in balance log book along with date and time.
7. Weigh each tare weight and enter this data in the balance log book. The 50, 100, and 200 mg tare weights should be weighed (without tares).

The two 500 mg tare weights should be weighed with the 100 mg and 200 mg weights used as tares.

8. If extreme changes (>0.05 mg) in the weights of the tares are noted, the zero and calibration of the balance should be checked and these values, along with any adjustment, should be noted in the log book. The tare weights should then be reweighed as described above. The problem could be that one of the tare weights is dirty and needs to be cleaned.
9. After the tares are weighed, the zero should be rechecked and recorded in the log book, along with any required adjustment.
10. Remove the first substrate from the dessicator. These should be weighed "one at a time" to avoid moisture uptake.
11. The entire control weight set, A through D, should be weighed as part of the first substrate set. These weights should be recorded on the control set weight sheet in the balance log book as well as on the weight sheet.
12. The zero should be checked and recorded, along with adjustments, each time tares are changed and between substrate sets (as shown on the weight sheet).
13. After the first substrate set is weighed, only control weight C need be reweighed with each subsequent set. If an extreme change in the weight of the control occurs, the zero and calibration of the balance should be checked. The entire control set should then be reweighed. If the weight change is still occurring, check for a dirty tare or control (clean if found) and reweigh each tare. Proceed with the weighing of the substrate sets only when this problem has been corrected.
14. Unless weight changes requiring recalibration of the balance occur, the calibration only needs to be checked every two hours.
15. When the weighing session is concluded, the balance zero and calibration should be checked a final time. Do not turn the balance off. Power should only be turned off when all weighings for the field test have been completed. This avoids long delays as the balance warms up and obtains thermal stability.

4.5.3.I Quality Assurance/Quality Control

Quality Assurance and Quality Control procedures are listed throughout this report. Section 6 summarizes procedures to be used with cascade impactor/precollector systems.

4.6 Calibration

One central laboratory/on-site log of all calibrations should be maintained. Entries from this log should also be posted in the equipment maintenance records. The following paragraphs describe the calibration procedures for the instrumentation used with cascade impactors.

4.6.1 Pitot Tube

As shown in Figure 4-1 a pitot tube is not used as an integral part of the Impactor Sampling Train. At many commonly encountered flow rates, the presence of the precollector could result in a flow interference at the pitot head causing it's coefficient, C_p, to differ from the baseline value even when the pitot is dimensioned as described in Method 2. This interference is dependent on nozzle size and stack velocity. For this reason the pitot is omitted from the sampling train.

A separate Method 2 Pitot Probe is used to measure the velocity profile at various times during a test program. This probe and it's components should be calibrated as per Section 4 of Method 2.

4.6.2 Precollector Nozzle

Each nozzle shall be permanently and uniquely inscribed with an identification number. All calibrations and maintenance repairs shall reference this number. Each nozzle shall be inspected and calibrated before initial use. If nicks, dents, or corrosion are discovered at a latter date, the maintenance logs shall be noted, the nozzle repaired and recalibrated as described below. Figure 4-12 is a data form that may be used for this purpose. A micrometer capable of measuring inside diameters to the nearest 0.025 mm (0.001 in.) shall be used to make three measurements of the inside diameter of the nozzle (undamaged nozzles only) each on a different axis as shown on the Form. The average of these three measurements is then calculated. The difference between the high and low numbers should not exceed 0.1 mm (0.004 in.).

4.6.3 Metering System Dry Gas Meter

Wet test meter calibrations of the Dry Gas Meters (DGM) are performed prior to initial use, and later as required, by comparison to a "Standard" Dry Gas Meter. After each field use the calibration of the metering system shall be checked by comparison to a Standard dry gas meter as described in Section 4.3 of Method 5. Leak checks shall be performed as described in Section 4.5.3.D.4 prior to any calibrations or comparisons.

The maximum acceptable leak rate (pump warm and running) is 0.00057 m^3/min (0.02 cfm) for systems to be used at flows higher than 0.2 cfm. For low flow rate sampling situations (flow rates <0.2 cfm) the leak rate should not exceed 0.00014 m^3/min (0.005 cfm). Leaks producing rates greater than these should be repaired before calibration. If leakless pumps suitable for low flow rate operation cannot be obtained, it may be necessary to place the pump downstream of the gas metering system. The field setup programs described in Appendix A make provision for this configuration.

Calibration procedures using a wet test meter are described in APTD-0576. NOTE--If the dry gas meter coefficient values obtained before and after a test

DATE/TIME	CALIBRATED BY	NOZZLE ID NUMBER	NOZZLE DIAMETER (INCHES)			ΔD	D_{avg}
			D_1	D_2	D_3		

WHERE:

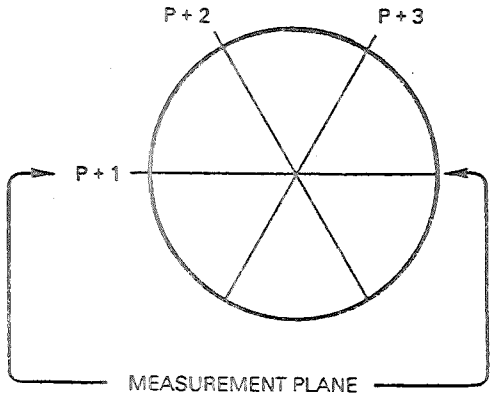
$D_{1, 2, 3}$ = THREE DIFFERENT NOZZLE DIAMETERS AT 60 DEGREES TO EACH OTHER. EACH MEASURED TO THE NEAREST 0.001 INCH

ΔD = MAXIMUM DIFFERENCE BETWEEN ANY TWO DIAMETERS, $\Delta D \leq 0.004$ INCH

$D_{avg} = (D_1 + D_2 + D_3) \div 3$

INSTRUCTIONS

1. INSPECT THE NOZZLE FOR NICKS, DENTS, AND CORROSION. IF THESE ARE FOUND THEY SHOULD BE CORRECTED BEFORE CALIBRATION.
2. PLACE A REFERENCE MARK ON THE NOZZLE. PLACE THE NOZZLE AT THE CENTER OF FIGURE, ALIGNED WITH POINT 1. MEASURE AND RECORD D_1.
3. ROTATE THE NOZZLE SO THAT THE REFERENCE MARK IS ALIGNED WITH POINT 2. MEASURE AND RECORD D_2.
4. ROTATE THE NOZZLE SO THAT THE REFERENCE MARK IS ALIGNED WITH POINT 3. MEASURE AND RECORD D_3.
5. CALCULATE ΔD AND D_{avg}.



5598-10

Figure 4-12. Nozzle calibraton

series differ by more than 5 percent, the test series shall either be voided, or calculations for the test series shall be performed using whichever meter coefficient value (i.e., before or after) gives the lower value of total sample volume.

4.6.4 Metering System Orifice Flow Meter

Calibration of the Metering System Orifice Flow Meter is described in Section 4.3 of Method 5.

4.6.5 Metering System Differential Pressure Meter

Calibration of the Metering System Differential Pressure Meter is described in Section 2.2 of Method 2.

4.6.6 Temperature Measuring Systems

Calibration of Temperature Measuring Systems is described in Section 2.3 of Method 2.

4.6.7 Barometer

Calibration of Barometers is described in Section 2.5 of Method 2.

4.6.8 Flue Gas Molecular Weight Determination Equipment

Calibration and operation of the Molecular Weight Determination Equipment (Fyrite Analyzer) is described in Method 3.

4.6.9 Impactor Stage Calibration Constants

As described in Section 2.4 (Verification of Impactor Theory) normal treatment of field data is to use stage impaction constants ($\sqrt{\psi_{50i}}$) calculated from the modified Marple theory rather than stage constants determined during laboratory calibration. The focus of laboratory impactor calibrations has been to validate the theory over a wide range of variations in each of the important parameters used in the model. The significance is that only impactor designs which have been validated by laboratory calibration should be used. Appendix B lists commercially available impactor designs which have been validated together with the physical parameters (stage geometry constants) used by the computer program of Appendix A to calculate the theoretical stage constants for the given test conditions of temperature, pressure, gas composition, particle density and impactor flow rate. Stage geometry constants are: number of holes, average hole diameter, and jet-to-plate spacing (distance). In the data reduction program, MPPROG, the stage impaction constants, $\sqrt{\psi_{50}}$, are designated as SI(i). It should be noted that program MPPROG requires the operator to select either theoretical or fixed calibration values (manually entered in the program DEF/IMP) for the impaction constants ($\sqrt{\psi_{50}}$). Selection of theoretical calibration values also incorporates adjustments to the stage constants due to the particular type of substrate material used (bare metal, coated metal, or fiberous matt). Choice of impactor flow rate and stage selection (Section 4.5.3.A.5) should be such that the Reynolds Number (Re) is

at least greater than 50. Calibrations have shown the theory to be questionable for some jet configurations at Re < 50.

4.6.10 Analytical Balance (1/100 mg)

The operating procedures for the analytical balance (Section 4.5.3.H) provide for frequent calibration using Class S standard weights traceable to the National Bureau of Standards. No further calibration is required beyond that specified in Section 4.5.3.H.

4.6.11 Triple Beam Lab Balance (1/2 g)

The lab balance is calibrated using a 50g Class P (or equivalent) analytical weight. After set up in the on-site lab, a silica gel drying column is placed on the balance and the reading is recorded. The 50g Class P weight (1.2mg tolerance) is added to the drying column on the balance pan and this second reading is recorded. The difference between the two weights, Δ, must satisfy the following criteria: $49.50g \leq \Delta \leq 50.5g$.

4.7 Calculations

The following paragraphs give equations involved in the setup, operation, and data analysis of cascade impactors. In practice, the calculations are performed by the computer programs documented in Appendix A of this report. Further explanation as to the use of the equations is given in various sections of this report, to include Section 4 (Field Protocol) and Section 5 (Data Reduction and Analysis Procedures).

4.7.1 Nomenclature

Variables are defined as they are used in the equations.

4.7.2 Preliminary Moisture Content Estimates

An initial guess at the stack moisture is used in the preliminary calculations for stage selection, impactor flow rate, and Target ΔH for use with the initial run. Accurate moisture data is obtained during the initial run or by application of Method 4, but an estimate must be made prior to the run. Plant operating personnel will frequently be able to provide stack moisture information. This data may also be available from previous test reports. If necessary, one may use a preweighed drying column and the meter box from the sampling train. Simply record the initial gas meter reading and pull filtered stack gas through the preweighed drying column until the indicating silica gel shows some moisture collection. Record the final gas meter reading and determine the final weight of the drying column. The weight change of the drying column and the gas meter change are used in Section 4.7.13 to estimate the stack moisture.

4.7.3 Gas Density

A Method 3 analysis (Fyrite or Orsat) is used to determine the dry gas volumetric fraction for oxygen (O_2) and carbon dioxide (CO_2). The preliminary

moisture content estimate (B_{ws}) is then used together with the O_2 and CO_2 values to calculate the dry mean molecular weight (M_d) and the wet mean molecular weight (M_w) of the flue gas as follows:

$$M_d = 32\ B_{O_2} + 44\ B_{CO_2} + 28(B_{N_2} + B_{CO}) \qquad (4\text{-}1)$$

where B_{O_2}, B_{CO_2}, B_{N_2}, and B_{CO}, are the dimensionless dry volumetric fraction for O_2, CO_2, N_2, and CO respectively. M_d has dimensions of lb/lb mole. Dry air has a value of 29 lb/lb mole.

$$M_s = M_d\ (1-B_{ws}) + 18\ B_{ws} \qquad (4\text{-}2)$$

where B_{ws} is the volumetric fraction for water (stack moisture), dimensionless.

4.7.4 Point Velocity

A Method 2 pitot is used to measure the temperature (T_i) and velocity pressure head (Δp_i) at each Method 1 traverse point across the duct. This data is used to calculate the velocity at this point (υ_i) as follows:

$$\upsilon_i = K\ (\Delta p_i\ T_i)^{1/2} \qquad (4\text{-}3)$$

where υ_i = pitot velocity (ft/sec) at point i,

T_i = absolute temperature at point i (°R = °F + 460),

Δp_i = pitot pressure reading (inches H_2O) at point i,

K = pitot-gas composition factor, given by:

$$K = 2.9\ C_p\ (29.92\ R'/P_s)^{1/2} \qquad (4\text{-}4)$$

where $R' = 28.95/M_s$, (4-5)

$P_s = P_{bar} + P_g$, (4-6)

C_p = Pitot calibration coefficient (dimensionless). For a Type S pitot which matches the criteria of Method 2, this coefficient has a value of 0.84. A Type S pitot which does not meet the criteria of Method 2 should be calibrated as described in Section 4 of Method 2. A standard pitot is constructed such that it has a coefficient of 0.99,

M_s = Wet mean molecular weight,

P_s = Absolute stack pressure (inches Hg),

P_{bar} = Ambient pressure, barometric pressure at the stack measurement site (inches Hg),

P_g = Stack gauge pressure, differential (±) to atmosphere, (inches Hg, 13.6 inches H_2O = 1.00 in. Hg). As described in Method 2 this value is measured by disconnecting the downstream side of

the pitot line so that we read the differential between ambient and the downstream side of the Type S pitot. The pitot manometer reads in inches H_2O so we must convert the ± reading to inches Hg by dividing by 13.6.

4.7.5 Velocity Profile/Average Stack Velocity and Regions

The velocity profile is determined by calculating the velocity at each point of the Method 2 traverse. These point velocities may then be averaged over the whole traverse or over regions of the full traverse (see Section 4.5.3.A.4). The average velocity for the full traverse (v_s) and the average temperature (T_s) are as follows:

$$v_s = \frac{1}{n} \sum v_i \quad (i = 1,n) \qquad (4\text{-}7)$$

$$T_s = \frac{1}{n} \sum T_i \quad (i = 1,n) \qquad (4\text{-}8)$$

where n is the number of points in the traverse. The Impactor Traversing Protocol (Section 4.5.3.A.4) gives equations for a division of the Method 1 traverse points into two or more regions, calculation of required sampling velocity for each region, and averaging over only the points in each region.

4.7.6 Hardware Selection (t_{50mg}, Nozzle, Stage Configuration - D_{50})

The first decision related to hardware selection is to decide upon the sampler flow rate. Each impactor has a designed range of flows, the exact limits of which depend on stack temperature, viscosity, and the substrate material being used. At outlets one generally desires a high flow rate and at inlets one usually desires a low flow rate. These factors are discussed in Section 4.5.3.A (Preliminary Determinations). When selecting a flow rate (Q_I) one is interested in calculating the approximate run time (t_{50mg}) associated with this value of Q_I. An initial guess is obtained by calculating the time required to collect a total sample of 50mg (sum of the precollector, all stage, and filter weights). The following equations are used for this calculation:

4.7.6.A Time (minutes) to Collect 50 mg Total Sample Given Loading and Impactor Flow Rate

$$t_{50mg} = 0.77162/(Q_I G_A) \qquad (4\text{-}9)$$

where Q_I = actual impactor flow rate (ACFM),

G_A = mass loading (gr/ACF).

NOTE:

$$G_A = 17.65\, c_s\, (1-B_{ws})\, P_s/T_s \qquad (4\text{-}10)$$

where c_s = mass loading (gr/SCF) corrected to standard conditions, (dry, 68°F, 29.92 in. Hg),

T_s = Absolute Stack Temperature (°R = °F + 460),

P_s = Absolute Stack Pressure (inches Hg) as given by Eq. 4-6.

NOTE: 1.00 lb = 7,000 grains = 453.6 gm
(gr is the abbreviation for grains)

One should select a flow rate that will allow for reasonable run times, subject to the υD_{50} limits for the selected stages.

4.7.6.B Nozzle Selection Given Impactor Flow Rate

Only a discrete set of nozzles is available, thus one should modify the selected Q_I to permit the impactor to be operated isokinetically to the average velocity (υ_{si}) (over the traverse region i) while using one of the real nozzle sizes. The following equations are used for this purpose. Using the flow rate obtained from the t_{50mg} calculation, calculate an ideal nozzle size then pick a real nozzle close to this size and calculate the corresponding Q_I. Note different nozzles may be used for the different regions.

$$D_n = 1.748\ (Q_I/\upsilon_{si})^{1/2} \qquad (4\text{-}11)$$

where D_n = nozzle diameter (inches),
Q_I = impactor flow rate (ft^3/min). actual stack conditions,
υ_{si} = average velocity over region "i" (ft/sec),

or

$$Q_I = 0.3272\ \upsilon_{si}\ D_n^2 \qquad (4\text{-}12)$$

to see what Q_I results when a given nozzle is selected.

4.7.6.C Stage D_{50} Calculation

The following equations are used to select the stage configuration by calculating the size cut for a given impactor stage, given the stage calibration constant (K_s), impactor temperature (T), gas viscosity (μ), particle density, and several pressures:

$$D_{50i} = K_s(\mu P_s/Q_I \rho_p P_A C_{i-1})^{1/2} \qquad (4\text{-}13)$$

where D_{50i} = the value of the ith iteration for the D_{50} for this stage (cm)

Note: To convert from cm to μm multiply by 10^4 μm/cm

K_s = stage calibration constant, a function of geometry and substrate materials calculated by the modified Marple Impactor Theory described in Section 2.4,
P_s = local absolute pressure downstream of the stage jet (inches Hg),
Q_I = impactor flow rate (cm^3/sec),
P_i = absolute pressure at impactor stage inlet (inches Hg). This is the same as the stack

pressure, P_s, less the accumulated pressure drop from the preceeding stages.

ρ_p = particle density (gm/cm^3) determined by helium pychometer measurements,

C_{i-1} = i-1 iteration for the Cunningham slip correction factor as described below,

μ = gas viscosity (gm/cm/sec) as described below:

The D_{50} is a function of the Cunningham slip correction factor (C) and the Cunningham slip correction factor is a function of the D_{50}, consequently our approach is to make an initial guess at the Cunningham slip correction factor (C_o) and calculate the corresponding value for the D_{50}, D_{501}. This value, D_{501}, is then used to calculate a new value for the correction factor, C_1, which is in turn used to calculate a new diameter, D_{502}. We continue to iterate in this manner until two successive C_i values satisfy the closeness criteria given below:

$$\left|1-(C_{i-1}/C_i)\right| \leq 0.001 \qquad (4\text{-}14)$$

The equation for the Cunningham correction factor is as follows: An initial guess, C_o, is used to calculate D_{501}, subsequent C_i using D_{50i} are given by:

$$C_i = 1 + (2L/D_{50i})[1.23 + 0.41 \text{ EXP } (-.44\ D_{50i}/L)] \qquad (4\text{-}15)$$

where D_{50i} = diameter (cm) as obtained by using the D_{50i} equation above and the previously calculated value for C (C_{i-1}),

L = mean free path of the gas (cm).

For a stack temperature of 180°C, pressure of 30 inches Hg, and flue gas composition close to that of ambient air the Cunningham correction factor is approximately 1.03 for a 1 x 10^{-3}cm (10μm) particle and approximately 2.03 for a 3 x 10^{-5}cm (0.3μm) particle. A good initial guess for C then is C_0 = 1.03.

For standard air the mean free path (L) (over the range 0°C to 410°C) is given by:

$$L = (1.04\ \mu/P_s)(1 + 0.00367\ T)^{1/2} \qquad (4\text{-}16)$$

for T (°C), μ in (gm/μm/sec) as given below, P_s (inches Hg), and L (cm).

For standard air the viscosity (μ) (over the range 0°C to 410°C) is given by:

$$\mu = (174.4 + 0.406\ T) \times 10^{-6} \qquad (4\text{-}17)$$

for T (°C) and μ (gm/cm-sec).

A rigorous algorithm for the calculation of the viscosity of a gas mixture in terms of its components has been given by Wilke (1950). A simplified

version for combustion gases has been adapted by Williamson (1983). The simplified version is as follows:

$$\mu = C_1 + C_2T + C_3T^2 + C_4 F_{H_2O} + C_5F_{O_2} \quad (4\text{-}18)$$

where μ = gas mixture viscosity (micropoise),
F_{H_2O} = stack gas moisture fraction (by volume),

F_{O_2} = stack gas oxygen fraction (by volume),

T = absolute temperature of the gas mixture (°R) and for T in °R, the coefficients are as follow:

$C_1 = 51.05$, $C_2 = 0.207$,

$C_3 = 3.24 \times 10^{-5}$, $C_4 = -74.14$, $C_5 = 53.15$.

4.7.7 Criteria (Re, υD_{50})

The Reynolds number, Re, is given by Equation 2-1. In this section the symbol υ will be used to represent jet velocity, not stack gas velocity. The υD_{50} criteria has units of μm m/sec. The D_{50} is given by Equation 4-13 for units of cm. This value must be multiplied by 10^4 μm/cm to obtain the needed units for the υD_{50} product. The stage jet velocity (υ_i) is the velocity at each of the jets on stage i and is given by Equation 4-20 below:

$$\upsilon_i = K(P_s/P_i)\ (Q_A/n_iA_i) \quad (4\text{-}19)$$

where: P_s = Pressure at the inlet to the impactor. This is the same as the stack pressure (Eq. 4-6),
P_i = Pressure at the inlet to stage i (Eq. 5-23),
Q_A = Actual impactor flow rate at inlet to impactor, stack conditions,
n_i = Number of holes in stage i,
A_i = Average jet area (all jets must have the same nominal diameter) given by the following:

$$A_i = \pi D^2/4$$

K = A unit conversion constant

For υ_i (m/sec), Q_A (ft^3/min), and A_i (cm^2), K has the value
$K = 4.72$ (m cm^2 min/ sec ft^3)

in terms of D_i (cm) we have the following:

$$\upsilon_i = 3.71\ (P_s/P_i)\ (Q_A/n_iD_i^2) \quad (4\text{-}20)$$

for the above units.

4.7.8 Target ΔH Control Parameter

The target ΔH control parameter (ΔH) is given below. The development of this equation is described by Aldina and Jahnke (1979) in Appendix C of EPA 450/2-79-006 "APTI Course 450 Source Sampling for Particulate Pollutants-Student Manual", December 1979.

$$\Delta H = \left[846.72\ D_n^4\ \Delta H_@\ C_p^2\ (1 - B_{ws})^2\ \frac{M_d\ T_m\ P_s}{M_s\ T_s\ P_m} \right]\ \Delta p \qquad (4\text{-}21)$$

where:
- ΔH = Target ΔH control parameter (inches H_2O),
- D_n = Nozzle diameter (inches),
- C_p = Pitot tube coefficient, Type "S" or standard (dimensionless),
- B_{ws} = Stack moisture fraction as defined above,
- M_d = Mean molecular weight, dry, of the stack gas, as defined above,
- M_s = Mean molecular weight, wet, of the stack gas at the pitot, as defined above,
- T_m = Average absolute temperature of the dry gas meter (°R =°F +460),
- T_s = Average stack temperature for this traverse region (°R = °F + 460),
- P_m = Absolute pressure at the dry gas meter (inches Hg) as described below,
- P_s = Absolute pressure at the stack (inches Hg) as given by Equation 4-6,
- Δp = Average pitot pressure drop for this traverse region,
- $\Delta H_@$ = Orifice meter calibration constant, defined as the ΔH which yields 0.75 cfm at 528°R, 29.92 inches Hg, and M_d = 29.00.

Further explanation is given by the following:

$$P_m = P_{bar} + \frac{\Delta H}{13.6} \qquad (4\text{-}22)$$

for ΔH in inch H_2O, P_m and P_{bar} in inches Hg

Note: Here we have a term which is dependent on Δh itself. To be rigorous we would need to iterate until a convergence requirement is satisfied. To do this one would calculate ΔH_1 using an assumed initial value of ΔH_o=1.75, use ΔH_1 to calculate P_{m_1} and a new ΔH_2, test for convergence then continue iterating until convergence is obtained. In practice, however; this is not necessary because of the small range of ΔH values (.1→ 5) and the 13.6 divisor. This type of iterative approach will be required for other calculations such as the D_{50} equation and its dependence on the Cunningham correction factor.

NOTE: For impactor operation a Target ΔH control parameter (ΔH) is calculated for each traverse region using the average velocity for the respective regions (υ_{sk}). The above equation was originally intended for calculation of a ΔH for isokinetic sampling at each point in the traverse. Adaptation of this equation to impactor operation (where a constant flow rate is maintained throughout the run) is accomplished by the following equation:

$$\overline{\Delta p_k} = \left(\frac{1}{j} \sum_{i=1}^{j} \sqrt{\Delta p_i} \right)^2 \qquad (4\text{-}23)$$

for all points in region k

thus we average the square roots of the pitot pressure at each point then square this value.

The basic orifice equation is given below. The development of this equation is described in Appendix C of EPA 45012-79-006 "APTI Course 450 Source Sampling for Particulate Pollutants-Student Manual", December 1979.

$$Q = K \left[\frac{T\Delta H}{PM} \right]^{1/2} \qquad (4\text{-}24)$$

where Q is the actual flow rate through the orifice, T and P are the absolute temperature and pressure of the gas passing through the orifice, M is the mean molecular weight of the gas and K is a proportionately constant determined by calibration. The value of K is dependent on geometry and choice of units.

Method 5 expresses the calibration constant in terms of $\Delta H_@$ where $\Delta H_@$ is defined to be the pressure drop across the orifice which would result in a flow rate of 0.75 ft^3/min for dry standard air at 68°F (528°R), 29.92 in. Hg, and mean molecular weight of 29.0, thus in terms of K

$$\Delta H_@ = \frac{0.9244}{K^2} \qquad (4\text{-}25)$$

Orifice calibration procedures are described in Section 4.6.4 which yield $\Delta H_@$ values for each orifice.

4.7.9 Traverse Point Dwell Time

Velocity weighted dwell times are not recommended since all points in any given region are within ±20% of the sampling velocity (Section 4.5.3.A.4). Equal dwell times are used for all traverse points in a given Region. Thus the dwell time (t) for each traverse point in a given region is obtained from

$$t = \Theta/n \qquad (4\text{-}26)$$

where Θ = Total Run Time (min),
n = number of traverse points in a given Region.

4.7.10 Average Dry Gas Meter Temperature, Flue Gas Temperature and Orifice Pressure Drop (ΔH)

The average dry gas meter temperature, flue gas temperature, and orifice pressure drop (ΔH) are calculated using the form shown in Figure 4-7. Figure 4-9 shows example data. The average inlet dry gas meter reading and the average outlet dry gas meter reading are used to determine the average dry gas meter temperature.

4.7.11 Dry Gas Meter Volume and Leakage Correction

The sample volume measured by the dry gas meter (DGM), V_m, must be corrected to normal (or engineering standard) conditions, $V_{m(std)}$, (68°F, 29.92 in. Hg) by the following equations:

$$V_{m(std)} = 17.64\ (P_m/T_m)\ V_m Y \qquad (4\text{-}27)$$

where P_m = Absolute pressure at the dry gas meter (inches Hg) as given by Equation 4-22,
T_m = Average dry gas meter temperature (°R = °F + 460) as calculate on the run sheet,
Y = Dry gas meter calibration constant,
V_m = Actual sample volume as measured by the dry gas meter (ft^3). Final DGM reading minus initial DGM reading.

If the post-test hot leak check with the sampler removed shows a leak rate in excess of either 4% of the impactor flow rate or 0.02 ft^3/min then the run should be rejected. If the leak is less than this value no volume correction is required. If the leak test with the sampler in place showed a leak in excessive of 10% of the impactor flow rate the run is rejected. If the leak is less than the 10% limit (and the "sampler removed" test is less than the limit above) no correction is required because the flow calculated by the dry gas meter reading is correct.

4.7.12. Volume of Water Vapor, $V_{w(std)}$

The total moisture catch from the condenser and drying column is calculated on the Run Sheet at position U2 as shown in Figure 4-7 (see also Section 4.5.3.D.5 Instruction for Using the Run Sheet). The Total Volume H_2O (V_{lc}) in mL is converted to vapor equivalent by the following equation:

$$V_{w(std)} = \left[(\rho_w/M_w)(R\ \ T_{std}/P_{std})\right]V_{lc} \qquad (4\text{-}28)$$

$$V_{w(std)} = K_2\ V_{lc} \qquad (4\text{-}29)$$

where: K_2 = 0.04707 ft^3 water vapor (at 68°F, 29.92 in. Hg) per mL liquid water.

