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Particulate Sampling and Support: Final Report

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Particulate Sampling and Support: Final Report

by

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ABSTRACT

This report summarizes the results from the research, development and support tasks performed during the three year period of this contract (11/75 - 11/78). These tasks encompassed many aspects of particulate sampling and measurement in industrial gaseous process and effluent streams. Under this contract Southern Research Institute calibrated and evaluated cascade impactors, designed and evaluated novel particle sampling cyclones, wrote technical and procedures manuals for control device evaluation and particle sampling methods, designed an electrostatic precipitator backup for high flowrate systems, and evaluated advanced concepts in monitoring particle mass and size by optical systems. A number of smaller tasks involving lower levels of effort are also discussed.

The appendix contains a list of technical documents published under this contract.

CONTENTS

Abstract ii
Figures v
Tables ix
Acknowledgment x

1. Introduction. 1
2. Technical Summary 3
Develop a computer based cascade impactor data reduction program 3
Pocket programmable calculators to facilitate source sampling calculations 6
Non-ideal cascade impactor behavior. 9
Sampling charged monodisperse and polydisperse aerosols with cascade impactors. 26
Evaluation of cascade impactor substrate media . . 29
Development of five-stage series cyclone system. . 35
Electrostatic precipitator back up for sampling systems 41
Guidelines for particulate sampling in industrial process streams 46
Technical manual for particulate sampling equipment and methods 48
Evaluation of the PILLS IV 51
Cyclone and precollector for Fugitive Ambient Sampling Train (FAST). 52
Design, construct and evaluate optimized cascade impactor 60
Design a high temperature test facility. 66
A massive volume sampler for health effects studies. 71
Calibration of source test cascade impactors . . . 75
Calibration of Soviet particle sizing instruments 88
Calibration of the Source Assessment Sampling System cyclones (SASS) 96
Procedures Manual for Electrostatic Precipitation Evaluation 114
Review of documents and reports furnished by EPA . 116
USA-USSR scientific information exchange program . 117
EPA/IERL/PMB exhibit booth at the 1977 APCA annual meeting. 118
Calibration of a SASS middle cyclone for the health effects research laboratory/RTP 121
Procedures manual for fabric filter evaluation 126

Advances in particle sampling and measurement symposium. 128
Presentation to Federal Republic of Germany. . . . 130
Particulate sizing instrument evaluation 131

References 132
Appendix 134

FIGURES

Number		Page
1	HP-65 and HP-25 programmable calculator source measurement booklets.	8
2	Composite of calibration data for the Andersen impactor stages 2 through 7	12
3	An illustration of the four modeled stage collection efficiency curves of a typical stage of the Andersen impactor. Model 1 is the ideal behavior model, Model 2 is the normal bounce model, Model 3 is the no bounce model, and Model 4 is the extreme bounce model.	14
4	Recovered size distributions on a cumulative percentage basis from the Brink impactor models for σg = 2.0 and MMD's of 1.5, 4.5, 13.5, and 27 μm..	15
5	Recovered size distributions on a cumulative percentage basis from the Brink impactor models as shown in Figure 4 with the backup filter catches omitted from the analysis	16
6	Recovered size distributions on a cumulative percentage basis from the Brink impactor models for σg = 3.0 and MMD's of 1.5, 4.5, 13.5, and 27 μm..	17
7	Recovered size distributions on a cumulative percentage basis for the Andersen impactor for σg = 2.0 and MMD's of 1.5, 4.5, and 13.5 μm. The backup filter was excluded from analysis in the results shown	18
8	Recovered size distributions on a differential basis from the Brink impactor models for MMD's of 4.5 and 27 μm and σg's of 2 and 3..	20
9	Recovered size distributions on a differential basis from the Andersen impactor models for MMD's of 1.5 and 13.5 μm and σg's of 2 and 3	21
10	Flow chart for acid wash treatment of glass fiber filter material	34

11 EPA-SoRI five stage cyclone 36

12 Collection efficiency of the EPA-SoRI cyclones at a flowrate of 28.3 ℓ/min, a temperature of 25°C, and for a particle density of 1.00 gm/cm^3 39

13 Collection efficiency of the EPA-SoRI cyclones at a flowrate of 14.2 ℓ/min, a temperature of 25°C, and for a particle density of 1.00 gm/cm^3 40

14 Schematic of the electrostatic collector with the disc discharge electrode installed. 42

15 ESP collector assembly drawing. 44

16 Electrostatic precipitator backup filter. 45

17 Schematic diagram of Fugitive Ambient Sampling Train 53

18 Berglund-Liu type vibrating orifice aerosol generator system. 54

19 Ammonium fluorescein aerosol particles generated using the vibrating orifice aerosol generator . . 56

20 Collection efficiency versus particle diameter for the FAST pre-separator impactor and cyclone . . . 59

21 Assembly drawing of 0.5 ACFM optimized cascade impactor. 65

22 Preliminary layout for high temperature, low pressure wind tunnel test facility. 67

23 Schematic diagram of massive volume sampler for Health Effects Studies. 72

24 Theoretical impactor efficiency curves for rectangular and round impactors showing the effect of jet-to-plate distance S, Reynolds number Re, and throat length T. 77

25 Collection efficiency vs. $\sqrt{\psi}$. Andersen Mark III stack sampler with glass fiber collection substrates 79

26 Collection efficiency vs. $\sqrt{\psi}$. Brink Model BMS-11 cascade impactor with glass fiber collection substrates 80

27 Collection efficiency vs. $\sqrt{\psi}$. Brink Model BMS-11 cascade impactor with greased collection plates . 81

28 Collection efficiency vs. $\sqrt{\psi}$. MRI Model 1502 inertial cascade impactor with greased collection plates 82

29 Collection efficiency vs. $\sqrt{\psi}$. Sierra Model 226 source cascade impactor with glass fiber collection substrates. Sampling flow rate is 14 LPM. 83

30 Collection efficiency vs. $\sqrt{\psi}$. Sierra Model 226 source cascade impactor with glass fiber collection substrates. Sampling flow rate is 7 LPM. 84

31 Collection efficiency vs. $\sqrt{\psi}$. University of Washington Mark III source test cascade impactor with greased collection plates. 85

32 Cascade impactor wall loss vs. particle diameter . . 86

33 Soviet 14-stage cascade impactor 89

34 Soviet 3-stage impactor/cyclone. 89

35 Collection efficiency vs. particle diameter. Soviet 12-stage impactor/cyclone. 90

36 Collection efficiency vs. particle diameter. Soviet 12-stage cascade impactor 91

37 Collection efficiency vs. particle diameter. Soviet 3-stage cascade impactor. 92

38 Collection efficiency vs. particle diameter. Soviet 14-stage cascade impactor (small cutpoints). 94

39 Collection efficiency vs. particle diameter. Soviet 14-stage cascade impactor (large cutpoints). . . . 95

40 Schematic of the Source Assessment Sampling System . 97

41 Collection efficiency vs. particle diameter. Large SASS cyclone 98

42 Collection efficiency vs. particle diameter. Middle SASS cyclone. 99

43 Collection efficiency vs. particle diameter. Small SASS cyclone. 100

44 SASS cyclone cutpoints 101

45 Collection efficiency vs. particle diameter. Large SASS cyclone 103

46 Collection efficiency vs. particle diameter. Unmodified middle SASS cyclone 104

47 Collection efficiency vs. particle diameter. Modified middle SASS cyclone 105

48 Collection efficiency - temperature relationship SASS middle cyclone. 109

49 D_{50} - viscosity relationship SASS middle cyclone . . 110

50 Collection efficiency - particle density relationship SASS middle cyclone. 111

51 Collection efficiency at 400°F, 4 SCFM SASS middle cyclone. 113

52 Exxon SASS cyclones. 123

TABLES

Number		Page
1	Program flow for the cascade impactor data reduction system	4
2	Simulation conditions of the modeled impactor performance.	11
3	Percent errors in $\Delta M/\Delta \log D$, Andersen impactor. . . .	23
4	Percent errors in $\Delta M/\Delta \log D$, Brink impactor	24
5	Percentage of trial cases in which recovered value of $(\Delta M/\Delta \log D)$ is within the indicated factor of the true value	25
6	Laboratory calibration of the five-stage cyclones. .	38
7	FAST impactor and cyclone calibration data	58
8	Criteria for impactor design	61
9	Optimized impactor design specifications	62
10	Optimized impactor design specifications	63
11	Optimized impactor design specifications	64
12	SASS middle cyclone calibration data	108

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SECTION 1

INTRODUCTION

The scope of the research, development, and support performed for the Environmental Protection Agency under Contract 68-02-2131 (November 20, 1975-November 19, 1978) by Southern Research Institute covered many aspects of particulate sampling in gaseous process and effluent streams. Specific objectives which were identified and given priority during this contract were to:

1. Identify current and future requirements for particulate sampling - the nature of the particles (shape, volatility, concentration, size distribution, charge, etc.), the sampling conditions (temperature, pressure, entrained fluids, etc.), and the goals of the sampling programs (control device evaluation, health effects, etc.).

2. Continue research on the non-ideal or unmodelled behavior of cascade impactors. Investigate problems in using impactors on nonroutine process streams (wet, high temperature, high pressure). Design cascade impactors which incorporate all that we have learned about their fundamental behavior and operational problems.

3. Design, fabricate, and test cyclone systems for particle sizing. Evaluate existing cyclone systems for particle sizing effectiveness. Consider alternatives to back up filters in high flow rate applications.

4. Study alternatives to impactors and cyclones for particle sizing such as optical, electrical, or hybrid systems. Concentrate on devices which offer the possibility of real time, automatic, sampling and analysis.

5. Study methods of Quality Assurance in sampling and calibration programs.

6. Generate and review documents on particulate sampling and continually update our bibliography and literature survey.

7. Continue to study and evaluate new techniques, ideas, and instruments for particulate sampling.

8. Attend and organize meetings and symposia on particulate sampling.

9. Provide consulting and research and development support to EPA programs.

There are two sections in the remainder of this report. The Technical Summary contains a description of the results from each task undertaken during the contract period. The Appendix presents a complete list of technical documents printed or to be printed under this contract.

SECTION 2

TECHNICAL SUMMARY

DEVELOP A COMPUTER BASED CASCADE IMPACTOR DATA REDUCTION PROGRAM

Cascade impactors have gained wide acceptance as a practical means of making particle size distribution measurements. These devices are regularly used in a wide variety of environments, ranging from ambient conditions to flue gas streams of 500°C (950°F). Specially fabricated impactors can be used for more extreme conditions.

Because of the usefulness of cascade impactors, research has been funded to explore the theoretical and practical aspects of impactor operation. As part of this research, an effort has been made to design a comprehensive data reduction system which will made full use of cascade impactor measurements.

The cascade impactor data reduction system (CIDRS) is designed to automatically reduce data taken with any one of four commercially available round jet cascade impactors: the Andersen Mark III Stack Sampler, the Brink Model BMS-11 (as supplied and with extra stages), the University of Washington Mark III Source Test Cascade Impactor, and the Meteorology Research Incorporated Model 1502 Inertial Cascade Impactor. Provision is not made in this system for reducing data taken with slotted jet impactors.

The computer programs which comprise this data reduction system are written in the FORTRAN IV language. The plotting subroutines used were written specifically for the Digital Equipment Corporation (DEC) PDP-15/76 computer, and these programs are not compatible with other plotting systems. However, these programs can be used as a guide when revision is made for use with another operating system. The overall system incorporates six programs: MPPROG, SPLIN1, GRAPH, STATIS, PENTRA, and PENLOG. These six programs are described briefly in Table 1. Impactor design, particulate catch information and sampling conditions from single impactor runs are used to calculate particle size distributions. MPPROG and SPLIN1 perform data analyses and make curve fits, while GRAPH is totally devoted to various forms of graphical presentation of the calculated distributions. The particle size distributions can be output in several forms. STATIS averages data from multiple impactor runs under a common condition and PENTRA or PENLOG calculates the control device penetration and/or efficiency.

TABLE I
PROGRAM FLOW FOR THE CASCADE IMPACTOR
DATA REDUCTION SYSTEM

BLOCK 1. SINGLE RUN ANALYSIS

I. Impactor Program (MPPROG)

Takes testing conditions and stage weights to produce stage D_{50}'s, cumulative and cumulative % mass concentrations $<D_{50}$, geometric mean diameters, and mass number size distributions. Executed for each run.

II. Fitting Program (SPLIN1)

Uses modified spline technique to fit cumulative mass loading points for each plot. Stores fitting coefficients and boundary points on file. Executed for each run.

III. Graphing Program (GRAPH)

Produces individual run graphs with points based on stage weights and impactor D_{50}'s. Also superimposes plot based on fitted data, if desired. Graphs include cumulative mass loading, cumulative % mass loading, and mass and number size distributions. Can be executed as desired for each run.

BLOCK 2. GROUPED DATA

IV. Statistical Program (STATIS)

Recalls cumulative mass loading fitting coefficients to produce average cumulative mass loading, average % cumulative mass loading, average mass size distribution, and average number size distribution plots each with 50% or 90% confidence bars. Executed for each group or data to be averaged.

Programs I-IV are used for both inlet and outlet data sets.

V. Efficiency Program (PENTRA) or (PENLOG)

Recalls average mass size distribution values along with 50% confidence limits for inlet and outlet to plot percent penetration and efficiency with 50% confidence bars. Executed once for each pair or group and used to define a fractional efficiency curve.

The system utilizes impactor specific calibration information together with operating conditions and other pertinent information such as stage weights, sampling duration, etc., to determine particle size distributions in several forms for individual runs. A spline technique is applied to fit a curve to the cumulative size distribution obtained from each individual impactor run. These fitted curves have forced continuity in coordinates and slopes. Averages of size distributions for multiple runs are made using the fitted curves to provide interpolation values at a consistent set of particle diameters, irrespective of the diameters at which the data points fall in the original individual run data sets. Statistical analyses are performed to locate and remove outliers from the data being averaged, following which averages, variances, standard deviations and confidence intervals are calculated. The averages and statistical information are available in tabular and graphical form in several size distribution formats (cumulative mass loading, cumulative percentage by mass, differential mass, and differential number). The averaged data are stored in disk files for subsequent manipulation. Additional programs permit data sets from control device inlet and outlet measurements to be combined to determine fractional collection efficiencies and confidence limits of the calculated efficiencies.

These results are available in graphical form with a choice of log-probability or log-log presentations. As mentioned above, the program is set up to handle all commercially available round jet cascade impactors, including common modifications, which are in current use in stack sampling. Other round jet impactors can be easily substituted and slot type impactors could be accommodated with slight program revision.

Two reports have been written which describe this data reduction system. An executive summary of the program including several examples is given in "A Data Reduction System for Cascade Impactors", EPA-600/7-78-132a, July 1978. The detailed program description with program listings can be found in "A Computer-Based Cascade Impactor Data Reduction System," EPA-600/7-78-042, March 1978.

POCKET PROGRAMMABLE CALCULATORS TO FACILITATE SOURCE SAMPLING CALCULATIONS

A library of twenty-two programs to facilitate calculations associated with source sampling and air pollution measurement studies was compiled for the Hewlett-Packard HP-65 and HP-25 Pocket Programmable Calculators. This library contains EPA Reference Methods 1-8, cascade impactor programs, and several others. Each program includes a general description, formulas used in the problem solution, a numerical example, user instructions, and a program listing.

A list of the calculator programs follows.

APol-01 Method 1 - Sample and Velocity Traverses for Stationary Sources

APol-02 Method 2 - Determination of Stack Gas Velocity and Volumetric Flow Rate (Type S Pitot Tube)

APol-03 Method 3 - Gas Analysis for Carbon Dioxide, Excess Air, and Dry Molecular Weight

APol-04 Method 4 - Determination of Moisture in Stack Gases

APol-05 Method 5 - Determination of Particulate Emissions from Stationary Sources

APol-06 Method 6 - Determination of Sulfur Dioxide Emissions from Stationary Sources

APol-07 Method 7 - Determination of Nitrogen Oxide Emissions from Stationary Sources

APol-08 Method 8 - Determination of Sulfuric Acid Mist and Sulfur Dioxide Emissions from Stationary Sources

APol-09 Cascade Impactor Operation

APol-10 Impactor Flow Rate Given Orifice ΔH

APol-11 Impactor Flow Rate, Given Gas Velocity and Nozzle Diameter

APol-12 Impactor Sampling Time to Collect 50 Milligrams

APol-13 Impactor Flow Rate, Sample Volume, Mass Loading

APol-14 Impactor Stage D_{50}

APol-15 $\sqrt{\Psi}$ Calculation - Round Jets

APol-16 $\sqrt{\Psi}$ Calculation - Rectangular Slots

APol-17 Cumulative Concentration vs D_{50} and ΔM/ΔlogD vs Geometric Mean Diameter

APol-18 Mean, Standard Deviation, 90/95% Confidence Interval, Mean ± CI

APol-19 Resistivity and Electric Field Strength

APol-20 Channel Concentrations for the KLD Droplet Measuring Device (1-600 μm) DC-1

APol-21 Aerotherm High Volume Stack Sampler; Stack Velocity, Nozzle Diameter, Isokinetic ΔH

APol-22 Flame Photometric Detector Calibration by Permeation Tube Technique

Both of the program documents were published in two formats. The first of these was the normal 8½"x11" bound version; the second was a special, 5"x7" spiral bound version with plastic laminated covers. The HP-65 document was published under the title "HP-65 Programmable Pocket Calculator Applied to Air Pollution Measurement Studies: Stationary Sources," EPA-600/8-76-002, October 1976 (NTIS-PB 264 284/1BE). The HP-25 document was published under the title "HP-25 Programmable Pocket Calculator Applied to Air Pollution Measurement Studies: Stationary Sources," EPA-600/7-77-058, June 1977 (NTIS-PB 269 666/4BE). A photograph of the two spiral bound booklets is shown in Figure 1.

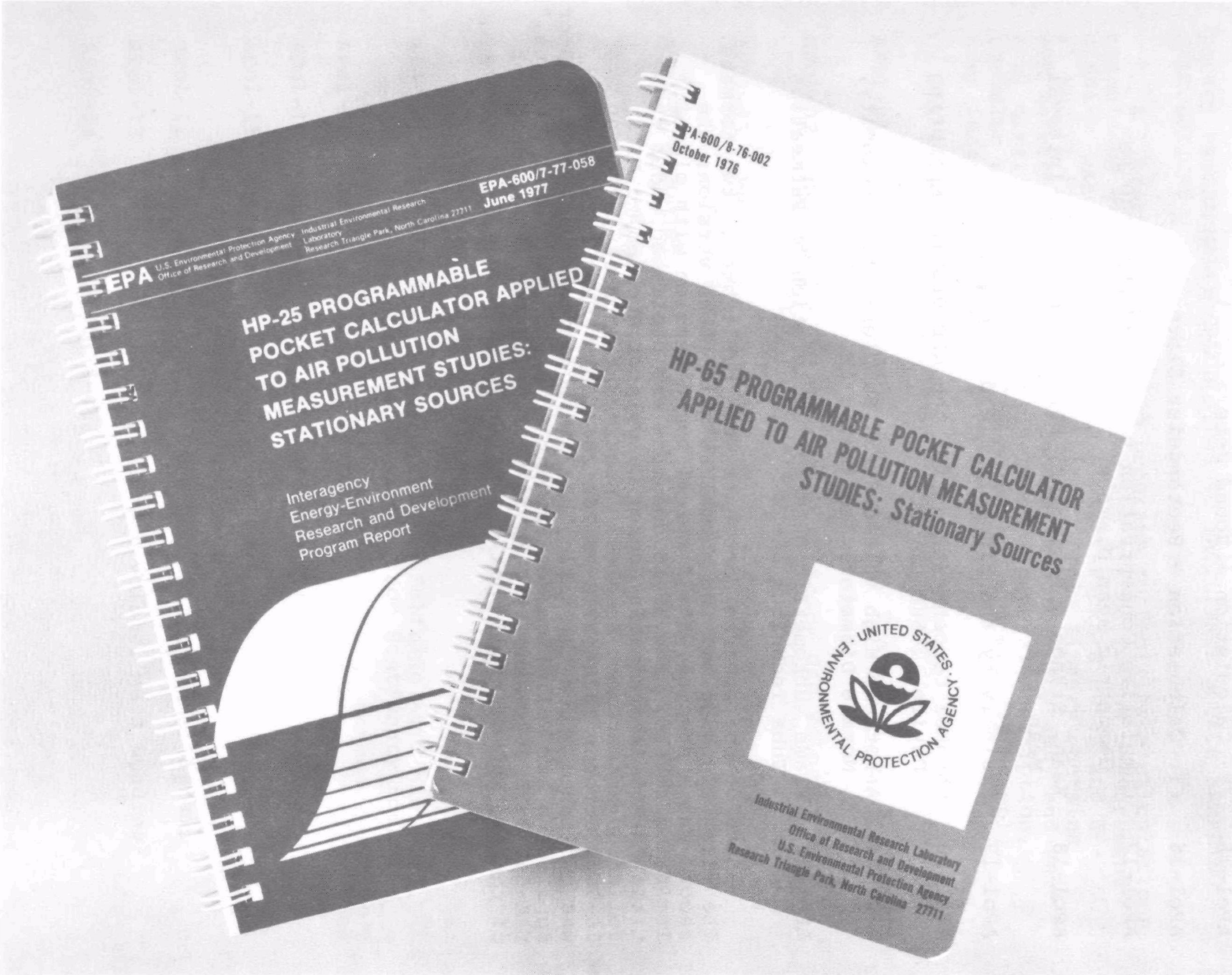


Figure 1. HP-65 and HP-25 programmable calculator source measurement booklets.

NON-IDEAL CASCADE IMPACTOR BEHAVIOR

Cascade impactors have become commonly used measurement devices for the determination of size distributions of particulate matter emissions from industrial sources. Data obtained with impactors are used to characterize emissions from sources, to determine the performance of particulate control devices, and in the selection and design of control devices for specific sources.

Data provided by impactors are of relatively low resolution and do not permit the exact reconstruction of the size distribution of the aerosol being sampled, even over the limited range of sizes normally covered by most impactors (approximately 0.5 to 10 µm). However, little has been done to estimate the magnitude of the uncertainties, or errors, which are inherent in the method insofar as they relate to industrial source emission measurements and determinations of fractional collection efficiencies of control devices. The study described here was one with the specific goals of estimating the effects of two non-ideal operating characteristics of impactors on the data obtained with them. These two non-idealities are (1) the lack of step function stage collection characteristics and (2) particle bounce. Several authors[1,2,3] have proposed various deconvolution procedures which, when applied to impactor data, would to a large degree, correct for the effect of the finite slopes of the stage collection efficiency curves. However, little use has been made of these procedures, primarily because noise in the data frequently results in oscillatory solutions with large negative values. In any case, little quantitative information regarding the magnitude of the errors introduced by the lack of sharp size cuts in impactors commonly used for stack sampling has been published. The magnitude of errors introduced by particle bounce has not previously been quantified although the existence of such errors has been described in the literature.[4,5,6,7]

Technical Procedures

The approach used in this study was the development of a computer model of cascade impactor performance. The model was based on actual impactor performance as measured in a calibration study of commercially available cascade impactors for stack sampling. A total of four simulation models were used for both a Brink impactor in a commonly used modified configuration for stack sampling and an Andersen Mark III stack sampler. The use of glass fiber collection substrates was assumed for both impactors. Both grease and glass fiber substrates are commonly used for sampling at temperatures below 150°C (300°F) but no satisfactory greases have been found for use at temperatures over 150°C. Therefore, glass fiber substrates must usually be used for collection substrates at elevated temperatures.

The first model for each impactor was one having ideal collection characteristics, i.e., step functions from 0% to 100% collection at the stage D_{50}'s. (The stage D_{50} is that particle diameter at which the stage has a collection efficiency of 50%. The D_{50} is generally used as the characteristic cut off diameter for particles collected by the stage.) This model was used as a performance standard against which the remaining three models could be compared and also provided a basis for checking the program.

The assumed operating conditions and resulting cut sizes (D_{50}'s) of the two impactors modelled in the study are given in Table II. The models of the Brink impactor included a cyclone precollector which was assumed to have the same performance characteristics in all three of the simulations other than that of the "Ideal Brink." The cyclone performance was based on calibration data for a cyclone in common use with the Brink impactor modified for stack sampling. This cyclone has a collection efficiency of 100% for particles larger than about 20 μm.

The second model for each impactor used the actual calibration data for each stage. In this model the stage collection efficiencies increased monotonically with increasing Stokes numbers (increasing particle size) to a maximum value of about 90% to 95%. The efficiencies then decreased for larger Stokes numbers to a value of 35% to 40% and remained constant thereafter. A composite of the calibration data for stages two (2) through seven (7) of the Andersen impactor, which illustrates the behavior described above, is shown in Figure 2. Data for Stages 1 and 8 were offset from the tight grouping of the data for the remaining stages and hence were omitted in Figure 2 for purposes of clarity in illustrating the behavior trends of the stage efficiency curves. The data for the Brink impactor exhibited similar trends. This model, Model 2, is called the "Normal Bounce" model.

The third model was identical to the second except that the rollover and decline in efficiency for larger Stokes numbers was ignored. Instead, the efficiencies were assumed to smoothly increase to 100% and remain at that value for increasingly larger Stokes numbers. This is called the "No Bounce" model. The fourth model was also identical to Model 2 with the exception that the collection efficiencies were assumed to drop

Table II. Simulation Conditions of the Modeled Impactor Performance

	Brink	Andersen
Temperature, °C (°F)	177 (350)	177 (350)
Gas composition	Std. air	Std. air
Particle density, gm/cm^3	2.27	2.27
Flowrate, alpm (acfm)	1.13 (0.040)	17.0 (0.600)
Barometric Pressure, mm Hg	749	749
Stage/D_{50} (μm)		
1	9.60[1]	7.84
2	6.18[2]	7.40
3	3.39	4.44
4	1.85	2.87
5	1.23	1.58
6	0.905	0.855
7	0.589	0.449
8	0.198[2]	0.200

1. Stage 1 is a cyclone precollector.

2. Stages 2 and 8 are part of the modifications to the impactor.

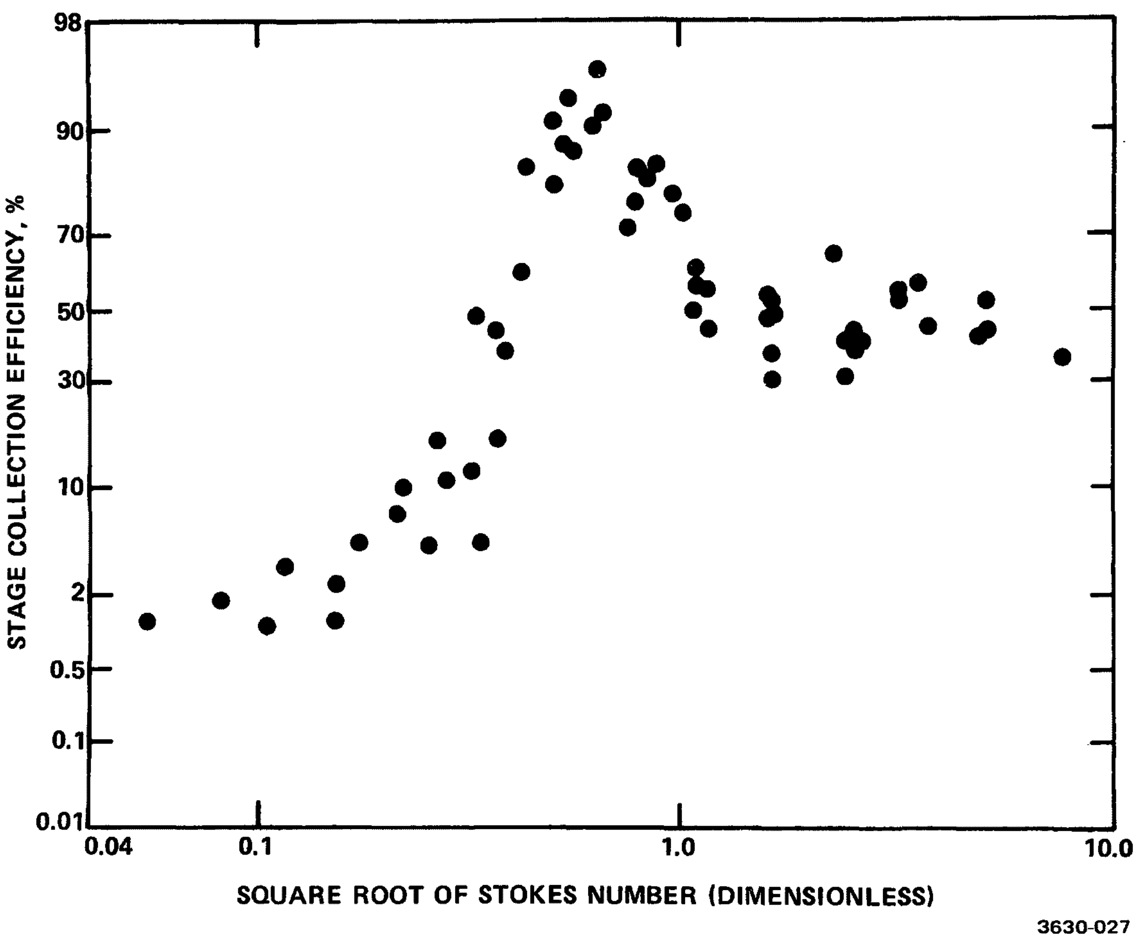


Figure 2. Composite of calibration data for the Andersen impactor stages 2 through 7.

rapidly to a value of 2% for Stokes numbers larger than that at which the collection efficiency reached a peak in the calibration data. This model was termed the "Extreme Bounce" model.

The use of the same basic collection efficiency curves for the "No Bounce," "Normal Bounce," and "Extreme Bounce" models for particle sizes smaller than those for which the collection efficiencies were maximal in the calibration data is probably a realistic representation of the actual performance of the impactors in collecting various types of particles. Rao[5] found that impactor collection characteristics for dry solid particles and oil particles were virtually identical when glass fiber substrates were used for Stokes numbers smaller than those at which the peak efficiency was reached for the dry solid particles. Beyond this point he found that oil particles were collected with efficiencies which increased to 100% with increasing Stokes number while the efficiencies declined for the dry particles as a result of bounce. Figure 3 shows an example of the four modelled collection efficiency characteristics of one stage of the Andersen impactor.

Results and Discussion

The performance of each model of the two impactors was evaluated for aerosols having log-normal size distributions with mass median diameters (MMD) of 1.5, 2.6, 4.5, 7.8, 13.5, and 27 micrometers and geometric standard deviations, σ_g, of 2, 3 and 4.

Figures 4 through 7 show typical results for the two impactors in a cumulative percentage presentation. It is evident from all four of these figures that particle bounce severely distorts the size distributions, especially for aerosols having large mass median diameters. Figures 4 and 5 show the results of the simulations for the same impactor and size distributions, the difference between the two being the omission of the back-up filter catch in presenting the results in Figure 5. Comparison of Figures 4 and 5 indicate that omitting the back-up filter in calculating the cumulative percentages greatly reduces the distortion resulting from bounce. Comparison of Figures 4 and 5 shows that increasing the width of the input size distribution (increasing σ_g) reduces the distortion caused by bounce although the distortion remains appreciable for the extreme bounce models at large MMD's.

Figure 7 shows the results from the Andersen models corresponding to three of the four cases for the Brink Model shown in Figure 5. Note that the deviations from the input distribution resulting from bounce are more severe in the Andersen results than in the Brink. This difference in the severity

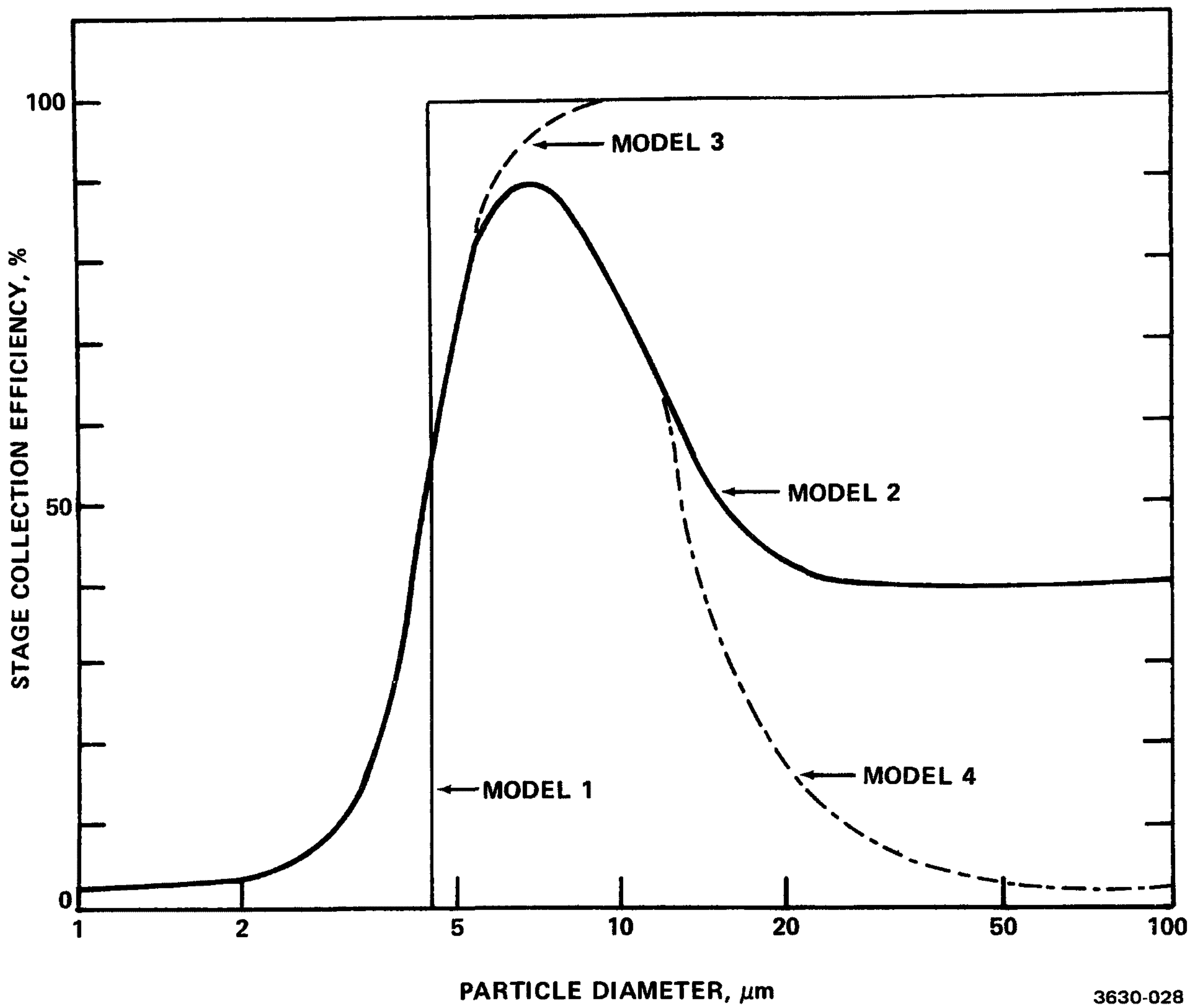


Figure 3. An illustration of the four modeled stage collection efficiency curves of a typical stage of the Andersen impactor. Model 1 is the ideal behavior model, Model 2 is the normal bounce model, Model 3 is the no bounce model, and Model 4 is the extreme bounce model.