4.7.13 Moisture Content

The moisture content (B_{ws}) is calculated by the following:

$$B_{ws} = V_{w(std)}/\left(V_{m(std)} + V_{w(std)}\right) \qquad (4\text{-}30)$$

4.7.14 Acetone Blank Concentration, C_a

Acetone is used to washdown the nozzle, precollector, and connecting tube. This washdown liquid/particulate solution is then evaporated, desiccated and

weighed. This weight includes both the weight of the particulate removed by the washdown and the residue (impurities) of the solvent used to perform the washdown. To determine the weight of the particulate alone, we mut correct for the residue present in the washdown solvent. The acetone blank concentration (C_a) is used to make this correction. By measuring the volume of the acetone used to perform the washdown and applying this residue concentration factor (C_a), we can determine the weight of the residue and subtract this number from the total weight change to determine the weight of the particulate alone.

Approximately 200 mL of the acetone used for washdown is placed in a beaker labeled "Acetone Blank". This solvent is then measured (volume or weight), evaporated, desiccated, and weighed. The acetone blank residue concentration, C_a (units of mg residue per mL liquid acetone) is then calculated from the following:

$$C_a = m_a/(V_a\rho_a) \qquad (4\text{-}31)$$

where m_a = mass of residue of acetone blank after evaporation and desiccation (mg),
V_a = Volume of acetone blank (mL),
ρ_a = Density of acetone liquid (mg/mL). Used to convert between liquid volume and liquid weight. Specified by manufacturer on bottle's label.

Note: Acetone used for washdown must be stored in glass bottles. C_a is calculated for each separate bottle. For acetone to be acceptable as a wash down solvent the following criteria must be met:

$$C_a \times 100\% \leq 0.001\% \qquad (4\text{-}32)$$

4.7.15 % Isokinetic (I)

Calculation of % Isokinetic is the same as with Method 5/17 except that volume corrections are not made for measured leak rates and the average velocity is the average for a given region. This equation is as follows:

$$I = \frac{T_s\ V_{m(std)}\ P_{std}\ 100\%}{T_{std}\ \upsilon_s\ \theta\ A_n\ P_s\ 60(1-B_{ws})} \qquad (4\text{-}33)$$

$$= K_4\ \frac{T_s\ V_{m(std)}}{P_s\ \upsilon_s\ A_n\ \theta(1-B_{ws})} \qquad (4\text{-}34)$$

where K_4 = 0.09450 for English units given below,
T_s = Absolute Stack Temperature (°R = °F + 460),
$V_{m(std)}$ = Dry Gas Meter Volume (ft^3) corrected to 68°F, 29.92" Hg as given by Equation 4-27,
P_s = Absolute Stack Pressure (in. Hg) as given by Equation 4-22,
υ_s = Average stack gas velocity (ft/sec) for this Region. The

average of the point velocities for all points in this region, Equation 4-7,

θ = Total Sampling time (minutes),

B_{ws} = Stack moisture fraction (given by Equation 4-30) for this run,

100% = Conversion factor to percentage,

60 = Conversion factor, 60 sec per minute,

A_n = Cross sectional area (ft^2) of the circular nozzle given by:

$$A_n = \pi d^2/(4 \times 144) \qquad (4\text{-}35)$$

$$= 0.005454\ d^2$$

for d = nozzle diameter (inches),

144 = conversion factor, 144 in^2/ft^2.

4.7.16 Acetone Wash Residue, W_a

The weight of residue from the acetone used to perform a washdown must be subtracted from the evaporated/desiccated weight in order to determine the true weight of the particulate removed by the washdown procedure. The weight of the residue is referred to as the acetone wash blank, W_a (mg), and is calculated by the following:

$$W_a = C_a V_{aw} \rho_a \qquad (4\text{-}36)$$

where C_a = Acetone blank residue concentration as given by Equation 4-31 (mg residue/mL liquid acetone),

ρ_a = Density of acetone liquid (mg/mL). Used to convert between liquid volume and weight of a liquid,

V_{aw} = Volume of acetone used to perform the washdown (mL).

This residue weight contribution (W_a)is then subtracted from the washdown evaporated/desiccated weight. In no case shall a blank value (W_a) greater than 0.001% of the weight of the acetone used for a washdown ($V_{aw}\rho_a$) be permitted (i.e., $C_a \times 100\% < 0.001\%$).

With an impactor precollector two separate washdowns are performed (1) nozzle, body of precollector, and brush and (2) exit tube of precollector, connecting tube, and brush.

4.7.17 Total Particulate Weight, M_n (mg) and Blank Weight Corrections

If the blank impactor run shows reproducible weight changes, corrections may be calculated to be applied to the measured stage weight gains. If the weight changes are not reproducible, alternate substrate materials should be selected. Consider the set (w_i) consisting of all weight changes for substrates from the Blank Impactor run together with the weight change for the Blank Substrate from each real run. If the range of this set is less than ±0.25 mg the set may be considered reproducible and the average for this set should be applied as a correction to all the weight sheet records. Separate blank corrections are determined for the filter using the weight change values

from the two filters in the blank impactor run together with the blank filter in each of the real runs The corrections (substrate and filter) are calculated as follows:

Calculate the average:

$$\overline{w} = \frac{1}{n} \sum_{i} w_i \qquad i = 1,n \tag{4-37}$$

for w_i = Final Weight (mg) - Initial Weight (mg).

Test for Reproducibiltiy:

$$\overline{w} - c \leq w_{min} \leq w_{max} \leq \overline{w} + c \tag{4-38}$$

where c = 0.25 mg or 10% of the stage catch of the most lightly loaded substrate in real runs; which ever figure is smaller

If Equation 4-38 is satisfied for the set of all blank substrates (filters) the new weight change ($\Delta m_i'$) is calculated as follows:

$$\Delta m_i' = \Delta m_i - \overline{w} \tag{4-39}$$

where Δm_i is the weight change for a substrate (filter) and $\overline{w}$ is as calculated by Equation 4-37 for the appropriate set. One for the substrates and a different correction factor for the filters.

If the values from the blank runs are reproducible but individual runs violate the criteria of Equation 4-38 the outlier tests described in Section 5.4 may be used to selectively reject individual runs. Note that the data from such runs may include substrates where the blank weight change is a small percentage of the change for any given substrate. In such cases, we need only reject those substrates where the blank change exceed 10% of the weight change for this substrate.

The total particulate weight may be calculated by summing all corrected catch weights (precollector, collection stages, filter) and the washdown weights (corrected for the respective wash blanks, W_a).

4.7.18 Particulate Concentration, C_s (g/dscf)

The stack loading or particulate concentration is calculated from the following:

$$C_s = (0.001 \text{ g/mg})(M / V_{m(std)}) \tag{4-40}$$

where C_s = Particulate concentration, dry basis, connected to dry standard conditions (g/dscf) for the above equation,
M = Total particulate weight (mg),
$V_{m(std)}$ = Dry gas meter volume (ft^3) corrected to standard condition (68°F, 29.92 in. Hg).

Note: The dry standard particulate concentration, C_s may be expressed in different units (the same symbol, C_s is used). Common units for C_s are grains per dry standard cubic foot (gr/dscf), pounds per dry standard cubic foot (lb/dscf), and grams per dry normal cubic meter (g/dncm). Conversion factors are as follow:

From	To	Multiply by
ft^3	m^3	0.02832
g	gr	15.43
g	lb	2.205×10^{-3}
lb	gr	7,000
g/ft^3	g/m^3	35.31
gr/ft^3	gm/m^3	2.288
lb/ft^3	gm/m^3	1.602

The particulate concentration may also be expressed in terms of actual stack conditions, wet. The volume $V_{m(std)}$ must be converted to stack conditions and the moisture fraction taken into consideration as follows:

$$V_{m(A)} = \left[T_s/(17.65\ P_s)\right]\left[V_{m(std)}/(1-B_{ws})\right] \quad (4\text{-}41)$$

$$G_A = (0.001\ g/mg)\left(M/V_{m(A)}\right) \quad (4\text{-}42)$$

where G_A = Particulate concentration at actual, wet, stack conditions (g/dscf),
$V_{m(A)}$ = Volume of the dry gas meter (ft^3) expressed as actual wet stack gas sampled through the impactor, stack temperature (T_s, °R), stack pressure (P_s, in. Hg) and stack moisture content (B_{ws}),
17.65 = 528°R/29.92 in. Hg,
M = Total particulate weight (mg) Section 4.7.17.

Note: The wet actual particulate concentration, G_A, may be expressed in different units (the same symbol, G_A, is used). Common units for G_A are grains per actual cubic foot, wet (gr/acf), pounds per actual cubic foot, wet, (lb/acf), and grams per actual cubic meter, wet (g/acm).

4.7.19 Stage Cut Points

Section 5 (Data Reduction and Analysis Procedures) gives the equations used to calculate the Stage Cut Points. Section 4.7.6 gives the D_{50} equation (Equation 4-13). Figure 4-5 shows the D_{50} for various stages of the Pollution Control Inc. University of Washington Mark 5 impactor at 300°F for dry air at various flow rates. Equation 4-13 in Section 4.7.6 (Hardware Selection) also gives the D_{50} equation. Optionally, the calculations may be performed by the computer programs described in Appendix A.

4.7.20 Particle Size Distributions

Section 5 (Data Reduction and Analysis Procedures) describes the D_{50} method used to obtain size distribution data from cascade impactor information. Section 5 includes a set of sample calculations detailing the steps which are required for manual data analysis. In practice these calculations are performed most readily by using the computer programs described in Appendix A.

4.7.21 Averaging Multiple Impactor Runs

Section 5.4 (Combining Data from Multiple Runs) describes the techniques and equations used to average multiple impactor runs. Again these calculations can be performed by the computer programs described in Appendix A. In general different impactor runs may have different stage cuts thus preventing the use of simple averaging techniques. For this reason, spline curve fitting techniques are applied to the cumulative mass data from each individual run. Averaging and all additional analysis is then performed using only the fitted coefficients (slopes) for this curve for a set of common diameters.

4.7.22 Control Device Efficiencies

Section 5 (Data Reduction and Analysis Procedures) describes the techniques and equations used to calculate fractional control device efficiencies using averaged inlet and averaged outlet dM/dLogD information for the common diameters obtained through the spline fitting procedure.

In general, for each different diameter from the spline fit, the penetration (P_i) at this size (i) is found by the following:

$$P_i(\%) = \left[(dM/dLogD)_{i \text{ outlet}} / (dM/dLogD)_{i \text{ inlet}} \right] \times 100\% \qquad (4\text{-}43)$$

The Efficiencies (E_i) at this same size is given by

$$E_i = 100 - P_i(\%) \qquad (4\text{-}44)$$

These calculations may also be performed by the computer programs described in Appendix A.

4.8 Data Forms

Data forms used with cascade impactors include Method 2 velocity profile forms (Figure 2-5 of Method 2), the manual version of the run sheet (lab and field) as shown in Figure 4-6 and 4-7, and the Weight Sheet shown in Figure 4-11. A run sheet form for use with the computer programs is given in Appendix A, Figure A-1. The weight book consists of the completed weight sheet forms (one for each substrate set) together with the Balance Record Book (chronological record of setup checks, zero's, repairs, etc.), controls "Weight Sheet" (date, time, and weight values for Control A, B, C, and D), and Tares "Weight Sheet" (date, time, and weight values for tares used).

Calibration forms include Figure 4-12 for nozzles, and Figures 5-8 of Method 5 for Dry Gas Meter and Orifice calibrations using a wet test meter. Figure 2-9 of Method 2 is used for calibration of Type S Pitot Tubes. Appendix C includes figures which may be used as photocopy masters for all of these forms.

A central record of calibration data and equipment maintenance records should be maintained separately. Appropriate copies should be made from records in this central file and stored with the Field Test Data Sheet. A bound notebook providing a chronological record of what happened during a test should also be maintained. This is used to prevent potentially important information from being lost or forgotten. This notebook becomes a part of the permanent test records. It is usually maintained by the leader of the test crew. Files should also be maintained for "other forms" such as velocity traverses, flue gas composition measurements, Barometric Pressure Readings, reports of post-test measurements such as fuel analysis (Ultimate and Proximate for coal, etc.), physical density by Helium Pycnometer, Bahco Particle Size Analysis of bulk fly ash samples, etc. Other files may be needed for plant data records (load conditions, product feed rates, etc.) and for data reduction computer printouts. Computer printouts of set-up parameters are normally filed with the appropriate Run Sheets. Data Reduction Printouts include printouts of both input data and outputs such as tabulated data and graphical output. Computer programs often evolve or are modified for various reasons, so it is advisable to maintain diskettes (computer storage media) of both the input data files and source listings of the data reduction routines so that future questions about "which version of the program was used" may be easily answered.

In summary, the field test data records can be divided into seven sections as follow: (1) chronological record, (2) Run Sheets (Run Side and Lab Side), (3) weight records, (4) calibration and maintenance records, (5) other forms, (6) plant data records, and (7) computer printouts and diskettes.

4.9 Reporting Requirements

Any written reports should include all the appropriate sections used in a report from a Method 5 test such as a description of the plant process, sampling port locations, control equipment, fuel/feed stocks being used, general plant load conditions during the test (descriptions of plant production equipment problems, etc.), and anything else necessary to characterize the condition being tested.

All raw data (Weight Sheets, Run Sheets, Calibration Records, Velocity Profile Data) should be listed in an appendix to the report and the following outputs should be given in a graphical form (tabulated form should be included in the appendix) for the average from multiple runs: (1) Plots of Cumulative Percent vs. Aerodynamic Diameter and (2) Plots of dM/dLogD vs. Aerodynamic Diameter, and (3) Plots of cumulative concentration vs. Aerodynamic Diameter.

Additional information may be required for any given project. The information listed above is to be considered as the minimum amount that should be included to characterize a given operating condition.

4.10 Computer Programs

Most of the calculations outlined in this report can be performed by the optional set of computer programs given in Appendix A. This appendix includes complete documentation, operating instructions, and illustrations for the computer programs.

4.11 Acceptable Results

The following criteria are used to determine the acceptability of test results. Criteria 1 and 2 relate to the test series in general, whereas criteria 3 through 19 relate to the individual impactor runs.

General Test Criteria

(1) Blank Impactor Gains: A blank impactor run is mandatory in order to demonstrate the suitability of the selected substrate material. The maximum recommended range (deviation from the average) in the substrate weight changes for this blank run is 0.25 mg. (Section 4.5.3.B)

(2) Minimum Number of Runs: It is recommended that seven (7) sets (multiple runs synthesizing a complete traverse) be performed. The minimum number of sets that may be used to characterize a condition is three (3). (Section 4.5.3.G and Appendix D.)

Criteria for Individual Impactor Runs

(3) Reproducibility of Control Weights: The control weights used in the operation of the analytical balance should be reproducible to within ±0.05 mg. The precision associated with the stage weights gains are determined by the reproducibility of the control weights. (Section 4.6)

(4) Reynolds Number Limit: The combination of selected jet stage and impactor flow rate must be such that Reynolds numbers are greater than 50. Reynolds numbers greater than 200 are desirable. (Section 4.5.3.A.5)

(5) Bounce Prevention: The combination of selected jet stage and impactor flow rate must be such that the product of the jet velocity (υ) and aerodynamic stage cut point (D_{50}) does not exceed the following values:

Bare Metal Substrate:	$\upsilon D_{50} < 5$ μm-m/s
Fiber Mat Substrate:	$\upsilon D_{50} < 15$ μm-m/s
Greased Substrate c/l:	$\upsilon D_{50} < 25$ μm-m/s

(Section 4.5.3.A.5)

(6) In-situ Sampling: Extractive sampling into an impactor is not permitted, even when heat traced lines are used and the impactor is placed in a heated oven. The nature of the problem is that excessive particulate losses occur in extractive probes. The ability of an extractive probe to remove particles of a given size is dependent on flow rate, tube diameter, number of

bends, and a host of other factors. Size selective losses occurring in the probe invalidate the data from the impactor. (Section 4.1)

(7) Straight Nozzles: Only straight nozzles may be used. Method 5 type goose neck (button hook) or other 90° bend nozzles may not be used. The impactor must either be rotated into the gas stream so that a straight nozzle can be used or a right angle precollector should be used to permit the impactor to be operated perpendicular to the direction of the gas flow. (Section 4.3.1.A)

(8) Minimum Nozzle Diameter: The primary problem associated with the use of small nozzles is pluggage of the nozzle by large particles. For this reason, 1.4 mm is recommended as a practical minimum nozzle ID. In practice, however, a smaller nozzle may be used if one is willing to accept the increased risk of a nozzle pluggage. (Section 4.5.3.A.5) A secondary problem may be a shift in the D_{50} of the entry stage to the system (i.e. precollector or the first impactor stage depending on the configuration).

(9) In-situ Heating: If the stack temperature is above 347°F (175°C), sampling may usually be performed at stack temperature. At stack temperatures less than this limit, it may be necessary to heat the impactor to at least 18°F (10°C) above the stack temperature by the use of external heaters wrapped around the impactor. The decision to externally heat the impactor depends primarily on the properties of the flue gas. Thus, high moisture stacks or high SO_3 levels may require in-situ heating of the impactors. The postrun visual examination of the impactor substrates will indicate the presence or absence of condensation problems. (Section 4.12)

(10) Warm-Up Requirement: Warm-up times should be 45 minutes to one hour. Shorter times may result in condensation occurring on various surfaces of the impactor. (Section 4.5.3.D.4)

(11) Minimum Run Time: The shortest permissible run time is 60 seconds. A desirable minimum run time is three minutes. If high loadings require run times shorter than 60 seconds, a lower flow or different sampling device should be used if possible. Great care must be taken when operating with such short run times. (Section 4.5.3.A.6)

(12) Leak Tests: The impactor must satisfy both the Pretest Hot Leak Test criteria and the Post-Test Hot Leak Test criteria given in Table 5-1. (Section 4.5.3.D.4)

(13) Anisokinetic Sampling Limits: At each traverse point sampled during a given impactor run, the point velocity (v_i) must be within ± 20% of the inlet velocity (v) for the impactor, thus $.8v \leq v_i \leq 1.2v$. (Section 4.5.3.A.4)

(14) Nozzle Inspection: The nozzle must pass the Post-Test nozzle damage visual check. (Section 4.5.3.D.5)

(15) Substrate Inspection: When the impactor is unloaded, the stage catches are inspected to see if overloading, scouring, bounce, condensation,

handling losses, etc., have occurred such that the data is compromised or invalidated. (Section 4.5.3.F)

(16) Isokinetic Requirements: The calculated % Isokinetic (I) for a given run must satisfy the following:

$$75\% \leq I \leq 125\%$$

(as calculated by Equation 4-34). (Section 4.5.3.D.7)

(17) Maximum Stage Loadings: Excluding the precollector and filter, the individual substrate catch should not exceed 15 mg. If this limit is exceeded one runs a risk of overloading the substrate. The actual point where overloading occurs depends on the design of the impactor used, the type of substrate material selected, and the properties of the material collected. The postrun visual examination is the best check for overloading. Other tests include unrealistic filter weight changes and microscopic examination of the filter and substrates for the presence of grossly oversize particles. (Section 4.5.3.C)

(18) Blank Substrate Weight Changes: The recommended range in weight changes for the blank substrate is 0.25 mg (or 10% of the expected weight change for the loaded substrates). The weight change of the blank substrate provides a cumulative measure of all balance errors (drift in the analytical balance), handling losses, flue gas-substrate interactions, etc., that might impact the weight change determinations for an impactor run. The change for each run should be compared to the grand average of all other blank substrates ("Blank" Impactor Run and blank substrate from each real run). Any given run is suspect if its change is significantly different (an outlier) from this grand average. Any temporal variations in the substrate flue gas interactions can be detected by the use of the blank substrate in each run. The outlier tests described in Section 5.4 may be used to reject individual runs. (Section 4.7.17)

(19) Blank Filter Weight Change: Same criteria as (18) above except that the criteria is applied to the set of all blank filter weight changes rather than the set of all blank substrate weight changes.

4.12 Special Sampling Conditions

The following paragraphs discuss various situations where the equipment and procedures described in Section 4 may need to be modified.

4.12.1 High Concentration Sampling Situations

As discussed in Section 4.1 most impactors are designed for sampling at relatively low concentration outlets, downstream of particulate control equipment. Consequently many of these impactors are not suitable for sampling upstream of control equipment (inlet sampling situations) where the particulate concentrations may be as much as 10,000 times greater than at the outlet. Some impactors permit the operator to select from multiple stages, permitting the impactor to be configured for low flow rates. If the concentration is still so high that unrealistic sampling times (less than 60 sec.) must be used to avoid

overloading one has the option of using the EPA/SoRI designed Five Series Cyclone Set described in Attachment 2 of the Project Final Report. The cyclone procedures described in Attachment 2 focus on obtaining size segregated samples for chemical analysis but the same equipment may also be used to obtain sizing information. The major modification to the cyclone operating procedures is the requirement of gravimetric analysis of the cyclone catches. This analysis is not specified in the Task 2 document because the additional handling can compromise the chemical integrity of the collected samples (particularly the organics) and is unnecessary to the chemical information. In general, if one desires both sizing and chemical information from the cyclones, any given run must be dedicated to either sizing information or chemical information and handled accordingly. Computer programs for the cyclone permit the calculation of sizing information in a fashion which parallels that for impactors when accurate catch weights are provided.

4.12.2 Wet Stacks and Supplemental Heating

In sampling situations where the process stream contains entrained moisture or is near a dew point, one must first define the measurement objectives: (1) Characterize only the particulate to be released to the atmosphere or (2) characterize both the particulate and entrained liquid/condensibles present in the flue. If the former is desired, as is normally the case, one must provide supplemental heating to the impactor to prevent condensation from occurring in the impactor and to reevaporate entrained liquid droplets that would be evaporated in the downwind plume. Heat is usually supplied either by means of a heating pad properly sized for the impactor/precollector or by lengths of electrical heating tape. Glass fiber cord or tape may be used to secure the heating devices to the precollector, connecting tube, and impactor. Insulation should then be placed around the assembly (outside the heating tape) and secured. A layer of aluminum foil wrap helps keep the insulation dry and aids in cleanup.

The temperature of the sample gas exiting the impactor should be monitored by a thermocouple exposed to the sample gas flow immediately downstream of the final filter, but the heating elements should be controlled by a second thermocouple between the impactor and the heater. A setting should be selected for this second thermocouple that will not damage the impactor but will raise the temperature of the exit gas to about 20°F above the stack gas temperature (as monitored by the first thermocouple). Field Test measurement techniques specific to Wet Scrubbers have been described by D.W. Cooper (Cooper, 1976).

If one wishes to characterize both the particulate and entrained liquid/condensibles, many modifications are necessary. Generally, a specially designed sampler is used. The Brink impactor using deep cups and operated in an upright position (top entry for horizontal ducts with a special 180° turn-around fitting for attaching the impactor to the probe) has been used for this purpose. Alternatively, blotter type substrate materials have been used with gravimetric analysis performed on the wet substrates. Also special optical based sampling equipment has been designed (McCain, 1986) for measuring outlet droplet size distributions on Mist Elimination equipment installed on wet scrubbers.

4.12.3 High Temperature Sampling

Most source sampling is performed at sampling sites where the gas temperature is less than 350°F, since industrial processes generally use economizers which utilize heat from the exhaust stream to preheat incoming combustion air. Consequently, the temperature of the gas exiting the smoke stack is generally maintained at temperatures of about 300°F. These low temperatures permit the use of coated metal substrates, Viton o-rings, and Teflon inserts. When it becomes necessary to sample at temperatures where the upper limits of these materials are exceeded, one must use high temperature substitutes such as quartz substrates, metal o-rings, and Kapton inserts. Also, high temperature heater tapes would need to be used in the probe rather than the more durable moisture resistant silicone insulated heater tapes. Longer prerun warmup times may also be required.

4.12.4 Top Entry Ports

In sampling situations where the duct is horizontal and the access ports are on the top of the duct, a special adapter must be used to attach the impactor to the probe. This adapter performs two major functions: (1) it rotates the impactor 180° so that it can be operated in an upright position rather than upside down and (2) it helps prevent the filter from being backwashed by water which might condense inside the probe and drain down to the end of the probe. Probe heaters are used and the adapter is wrapped with heater tapes and insulation. A thermocouple is used to monitor the probe exit temperature. Heater tapes on the adapter and probe are maintained at sufficiently high temperatures to assure that the gas exiting the probe is well above the dew point.

4.12.5 Small Ducts

Special procedures and equipment must be used in small ducts when the cross-sectional blockage of the duct by the impactor/precollector assembly exceeds 5 percent of the duct cross section area. In such situations one should attempt to rotate the impactor into flow and use straight nozzles, provided the cross-sectional blockage for this configuration does not exceed the 5 percent limit. A second option would be to connect a long pipe nipple to the port and install a longer connecting tube to the precollector so that only the precollector body is in the gas flow, the body of the impactor being located out of flow inside the long nipple. If such a configuration is used, one should construct a special removable curved flow shield around the connecting tube between the precollector and impactor body to prevent major flow interruptions being introduced by the port opening. This can be very significant when the port diameter is a substantial percentage of the duct diameter. The long pipe nipple will need to be heated and insulated and it may be necessary to use supplemental heating on the impactor body as described in Section 4.12.2.

4.12.6 Size Segregated Samples for Chemical Analysis

If it is desired that size segregated samples be obtained for chemical analysis, special substrate material will be necessary. Attachment 2 of the

Project Final Report addresses this situation directly by specifying special equipment (cyclones) designed to collect bulk quantities of size segregated particulate for post-test chemical analysis. It is not possible to collect bulk quantities with cascade impactors but one can collect milligram quantities that may be analyzed by using trace element techniques such as x-ray analysis and Neutron Activation Analysis (NAA). Special substrates and filters must be used which give a very low background signature for the elements desired. The polypropylene polymers (Section 4.5.2.B.1) substrate coatings and quartz filters provide relatively clean signatures.

4.13 Safety

General field testing safety precautions used in Method 5 testing should be observed. Table C-2 is a safety checklist that may be used. Various items of safety equipment are listed also in Section 4.3.1.J. No additional unusual safety procedures are required by the use of cascade impactors as such.

SECTION 5

DATA ANALYSIS

After obtaining a sample using a cascade impactor the data must be reduced to obtain the desired size distribution from the stage weights, sampling information, and hardware specifics. This information is used to obtain the size distribution in both differential and cumulative forms using the D_{50} method of data analysis.

The D_{50} of a stage is the particle diameter at which the stage achieves 50% efficiency: half of the particles of that diameter are captured and half are not. The D_{50} analysis method simplifies the capture efficiency distribution by assuming that a given stage captures all of the particles with a diameter equal to or greater than the D_{50} of that stage and less than the D_{50} of the preceding stage. Thus, for the purpose of constructing a size distribution, particles collected on a specific stage are assumed to have diameters between the D_{50} of that stage and the D_{50} of the stage immediately upstream of it. The typical or average size of the particles collected by a stage is generally taken to be the geometric mean of the stage D_{50} and that of the preceding stage. Note that there is no good way to assign a typical, or average, diameter to the material collected by the first stage or the backup filter because one of the limiting diameters is undefined for them.

The simplification described above does not take into account the shape or slope of the calibration collection efficiency curves. It is assumed, rather, that the collection efficiency curve is a step function (see Figure 5-1). Some compensation for the errors implicit in this assumption occurs as a result of the efficiency curves being rather symmetric about the D_{50}. Errors resulting from not collecting some of the particles that are larger than the D_{50} are compensated for by the collection of some particles smaller than the D_{50}. If the efficiency curves were completely symmetric and the size distribution of the aerosol being sampled were flat in the vicinity of the stage D_{50}, then the compensation would be perfect. The former is very nearly true in most cases; however, the latter is true only near modal peaks or saddle points in size distributions found in actual aerosol sources. Notice that if the stage efficiency curves were true step functions, the D_{50} method would be exact; therefore the sharper the true efficiency curves are, the more nearly exact the method becomes.

Computer models of particle collection by cascade impactors which attempt reconstruction of the input size distributions using the D_{50} method yield results of tolerable accuracy when the aerosol distributions are approximately log-normal with geometric standard deviations larger than about 1.8 (McCain, 1979). This is the case for most industrial particulate emission sources.

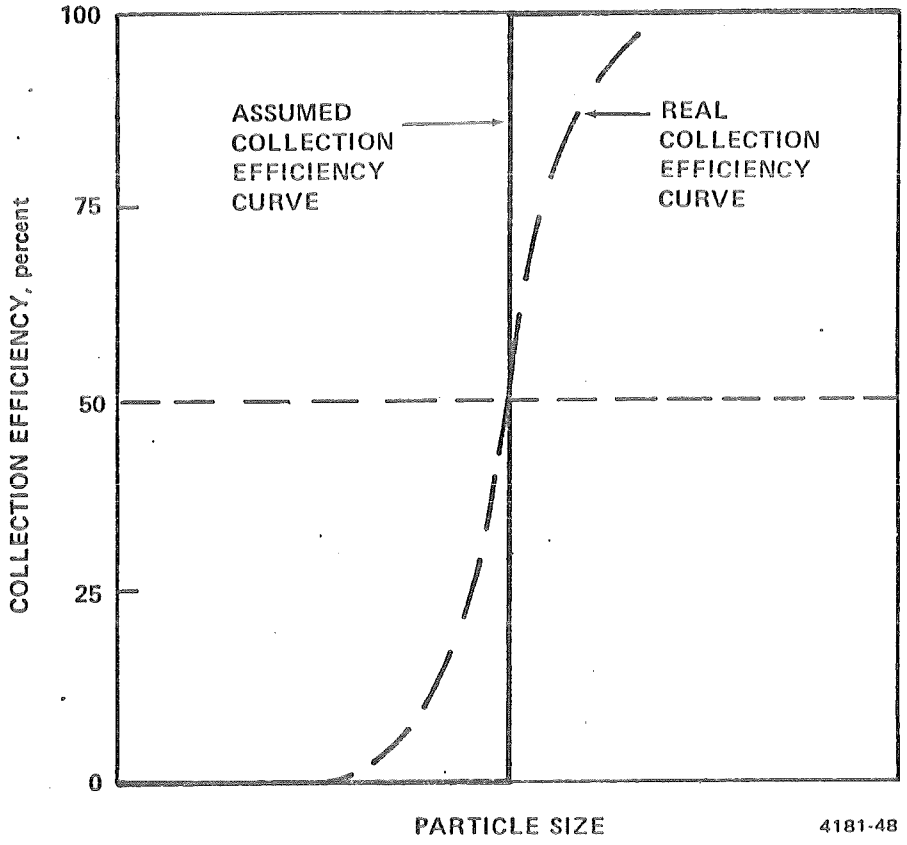


Figure 5-1. The assumed collection efficiency curve of the D_{50} method compared to the real collection efficiency curve of an impactor stage or cyclone.

A number of more sophisticated data reduction schemes which use measured stage efficiency curves for deconvolving the data have been proposed. However, inaccuracies in both the measured calibration curves and in the data from actual sampling runs cause serious difficulties in the application of all such methods proposed to date. Because they are not advanced enough to give reliable results at present, the D_{50} method is recommended and is the only one that will be described here.

5.1 Calculation of Stage D_{50} Values

As described in Section 2, the basic equation that defines the impaction behavior of a given stage of a cascade impactor is:

$$D_{50} = \left(\frac{18\ \mu\ D_j \psi_{50}}{C \rho_p \upsilon_j}\right)^{1/2} \qquad (5\text{-}1)$$

where D_{50} = diameter of a particle having 50% probability of impaction on the stage, cm

μ = viscosity of gas passing through the impactor jet(s), poise

D_j = diameter of impactor jet, cm, or, alternatively, the width, W_j, of slot in a slotted impactor, cm

ψ_{50} = inertial impaction parameter determined from theory or calibration, dimensionless

C = Cunningham slip correction factor, dimensionless (given below) (calculated using upstream conditions)

ρ_p = density of particle, g/cm^3

υ_j = mean velocity of gas through an impactor jet, cm/sec (calculated using upstream pressure)

and

$$C = 1 + \frac{2\ \ell}{D_{50}}\left[1.23 + 0.41\ \exp\left(\frac{-0.44\ D_{50}}{\ell}\right)\right] \qquad (5\text{-}2)$$

where ℓ = mean free path of air molecules at impactor stage (at upstream conditions), cm

Note that upstream pressure conditions are used here. As described in Section 2, this convention is theoretically more appropriate and experimentally produces values of ψ_{50} which show less senstitivity to operating pressure drops.

The Stokes diameter of a particle, as defined by equation 5-1, is of interest for most applications. However, at times, for example for PM_{10} purposes, data must be expressed in terms of the aerodynamic diameter, defined

as the diameter of a sphere having unit density and the same settling velocity as the particle of interest. In order to calculate the D_{50} of an impactor stage on an aerodynamic basis, ρ_p is set equal to 1.0 g/cm^3 and equation 5-1 becomes:

$$D_{50} = \left(\frac{18\psi_{50}\mu D_j}{C\, v_j}\right)^{1/2} \qquad (5\text{-}3)$$

The values of ψ_{50} for each stage of the impactor can be found by using the calibration procedures or theoretical curves given in Section 2. Then, since C is dependent on particle size, the D_{50} can be calculated using an iterative solution of equations 5-2 and 5-1.

5.2 Single Run Data Analysis and Presentation

The true particle-size distribution of almost any particle-laden gas stream (outside the laboratory) is a smooth and continuous curve. As impactors have a finite number of stages, they break this continuous particle-size distribution into a series of discrete sets of particulate matter in separate size intervals. In actuality, these intervals overlap somewhat, but they are not generally treated as doing so. If the widths of the intervals are large compared with the ranges of overlap, the errors introduced by ignoring the overlaps are small. The object of impactor data analysis is to transform the discrete data into a good approximation of the real, continuous distribution.

Anomalies are introduced into the reconstructed size distributions obtained using the D_{50} method if the D_{50}'s of two successive stages are close enough to one another that the efficiency curves overlap significantly. In such cases, the second (downstream) stage receives an aerosol whose concentration varies rapidly with diameter within the vicinity of its D_{50}, violating the basic assumption of the D_{50} method. It can be shown that the effect of the overlap is a positive bias in the apparent concentration of particles in the nominal size range of those caught on the second stage. Thus, the differential distribution is biased high in the interval between the D_{50}'s of the two stages, and is correspondingly biased low in the interval covered by the next successive stage. As an illustration, consider two successive stages whose D_{50}'s are infinitesimally close to one another. The mass which should be collected between the two D_{50}'s to properly represent the aerosol size distribution would then also be infinitesimally small. However, the second of the two stages will in fact collect an appreciable amount of particles whose diameters lie in the region where the collection efficiency values of the two stages lie between 5 and 95 percent. Particles in this size range have a significant probability of passing the first stage and being captured by the second. For the case of D_{50} values which are essentially identical, the mass on the second stage has the effect of introducing an apparent discontinuity in the reconstructed cumulative distribution or a spike in the differential distribution. In practice, one can avoid the problem introduced by this effect by combining the mass collected by the second of the two closely spaced stages with that of the stage immediately following it and omitting the second stage

from the analysis. A good working practice is to maintain the ratio of successive D_{50}'s at values of 1.4 or greater.

It is assumed for the purpose of analysis that all of the material caught on an impaction stage consists of particles having aerodynamic diameters equal to, or greater than, the D_{50} for that stage, and less than the D_{50} for the next higher stage. For the first stage (or precollector), it is assumed that all of the particles caught have aerodynamic diameters greater than, or equal to, the D_{50} for that stage (or precollector), but less than the maximum particle size. When possible, the maximum particle size should be measured, for example, with an optical microscope. If this is impossible, an arbitrary large value of 1000 μm or larger should be used for uncontrolled sources and a value of about 100 μm for controlled sources.

Data should be presented as both differential and cumulative particle-size distributions as described in the following discussion.

5.2.1 Differential Particle-Size Distributions

Since the true particle-size distribution is continuous, the mass of material with particle diameters between D and D + dD can be represented by dM. Then the integral

$$\int_{D_1}^{D_2} \left(\frac{dM}{dD}\right) dD \qquad (5\text{-}4)$$

yields the total mass made up of particles with diameters between D_1 and D_2.

Many cascade impactors are designed so that the relationship between successive stage D_{50}'s is logarithmic. Further, many natural aerosol size distributions are very nearly log-normal. That is, the distributions are gaussian if the logarithm of diameter is used as the independent variable. For these reasons, and to minimize graph scaling problems, the differential particle-size distributions are plotted on log-log or semi-log paper with dM/dLogD as the ordinate and Log D as the abscissa. The mass of the material on stage "n" is designated by ΔM_n and is, in approximation, the mass of particulate matter with particle diameters between $(D_{50})_n$ and $(D_{50})_{n+1}$. The Δ(Log D) associated with ΔM_n is $\text{Log}(D_{50})_{n-1} - \text{Log}(D_{50})_n$. Note that diameters decrease as "n" increases. Using these approximations, the derivative term associated with stage "n" is defined as follows:

$$[dM/d\text{Log}D]_n \simeq \frac{\Delta M_n}{\Delta(\text{Log}D_{50})_n} = \frac{\text{mass on stage "n"}}{\text{Log}(D_{50})_{n-1} - \text{Log}(D_{50})_n} \qquad (5\text{-}5)$$

Plotting this approximation of dM/dLogD versus Log D results in a histogram. From such a histogram, the total mass of particles with diameters between $(D_{50})_i$ and $(D_{50})_j$ can be calculated as the sum:

$$\text{Mass} = \sum_{k=i}^{j} \frac{\Delta M_k}{\Delta(\text{Log } D_{50})_k} \Delta(\text{Log } D_{50})_k \qquad (5\text{-}6)$$

where "k" takes on values corresponding to the discrete increments of the histogram.

If an impactor with an infinite number of stages having step function efficiency curves were available, the histogram would approach a continuous function, the $\Delta(\text{Log } D_{50})$ terms would approach d(Log D), and the mass between D_m and D_n could be calculated as:

$$\text{Mass} = \int_{D_m}^{D_n} \left(\frac{dM}{d(\text{Log } D)}\right) d(\text{Log } D) \qquad (5\text{-}7)$$

Such an impactor does not exist, but the histogram can be plotted as a smooth curve by assigning some average of $(D_{50})_{n+1}$ and $(D_{50})_n$ to the $\Delta M/\Delta(\text{Log } D_{50})_n$ term and drawing a smooth curve through the resulting points. The geometric mean of the D_{50}'s is generally used. This curve is then a continuous function approximating the actual particle-size distribution. Note that the area under the curve in a given size range is equal to the mass of the particulate matter in that interval. Such a curve is needed to calculate fractional collection efficiencies of control devices if the D_{50}'s differ for inlet and outlet measurements. To normalize the differences in the masses of samples collected by various instruments, the mass on each stage is usually divided by the volume of the sampled gas at standard temperature and pressure, yielding concentration units. Figure 5-2 illustrates a typical dM/dLogD plot. The accuracy of the approximation described above is limited by the number of data points and by neglecting the non-ideal behavior of the impactors, especially overlapping collection efficiencies for adjacent stages.

5.2.2 Cumulative Particle-Size Distributions

Two forms of cumulative distributions are commonly used - cumulative concentration and cumulative percentage. These are generated, respectively, by summing the concentrations of particles smaller than the D_{50}'s of successive stages or by summing the percentages of the total concentration smaller than the successive D_{50}'s. Distributions in this form are conventionally plotted commencing at the smallest diameter for which data was obtained and progressively summing to the larger sizes.

Cumulative distributions do have some disadvantages compared to differential distributions. An error in a stage weight is propagated forward throughout the remainder of the distribution in a cumulative analysis, but is isolated by the differential approach. Also the differential method need not involve the use of data for sizes outside of the range over which the sampler provides size resolution and so is useful in comparing results obtained with impactors with those obtained from instruments which cover only restricted particle size intervals (e.g. optical particle counters). Cumulative

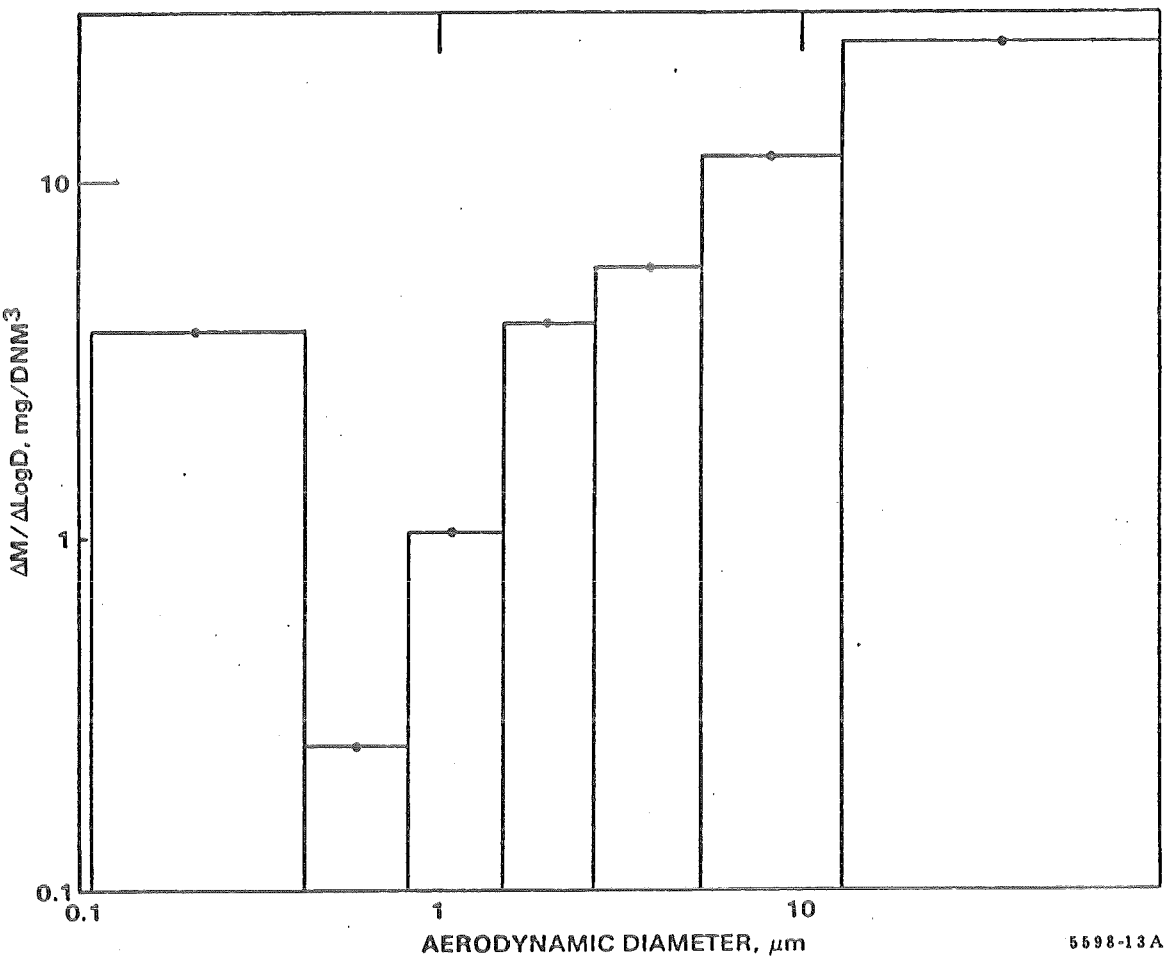


Figure 5-2. Differential size distribution estimated directly from the stage weights and $D_{50's}$ of an impactor run.

distributions are also not amenable to making direct comparisons of concentrations at selected sizes as can be done with differential distributions.

5.2.2.A Cumulative Concentration Format

A cumulative concentration particle-size distribution is shown in Figure 5-3. Distributions in the cumulative concentration format are formed by first calculating the concentrations for each size fraction provided by the sampler and successively summing these. If the conventional format is followed and the summation begins at the smallest D_{50}, any error in the sample collected on the backup filter is propagated throughout the entire presentation. Because the backup filter catch is affected to a far greater extent than the remaining stage catches by particle bounce and reentrainment, it is especially important that the magnitude of these effects be held to a minimum if the cumulative distributions are to be kept relatively unbiased. Summing from the large particle end of the size spectrum does not necessarily rid the distribution of bias since the measured concentrations of large particles are susceptible to bias from, among other things, the inability to maintain true isokinetic sampling conditions (because of the requirement of fixed sampling flow rates). The small particle end of the size spectrum is selected for the beginning of the summation because in most instances the larger particles dominate the distribution and the addition of the smaller particles to the larger would be undetectable in the presentation. Note that it is possible to present data in a form of cumulative concentration format in the absence of information regarding concentrations at one extreme of the distribution.

The value of the ordinate at a given D_{50} would be:

$$\text{Mass concentration smaller than } (D_{50})_k = \sum_{i=0}^{k-1} C_i \qquad (5\text{-}8)$$

where i = 0 corresponds to the filter,
i = k corresponds to the selected stage,
C_i = concentration determined from the stage i particulate catch,
N = total number of stages (including the precollector).

This equation requires that the stages be counted upward from the final filter. There is no $(D_{50})_0$ since the "0" stage corresponds to the backup filter. $(D_{50})_1$ is the cut-point of the final impaction stage.

5.2.2.B Cumulative Percentage Format

Many aerosols have particle size distributions which follow, or can be approximated by, the "Normal" or Gaussian function if the logarithm of the particle diameter is used as the independent variable. Such distributions, called log-normal distributions, can be characterized or described by three parameters: a normalizing constant which defines the total concentration, and two constants which define the location and shape of the distribution. Generally, the mass median diameter and the geometric standard deviation are

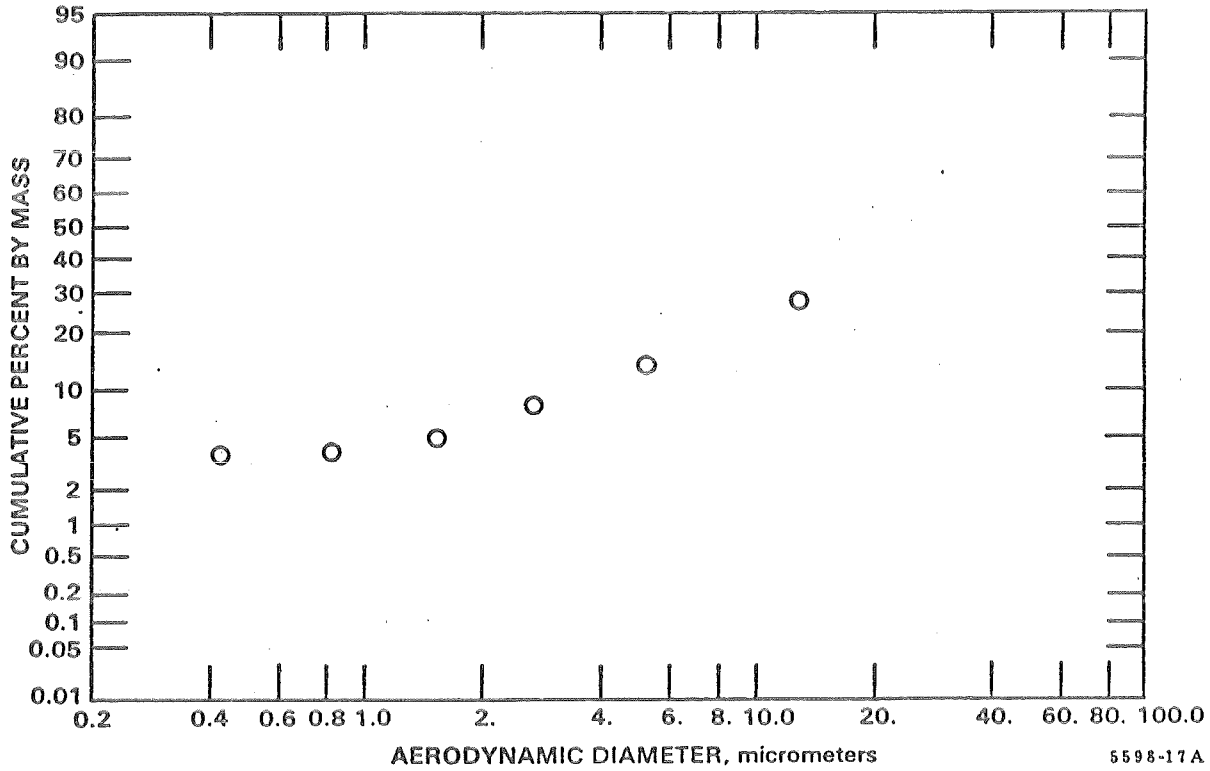


Figure 5-4. Particle size distribution on a cumulative percentage by mass basis as measured with a cascade impactor.

with the sampling parameters listed in Table 5-1. Background masses, as measured by blank impactor runs, have already been subtracted from the stage weights. Due to the close spacing of the D_{50}'s for a precollector (Stage 1) and Stage 2 of this impactor, the stages 2 and 3 are to be considered to act as a unit and the weights at the material collected by them are to be combined. Stage 2 should then be omitted in the analysis. The data from this example were used to generate the distribution curves shown previously as Figures 5-2 through 5-4. Results of the analysis of this sample data by the computer program are given as TORSAMPLE CALC.OT in Appendix A following the description of the program MPPROG.

5.3.1 Stage Cut Diameters (D_{50})

The aerodynamic D_{50} cut points of the impactor stages can be calculated using equations 5-2 and 5-3, and the other equations shown below.

The mean free path, ℓ, in cm, is calculated by the following equation:

$$\ell = \frac{2\mu}{(1.01325 \times 10^{6})P}\left[\frac{\pi(1.18 \times 10^{-16})\,(6.02 \times 10^{23})T}{8\,M_G}\right]^{1/2} \qquad (5\text{-}10)$$

where μ = gas viscosity (poise),

P = gas pressure at stage inlet conditions (atm),

T = gas temperature (°K),

$$M_G = \text{mean molecular weight of wet flue gas} = f_1 44.10 + f_2 28.01 + f_3 28.01 + f_4 32.00 + f_5 18.02, \qquad (5\text{-}11)$$

where f_{1-5} = wet gas fractions of CO_2, CO, N_2, O_2, and H_2O, respectively. If only the dry gas components are known, they may be converted to wet gas fraction by using the relationship $(f_i, \text{wet}) = (f_i, \text{dry})\,(1-f_{H_2O})$

The gas viscosity, μ, is calculated (in poise) by equations 5-12 and 5-13 from the gas composition and the viscosities of the individual gas components (Wilke, 1950). The viscosities of the gas components are calculated from polynomial fits to published data (Hodgman, 1959). Note: a simpler, approximate, method for calculating the gas viscosity is given in paragraph 4.7.6. The latter is suggested for use if the data are to be reduced manually. Both methods will be illustrated here.

TABLE 5-1. SAMPLING PARAMETERS FOR AN IMPACTOR TEST*

Impactor type	University of Washington, Mark III
Substrate type	Greased metal
Precollector	Yes
Stack temperature	149°C (300°F)
Impactor temperature	149°C (300°F)
Stack pressure	75.3 cm Hg (29.6 in. Hg)
Impactor pressure drop	2.8 cm Hg (1.1 in. Hg)
Impactor flowrate	14.2 ℓ/min (0.50 acfm)
Sampling duration	120 min
Gas composition (wet gas)	0.21% CO_2, 0.03% CO, 76.08% N_2, 18.78% O_2, 4.90% H_2O
Assumed particle density	1.00 g/cm^3
Maximum particle diameter	100 μm

	Mass, mg	Jet diameter, cm	$\sqrt{\psi}$	Number of holes
Precollector	21.78	1.27	0.24	1
Stage 2	3.32	0.5791	0.331	6
Stage 3	5.05	0.2438	0.350	12
Stage 4	1.81	0.0787	0.365	90
Stage 5	1.10	0.0508	0.371	110
Stage 6	0.30	0.0343	0.383	110
Stage 7	0.08	0.0254	0.386	90
Filter	1.28			

* Based on data from the example Run Sheets shown in Figures 4-8 and 4-9.

$$\mu = \sum_{i=1}^{5} \frac{\mu_i}{1 + \frac{1}{f_i} \sum_{\substack{j=1 \\ j \neq i}}^{5} (f_j \Phi_{ij})} \times 10^{-6} \qquad (5\text{-}12)$$

$$\text{where } \Phi_{ij} = \frac{[1 + (\mu_i/\mu_j)^{1/2} (w_j/w_i)^{1/4}]^2}{(4/\sqrt{2})[1 + (w_i/w_j)]^{1/2}} \qquad (5\text{-}13)$$

μ_{1-5} = viscosity of pure gas (micropoise),

μ_1 = gas viscosity of CO_2

$$= 138.494 + 0.499\ T - (0.267 \times 10^{-3})\ T^2 + (0.972 \times 10^{-7})\ T^3 \qquad (5\text{-}14)$$

μ_2 = viscosity of CO

$$= 165.763 + 0.442\ T - (0.213 \times 10^{-3})\ T^2 \qquad (5\text{-}15)$$

μ_3 = viscosity of N_2

$$= 167.086 + 0.417\ T - (0.139 \times 10^{-3})\ T^2 \qquad (5\text{-}16)$$

μ_4 = viscosity of O_2

$$= 190.187 + 0.558\ T - (0.336 \times 10^{-3})\ T^2 + (0.139 \times 10^{-6})\ T^3 \qquad (5\text{-}17)$$

μ_5 = viscosity of H_2O vapor

$$= 87.800 + 0.374\ T - (0.238 \times 10^{-4})\ T^2 \qquad (5\text{-}18)$$

where T = flue gas temperature (°C),

At T = 149°C (300°F), as in Table 5-1, the viscosity for each flue gas component is calculated as follows:

For CO_2

$$\mu_1 = 138.494 + 0.499\ (149) - (0.267 \times 10^{-3})\ (149)^2 + (0.972 \times 10^{-7})\ (149)^3$$

$$= 207.2 \text{ micropoise.}$$

Likewise

μ_2 = 226.9 micropoise (CO)

μ_3 = 226.1 micropoise (N_2)

μ_4 = 266.3 micropoise (O_2)

μ_5 = 143.0 micropoise (H_2O)

The molecular weights are

w_1 = 44.10 (CO_2)

w_2 = 28.01 (CO)

w_3 = 28.02 (N_2)

w_4 = 32.00 (O_2)

w_5 = 18.02 (H_2O)

With these values and the wet gas fractions, the gas viscosity can be calculated from equations 5-12 and 5-13 to be 230 micropoise (or 230 x 10^{-6} poise).