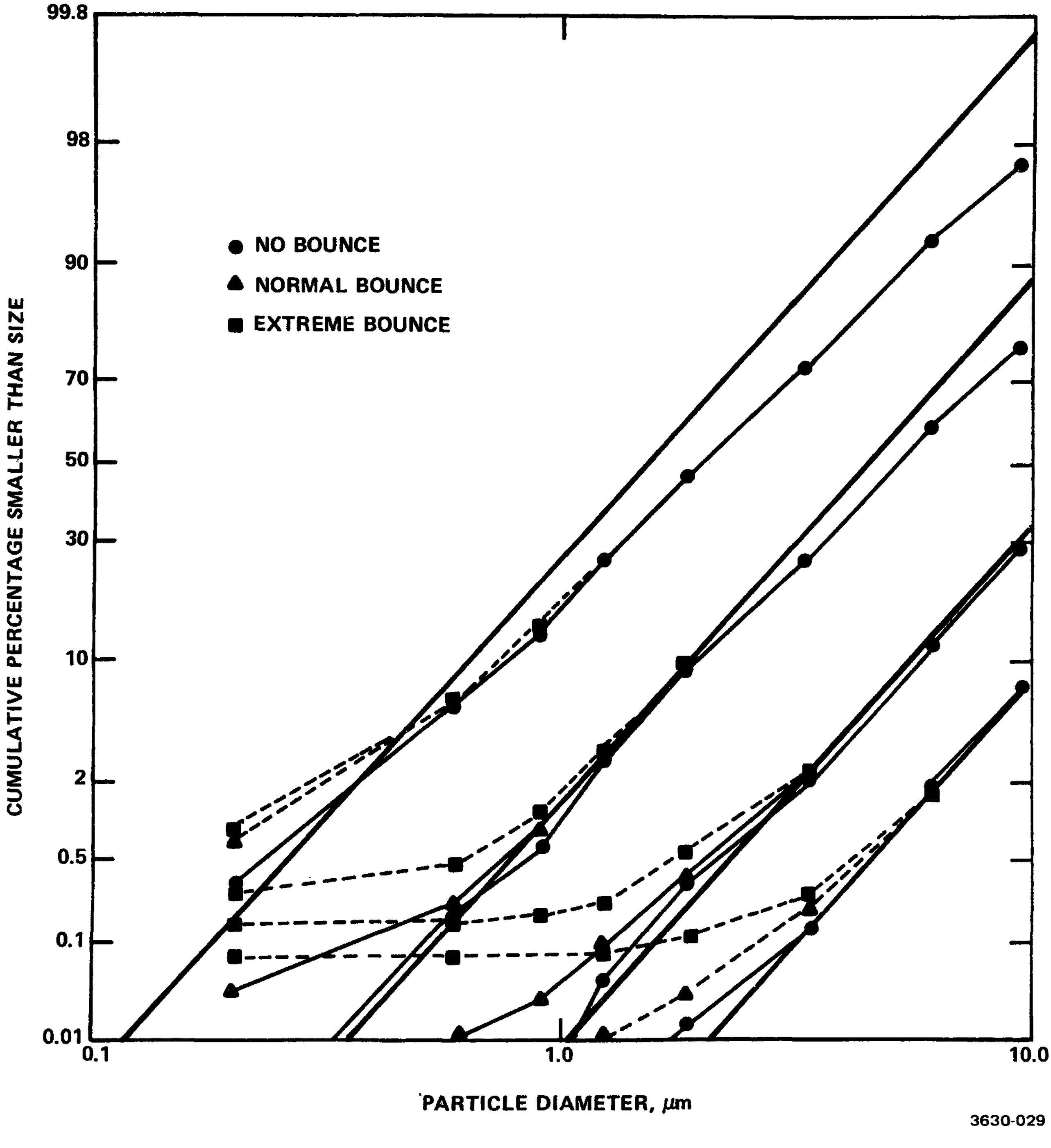


Figure 4. Recovered size distributions on a cumulative percentage basis from the Brink impactor models for σg = 2.0 and MMD's of 1.5, 4.5, 13.5, and 27 μm. The bold lines represent the input distributions.

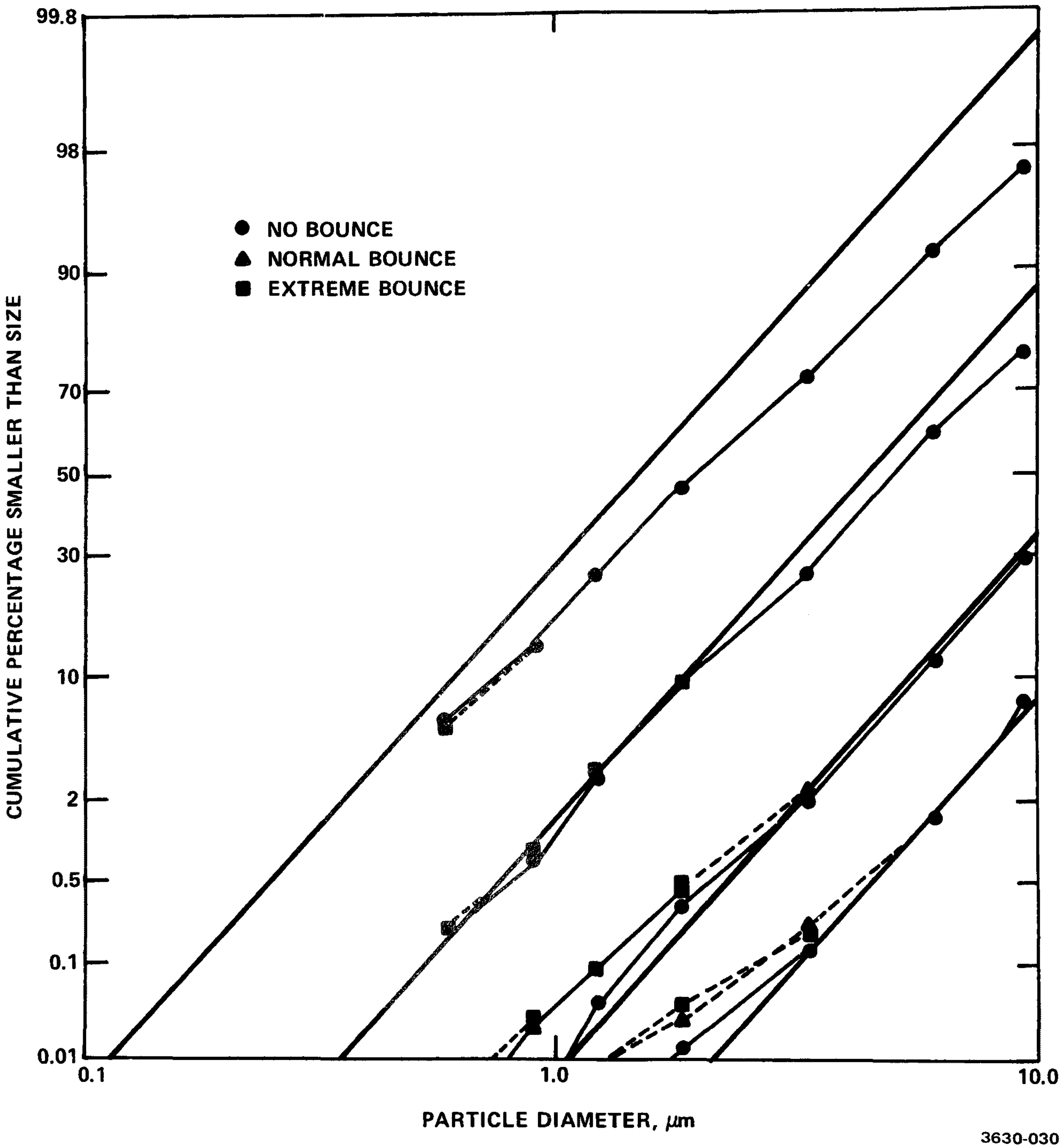


Figure 5. Recovered size distributions on a cumulative percentage basis from the Brink impactor models as shown in Figure 4 with the backup filter catches omitted from the analysis. The bold lines represent the input distributions.

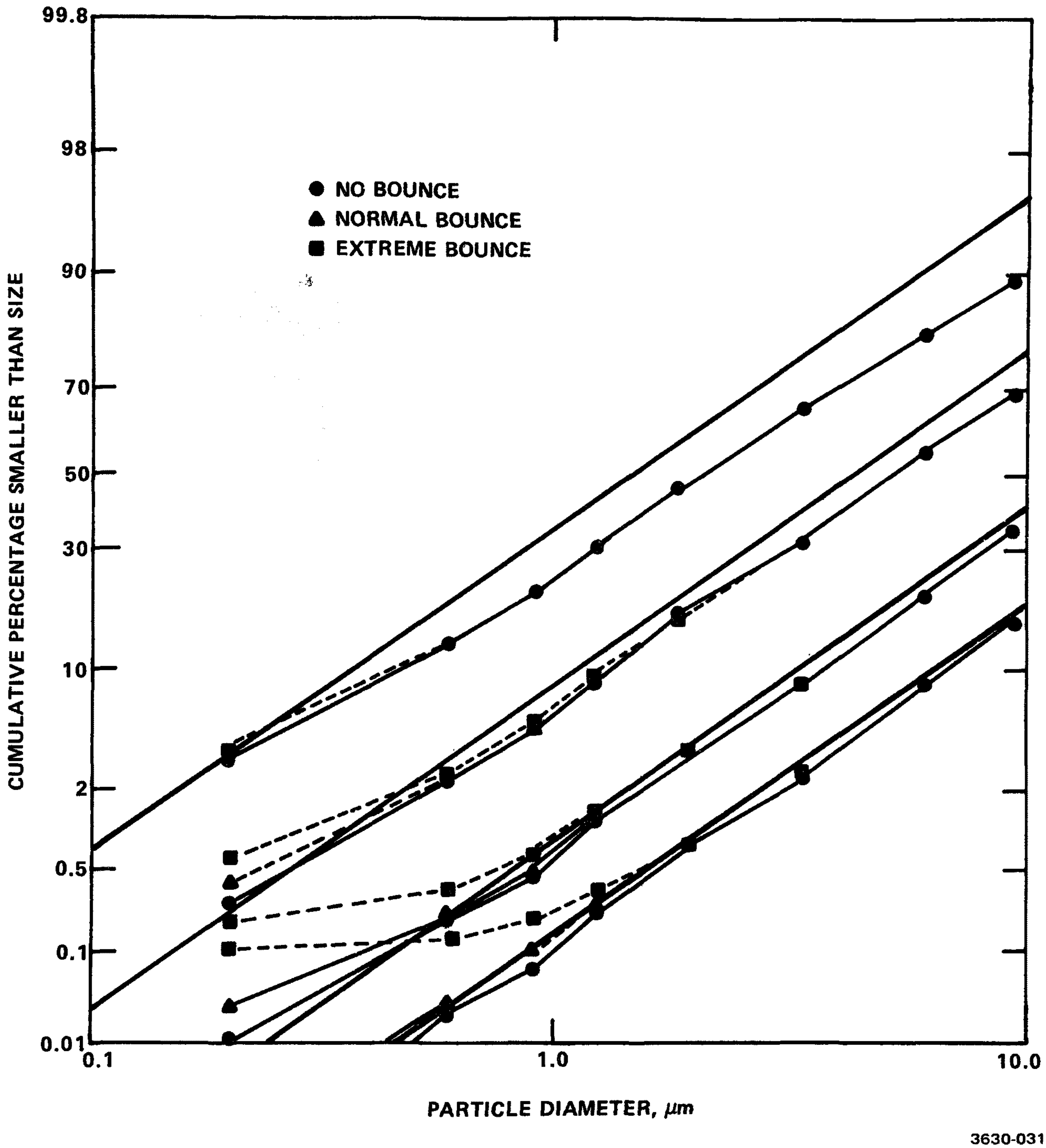


Figure 6. Recovered size distributions on a cumulative percentage basis from the Brink impactor models for σg = 3.0 and MMD's of 1.5, 4.5, 13.5, and 27 μm (backup filter included in the analysis). The bold lines represent the input distributions.

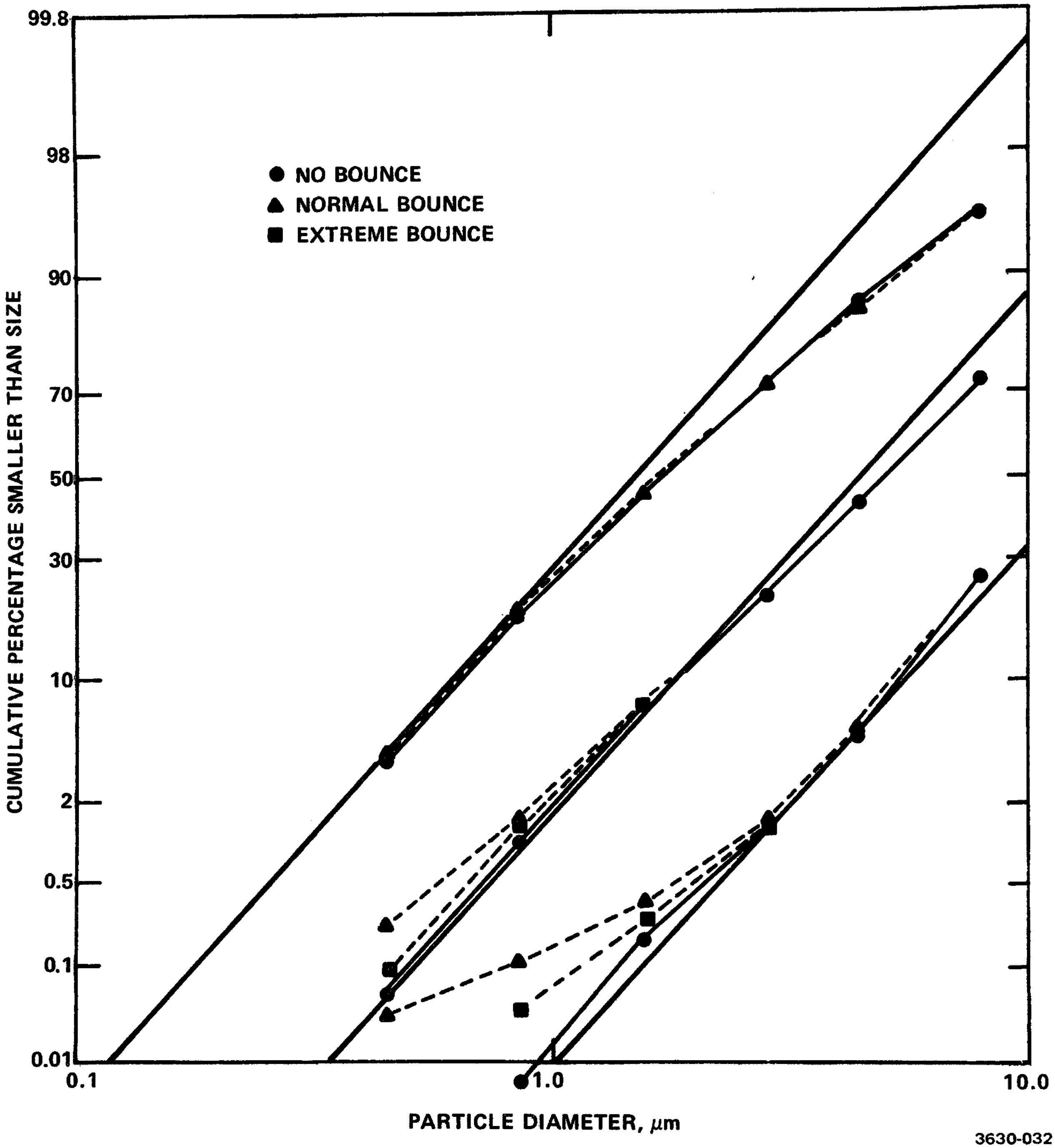


Figure 7. Recovered size distributions on a cumulative percentage basis for the Andersen impactor for σg = 2.0 and MMD's of 1.5, 4.5, and 13.5 μm. The backup filter was excluded from analysis in the results shown. The bold lines represent the input distributions.

of the distortions apparently results from the cyclone pre-collector on the Brink which removes most of the larger particles that are responsible for raising the apparent percentages of fines in the recovered size distributions.

It should also be noted that the relative errors in mass median diameters become increasingly large as the MMD of the input aerosol decreases. The recovered MMD's were found to be systematically large for test aerosol MMD's below 10 μm. The recovered values of σ_g were also systematically high with larger relative errors at the lower values of σ_g, as would be expected because of the low resolution afforded by impactors.

In many cases (e.g., control device fractional collection efficiency studies) the slope of the size distribution curve, expressed in mass concentration units, is the quantity of greatest interest. The most common manner of presentation of this slope is the form dM/dlogD (units of mass concentration). The quantity dM/dlogD is often approximated directly from the impactor data, stage by stage, as $\Delta m_i/\Delta \log D_i$, where

m_i = mass concentration of particles retained by the i^{th} stage

$$\text{and } \Delta \log D_i = \log \frac{(D_{50})_{i-1}}{(D_{50})_i} .$$

The particle diameter is then taken to be the geometric mean of $(D_{50})_i$ and $(D_{50})_{i-1}$,

$$\bar{D}_g = \sqrt{(D_{50})_i \times (D_{50})_{i-1}}$$

Figures 8 and 9 illustrate recovered size distributions presented in such a manner, together with the input distributions, for representative sets of Brink and Andersen results. The results for the "extreme bounce" case are not shown in Figures 8 and 9 but the values in those cases generally fall between the "no bounce" and "normal bounce" cases except for the back-up filters, for which the values were much higher in the "extreme bounce" case than in the other two cases. Except for the finest size fractions, represented by the back-up filter catches, and the fine fraction tails of the low σ_g distributions, the agreement between the recovered values of $(\Delta M/\Delta \log D)_i$ generally lie reasonably close to the input distributions. However, errors of up to ±35% are not infrequent.

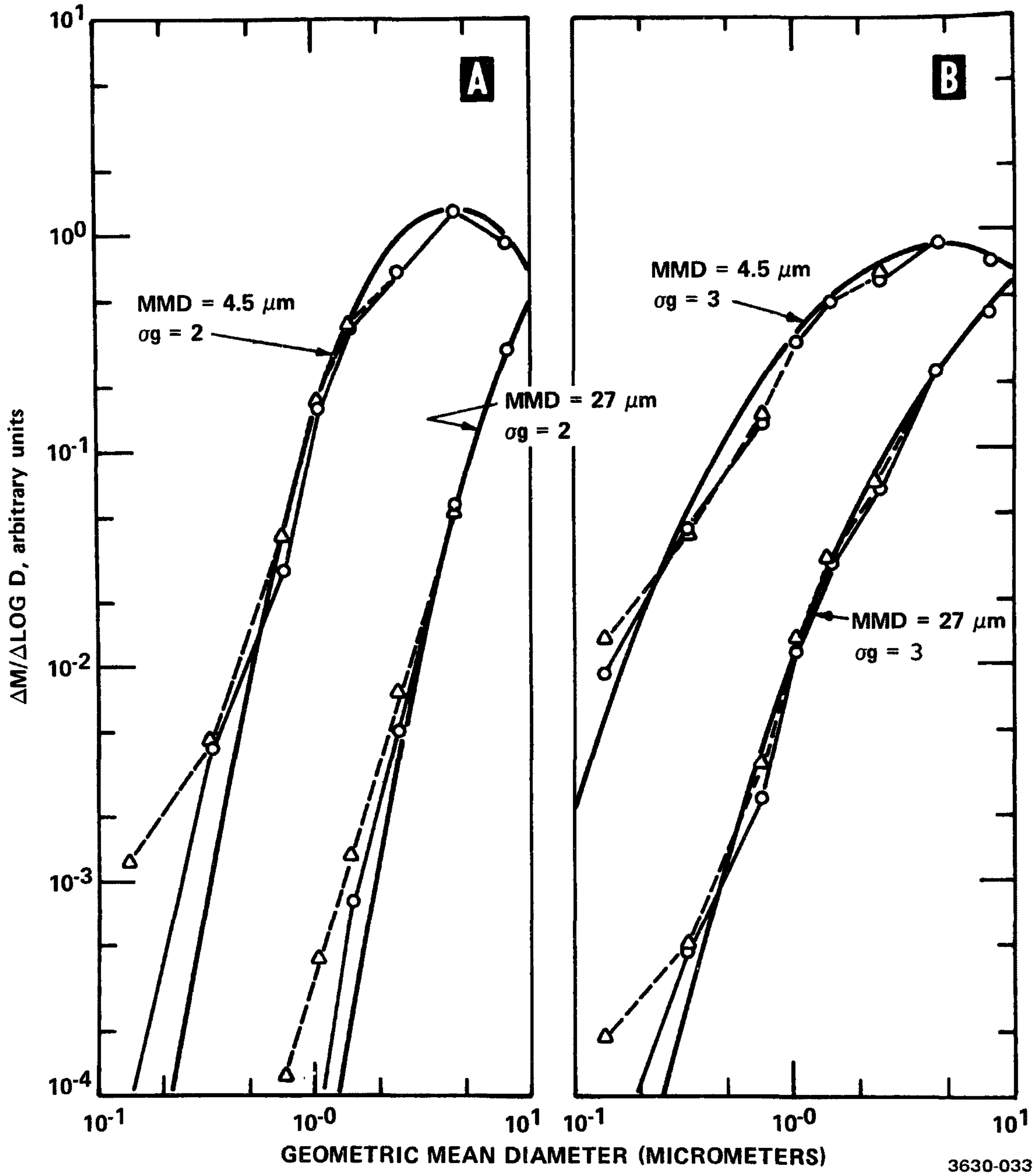


Figure 8. Recovered size distributions on a differential basis from the Brink impactor models for MMD's of 4.5 and 27 μm and σg's of 2 and 3. The bold curves represent the input distributions.

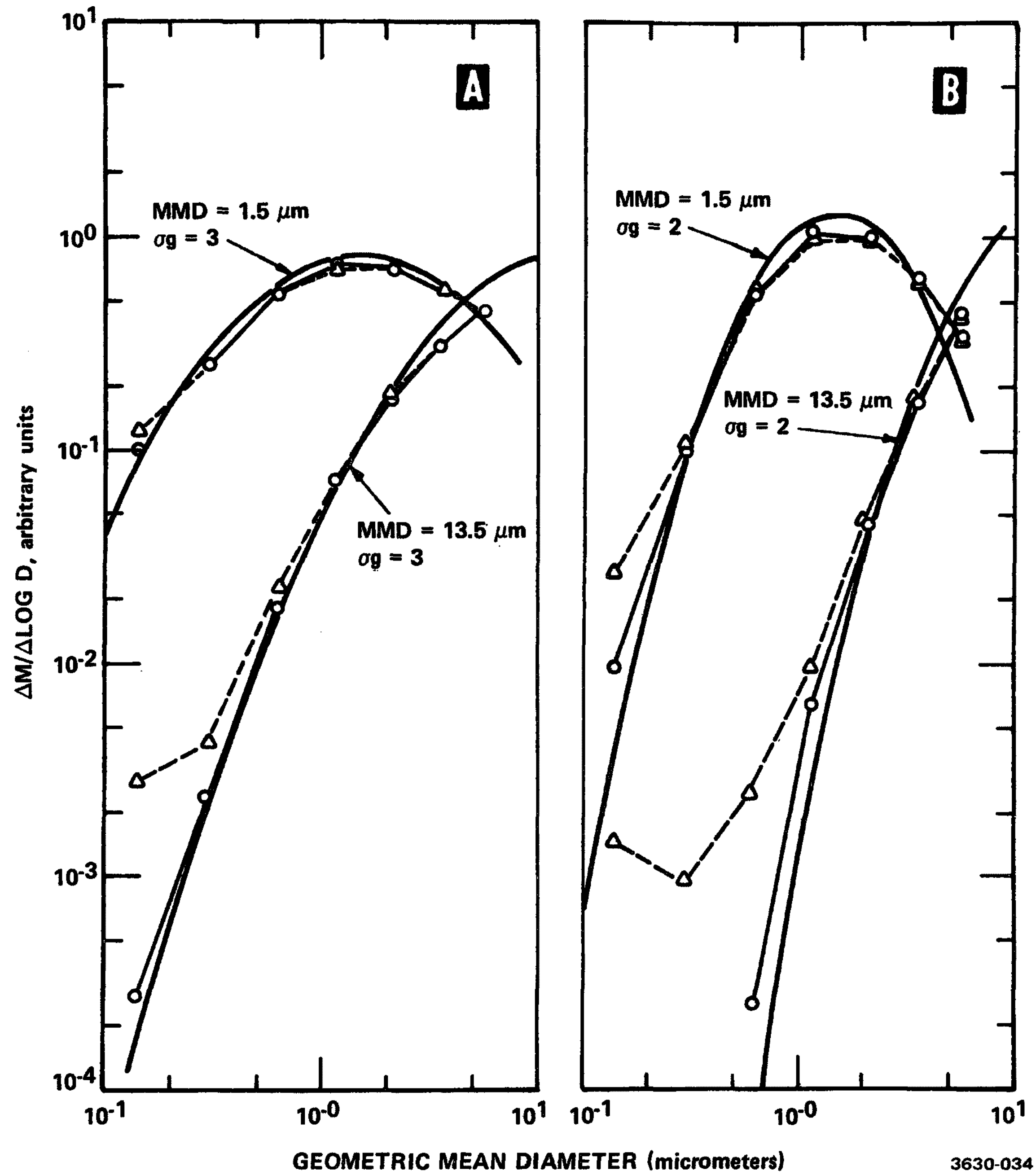


Figure 9. Recovered size distributions on a differential basis from the Andersen impactor models for MMD's of 1.5 and 13.5 μm and σg's of 2 and 3. The bold curves represent the input distributions.

Tables III and IV show the errors, expressed as percentages, in the recovered values of $(\Delta M/\Delta \log D)_i$ for several cases for each of the two impactors. (For the purpose of calculating $\overline{\log D}$ and $\bar{D}$ for the filter catches, it was assumed that the diameter range covered by the filter was $(D_{50})_8$ down to $\frac{1}{2}(D_{50})_8$.

Although no results for $\sigma_g = 4$ have been shown, the agreement between the recovered size distributions and the input distributions was progressively better as σ_g increased and was quite good in all cases for $\sigma_g = 4$ with the exception of back-up filter catches when bounce was present.

Table V shows the percentages of cases in which the recovered values $(\Delta m/\Delta \log D)_i$ lay within factors of 1.2, 1.5, and 2 of the true value. From these results it appears that the concentrations of fine particles as measured with impactors can seldom be taken to be known better than to within a factor much smaller than 1.5 unless the particles are known to be adhesive or an effective adhesive coating can be applied to the substrates.

There is some evidence,[8,9] although it is not conclusive, that the use of adhesive coatings (greases) on the substrates may become ineffective as the particulate deposits build up under the impactor jets. This would result in the same type of errors due to particle bounce resulting in back-up filter contamination by oversize particles with greased substrates as has been shown to occur with glass fiber substrates.

Conclusions and Recommendations

From the evidence presented here, it is suggested that back-up filter catches generally should be omitted from data presentation when dry, non-sticky particulates are sampled. Exceptions should be made only if the MMD is smaller than about 2.5 μm. In addition it is suggested that cyclone precollectors having D_{50}'s somewhat larger than the first impaction stage D_{50} be used whenever a non-sticky particulate is sampled. The use of such cyclones tends to greatly reduce errors due to particle bounce.

The results of this study were reported at the 1977 Air Pollution Control Association Annual Meeting in Toronto, Ontario, as Paper No. 77-35.3, entitled "Non-Ideal Behavior in Cascade Impactors."

Table III. Percent Errors in $\Delta M/\Delta \log D$, Andersen Impactor

No Bounce

σ_g =	2			3		
MMD:	1.5	4.5	13.5	1.5	4.5	13.5
Stage/Error						
F	144			22	38	
8	9			-14	-5	
7	-8	56		-11	-4	
6	-18	13		-10	-8	4
5	-14	-19	18	-12	-17	-24
4	6	-26	-20	-7	-21	-25
3		-19	-30	10	-15	0
2		-23	-28	9	-22	-24

Normal Bounce

F	568	121000		44	173	1720
8	22	920		-12	8	103
7	-6	111		-11	1	37
6	-20	9	293	-12	-11	4
5	-16	-18	39	-12	-16	-11
4	5	-27	-17	-7	-21	-24
3		-20	-30	9	-16	-25

NOTE: Values are omitted for stages for which the collected mass would be too small to be detected in field sampling programs.

Table IV. **Percent Errors in ΔM/ΔlogD, Brink Impactor**

No Bounce

σ_g =	2				3			
MMD:	1.5	4.5	13.5	27	1.5	4.5	13.5	27
Stage/Error								
F	220				24	53		
6	-6	220			-37	-21	13	
5	-43	-35			-32	-39	-40	-37
4	-19	3			-9	-12	-5	4
3	-15	-3	84		-4	-9	-3	8
2	-1	-10	-8	33	4	-20	-23	-22
1	88	-14	-15	7	34	-3	-14	-14

Bounce

F	550				41	123		
6	-10	238			-39	-24	12	
5	-40	-8			-29	-33	-26	-10
4	-20	10			-10	-12	0	17
3	-16	-4	107		-4	-10	-3	10
2	-1	-28	7	100	4	-18	-20	-16
1	86	-15	-18	3	33	-4	-16	-17

NOTE: Values are omitted for stages for which the collected mass would be too small to be detected in field sampling programs.

Table V. Percentage of Trial Cases in Which Recovered Value of ($\Delta M/\Delta \log D$) is Within the Indicated Factor of the True Value

	Andersen		
Factor:	1.2	1.5	2.0
Stage/Percent of cases			
F	0	31	38
8	57	71	79
7	65	76	82
6	65	80	90
5	75	100	100
4	30	100	100
3	40	90	90
2	(30)	(90)	(90)

	Brink		
Factor:	1.2	1.5	2.0
Stage/Percent of cases			
F	0	33	56
6	35	59	82
5	11	47	100
4	80	95	100
3	74	91	91
2	42	96	100
1	71	72	100

Andersen table covers all cases with
MMD = 1.5, 2.6, 4.5, 7.8, 13.5 and
σ_g = 2, 3
for both normal bounce and no bounce

Brink table covers all cases with with
MMD = 1.5, 2.6, 4.5, 7.8, 13.5, 27, and
σ_g = 2, 3
for both normal bounce and no bounce

SAMPLING CHARGED MONODISPERSE AND POLYDISPERSE AEROSOLS WITH CASCADE IMPACTORS

In performing particle size distribution measurements at control devices operating on industrial process streams, investigators are usually aware that in some cases charged particles will be present in the gas stream. In order to assess the influence of particle charge, three different experiments were performed to determine whether or not cascade impactors sampling charged aerosols can yield erroneous particle size distribution measurements. The commercially available cascade impactors utilized in this study were the Andersen Mark III Stack Sampler, the Brink Model BMS-11 Cascade Impactor, the Meteorology Research, Inc. Model 1502 Cascade Impactor, and the University of Washington Mark III Source Test Cascade Impactor. In general, the measured distributions indicated more large particles and fewer small particles than actually existed. The deviations from the true size distribution were found to be a function of the magnitude of charge. The deviations were smaller if glass fiber substrates were used as impactor collection surfaces instead of the metal collection plates alone. For charge levels representative of electrostatic precipitators operating at normal charging conditions (an electric field strength of 400,000 V/m and a current density of 3×10^{-4} A/m^2), the differences between the true and measured polydisperse size distributions sampled with glass fiber substrates were small.

The three experiments are briefly described below. In the first experiment monodisperse aerosols were sampled by the University of Washington Mark III, Andersen Mark III, and MRI Model 1502 cascade impactors. The second test involved the sampling of polydisperse aerosols with a Brink cascade impactor. The third experiment involved the sampling of polydisperse aerosols with the Andersen Mark III cascade impactors. A review of the important parameters and conclusions for each experiment are described below.

<u>1st Test - Monodisperse Aerosol</u>

1. Tests were done with the impactors operated at the recommended flow rate and with particle charges equivalent to those expected at precipitator outlets. However, only two particle sizes were used.

2. Wall losses were measured along with the stage collection efficiency.

3. For charge levels approximately five times higher than those expected at a precipitator outlet, very large effects were noted.

4. For samples taken using glass-fiber substrates at representative particle charge levels, the effect of particle charge on impactor performance was found to be minimal.

5. Grounding the impactors generally increased stage collection efficiencies.

6. The data from this experiment were not taken with particle concentrations high enough to be representative of those to be found at the outlet of industrial precipitators.

2nd Test - Polydisperse Aerosol Sampled with a Brink Impactor

1. Tests were done with the impactors operated at the recommended flow rate with a polydisperse aerosol and particle charges equivalent to those expected at precipitator outlets. Only two stages of a Brink impactor were used.