The viscosity from the equation 4-18 approximate method is:

$$M = 51.05 + 0.207\ (460+300) + 3.24\times10^{-5}\ (460+300)^2$$
$$-74.14\ (0.049)\ +53.15\ (.1975)\ \mu\text{poise}$$
$$= 233\ \mu\text{poise}$$

The wet mean molecular weight of the gas is

$$M_G = (0.0021)\ 44.10 + (0.0031)\ 28.01 + (0.7608)\ 28.02 + (0.1878)\ 32.00 + (0.0490)\ 18.02$$

$$= 28.3$$

Stage pressure drops are calculated by treating the stage as an orifice plate. The pressure drop is then given by the expression:

$$\Delta P_i = \frac{K\ \rho_i v_i^2}{2\ C_d^2} \qquad (5\text{-}19)$$

where ρ_i = gas density at the stage inlet

$$= \rho_{STP} \times \frac{M_G}{MW_{STP}} \times \frac{P}{P_{STP}} \times \frac{460 + T_{STP}(°F)}{460 + T\ (°F)} \quad (5\text{-}20)$$

$$= \rho_{STP} \times \frac{M_G}{MW_{STP}} \times \frac{P}{P_{STP}} \times \frac{273}{273 + T\ (°C)} \quad (5\text{-}21)$$

υ_i = jet velocity at stage inlet conditions.

$$= \frac{4\ (P_o/P)\ Q_I}{X_i \pi\ D_i^2} \quad (5\text{-}22)$$

C_d = coefficient of discharge,

= 0.61 for flat orifice plates,

K = conversion factor from cgs units to inches of Hg.,

= 2.953×10^{-5},

M_G = molecular weight,

MW_{STP} = 28.97,

P = stage inlet pressure (in. Hg or mm Hg),

P_{STP} = 29.92 in.Hg = 760 mm Hg,

P_o = Impactor inlet pressure (in. Hg or mm Hg),

T = gas temperature (°F),

T_{STP} = 0°C = 32°F,

Q_i = sample flow rate at impactor inlet conditions (cc/s),

X_i = number of jets on stage,

d_i = jet diameter (cm),

and $\rho_{STP} = 1.292 \times 10^{-3}$ g/cm^3.

The inlet pressure at any stage is given by the equation

$$P_i = P_{IN} - \sum_{n=1}^{n=i-1} \Delta P_n \qquad (5\text{-}23)$$

Where P_{IN} = gas pressure at impactor inlet, with the stages being counted from the impactor inlet.

For stage 3:

$$P_3 = 29.6 - \Delta P_2 = 29.6 \text{ inches Hg},$$

$$\rho_3 = 1.292 \times 10^{-3} \times \frac{28.31}{28.97} \times \frac{753}{760} \times \frac{273}{(273 + 149)}$$

$$= 0.809 \times 10^{-3} \text{ g/cm}^3$$

$$\upsilon_3 = \frac{4 \times 236.7}{12 \times \pi \times (.2438)^2} = 422 \text{ cm/s}$$

$$\Delta P_3 = 2.953 \times 10^{-5} \times \frac{.809 \times 10^{-3} \times (422)^2}{2 \times (.61)^2} = 0.005 \text{ inches Hg}$$

Note: Stage pressure drops in the computer program are calculated using coefficients of discharge from a curve of Cd versus jet Reynolds number (Brown, 1950) and the effects of gas compressibility are accounted for from a curve given by Considine (1957). The latter approach is more general and can be used at low pressure and high mach numbers but is not warranted for manual calculations for impactors operated as described in this document.

The mean free path, ℓ for use in calculating the Cunningham correction, C, for stage 3 can now be found by substituting in equation 5-10:

$$\text{and } \ell_3 = \frac{2(230\times10^{-6})}{(1.01325\times10^{6})(\frac{753}{760})} \left[\frac{\pi(1.38\times10^{-16})(6.02\times10^{23})(149+273)}{8\ (28.39)}\right]^{1/2} = 10.1\times10^{-6}\text{cm}$$

The velocity υ_j, through the stage jet(s) is given by equation 5-22 above. Thus, by substituting for υ_j in equation 5-1 we have:

$$D_{50} = \left[\frac{\pi \ 18\psi_{50} \mu \ X_j \ D_j^3 \cdot P_s}{4 \ C \ \rho_p P_o \ Q_I} \right]^{1/2} \qquad (5\text{-}24)$$

The values for stage 3 are

$$(P_s = P_o, \ \rho_p = 1 \text{ g/cm}),$$

$$\mu = 230 \times 10^{-6} \text{ micropoise, and}$$
$$Q_I = 14.2 \text{ l/min.}$$
$$\psi = (0.381)^2 = 0.145$$

&

$$D_{50} = \left[\frac{(\pi/4)(18)(0.145)(230 \times 10^6)(12)(0.2438)^3}{4C \ (237)} \right]^{1/2}$$

An iterative solution of equations 5-2 and 5-3 yields

$$D_{50} = 5.76 \times 10^{-4} \text{ cm} = 5.76 \ \mu\text{m},$$

and

$$C = 1.047$$

If the ratio of the stage D_{50} to the mean free path, D_{50}/ℓ is greater than 2.7, the exponential term can be neglected in equation 5-2 for the Cunningham correction, C. Substitution for C in equation 5-3 then results in a quadratic equation for the D_{50} which can be solved exactly (in which case C need not be calculated).

$$D_{50} \text{ (cm)} = -1.23\ell + \sqrt{1.513\ell^2 + (18\mu D_j \psi_{50})/(\rho_p \upsilon_j)} \text{ cm} \qquad (5\text{-}25)$$

Equation 5-25, although not generally applicable, is much more amenable to use in manual data reduction than the iterative solutions of equations 5-2 and 5-3. (The iterative solution is used in the computer program.) Substituting in equation 5-22, we have:

$$\upsilon_3 = \frac{4(75.3/75.3)(14.2)(1000/60)}{12\pi \ (.2438)^2}$$

$$= 422.5 \text{ cm/s}$$

and substituting in equation 5-25 we have

$$D_{50} = -1.23 \times 10.1 \times 10^{-6} + \sqrt{1.513(10.1 \times 10^{-6})^2 + (18 \times 230 \times 10^{-6} \times 0.2438 \times 0.145)/(1 \times 422.5)}$$

$$= 1.23\times10.1\times10^{-6} + \sqrt{3.4655\times10^{-7}}$$

$$= -1.242\times10^{-5} + 5.887\times10^{-4}$$

$$= 5.76\times10^{-4} \text{ cm} = 5.76 \text{ } \mu\text{m}$$

If the D_{50} is calculated using equation 5-25, the validity of the assumption that $D_{50}/\ell > 2.7$ should be tested. This is especially true if the D_{50} is smaller than 1 μm or if the gas pressure at the stage inlet is substantially below atmospheric (<50 cm Hg).

5.3.2 Mass Loading

After the D_{50}'s have been calculated using the above equations, the process of transforming the stage weights into particle size distributions can begin. Impactor run data needed are impactor flowrate, Q; stack temperature, T_s; stack pressure, P_s; sampling duration, t; and the mass of particulate collected on each stage, M_j. The mass loading, M_L, is calculated from the total gas volume sampled, Qt, and the total mass, M, of the particles collected:

$$M_L = \frac{M}{Qt} \tag{5-26}$$

where

$$M = \sum_{j=1}^{N+1} M_j \tag{5-27}$$

where j = Stage 1 (precollector), stage 2, stage 3, stage 4, ...stage N, backup filter,

N = number of stages in impactor.

Note that the backup filter is assigned the index N+1 and that the stages are numbered sequentially from 1 beginning with the precollector.

The preferred units of M are milligrams per dry normal cubic meter (mg/Nm^3) of gas at normal conditions, defined as 20°C and 760 mm Hg. In addition, the mass loading may be given in mg/Am^3 (milligrams per actual cubic meter at stack conditions), gr/Ncf (grains per normal cubic foot), and gr/Acf (grains per actual cubic foot).

For this example, at actual conditions,

$$M_L = \left(\frac{34.72 \text{ mg}}{(14.2\times10^{-3} \text{ m}^3/\text{min})(120 \text{ min})}\right) = 20.4 \text{ mg/Am}^3$$

$$= 31.2 \text{ mg/Nm}^3$$

5.3.3 Cumulative Size Distribution

The percentage of the total mass sampled contained in particles with diameters smaller than a particular D_{50} is designated the cumulative percent (CUM %) of mass smaller than D_{50}. It is the mass accumulated to stage j divided by the total mass collected on all the stages, and converted to a percentage:

$$(\text{CUM \%})_j = \frac{\sum_{i=j+1}^{N+1} M_i}{M} \times 100\% \qquad (5\text{-}28)$$

For stage 3,

$$(\text{CUM \%})_3 = \frac{(1.81 + 1.10 + 0.30 + 0.08 + 1.28)\ \text{mg}}{34.72\ \text{mg}} \times 100\%$$

$$= 13.2\%$$

The cumulative mass loading at actual conditions, CUM(A), of particles smaller in diameter than the corresponding D_{50} for a particular stage j is given by:

$$\text{CUM (A)}_j = \frac{\sum_{i=j+1}^{N+1} M_i}{Qt} \qquad (5\text{-}29)$$

The cumulative mass loading at dry-normal conditions, CUM(DN), of particles smaller in diameter than the corresponding D_{50} for a particular stage j is given by:

$$\text{CUM (DN)}_j = \frac{\sum_{i=j+1}^{N+1} M_i}{Qt} \times \frac{T_s \times (760\ \text{mm Hg})}{P_s \times (293°\text{K})} \times \frac{1}{(1 - f_{H_2O})} \qquad (5\text{-}30)$$

where T_s = stack temperature (°K),

P_s = stack pressure (mm Hg),

f_{H_2O} = fraction of water vapor in the gas sampled.

For stage 3:

$$CUM\ (A)_3 = \frac{4.57}{(14.2\times10^{-3}\ m^3/min)(120\ min)}$$

$$= 2.68\ mg/Am^3$$

$$CUM(DN)_3 = 2.68\ mg/cm^3 \times \frac{(149+273°K)(760\ mm\ Hg)}{(753\ mm\ Hg)(293°K)} \times \frac{1}{(1-0.049)}$$

$$CUM(DN)_3 = 2.68 \times 1.53 = 4.10\ mg/Nm^3$$

For graphical presentation, the cumulative mass loading is plotted as the ordinate and the corresponding aerodynamic D_{50} as the abscissa.

5.3.4 Differential Size Distribution

The mass concentration for each size range defined by the D_{50} cut points is labeled ΔM_j and is calculated by dividing the mass collected on each stage by the total volume of gas (at normal conditions) sampled.

$$\Delta M_j = \frac{M_j}{Qt} \times \frac{T_s \times (760\ mm\ Hg)}{P_s \times (293°K)} \times \frac{1}{(1-f_{H_2O})} \qquad (5-31)$$

For stage 3, because the D_{50} of stage 2 is larger than that of the precollector, the stage 2 catch will be added and stage 2 will be ignored.

$$\Delta M_3 = \frac{5.05\ mg + 3.32\ mg}{(14.2\times10^{-3}\ m^3/min) \times 120\ min} \times 1.53$$

$$\Delta M_3 = 7.52\ mg/Nm^3$$

(1.53 is the correction factor found above to convert from concentrations at actual conditions to dry normal conditions.)

Now $\Delta LogD$ is defined as:

$$(\Delta LogD)_j = Log_{10}(D_{50})_{j-1} - Log_{10}(D_{50})_j \qquad (5-32)$$

For stage 3 (again ignoring stage 2):

$$(\Delta LogD)_3 = Log_{10}(12.6) - log_{10}(5.76)$$

$$(\Delta LogD)_3 = 0.340$$

In the calculation of ΔLogD for the precollector, the maximum particle diameter is used. For a maximum particle diameter of 100.0 μm:

$$(\Delta LogD)_0 = Log_{50}(100) - Log_{10}(12.6) = 0.900$$

No truly satisfactory value is available for the effective minimum particle size collected by the backup filter. However, it is frequently arbitrarily chosen to be half of the D_{50} of the final impaction stage (stage n).

$$(\Delta LogD)_{n+1} = Log_{10}(D_{50n}) - Log_{10}\left(\frac{D_{50n}}{2}\right) = 0.301$$

The differential mass distribution is calculated from:

$$\left(\frac{\Delta M}{\Delta LogD}\right)_j = \frac{\Delta M_j}{(\Delta LogD)_j} = \frac{\Delta M_j}{Log_{10}(D_{50})_{j-1} - Log_{10}(D_{50})_j} \qquad (5\text{-}33)$$

For stage 3:

$$\left(\frac{\Delta M}{\Delta LogD}\right)_3 = \frac{\Delta M_3}{(\Delta LogD)_3} = \frac{7.52 \text{ mg/m}^3}{0.340} = 22.1 \text{ mg/Nm}^3$$

The differential size distribution is usually plotted as the ordinate on a graph where the abscissa is the geometric mean diameter, GMD_j, for the corresponding stage j.

$$GMD_j = \sqrt{(D_{50})_j \times (D_{50})_{j-1}}$$

For stage 3:

$$GMD_3 = \sqrt{D50_3 \times D50_2} = \sqrt{5.76 \times 12.6}$$

$$GMD_3 = 8.52 \text{ μm}.$$

As in the ΔLog D calculation, the maximum particle diameter is again used for the precollector calculation and half the D_{50} of stage n for the filter stage calculation. For the precollector (assuming the maximum particle diameter = 100 μm):

$$GMD_0 = \sqrt{12.6 \times 100} = 35.5 \text{ μm}$$

and for the backup filter:

$$GMD_{n+1} = \frac{(D_{50})_n}{2} \times (D_{50})_n = \frac{(D_{50})_n}{\sqrt{2}} = 0.304 \qquad (5\text{-}34)$$

The finite-difference methods used here result in values for $\Delta M/\Delta LogD$ for the cyclone and the backup filter which can have little physical meaning because of the large and somewhat arbitrary size intervals in $\Delta LogD$ assigned to them.

An alternative method of calculating the differential particle size distribution is to measure the slope of the cumulative mass loading curve at selected intervals and plot this slope versus the corresponding particle size.

A differential number distribution can also be derived. Since ΔM_j is the mass per unit volume for stage j then we can define ΔN_j as the number of particles per unit volume for stage j. Now ΔM_j and ΔN_j are related by the equation $\Delta M_j = \Delta N_j \times M_p$, where M_p is the average mass of the particles collected on the stage. Dividing both sides of the equation by $M_p \times \Delta LogD$ yields:

$$\frac{(\Delta M/\Delta LogD)_j}{M_p} = \frac{\Delta N_j}{(\Delta LogD)_j} \qquad (5\text{-}35)$$

Where $M_p = \rho_p V_p$ and ρ_p is the assumed density of the particle and V_p is the average volume of one particle on a given stage:

$$M_p = \frac{\pi \rho_p (GMD)_j^3}{6} \qquad (5\text{-}36)$$

Therefore:

$$(\Delta N/\Delta LogD)_j = 6\ (\Delta M/\Delta LogD)_j / \pi \rho_p (GMD)_j^3 \qquad (5\text{-}37)$$

For stage 3:

$$(\Delta N/\Delta LogD)_3 = 6(11.6\ mg/m^3)/(3.14)(10^3\ mg/cm^3)(8.29 \times 10^{-4}\ cm)^3$$

$$= 3.89 \times 10^7\ particles/m^3.$$

5.4 Combining Data from Multiple Runs

The previous parts of this section deal with the analysis and presentation of data from a single impactor run (sample). However, in most cases a number of runs will be made at each source and condition tested, and the data from these several runs are to be combined or averaged to produce the desired final distribution. These runs may represent repeated samples taken at a common location, or they may be samples taken from a number of locations across a duct to insure that a representative result is obtained in circumstances where stratification may or does exist. Even under the best of circumstances, combining data from multiple samples can be difficult. Differences in sampling flow rates, temperatures, and perhaps in the hardware used from one run to another will result in variations in the cut diameters (D_{50}'s) for any one impactor stage from one run to the next at any location. Because of these differences in stage D_{50}'s, it becomes improper to simply average the results for individual stages or to directly compare them for calculating control device efficiencies. The solution to the problem is to generate a continuous analytic function (or series of functions) which fit the measured results for each run. Interpolation using these functions permits one to express the results of all the runs at a common set of selected diameters. Once the data are adjusted to a common diameter basis, it becomes a simple matter to average and compare runs.

Two approaches have been tried in generating analytic expressions fitted to measured data. In one approach, least squares or other optimizing procedures are used to fit any one of a number of common distribution functions to the data (e.g. the log-normal function). However, except in rare instances, these functions are only approximations and may be poor approximations at that. The more widely favored and used approach is to make a piecewise continuous spline fit to the data. Usually such a fit is made to one of the forms of the cumulative distribution because in the limit the stage cuts become true step functions and, fits to the cumulative distribution become exact. In any case, such techniques provide useful interpolation methods, and, by making use of some boundary conditions, can be used to make reasonable extrapolations beyond the size range spanned by the largest and smallest D_{50}'s of the impactor.

A spline technique was recommended for use by the ARB and is implemented in the computer data reduction package detailed in Appendix A. The technique is a modification of one proposed by Lawless (1978) in which a cubic spline fit is made to the cumulative percentage form of the measured distribution in log-probability space. Modifications have been made to Lawless's technique to insure that no negative slopes are generated and to force continuity in slope in the extrapolation regions beyond the span of the impactor D_{50}'s. The results of the fit to the cumulative percentage data points are converted back to a concentration basis for the remaining steps. Once obtained, the analytic expression(s) for the fit can be used to generate values of the cumulative distribution at user selected particle sizes and can be differentiated to obtain values of dM/dLogD at any desired diameter. Results from the spline fit to the data from the sample run used in the previous paragraphs can be found as an example in Appendix A.

An alternative spline fit procedure was developed by Johnson et.al. (1978) as a part of the development of CIDRS (Cascade Impactor Data Reduction System) for the US EPA. In the EPA CIDRS the fit is made in log-log space to the cumulative concentration form of the distribution. Modeling of impactor performance in sampling unimodal and bimodal particle size distributions and comparisons of the resulting apparent distributions produced by the EPA CIDRS with the originals showed excellent agreement within the span of the impactor D_{50}'s and fair agreement in extrapolations to beyond a factor of two in diameter from the limits of the measurement range (McCain et.al., 1979). Similar tests of the EPA CIDRS by Smith et.al. (1982) showed that the maximum errors which might be expected in extrapolations of cumulative concentrations to diameters of about twice the D_{50} of the first impactor stage were about 15% and typical errors would be 5% or less. Because most aerosol size distributions are approximately log-normal, the curvatures of the distribution plots are much less radical in log-probability space and consequently easier to fit without generating artifacts; therefore, the cubic spline fit in log-probability space was selected for use by CARB. Experience in fitting the same data by both the Lawless and SoRI techniques has shown good agreement between the two when the data are well behaved and superior performance by the log-probability fit when the cumulative concentration curve showed extreme curvatures. Therefore, the errors associated with the extrapolations made using the Lawless method are expected to be comparable to those from the EPA CIDRS technique.

Averages of size distribution data are generally desired in both differential and cumulative forms together with measures of the scatter in the data (e.g., standard deviations and/or confidence limits). Having obtained the spline fits, it becomes a simple matter to obtain average values of dM/dLogD and associated variances and standard deviations for a standard set of user selected diameters. In addition, standard statistical tests for outliers can be used to flag and, if desired, remove values from the averaging process if they deviate too greatly from the rest of the data. Outliers are identified by comparing the deviation of the suspect data from the mean of the entire set relative to the standard deviation of the set to the critical value of Student's t-Distribution for the number of samples and desired confidence level. The value X_i is considered to be an outlier and may be excluded if the following condition is met:

$$\frac{[X_i - X_m]}{S} > C_n \qquad (5\text{-}37)$$

where

X_i = individual value,

X_m = mean of all values,

S = standard deviation of the data set,

C_n = critical value from Student's t-Table for the desired confidence level and number of observations, n.

The application of this test requires that there be three or more runs to be averaged. Care should also be taken by the user to not exclude values arbitrarily which might represent real states of the process being measured.

If the data are being reduced manually, the values of dm/dlog D for the selected standard intervals of diameter can best be obtained by graphical means. This is accomplished by plotting the cumulative concentration curve on log-log paper for each run to be included in the average. A smooth curve should be drawn through the points for each run and extrapolated from the largest D_{50} to D_{MAX}, arriving at D_{MAX} with 2 slope of zero. The cumulative concentration must be zero at infinitely small diameters, so the curve is extrapolated toward zero concentration (infinite slope) for diameters substantially smaller than 0.1μm. The curve should then be broken into equal segments of dlogD with the segments centered on the standard diameters which have been selected. Four or five segments per decade in diameter are suggested (ΔlogD=0.25 or 0.20). dM/dlogD can then be estimated at the geometric mean diameter of each segment by dividing the concentration difference between the segment end points by ΔlogD for the segments. This process is illustrated in Figure 5-5 for obtaining dM/dlogD for the interval from 2.51 μm to 3.98 μm centered at 3.16 μm. The intervals for ΔlogD in the figure are 0.20. The grid lines were omitted in the figure for clarity in reproduction.

$$(dm/d\log D)_{3.16\,\mu m} \approx \Delta M/\Delta \log D = \frac{(3.23-2.25)\,mg/Nm^3}{0.20}$$

$$= \frac{0.98}{0.20}\ mg/Nm^3$$

$$= 4.9\ mg/Nm^3$$

By repeating the above process for each of the intervals in ΔlogD from 0.1 μm to D_{MAX}, one can obtain a complete set of values for the run at a standard set of diameters. Repeating the entire process for each run will then provide the values needed for manual averaging of the data.

The situation becomes more complicated when averages for the cumulative forms of the distribution are sought. Direct averaging of data in the cumulative percentage form is quite inappropriate because all information regarding relative concentrations among the runs is lost in the cumulative percentage distribution form. The average cumulative percentage distribution must instead be generated from the average cumulative concentration. Because errors in values for single impactor stages are propogated forward from the D_{50} of the stage throughout the remainder of the distribution, valuable information from stages other than the one with the bad data will be lost if the cumulative distributions are averaged directly with removal of outliers. On the other hand if direct averaging is used without omitting erroneous values detected through outlier analysis, the errors are incorporated in the final results. In order to circumvent these problems, average cumulative distributions are better

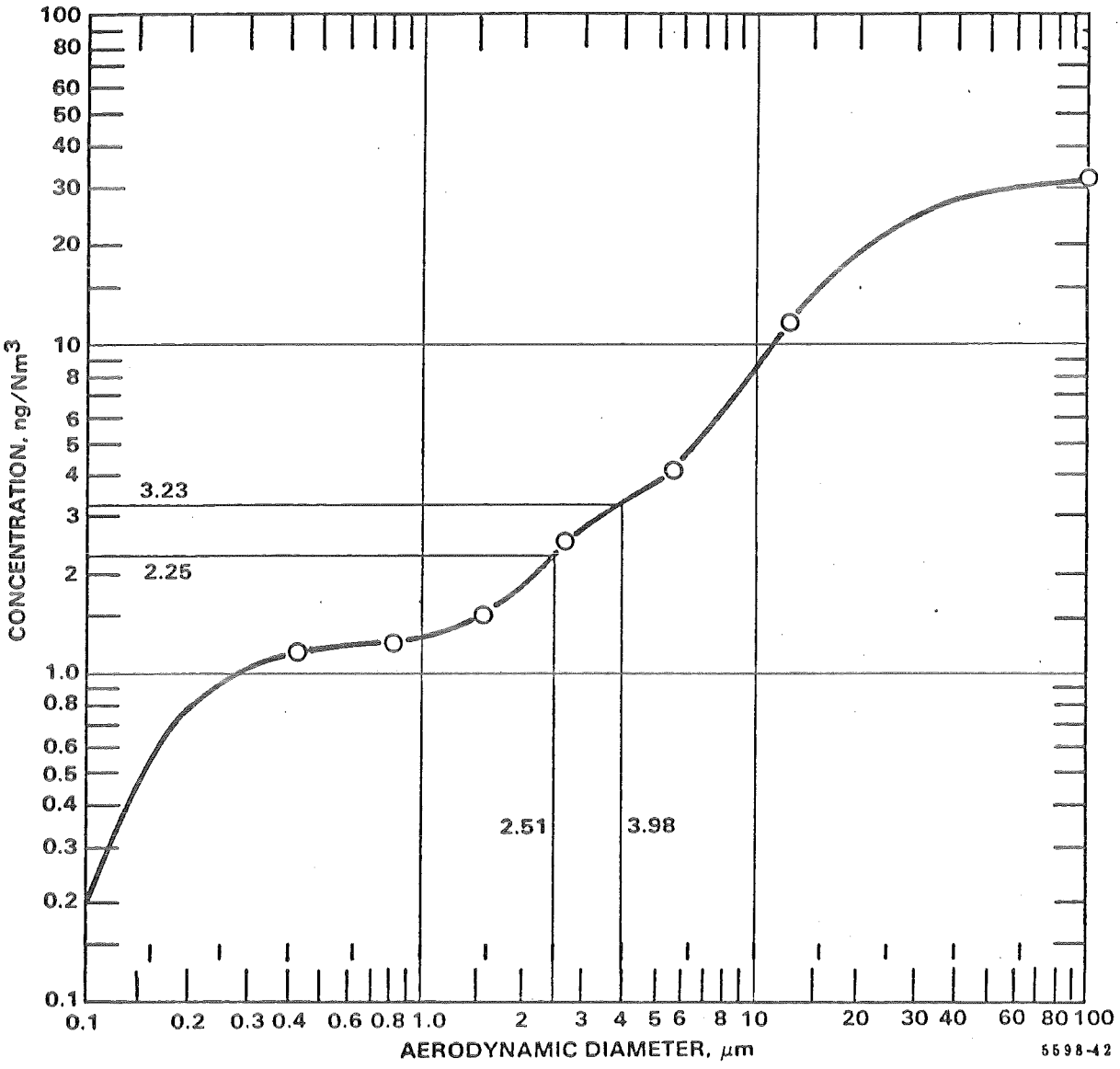


Figure 5-5. Manual method of obtaining dM/dLogD values at preselected diameters.

constructed by numerically integrating the averaged differential distribution. This results in the omission of data from the averaging process only for sizes in the immediate vicinity of the range covered by the stage(s) for which the values are suspect. Variances for the resulting points on the cumulative distribution curve are estimated by using the fact that the variance in the sum of two quantities is equal to the sum of their individual variances.

Manual integration to obtain the average cumulative distribution is accomplished by averaging the values of the (extrapolated) cumulative curves at 0.1μm, omitting outliers if desired. The value of the cumulative concentration curve at the end points of successive intervals is then given by the equation

$$Cum_j = Cum_0 + \sum_{i=1}^{j} \overline{(\Delta M/\Delta \log D)}_i \cdot \Delta \log D \qquad (5\text{-}39)$$

where CUM_j = cumulative concentration at interval endpoint

CUM_0 = average of extrapolated concentrations at 0.1μm

$\overline{(\Delta M/\Delta \log D)}_i$ = averaged value of $\Delta M/\Delta \log D$ for the ith interval (beginning at 0.1μm).

and $\Delta \log D$ = width of the standardized interval in terms of log diameter.

The summation should be taken through the upper extrapolation region to D_{MAX} so that the average total concentration, less the effects of any outliers, can be obtained to use in constructing the averaged distribution in a cumulative percentage form.

Another complication is introduced if the velocity profile across the duct from which the samples are taken is not uniform. The actual transport rate of particles, R_i, of any given size interval through the duct is given by the expression

$$R_i = \text{area} \int C_i \cdot \upsilon dA \qquad (5\text{-}40)$$

where C_i = the local particle concentration for size i,

and υ = the local gas velocity.

This integral is normally approximated by the sum:

$$R_i = \sum_n C_{i,n} \cdot \upsilon_n \cdot A_n \qquad (5\text{-}41)$$

where A_n = partial duct area represented by a particular sample,

$C_{i,n}$ = the concentration measured at point n,

and υ_n = the velocity at point n.

(Note that this is exactly analogous to the manner in which emission rates are measured using Methods 5 and 17.) Therefore, the correct procedure for combining data from runs made at several different locations in the duct cross section is to construct averages which are weighted by the velocities at the sampling points and by the cross sections for which the velocities are representative. Provision for making these weighted averages is made in the computer data reduction package described in Appendix A.

5.5 Calculation of the Fractional Efficiencies of Control Devices

The efficiency with which a control device collects particles of a given size is given by the expression:

$$E = 1 - C_o/C_i \qquad (5\text{-}42)$$

where

C_o = the outlet concentration at that size

and C_i = the inlet concentration at that size

with both concentrations being expressed at the same gas conditions. Since $(dM/dLogD)_i$ represents the concentration of particles having diameter, between D_i and D_i + dLogD, respective inlet and outlet values of dM/dLogD may be substituted for the concentrations in the equation. These values can be obtained from the spline fits if data from individual runs are to be compared, or from averages of the differential distributions if data from multiple runs are to be compared.