2. The particle concentration was less than would be expected at a precipitator outlet.

3. A test on wall losses showed that they play a significant part in impactor performance when a charged aerosol is sampled.

4. Tests using glass-fiber substrates did not show an appreciable difference in the collection of charged and uncharged particles. Tests using bare metal substrates, however, showed quite a difference between the collection of charged particles and the collection of uncharged particles.

3rd Test - Polydisperse Aerosol Sampled with Andersen Impactors

1. Tests were performed with entire Andersen impactors operated at the recommended flow rate and with glass-fiber substrates only.

2. The particle concentration was similar to that expected at the outlet of an industrial electrostatic precipitator. The aerosol contained polydisperse ammonium fluorescein particles.

3. Wall losses were not considered separately, however, no visible wall loss was observed for tests with particles having moderate charge. The wall losses were visibly evident in the high charge tests.

4. Moderate particle charge levels had little effect on impactor performance for the middle and lower stages. For stages with D_{50}'s above 3 micrometers, up to about twice as much mass was caught in the charged particle impactor than in the neutral one.

5. For charging conditions higher than those considered moderate here, the effects of particle charge were more significant both for the lower impactor stages and the upper impactor stages, with the middle stages giving approximately true mass measurements.

The details of the experimental work performed under these tasks is presented in a report entitled "Sampling Charged Particles with Cascade Impactors," EPA-600/7-79-027, January 1979.

EVALUATION OF CASCADE IMPACTOR SUBSTRATE MEDIA

Cascade impactors are widely used to determine particle size distributions in air pollution control device research programs. In these research programs a large variety of flue streams are encountered with temperatures ranging from ambient to around 370°C (700°F). Gas analyses show that many of these sources contain some SO_x components, particularly those associated with fossil fuel fired boilers.

Most impactors have collection stages which are too heavy to allow accurate measurements of the mass of the particles collected in each size fraction. Weighing accuracy can be improved by covering the stage with a lightweight collection substrate made of aluminum foil, teflon, glass fiber filter material, or other suitable lightweight material , depending upon the particular application. Some manufacturers now furnish lightweight inserts to be placed over the collection stages. With such arrangements it is possible to collect enough material on each stage to make an accurate determination of the mass collected and avoid overloading the stage. If the stage is overloaded, some deposited particulate matter can be reentrained and deposited on another stage or the back-up filter and lead to erroneous results.

Substrate materials may also serve the purpose of changing the surface characteristics from those of a bare metal or plastic to something better suited to holding particles which impact. Thus, various greases are often used, either on bare impactor plates, or, more frequently, on metal foil substrates.

Presented in the published final report (see page 32) are the results of investigations concerning the use of two classes of impactor substrates--greased metal foils, and glass fiber filter materials. Tests were made under both laboratory and field conditions to evaluate each of several greases and filter materials. The general purpose of this study was to identify specific materials and handling techniques which may be used to improve the accuracy of weight measurements in impactors by reducing uncertainties arising from changes in substrate weights.

Although normal glass fiber substrate preparation includes baking and desiccation before the initial weighing, it is frequently found that weight losses can occur when sampling clean air. Previous tests were conducted to investigate this phenomenon in detail.[10] It was found that with careful handling, weight loss per glass fiber substrate for Andersen impactors can be kept below 0.1 mg. This loss is attributed to loss of fibers which stick to seals within the impactor and to "superdrying" when sampling hot, dry air. Weight losses of 0.1 mg are small compared to most stage catches when sampling particulate matter, and they are within an acceptable range for sampling errors.

A more significant problem is excessive weight gain of the glass fiber material itself due to gas phase reactions. These reactions appear to be caused by the SO_x component in flue gases. A series of studies was thus directed toward developing procedures to passivate glass fiber materials against the effect of SO_x components in flue gas.

Although greases offer good impedance to particle bounce on substrates, they are subject to temperature limitations. Sampling clean, hot air while using greased substrates may result in severe weight losses. These losses appear to result from one or more of several mechanisms which may include continued loss of volatile components, erosion of grease by the action of the gas jet in the impactor, and occasional flow of grease from the substrate to other surfaces within the impactor. In addition, chemical reactions may play a role in some cases. Occasionally, some of the weight lost on upper impactor stages has been found to reappear as a weight gain on a back-up filter, which is an indication that the grease has been blown off the collection surface or has chemically reacted to form a fine "smoke" which was then collected by the back-up filter.

Summary of Results of Evaluation of Greases

Upon preliminary screening by static heating tests in the laboratory, six of the nineteen greases tested were found to have acceptable characteristics at elevated temperatures. Among those greases eliminated by these tests, large changes in mass or in consistency had occurred.

In the field tests these six greases were applied to metal foil impactor substrates and were subjected to a flue gas sampling procedure. Particulate matter was removed by a prefilter so that the effects of the flue gas alone on the greased substrates could be observed.

As a result of the field studies it was concluded that Apiezon H grease performed best of the greases tested. Other greases studied displayed changes in consistency or a tendency to flow under the influence of the gas stream.

Further tests on Apiezon H have demonstrated that this grease is a suitable substrate material for applications where the temperature does not exceed approximately 177°C (350°F).

Summary of Results of Evaluation of Filter Media

Untreated glass fiber filter materials used as impactor substrates will almost invariably increase in mass when subjected to the hot flue gases normally encountered in field applications. Conversion of SO_2 to various sulfates appears to be the cause of mass gains. The various filter materials tested vary widely in the amount of mass change which occurs under a particular set of flue gas conditions.

Preconditioning techniques can be used to force the production of sulfates in a filter medium, leaving a minimal number of sites available for chemical reaction in the flue gas, and hence, providing substrate material for which minimum mass gains occur during use in an impactor. The best results were achieved when substrates were washed in sulfuric acid, baked, and conditioned *in situ*.

Of the filter materials studied, Reeve Angel 934AH was found to be most suitable in all respects for use as cascade impactor substrates.

Conclusions and Recommendations

Collection stages of most types of cascade impactors are very heavy in comparison with the amounts of particulate material normally collected. It is therefore the usual practice to augment each collection stage with a lightweight substrate to improve weighing accuracy. Generally, two classes of substrates are used--greased metal foils, and glass fiber filter material.

Greased foils provide resistance to particle bounce and scouring effects, but greases tend to be unstable at elevated temperatures. Some tend to harden, and in others the viscosity may become reduced so that they may flow or be blown off the surface by the high velocity gas flowing through the impactor jets. Of the greases tested, Apiezon H was found to perform most satisfactorily. This grease may be used at temperatures up to approximately 177°C (350°F). No greases were found to be usable at higher temperatures.

Mass gains exhibited by glass fiber filter materials when they are exposed to the SO_x components in flue gas streams pose a complicated problem. Experiments show that these mass gains are caused by formation of sulfates due to a gas phase reaction with SO_x. Laboratory and field experiments indicate that the only glass fiber filter material suitable for use as a cascade impactor substrate is Reeve Angel 934AH. When this material is acid treated, according to a procedure given below, mass gains caused by flue gas reactions can be kept quite small.

It is recommended that acid washing, baking and *in situ* conditioning be used whenever large blank mass gains with large standard deviations are expected. In this context, "large" refers to glass fiber substrate mass gains greater than several tenths of a milligram.

Further research may provide a technique for passivating glass fiber materials to all mass gains. It has been suggested that a high temperature polymer or silicon compound might be developed to coat the glass fibers in much the same way that the Gelman Spectro-Grade material is prepared for use at low temperatures.

The Final Report for this task was published in a document entitled "Inertial Cascade Impactor Substrate Media for Flue Gas Sampling," EPA-600/7-77-060, June 1977 (NTIS-PB 276 583/2BE).

Procedure for Acid Washing Substrates

1. Submerge the glass fiber substrates to be conditioned in a 50-50 mixture (by volume) of distilled water and reagent grade concentrated sulfuric acid at 100°-115°C (230-239°F) for 2 hours. This operation should be carried out in a hood with clean glassware. Any controllable laboratory hotplate is suitable.

The substrates may need to be weighted down to keep them from floating. For this purpose, place a teflon disc on the top and bottom of the substrate stack. The top disc can be held down with a suitable glass or teflon weight.

2. When the substrates are removed from the acid bath they should be allowed to cool to room temperature. They are next placed in a distilled water bath and rinsed continuously with a water flow of 10-20/cm^3/min. The substrates should be rinsed until the pH of the rinse water, on standing with the substrates, is nearly the same as that of the distilled water. The importance of thorough washing cannot be over-emphasized.

3. After rinsing in distilled water the substrates are rinsed in reagent grade isopropanol (isopropyl alcohol). They should be submerged and allowed to stand for several minutes. This step should be repeated four to five times, each time using fresh isopropanol.

4. Allow the substrates to drain and dry. They can be spread out in a clean dry place after they have partially dried (dry enough to handle).

5. When the filters are quite dry to the touch they should be baked in a laboratory oven to drive off any residual moisture or isopropanol. Bake the substrates at 50°C (122°F) for about two hours, at 200°C (392°F) for about two hours, and finally at 370°C (700°F) for about three hours. The substrates are now ready for *in situ* conditioning.

As a final check, place two substrates in about 50 ml of distilled water, and check the pH. The substrates to be checked for pH should be torn into small pieces, placed in the water, and stirred for about 10 minutes before the pH is measured. If the pH is significantly lower than that of the distilled water, then the filters should be baked out at 370°C (700°F) for several hours more to remove any residual sulfuric acid. The boiling point of sulfuric acid is 338°C (640°F), so high temperatures must be used.

Figure 10 is a flow chart representing the acid wash procedure described in the foregoing paragraphs.

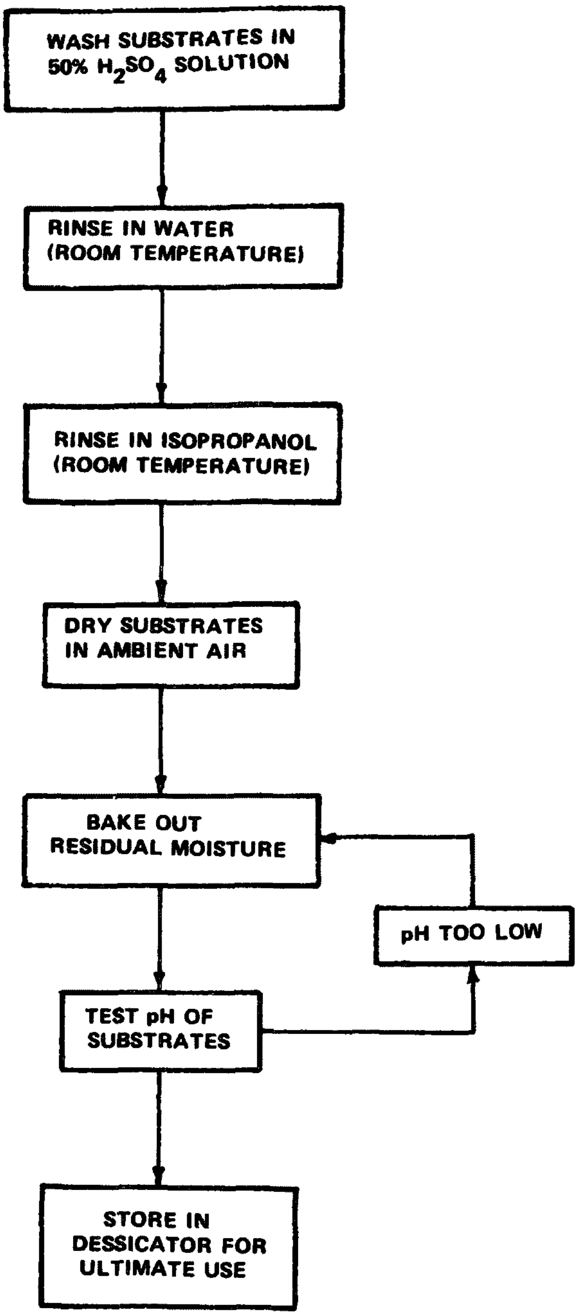


Figure 10. Flow chart for acid wash treatment of glass fiber filter material.

DEVELOPMENT OF FIVE STAGE SERIES CYCLONE SYSTEM

The majority of measurements to determine the particle-size distribution in process streams are made with cascade impactors. Impactors, however, have several limitations:

- There is not enough mass collected for chemical analysis of the particles in each size fraction.
- Frequently there is not enough mass collected on some stages to be weighed accurately.
- Particle bounce and reentrainment cause an unpredictable, but significant, error in the stage and backup filter catches.[11]
- When the mass concentration is high, the sampling time may be undesirably short.
- Impactors are used with lightweight collection substrates which are often unstable in mass when exposed to the process stream.[12]

A series of cyclones with progressively decreasing cut points will perform similarly to impactors, but without many of the associated problems.

Cyclones, however, also have limitations to their applicability:

- There is no general theory to describe the performance of small cyclones under field test conditions.
- Sampling times may be undesirably long at sources where the mass concentration is low.

An experimental study was undertaken to develop and evaluate a system containing five cyclones and a backup filter in series.

The EPA-SoRI cyclone system as shown in Figure 11, is an inertial particle sizing device that is designed for in-situ sampling of industrial process streams. It will fit through a 10 cm diameter port and is equipped with nozzles of different diameters to allow isokinetic sampling at a nominal sample flow rate of 28.3 ℓ/min.

In this study, the individual cyclones of the system were tested and calibrated in the laboratory under conditions similar to those frequently encountered in field tests: gas temperatures of 25, 93, and 204°C, flow rates of 7.1, 14.2, and 28.3 ℓ/min, and particle densities of 1.05, 1.35, and 2.04 gm/cm^3.

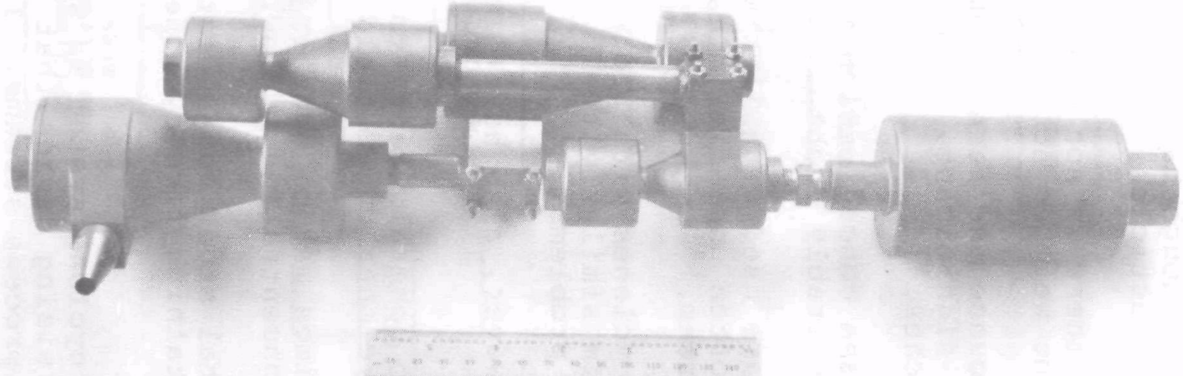


Figure 11. EPA-SoRI Five Stage Cyclone.

The D_{50} cut points for the cyclone system at various operating conditions are given in Table VI. For laboratory test conditions (25°C, 28.3 ℓ/min, particle density 1.0 gm/cm^3) the cut points for cyclones I-V are 5.4, 2.1, 1.4, 0.65, and 0.32 μm, respectively. Figures 12 and 13 show some of the calibration curves that were obtained. Figure 12 shows efficiency vs. aerodynamic (particle density = 1.0 gm/cm^3) particle diameter plots for a sampling rate of 28.3 ℓ/min and Figure 13 shows similar data where the flow rate is 14 ℓ/min . These two figures illustrate that the small cyclones have "sharp" efficiency curves and indicate that the system should function adequately as a particle sizing device. At the test conditions for Figure 12, the pressure drop across the cyclone system was 170 mm Hg.

Data from this study wherein different particle densities (ρ) were used tend to support the D_{50} vs. $\rho^{-1/2}$ relationship suggested by several theories.[13,14] On the other hand, the experimental results indicated that the cut points were directly proportional to the gas viscosity which is in opposition to most theories.[13,14,15,16] Also, it was found in this study and by Chan and Lippmann[17] that the D_{50}'s of small cyclones are not inversely proportional to the square root of the flow rate as some theories predict.

A detailed description of this cyclone system development and calibration program can be found in "Development And Laboratory Evaluation Of A Five-Stage Cyclone System," EPA-600/7-78-008, January 1978 (NTIS-PB 279 084/8BE).

Table VI

LABORATORY CALIBRATION OF THE FIVE-STAGE CYCLONES
D_{50} Cut Points

Cyclone		I		II		III			IV		V	
Particle Density (gm/cm^3)		2.04	1.00	2.04	1.00	2.04	1.35	1.00	1.05	1.00	1.05	1.00
Flow ℓ/min	Temperature °C	Cyclone D_{50} cut points micrometers										
7.1	25								2.5	(2.5)	1.5	(1.5)
14.2	25	5.9	(8.4)	2.4	(3.5)	(1.7)	2.1	(2.4)	1.5	(1.5)	.85	(.87)
28.3	25	3.8	(5.4)	1.5	(2.1)	.95	-	(1.4)	.64	(.65)	.32	(.32)
28.3	93	4.4	(6.3)	2.3	(3.3)	1.2	-	(1.8)				
28.3	204	6.4	(9.1)	2.9	(4.1)	1.9	-	(2.8)				

D_{50} cut points enclosed in parentheses are derived from the experimental data using Stoke's law.

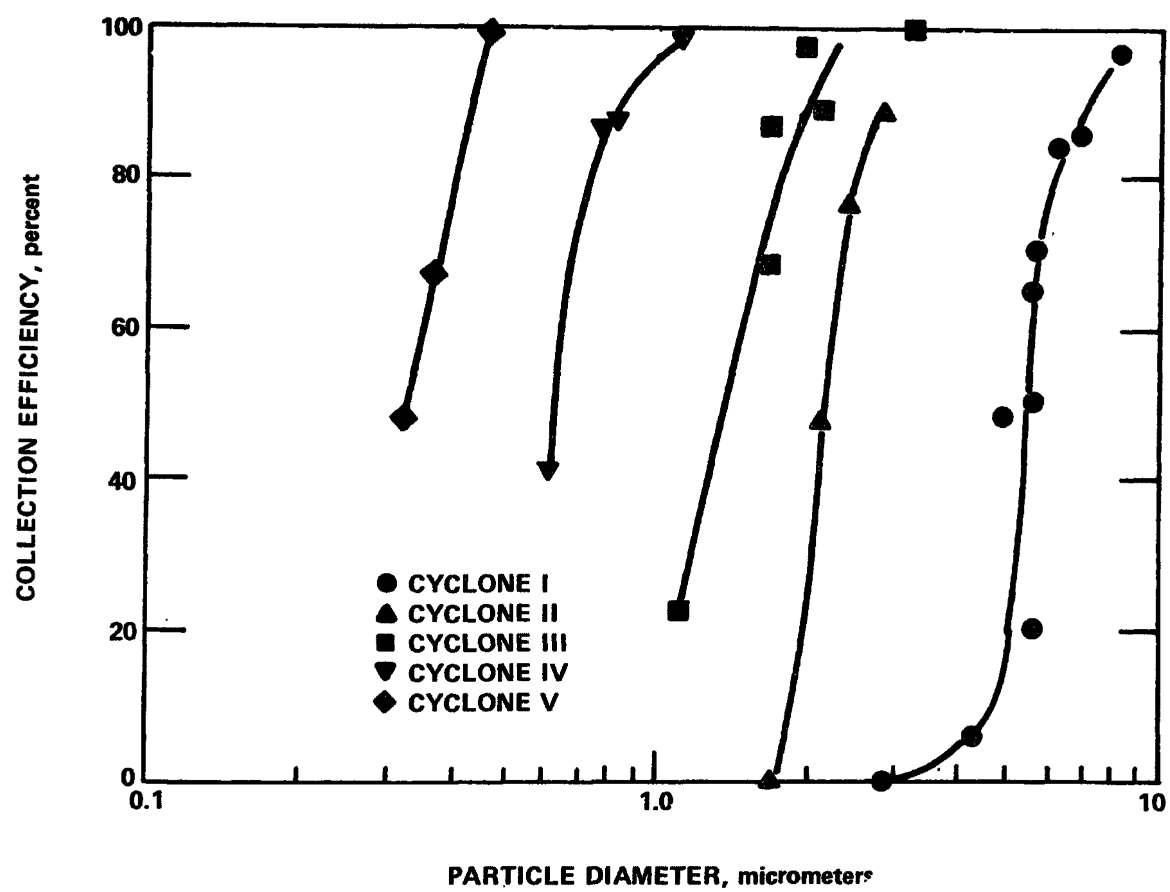


Figure 12. Collection efficiency of the EPA-S.R.I. Cyclones at a flowrate of 28.3 ℓ/min, a temperature of 25°C, and for a particle density of 1.00 gm/cm^3.

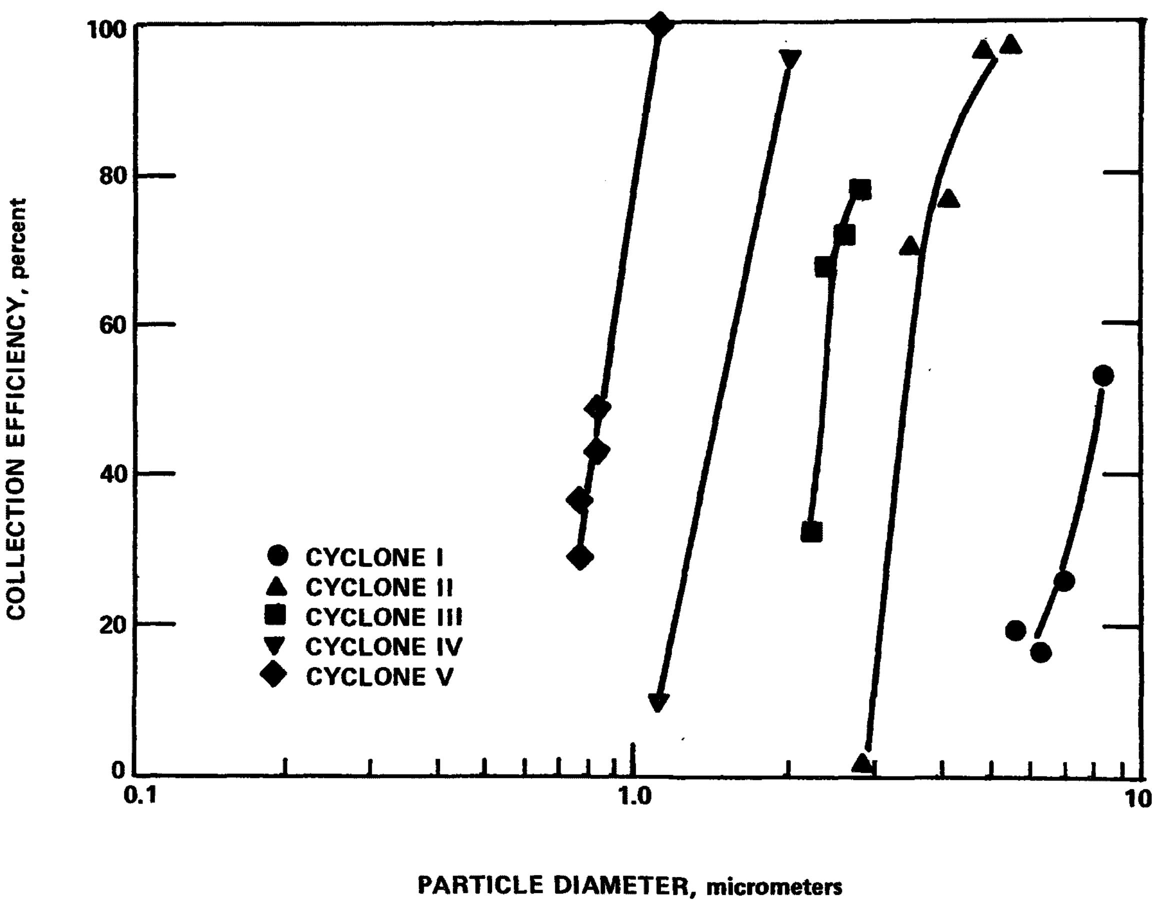


Figure 13. Collection efficiency of the EPA-SRI Cyclones at a flowrate of 14.2 ℓ/min, a temperature of 25°C, and for a particle density of 1.00 gm/cm^3.

ELECTROSTATIC PRECIPITATOR BACK UP FOR SAMPLING SYSTEMS

Filters used to collect fine particles in source sampling trains are troublesome in several ways. A large pump is usually required to pull the sample gas through a high efficiency filter, and many tests are terminated prematurely because of the large pressure drop that results as a dust cake builds up on the filter as a result of the filter cake being less for small particles. This problem is especially severe when the test objective is to collect a large sample of submicron particles. Contamination of a sample with filter material or physical removal of the dust from the filter can also be problems.

This program's goal was to design and evaluate the performance of an electrostatic collector to be used as an alternative to filters as a fine particle collector. Potential advantages of an ESP would be low pressure drop and high capacity. Potential problems would be unreliability and poor collection due to back corona or lack of particle adhesivity.

The electrostatic precipitator back up filter was designed to be operated at a nominal sample flow rate of 6.5 ft^3/min., (184 ℓpm) at a temperature of 205°C, and to achieve near 100% collection of submicron particles. Since it is possible that there would be a need to operate the collector in situ, a secondary requirement was that the collector pass through a 4 inch diameter port. Furthermore, the system was designed to be convenient to operate and clean, and to require a minimum of operator training or attention.

Figure 14 is a schematic diagram illustrating the main features of the system that was designed and fabricated. The collector is of a cylindrical geometry with the collection electrodes arranged concentrically to allow a large surface area to be contained within a relatively short outer cylinder. Disc and needle discharge electrodes were designed and fabricated, but only the disc-cylinder geometry was evaluated during this program. The system shown in Figure 14 is mechanically rugged and the collection electrode geometry is such that the flow is laminar at the design flow rate; thus, it is a simple matter to calculate particle trajectories and the electrode length required for 100% collection efficiency.

The ESP back up is a highly efficient collector of submicron particles. When set to 200 μA on the corona disc electrode and 2 kV on the collector (both well below breakdown values), no further adjustments are necessary for proper operation. The power supply developed for the ESP collector facilitates correct operation. Since there is a potential for degraded performance due to back corona if the collected particles are of high resistivity, the collector can be routinely used with a back up filter following it in the sampling train.

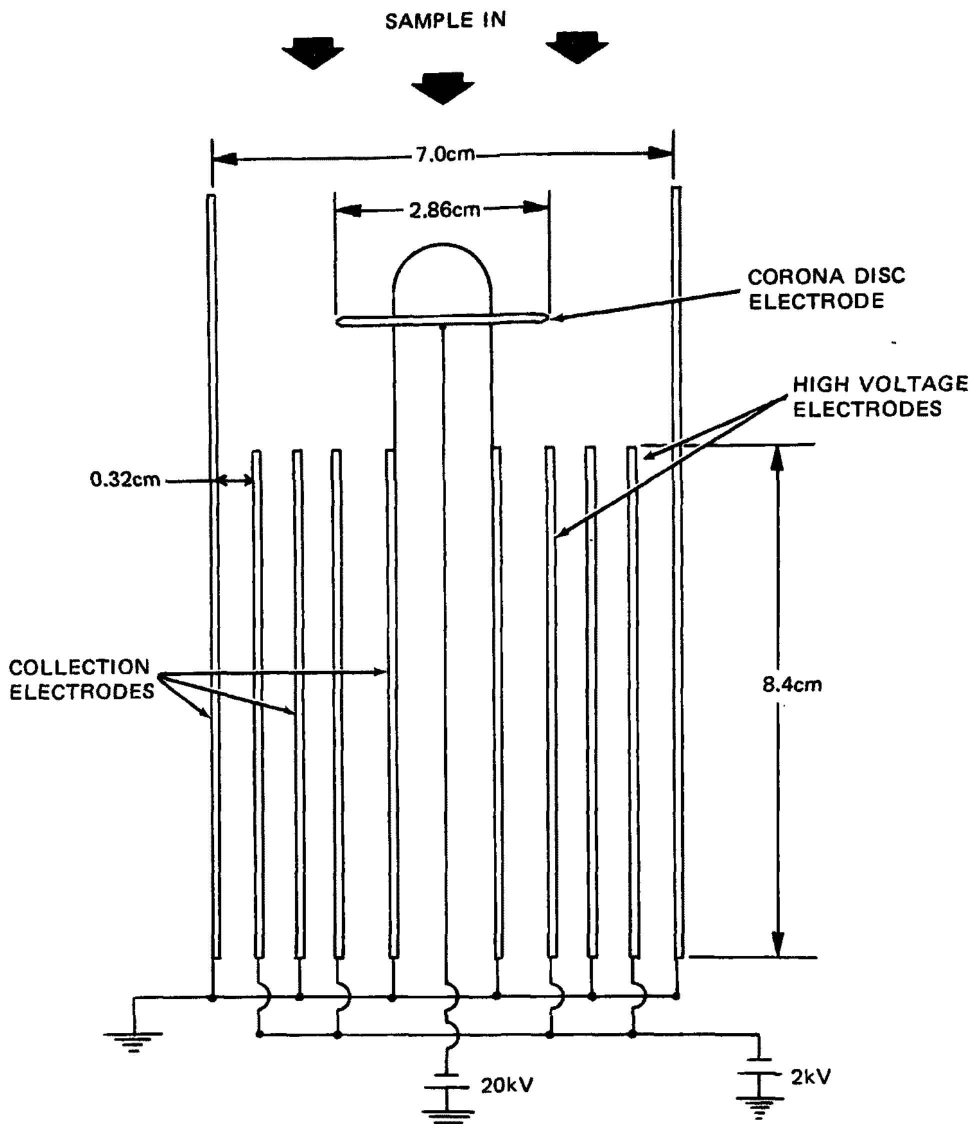


Figure 14. Schematic of the electrostatic collector with the disc discharge electrode installed.

If experience shows the system to operate reliably at a particular source, the filter can be eliminated.

After the sample is collected, the ESP is disassembled, immersed in a suitable liquid, and agitated ultrasonically. The wash can be filtered or evaporated to dryness, depending on the nature of the dust and the objectives of the test.

The electrostatic collector prototype developed and tested in this research effort fulfills the design criteria: near 100% collection of submicron particles when operated at a nominal sample flow rate of 6.5 ft^3/min and a temperature of 200°C, sized to fit through a 4 inch diameter port for in situ operation, convenient to operate and clean.

Figure 15 shows a detailed assembly drawing of the electrostatic precipitator back up. A photograph of the complete system is shown in Figure 16. The report describing the development of this device is entitled "An Electrostatic Precipitator Back Up For Sampling Systems," EPA-600/7-78-114, June 1978.

We acknowledge that the disc-cylinder electrode geometry and method described in this report for ionization and particle charging are developments of Air Pollution Systems, Inc., Kent, Washington and the Electric Power Research Institute, Palo Alto, California, and that we have been advised by Air Pollution Systems, Inc. that United States and Foreign patents have been obtained and others applied for.*

We are not aware of the details of said patents or any pending applications and provide no assurance that practice of any of the systems or methods disclosed in this report do not infringe either said patents or any other private rights.

*U.S. Patent No. 4093430

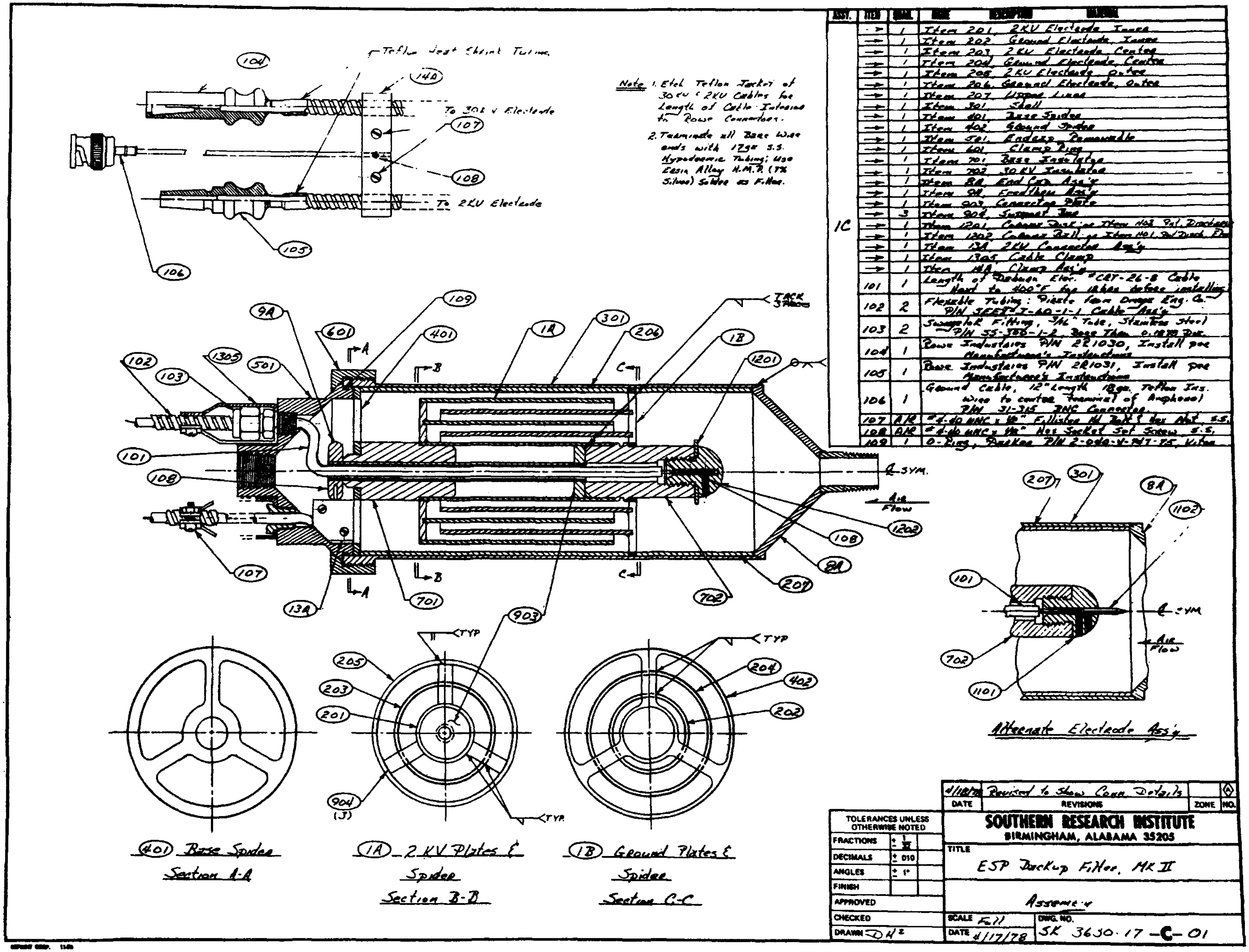


Figure 15. ESP Collector Assembly Drawing.