If data from single runs are used in calculating fractional efficiencies, it is not possible to estimate uncertainties in the efficiencies directly from the results. However, if data from multiple runs are used for both the inlet and outlet, the confidence interval, CI, for the penetration, 1-E, is given by the expression (Beers, 1957):

$$CI = \left[p^2 \cdot \frac{\left[t_o \frac{\sigma_o}{C_o} \right]^2}{N_o} + \frac{\left[t_i \frac{\sigma_i}{C_i} \right]^2}{N_i} \right]^{1/2} \qquad (5\text{-}43)$$

where

$P = C_o/C_i$,

t_o = Student's t value for the desired confidence level for the number of outlet samples used,

t_i = Student's t value for the desired confidence level for the number of inlet samples used,

N_o = the number of outlet samples used,

N_i = the number of inlet samples used,

σ_o = the standard deviation of the outlet data set,

and σ_i = the standard deviation of the inlet data set.

SECTION 6

QUALITY ASSURANCE/QUALITY CONTROL

As outlined in Section 3, there are a number of problems inherent in cascade impactor sampling which could result in the invalidation of whole sets of data. The intent of this section is to outline measures which, if integrated into standard impactor operating procedures, will reduce these potential errors to acceptable levels or eliminate them altogether.

6.1 Pretest QA activities

Several important quality-related decisions are required prior to an impactor sampling run. These decisions, and their effect on the quality of the test data, will be discussed in the following paragraphs.

6.1.1. Pretest Site Survey

Some prior knowledge of the test site and flue gas conditions is required for efficient test preparation. One method of obtaining the necessary information is a pretest site survey by one or two experienced individuals.

The goal of the survey is to gather information needed by the sampling crew for adequate planning of the test. The minimum data required are the identification of special or unusual problems so that work can be begun on tasks which must be completed prior to testing (such as installation or enlargement of ports). Usually, the more complete the survey, the more efficient and profitable the testing will be.

In cases where the sampling crew is unfamiliar with both the site and the type of process stream to be sampled, data concerning the process itself should be collected during the pretest survey. It is important to insure that enough information is available so that sampling can be performed under typical operating conditions, particularly if a batch or cyclical process is to be tested or if the source is occasionally operated in an anomalous mode. Other important plant information includes availability of facilities and supplies such as electrical power, water, ice, and laboratory space. An additional aspect of the plant survey which must not be neglected is a thorough safety inspection.

In addition to the plant data mentioned above, a site survey should include careful annotation of gas stream conditions expected at the sampling points. Information concerning gas temperature, pressure, composition, and approximate particulate loading will be needed to select the optimum equipment

and sampling strategy. If possible, an impactor should be operated during the survey to identify potential problems. Such a test can be valuable in the determination of mass loading, proper sampling duration, and collection substrate and impactor suitability.

The precision of testing performed during a survey should not be expected to equal that of the actual test, but it should be close enough so that problems that might be encountered in the actual test can be anticipated from the results of the survey. This will make d cisions regarding the correct equipment and techniques possible. If a pretest survey is not possible, it may be necessary to use the first impactor runs of the test series as "trash" runs to provide information for the proper setup of the remaining test runs.

In situations where the source is of a type previously tested and sampling conditions at the site are familiar to the sampling team, only a site inspection would be needed. This visit should be made by a member of the sampling team who should establish contact with plant personnel, inspect sampling ports for size, location, and suitability, request needed items or work (such as port enlargement or placement, sampling platforms, laboratory space, and electrical power), and identify sources of possible problems. Port size, port extension, inside duct dimensions, and port adapter configuration can be easily measured with a tape measure. Specifically, the pretest site inspector should look for unusual problems or circumstances that will need attention before the test date.

6.1.2 Cyclic Processes

As previously mentioned, cyclic processes can introduce greater difficulty into a sampling program. The test procedure should be planned and coordinated with plant personnel so as to span an integral number of process cycles, if possible. While in the planning stages, consideration should also be given to less obvious cycles such as ESP rapping, to guarantee the data is truly representative of duct conditions.

6.1.3 Substrate Collection Surface

Extensive studies of substrate media have shown that suitable substrates exist for most applications if caution is exercised in selection and use. It should be noted that impactor calibration and performance depend upon the type of substrate used and that calibration is required for each type. Also, the stability of the substrate should be checked in each gas stream being sampled. Both greases and glass fiber mats typically experience anomalous weight changes when exposed to stack gasses, as discussed in Section 3.

The pretest survey should include a series of blank impactor runs to aid in the selection of the substrate material. A good rule of thumb is that the maximum allowable change in weight of the blank substrate should be no more than 10% of the mass of the particulate matter that is expected to be collected on the impactor stage collecting the least mass. In most instances, a blank substrate weight change of 0.25 mg is excessive. Reproducibility of blank weights is of greater concern here than the absolute magnitude of the change. If the changes are reproducible, corrections for them can be made to the data with confidence that valid results will be obtained.

6.1.4 Impactor Jet Stages

Most commercially available impactors come with a fixed set of stages which are used at all times and no decision as to which stages to use is required. However, in some cases, most notably the University of Washington Mark V impactor, a variety of jet stages are available and those most suited to the sampling conditions should be used.

A trade-off exists between three major considerations when choosing jet stages. Because of the non-ideal behavior of jet stage efficiency curves, a factor of two should separate the cutpoints of adjacent stages. The separations should not be smaller than about a factor of 1.5. Excessive jet velocities result in increased chances of particle bounce. Very low jet velocities can result in low Reynolds numbers and uncertainty in the value of the impaction perimeter.

If data regarding a particular particle diameter is desired, the cutpoint of two stages should bracket this diameter for reliable interpolation of the mass less than this diameter. If the target diameter is large, the cutpoint of the largest stage should be as close to the desired diameter as possible to reduce extrapolation errors.

6.1.5 Sample Nozzle Size

The particle size cuts of cyclones and impactors are dependent on a number of factors. Other than the selection of stages, the sampling flow rate is the only variable affecting the cut sizes which can be adjusted by the user. If a multi-stage device is used to measure the complete size distribution, some latitude is available in setting the flow because interpolation can be used to determine the concentration of particles in any designated size range within the operating limits of the sampler.

If a given stage is required to produce a stated size, say 10 μm, the sample flow rate required to obtain that cut will be dictated by the sampler used (given the gas composition and temperature of the process stream being measured). This means that if a cut at a specified target diameter must be obtained, one may not have the latitude in selecting the sampler flow to be used that one has in simple total particulate measurements or even for standard impactor runs. The matching of the sample inlet velocity with the gas stream velocity for isokinetic sampling must be accomplished entirely through the cross-sectional area of the sampling nozzle. This means that a much larger array of nozzles must be available than those used in Method 5 sampling. If the isokinetic error is no larger than 20%, the maximum error in the measured emission rate of 10-μm particles will be about 15% and the errors for smaller particles will be lower. Errors for large particles will be approximately equal to the isokinetic error. Deviations of 20% from isokinetic can probably be tolerated. If sampling is to be done within 20% of isokinetic, an array of nozzles must be available that step by 10% in diameter from one to the next.

Once the flow rate is determined, it can be used with the gas velocity to select the appropriate nozzle to use. Only straight nozzles should be used as

"gooseneck" or bent nozzles will, in most cases, severely perturb the results. A more complete discussion of this nozzle effect can be found in Section 3.

If there is no requirement for a specific size cut as may be required in PM_{10} sampling, the operator has more flexibility to choose a flow rate suitable to the requirements of his sampler and the particulate loading of the gas stream. Typically the average velocity of the points to be traversed is determined using EPA Method 2. Next a nozzle is selected whose isokinetic flow rate at this average velocity is judged to be suitable for the particular site and impactor. The flow rate determined in this way is maintained at all sampling points on the traverse. If the velocity distribution is poor, several runs may have to be made, each covering a part of the duct, to synthesize a complete traverse.

The flow rate mentioned above is considered to be suitable for a particular impactor if it falls within the recommended operating limits of the impactor and restricts bounce and reentrainment of particles.

As discussed in Section 3, studies have been conducted which have supplied the following operating criteria which, if met, may be expected to yield acceptable impactor samples:

1. If bare metal substrates are used, the vD_{50} products for the various stages should not exceed 5 μm•m/s.

2. If glass or quartz fiber substrates are used, the vD_{50} products should not exceed 15 μm•m/s.

3. If greased substrates are used, the vD_{50} products should not exceed 25 μm•m/s.

4. The spacing between the D_{50}'s of adjacent stages should not exceed a factor of about 2.5. If this spacing is exceeded, particles having momenta too high for reliable collection will be passed to the succeeding stage.

5. Operation at flow rates which result in very low Reynolds numbers should be avoided.

These are very generalized guidelines and should not be considered as hard and fast rules for all situations. The properties of the particles (e.g., hard dry particles or sticky particles) may dictate some modification of these criteria. An impactor run during the pretest site survey is recommended to properly assess these considerations.

The time required to collect an adequate sample depends on the mass loading of the aerosol, the size distribution of the particles, and the gas flow rate in the sampler. 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 pretest survey or other information. Given the mass concentration, an estimate of the sampling time for initial tests can be

obtained from nomographs. Results from the initial tests can then be used to more accurately establish the optimum sampling time.

The amount collected on each stage also depends on particle size distribution. If the flue gas contains mostly large particles, the precollector and upper stages of the impactor will contain more particulate matter than the filter or the lower stages. Two conflicting criteria complicate the choice of the sampling time. It is desirable, for minimizing weighing errors, to collect several milligrams on each stage; however, most size distributions are such that the upper stages are overloaded and particles become reentrained before the lower stages collect as much as a few milligrams. A rule of thumb is that no stage should be loaded above 15 mg, but the determining factor is whether or not reentrainment occurs. The deposit on each stage must always be visually observed to judge the "quality" of the deposits and the appropriate sampling time.

6.1.6 Calibrations

In most projects involving impactor sampling, the accuracy, precision, and comparability of gas volume and flow rate measurements are critical to the project data quality objectives. For this reason the flow metering system of each sampling train should have dependable calibrations. A pretest calibration check of the dry gas meter and orifice, using the procedure outlined in EPA Method 5 for post test calibration checks, is suggested but not required. This is especially true if the system has not been used for an extended period of time.

The type S pitot tube should be calibrated prior to testing according to the procedure in Method 2. All temperature sensors in the system should be checked for proper calibration using the procedures outlined in Method 5.

6.2 Onsite Operational Checks

There are a number of in-field checks of the sampling system that can be performed to insure the quality of data collected. Although the procedures outlined below cannot detect all possible problems, the suggestions listed can help eliminate several sources of error. One operational check that should never be neglected is a leak check of the entire sampling train. This is best done in three steps: the assembled collection device only, the sampling train without the collection device, and the sampling train with the collection device mounted on the probe.

The procedure to leak check the impactor should be performed after the impactor is loaded and assembled. If a precollector is to be used, this should be attached to the impactor and the whole assembly leak checked as a unit. The inlet to the collection device should be plugged and the outlet attached to the suction side of a small pump. The vacuum side of a mercury manometer or vacuum gauge should be connected in parallel to the impactor with the positive pressure side open to ambient. The pump valving should be adjusted until the manometer registers a vacuum of approximately 11 inches Hg. The impactor should then be sealed off. Field use of this leak check procedure has indicated that impactor assemblies experiencing pressure losses of less than 5

to 6 inches Hg in 60 seconds generally passed the EPA leak check criterion when checked with the entire sampling train. More significant leaks should be corrected. To prevent rupturing the impactor backup filter, the vacuum should be released at the sample nozzle.

It should be noted that the intent of this leak check procedure is not the elimination of every leak, but rather the detection of major problems such as missing o-rings. Small leaks are tolerated in this test because they do not significantly effect the quality of impactor data. This is true for two reasons. First, the volume of the impactor is so small that a 60 second pressure drop of 5 to 6 inches Hg corresponds to a flow rate well within the EPA criterion of 0.02 cfm. Furthermore, most impactors are not designed to be leak tight near the inlet of the device. This is due to the fact that during operation, the pressure drop to ambient at this point is essentially zero.

A negative pressure leak check of the sampling train both with and without the collection device, should be performed as described in Section 5. When leak checking the system with the impactor mounted on the probe, care should be taken to prevent rupturing the backup filter by backflow through the impactor.

An internal audit of the flow metering system is suggested as another method of detecting problems with the sampling train. To perform this system check, the metering orifice ΔH is set to achieve a desired flow rate. It is recommended that the flow rate chosen be an actual calibration point for the 1.0 orifice such as the flow rate required to produce an orifice pressure drop of inches of water. This recommendation is made on the basis that, occasionally, the curve fitted to orifice calibration data introduces significant error into the flow rate determination. Given the calibration flow rate for the orifice and the dry gas meter flow rate (obtained by measuring the length of time for an arbitrary volume, such as 2.000 ft^3, to pass through the meter) correct these two dry gas meter flow rates (calibration and audit) to standard conditions then determine their percent difference. An acceptance criterion of ± 5 percent is suggested but the needs of the sampling program may dictate adjustments to this value.

Problems such as impactor leaks, impactor stage overloading, bounce or reentrainment of particles can often be detected by examining the impactor substrates as they are unloaded. Note the appearance of each stage, substrate, or cyclone in a notebook or run sheet such as was shown in Section 4. A magnifying glass or low-power microscope will be useful when examining the deposits.

The shape of the deposits will provide some indication of whether or not bounce or reentrainment occurred during the run. An acceptable velocity through the jets usually results in a well-defined, cone-shaped pile of particulate matter while an excessive jet velocity yields a diffuse deposit. In extreme cases virtually none of the particles will be collected directly under the jets. Reentrainment is also more likely to occur at higher sampling flow rates. Streaks of particulate radiating out from the deposits may indicate that blow-off occurred and clumps of agglomerated material on the inlet surfaces of the jet plates almost certainly indicate that blow-off has occurred.

the same way as the impactors for the regular runs. Every aspect of the treatment of the control is the same as that of a real run except that it is not operated in the stack. If the substrate loses or gains more than an average of 0.05 mg, additional care must be taken to improve the handling and/or weighing procedures.

Prior to performing the first impactor run, the isokinetic setup table should be checked to insure that the orifice and nozzle size chosen are acceptable. The recommended lower limit of orifice pressure drop, ΔH, is 1.0 inch of water. Smaller values of ΔH make it difficult to adjust to the correct flow rate. In cases where a particular cutpoint is desired from the sampler, such as 10 μm, the proper flow rate can be critical. In most cases, the sample flow rate for an impactor will be much smaller than the flow rate used for Method 5 or Method 17 and the orifices used in the system for these methods will be too large to provide effective flow metering. In such a situation one of the smaller orifices should be used to obtain a larger ΔH for the same impactor flow rate.

The sample flow rate required for near isokinetic sampling with this nozzle should also be checked to insure it falls within the suggested operating limits of the impactor and does not contribute to the occurrence of bounce and reentrainment. Improper sample flow rates can be changed if a differerent nozzle size is used. If changes are made in either nozzle or orifice size, a new isokinetic setup table should be calculated.

A "wet" weighing of the undesiccated substrates from the first impactor run should be made to determine approximate stage loadings. Any adjustments in run time indicated should be made in subsequent runs.

At least one post test dry weight of each substrate should be recorded on site. If possible, second weighings should also be performed in the field. Second weighings of every substrate may be avoided by performing second weighings on a random selection of 10 to 20 percent of the substrates. If the first weight in each case is reproduced to within 0.05 mg, the first post test weighing may be accepted as the final dry weight of all the substrates.

The final dry weight change of each substrate should be corrected for any blank weight changes. The magnitude of this correction is determined by averaging the weight changes for all blank substrates of the same geometry. This average value is subtracted as a background correction from substrate weight gains for each test run.

Field data sheets should be checked during and after each run to insure that all needed information is (or has been) recorded. Pressure in the field to complete the sampling often leads to an attitude that one can fill in information at a later time from memory - this is a very poor practice and should be avoided.

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Chapter 2

Use and Misuse: Operating Guide

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2.1 Introduction

The cascade impactor is a dependable instrument for measuring particle size distributions based on inertial principles. Particle size distribution and concentration can be determined. The aerosol may consist of solid or liquid particles, ranging in shape from spheres to crystals to complex aggregates. The impactor is used to separate airborne particles according to their sedimentation and other inertial behavior, as discussed in Chapters 1, 3, 4 and 5.

In this chapter, the use and misuse of the impactor in collecting an airborne sample will be discussed in detail. Our focus is directed to the industrial hygienist who has the need to use cascade impactors in the assessment of occupational health hazards. Detailed outlines of procedures and materials needed to obtain reliable samples of airborne particles with a cascade impactor will be provided. Brief discussions on the applications of the instrument in industrial hygiene, correct usage, expectations, limitations and a trouble-shooting guide are also included.

2.2 Criteria for Use

The cascade impactor is one of many instruments used for sampling airborne particles. If the total particulate mass concentration is desired, a filter sample is often adequate to provide the information with considerably less effort. Sampling with a cascade impactor may not be advisable when the material to be sampled can sublime or become unstable when it remains on the collection surfaces. In many cases, information on detailed particle-size distributions is not required but some knowledge of the inhalable or respirable fraction is helpful. A rough estimate of coarse particles (those not likely to be inhaled) and fine particles (those likely to be inhaled) may be sufficient to determine whether a particular aerosol deserves further hazard evaluation. A single-cut device such as a cyclone or an elutriator may provide such information.

Cascade impactors are used to provide airborne particle size distribution data in the research laboratory and the occupational or atmospheric environment. In many occupational health-related situations, the data are essential in establishing guidelines for good industrial hygiene practice or in radiological health protection. An aerosol sample collected by cascade impactor can be analyzed to provide information on specific inquiries such as:

- What is the aerodynamic particle size?
- What is the airborne concentration of contaminant?
- Does the composition of the aerosol change with particle size?

The cascade impactor is occasionally used to estimate aerosol concentrations since the amount of airflow through the unit and the mass of aerosol collected over time are known.

The inertial separation of airborne material, by size, in quantities large enough for most chemical analyses makes the cascade impactor one of the simplest devices to use in determining chemical composition as a function of particle size of airborne particles. A wide variety of cascade impactors designed for different purposes are now commercially available. Table 1 in Chapter 1 provided a comprehensive list of information on available impactors and the types of models available.

2.3 Industrial Hygiene Applications

The first application of the cascade impactor in the evaluation of occupational hazards was done by May (1945). Later, a final filter stage was added (Laskin, 1949), thus capturing all particles penetrating the last stages. With this one modification, the cascade impactor became a useful monitoring device in the workplace. A current miniature version is small enough to be worn by brass foundary workers as a personal sampler (see Hinds *et al.* 1985). Another example of cascade impactor use in a wood working plant was reported by Whitehead *et al.* (1981).

Data obtained from sampling with such cascade impactors are often used to determine the types and levels of radioactive aerosols. The size distribution, concentration, and solubility characteristics of individual particles in an effluent can be determined from impactor samples (Cember, 1963). The measured particle size and solubility of a radioactive aerosol are essential in estimating the delivered dose to exposed populations. More accurate dosimetry is possible if the solubility of each size-segregated fraction is known. Data collected from cascade impactors can also be used to estimate the respirable fraction; the technique is presented in Chapter 3. Any significant changes in the particle size distributions as a result of process or operational variations can be measured by sequential sampling with cascade impactors. Measurements such as those in the evaluation of the performance of respirators or particulate emission control equipment as a function of particle size require the use of cascade impactors as well.

Impactor samples are also used in environmental sampling programs to characterize the particle size of aerosols in effluents from chemical and nuclear facilities as well as from urban and natural sources. Samples are usually drawn directly from high-velocity gas process streams or from a stack for short sampling periods. Some samples require extended sampling periods in order to obtain sufficient material for analysis. Refer to section 2.5 on sampling strategy in this chapter.

2.4 Pre-Sampling Procedures

Preparation to use cascade impactors properly consists of setting up a tidy work area, inspecting and cleaning the impactor and its parts, testing for leaks, and checking the air flow calibrations of the sampling train. These steps should be followed prior to the use of each cascade impactor.

2.4.1 *Preparations*

Adequate preparation is most important before using a cascade impactor. Without good planning, samples may be contaminated or damaged in the process of merely searching for the proper tools to load an impactor. This section provides a checklist of supplies, equipment and facilities that are essential for the proper operation and use of cascade impactors. An expanded list of materials and supplies needed for five key operating steps is given in the Appendix, Section 2.9 under the following headings:

- General setup
- Loading and unloading
- Cleaning
- Air Flow Calibration
- Sampling

A critical list of ten key items essential for the use of a cascade impactor is as follows:

- A work surface
- Method to check jet diameters
- Tweezers
- Substrates (aluminium foil, plastic film, membrane filters)
- Final stage backup filter
- Replacement O-rings
- Balance (electrobalance accurate to ± 2 μg)
- Dry-test meter
- Vacuum pump
- Standard operation procedures with data sheet

2.4.2 *Inspection*

An inspection checklist should include the following:

- Wear or cracks in the O-rings or gaskets
- Tightness of clamps
- Uniformity of jet diameters, number of holes/slots on each stage
- Proper order of impaction stages
- Condition (flatness) of the impaction plates and substrates

Inspection of all gaskets is especially important since a leak in the cascade impactor will reduce the particle velocity on each stage above the leak. This will cause deposition of larger particles on the lower stages. The order of the impactor stages must be checked during unloading and loading operations. If a lower impaction stage is erroneously placed above a stage designed to collect larger particles, all material that would normally have deposited on those stages will deposit on the first stage with little deposit on the second stage. Such deposition patterns, if seen in examining the amount of material collected on each stage, are undesirable and may result in

an uninterpretable data set. Therefore, verify that each stage is in good condition and that all stages are assembled in the correct sequence. A mechanically-defective impaction plate in an impactor with multiple jets can change the cutoff characteristics significantly.

2.4.3 *Cleaning*

The user should be able to determine both the best method for handling the impactor parts during cleaning and the proper method to rinse or dry the stages to avoid interference with the analytical technique. Cleaning the impactor comprises two separate operations: 1) cleaning the reusable collection surfaces, and 2) cleaning the internal portions of the impactor body.

The impaction nozzles and collection surfaces from the impactor are removed and washed thoroughly. If chemical analysis is to be used, these parts should be cleaned to obtain the lowest possible background levels. During rinsing, drying and reloading, precautions must be taken to avoid contamination. This may mean working in a well-ventilated hood or using an ultrasonic bath to clean a clogged jet.

An important element in the care and maintenance of cascade impactors is the cleaning of the jets. They should be purged with clean air by using a vacuum source or with compressed air (with adequate precaution to filter the air), followed by ultrasonification. Rigid wires should not be used to check or unclog a jet orifice. The internal parts of the impactor may be washed separately, or the impactor body may be washed as a unit by flushing cleaning solutions through it. This latter case is useful when toxic or hazardous solvents must be applied to clean the impactor. Fluid is pumped from the bottom of a reservoir, through a pump, and into the bottom of the cascade impactor body. The fluid then flows upward through the assembled impactor and is returned from the top of the reservoir. The appropriate solvent, or the entire reservoir, can be changed between wash and rinse cycles. The last cycle is followed by disassembly of the impactor to air-dry the parts.

2.4.4 *Preparing Collection Media*

In most cases, the impaction surface of the cascade impactor is removable and made of metal or glass. Filter paper or plastic film may be used as substrates. The surface of the collection substrate may be covered with an adhesive coating. The actual choice of a coating in preparing the collection substrate is important.

The performance of an impactor and the precision of particle separation can be affected by the flow field, particle trajectory, and properties of the substrates and collection media. The collection efficiency of an ideal, perfectly sticky impaction surface should resemble the characteristic S-shape curve shown in Figure 1a with particle collection efficiency plotted against the square root of the Stokes number, $\sqrt{St}$. If particle bounce occurs, the actual efficiency curve will likely be represented by Figure 1b, where larger particles will be affected to a greater extent due to their inertia. Recommended procedures to pre-treat the collection substrate with adhesive coatings to avoid particle bounce in cascade impactors are discussed in detail in Section 2.7.2. Stopcock grease, oil, Apiezon® L and H high vacuum greases, and Vaseline® are examples of substances that can be used to minimize particle bounce.

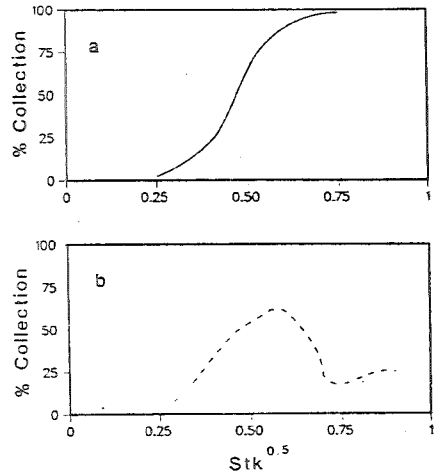

Figure 1. Characteristic shape of cascade impactor collection efficiency curves: A) no particle bounce; B) some particle bounce.

The simplest approach in preparing the cascade impactor for use is to load clean, uncoated impaction substrates. Barr, *et al.* (1982) showed that uncoated metal substrates exhibited collection characteristics for plastic spheres in agreement with theoretical predictions. However, fiber-type substrates used in sampling particles at high temperatures have been shown to exhibit the greatest deviations from theory (Felix *et al.* 1977).

Cheng and Yeh (1979) showed that the influence of particle bounce on the collection characteristics of an impactor with clean, uncoated substrates can be reduced by a lower volumetric flow through the impactor. Their maximum volumetric flow for minimum particle bounce was related to the product of three parameters:

- Calculated particle impact velocity, V_p in m/sec
- Particle Diameter, D_p in m
- Square root of the specific gravity of the particle, $\sqrt{(\rho_p/\rho_o)}$

where ρ_p is the particle density and ρ_o is the density of a unit density sphere. For particles similar to latex spheres, there is no significant bounce from clean metal impaction surfaces when the value of $\sqrt{(\rho_p/\rho_o)}(V_p D_p)$ is less than 5×10^{-5} m²/sec. The particle impact velocity, V_p, can be approximated by:

$$V_p = V_o\left[1 - \frac{1}{4St}\right]$$

according to Cheng and Yeh (1979).

The type of substrate and coating to be used depend on the aerosol to be sampled, the flow rate through the impactor, environmental conditions during sampling, and the analytical method chosen. The best media for collecting particles with minimum particle bounce appear to be those in which oil can be wicked up to the impaction surface as particles deposit (Reischl and John, 1978). For uncoated collection surfaces, particles tend to rebound when impacting on the surface or colliding with each other. Effective coatings function best on collection surfaces only for light mass loadings. Under heavy mass loadings, the problem of particle bounce will reappear (refer to Section 2.7.2 on Particle Bounce).

Cascade impactor samples can be analyzed by optical counting, gravimetric determination, radiometric counting, or chemical analysis. When analysis is accomplished by optical counting, the collection medium used must be clean enough to allow clear distinction between particle and background.

Gravimetric analysis of the collection substrate requires that the substrate coatings and samples be stabilized before and after sampling. A list of commonly-used substrate coatings are as follows:

- Stopcock grease
- Oil
- Vaseline® (applied directly or after dilution with cyclohexane)
- Paraffin (applied directly or after dilution with toluene)
- Apiezon® L and H high-vacuum grease (applied directly or after dilution with toluene)
- Silicone grease
- Polyethylene glycol 600 (carbowax diluted with chloroform)
- Methyl silicone (SE 30 or UCW-982 diluted with chloroform)

The last two coatings are generally used as stationary-phase GC column materials and can be obtained through chromatography supply sources. Additional discussion on the use of these substrate coatings is provided in Section 2.7.2 on Particle Bounce. Application of the coatings is accomplished by spreading or spraying a diluted solution on the collection substrate surface followed by drying.