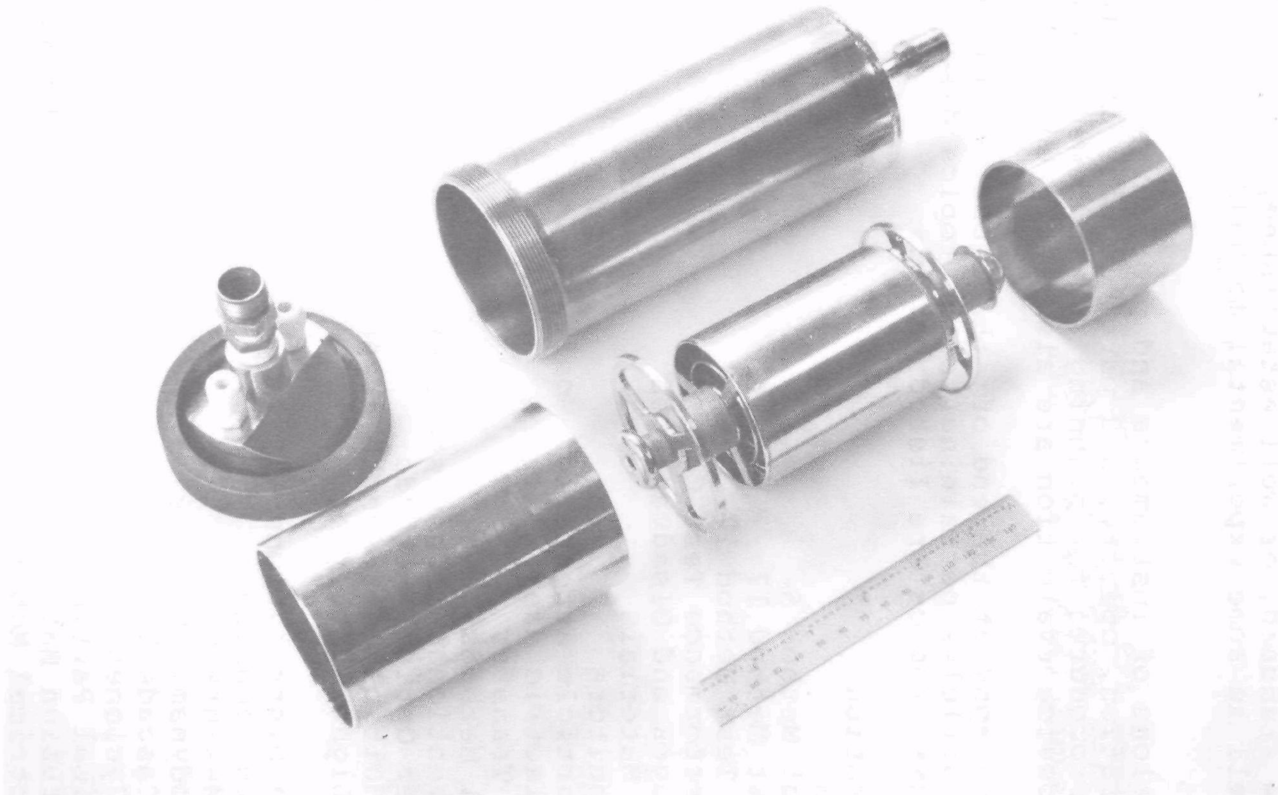


Figure 16. Electrostatic Precipitator Backup Filter.

GUIDELINES FOR PARTICULATE SAMPLING IN INDUSTRIAL PROCESS STREAMS

The guideline document written under this technical directive lists and describes briefly many of the instruments and techniques that are available for measuring the concentration and/or size distribution of particles suspended in process streams. The standard, or well established, methods are described as well as some experimental methods and prototype instruments.

Descriptions of instruments and procedures for measuring mass concentration, opacity, and particle size distribution are given. Procedures for planning and implementing tests for control device evaluation are also included.

A bibliography at the end of the report contains 141 citations to articles pertaining to the topics discussed in the text. These topics are listed below:

- Mass Concentration
  - Filtration
    - EPA Test Method 5
    - EPA Test Method 17
    - ASTM - Test Method 17
    - ASME Performance Test Code 27
    - Advantages and Disadvantages
    - Filter Materials
  - Process Monitors
    - Beta Particle Attenuation Monitors
    - Piezoelectric Mass Monitors
    - Charge Transfer
    - Optical Methods
      - Conventional Transmissometers
      - Other Optical Methods
        - Multiple-wavelength transmissometers
        - Light scattering
- Opacity
- Particle Size Distributions
  - Established Techniques
    - Field Measurements
      - Aerodynamic Methods
        - Cascade impactors
        - Cyclones
      - Optical Particle Counters
      - Diffusion Batteries with Condensation Nuclei Counters
      - Electrical Mobility
    - Laboratory Measurements
      - Sedimentation and Elutriation
      - Centrifuges
      - Microscopy
      - Sieves
      - Coulter Counter

- New Techniques
  - Low Pressure Impactors
  - Impactors with Beta Radiation Attenuation Sensors
- Cascade Impactors with Piezoelectric Crystal Sensors
- Virtual Impactors
- Optical Measurement Techniques
- Hot Wire Anemometry
- Large Volume Samplers

Control Device Evaluation

Bibliography

This document has been published as an EPA report entitled "Guidelines for Particulate Sampling in Gaseous Effluents from Industrial Process Streams," EPA-600/7-79-028, January 1979.

TECHNICAL MANUAL FOR PARTICULATE SAMPLING EQUIPMENT AND METHODS

This technical manual lists and describes the instruments and techniques that are available for measuring the concentration or size distribution of particles suspended in gaseous process streams. The standard, or well established methods are described as are some experimental methods and prototype instruments. To the extent that the information could be found, an evaluation of the performance of each instrument is included.

The manual describes instruments and procedures for measuring mass concentrations, opacity, and particle size distributions. It also includes procedures for planning and implementing tests for control device evaluation, a glossary, and an extensive bibliography containing 422 citations.

In order to briefly convey the scope of this document a list of the topics discussed is presented below.

- Mass Concentration
  - Filtration
    - Introduction
    - EPA Test Method 5
      - Nozzle
      - Probe
      - Pitot Tube
      - Particulate Sample Collector
      - Gaseous Sample Collector
      - Sampling Box
      - Meter Box
      - Performance
    - ASTM - Test Method
    - ASME Performance Test Code 27
      - Isokinetic Sampling
    - High Volume Samplers
    - Filter Materials
    - Summary
  - Process Monitors
    - Introduction
    - Beta Particle Attenuation Monitors
      - Instrument Development
      - Performance
      - Summary
    - Piezoelectric Mass Monitors
      - Performance
        - Temperature
        - Humidity
        - Particle collection characteristics
        - Linear response limit
        - Considerations for stack application
      - Summary

        - Charge Transfer
            - Instrument Development
            - Performance
            - Summary
        - Optical Methods
            - Conventional Transmissometers
                - Summary
            - Other Optical Methods
                - Multiple-wavelength transmissometers
                - Light scattering
            - Other Methods
- Opacity
- Particle Size Distributions
    - Established Techniques
        - Field Measurements
            - Aerodynamic Methods
                - Cascade impactors
                - Cyclones
            - Optical Particle Counters
            - Diffusion Batteries with Condensation Nuclei Counters
            - Electrical Mobility
        - Laboratory Measurements
            - Sedimentation and Elutriation
            - Centrifuges
            - Microscopy
            - Sieves
            - Coulter Counter
    - New Techniques
        - Low Pressure Impactors
        - Impactors with Beta Radiation Attenuation Sensors
        - Cascade Impactors with Piezoelectric Crystal Sensors
        - Virtual Impactors
        - Optical Measurement Techniques
        - Hot Wire Anemometry
        - Large Volume Samplers
- Control Device Evaluation
    - Objectives of Control Device Tests
    - Type and Number of Tests Required
    - General Problems and Considerations
        - Plant Location
        - Laboratory Space
        - Sampling Location and Accessibility
        - Power Requirements
        - Type of Ports
        - Flue Gas Velocity and Nozzle Sizes
        - Duct Size
        - Gas Temperature and Dew Point
        - Water Droplets and Corrosive Gases
        - Volatile Components
        - Process Cycles and Feedstock Variations
        - Long and Short Sampling Times
        - Planning a Field Test

This report has been published as: "Technical Manual: A Survey of Equipment and Methods For Particulate Sampling In Industrial Process Streams," EPA-600/7-78-043, March 1978.

EVALUATION OF THE PILLS IV

The operating characteristics of the PILLS IV in situ particle sizing instrument have been investigated theoretically and experimentally. The results of both types of work show large errors in this instrument's ability to size particles. Attempts to correlate the experimental findings with qualitative theoretical explanations have been successful.

This prototype device is an extension of the PILLS (Particulate Instrumentation by Laser Light Scattering) technology to fine particles designed by Environmental Systems Corporation, Knoxville, Tennessee. It measures particle size using the ratio of intensities of light scattered from a particle at two small angles (14° and 7°) with respect to an incident laser beam. The intensity ratio was chosen as the sizing parameter because of its relative independence of particle refractive index. However, the magnitude of the scattered intensity at 14° is also used for several important decisions in the electronic processing logic, which, for this particular optical system, render it especially sensitive to refractive index and detector variations for the determination of particle size distributions. This investigation established a sensitivity to particle refractive index and detector response that seems to account for the observed characteristics of the instrument. Further measurements would be required to test this explanation quantitatively. Possible solutions to these problems with only minor hardware changes are offered in the published final report entitled "Evaluation of the PILLS IV," EPA-600/7-78-130, July 1978.

CYCLONE AND PRE-IMPACTOR FOR FUGITIVE AMBIENT SAMPLING TRAIN

Under this task Southern Research Institute designed and calibrated the impaction preseparator stage and cyclone collector of the Fugitive Ambient Sampling Train (FAST) developed by The Research Corporation of New England (Project Manager: Mr. Roland Severance).

The FAST system, shown in Figure 17, was designed to operate at a flow rate of approximately 184 ACFM with the impaction stage designed to have a 95% collection efficiency for aerodynamic 15 μm diameter particles and thy cyclone collector designed to have a 50% collection efficiency for 2.5 μm diameter particles.

In order to verify the 95% collection efficiency of the impaction stage, ammonium fluorescein particles with Stokes diameters of 15 μm and 10 μm were sampled. To verify the 50% collection efficiency of the cyclone collector, ammonium fluorescein particles with Stokes diameters of 2 μm and 3 μm were sampled. The impaction stage was initially evaluated with pre-cut glass fiber collection substrates. After this system proved unsuccessful, two tests were performed using a thin grease coating on the bare metal impaction plates.

Figure 18 is a schematic diagram showing the operating principle of the Vibrating Orifice Aerosol Generator (VOAG) used in this study. A solution of known concentration [in our case, a solution of fluorescein ($C_{20}H_{12}O_5$) in 0.1N$_4$NH OH is forced through a small orifice (5, 10, 15, or 20 μm diameter)]. The orifice is attached to piezoelectric ceramic which, under electrical stimulation, will vibrate at a known frequency. This vibration imposes periodic perturbations on the liquid jet causing it to break up into uniformly-sized droplets. Knowing the liquid flow rate and the perturbation frequency, the droplet size can be readily calculated. The solvent evaporates from the droplets leaving the non-volatile solute as a spherical residue. The final dry particle size can be calculated from the droplet size through the known concentration of the liquid solution.

To calculate the dry particle size, the expression

$$d_p = \left(\frac{QC_v}{10\,\pi F}\right)^{1/3}$$ is used,

where C_v is the solution concentration or volume of solute/volume of solution,
Q is the solution flow rate (cm^3/min), and
F is the perturbation frequency (Hz).

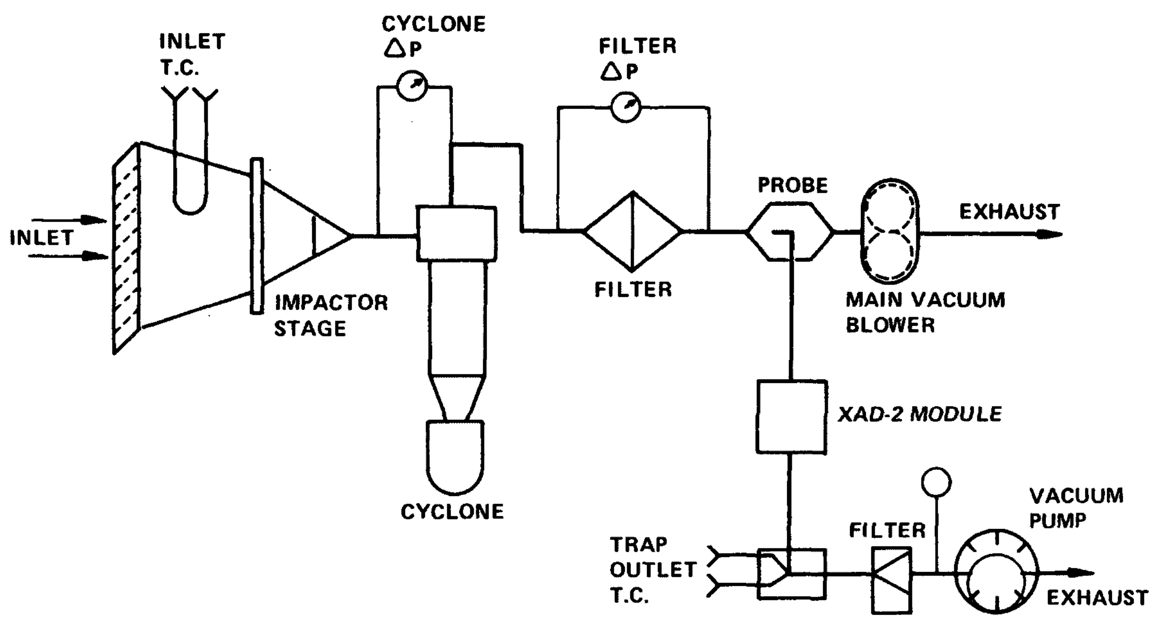


Figure 17. Schematic diagram of Fugitive Ambient Sampling Train.

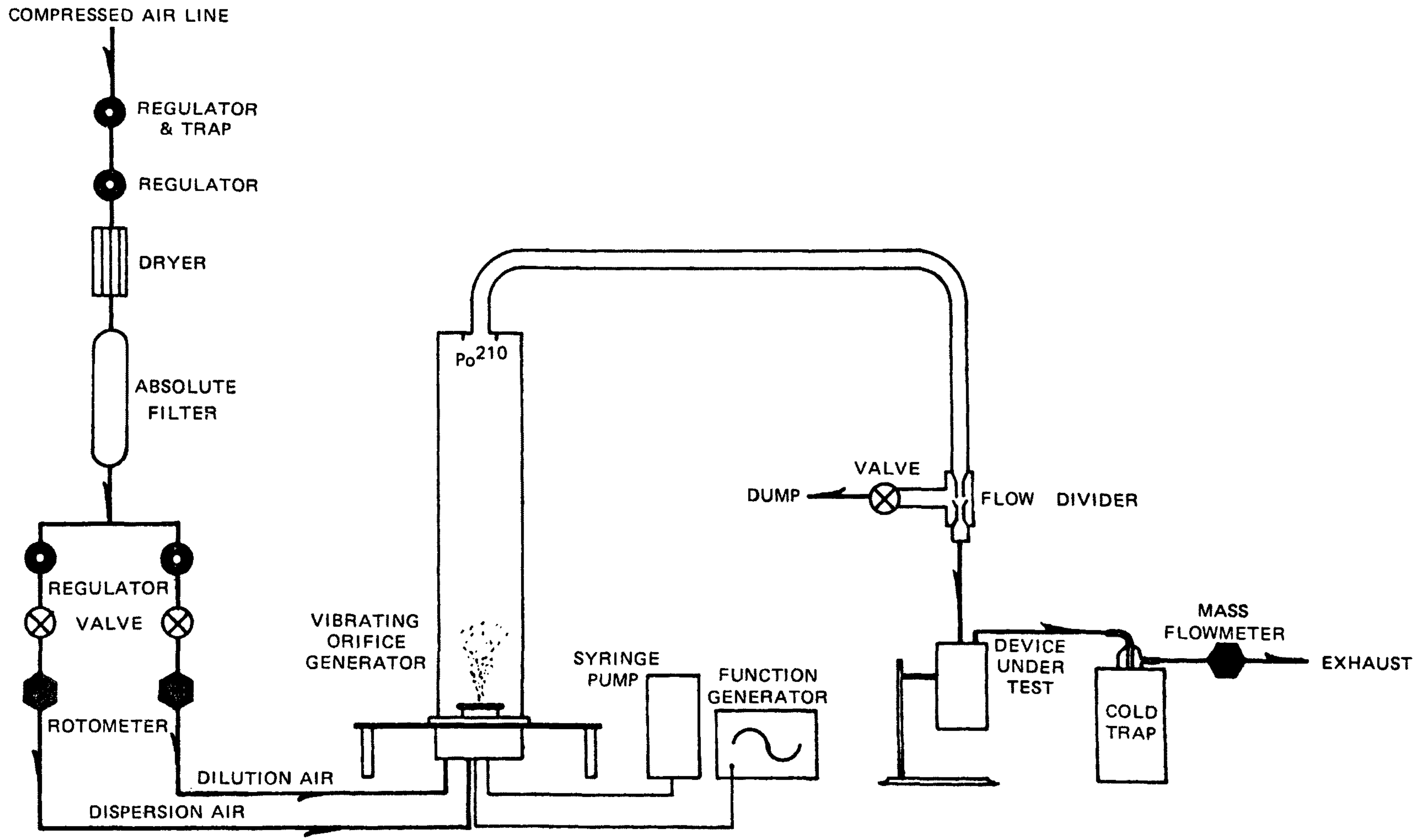


Figure 18. Berglund-Liu type vibrating orifice aerosol generator system.

By the use of smaller orifices, one can obtain much higher operating frequencies. This in turn yields higher particle number concentrations and allows a shorter running time to collect the same mass per stage. The running time must be sufficiently long, however, to allow accurate determination of the collection efficiencies. It was our experience that the 20 μm orifice was consistently easier to use in particle generation, primarily because of fewer clogging problems.

Prior to particle generation the orifices were washed in detergent with ultrasonic agitation and then rinsed several times in distilled water, also with ultrasonic agitation. The aerosol solution is fed from a syringe under pressure provided by a syringe pump. As a final precaution for cleanliness, the syringe is fitted with a filter so that the aerosol solution is filtered before it is transported to the orifice. After the filter and liquid handling system were flushed several times with the aerosol solution to be used, an orifice was placed, still wet with distilled water, or blown dry, into the crystal holder, and the syringe pump was turned on. A jet of air was played over the orifice to keep the surface clean until enough pressure was built up behind the orifice to form a jet.

After a stream of particles was generated, a determination of monodispersity had to be made. Two methods were used to accomplish this. By using a small, well-defined air jet to deflect the stream of particles, it was possible to tell when the aerosol was mono- or polydisperse. Depending on particle size, the stream was deflected by the air at different angles, and if the aerosol was polydisperse, several streams could be seen at one time. By varying the crystal oscillation frequency, the system could be fine-tuned to give only a single deflected particle stream, thus indicating monodispersity. On several occasions, the aerosol tended to drift from monodispersity. To protect against this occurrence, periodic filter samples were taken and checked by optical microscopy. This also provided a good check on the sphericity of the aerosol because the final particles were observed instead of the primary liquid droplets. The microscopy thus served as a check on proper drying, satellites, correct size, and multiplets. Polonium 210 alpha particle sources were placed near the air stream as charge neutralizers to reduce agglomeration and loss of particles due to electrostatic forces. A three-foot-high plexiglass cylinder was placed on the generator and dispersion and dilution air turned on to disperse, dilute and loft the particles. During each test, filter samples were drawn at intervals to insure continued monodispersity. Because of its nonhygroscopicity and physical properties, ammonium fluorescein was used throughout these studies as the test aerosol, although in theory, any material that will dissolve readily in an evaporable solvent could be used. Figure 19 shows one of the test aerosols generated with the VOAG. In general, it was found that about 4% to 8% by mass of the particles were of twice the volume (1.26 x diameter) of the primary particles.

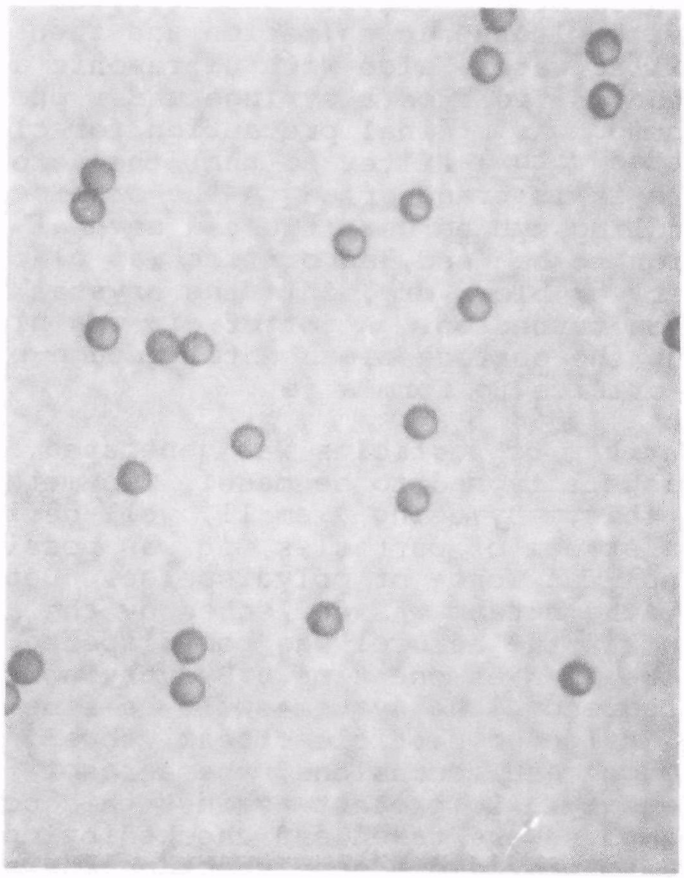


Figure 19. Ammonium fluorescein aerosol particles generated using the vibrating orifice aerosol generator. The particle diameters are 5.4 μm.

When it had been determined that particles of the correct size were being generated, the FAST was allowed to sample from the VOAG outlet for the required length of time to collect a suitable sample. Point sampling was utilized across the face of the louvered FAST inlet. On the majority of the tests the VOAG outlet tube was situated at eighteen different points. Sampling duration at each point ranged from one minute to 60 minutes depending on the particle size being sampled.

At the conclusion of the sampling period, the FAST was carefully disassembled and all surfaces cleaned with a solution of 0.1N NH_4OH. Using a known amount of the solution, each surface was washed to dissolve and rinse off the ammonium fluorescein particles. Where petroleum jelly was used, a small amount of benzene was poured over the greased collection plate in a small dish which was then placed in an ultrasonic cleaner. A small amount of agitation caused the grease to dissolve and the ammonium fluorescein particles to become well mixed. Adding a known abount of 0.1N NH_4OH to the mixture with stirring caused the ammonium fluorescein to dissolve. After the benzene mixture floated to the top of the NH_4OH, the ammonium fluorescein solution was pipetted off.

The quantity of material on each surface was determined by absorption spectroscopy. A Bausch and Lomb Spectronic 88 Spectrophotometer, calibrated with solutions of known concentration of ammonium fluorescein, was used to measure the concentration of ammonium fluorescein in each wash. From knowledge of the amount of wash solution, the dilution factor, if any, and the absolute concentration, the mass of particles on each surface could be calculated. All particles from the Louvers to the Substrates were combined with the Impactor Catch. All particles from the Substrate Support Plate to the Cyclone Cup were combined as the Cyclone Catch. The remaining material was associated with the Filter Catch. This scheme of combining the dust from various parts of the system is based on the manner in which the system will be cleaned after each field test. With the mass on each surface known, the collection efficiencies could be calculated.

During each run the pressure drops across the cyclone, filter, and blower were monitored as were the ambient temperature and pressure. All data from the individual tests and the calculated collection efficiencies are given in Table VII. The efficiency data are plotted in Figure 20. The D_{50} for the cyclone is approximately 2.8 μm aerodynamic diameter. The impactor was not able to achieve the 95% collection efficiency even with a grease layer on the impactor collection plate. Further study will be required to satisfactorily achieve the desired pre-separator performance.

Table VII

FAST IMPACTOR AND CYCLONE CALIBRATION DATA

	15.0 µm Concentration (C) = 3.949×10^{-2}					10 µm C = 1.171×10^{-2}	9 µm C = 8.531×10^{-3}				3 µm C = 3.161×10^{-4}	2 µm C = 9.3662×10^{-3}
Date	6/20-21/78		6/22/78	7/28/78	8/1/78	8/10/78	6/12/78		6/15/78		6/26-30/78	7/20-26/78
Measured Particle Size (µm) (ρ = 1.35 gm/cm^3)	15.75		14.07	15.41	14.72	10.72	10.05		10.72		3.0	2.0
Impactor Substrate Type*	GF		GF	GF	Gr	Gr	GF		GF		GF	GF
$\Delta P_{cyclone}$ (in. H_2O)	3.1		3.0	2.65	2.7	3.0	3.0		3.1		3.15	3.0
ΔP_{filter} (in. H_2O)	22.0		22.0	22.0	22.0	20.0	20.0		22.5		23.4	22.8
ΔP_{system} (in. Hg)	2.3		2.3	2.3	2.2	2.2	2.1		2.3		2.4	2.3
Temperature (°C)	21.0		21.0	21.0	21.0	21.0	20.80		20.26		21.0	21.0
Duration/point (min)	1.0		4.0	4.0	4.0	3.0	3.0		3.0		20.0	60.0
Total Duration (min)	45.0		72.0	72.0	72.0	54.0	54.0		150.0		360.0	18 hrs.
	1st Sample	2nd Sample					1st Sample	2nd Sample	1st Sample	2nd Sample		
Collected Masses (mg)												
Louvres	0.177	0.183	0.081	0.077	0.167	0.089	0.121	0.116	0.143	0.143	0.035	0.019
Screen	0.113	0.116	0.417	0.365	0.446	0.368	1.274	0.821	0.589	0.610	0.332	0.038
Inlet Transform	0.026	0.035	0.119	0.267	0.042	0.071	0.035	0.025	0.010	0.007	0.043	0.025
Impactor Top Plate	0.003	0.000	0.016	0.015	0.005	0.009	0.010	0.010	0.005	0.005	0.003	0.003
Jet Plate	0.043	0.054	0.083	0.060	0.022	0.015	0.034	0.034	0.021	0.017	0.062	0.025
Substrates	0.459	0.469	2.192	1.800	6.766	5.709	0.565	0.525	5.640	5.925	0.100	0.017
Substrate Support Plate	0.012	0.012	0.188	0.077	0.066	0.026	0.038	0.038	0.030	0.039	0.187	0.034
Cyclone Inlet Transform	0.032	0.023	0.345	0.237	0.125	0.041	0.055	0.049	0.048	0.042	0.137	0.043
Cyclone (Top)	0.133	0.144	0.684	0.390	0.419	0.108	0.077	0.069	0.284	0.280	0.494	0.072
Cyclone (Body)	0.239	0.265	0.862	3.511	1.190	0.226	0.252	0.245	0.889	0.880	3.695	0.425
Catch Cup	0.337	0.342	3.915	0.713	1.884	0.159	0.121	0.120	0.958	0.958	3.353	0.756
Cyclone Outlet Tube	0.012	0.011	0.023	0.627	0.045	0.016	0.044	0.033	0.049	0.055	3.059	0.536
Filter Transform	0.008	0.004	0.009	0.022	0.019	0.006	0.018	0.011	0.028	0.034	0.132	0.202
Filter	0.046	0.040	0.033	0.499	0.043	0.016	0.153	0.130	0.124	0.118	1.488	2.280
Total Mass	1.640	1.698	8.967	8.660	11.239	6.859	2.797	2.226	8.818	9.113	13.120	4.475
Impactor % Collection Efficiency	50.1	50.5	32.4	29.8	66.3	91.3	72.9	68.8	72.7	73.6	4.4	2.8
Cyclone % Collection Efficiency	91.9	93.5	98.9	81.1	97.2	93.6	71.6	75.0	91.7	91.4	62.7	30.6

*GF = Glass Fiber; Gr = Greased (Vaseline and Toluene)

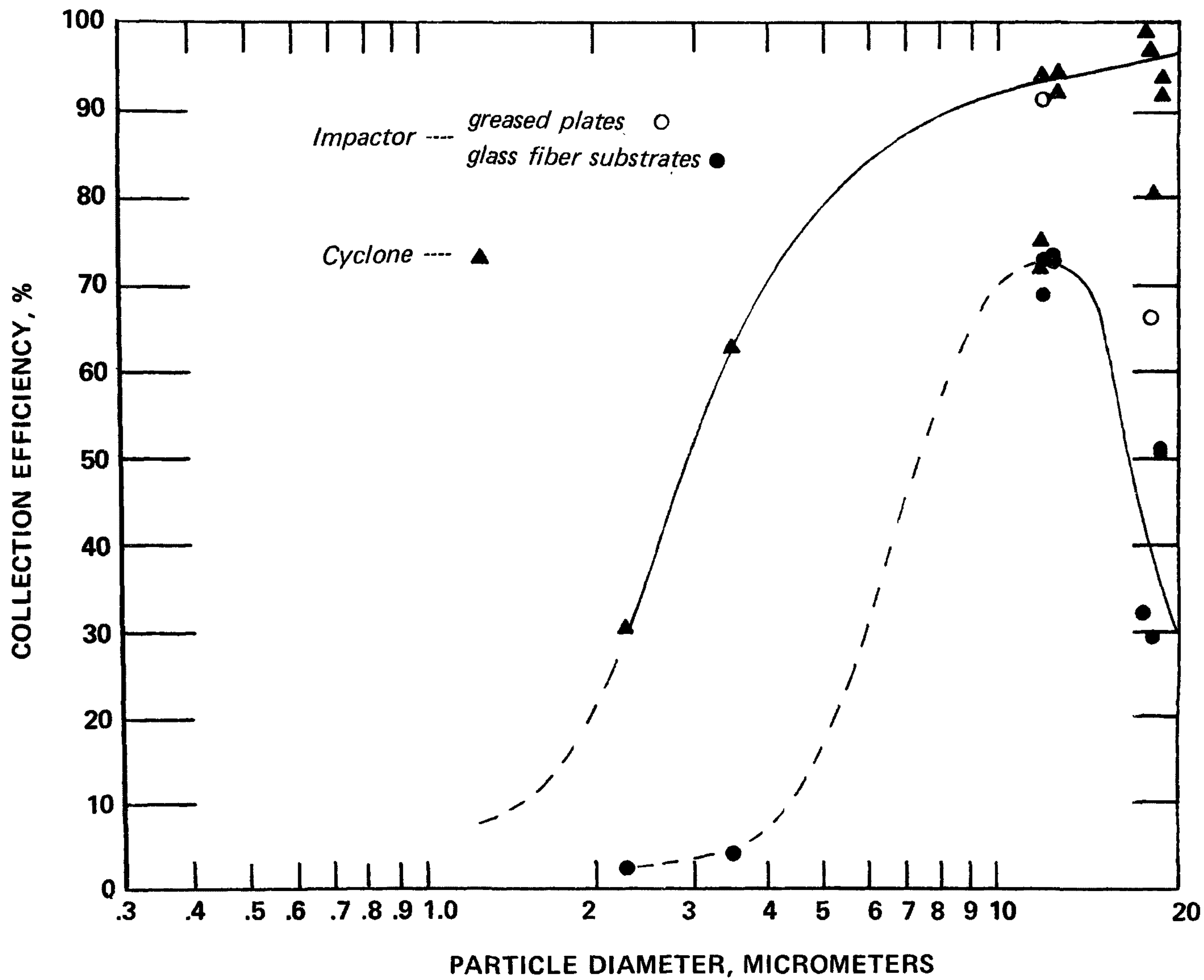


Figure 20. Collection efficiency versus particle diameter for the Fugitive Assessment Sampling Train pre-separator impactor and cyclone.

DESIGN, CONSTRUCT, AND EVALUATE OPTIMIZED CASCADE IMPACTORS

Based on the current knowledge of impactor operation theory and the results of field and laboratory testing of currently available commercial and prototype cascade impactors by Southern Research Institute, high and low flow rate impactors are being designed which will attempt to meet the criteria for optimized cascade impactors. An optimized cascade impactor can be defined as one which is designed to operate both in a laboratory and field environment in such a way that the effects of particle bounce, reentrainment, wall loss, non step function collection efficiency curves, etc., are minimized. Mechanical reliability and ease of operation are also to be considered in the design of these impactors. Our criteria for optimized cascade impactors are listed in Table VIII.