The drying and weight-stabilization processes depend on the collection medium used. For example, Harris (1977) used a solution of 20% grease in toluene to coat the substrate. The substrate was then heat-treated at 204°C for one hour, followed by desiccating for 12 hours before preweighing. The optimal weight-stablization process may differ from one medium to another and must be determined through several trials.

When a chemical technique such as gas chromatography (GC) is to be used to analyze the size-fractionated samples on the collection surfaces, the substrate coating used should not increase the background level to a point where accuracy of the assay is compromised. Stable GC-column materials such as polyethylene glycol-600 or methyl silicone (UCW-982) have been proposed as substrate coatings. They can be diluted in chloroform and then applied to the collection surface with a small, air-brush spray applicator. Of course, one must exercise caution in handling the substrates to avoid contamination. A guideline to assure high-quality data is that the substrate coating should not double the lower detection limit of the instrument.

Substrate media composed of agar or other growth medium are used in the sampling viable organisms or other microbiological contaminants. Special procedures for handling the stages are needed to assure that the samples remain uncontaminated. Storage procedures or incubation are required immediately after sampling.

2.4.5 Assembly

Prior to assembly the cascade impactor, one must have adequate work space to record pre-weights and sample numbers on data sheets. In most cases, weight-stablization of the collection surfaces, filters, metal substrates or organic film substrates must be achieved. All pertinent information that may be relevant in interpreting cascade impactor data must also be recorded on a data sheet, including weights of each impaction stage before and after sampling, radiometric background counts or baseline levels for a chemical assay. Before loading each stage into the appropriate position, one should take care not to contaminate the collection surface. Sources of potential air leaks should be checked to prevent leakage. A well-organized work area will be helpful.

2.4.6 Leak-test Procedures

Two types of leaks can occur in a cascade impactor: 1) a leak from the outside, and 2) an internal leak inside the impactor which can cause airflow to by-pass an impaction stage. An outside leak can be located readily by sealing the inlet and exhaust of the entire cascade impactor while it is under a slight vacuum and then checking for any increase in the pressure. A manometer or a Magnehelic® pressure gauge is adequate to make these measurements. Leaks between successive stages are more difficult to detect: unusual or unexpected particle deposition patterns on various stages, or significant interstage losses, are often clues to suggest leakage in the cascade impactor. Proper loading procedures and good O-rings should prevent leaks between the stages.

2.4.7 Calibration of the Sampling System

Stage collection efficiencies for each impaction stage must be determined and the effective cutoff diameters known prior to sampling. Experimental confirmation of theoretical predictions of particle collection efficiency must be made as discussed in Chapters 4 and 5. Air flow calibration of the loaded impactor is also critical.

2.4.7.1 Impactor Calibration

Effective cutoff diameters (ECD) and collection efficiencies for an impaction stage can be computed theoretically based on the equations and procedures described in Chapter 4. Obviously, the critical dimensions of the impactor, such as the jet diameters or slit widths, and distance between the jets and collection substrates, must be verified. In actual practice, some particle bounce, re-entrainment, electrostatic charge effects, and wall losses will occur and the theoretical impaction efficiency may differ from the experimentally-determined collection effi-

ciency. A typical collection efficiency calibration requires the use of monodispersed aerosols of different sizes at one or more flow rates. Examples of cascade impactor efficiency calibrations are discussed in Chapters 4 and 5.

Figure 2 is a schematic diagram of a typical calibration apparatus for a multistage cascade impactor (Harris, 1977). It includes an aerosol generator, drier, charge neutralizer, dilution air, air flow monitoring equipment, optical counting equipment, and the impactor to be evaluated. The aerosol generator can be a compressed-air driven atomizer by which monodispersed or polydispersed aerosols can be generated. Other aerosol generating devices such as the vibrating orifice generator, spinning disc, fluidized bed or ultrasonic nebulizers can also be used. The calibration should be conducted with aerosols in the same size range as the stage cutoff diameter at the appropriate flow rate. Different sizes of aerosols will have to be generated in order to calibrate all the stages of a cascade impactor. Particle concentrations as a function of size are measured upstream and downstream of the impactor. Calibrations at different flow rates should also be conducted.

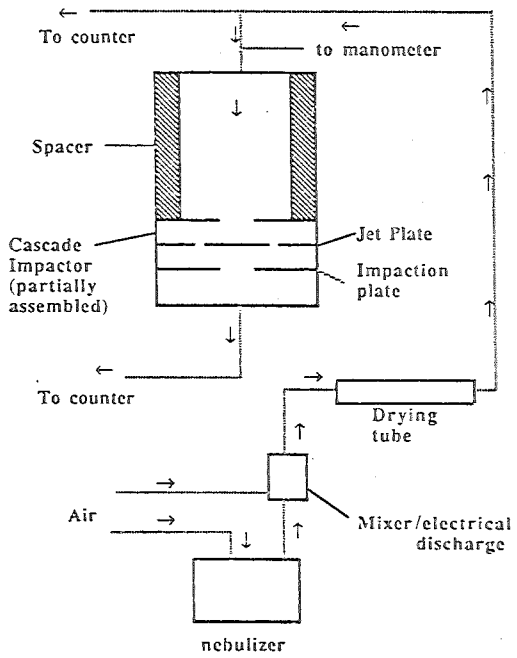

Figure 2. Schematic diagram of the impactor calibration apparatus (modified from Harris, 1977).

The impaction stage to be calibrated should be placed in the calibration apparatus as shown in Figure 2. The impactor housing can be used to mount the stage to ensure proper alignment. To provide the proper flow pattern, an impaction plate should be placed upstream and downstream of the jet plate. The collection substrate should be prepared as it would be in normal use of the impactor.

One method to determine the collection efficiency of an impaction stage is by determining the real-time particle concentrations before and after that stage. However, most electro-optical or radiometric detectors require proper dilution as these instruments are subject to coincidence counting errors if particle concentration is high. When the inlet and outlet particle concentrations are determined, the concentrations may have to be adjusted to account for any dilution differences used for the optical counters. The particle collection efficiency of a stage, expressed in percent, is defined as:

$$\text{Efficiency} = [1 - C_{out}/C_{in}] \times 100$$

Particle collection efficiencies in an impactor depend on an impaction parameter, the square root of the Stokes number, $\sqrt{St}$. The results of the experimental calibrations can be compared to theory or calibrations reported by other investigators. Refer to Chapters 4 and 5 for more details.

2.4.7.2 *Air Flow Calibration*

Air flow calibration standards, primary or secondary, can be used to calibrate the cascade impactor. Primary standards for volume are based on actual displacement of known volumes. They include spirometers, "frictionless" piston meters and calibrated wet-test or dry-gas meters. Secondary standards are reference instruments which had been calibrated against primary standards. They include rotameters, orifice meters, venturi meters, laminar-flow meters, Pitot tubes, pressure transducers or by-pass flow indicators. The accuracy of many of these devices is often better than 2%. A comprehensive review of the calibration standards and procedures can be found in the ACGIH Air Sampling Instrument Manual (Lioy and Lioy, 1983).

The following steps are recommended for air flow calibration for a cascade impactor sampling train:

1. Assemble the impactor with properly loaded stages and substrates.
2. Assemble the sampling train in the exact manner in which it will be used in field sampling.
3. Calibrate flow with a primary calibration standard or a reliable secondary standard.
4. Measure the volumetric flow with respect to time with the calibrated flow instrument and an accurate stopwatch.

If a critical orifice is used in sampling, the vacuum source must be powerful enough to maintain sonic velocity through the orifice. This is especially important when operating a critical orifice downstream of the backup filter. As the filter gets loaded with particles or when the impactor orifices become partially clogged, a significant increase in pressure drop will develop between the impactor inlet and the orifice to cause total pressure drop through the entire sampling train to increase.

If a rotameter is used to monitor air flow downstream of the impactor, the indicated flow rate must be corrected for the decreased pressure present at those points in the sampling train. The true flow rate can be approximated to within a few percent by the following equation:

$$Q = Q_r[(P_{atm} - \Delta P)/P_{atm}]^{-0.5}$$

where Q = actual flow rate
Q_r = air flow rate, as indicated by the rotameter
P_{atm} = atmospheric pressure
ΔP = Gauge pressure downstream of the sampler

Measurement of the pressure drop as a function of the flow rate provides an indirect method for checking the jet orifice diameter by comparing the data against those for a known hole size. The flow rate can be measured with a calibrated rotameter or other calibrated flow- or volume-measurement device. The pressure drop across the impaction stage can be measured with an open-end manometer attached to the downstream side of the impactor.

2.5 Sampling Strategy

Impactor characteristics, sampling requirements, and the specific objectives must be considered in establishing a sampling protocol. Although it is desirable to obtain a representative sample, one usually has to work out a compromise between the best sampling location, work schedules, and what is practical. The sample required may have to be obtained in the workplace, inside an exhaust duct or stack, or outdoors. The chemical characteristics of the effluent, such as unknown species, corrosiveness and combustibility, may affect sampling capability (ANSI, 1974). Sampling requirements and conditions that need to be considered include: sampling rate, sampling time, number of samples, sampling locations, orientation of the impactor inlet, thermal conditioning and the need for *in situ* sampling. Specific examples in adapting different sampling strategies for certain workplace aerosols are illustrated by Molker *et al.* (1979a & b), and Chan *et al.* (1986).

Other factors that may affect sampling are the physical and chemical conditions of the air stream, sampling location, and inlet probe design. The criteria for using the correct probe in various sampling situations have been described in detail by Durham and Lundgren (1980) and by Davies and Subari (1982).

2.5.1 Selecting an Impactor

The type of impactor needed for a specific sampling situation can depend on the flow rate (high or low), the particle size range of interest, the desired resolution in measuring particle size, material used in impactor construction, and the need for a particle pre-collector. A pre-collector can serve two useful functions: 1) it provides an additional upper cut size, and 2) it prevents the large particles from depositing and building up on the first two stages, which can cause overloading problems.

2.5.2 Sampling Location

Determining the best location at which to obtain samples depends on the purpose of the study. Sampling in the workplace may require that the sample be obtained as close to the nose or mouth (i.e., breathing zone) of the workers as practical without interfering with their normal work assignments (Cember, 1983). A sample located in a representative area of the workplace may be adequate if there are multiple sources of the same aerosol in that occupational environment. For both personal and area sampling with a cascade impactor, the flow rate through the instrument is usually fixed, leaving only the diameter and orientation of the inlet probe as variables. In still air (a rare condition in the workplace), Agarwal and Liu (1980) concluded that the true concentration of airborne particles can be determined to within 10% provided that the probe diameter, D_{probe}, is greater than 20 times the quotient of the square of the particle setting velocity, V_{ST}, and the gravitational constant, g. That is, $D_{probe} > 20V_{ST}^2/g$. In most sampling situations, air movements will give rise to local velocities greater than 0.5 m/sec. The best approach is to align the probe parallel to the air currents and try to match the sampling velocity entering the probe inlet to the free stream velocity. A short sampling tube may be used to provide an approximate isokinetic sampling condition (Chan *et al.* 1986). One can also make adjustments to the collected data for anisokinetic sampling. However, these calculations are likely to introduce more errors, and adherence to isokinetic sampling conditions is strongly recommended (Hinds, 1982; Mercer, 1973).

In a typical occupational environment, the air is exhausted through a number of ducts. Therefore samplers placed at the ventilation duct exits may provide only an integrated average of the exhaust air concentration which may differ from the breathing zone concentration. Sampling in large exhaust ducts is usually a tradeoff between selecting the best location from a technical standpoint and accessibility. For stack sampling, one standard (ANSI, 1969) recommended sampling at a minimum of five diameters downstream from any abrupt change in flow direction. Corley and Corbit (1983) recommended a sampling location of between 8-10 diameters downstream from transitions or bends. The more conservative approach should be followed whenever possible. Since it cannot be assumed that particle distribution is uniform across an exhaust duct, representative samples must be taken over a cross section and averaged. In a circular duct, each sampling point should be placed in concentric annular areas of equal area. Square and rectangular ducts should be sampled from points in cross sections representing approximately equal areas (ANSI, 1969). Each stack or duct should be monitored downstream of all locations where effluents may enter the exhaust system. If the system discharges to the atmosphere, the sample should be at or near the release point (ANSI, 1969 & 1978). Other technical details involved in stack sampling for regulatory purposes are discussed in the EPA reference methods published in the Federal Register (EPA, 1977).

Obtaining samples during acute pollution episodes such as fires, explosions or accidental release of hazardous substances requires special considerations. For one thing, particle concentrations are expected to be very high, which limits the sampling duration. Fire-resistant protective wrappers or methods to prevent the thermal destruction of the impactor and the samples may

be required. Remote sampling lines (with an understanding of their losses) may be a last resort under extreme environmental conditions. If sampling lines must be used, they should be as short and straight as possible to reduce gravitational or inertial losses. Similarly, a vertical duct is preferable to a horizontal one to avoid losses due to gravimetric setting and subsequent re-entrainment. To avoid condensation, the line or sampler may be heated to the appropriate temperature. In health physics applications, the relative levels of radioactivity or other hazardous materials in the sample during accidental releases should also be anticipated and designed into emergency sampling protocols.

Sampling at a location at high altitude or at high/low temperatures require a re-calibration of an impactor because the Stokes number will be different under those operating conditions. Procedures to make the necessary corrections for operating the impactor at reduced pressures or at elevated temperatures are described in Chapter 4. The effect of temperature and pressure on the effective cutoff diameters of inertial impactors was also described by Biswas and Flagan (1984).

2.5.3 *Number of Samples*

The number of samples required is usually determined by the specific objectives of the investigation. If the size distribution of airborne particles near a single worker is desired, then one sample may be all that is required. A personal cascade impactor would be attached to the worker throughout the workshift. If the aerosol size distribution within a room, a large duct, or an environmental site is to be determined, then a larger number of samples may be required to examine the temporal and spatial variability in aerosol concentration and size differences. If the source of workplace aerosols is to be determined, a comprehensive characterization program may require a great number of samples.

For duct or stack sampling, the number of samples required to warrant good representation depends on the shape and cross-sectional area of the exhaust system. For circular stacks less than 8 inches (20 cm) in diameter, one sampling point may be adequate. A large duct with a diameter of 50 inches (130 cm) may require a minimum of six points. For a rectangular duct of less the 0.5 ft^2 (460 cm^2) in cross-sectional area, one point is suggested, but 20 points may be needed for a duct greater than 25 ft^2 (2.3 m^2) in cross sectional area. However, fewer sampling traverse points would be required if the velocity profile has been mapped out to show uniformity throughout the cross section.

2.5.4 *Isokinetic Sampling*

Velocity profiles near or at the sampling locations must be determined prior to sampling to ensure accurate results. The velocity and flow distribution in a duct at the sampling section should be known so that the rate of sampling can be nearly isokinetic. Sampling is isokinetic when the inlet of the sampler is aligned with the gas streamlines, and the mean gas velocity entering the sampler matches the mean free stream velocity at the inlet. If isokinetic conditions are not met, the measured particle size distributions may be distorted: 1) larger particles will be preferentially collected if the sampling velocity is less than the free stream velocity, and 2) larger particles will be undersampled if the sampling velocity exceeds the free stream velocity (Hinds, 1982; Mercer, 1973). In general, particles having aerodynamic diameters of 2 μm or less are capable of following the streamlines, and sampling errors due to anisokinetic sampling are not serious. If the flow rate of the sampler is to be fixed, the inlet nozzle or probe size may be changed to ensure isokinetic conditions. The following equation can assist in calculating the dimensions and flows needed for a nozzle of circular cross-section in a circular duct (Hinds, 1982):

$$\frac{Q}{Q_{duct}} = \left[\frac{D_{probe}}{D_{probe}}\right]^2$$

where Q = sampling flow rate
Q_{duct} = flow rate in duct
D_{probe} = diameter of probe, and
D_{duct} = diameter of duct

2.5.5 *Sampling Duration*

The minimum sampling duration must be chosen so that the volume of air sampled is much larger than the internal volume of the impactor (Mercer, 1973). The amount of material collected should be enough for accurate sample analysis, but the actual deposits should not overload the impaction stages to cause particle bounce or particle re-entrainment problems. The key decision is the mass of material to sample. For example, for an ambient cascade impactor such as the Andersen® impactor which operates at 1 ft^3/min (28.3 L/min), the recommended maximum mass per stage is 10 mg (Harris, 1977). A usable rule of thumb is to keep the total mass of material sampled by this unit to less than 50 mg (see Section 2.7.1 on Sources of Erroneous Data). This guideline can be extended to other impactors, but must be reduced for monodispersed particles that are collected only on a single impaction stage. The desired target sampling duration can be approximated by:

$$\text{Sampling time (min)} = \frac{\text{Desired Impactor Load (mg)} \times 1000\ \text{L/m}^3}{\text{Concentration (mg/m}^3) \times \text{Flow rate (L/min)}}$$

The sensitivity and accuracy of the analytical method will determine the minimum volume of gas needed to meet sampling requirements. The time interval required is a function of aerosol concentration. Depending on the analytical method used, the mass of sample required may range from a fraction of a milligram to several grams. If the sample is to be evaluated microscopically, only a very light deposit would suffice so that the particles would not overlap. Gravimetric or chemical analysis, however, requires a greater amount of material. On the other hand, requirements for radioactive analysis depend on the specific activity of the radionuclide, its half-life, the type of emission, and the detection limit of the radiometric counting system.

2.6 Data Collection

The calibrated sampling train, consisting of the impactor, pump (or vacuum source), appropriate flow meters and control valves, should be taken to the sampling point and a sample

obtained. Immediately after sampling, the cascade impactor should be sealed and placed in a location where it can be carefully opened, in a clean environment, with little chance of contaminating the collection substrates or losing materials collected. The substrates should be removed, weighed, and analyzed as soon as possible, depending on the stability of the material and the analytical method.

All relevant data associated with sampling workplace aerosols with a cascade impactor should be recorded in a data sheet (see Figure 3) containing the following information:

- Name of person(s) taking the sample
- Date and time of sample
- Sample number or identification (area or breathing zone sample)
- Condition of environment (temperature, humidity, etc)
- Flow rate, pressure drop through impactor
- Specification of inlet probe used
- Sampling duration
- Name(s) of contaminant(s) sampled
- Location of sample
- Location of nearest source of emission

In addition, the following information should also be available for each stage of the cascade impactor:

- Stage number
- Stage cutoff diameter
- Particle mass, count or activity (before and after sampling)

All of this information is required to enable the proper interpretation of particle size distribution and concentration data.

2.7 Misuse of the Impactor

2.7.1 Sources of Erroneous Data

Imperfections in the manufacture of cascade impactors can cause errors. Small deviations in the critical jet diameters may lead to large, systematic shifts in predicted particle size distribution. Thus, any burrs in the jets should be removed and the jet diameter verified before using a new impactor.

Insufficient or excessive mass collected in the impactor can cause erroneous data. For an Andersen® cascade impactor that operates at 28.3 L/min, more than 10 mg on a stage or a total mass of 50 mg may be excessive. Too much deposit can result in overloading the stages and can cause particle bounce, particle re-entrainment, and changes in particle collection characteristics. On the other hand, insufficient mass will result in errors in the analysis of deposited material on each stage and will lead to large uncertainties in interpreting the particle size distribution. A rule of thumb in judging an acceptable error in the analysis of the material depositing on each stage is that it should be less than 0.5% of the total mass collected on all stages. Otherwise, the particle size distribution data may not be very meaningful.

Sample ID: _____ Purpose: _____ Date: _____

Material Sampled: _____ Impactor Type: _____ Time: _____

Impactor Flow Rate [l/min]: _____ Sample Number: _____ Sample Time: _____

Temperature/Relative Humidity: _____ Pressure: _____

Stage #	Slit Width or Hole Diameter	Number of holes	Amount Collected	Tare or Background	Net Amount	Percentage of Total	Cumulative Amount	ECD [µm]
			Total Amount Collected =					

Comments: (location, inlet probe, etc) _____

Data Taken By: _____ Date: _____

Reviewed By: _____ Date: _____

Figure 3. A sample data sheet for cascade impactor sampling.

If the material deposited on each stage is to be weighed, sample losses due to sublimation or evaporation can interfere with the measurements. It may be possible to determine the initial weight of the material on the stage by plotting the weight of that stage (on a logarithmic scale) as a function of time and then extrapolating back to time zero. A limitation of this method of estimating the initial weight is the assumption that the air was saturated with the volatile material during sampling and that the losses occurred only after sampling. A suggestion in treating such problems is to compare the size distribution of the sample with or without the volatile species in order to ascertain the significance of the volatile fraction.

Errors in measuring the actual particle weight may result from the attachment of gas molecules to the substrates. This can occur in stack sampling, where the hot effluent contains gases that may even react with the particles at catalytic sites on the substrate surface. To avoid this, the impactor substrates should be equilibrated in the gas being sampled and their preweights determined prior to loading the impactor. The purpose of this additional step is to allow the substrate to reach an equilibrium level such that subsequent weight gain due to sorption or reaction will be small compared to the weight gain from the actual particle deposits during sampling.

Even with the greatest care in calibration, sampling and analysis, the simplest operation in handling impactor samples can cause errors. Great care must be taken when handling the cascade impactor following sampling to prevent contamination or loss of sample from the collection stages. This is critical if samples have to be shipped over long distances for analysis. Whenever possible, arrangements should be made to have the samples weighed and analyzed at or near the sampling site.

2.7.2 *Overloading and Particle Bounce*

In order to obtain accurate particle size measurements with a cascade impactor, it is necessary for the impacting particles to adhere to the collection surfaces. The problem of particle bounce exists when hard, solid particles have sufficient kinetic energy to bounce off the collection surfaces and are then deposited on lower stages or on the interstage walls of the impactor. This results in a measured size distribution biased toward the smaller sizes. Investigations on particle bounce were described first by May (1945), followed in recent years by Dzubay *et al.* (1976), Walsh *et al.* (1978), Wesolowski *et al.* (1980), Reischl and John (1978), Rao and Whitby (1978), Chan and Lawson (1980), Hinds *et al.* (1985), and Turner and Hering (1986).

When particle bounce occurs, the collection efficiency is not governed by the Stokes number alone (see Chapters 4 and 5). The jet diameter, velocity, and other factors affecting particle adhesion to surfaces can influence the actual collection efficiency (Rao and Whitby, 1978). The magnitude of bounce is very sensitive to jet velocity and, to a lesser extent, to particle size. If particle bounce is suspected as a potential problem, the use of adhesive substrate coatings is highly recommended. A variety of coatings have been used on collection substrates to absorb the kinetic energy of the impacting particles. Examples include stopcock grease, oil or other petroleum-based greases. Refer to section 2.4.4 for a complete list of substrate coatings.

Many studies have been conducted in which the collection efficiencies of coated and uncoated substrate surfaces were compared. In almost all cases, a higher collection efficiency was measured with the coated surface as compared to the uncoated surface. This was observed for a glass surface, with or without Vaseline® (Turner and Hering, 1987), steel plates, with or without oil (Rao and Whitby, 1978), Mylar®, with or without Apiezon® greases (Wesolowski *et al.*, 1980) or Vaseline® (Chan and Lawson, 1980), and aluminum foil, with or without grease (Dzubay *et al.* 1976). In cascade impactors, the lower collection efficiency due to particle bounce will result in a smaller measured mass median diameter (MMD) for an aerosol. The MMDs measured by Dzubay *et al.* (1976) were lower by a factor of 2 to 5. Chan and Lawson (1980) reported a 41% decrease in the measured MMD for uncoated vs. Vaseline®-coated Mylar® in one impactor. Hinds *et al.* (1985) measured a 50% decrease in the MMD of grinding dust using bare-metal surfaces as compared to ones with a silicone-greased coating. In a comparison of coatings by Lawson (1979), Apiezon® L and Vaseline® were shown to be the preferred choices. Vaseline® was better because it did not interfere with his analytical method of Proton-Induced-X-ray Emission (PIXE). The coatings were applied as solutions: 4% of Apiezon® by weight in toluene, and 4% of Vaseline® by weight in cyclohexane.

As particle loading increases on a coated impaction surface, the collection efficiency may decrease. This decrease is due to the fact that all impacting particles no longer land on the greased layer but instead are bouncing off the collected particles. This was observed even when coverage was less than a monolayer (Reischl and John, 1978; Turner and Hering, 1986; Hinds *et al.* 1985). However, the same investigators have shown that when sintered metal, or porous membrane backed with solid glass disks, was oil-coated properly, there were only minimal changes in the collection efficiency with particle loading. The oil from the substrate apparently was coating the collected particles by capillary action, and thus provided a renewed coated surface for a new wave of particles.

Different substrates have also been investigated to reduce particle bounce. They include glass disks, Mylar®, aluminum foil, stainless steel plate (solid or sintered), and membrane filters. Glass fiber filters have been used effectively to reduce bounce. However, the collection characteristics of impactors with these surfaces are significantly altered. The surface roughness of the fiber affects the flow field enough to collect a significant fraction of smaller particles. Therefore, calibration of the impactor with the glass fiber filters as substrates is required (Rao and Whitby, 1978).

2.7.3 *Troubleshooting*

Other than the obvious errors associated with an incorrect sampling train, several factors during sampling can affect the accuracy, representativeness, quality, and reproducibility of the samples. These may include particle bounce, particle re-entrainment or blowoff, inlet and wall losses, electrostatic losses, poor cutoff characteristics and partially clogged impactor stage holes or slits. The symptoms, possible causes and suggested solutions associated with these problems are addressed in detail in Table 1.

TABLE 1. Troubleshooting Guide

Symptom	Possible Problem	Possible Solution
Flow through impactor too low	Line from impactor to vacuum source clogged	Replace or repair line
	Holes or slits clogged	Take impactor apart, clean, and reassemble
	Defective or inappropriate critical orifice	Replace orifice
	Vacuum inadequate for critical orifice	Increase vacuum
	Backup filter partially clogged	Use different type of filter to correct mass overload
	Leakage	Locate and repair leak
Particles deposited on inner surfaces of impactor	Interstage or inlet losses	Use impactor with lower wall losses of particles
	Electrostatic losses	Use an aerosol neutralizer during sampling
Particle size distribution distorted toward smaller size	Particle bounce	Use thin film of oil or grease, compatible with analysis technique, to coat impaction plate
	Particle blowoff due to overloading	Sample for shorter time or at lower velocity; use precollector if overload is on first stages; use rotating collection surfaces.
Particle size distribution distorted toward larger size	Impactor stages in wrong order	Reassemble correctly
	Water or other vapor condensation on particles	Heat impactor
	Overloading on first stages such that smaller particles impact on conical mound	Use precollector or shorten sampling time
Amount of material deposited on stages is less than expected	Leaks in line or impactor	Replace leaky sampling lines and check seals of impactor around "barrel" of unit
	Particulate concentration is less than expected	Sample for longer time
Condensation in lines or impactor	Temperature of aerosol is higher than sampling lines or impactor	Heat lines or impactor to match temperature of aerosol
Distorted deposition pattern on collection surface	Hole or slit partially clogged	Disassemble impactor, clean all stage and reassemble unit
Halo formation of deposit	Reynolds number too high (flow too high, jets partially clogged, or overloading)	Sample at lower velocity or for shorter duration

2.8 Summary

Useful information on particle size, concentration and composition can be obtained through analysis of size-fractionated samples from a properly-operated cascade impactor. It cannot be emphasized enough that the cascade impactor should be calibrated and proper handling of samples to avoid contamination must be practiced. When solid particles are sampled, the total flow through the impactor and the specific particle impact velocities should be examined in order to avoid particle bounce. Substrate coatings should be used whenever possible.

For industrial hygiene applications, planning the sampling strategy to achieve specific objectives is often more critical than the actual sampling operation. Cascade impactors, even those attached to electronic components to enable rapid feedback for data analysis, are not intended to be "push button" type devices. A thorough understanding of the operating principles (theoretical and experimental), correct sampling procedures, standardized data presentation techniques, and limitations of impactors is essential to warrant good particle size distribution data.

2.9 Appendix

An inventory of the essential supplies, equipment and facilities for cascade impactor operation is summarized under the categories of general setup, loading and unloading, cleaning, air flow calibration, and sampling.

2.9.1 General Setup

- Cascade Impactor
- Balance (preferably with an accuracy of ± 2 μg)
- Checklist and Data Sheets
- Light Microscope (with a Porton eyepiece graticule and a stage micrometer)
- Tidy Work Area

2.9.2 Loading and Unloading

- Tweezers
- Final-stage filters
- Replacement O-rings
- O-ring grease
- Substrate material
- Substrate punch
- Substrate coatings
- Air-brush applicator (to apply coating to substrate)
- Stage holders
- Loading and unloading tool
- Lint-free tissues or towel

2.9.3. *Cleaning*

- Detergent
- Distilled water
- Solvent
- Ultrasonic Bath
- Compressed air (filtered)

2.9.4 *Air Flow Calibration*

- Dry-test meter
- Method to check jet diameter
- Stopwatch
- Vacuum gauge/system

2.9.5 *Sampling*

- Vacuum source
- Flow monitoring device (orifice meter, rotameter, etc.)

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Chapter 4

Theory & Design Guidelines

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4.1 Introduction

In previous chapters impactors have been described as useful instruments for classifying particles by their aerodynamic diameters and for measuring particle size distributions. These impactors can be used most reliably if the user has some understanding as to how the impactor classifies particles and what parameters are important in this classification process. This understanding can best be obtained by a theoretical inspection of inertial principles.

This chapter reviews the most recent theoretical impactor work and the latest theoretical efficiency curves. Procedures are then given for using these efficiency curves in the design and evaluation of cascade impactors. Finally, several examples are given comparing theoretical and experimental efficiency curves, pointing out when the theory can be used with great confidence and when the theory should be used only as a guideline.

Due to the rather simple principle of operation of an inertial impactor (i.e., the impingement of a jet of particle-laden air on a flat plate) the impactor readily lends itself to theoretical analysis. Three notable works in the early 1950's were those of Davies and Aylward (1951), Davies *et al.* (1951), and Ranz and Wong (1952).

Davies and Aylward (1951) used a method of conformal mapping to obtain an analytical solution to Euler's equation for the flow of a frictionless fluid through a rectangular impactor. Numerical calculations were then carried out whereby the equations of motion of the particles were solved in a stepwise manner, leading to a determination of the efficiency curves. Since this theory assumed potential flow, the effect of Reynolds numbers on the characteristics of the impactor could not be determined.

Ranz and Wong (1952) used an approximate flow field to calculate the efficiency of both round and rectangular nozzle impactors. In the vicinity of the stagnation point, the flow field was assumed to be that of frictionless stagnation flow. Here, the resulting equation of motion for the particles was found to be in a form similar to equations for free vibration with viscous damping. Therefore, the known solutions of the vibration equations were applied directly to the problem and the efficiency curves calculated. This solution technique, however, could not take into account the various geometric variations such as the jet-to-plate distance in the determination of the efficiency curves.

The work of Ranz and Wong (1952) was later modified by Mercer and Chow (1968) and Mercer and Stafford (1969) so that the rather simple flow fields of Ranz and Wong (1952) could be used to account for various jet-to-plate distances. The same techniques, however, were used to determine the impactor collection efficiency curves.

With the advent of high-speed computers and the development of numerical analysis techniques in the late 1960's it was possible to perform a detailed study of the flow fields and particle trajectories within impactors (Marple, 1970; Marple *et al.*, 1974a and 1974b; Marple and Liu, 1974; Marple and Liu, 1975). This not only resulted in obtaining theoretical efficiency curves as a function of the geometric parameters such as jet-to-plate distance and throat length, and fluid mechanic parameters such as nozzle Reynolds number, but also a good insight into how an impactor must be designed and used. This theory was further updated in the early 1980's (Rader and Marple, 1985) to include second order effects such as ultra-Stokesian drag on the particles and particle interception at the impaction plate.

4.2 Theoretical Collection Efficiency Curves

In the first comprehensive theoretical work utilizing high speed computers, the impactor efficiency curves were determined by numerical analysis techniques (Marple, 1970). This work, as well as that of Rader and Marple (1985), is for single-jet impactors. For the case of multiple-jet impactor stages, the jet-to-jet interaction may affect the cutoff characteristics.

The technique included the finite difference solution of the Navier-Stokes equations to determine the flow field (Marple, *et al.* 1974 a, b) and the subsequent calculation of particle trajectories in the flow field by numerically integrating the particles' equations of motion (Marple and Liu, 1974). This method was applied to the two-dimensional geometries of round (circular jet with diameter W) and rectangular (rectangular slit of length L much greater than the nozzle width W) impactors. The study determined the collection efficiency curves for both nozzle configurations as the dimensionless parameters of jet Reynolds number, Re, jet-to-plate distance, S/W, and nozzle throat length, T/W, were varied. Results of that parameteric study are presented in Figure 1 where the values of Re, S/W and T/W are parameters. The symbols W, S and T indicate the jet width or diameter, jet-to-plate distance, and nozzle throat length, respectively, as indicated in Figure 2.

In Figure 2 the particle size on the abscissa is expressed in dimensionless form as the square root of the Stokes number, $\sqrt{St}$, defined as:

$$\sqrt{St} = \sqrt{\frac{\rho_p V_o C D_p^2}{9\mu W}} \tag{1}$$

where ρ_p is the particle density, V_o is the average air velocity in the nozzle throat, C is the slip correction, D_p is the particle diameter, μ is the fluid viscosity, and W is the nozzle diameter (round) or nozzle width (rectangular).

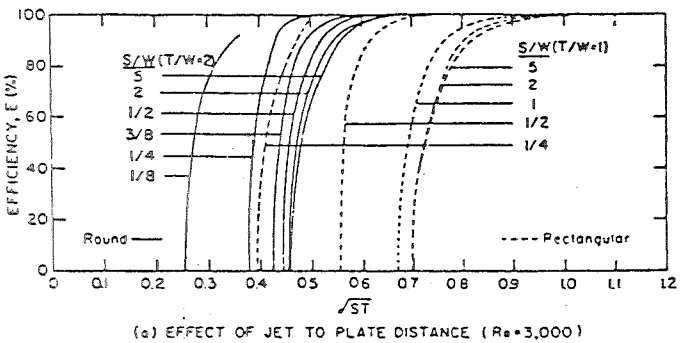
The Reynolds number, Re, is expressed as:

$$Re = \frac{\rho W V_o}{\mu} \qquad \text{(round)}$$

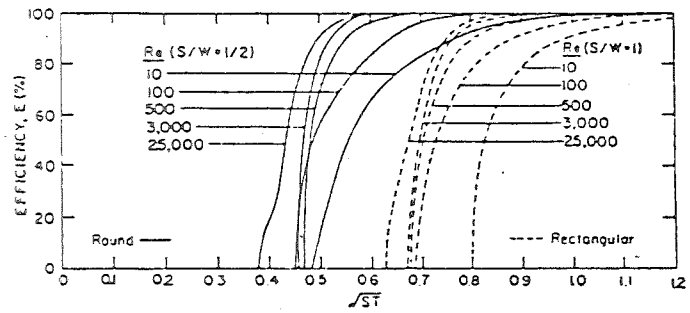
and

$$Re = \frac{2\rho W V_o}{\mu} \qquad \text{(rectangular)} \tag{2}$$

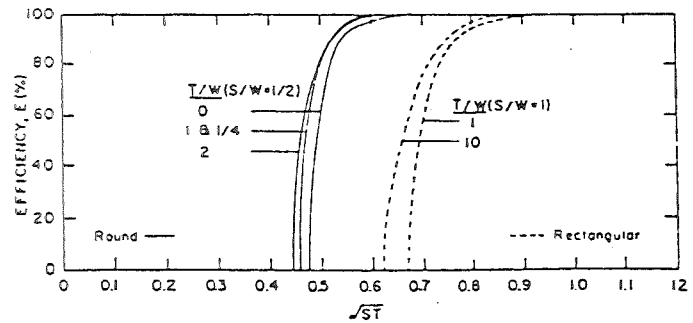
where ρ is the air density.



(a) EFFECT OF JET TO PLATE DISTANCE (Re=3,000)



(b) EFFECT OF JET REYNOLDS NUMBER (T/W=1)



(c) EFFECT OF THROAT LENGTH (Re=3,000)

Figure 1. Original impactor efficiency curves for rectangular and round impactors showing the effect of jet-to-plate distance S, jet Reynolds number Re, and throat length T (from Marple, 1970).

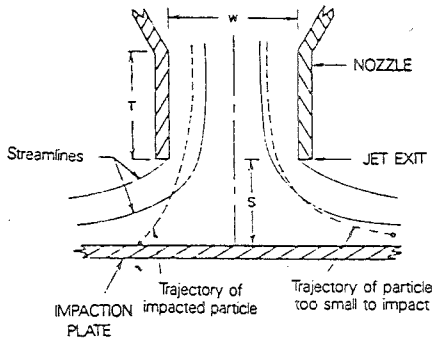


Figure 2. Schematic diagram of a typical impaction stage showing streamlines and particle trajectories.

The Reynolds number can also be expressed in terms of the air mass flow rate, $\dot{m}$, passing through the impactor as follows

$$Re = \frac{\dot{m}W}{\mu} \qquad \text{(round)}$$

and

$$Re = \frac{2\dot{m}W}{\mu} \qquad \text{(rectangular)} \tag{3}$$

This form of the Reynolds number is advantageous since $\dot{m}$ is a constant for all stages of the impactor.

It can be seen from the calculated efficiency curves in Figure 2 that the cutoff characteristics are good for efficiencies less than about 0.80. Above this value the cutoff characteristics are not as sharp due to the air and particles moving at lower velocities in the fluid boundary layer near the nozzle wall than in the central portion of the jet. Since the particle velocities are lower in this region, the particles must be larger to be collected, causing the nonsharp collection characteristics in the upper portion of the curves. A more detailed discussion of this phenomenon has been presented elsewhere (Marple and Liu, 1975).

Comparisons of the theoretical efficiency curves in Figure 2 to experimentally determined efficiency curves have indicated good agreement in most cases, if the nozzle configuration is similar to that shown in Figure 1. Differences between experimental and theoretical efficiency curves have primarily been in the shape of the efficiency curves. For example, in the portion of the curve represented by efficiencies less than about 0.10, the experimental curves have tended to flare to the left (small values of $\sqrt{Stk}$) while theoretical curves (Figure 2) tend to show sharp cutoff characteristics in this region. Thus, the actual experimental curve is "S" shaped while the

theory predicted only the upper portion of the "S" curve. In addition the experimental efficiency curves have, in general, been steeper (sharper cutoff characteristics) than the theoretical curves shown in Figure 2.

In an attempt to define theoretical curves that are even in better agreement with experimental curves than the theory described above (steeper "S" shaped curves), the theoretical technique was revised in three areas and the efficiency curves recalculated (Rader and Marple, 1985). The first area of improvement was to make the grid finer over the area for which the Navier-Stokes equations were solved. This allowed for the flow field to be described more accurately. This grid refinement was made possible by the higher-speed and larger-capacity computers available now compared with those used in the earlier study. The second area of improvement was employment of a more accurate particle drag coefficient in the particle equation of motion. Finally, the third area was inclusion of the effect of the interception distance of the particle as it approached the impaction plate. This differs from the previous theoretical technique where the particles were assumed to be represented as point masses. The effect of these three revisions in the theoretical technique is described in detail by Rader and Marple (1985) and will not be described here. However, for most of the efficiency curves the effects were small.

The efficiency curves calculated by the revised theoretical technique are shown in Figure 3. These curves are too new to have had many comparisons with experimental curves; however, the agreement should be better. Comparison of the curves in Figures 2 and 3 will generally show that the efficiency curves in Figure 3 are steeper and have the characteristic S-shape found in experiments. Therefore, this most recent theory appears to be an improvement.

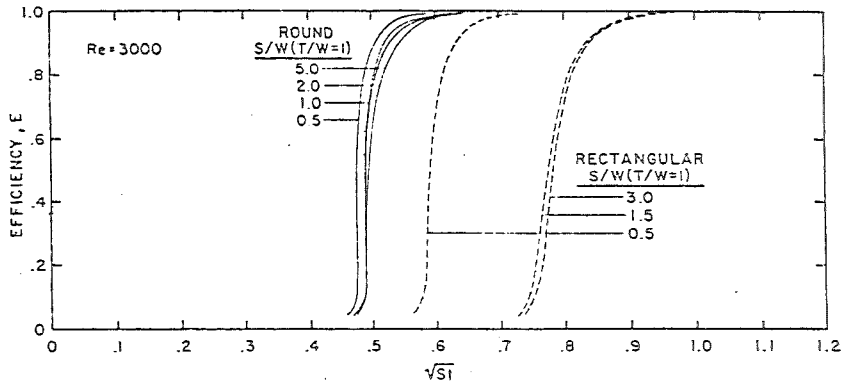
In the remainder of this chapter both sets of efficiency curves will be used. The original set (Figure 2) is presented since they have been in use for many years and many impactor designs, comparisons between theory and experiments, and impactor developments have been based upon these curves. The more recent curves, shown in Figure 3, are presented since they include more of the second order effects and should be the most accurate theoretical curves presently available. It is recommended that any future work be based upon the theoretical curves in Figure 3.

Although the revised theoretical curves in Figure 3 are to replace the original curves in Figure 2 that have been used for about 15 years, the basic guidelines have not changed, since the differences in the two sets of curves are slight in most cases. For example, both sets of curves indicate that S/W values should be greater than 1.0 for round impactors and 1.5 for rectangular impactors to avoid small changes in S/W radically changing $\sqrt{Stk_{50}}$, the Stokes number corresponding to 50% collection efficiency, and that the Reynolds number should be between about 500 and 3000 for both round and rectangular impactors to achieve efficiency curves with sharp cuts.

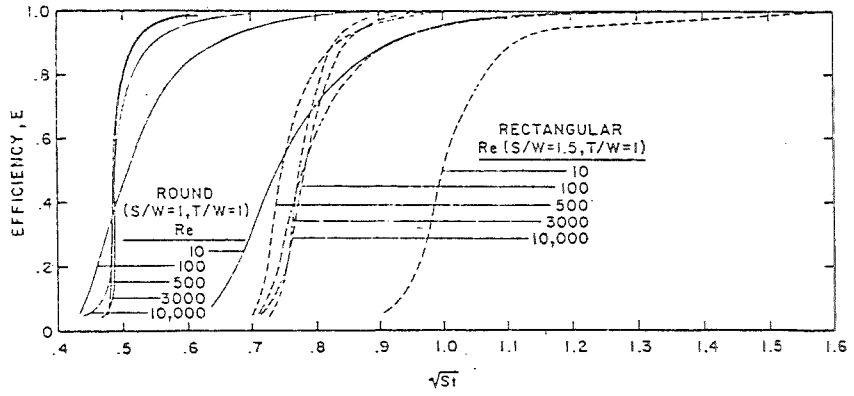
4.3 Slip Correction Considerations

In solving the Stokes number equation (equation 1) for the value of the particle diameter, a difficulty arises since the slip correction C is also a function of the particle diameter:

$$C = 1 + 1.257\frac{2\lambda}{D_p} + 0.40\frac{2\lambda}{D_p}\exp\left(-1.10\frac{D_p}{2\lambda}\right) \tag{4}$$



(a) EFFECT OF JET TO PLATE DISTANCE (Re = 3000)



(b) EFFECT OF JET REYNOLDS NUMBER

Figure 3. Revised impactor efficiency curves for rectangular and round impactors showing effects of jet-to-plate distance S, and jet Reynolds number Re (from Rader and Marple, 1985).

where λ is the mean free path of the air molecules (Davies, 1945). Therefore, the solution of equation 1 for particle diameter normally is a value for $\sqrt{C}D_p$ from which D_p must subsequently be solved. The value for the mean free path of the air molecules is taken as 0.66×10^{-5} cm at normal temperature of 20°C and pressure of 1 atm (101.3 kPa).

Although the mean free path is a function of both pressure and temperature, in most cases only the variation in the pressure as the aerosol passes through a cascade impactor must be considered.

The temperature is usually relatively constant and not far removed from the absolute normal temperature. Therefore, since the mean free path is inversely proportional to the pressure, it is possible to express the mean free path at a normal temperature of 20°C as:

$$\lambda = 0.66 \times 10^{-5}/P \tag{5}$$

where λ and P are in units of centimeters and atmospheres, respectively. The slip correction can now be expressed as:

$$C = 1 + \frac{1.659 \times 10^{-5}}{D_p P} + \frac{5.28 \times 10^{-6}}{D_p P} \exp(-83.300 D_p P) \tag{6}$$

One method for obtaining D_p when the value of $\sqrt{C}D_p$ is known is by iteration. With this technique a value for D_p is selected, C calculated from equation 4 and then the value of $\sqrt{C}D_p$ compared to the known value from equation 1. Next a new value of D_p is selected and the process repeated. This continues until the value of D_p has been found.

A more straightforward method of obtaining D_p from equation 6 is to express $\sqrt{C}D_pP$ as a function of D_pP (Marple, 1986). This is possible since C is a function of D_pP (equation 6). By plotting the relationship of $\sqrt{C}D_pP$ versus D_pP as shown in Figure 4, it is quite easy to obtain D_p when $\sqrt{C}D_p$ is known. This is done by multiplying the known value of $\sqrt{C}D_p$ by the pressure P in atmospheres. From Figure 4 the corresponding value D_pP can be found on the abscissa. Division of this value of D_pP by P gives the value of D_p.

The value of C versus D_pP from equation 6 is also shown in Figure 4. This indicates that for values of D_pP greater than 10 μm-atmospheres the value of C is unity and this solution technique need not be used.

One final use of Figure 4 is the determination of the aerodynamic diameter D_{ae} (diameter of a unit density sphere with same settling velocity) when the diameter of a particle D_p of non-unit density is known. The governing relationship is:

$$\sqrt{\rho_o}\sqrt{C_{D_{ae}}}D_{ae} = \sqrt{\rho_p}\sqrt{C_{D_p}}D_p \tag{7}$$

when $\rho_o = 1$ g/cm^3. If D_p and ρ_p are large enough so that D_p and D_{ae} are in the regime where $C_{D_{ae}}$ and C_{D_p} are unity then:

$$D_{ae} = \sqrt{\rho_p/\rho_o}D_p \tag{8}$$

However, if the C's are greater than unity, then Figure 4 can be used by multiplying both sides of equation 7 by the pressure P:

$$\sqrt{\rho_o}\sqrt{C_{D_{ae}}}D_{ae}P = \sqrt{\rho_p}\sqrt{C_{D_p}}D_pP \tag{9}$$

As illustrated in the insert in Figure 4, the procedure for finding D_{ae} is to first multiply D_p by P and find $\sqrt{C_{D_p}}D_pP$. Multiply this value by $\sqrt{\rho_p}$, the result of which is equal to $\sqrt{C_{D_{ae}}}D_{ae}P$, since $\rho_o = 1$. The value of $D_{ae}P$ can now be found from Figure 4 and the division by P gives D_{ae}. If the value of D_{ae} is known, D_p can be found by simply reversing the above procedure.

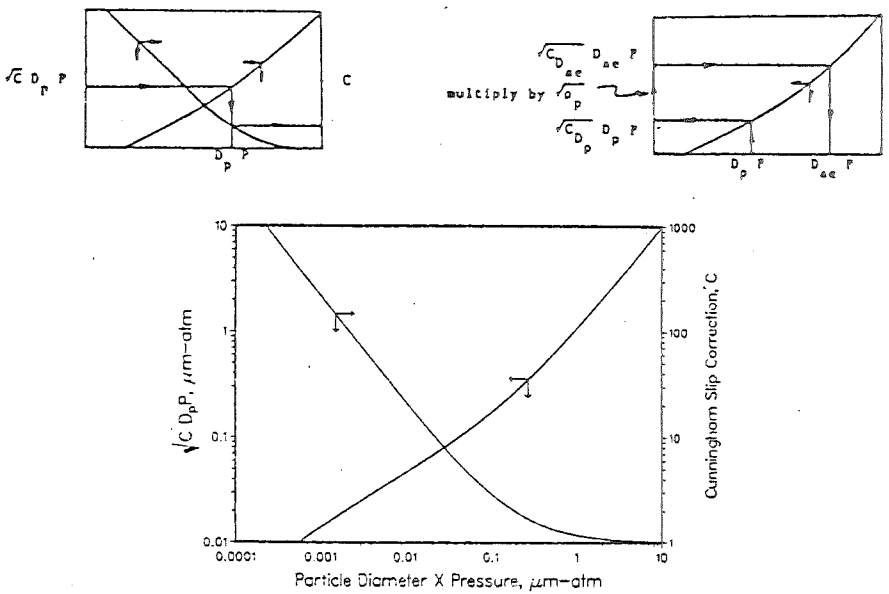


Figure 4. $\sqrt{C}D_pP$ vs. D_pP and C vs. D_pP. (A detailed plot is included in the instruction manual for the circular slide rule.)

4.4 Importance of the Flow Field

Since impactors collect particles by making use of the particles' inertial properties to move the particles through the air streamlines onto the impaction plate, the fluid flow field within an impactor is very important. For example, Marple and Liu (1974) showed that impactors with sharp collection efficiency curves can be obtained if the velocity profiles at the nozzle exit are uniform across the nozzle. The theoretical analysis, resulting in the efficiency curves in Figures 2 and 3, indicate that the two parameters of primary importance in controlling the flow field are the impactor configuration and the Reynolds number of the fluid at the nozzle.

Basically there is not much that can be done with the configuration to achieve uniform flow at the nozzle exit with the exception of controlling the jet-to-plate distance. We have already shown that the S/W value should be greater than 1.0 and 1.5 for round and rectangular impactors, respectively, to avoid sizable changes in particle cutoff size as a result of small changes in jet-to-plate distance.

The Reynolds number of the fluid at the nozzle throat, however, is very important in achieving a uniform velocity at the nozzle exit. If the Reynolds number is too low, a large viscous boundary layer exists at the nozzle wall and the velocity profile becomes parabolic. Smaller particles are

collected from the center of the nozzle where the fluid velocity is higher than near the wall where the velocity is low. This leads to a particle collection efficiency curve that has poor sharpness-of-cut characteristics as shown in Figure 3 for low Reynolds numbers.

Marple and Willeke (1976) investigated controlling the Reynolds number by controlling the number of nozzles used per stage of the impactor. This resulted in the development of a set of design curves for both round and rectangular impactors shown in Figures 5 and 6.

Figure 5 is actually three sets of curves for Reynolds numbers of 500, 3000 and 10000. In each set, the ordinate is the total flow rate through the impactor stage and the abscissa the number of nozzles in that stage. In this analysis there is a one-to-one relationship between the value of the $\sqrt{C}D_p$ and the nozzle diameter W. Therefore, $\sqrt{C}D_p$ and W are used as parameters for the curves in each set.

The curves in Figure 5 are to be used only as a guideline in analyzing or designing impactors. For example, if an impactor is to be designed with a Reynolds number of 3000 and a total flow rate of 10 L/min, the number of nozzles to achieve a cutoff size of $\sqrt{C}D_{50} = 1$ μm will be 5. The nozzle diameter for this stage would be about 0.113 cm. If the Reynolds number was to be lowered to 500, the same cutsize would be achieved with about 30 nozzles of 0.0894 cm diameter. If the Reynolds number was to be raised to 10000, then the impactor would take less than one nozzle and, thus, could not be a solution to the problem.

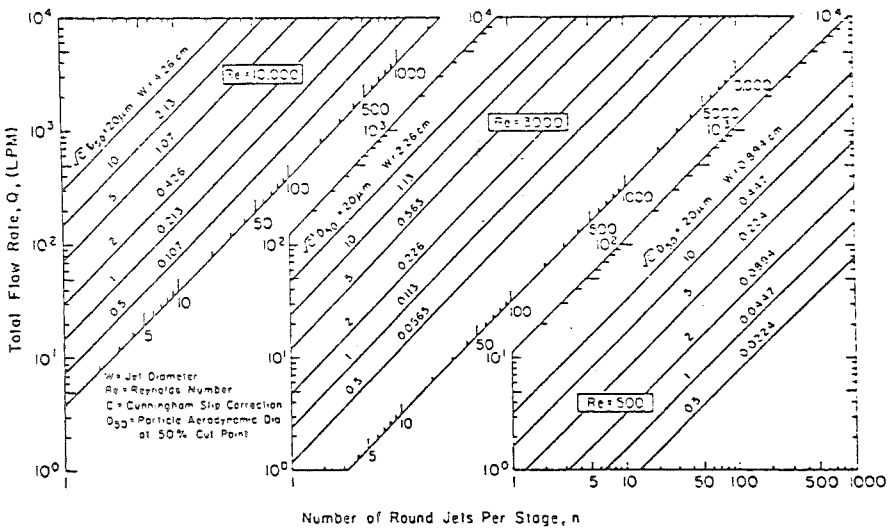


Figure 5. Design chart for round impactors (D_{50} = aerodynamic diameter at 50% cut point), from Marple and Willeke (1976).

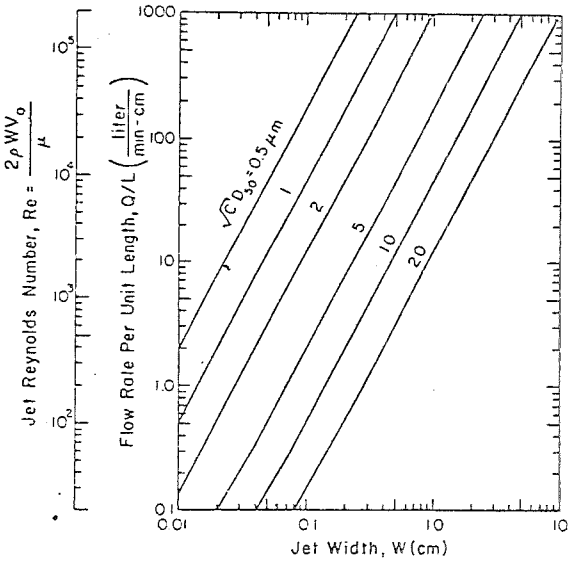


Figure 6. Design chart for rectangular impactors (D_{50} = aerodynamic diameter at 50% cut point), from Marple and Willeke (1976).

Although using multiple round nozzles in a stage of an impactor to control the Reynolds number is effective for round nozzles, it is not the case for rectangular impactors. If the nozzle of the rectangular impactor is divided into smaller nozzles the width of the nozzle remains constant and only the length and number of nozzles changes. This does not serve to change the Reynolds number or the cutoff size of the impactor. Therefore, the design curves for the rectangular impactors shown in Figure 6 indicate a one-to-one relationship between the Reynolds number and the flow rate per unit length. If a specific Reynolds number is desired, the flow rate per unit length is dictated as well as the nozzle width W for a specific cutoff $\sqrt{C}D_p$. For example, if the Reynolds number is to be kept at 3000 and the cutsize is to be 1 μm, then Figure 6 shows that a nozzle width of about 0.06 cm is needed and the flow rate will be about 16 L/min/cm. If the flow rate was to be 10 L/min then the length of the nozzle would be 0.625 cm. This stage could be designed with a one 0.625 cm by 0.06 cm wide nozzle or the length could be divided into any number of segments desired; the total length would have to be held at 0.625 cm.

It must be noted that the curves of Figures 5 and 6 were developed at the time when only efficiency curves of Figure 2 were in existence. Thus, these curves pertain only to Figure 2. However, in development of Figures 5 and 6 only the value of $\sqrt{C}D_{50}$ as a function of the Reynolds number at 500, 3000 and 10000 were used. Since these values are very similar for the

efficiency curves in Figures 2 and 3 the design curves of Figures 5 and 6 are still valid. As explained above, the curves in Figures 5 and 6 are to be used only as guidelines in designing or analyzing impactors.

4.5 Summary of Theoretical Considerations

Before starting a design one must first have at hand the necessary curves, equations and design criteria. Although some of this information has been presented in previous sections of this chapter it will be summarized here also.