Design parameters for the 0.1, 0.5, and 2.0 ACFM, optimized, cascade impactors have been generated by a special computer program written at Southern Research Institute. Six impaction stages with cut points of 9.6, 4.8, 2.4, 1.2, 0.6, and 0.3 micrometers aerodynamic diameter were chosed as a design goal for these cascade impactors. The actual theoretical stage D_{50}'s as calculated by the computer program were very close to the desired stage cut points. Identical stage cut points were not realized because there was neither an unlimited number of holes per stage available, nor an infinite range of drill sizes. The final design parameters are presented in Tables IX, X, and XI. An assembly drawing of the 0.5 ACFM impactor is shown in Figure 21.

A prototype of the 0.5 ACFM optimized cascade impactor is to be fabricated by Southern Research Institute for calibration and testing purposes.

TABLE VIII. CRITERIA FOR IMPACTOR DESIGN

1. The jet Reynolds number should be between 100 and 3000.
2. The jet velocity should be 10 times greater than the settling velocity of particles having the stage D_{50}.
3. The jet velocity should be less than 110 m/sec.
4. The jet diameter should not be smaller than can be attained by conventional machining technology.
5. The ratio of the jet-plate spacing and the jet diameter or width (S/W) should lie between 1 and 3.
6. The ratio of the jet throat length to the jet diameter (T/W) should be approximately equal to unity.
7. The jet entries should be streamlined or countersunk.

Table IX
OPTIMIZED IMPACTOR DESIGN SPECIFICATIONS

Impactor Sampling Rate = 0.1 ACFM   Gas Temperature = 204.0°C   Particle Density = 1.0 gm/cc

	Initial Cut Point Guess (μm)					
Initial Guess of Stage D_{50}	9.6	4.8	2.4	1.2	0.6	0.3
Jet Inlet Pressure (atm)	0.987	0.986	0.985	0.975	0.953	0.921
Best Jet Drill Diameter (cm)	0.47	0.30	0.19	0.098	0.0254	0.0254
Number of Jets on this Stage	1	1	1	2	31	19
Actual Jet Reynolds Number	362.6	568.0	895.3	859.2	209.0	396.9
Jet Velocity (m/sec)	2.72	6.68	16.65	31.29	30.05	71.05
Actual Square Root of Stokes #	0.478	0.476	0.475	0.475	0.480	0.477
Cunningham Slip Correction Factor	1.017	1.034	1.070	1.145	1.297	1.777
Theoretical Stage D_{50} (μm)	9.474	4.776	2.359	1.195	0.589	0.297

Table X
OPTIMIZED IMPACTOR DESIGN SPECIFICATIONS

Impactor Sampling Rate = 0.5 ACFM　　Gas Temperature = 204.0°C　　Particle Density = 1.0 gm/cc

	Initial Cut Point Guess (μm)					
Initial Guess of Stage D_{50}	9.6	4.8	2.4	1.2	0.6	0.3
Jet Inlet Pressure (atm.)	0.987	0.986	0.981	0.970	0.931	0.901
Best Jet Drill Diameter (cm)	0.794	0.518	0.206	0.107	0.025	0.016
Number of Jets on this Stage	1	1	4	8	155	235
Actual Jet Reynolds Number	1073.6	1643.4	1030.1	981.5	204.4	206.9
Jet Velocity (m/sec)	4.77	11.19	17.75	32.99	30.05	49.95
Actual Square Root of Stokes #	0.474	0.471	0.474	0.474	0.480	0.480
Cunningham Slip Correction Factor	1.017	1.035	1.070	1.146	1.304	1.707
Theoretical Stage D_{50} (μm)	9.221	4.797	2.372	1.212	0.588	0.316

Table XI
OPTIMIZED IMPACTOR DESIGN SPECIFICATIONS

Impactor Sampling Rate = 2.0 ACFM | Gas Temperature = 204.0°C. | Particle Density = 1.0 gm/cc

	Initial Cut Point Guess (μm)					
Initial Guess of Stage D_{50}	9.6	4.8	2.4	1.2	0.6	0.3
Jet Inlet Pressure (atm.)	0.987	0.986	0.983	0.973	0.934	0.849
Best Jet Drill Diameter (cm)	0.794	0.404	0.206	0.107	0.045	0.022
Numberof Jets on this Stage	4	8	17	32	119	355
Actual Jet Reynolds Number	1073.6	1054.1	971.0	984.3	602.5	375.6
Jet Velocity (m/sec)	4.77	9.21	16.71	32.99	49.88	69.95
Actual Square Root of Stokes #	0.474	0.474	0.474	0.474	0.476	0.478
Cunningham Slip Correction Factor	1.017	1.035	1.070	1.145	1.324	1.844
Theoretical Stage D_{50} (μm)	9.221	4.694	2.448	1.212	0.598	0.300

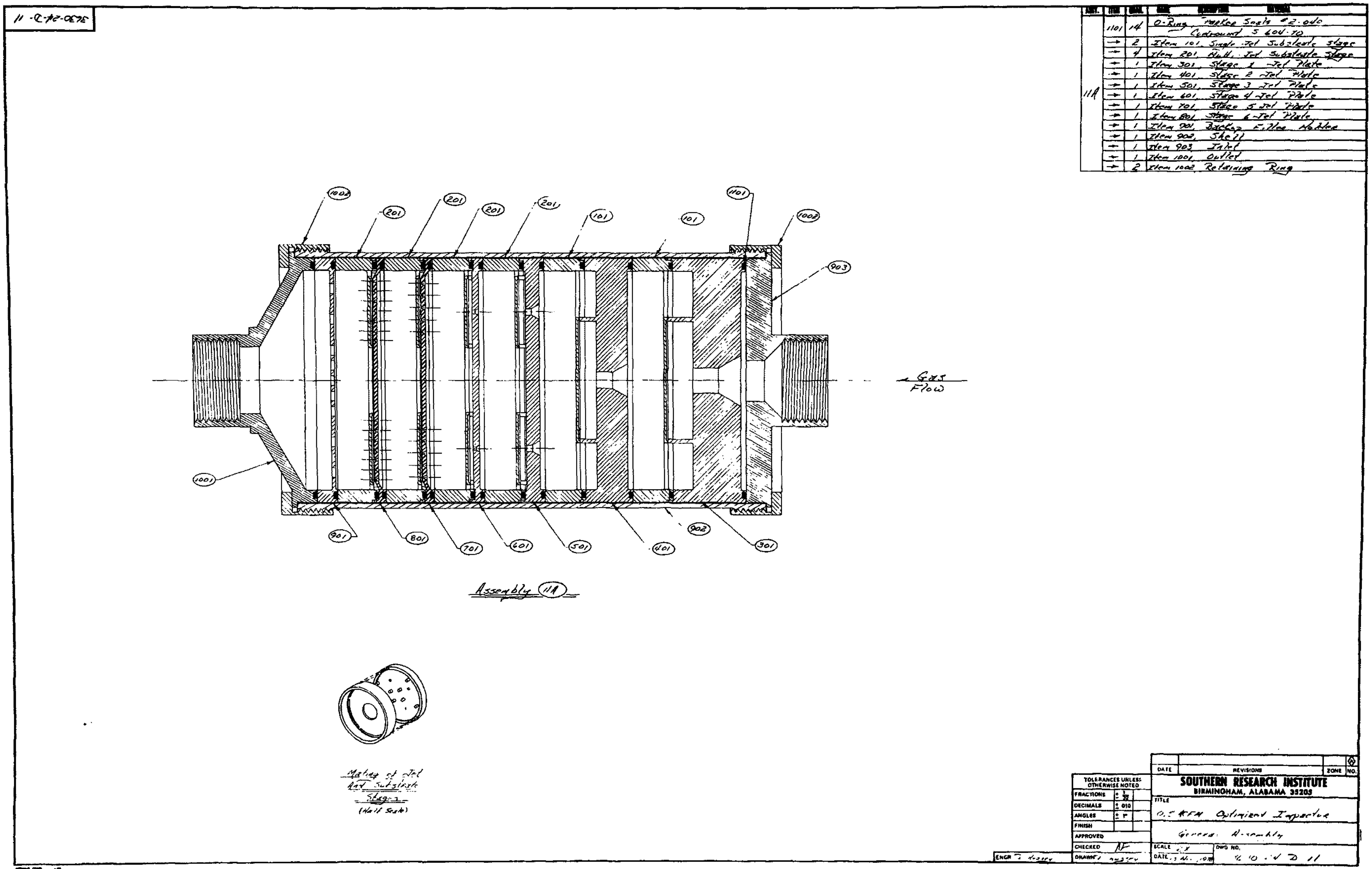


Figure 21. Assembly drawing of 0.5 ACFM optimized cascade impactor.

DESIGN A HIGH TEMPERATURE TEST FACILITY

A particle sampling test facility has been designed. An engineering drawing of the proposed test facility is shown in Figure 22.

The facility will be used to simulate the behavior of various process streams. Gas temperatures will be variable between ambient and 500°C (932°F). Duct pressure will be variable from 0.7 atm to 1.0 atm, and gas velocity will be adjustable from 1.5 m/sec (5 ft/sec) to 15 m/sec (50 ft/sec). This range of velocities is adequate to simulate most process streams. A velocity range was chosen which is representative of many process streams, and a duct size was chosen which would keep the size and cost of piping within reason, but not lead to any objectionable blockage of the duct by any of the devices to be tested. A diameter of 30 cm (12 inches) was chosen. This gives a resulting gas volume flow from 0.11 m^3/sec (232 cfm) to 1.1 m^3/sec (2320 cfm).

In order to have a low pressure system without excessive pumping capacity, a closed loop system was selected. However, with a closed circuit, the dust must be removed after each circuit so that control can be maintained over the test aerosol. Since a bag collector will be used, the temperature must be reduced from the 540°C maximum test temperature to a feasible operation temperature for the collector, about 260°C (500°F). A cooler to cool down to 260°C plus a heater to heat up to 540°C would be expensive to operate. Therefore, an air-to-air shell-and-tube heat exchanger was chosen to cool the air down to 260°C and then to heat it back up again to 455°C. A temperature difference of about 85°C is needed to establish good heat flow. If too much insulation were used on the fan and filter piping, there would be too low a temperature difference, and the gas would not be cooled enough for the survival of the filter bags. Thus, it will be necessary to install the insulation on a trial basis, gradually increasing the insulation to minimize the required reheat while making sure that the bag temperature does not exceed 260°C.

The size of the wind tunnel has been dictated by the size of the apparatus to be tested. The largest presently used probe is about 10.2 cm (four inches) in diameter; and if inserted into a 30.5 cm diameter pipe to 5 cm beyond the centerline, the probe will obscure 27% of the open area. It is expected that impactors and cyclones would obscure a much smaller area. The required velocity times the area of the test section gives the total volume of gas for determining the size and cost of piping and ancillary equipment.

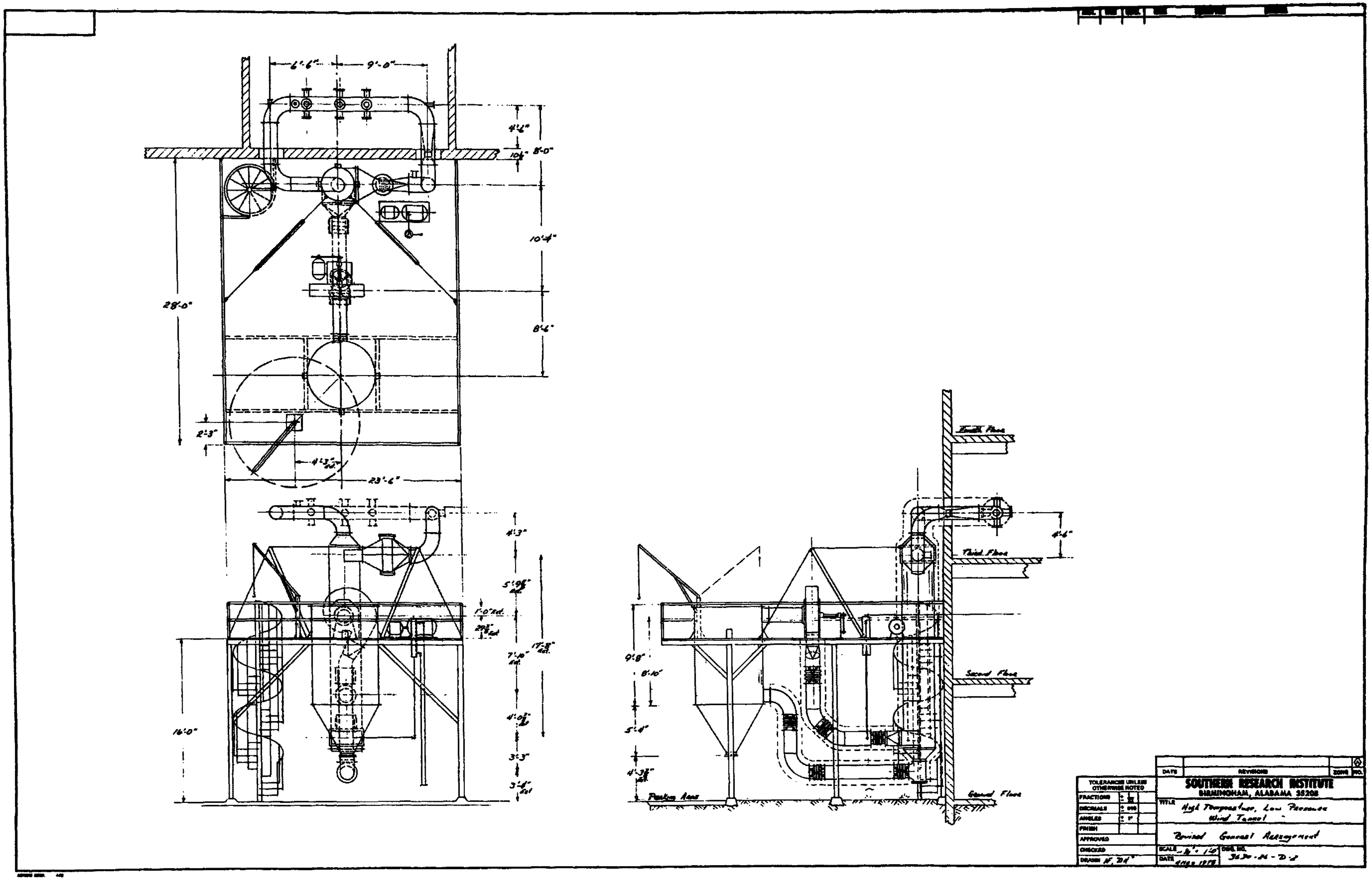


Figure 22. Preliminary layout for high temperature, low pressure wind tunnel test facility.

It will be necessary to provide sufficient strength in all components to withstand 0.35 kilogram per square centimeter of negative pressure. Therefore, a cylindrical heat exchanger and cylindrical bag collector with reinforced top cover will be required. The circulating fan housing must be stiffened, and the fan provided with a shaft seal good for 260°C and 0.35 kg/cm^2.

Thermal expansion of the materials of construction must be accommodated by either motion or stress. Flexible expansion joints would have to be anchored solidly against the 0.35 kg/cm^2 suction forces, or solidly joined members would have to be anchored against extremely high expansion forces. To reduce the magnitude of such forces, the design provides for a symmetrically overhung, high temperature test section in which the expansions either tend to compensate, or merely expand out into unrestrained space as a cantilever beam. The overhung, cantilevered weight is restrained by two guy wires with turnbuckles. These guys are supported by struts to bring the angle of the wires perpendicular to the direction of expansion so that negligible changes in alignment will occur.

The thermal expansion of the connecting piping is accommodated by using hinge type expansion joints which permit a hinge action in one plane without any axial change due to pressure or vacuum. Three such joints in a run of pipe are the equivalent of a three hinged arch, which is statically determinate and has zero built-in stress.

The circulating fan will be solidly joined to the piping from the dust collector, and the base will be mounted on sliding pads of oil impregnated sintered bronze positioned to slide parallel to the piping between the dust collector and fan.

Because the volumetric efficiency of a vacuum pump is reduced by high temperature, low density gas, a water jacketed cooler will be used between the hot circulating loop and the vacuum pump. Simple coolers for air compressors are commercially available. The vacuum pump itself should be protected against high temperatures resulting from cooling water failure, and from dust carryover from torn bags, or from bag changing operations. Therefore, a fluid piston Nash vacuum pump was selected to meet the above fail-safe conditions. Because the vapor pressure of water is a half an atmosphere at 82°C, water cannot be used as a compressant fluid. Therefore, a recirculated and cooled oil will be used as a compressant fluid.

The heat exchanger, fan, dust collector, and vacuum pump are bulky pieces of equipment and do not need to be inside the building. We therefore chose to pierce the building wall in a third floor laboratory and to locate everything except the test section on a structural steel platform outside. We selected a spiral access stairway because a ladder is less safe and a zig zag stairway requires more space. A manual full circle winch crane of 455 kg (1000 lb) capacity is included for lifting the covers off the dust collector and for raising miscellaneous material to the platform.

The test section is furnished with 15 cm (6 inch) pipe flanged access ports about 4, 6, and 8 diameters downstream from the dust injection point. Ports are arranged on all four sides so that equipment may be mounted either horizontally, vertically, or through, (as for obscurometers or for Schlieren photography).

The SoRI PDP 11/34A Minicomputer Based Data Acquisition System will be used for digital display of the operating conditions of the components of the facility as well as control of the system.

The conditions to be monitored are:

1. test section gas temperature;
2. test section pressure;
3. test section gas flow rate (using a venturi meter);
4. temperature of the device under test;
5. pressure drop across the device under test;
6. gas flow through the device under test;
7. gas temperature at the inlet to the bag house;
8. pressure drop across the bag house;
9. gas temperature at the outlet of the heater; and,
10. gas temperature at the inlet of the vacuum pump.

Provisions will be made for multipoint injection of a test aerosol generated by dispersion of dry powder, nebulization, and high output generators of monodisperse aerosols. Care will be taken in design of the injection system to insure an even distribution of the test aerosol through the test section of the facility. Included in the available equipment are:

1. Climet Model 208 Particle Size Analyser modified for operation to 0.3 μm;

2. Royco Model 225 Particle Size Analyser;

3. a large particle dilution system;

4. a small particle dilution system;

5. Nuclear Data Model ND60 Multichannel Analyser for use with the above particle counters;

6. Lear Siegler Model RM41P Transmissometer;

7. Thermo Systems Model 3030 Fine Particle Electrical Aerosol Analyser; and,

8. Environment One Model Rich 100 Condensation Nuclei Counter with diffusion batteries.

All control and monitoring equipment will be designed for interfacing with a laboratory computer system.

A MASSIVE VOLUME SAMPLER FOR HEALTH EFFECTS STUDIES

Today, there is a critical need for information pertaining to the health effects of the particulate pollution emitted from emerging alternative energy sources. These data are obtained from bioassay and animal inhalation studies conducted with samples of these particulate emissions. The extended time periods needed to perform these studies requires large particulate samples. The purpose of this task was to design, fabricate, and test a sampling system which would collect large particulate samples in relatively short time periods. In order to meet this objective a sampling rate of 340 Nm^3/hr (200 SCFM) was chosen. Task requirements also demanded that the sampler also separate the sample into two size fractions, a coarse fraction and a fine fraction. This necessitated a two stage sampler design. Minimization of wall loss deposition at other locations within the system was also an important consideration.

The ultimate goal of this task was that the particle size distribution and biological impact of the collected sample should be an accurate representation of the particulate emissions produced by the energy source. Fulfilling the particle size distribution aspect necessitated building a traversing sampler capable of near isokinetic sampling. Accomplishing the biological impact goal required a sampler that would prevent or minimize contamination of the sample. This was accomplished by maintaining flue gas temperatures in the sampler thus eliminating condensation of organic and inorganic vapors in the gas stream. Also special materials for construction were used to minimize sample contamination on the walls of the sampler. Since the device would be used at various sites, the sampler had to be built to make it readily movable from site to site and conveniently adaptable to different site conditions.

The prototype system (see Figure 23) consists of a probe, a cyclone dust collector, fabric filter, flowmeter, blower, and sampling/interconnecting line.

The probe is 2.1 m (7 ft.) long and possesses an adjustable opening at its insertion end to establish isokinetic sampling. The probe is capable of traversing and although it is designed for a 9 cm (4") nominal port, it can be easily adapted to larger ports.

A Fisher-Klosterman XQ-5 cyclone with a calibrated cut point at 50% efficiency of 2.5 micrometers aerodynamic diameter at 340 Nm^3/hr (200 SCFM) is the initial particle collector. The cyclone with its heated enclosure measures approximately 2.1 m H x 0.6 m W x 0.6 m L (6' H x 2' W x 2' L) and weighs 91 kg (200 lbs).

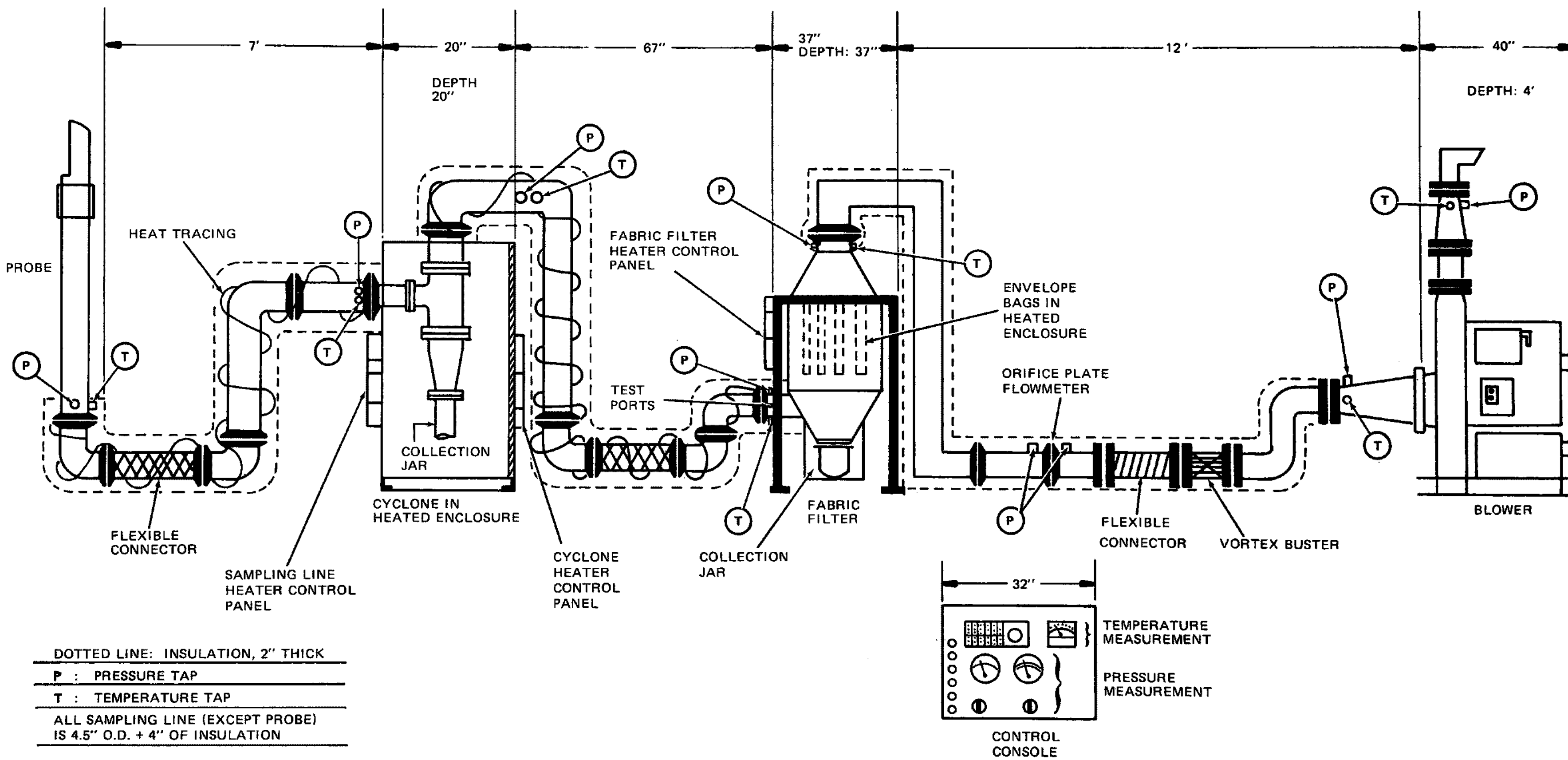


Figure 23. Schematic diagram of massive volume sampler for Health Effects Studies.

Immediately following the cyclone is a single chamber fabric filter. Its dimensions are approximately 2.1 m H x 0.9 m W x 0.9 m L (7' H x 3' W x 3' L) and its mass is 113 kg (250 lbs). It can accommodate from 1 to 20 envelope bags. The filtration surface of the bags is composed of Gore-Tex porous teflon laminate; the filtration surface is backed by Nomex. Each bag contributes 0.5 m^2 (5.0 ft^2) of collection surface. The fabric filter is equipped with a manual shaker and can be easily modified to become a double chambered, automatic shaker design.

The flowmeter is an orifice plate type meter which is used to monitor the 340 Nm^3/hr (200 SCFM) flow rate selected for the sampler. This 340 Nm^3/hr (200 SCFM) flow rate must be stable in order to maintain the 2.5 μm D_{50} of the cyclone. A hand operated damper attached to the outlet of the blower is used to adjust the flow rate. At this flow rate the sampler requires about 2½ days of continuous sampling in order to collect 1 kilogram of particulate matter from the outlet of an efficient control device with a particulate mass concentration of 0.05 grams/Nm^3 (0.2 gr/Nft^3).

The blower is a centrifugal pressure blower powered by a 3ϕ, 7½ HP motor. The blower is approximately 1.5 m H x 0.9 m W x 0.6 m L (5' H x 3' W x 2' L) and has a mass of approximately 453 kg (1000 lbs).

Condensation was minimized by heat tracing the entire sampler from the probe to the outlet of the fabric filter. Interaction between the sample and interior surfaces of the sampler was minimized by fabricating all these surfaces from either 304 or 316 stainless steel, teflon or glass.

Heating is controlled from three heater control panels; each panel handling a separate heater load, i.e. sampling/interconnecting line, cyclone and fabric filter loads. The individual heaters can be hooked up in any arrangement to accommodate different sampling site voltages and heating requirements. The usual total heater load is 5000 watts.

The sampling/interconnecting line is 9 cm (4") nominal pipe. This size was chosen so that additional lengths of pipe could be used when required without introducing excessive pressure drops. Both the cyclone and fabric filter have take-offs which bring the inlet and outlet of each device to ground level. This will enable the individual devices to be placed at various distances from each other simply by the insertion of additional horizontal pipe sections. The total length of the assembled sampler when it is set up in a straight line is approximately 9.5 meters (31 feet). This distance can be considerably shortened by using a different interconnecting line and device arrangement.

Provisions exist to monitor both the temperature and pressure at the probe and at the inlet and outlet of the cyclone, fabric filter and blower.

Design operating temperature of the sampler is 204°C (400°F). Use of the sampler between the temperatures of 204°C (400°F) and 316°C (600°F) may be possible. This would depend on the effects of such temperatures on the sealing integrity of the teflon gaskets, and the degree of degradation experienced by the fabric filter bag material. Other factors subject to the temperature of the gas stream are the magnitude of the pressure drop presented to the blower (the static pressure available from the blower decreases with increasing temperature), and the heating load placed on the heaters.

The construction of this sampler has been completed and initial field tests will take place early in 1979.

CALIBRATION OF SOURCE TEST CASCADE IMPACTORS

To the user of an inertial cascade impactor the most important consideration is the degree to which the data obtained will duplicate the actual particle size distribution sampled. In order to transform the mass collected by several impaction stages into a size distribution, an accurate knowledge of the relationship between collection efficiency and particle size for each stage is essential.

The impaction efficiency of a jet-plate system is defined as the fraction of particles of a certain size in the jet that impact on the collection plate. The collection efficiency of an impactor stage, however, is the ratio of the mass (or number) of particles of a certain size collected on an impaction surface to the total mass (or number) of particles of the same size in a jet impinging on that surface. The collection efficiency is the product of the impaction efficiency and the adhesion efficiency.[5] The adhesion efficiency is the fraction of the number of particles that adhere to the surface after touching it by the impaction process, depending mainly on the surface characteristics of the particle and the collection surface. Thus, there is disagreement between the theoretical impaction efficiency and the experimentally determined collection efficiency in the cases where particle bounce, reentrainment, electrostatic effects, wall losses, and non-ideal geometry have an effect. For this reason, the theory of impaction may not be sufficiently accurate in predicting impactor performance.

The theory of the impaction process has been developed by several researchers[18,19] to a state where the efficiency, E, of impaction can be estimated as a function of the particle size (D_p), Reynolds Number (Re), the jet diameter or width (D_j,W), the jet to plate distance (S), and the jet throat length (T). (Marple[19] specifically uses the dimensionless reduced quantities (D/D_j, S/W) and (T/D_j, T/W) when considering the jet to plate distance and the jet throat length, respectively.)

$$E = E\ (D_p,\ Re,\ S/D_j.\ T/D_j) \qquad (1)$$

It is common practice to relate the particle diameter D_p to the square root of the inertial impaction parameter ($\sqrt{\psi}$), which is the ratio of the particle stopping distance (ℓ) to the jet diameter or width (D_j or W). Thus,

$$\psi = \ell/D_j$$

or

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

where C = Slip Correction Factor,
V_o = Jet Velocity (cm/sec),
μ = Gas Viscosity (poise),
ρ_p = Particle Density (gm/cm^3), and
D_j = Jet Diameter (cm).

The square root of the inertial impaction parameter, $\sqrt{\psi}$, is used in impaction theories as a dimensionless quantity proportional to particle diameter,

$$\sqrt{\psi} = D_p \left[\frac{C \rho_p V_o}{18 \mu D_j}\right]^{1/2} \qquad (3)$$

The inertial impaction parameter is useful in graphing impactor calibration data because information from all stages of an impactor can be placed on a single graph, and under many circumstances would, in theory, lie along a common curve. The value of $\sqrt{\psi}$ at 50% collection efficiency, $\sqrt{\psi_{50}}$, defines the impaction stage D_{50}, which is the particle diameter for which half of the particles are collected and half are passed to the next stage. In data reduction the D_{50} is used as the effective stage cut diameter.

Recently Marple[19] has been able to calculate theoretical impaction efficiency curves for several values of the jet to plate distance, jet Reynolds Number, and jet throat length. Figure 24 shows the results of these calculations for both round and rectangular jet impactors. It can be seen from Figure 24 that for certain ranges of jet to plate spacing, Reynolds Number, or jet throat lengths, the magnitude of $\sqrt{\psi_{50}}$ is sensitive to these parameters.

In this study five source-test cascade impactors, all of which are commercially available in the United States, have been calibrated using monodisperse aerosols in order to determine both their inertial sizing parameters and wall losses as a function of particle size.

A Vibrating Orifice Aerosol Generator was used to produce monodisperse ammonium fluorescein aerosol particles 18 micrometers to one micrometer in diameter. A Pressurized Collison Nebulizer System was used to disperse Polystyrene Latex (PSL) and Polyvinyltoluene Latex (PVTL) Spheres 2.02 micrometers to 0.46 micrometer in diameter.

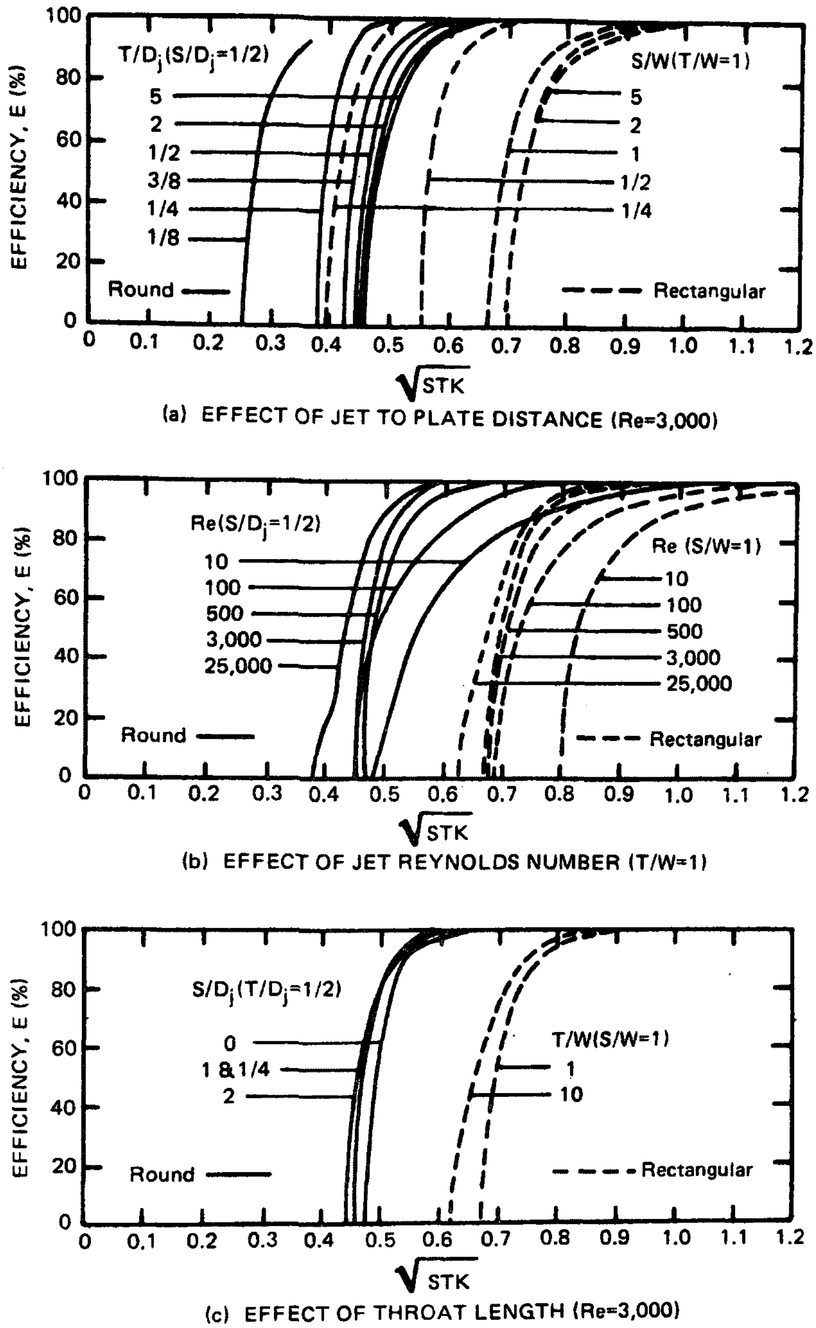


Figure 24. Theoretical impactor efficiency curves for rectangular and round impactors showing the effect of jet-to-plate distance S, Reynolds number Re, and throat length T. Note that $\sqrt{STK} = D_p(C\rho_p V_0/9\ \mu D_j)^{1/2}$, whereas $\sqrt{\psi} = D_p(C\rho_p V_0/18\ \mu D_j)^{1/2}$. After Marple.[19]

The impactors tested and their manufacturers are:

1. Andersen Mark III Stack Sampler (Andersen)
   Andersen Sampler, Inc.
   Atlanta, Georgia 30336

2. Brink Model BMS-11 Cascade Impactor (Brink)
   Zoltek, Inc.
   St. Louis, Missouri 63166

3. MRI Model 1502 Inertial Cascade Impactor (MRI)
   Meteorology Research, Inc.
   Altadena, California 91001

4. Sierra Model 226 Source Cascade Impactor (Sierra)
   Sierra Instruments, Inc.
   Carmel Valley, California 93924

5. University of Washington Mark III Source Test
   Cascade Impactor (U. of W.)
   Pollution Control Systems, Inc.
   Renton, Washington 98055

The 5-stage Brink Impactor was modified to include an in-line cyclone pre-collector, a "0" stage, and a "6" stage.

The Andersen impactor was used with glass fiber collection substrates supplied by the manufacturer. For the Brink impactor a small disc of glass fiber material was used as a substrate as well as a thin grease layer (petroleum jelly). The MRI and U. of W. impactors were tested with thin films of grease (Petroleum jelly) on the collection plates. The Sierra was operated with pre-cut glass fiber mats, supplied by the manufacturer.

Results were reported showing stage collection efficiencies versus the square root of the inertial impaction parameter, ψ, (see Figures 25 through 31) and impactor wall losses versus particle size (see Figure 32).

Based on this work, several conclusions can be drawn.

1. The value of $\sqrt{\psi_{50}}$ for each stage of a multiple stage impactor may be different. (It has been the practice of many cascade impactor manufacturers and users to assume that the value of $\sqrt{\psi_{50}}$ for every stage was identical. In many cases the experimental value determined by Ranz and Wong[18] was used.)

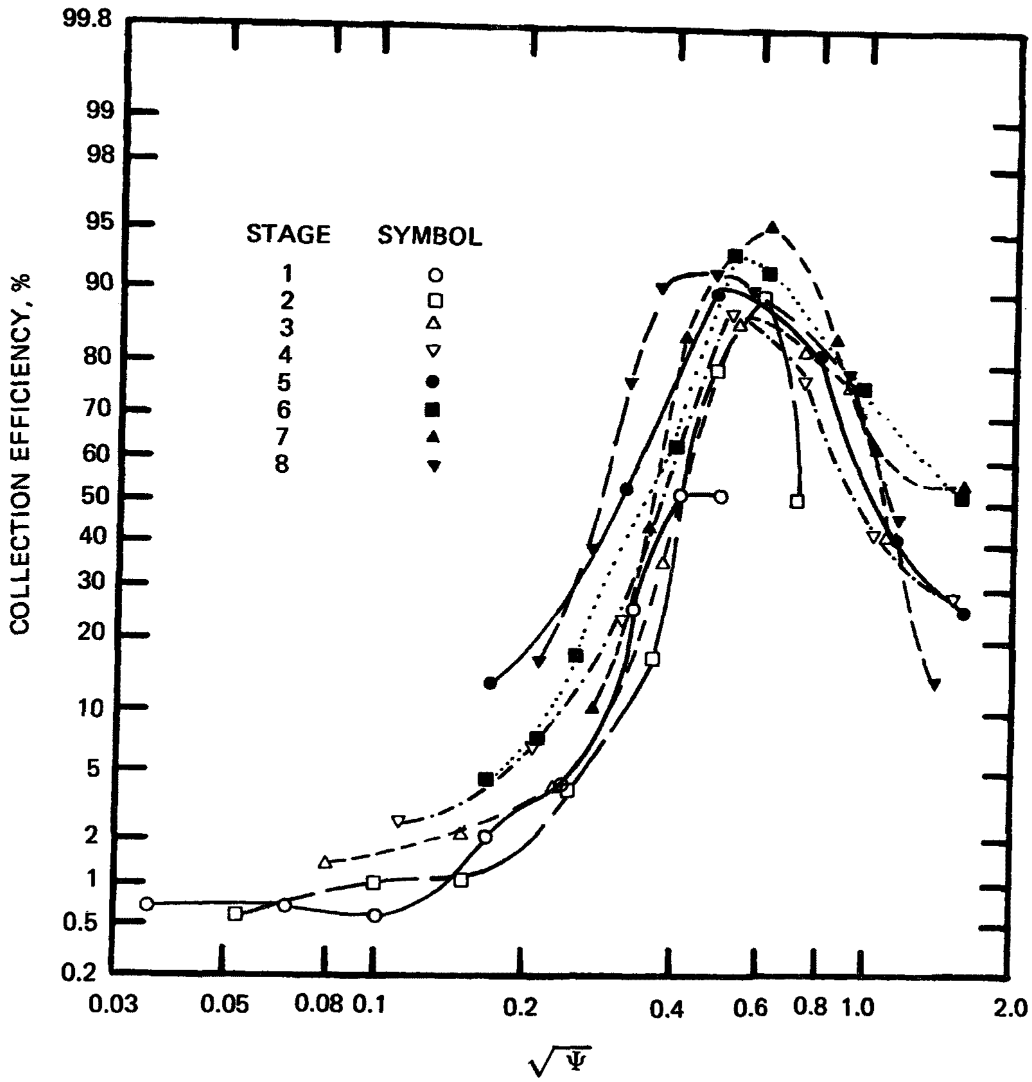


Figure 25. Collection efficiency vs. $\sqrt{\psi}$. Andersen Mark III stack sampler with glass fiber collection substrates.

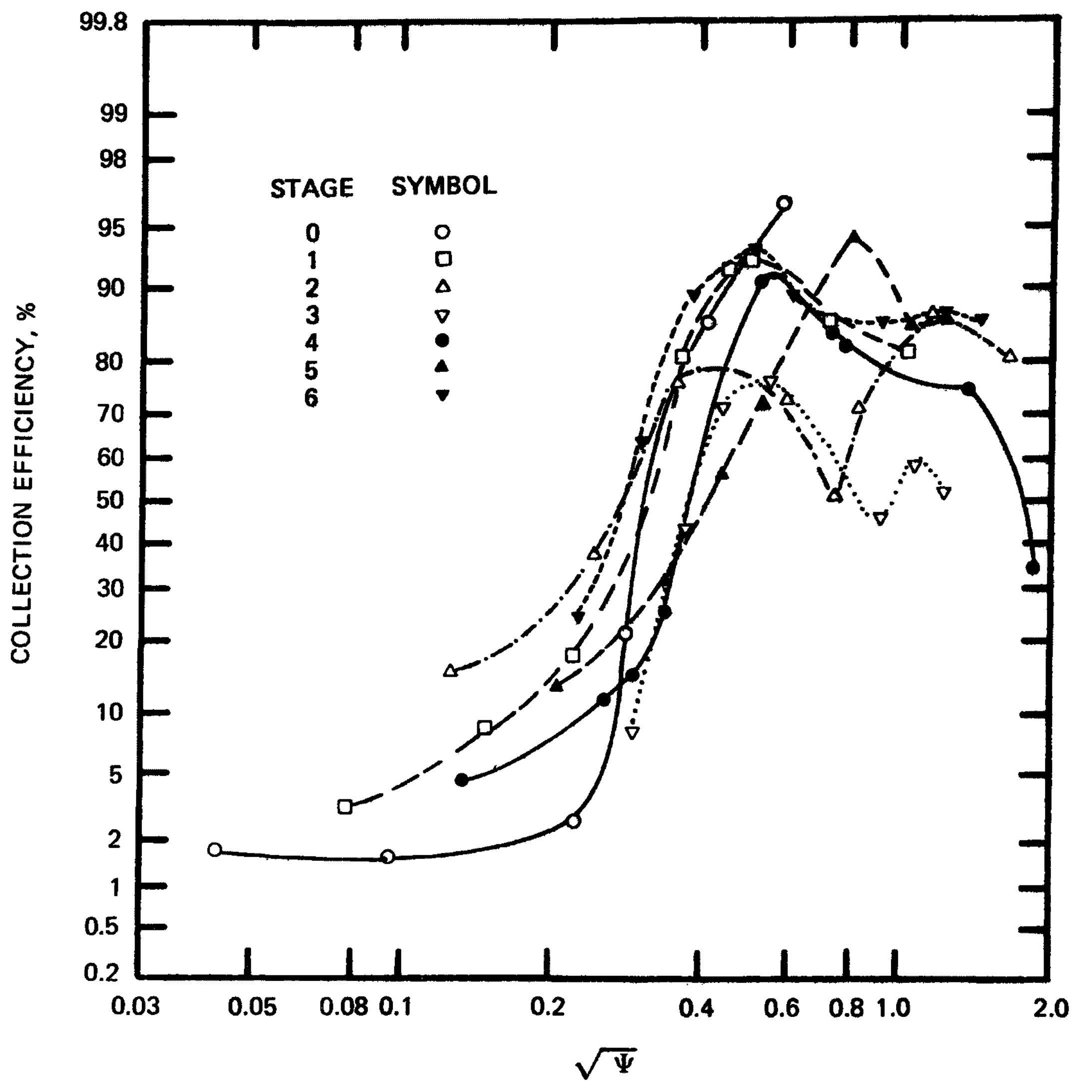


Figure 26. Collection efficiency vs. $\sqrt{\psi}$. Brink Model BMS-11 cascade impactor with glass fiber collection substrates.

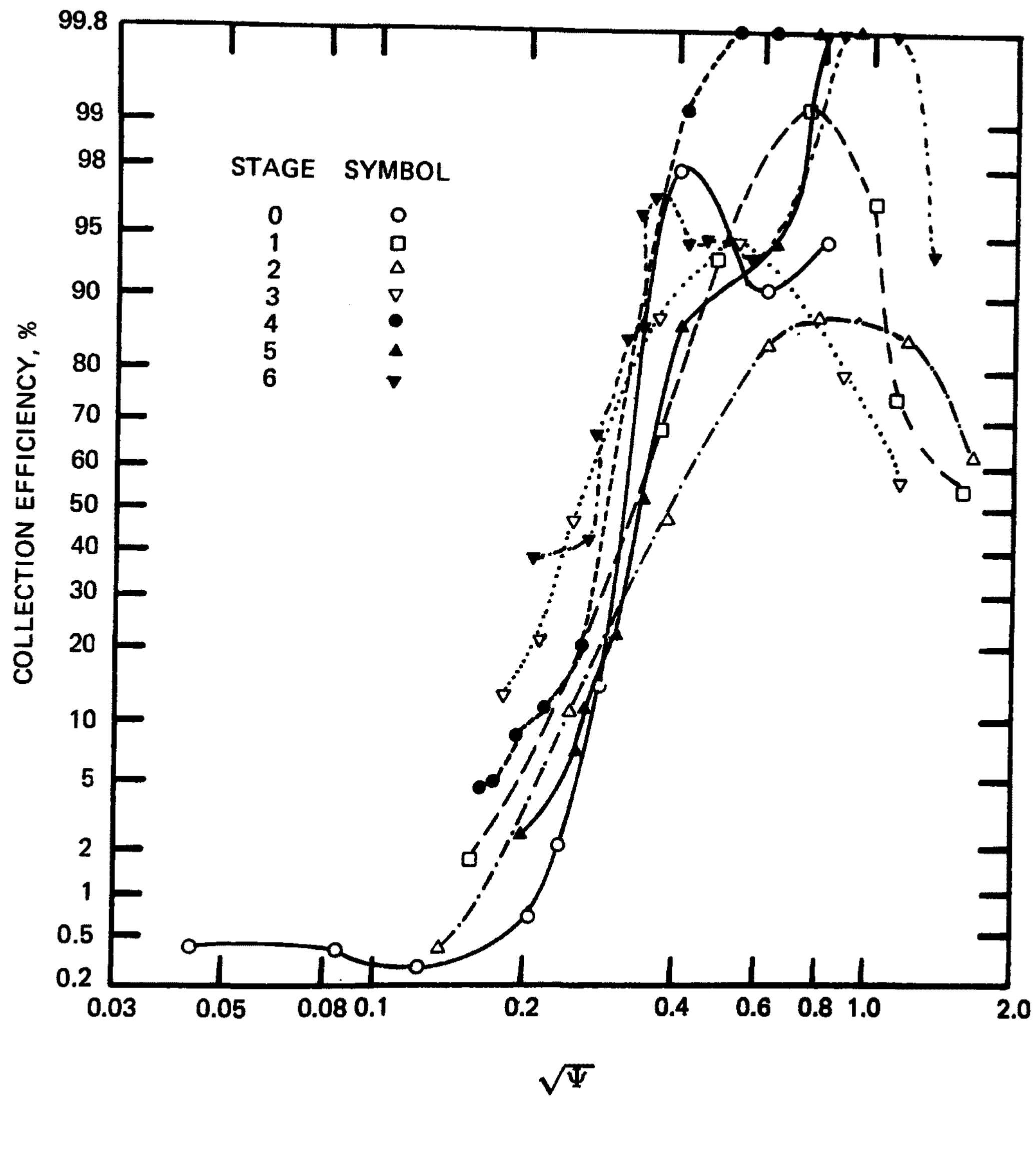


Figure 27. Collection efficiency vs. $\sqrt{\psi}$. Brink Model BMS-11 cascade impactor with greased collection plates.

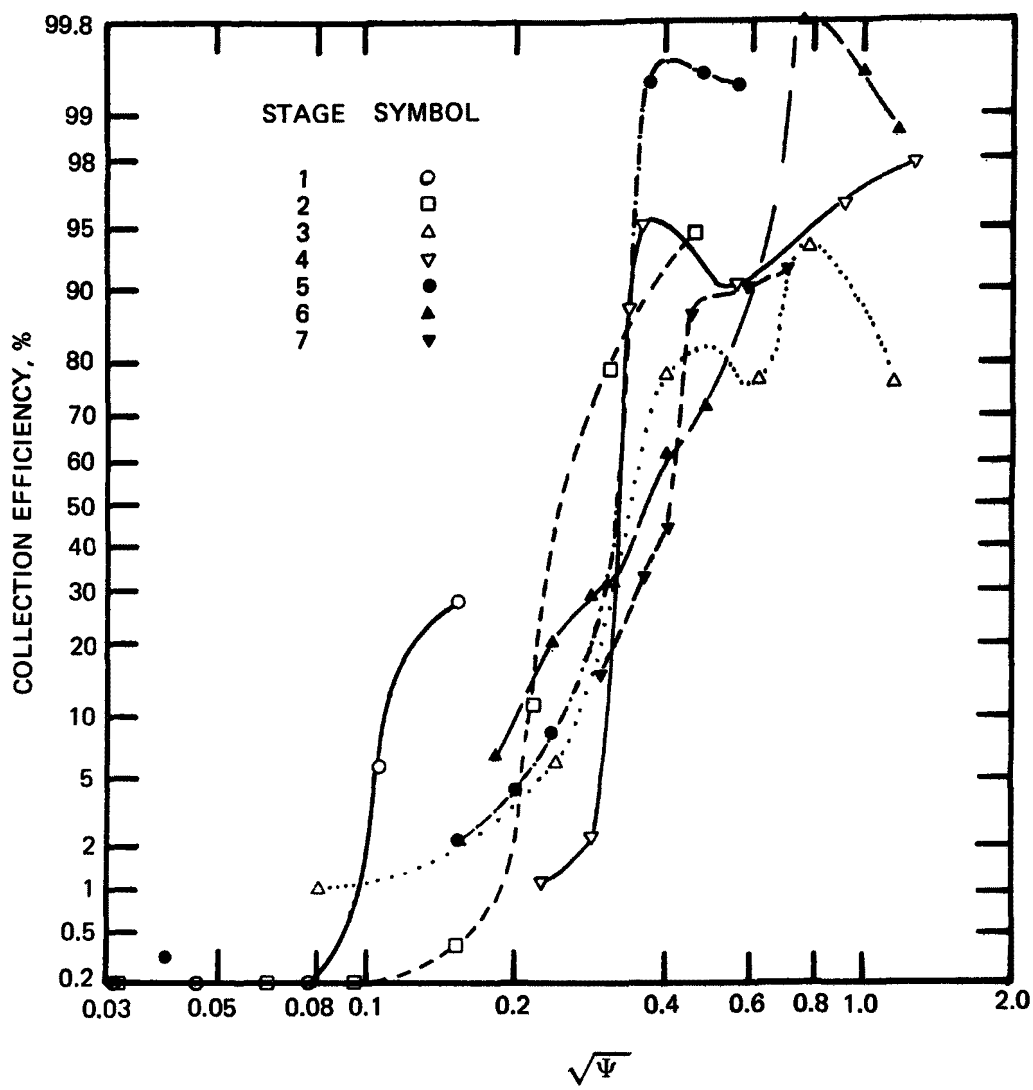


Figure 28. Collection efficiency vs. $\sqrt{\psi}$. MRI Model 1502 inertial cascade impactor with greased collection plates.

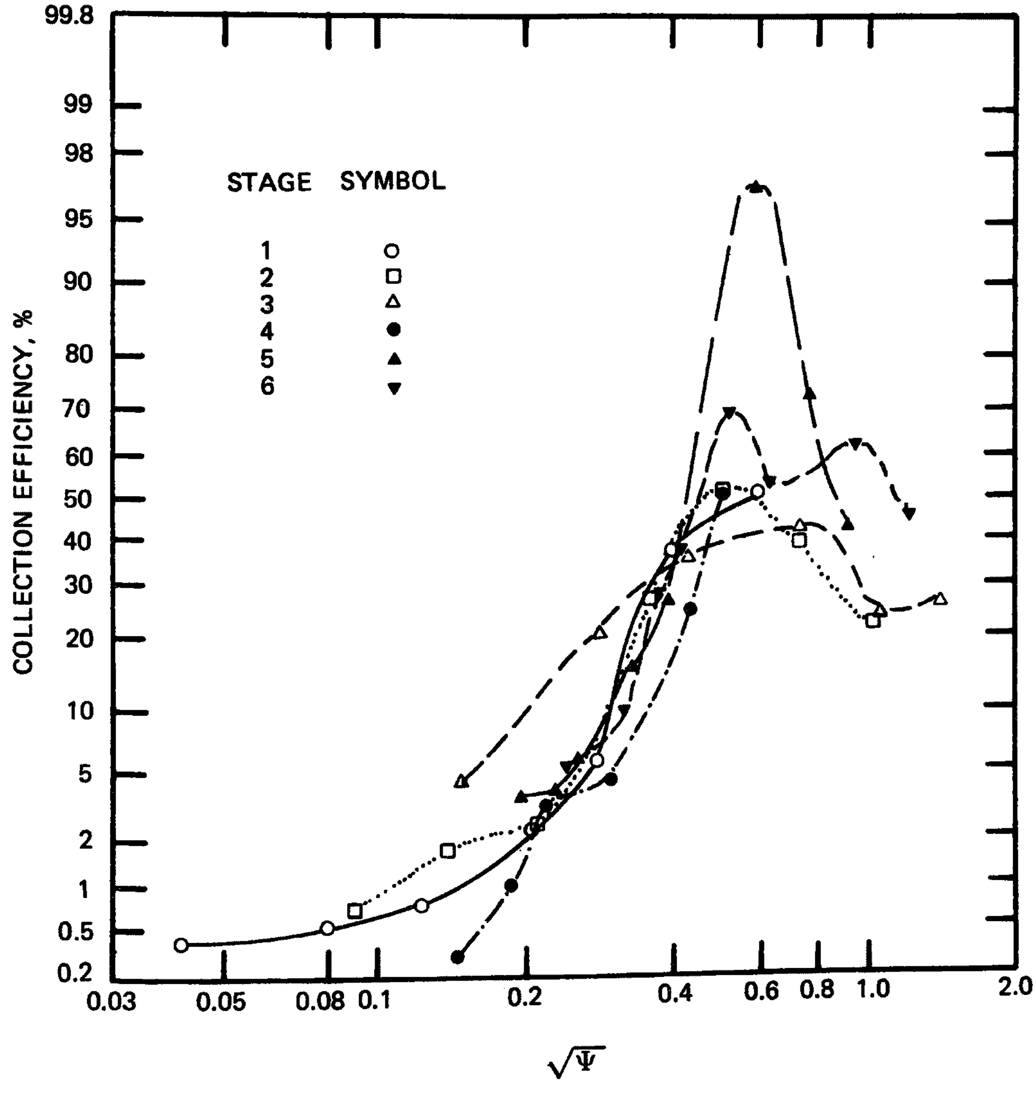


Figure 29. Collection efficiency vs. $\sqrt{\psi}$. Sierra Model 226 source cascade impactor with glass fiber collection substrates. Sampling flow rate is 14 LPM.

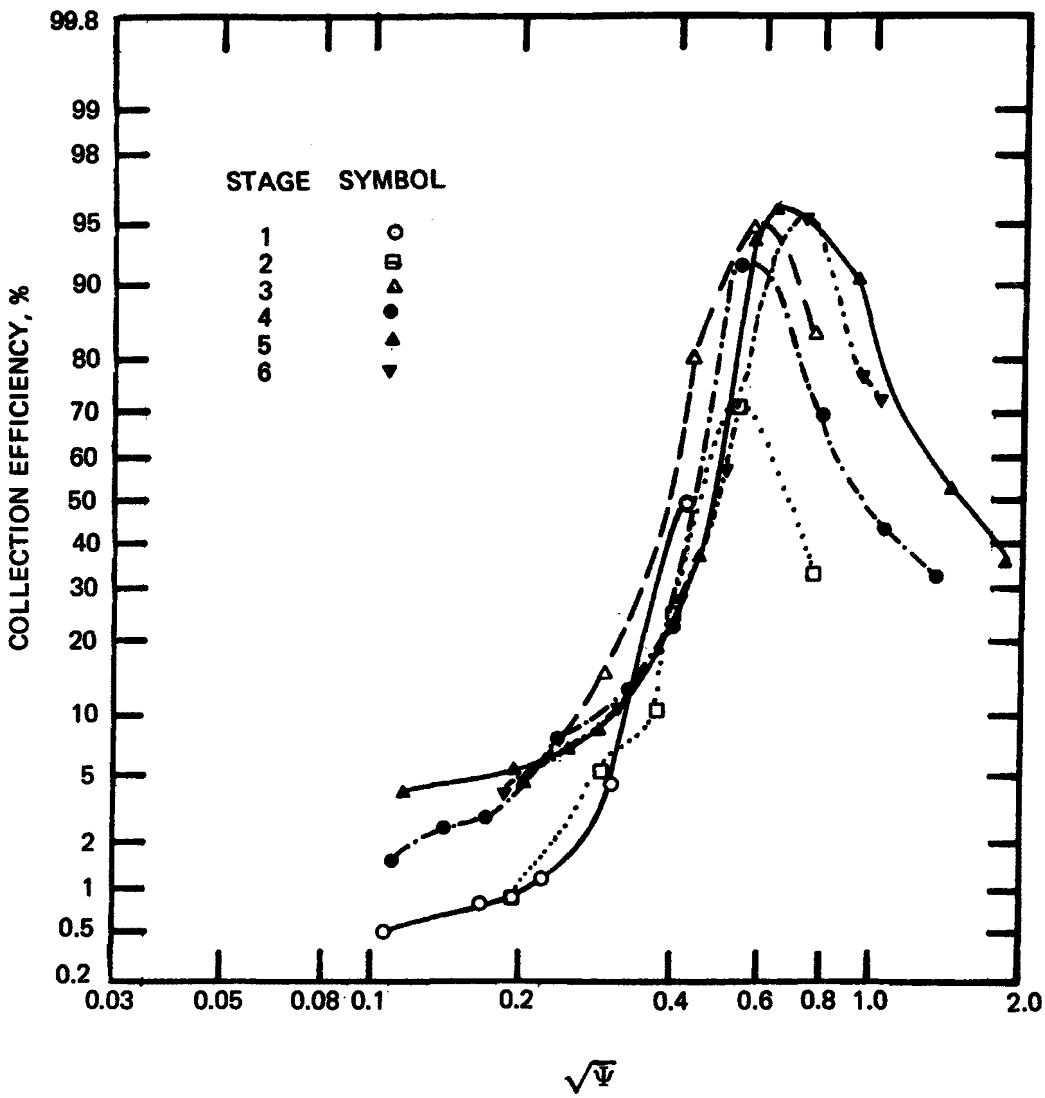


Figure 30. Collection efficiency vs. $\sqrt{\psi}$. Sierra Model 226 source cascade impactor with glass fiber collection substrates. Sampling flow rate is 7 LPM.

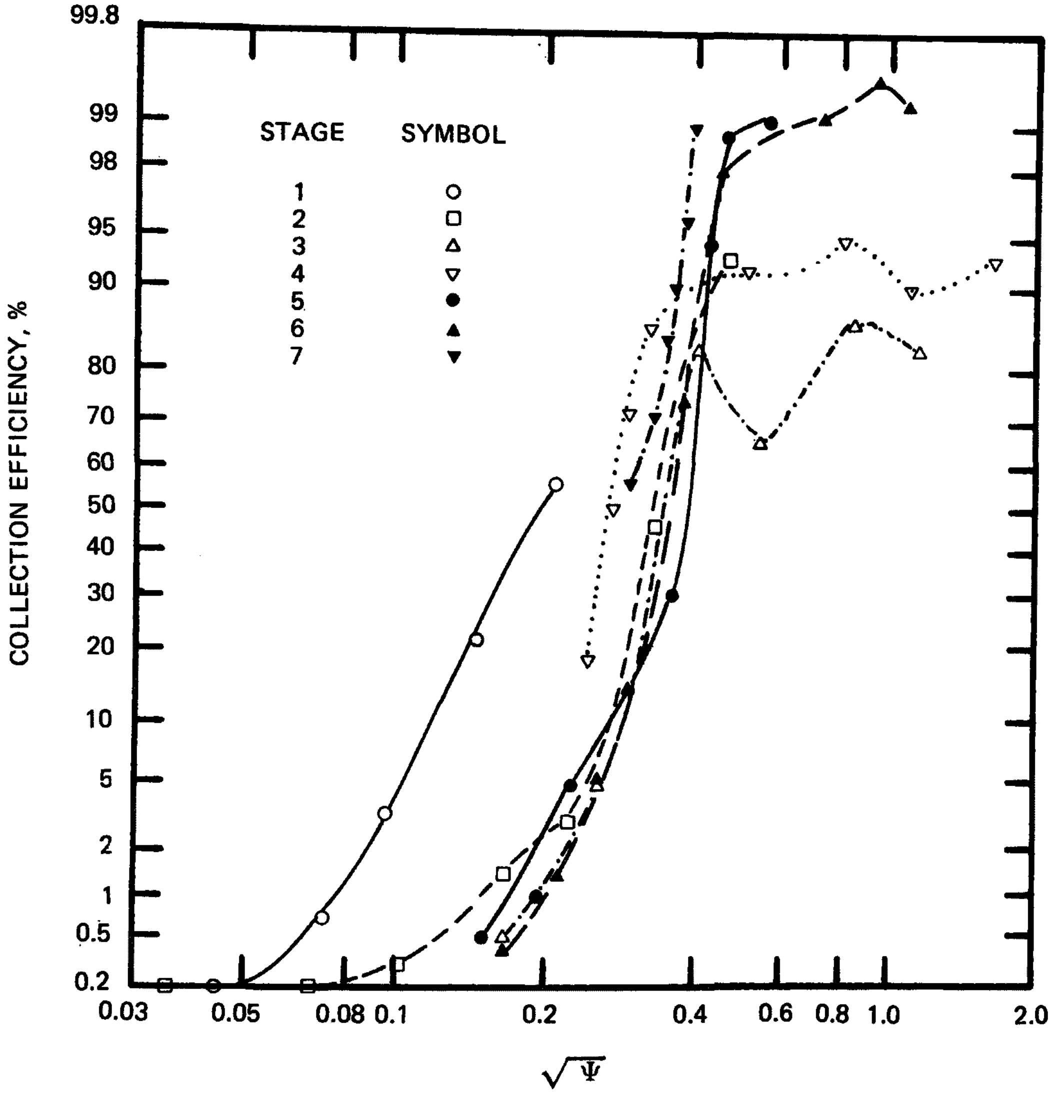


Figure 31. Collection efficiency vs. $\sqrt{\psi}$. Universtiy of Washington Mark III source test cascade impactor with greased collection plate.

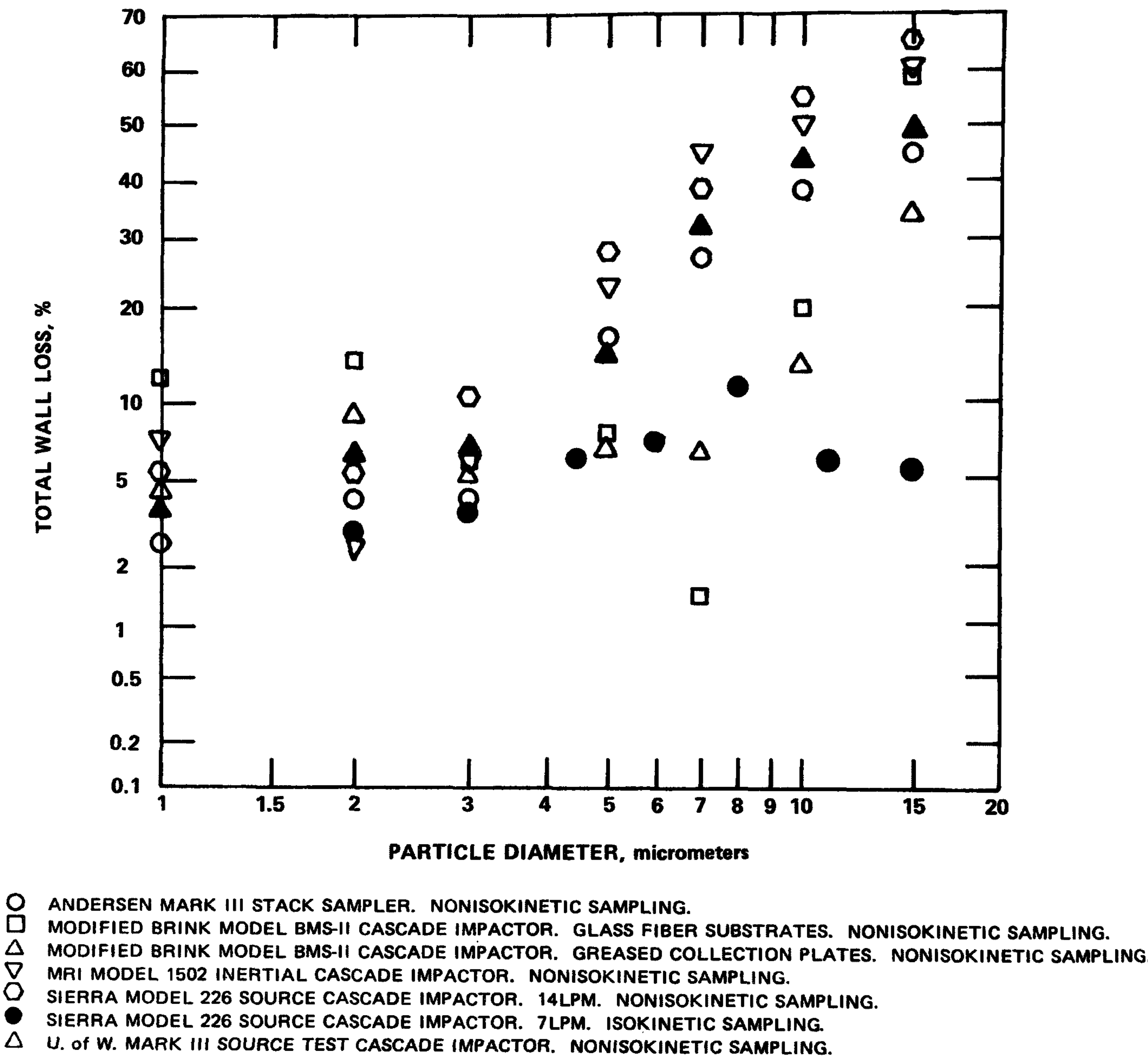


Figure 32. Cascade impactor wall loss vs. particle diameter.

2. The theories of cascade impactor operation at this time do not describe the behavior of cascade impactors accurately enough to obviate empirical calibration of each device.

3. The stage collection efficiencies are sensitive to the type of impactor collection substrate that is used. This dependence is evident in the comparison of the Brink Cascade Impactor data using glass fiber collection substrates and greased collection plates. The strong dependence of collection efficiency on stage collection substrate material has also been illustrated and discussed by Willeke[20] and Rao.[5]

4. In the majority of cases the stage collection efficiency never reaches 100% for any particle size but reaches a maximum value that usually falls between 80% and 95%. Hence, some greatly oversized particles will reach every stage beyond the first stage. Unless suitable compensation can be made for the presence of these oversized particles, their presence will tend to bias the apparent particle size distribution toward higher than actual concentrations of fine particles and reduced concentrations of large particles. The errors probably tend to be more significant for the fine particle end of the distribution.

5. The use of grease on the collection plates as well as a reduction in the impactor flow rate tends to decrease the magnitude of this problem. The Sierra impactor data illustrate the increase in collection efficiency which resulted from a decrease in sampling flow rate and concomitant reduction in bounce and cascading of large particles to lower stages. This study shows that in some cases the maximum efficiency was almost doubled by lowering the flow rate. A discussion of this phenomenon has also been presented by Rao.[5]

6. All of these cascade impactors are roughly equivalent in performance, except for the Sierra operated at 14 LPM. It must be remembered, however, that the type of substrate and the sampling flow rate which are employed will cause some differences in impactor operation as well as other possible factors associated with sampling at industrial sites (temperature and pressure extremes, particle density, particle adhesiveness, moisture content, etc.).