1. The collection efficiency curves in Figure 3 are the most recent theoretical results.
2. The minimum value of S/W should be:

$$S/W = 1 \qquad \text{(round impactor)}$$

and

$$S/W = 1.5 \qquad \text{(rectangular impactor)} \tag{10}$$

so that small changes in S/W do not alter the value of D_{50}. The theory does not predict an upper value of S/W but designs close to the values in equation 10 are preferred. For small nozzle diameters, S/W values may have to be as large as 5 or 10. In such cases, an experimental study should be performed to ascertain the sensitivity of the particle cut size to the nozzle-to-plate distance.

3. The Reynolds number should be between 500 and 3000 to achieve as sharp a collection efficiency curve as possible.
4. The value of the Reynolds number in the nozzle can be controlled by the number of nozzles per stage for round impactors and by the flow rate per unit length for rectangular impactors. Figures 5 and 6 should be used in estimating the number of nozzles that will be needed (round) or the flow rate per unit length (rectangular) required.
5. The Stokes number equation can be used to predict the cut size (size of particles collected at 50% efficiency) if the St_{50} (Stokes number at 50% collection efficiency) is used in equation 1. Thus,

$$\sqrt{C}D_{50} = \sqrt{\frac{St_{50}9\mu W}{\rho_p V_o}} \tag{11}$$

is a governing equation for determining the cut size when the Stokes number is known. D_{50} is found from $\sqrt{C}D_{50}$ by use of Figure 4. Based on conditions 2 and 3 above, $\sqrt{St_{50}}$ is 0.49 and 0.77 for round and rectangular nozzles, respectively.

It is often more convenient to express equation 11 in terms of the flow rate per nozzle q rather than the velocity V_o. Using the relationships

$$V_o = \frac{q}{\pi W^2/4} \qquad \text{(Round)}$$

$$V_o = \frac{q}{LW} \qquad \text{(Rectangular)} \tag{12}$$

equation 11 becomes:

$$\sqrt{C}D_{50} = \sqrt{\frac{9St_{50}\pi\mu W^3}{4q\rho_p}} \quad \text{(Round)}$$

$$\sqrt{C}D_{50} = \sqrt{\frac{9St_{50}\mu\left(\frac{L}{W}\right)W^3}{q\rho_p}} \quad \text{(Rectangular)} \qquad (13)$$

6. It is necessary to know the pressure in the impaction region so that the slip correction C can be calculated and the volumetric flow rate q or the velocity V_o can be adjusted. Both of these parameters influence the calculation of the cut size, D_{50}, in equations 11 and 13.

The dependency of C on pressure has already been discussed. The only question that remains is what pressure to use: the pressure upstream or downstream of a nozzle. Both pressures have been used at various times by various researchers. In actuality, the local static pressure at the particle should be used as the particle passes through the nozzle. However, since this is not known, and since the static pressure in the stagnation region at the impaction plate is probably close to the static pressure at the nozzle inlet, the authors have generally used the static pressure upstream of the nozzle in the calculation of C. Thus the static pressure at the impaction region is being approximated by the upstream static pressure.

The same reasoning does not hold true in the calculation of q or V_o, since V_o is the velocity of the air in the nozzle throat. Therefore, q and V_o must be calculated at conditions in the throat. The calculation of q or V_o is not difficult if it is realized that the mass flowrate of air is constant for all stages. Therefore, q is inversely proportional to pressure.

$$q_2 = q_1\left(\frac{P_1}{P_2}\right) \qquad (14)$$

where subscripts 1 and 2 refer to conditions at the impactor inlet and the impaction plate in question, respectively. The velocity is calculated from the relationship

$$V_o = q/A_t \qquad (15)$$

where A_t is the throat area.

The only difficult step is the determination of the pressure appropriate for these calculations. Normally, it is assumed that the dynamic pressure of the jet at any stage is lost to turbulence. Therefore,

$$\Delta P = \frac{1}{2}\rho V_o^2 \qquad (16)$$

where ΔP is the pressure drop across a stage. The values for ρ and V_o should be calculated at the downstream pressure. The ideal gas equation can be assumed for the calculation of ρ. Therefore, an iterative procedure must be used in the solution of equation 16. It is realized that this is a simplistic approach to dealing with the influence of pressure, in that such phenomena

as pressure recovery in the impaction zone are ignored, but experience has shown that it is a satisfactory procedure for most impactor calculations.

4.6 Design Procedure

Marple and Willeke (1976) presented a step-by-step design procedure for designing a cascade impactor. That procedure is described below for a cascade impactor of either round or rectangular design. The details have been modified so that the design procedure corresponds with the curves, equations, etc. presented in this chapter. The procedure starts with the design of the first stage (i.e., stage with largest particle cutsize).

1. Choose a desired cutoff diameter, D_p, for first stage. Although the Stokes number equation (equation 11 or 13) is applicable to particles of any density, it is generally easier to design an impactor if the cutoff size is expressed as the equivalent aerodynamic diameter D_{ae}. The relationship between D_p and D_{ae} has been presented in equations 7 through 9. In addition, the procedure using Figure 4 to solve for D_{ae} when the slip correction is important has already been described.

2a. (Round) Use Figure 5 and determine the number and size of nozzles required for the desired operating Reynolds number and the aerodynamic cutoff size $\sqrt{C}D_{50}$. The curves for Reynolds number 3000 should be satisfactory for this step.

2b. (Rectangular) Use Figure 6 and choose a desired Reynolds number ($Re = 3000$ should be satisfactory) and determine the flow rate per unit length, and the nozzle width for the desired aerodynamic cutoff size $\sqrt{C}D_{50}$. From the values of Q/L and Q, the nozzle length L must be calculated and compared to the nozzle width W to be assured that the nozzle is actually a rectangular slit. If L and W are approximately equal, the nozzle would act as a round nozzle. It is felt that L should be on the order of about $10W$ for the nozzle to be rectangular.

3. Select a convenient nozzle diameter (or nozzle width) which is close to the value found in step 2. For a round impactor this would be a standard reamer size, and for a rectangular impactor it may be a standard slitting saw width.

4. For this value of nozzle diameter (or nozzle width), check the Reynolds number using equation 2. If the Reynolds number is far removed from the value assumed in step 2, repeat the process in step 2.

5. At this point it is important to calculate the pressure in the impaction region of the impactor so that corrections can be made in the value of flow rate Q. It is usually assumed, for stages collecting particles of 1 μm diameter or greater, that the pressure drop across the nozzle is negligible, and that the flow rate and pressure can be assumed to be that of the impactor entrance. However, as the air passes through the stages of a cascade impactor, the pressure drop can become appreciable at the lower stages.

The pressure for any stage, P_n can be calculated using equation 16 to give

$$P_n = P_{n-1} - \frac{1}{2}\rho V_o^2 \qquad (17)$$

6. Determine the value of $\sqrt{Stk_{50}}$ from Figure 3 and calculate the cutoff size $\sqrt{C}D_p$ using equation 13.
7. Determine the particle cutoff size D_p from $\sqrt{C}D_p$ by the procedure outlined in Figure 4.
8. Repeat the steps, starting at step 1, for the next stage of impactor and continue until the entire impactor has been designed.

Remember that for all stages the value of S/W should be kept at

$$S/W \geq 1.0 \text{ (Round)}$$

$$S/W \geq 1.5 \text{ (Rectangular)} \tag{18}$$

Also for the impactors to have sharp cuts the Reynolds number should be

$$500 < Re < 3000 \tag{19}$$

for both round and rectangular impactors.

4.7 Case Studies

The authors of this chapter have used the above theory to design many impactor stages that have subsequently been calibrated. In this section, a few examples are presented, as well as how the theoretical and experimental efficiency curves agreed.

4.7.1 Single Stage, Single Round Nozzle Impactor

The object of this design was to design two single stage impactors with single round nozzles to provide cuts at either 2.5 μm or 10 μm aerodynamic diameters. These impactors are used in the MST Indoor Air Sampler (MSP Corp., Maple Plain, MN 55359). This design is of particular interest in that the boundary conditions in the impactor are exactly matched to theory, since the theory considers only single nozzles. The only design constraint was that the flow rate had to be 4 L/min.

With this information, and using the design procedures outlined, the impactor described in Table 1 and shown in Figure 7 was designed. As can be seen in Table 1, the values of S/W and Re are within the guidelines for good impactor operation. It was expected, then, that the theoretical and experimental collection efficiency curves should be in good agreement, and this was found to be true as shown in Figure 8. The theoretical curves are taken from Figure 3. The experimental data points were generated with monodispersed aerosols of oleic acid droplets tagged with a uranine dye tracer. The quantities of dye collected on the impaction plate and afterfilter were determined using a fluorometer and the subsequent collection efficiency calculated. Since the sharpness of cut was so steep for these stages ($\sigma_g = 1.02$ and 1.09 for the 2.5 and 10 μm impactor, respectively), special care had to be taken to measure the quantity of doublet and triplet particles generated by the vibrating orifice aerosol generator and back out their higher collection efficiency from the calculations of collection efficiency.

Figure 8 shows the comparison between the theoretical and experimental collection efficiency curves. The agreement is excellent for the 2.5 μm impactor, but shows a 6% discrepancy for

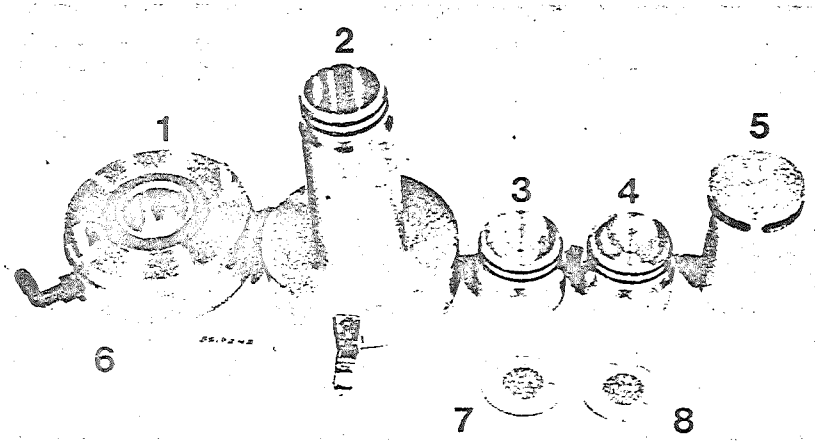


Figure 7. The MST Indoor Air Sampler Showing: (1) Base and Filter holder, (2) Cover for afterfilter and support for impactor stages, (3 & 4) Impaction stages with same cut size to decrease probability of overloading, (5) Cover, (6) Afterfilter, and (7 & 8) Impaction plates.

TABLE 1. Design parameters and cutoff diameters of the impactors in the MST indoor air sampler

Nominal Cutoff Diameters, μm	2.5	10
Nozzle Diameter, cm	0.244	0.620
S/W	2.0	0.86
Re	2140	900
Cutoff Diameter, μm		
Theoretical	2.52	10.4
Experimental	2.52	9.8

the 10 μm impactor. This discrepancy is thought to be due to gravitation effects and is discussed in greater detail in Section 4.7.2. It should be noted that in the design procedure, the first estimate of the nozzle diameter was 0.248 cm which provided for an experimental cutoff size of 2.60 μm. Since this cut size was 4% larger than desired, the nozzle diameter was changed to 0.244 cm, which provided the cutoff size of 2.52 μm. A similar iteration was experienced

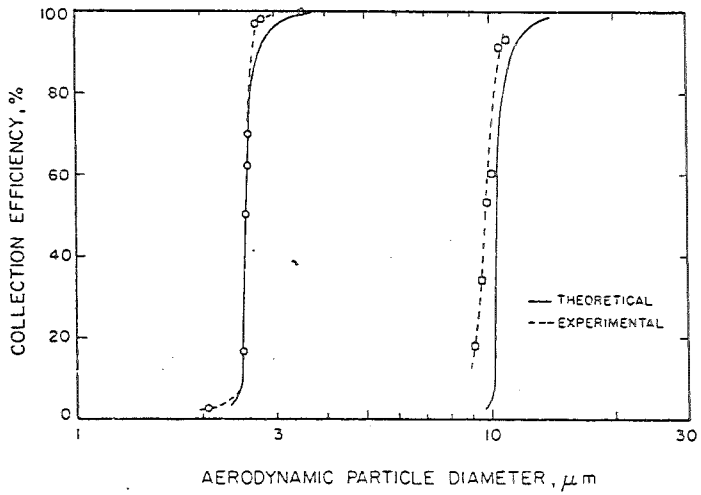


Figure 8. Comparison of the theoretically and experimentally determined collection efficiency curves for the impaction stages (D_{50}'s of 2.5 or 10 μm) used in the MST Indoor Air Sampler.

with the 10 μm cut impactor. The process of designing an impactor stage is, therefore, one of iteration. The theory is used to obtain the best estimate of the correct nozzle diameter. In many cases, the resulting true cutoff size, as determined by experimentation, is close enough to the desired cutoff size to be satisfactory. However, if closer agreement is desired, a second iteration is necessary. It must be noted, however, that to do this iteration, the experimental determination of the collection efficiency curve must be painstakingly performed or the experimentally determined cutoff size will be in greater error than the theoretically determined size.

4.7.2 *Cascade Impactor With Multiple, Rectangular and Round Nozzles*

The object of this project was to design a personal cascade impactor with a flow rate of 2 L/min. This impactor is the Marple Personal Cascade Impactor (Andersen Samplers, Inc., Atlanta, GA 30336). A more complete description, together with the calibration data, is given by Rubow *et al.* 1986). Rectangular nozzles were used for the upper six stages and round nozzles for the two lower stages. The parameters describing the impactor are given in Table 2, along with the theoretical and experimental 50% cutoff diameters (Figure 3 was used for the theoretical design). The experimental efficiency curves are shown in Figure 9. The theoretical curves are not shown because parameters were such as to require interpolation of the curves in Figure 3. Only the theoretical 50% cutoff diameters were determined (Table 2).

TABLE 2. Design parameters and cutoff diameters of Marple Personal Cascade Impactor (from Rubow *et al.*, 1986)

Stage	1	2	3	4	5	6	7	8
Nozzle Shape	slot	slot	slot	slot	slot	slot	round	round
Number of Nozzles	6	6	6	6	6	6	12	12
Nozzle-width, cm	0.264	0.145	0.0813	0.0432	0.0254	0.0173	- -	—
-diameter, cm	—	—	—	—	—	—	0.0457	0.0318
Slot Length, cm	0.953	0.953	0.953	0.953	0.953	0.480	—	—
S/W	1.2	2.2	1.3	2.4	2.0	2.9	1.7	2.4
Re	76	76	76	76	76	230	490	710
Cutoff Diameter, μm:								
Theoretical	35.8	19.6	11.0	5.8	3.38	1.59	0.94	0.52
Experimental	21.3	14.8	9.8	6.0	3.5	1.55	0.93	0.52

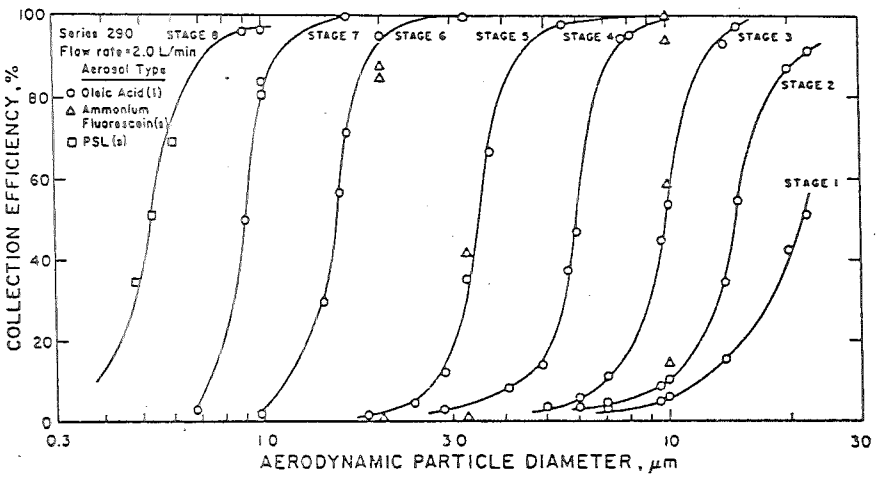


Figure 9. Experimentally determined collection curves for the Marple Personal Cascade Impactor (from Rubow *et al.* 1986).

The design of an entire cascade impactor is a lengthy process and will not be described in detail here. However, several points of interest concerning the design procedures and the agreement between the experimental and theoretical efficiencies curves will be discussed.

First note that the agreement between theoretical and experimental efficiency cutoff diameters is quite good for diameters of 10 μm and less. For larger cutoff sizes, the theory predicts a larger cutoff size than found experimentally, which has been the case for nearly all impactors the authors have designed. It is felt that these differences may be due to gravitational effects for these larger particles, and this is currently being investigated.

Another area of interest, and where special care must be taken, is in designing impactors with small cutoff sizes as in Stage 8. Here the pressure drop is sufficient to increase the volumetric flow rate, and the particles are small enough so that the slip correction must be considered. In Stage 8, the pressure was measured to be 100.0 kPa compared to 101.3 kPa at the inlet. Therefore, the volumetric flow rate is 1.013 times larger or 2.03 L/min instead of 2 L/min as for the upper stages. Although the correction for volumetric flow rate was not large for this particular impactor, for impactors with cutoff sizes less than 0.5 μm it can become much more significant. The slip correction can be much larger than the volumetric flow correction. In the particular impactor considered here, for a cutoff size of 0.5 μm and a pressure of 0.997 atmospheres, the slip correction from Figure 4 is found to be 1.33. If the slip correction had been assumed to be unity, the theory would have predicted a cutoff size of 0.60 μm.

4.7.3 Impactors With Respirable Cutoff Characteristics

Most of the information presented in this chapter has been on how to design an impactor with sharp cutoff characteristics. However, at times it may be desirable to design an impactor stage with classification characteristics that match a specific curve. This was a case in designing an impactor stage with a penetration curve that approximated the American Conference of Governmental Industrial Hygienists (ACGIH) respirable curve (Marple, 1978, Marple and McCormack, 1983, and Marple and Rubow, 1983). An impactor of this design is shown in Figure 10.

If a single nozzle impactor is designed to approximate the respirable curve, the 50% value can be designed to be correct, but the cutoff characteristics will be too sharp. The approximation can be improved by using a stage with multiple nozzles of two different sizes so the respirable curve is approximated in two steps. Even better approximation can be obtained by using multiple nozzle stages with nozzles of even more sizes. We have found that three nozzle sizes are usually satisfactory.

The procedure for such a design is rather simple. As shown in Figure 11, the respirable curve is divided into three equal segments of collection efficiency (i.e., 0 to 33⅓%, 33⅓% to 66⅔% and 66⅔% to 100%). Nozzle diameters must now be sized so that the 50% cut points correspond to the particle sizes at the midpoints of the three segments (i.e. particle sizes corresponding to 17%, 50% and 83%). The flow rate through each size of nozzle must be ⅓ of the total flow rate. The first nozzle diameter to be designed must be that of the largest cut size, and this can be accomplished with a single nozzle. Since the pressure drop is the same across all nozzles, the velocity through all nozzles will be approximately the same. Thus, the velocity through the

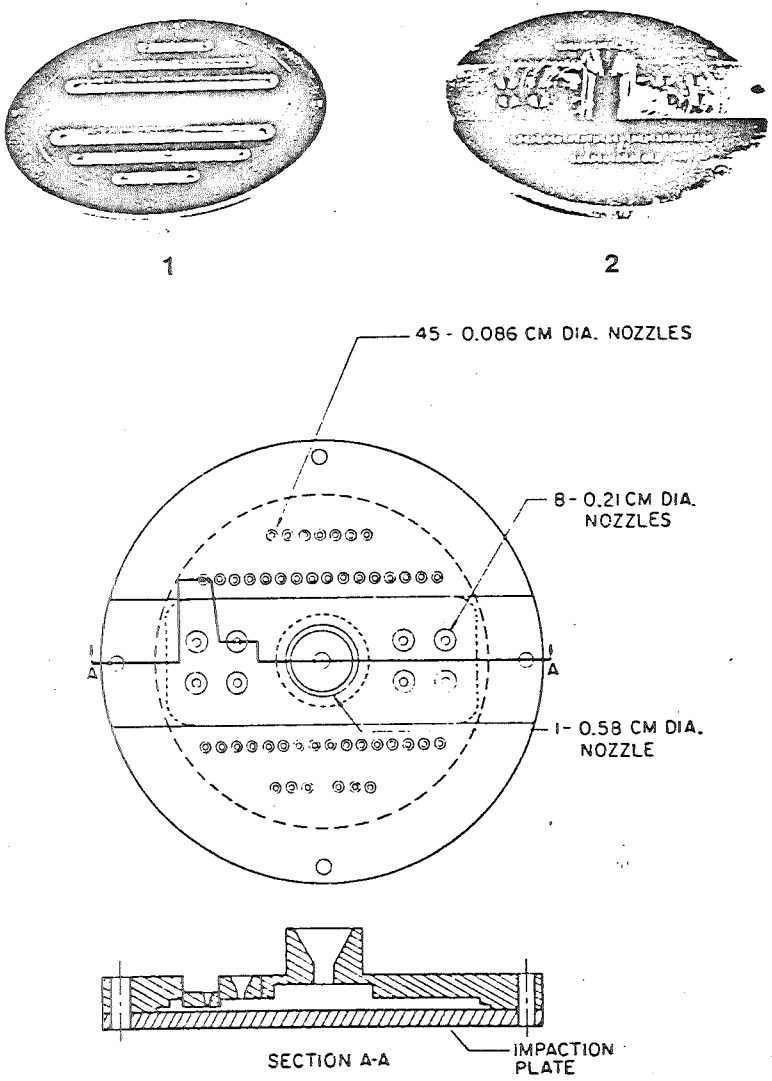


Figure 10. Three-nozzle size impactor designed for a flow rate of 28.3 L/min (from Marple, 1978).

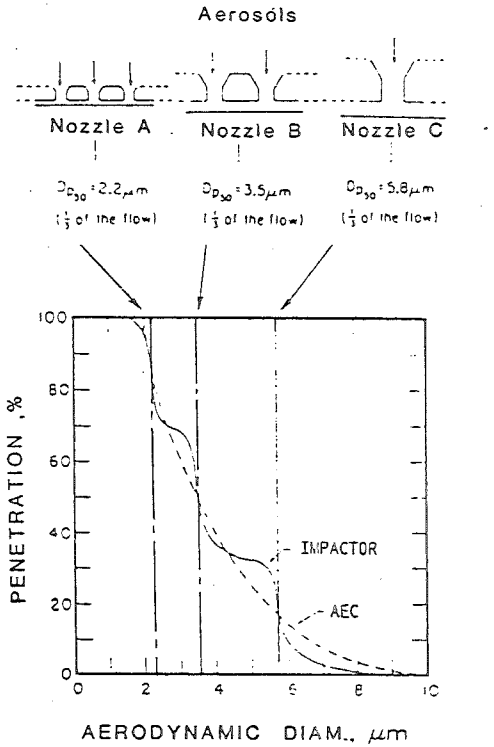


Figure 11. Approximation of the penetration curve for the single-stage impactor with three nozzle sizes to the AEC-ACGIH criteria for respirable mass sampling (from Marple and Rubow, 1983).

nozzle designed for the largest cut size must be calculated and this velocity used in the calculation for the nozzle diameters of the smaller two cut sizes. By knowing the cut size and the velocity, the nozzle diameters for these two cut sizes can now be calculated. The final step is to determine the number of nozzles of each size which is needed for the lower two cut sizes, and this can be determined by using the known nozzle diameters and velocities for these cut sizes and by providing enough nozzles to obtain ⅓ of the total flow. The impactor stage is now designed.

This procedure can be used to design impactors with a variety of flow rates, number of nozzle sizes, and respirable curves. We have used the technique for approximating the ACGIH and the British MRC respirable curves, as shown in Figure 12. Note in these figures that the experi-

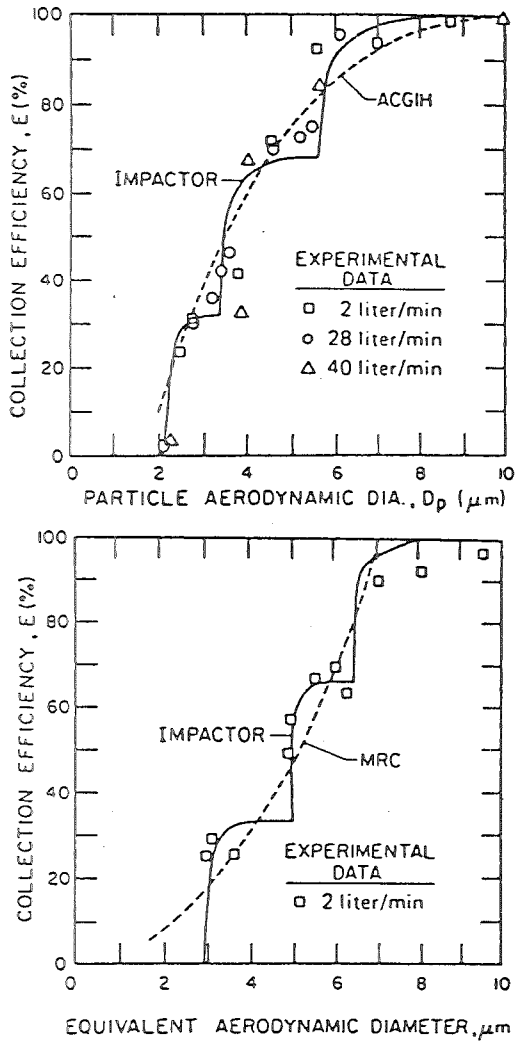


Figure 12. Comparison of the experimentally and theoretically-determined collection efficiency curves for three single-stage impactors with the ACGIH and BMRC respirable curves (from Marple and Rubow, 1983).

TABLE 3. Impactor designs with penetration characteristics that simulate respirable penetration curves (from Marple & Rubow, 1983)

Impactor	Total Flowrate (liter/min)	Respirable Curve	No. of Nozzle Sizes	Nozzle Cut Diam. (μm)	Nozzle Diam. (cm)	No. of Nozzles
A	2	ACGIH	2	5.0	0.25	1
				2.5	0.063	16
B	2	ACGIH	3	5.8	0.24	1
				3.5	0.087	8
				2.2	0.033	53
C	2	BMRC	2	6.1	0.28	1
				3.5	0.093	9
D	2	BMRC	3	6.4	0.26	1
				5.0	0.15	3
				2.9	0.048	28
E	28	ACGIH	2	5.0	0.60	1
				2.5	0.16	14
F	28	ACGIH	3	5.8	0.58	1
				3.5	0.21	8
				2.2	0.086	45
G	40	ACGIH	3	5.8	0.65	1
				3.5	0.24	8
				2.2	0.097	45

mentally determined efficiency curves are very nearly that predicted by the theory, and they both approximate the respirable curves quite well.

Impactors with a variety of flow rates have been designed using this procedure, as indicated in Table 3. The impactors with 2 L/min flow rates have been used for personal samplers where a personal sampling pump has been used as the air mover, and the impactor with 30 L/min flow rates have been used as a respirable sampler standard in an aerosol test chamber in our laboratory.

4.8 Impactor Calculator

As has been described in previous sections of this chapter, the important considerations in designing an impactor are control of the Reynolds number, the Stokes number and the jet-to-plate distance. Therefore, in the design of an impactor, there are repetitious calculations of the Reynolds number and the Stokes number, or manipulation of these equations, which must be made to find flow rates or nozzle diameters to give a specific cutoff size. To facilitate the solution of these equations a circular slide rule is included in an envelope of this book. Side 1 of the slide rule is used for solving the Stokes number equation, and Side 2 is used for solving the Reynolds number equation. The instruction booklet with the slide rule gives details on its use as well as some examples. Furthermore, in the instruction manual, Figure 4 is reproduced, and instructions are given on how to solve for the value of D_p when the value of $\sqrt{C}D_p$ is known.

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