This work has been reported in "Particulate Sizing Techniques For Control Device Evaluation: Cascade Impactor Calibrations," EPA-600/2-76-280, October 1976 (NTIS-PB 262 849/3BE).

CALIBRATION OF SOVIET PARTICLE SIZING INSTRUMENTS

Under this task three Soviet cascade impactors and one Soviet impactor/cyclone were calibrated. The three cascade impactors included one twelve stage device and two fourteen stage impactors. The three stage impactor/cyclone had a single impaction stage followed by two cyclonic stages. All four devices had an integral back-up filter holder which used a plug of glass wool fibers.

A photograph of one of the fourteen stage Soviet impactors is shown in Figure 33. Figure 34 shows the Soviet impactor/cyclone. The upper stages of these sizing devices were calibrated using ammonium fluorescein aerosols (20 μm to 2 μm) dispersed by a Vibrating Orifice Aerosol Generator. The lower stages were calibrated using monodisperse polystyrene latex or Polyvinyltoluene latex spheres (2.02 μm to 0.46 μm) dispersed by a Pressurized Collison Nebulizer System.

Soviet Three Stage Impactor/Cyclone

As mentioned above, this instrument consisted of a single impaction stage followed by two cyclonic stages. A back-up filter collected all particles passing the last stage. This device was constructed from a titanium alloy. A set of nozzles was supplied with the impactor/cyclone. All three stages were calibrated using monodisperse ammonium fluorescein particles with sizes ranging from 18 micrometers diameter to 2.3 micrometers diameter. The ambient pressure was 29.5" Hg, the temperature was 22°C, the particle density was 1.35 gm/cm^3, and the sampling flow rate was 10 liters per minute. At these conditions the cut points of the three stages were determined to be 13.5, 6.4, and 2.6 micrometers. The results are presented graphically in Figure 35.

Soviet 12-Stage Cascade Impactor

This impactor was unique in that several stages were designed to have identical cut points. Because of this feature, the impactor had seven effective stages. The twelve stages were paired as follows: 1 and 2, 3 and 4, 5, 6 and 7, 8, 9 and 10, 11 and 12. In field use the mass collected by single stages 1 and 2 was combined as the catch for effective stage 1. In a similar manner the mass collected by single stages 11 and 12 became the combined catch for effective stage 7. The calibration conditions were an ambient pressure of 29.5" Hg, a temperature of 22°C; the particle density was 1.35 gm/cm^3 and the sampling rate was ten liters per minute. Because of the type of construction of this impactor, it was only possible to calibrate it using ammonium fluorescein aerosols between 2 and 20 micrometers diameter. The calibration data are shown by stage both on an individual basis (Figure 36) and on an effective stage basis (Figure 37).

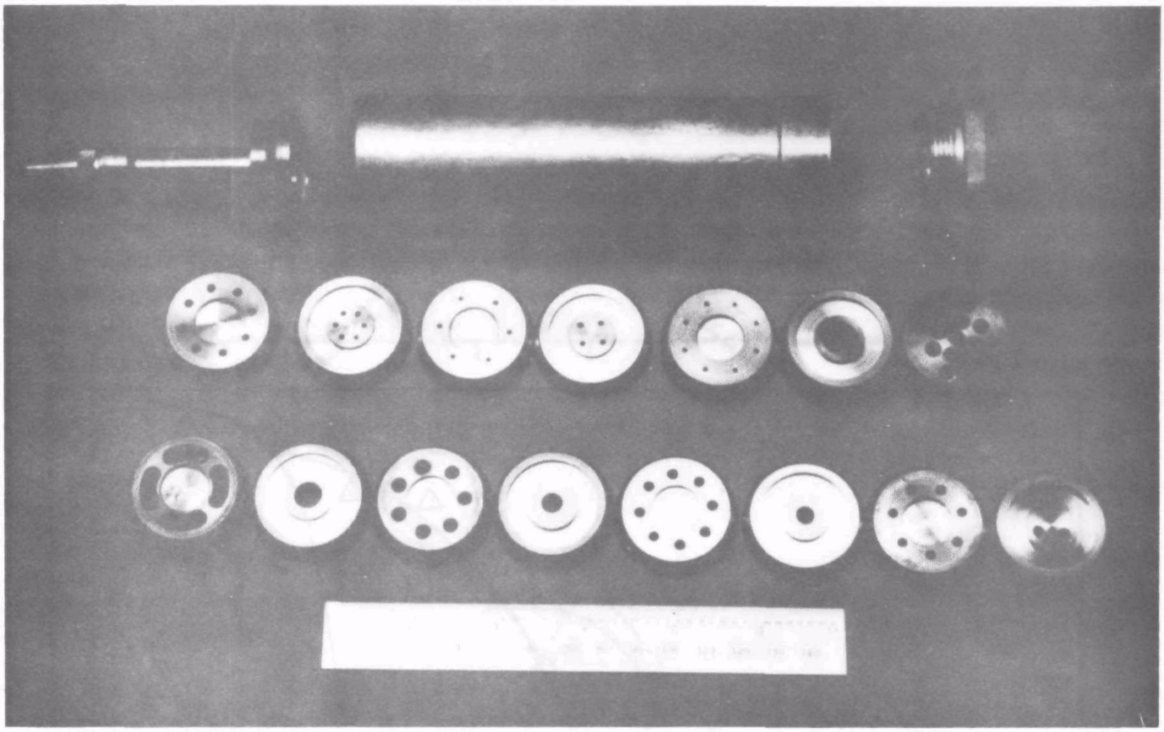


Figure 33. Soviet 14-stage cascade impactor.

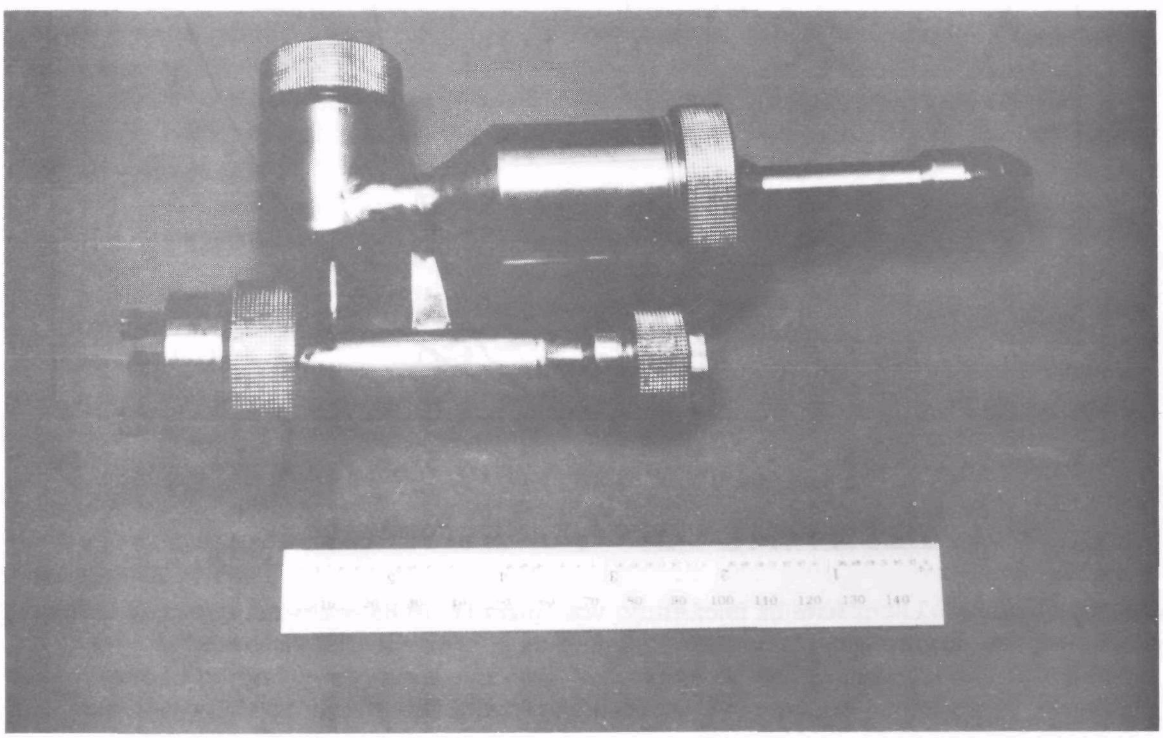


Figure 34. Soviet 3-stage impactor/cyclone.

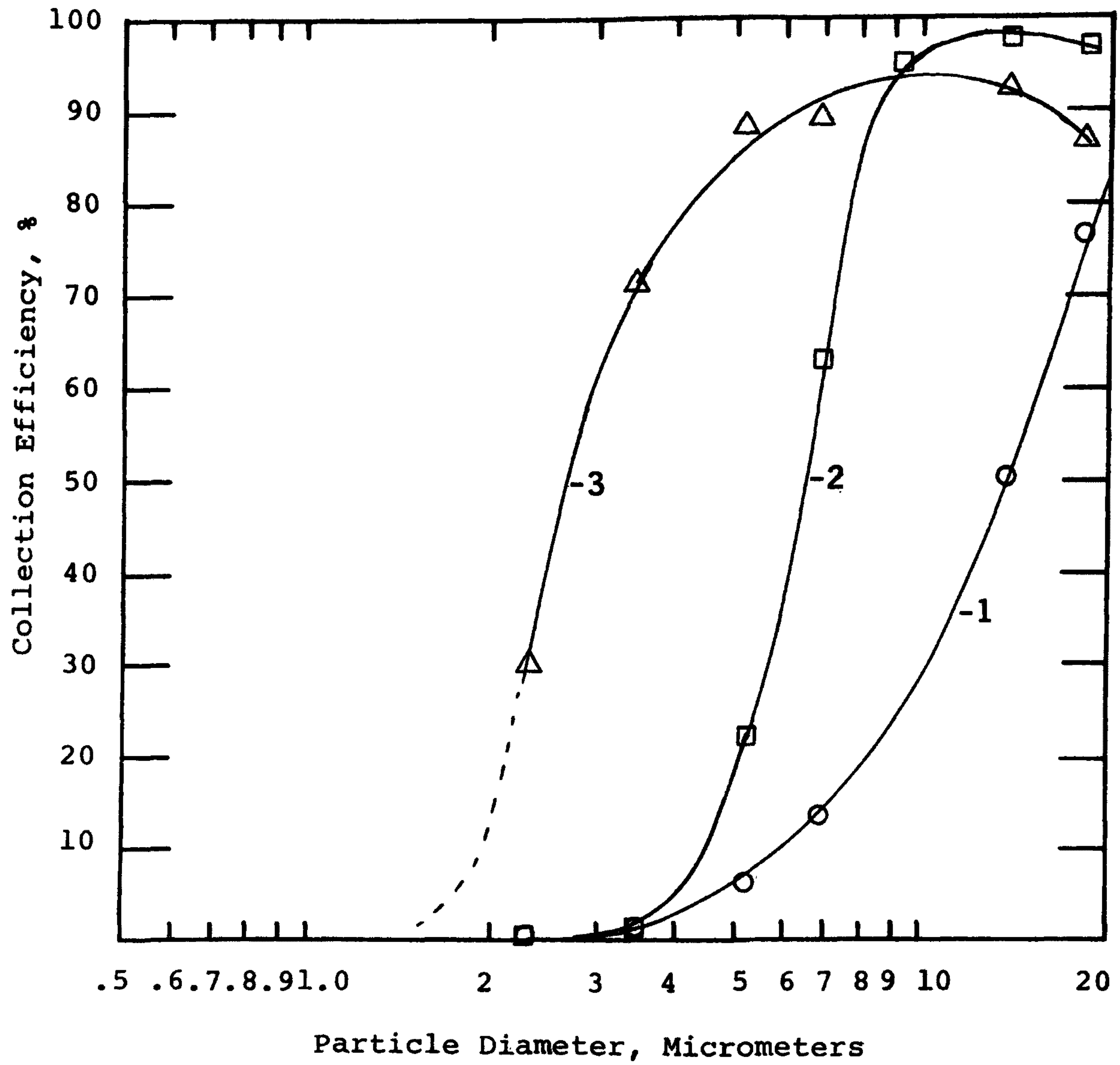


Figure 35. Collection efficiency vs. particle diameter. Soviet 12-stage impactor/cyclone.
1 - impaction stage 2 - 1st cyclone 3 - 2nd cyclone
(29.5 in. Hg, 22°C, 1.35 gm/cm^3, 10 LPM)

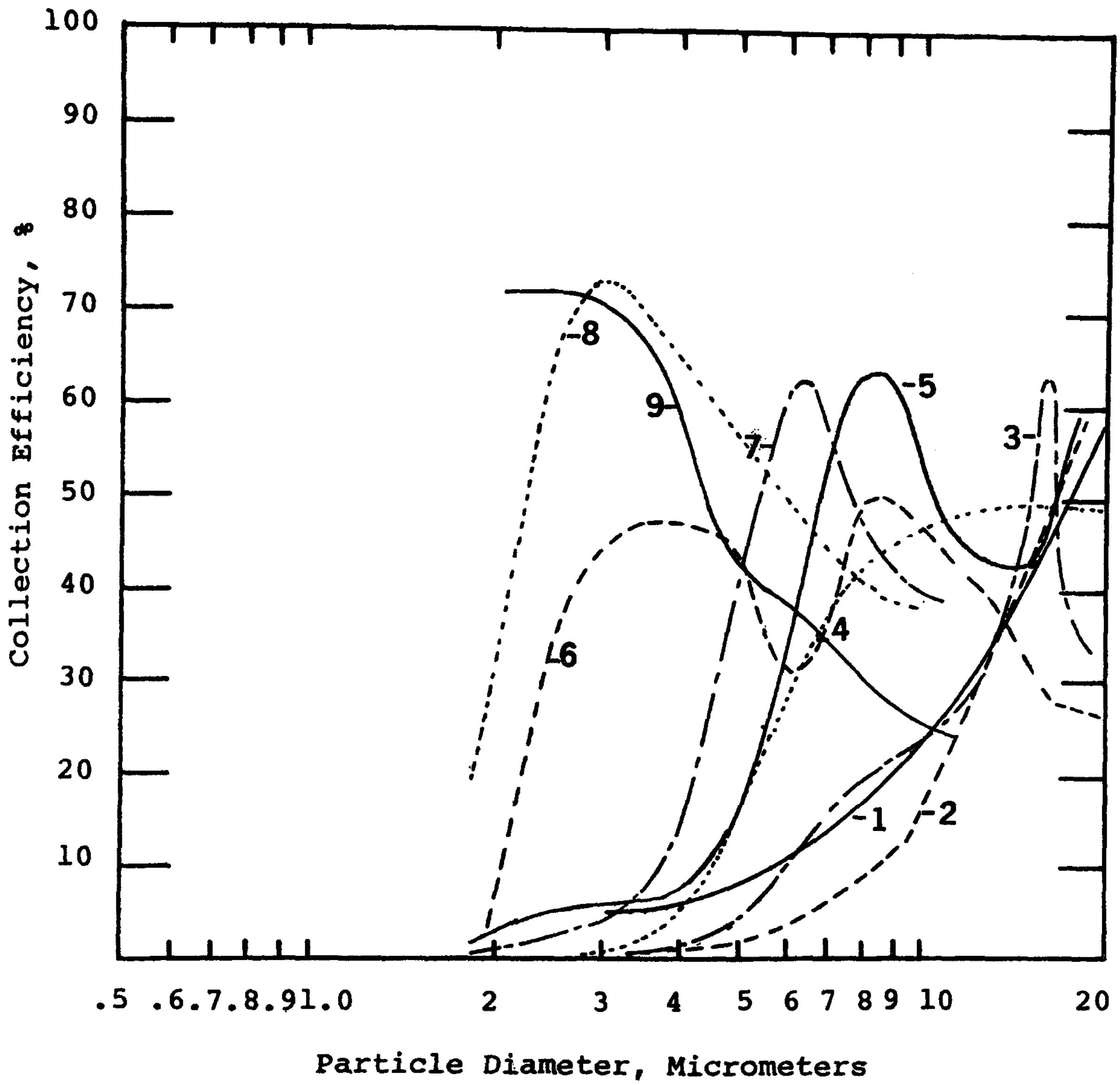


Figure 36. Collection efficiency vs. particle diameter. Soviet 12-stage cascade impactor. Data shown for the first nine stages from 2 to 20 microns. (29.5 in. Hg, 22°C, 1.35 gm/cm^3, 10 LPM).

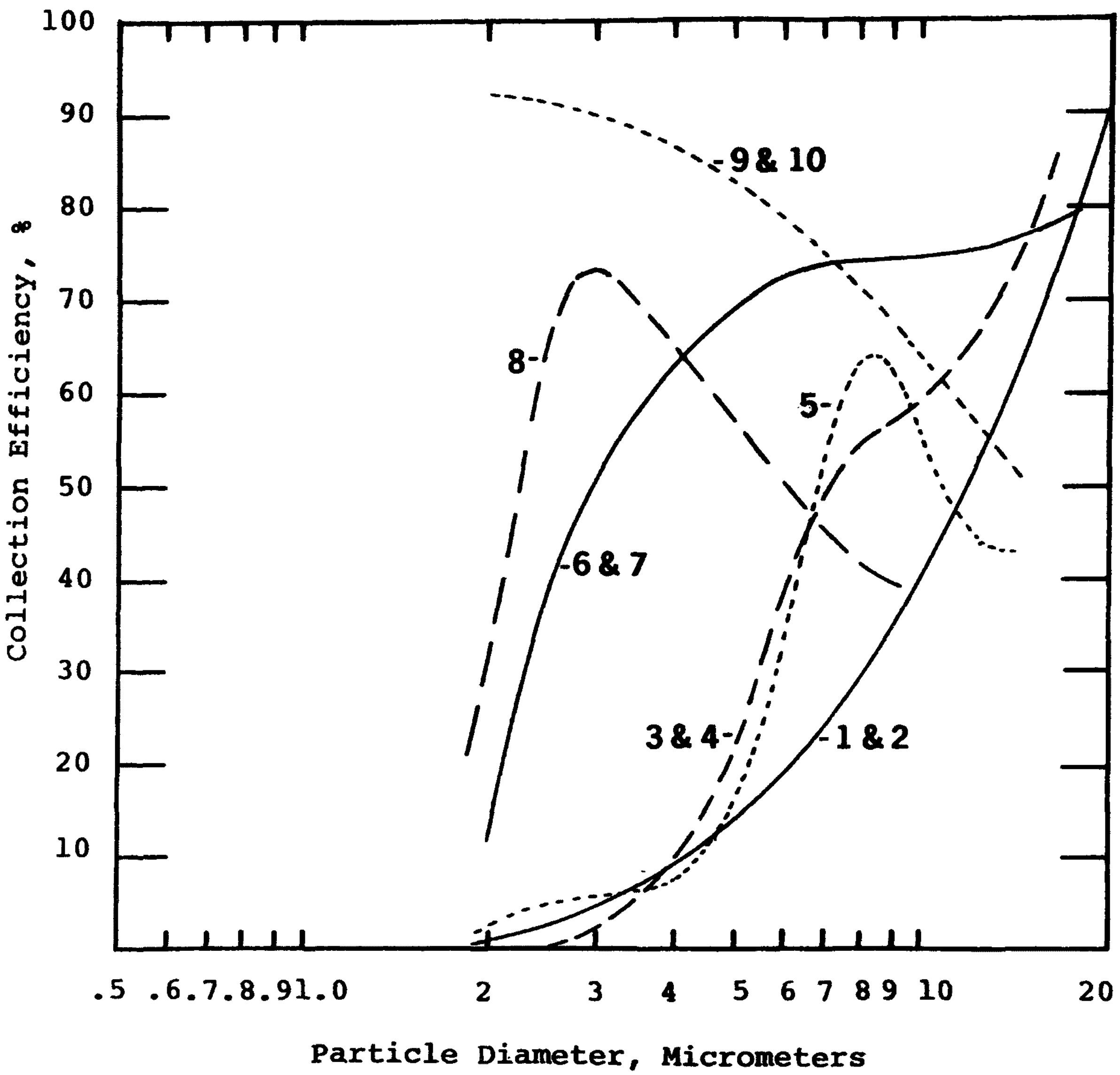


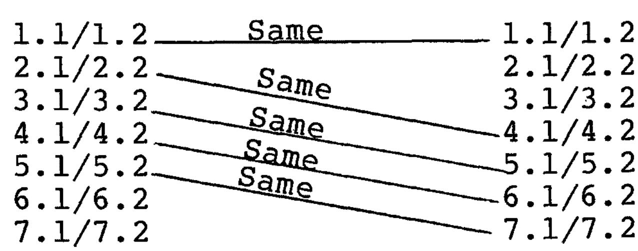
Figure 37. Collection efficiency vs. particle diameter. Soviet 3-stage cascade impactor. Data shown in combined form in the configuration for field measurements. (29.5 in. Hg, 22°C, 1.35 gm/cm^3, 10 LPM).

Soviet 14-Stage Cascade Impactor (Small D_{50}'s)
Soviet 14-Stage Cascade Impactor (Large D_{50}'s)

These cascade impactors were similar in design to the Soviet 12-Stage impactor in that their 14 single stages were divided into seven effective stages with a pair of single stages per effective stage; each member of a pair is theoretically designed to have the same cut point. These seven effective stages were numbered 1.1/1.2, 2.1/2.2, 3.1/3.2, 4.1/4.2, 5.1/5.2, 6.1/6.2, and 7.1/7.2. In practice the mass collected by individual stages 1.1 and 1.2, for example, was combined to give a total mass collected by the first effective stage. This procedure was repeated for the rest of the impaction stages. These two impactors had different cut points but shared identical stages on five of the seven effective stages as illustrated in the following chart.

14-Stage Cascade Impactor

Small D_{50}s　　　　Large D_{50}s



Effective stages 1, 2, 3, 4, and 5 of the small D_{50} impactors were identical with stages 1, 4, 5, 6, and 7 of the large D_{50} impactor, respectively. It was possible to calibrate both impactors with ammonium fluorescein and polystyrene latex particles; however, it was not possible to complete the calibration on stages 7.1/7.2 of the small D_{50} impactor since the pressure drop across these stages was greater than our calibration apparatus could maintain. The results of the calibration are depicted graphically in Figures 38 and 39.

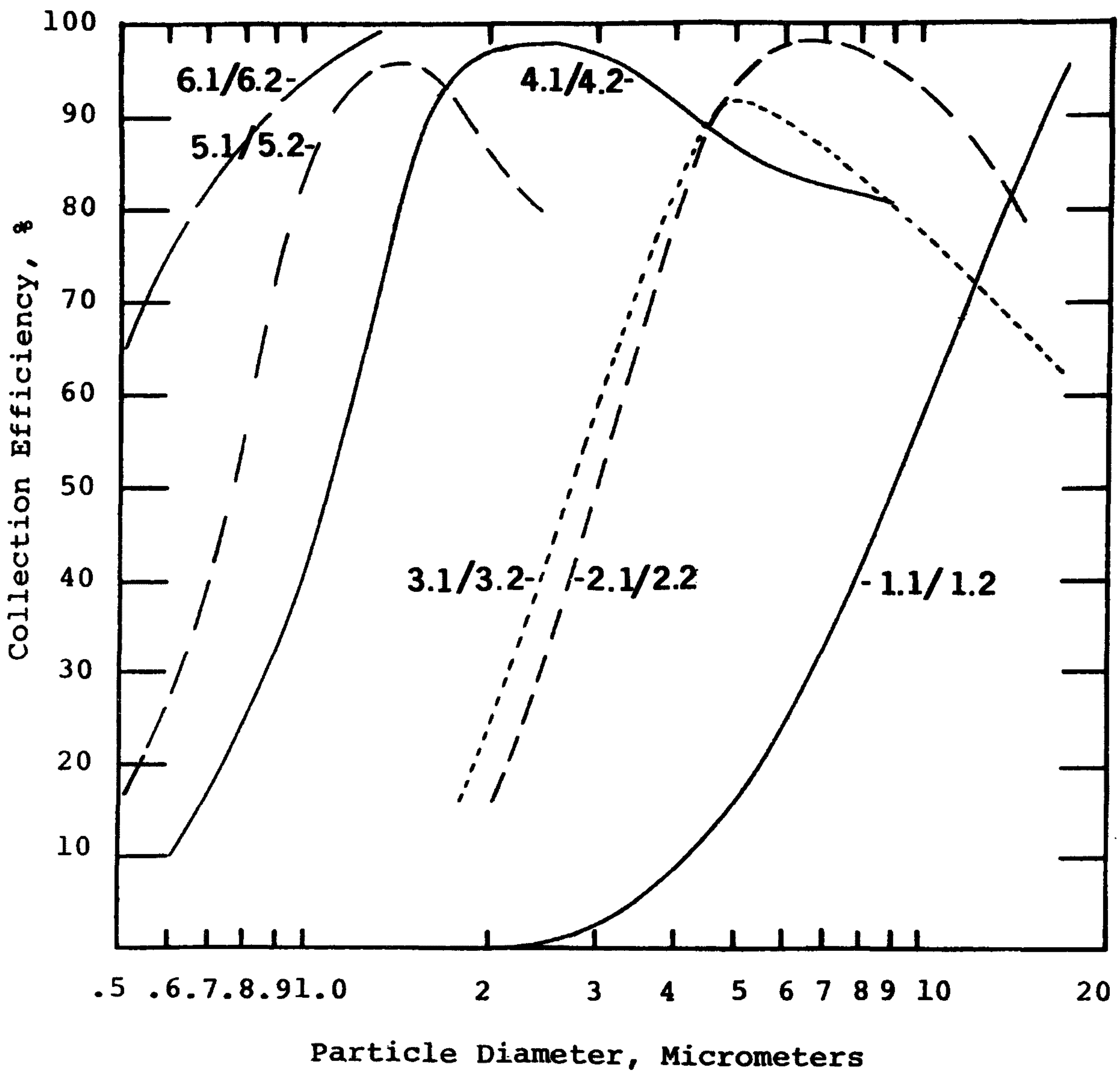


Figure 38. Collection efficiency vs. particle diameter. Soviet 14-stage cascade impactor. (Small cutpoints) Data shown in combined form for the first six of the seven stage pairs. (29.5 in. Hg, 22°C, 1.35 gm/cm^3, 10 LPM)

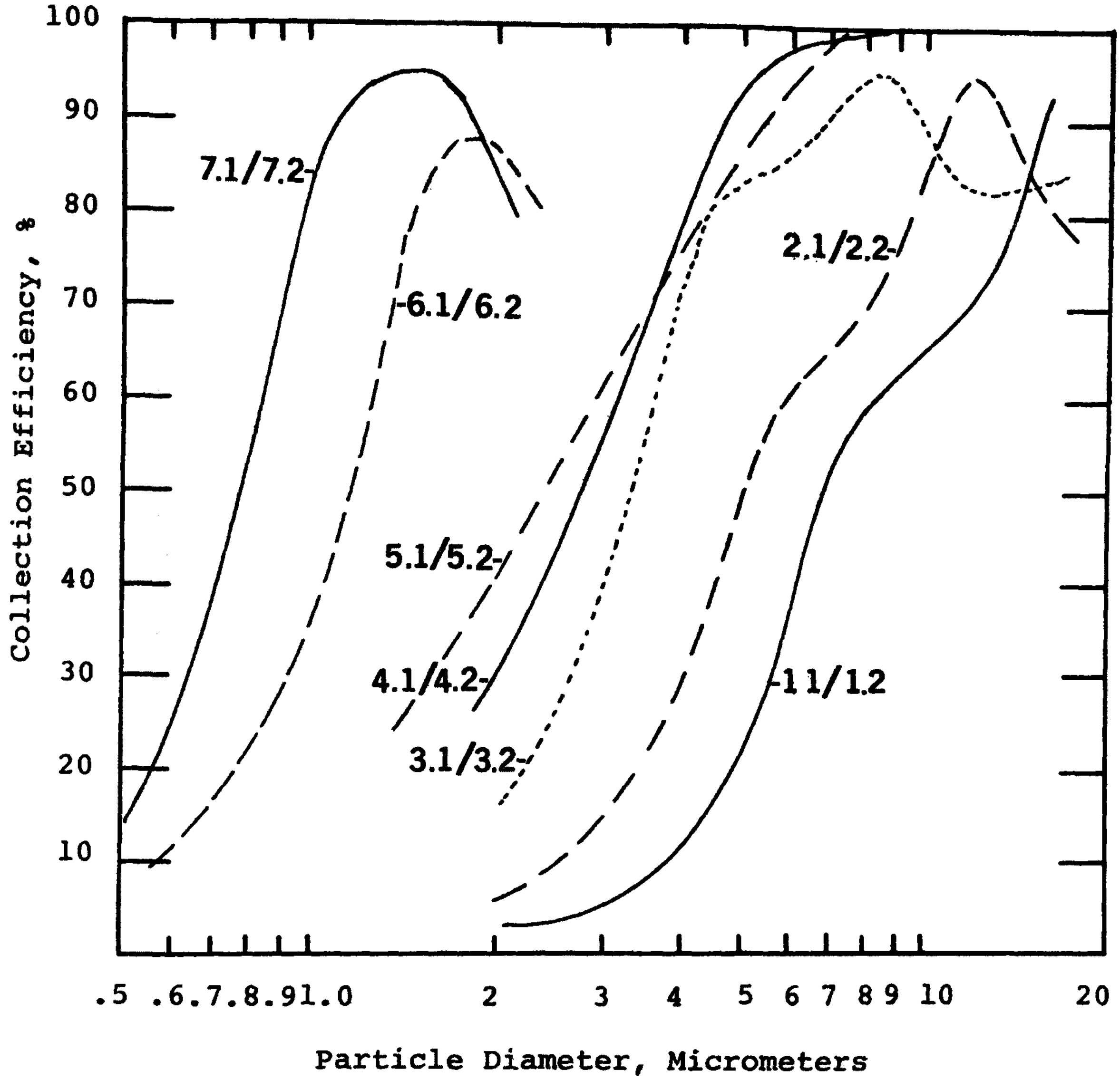


Figure 39. Collection efficiency vs. particle diameter. Soviet 14-stage cascade impactor. (Large cutpoints) (29.5 in. Hg, 22°C, 1.35 fm/cm^3, 10 LPM)

CALIBRATION OF THE SOURCE ASSESSMENT SAMPLING SYSTEM CYCLONES

Three separate Technical Directives were issued under this contract covering various aspects of calibrating the SASS cyclones. A schematic of the SASS instrument is shown in Figure 40. The first technical directive called for the calibration of the three cyclones at ambient temperatures and pressures.

The calibrations of the Large (10 μm) and Middle (3 μm) Cyclones were performed using ammonium fluorescein aerosols generated with Southern Research Institute's Vibrating Orifice Aerosol Generator (VOAG). Monodisperse ammonium fluorescein aerosols with diameters of 2, 3, 4, 5, 7.5, 10.5, and 14.5 micrometers were sampled at flow rates of 4 ACFM and 3 ACFM. These particles have a density of 1.35 gm/cm^3. After sampling for a sufficient length of time, each cyclone was washed with a known amount of NH_4OH to dissolve the ammonium fluorescein aerosol. The total mass of the collected aerosol was determined using absorption spectroscopy. The collection efficiency of each cyclone was calculated and plotted versus particle diameter. Figures 41 and 42 present these Collection Efficiency Versus Particle Diameter data for the Large and Middle Cyclones, respectively.

The Small Cyclone was calibrated using Dow Corning polystyrene latex (PSL) and polyvinyltoluene latex (PVTL) spheres dispersed with the Institute's Pressurized Collison Nebulizer System. Using an auxiliary pump, aerosols were pulled through the Small Cyclone at two flowrates, 3.1 ACFM and 1.8 ACFM. A Climet Instruments Model 208A Particle Analyzer was used to measure the number concentration of unit density 0.82 μm and 1.1 μm diameter PSL spheres and 2.02 μm diameter PVTL spheres upstream and downstream of the Small Cyclone. The collection efficiencies were calculated and plotted versus the particle diameter as shown in Figure 43.

Based on the results of this limited calibration study, it appeared that the cyclone D_{50} cut point varied approximately inversely with the square root of the particle density as predicted by theory.

The specific data obtained in this study were extrapolated to obtain cyclone D_{50}'s for four combinations of flow rate and particle density (4 ACFM and 3 ACFM flow rates and 1.00 gm/cm^3 and 2.3 gm/cm^3 particle densities). The resulting graphs shown in Figure 44 indicate the approximate range of D_{50} cut points which can be expected of the SASS cyclones at temperatures near ambient.

After the above ambient calibration work was completed, a recalibration of the three cyclones of the Source Assessment

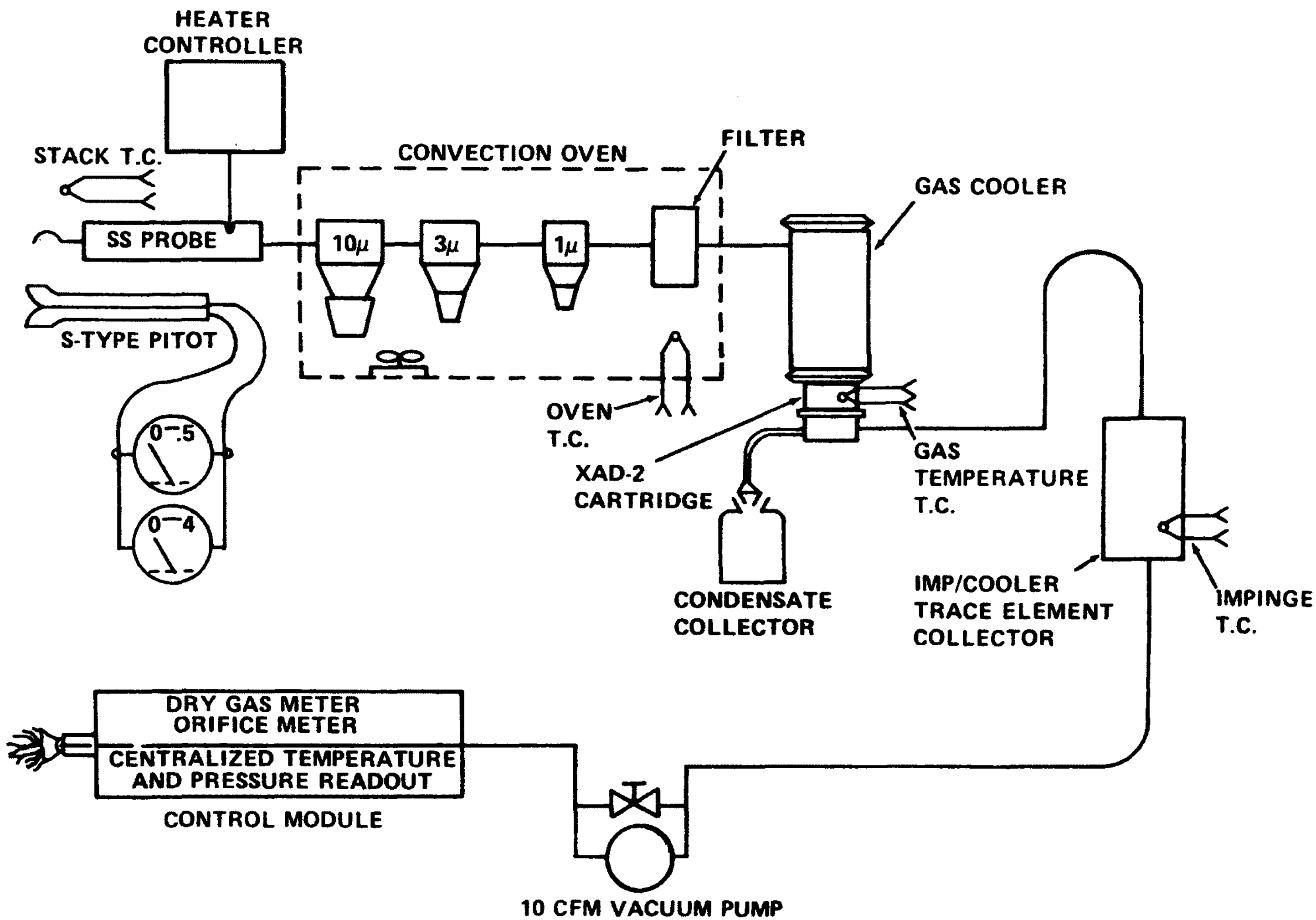


Figure 40. Schematic of the Source Assessment Sampling System.

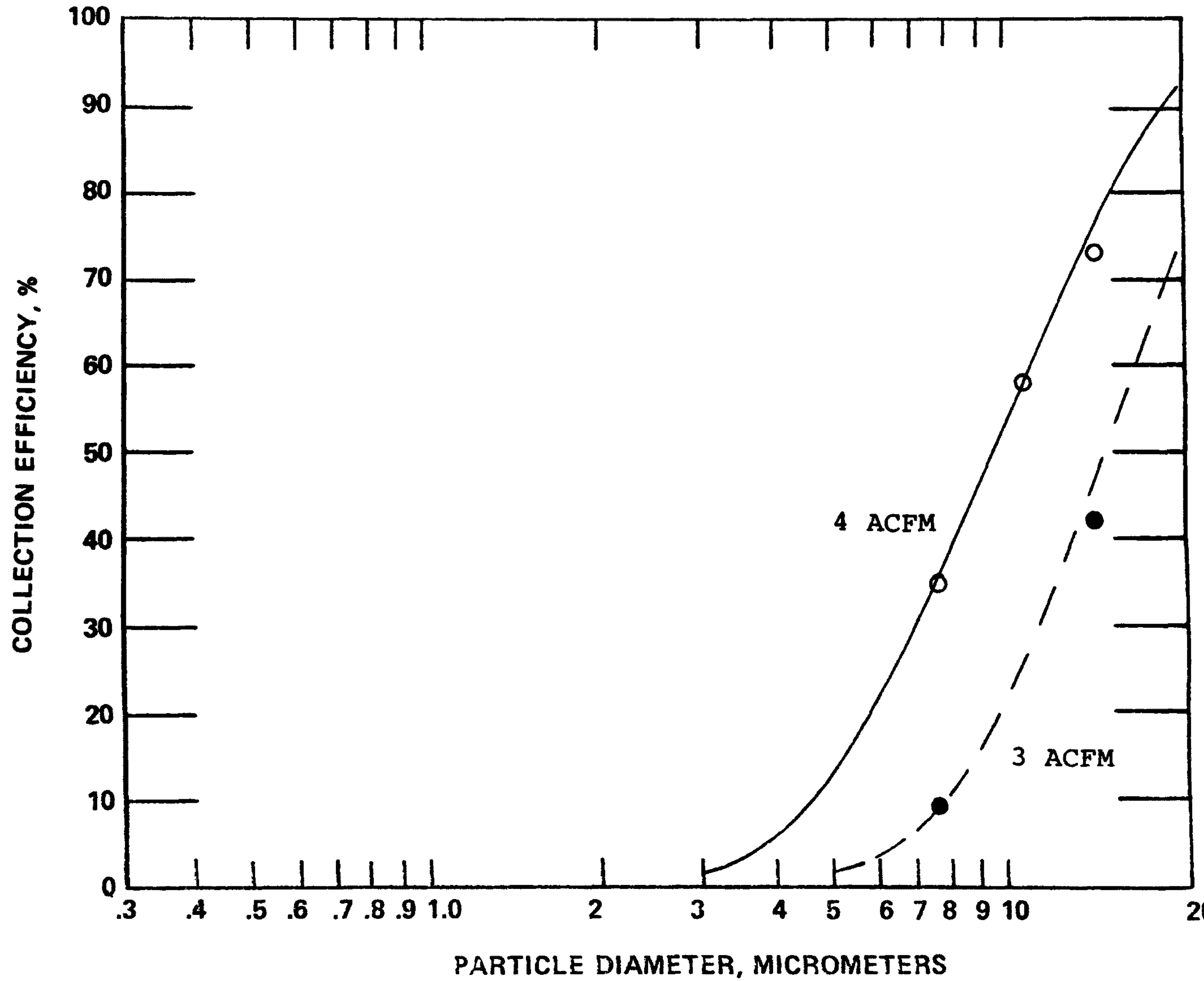


Figure 41. Collection efficiency vs. particle diameter. Large SASS cyclone. Particle density - 1.35 gm/cm^3.

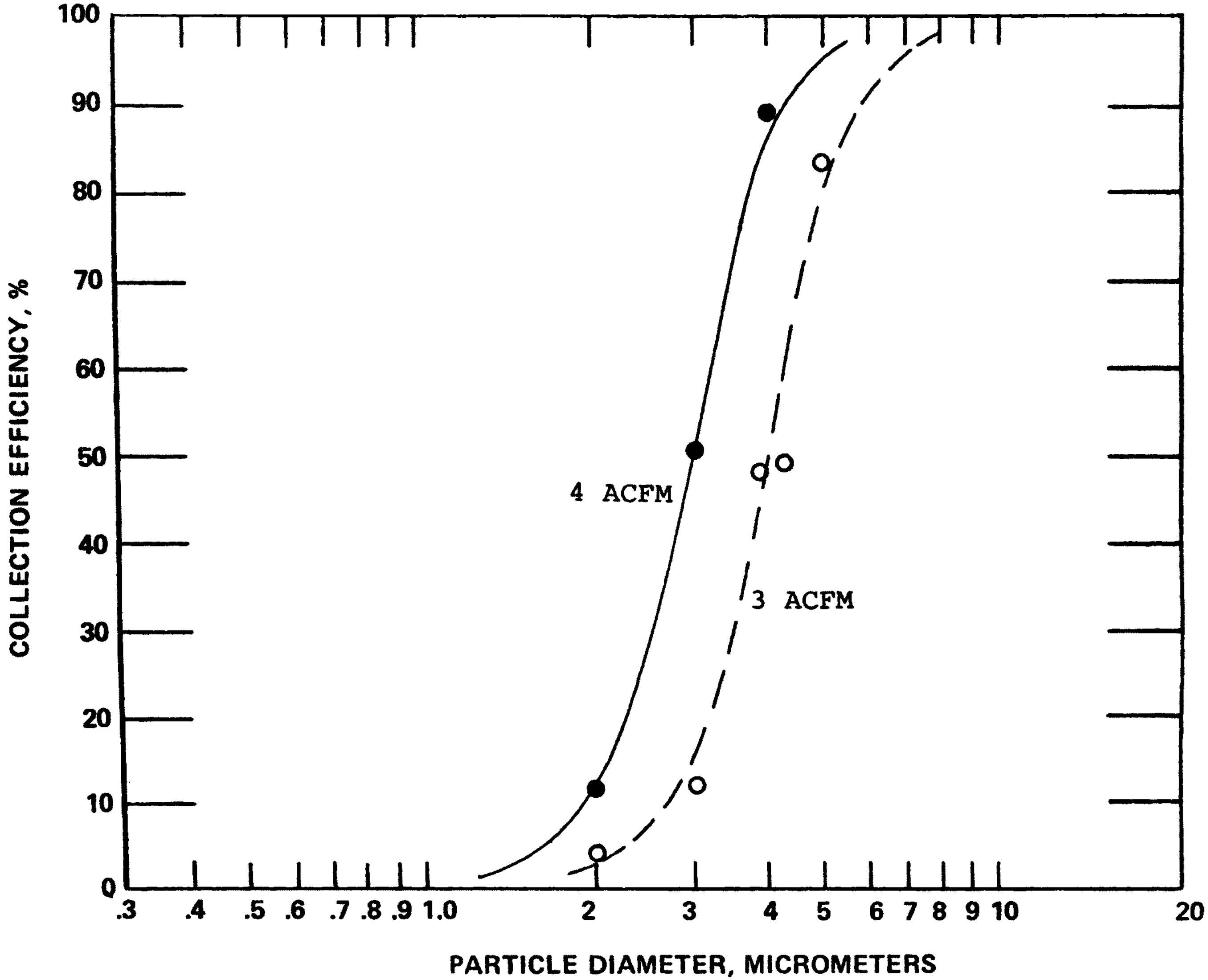


Figure 42. Collection efficiency vs. particle diameter. Middle SASS cyclone. Particle density - 1.35 gm/cm^3.

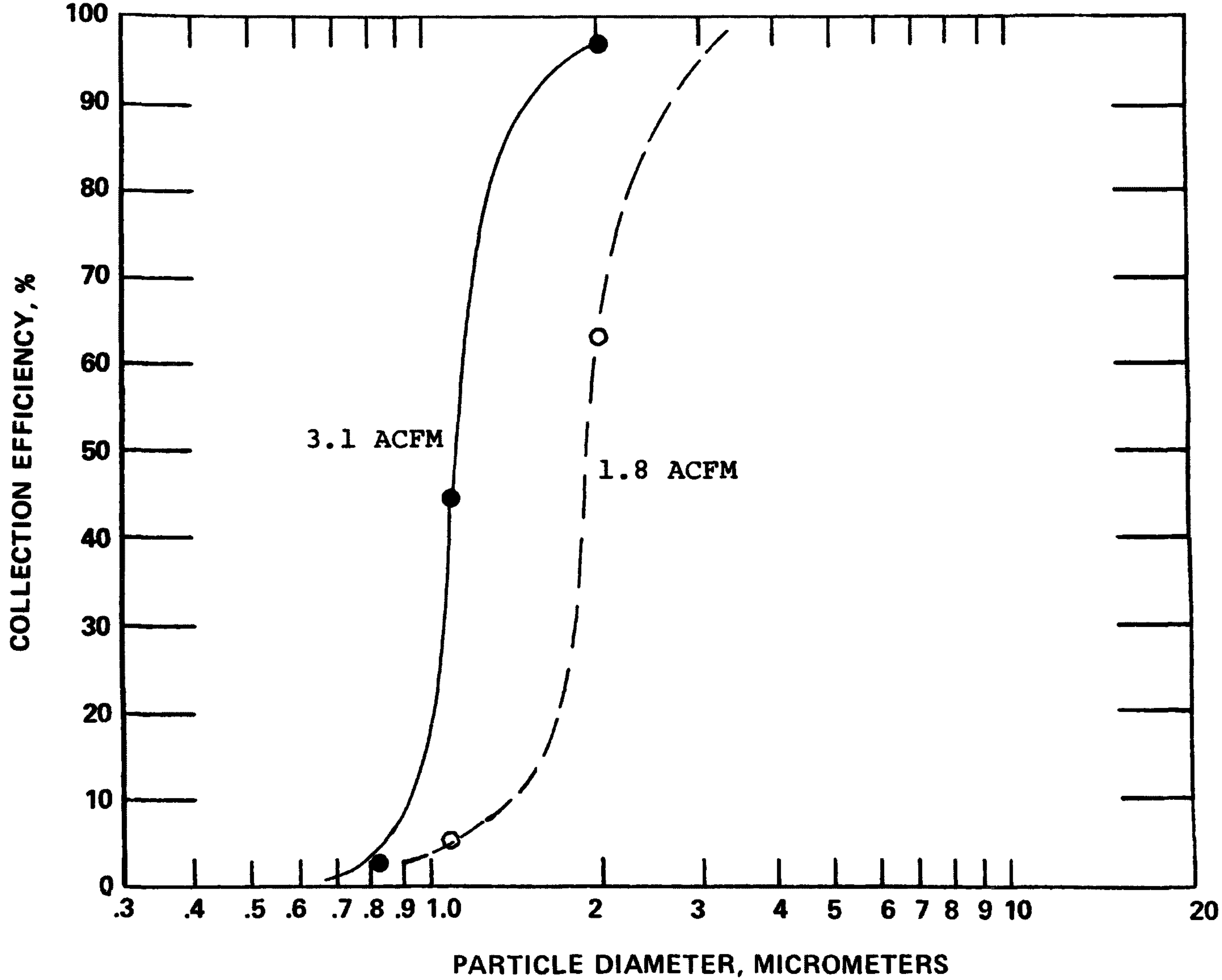


Figure 43. Collection efficiency vs. particle diameter. Small SASS cyclone. Particle density - 1.35 gm/cm^3.

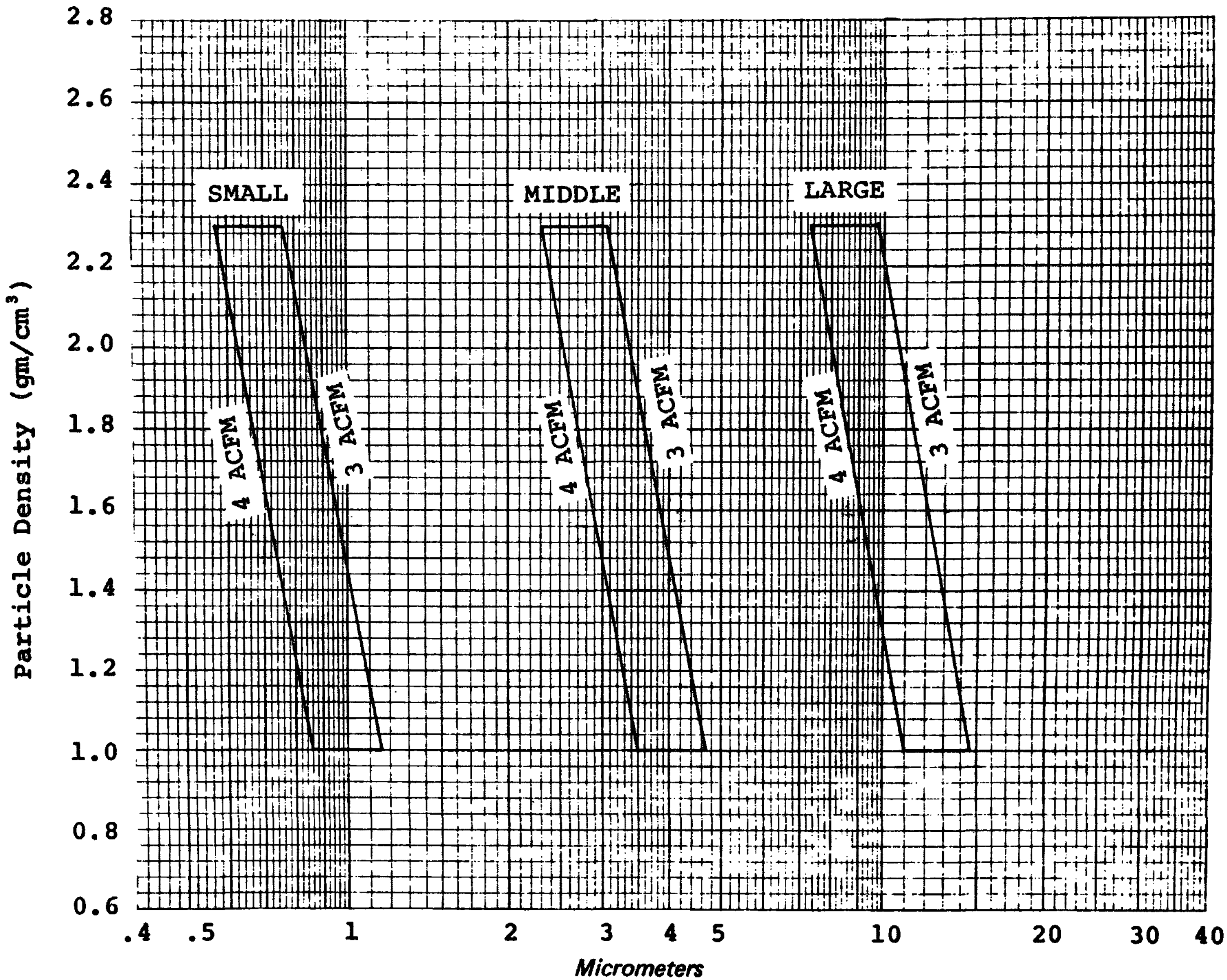


Figure 44. SASS cyclone cut points. (At 23°C)

Sampling System (SASS) at 400°F and 4 SCFM was performed. The previous calibration at 75°F and 4 ACFM gave approximately 0.86 μm, 3.5 μm, and 11.0 μm D_{50}'s for the Small, Middle, and Large Cyclones, respectively.

The calibration of the Large and Middle Cyclones was performed using ammonium fluorescein aerosols generated with Southern Research Institute's Vibrating Orifice Aerosol Generator (VOAG). With the cyclones placed in a heated oven and using a heated inlet line, the temperature of the gas stream at the inlet to the Large Cyclone was maintained at 400°F. Particle integrity of the ammonium fluorescein at high temperature was a major problem. It appeared that rapid heating of aerosol particles which had not dried sufficiently after generation caused these particles to rupture creating a large concentration of contaminating small particulate matter. This problem was alleviated by allowing the aerosol to come up to temperature more slowly. A color change in the ammonium fluorescein before and after heating was observed. Microscopic observation also indicated a possible crystalline change, causing the integrity of the dry ammonium fluorescein particles to be questioned.

The Large Cyclone was modified to try to obtain a D_{50} closer to the desired 10 micrometers. This modification involved the removal of the vortex buster from the Large Cyclone outlet. Unfortunately, there was no apparent effect on the performance of this cyclone. The data for the Large Cyclone is shown in Figure 45.

The Middle Cyclone was also modified in an attempt to obtain a D_{50} closer to the desired 3 micrometers. This was done by reducing the Middle Cyclone inlet diameter from 0.62 inches to 0.53 inches. The effect of this change was minimal as can be seen in Figure 46 and Figure 47 for the Unmodified and Modified Middle Cyclone, respectively.

As a result of this laboratory calibration, the approximate D_{50}'s for the Large and Middle Cyclones at 400°F and 4 SCFM are 15 micrometers and 4.4 micrometers, respectively.

After considering the data obtained during this recalibration, it was felt that the desired D_{50}'s might possibly be obtained by removal of the vortex busters in the collection cups of the Large and Middle Cyclones. The resulting large tangential velocities near the walls of these cups would remove a sufficient number of particles to cause a significant and measurable change in the cut points.

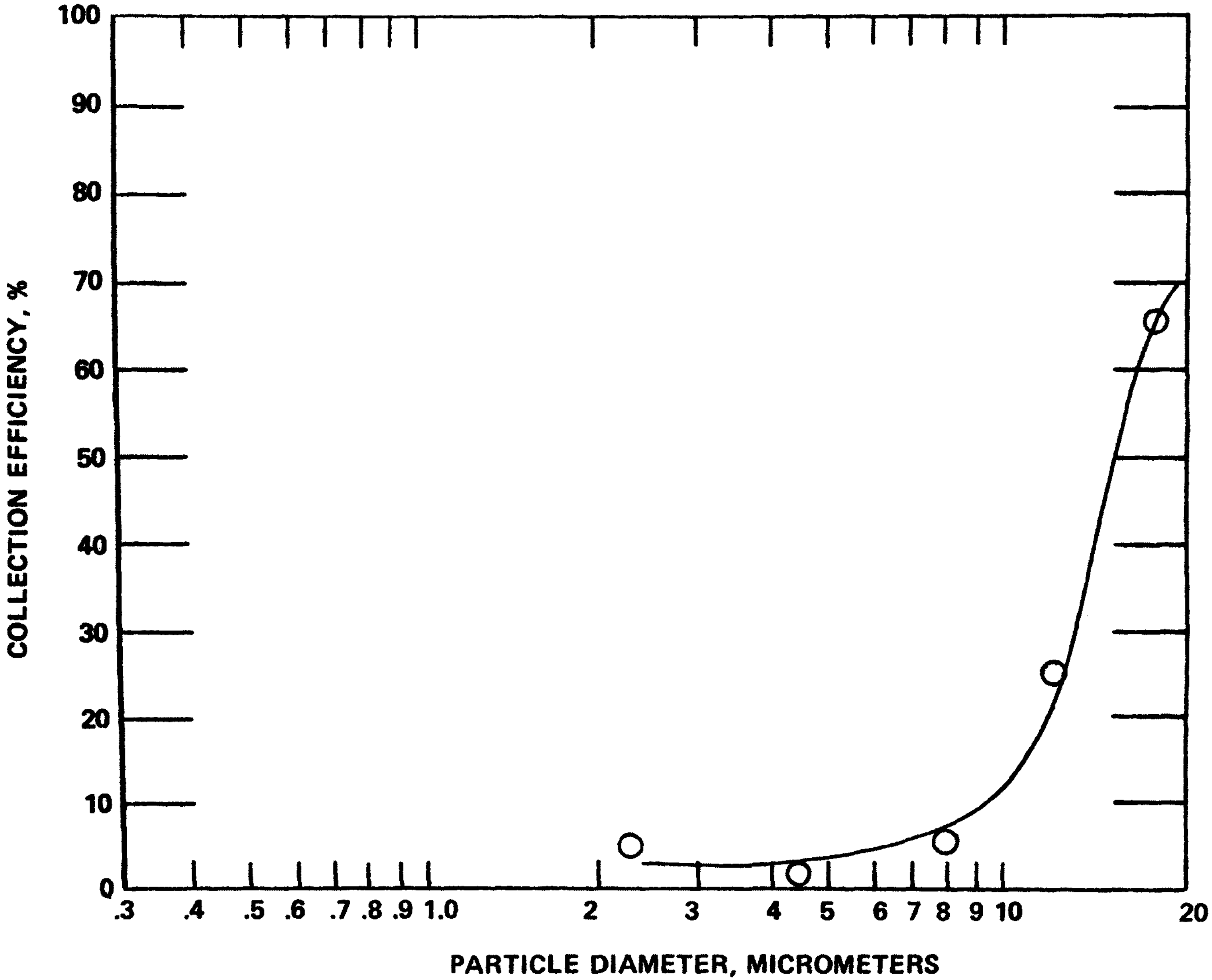


Figure 45. Collection efficiency vs. particle diameter. Large SASS cyclone. (4 SCFM, 400°F, 1.00 gm/cm^3)

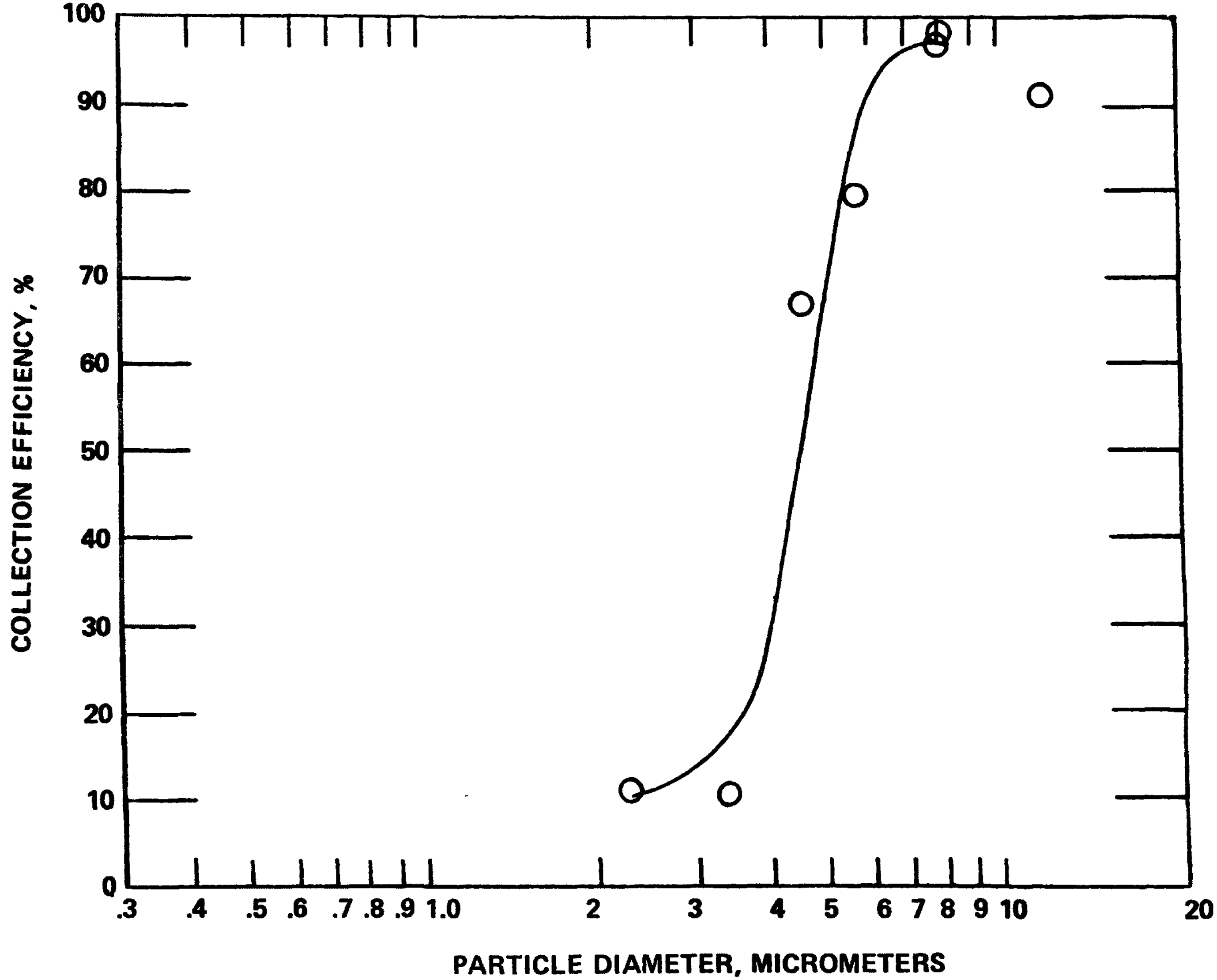


Figure 46. Collection efficiency vs. particle diameter. Unmodified middle SASS cyclone. (4 SCFM, 400°F, 1.00 gm/cm^3)

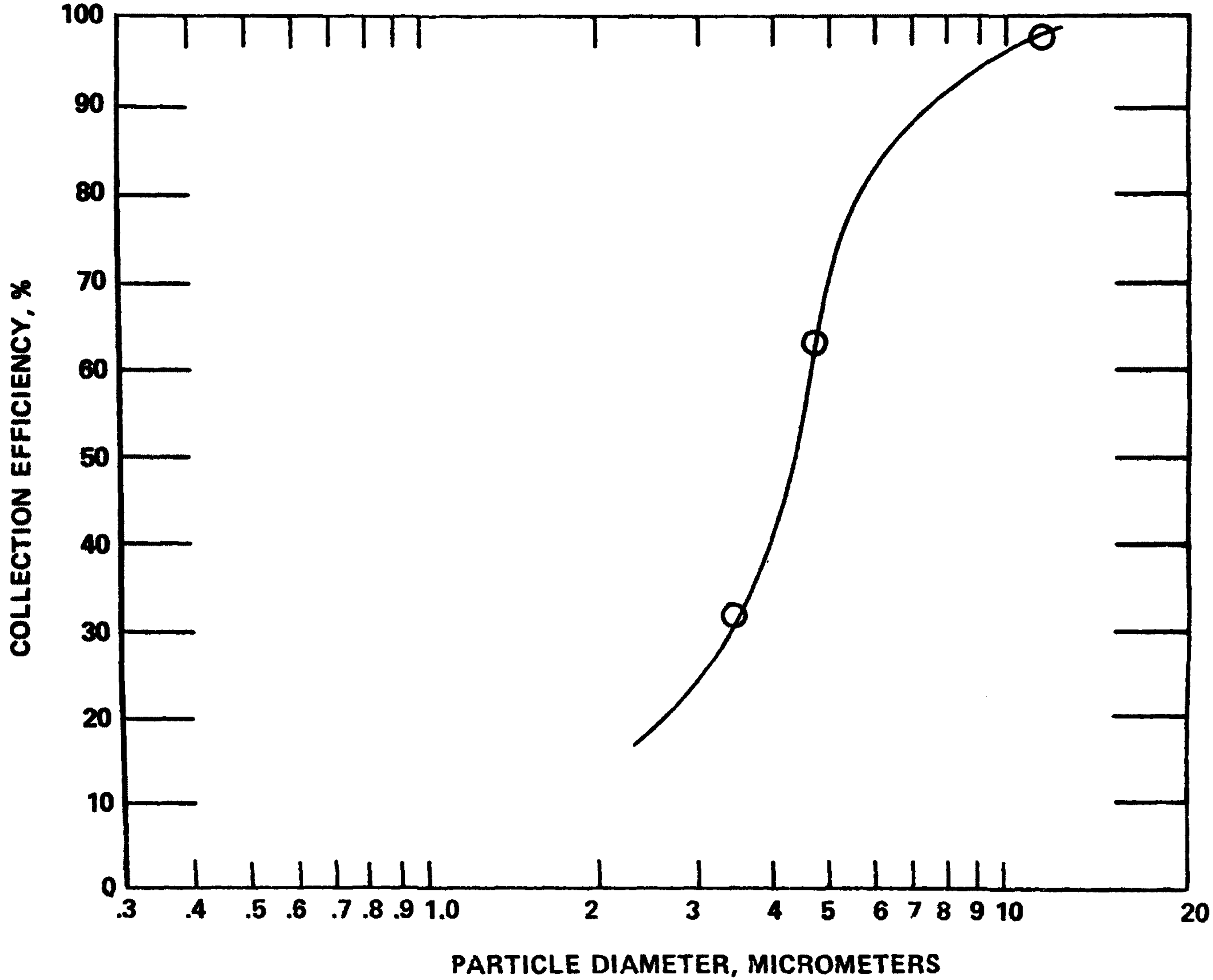


Figure 47. Collection efficiency vs. particle diameter. Modified middle SASS cyclone. (4 SCFM, 400°F, 1.00 gm/cm^3)

On September 14, 1976, a meeting was held at Research Triangle Park to discuss the results of the recalibration of the SASS train cyclones at 4 SCFM and 400°F. It was decided that the results of this study were not sufficiently conclusive to recommend changes in the cyclone construction to obtain the desired cut points of 10, 3, and 1 micrometer at operating conditions of 400°F and 4 SCFM. Data were presented indicating possible physical changes in the ammonium fluorescein aerosol at high temperature. Also the shift in the cyclone calibration curves at these conditions was not expected based on current cyclone operation theories.

It was concluded that calibration with aerosols which could withstand these high temperatures should take place.

As a result of this meeting a decision was made to calibrate the Source Assessment Sampling System Middle Cyclone at 400°F and 4 SCFM. Because previous tests have indicated ammonium fluorescein was unstable at 400°F, a search was initiated for an aerosol with some or all of the following characteristics:

- Non-toxic
- Stable at temperatures up to 500°F or above
- Soluble in water or other non-toxic, non-residue forming solvent
- Amorphous - dries to form solid, homogeneous spheres when dispersed in solution from a VOAG
- Known or easily measured density
- Has a definite, distinct absorption spectrum peak for absorption spectroscopy measurement between 400 NM and 900 NM.

The initial search for such an aerosol was unsuccessful, so, ammonium fluorescein was used to determine the D_{50} cut points of the Middle Cyclone at 70°F, 200°F, and 350°F and 5.45 ACFM and the data obtained from these tests was used to extrapolate to determine the D_{50} cut point at 400°F. This method proved to be difficult when it was found that ammonium fluorescein particles smaller than 4 μm in diameter were unstable at 350°F. Attempts to alleviate this problem were largely unsuccessful. Meanwhile the search for an acceptable aerosol was continued using commercially available dyes.

Of several samples from three chemical companies, du Pont's "Pontamine" Fast Turquoise 8 GLP dye was the first found to satisfactorily meet the requirements listed above. A spectral analysis performed on a dilute water solution of this dye indicated a distinct absorption peak at 622 nanometers. Measurements with a Helium-Air pycnometer gave a density of 2.04 gm/cm^3. The sample seemed pure and its stability at 400°F was excellent. The expansion problems encountered with small diameter ammonium fluorescein particles were absent. Aerosol particles made from a solution of the dye in distilled water were very nearly, if not perfectly, spherical.

The calibration of the SASS train cyclones was performed using the Institute's Vibrating Orifice Aerosol Generator (VOAG). The VOAG generated monodisperse ammonium fluorescein particles and turquoise dye particles with diameters from 2 micrometers to 7 micrometers.

Throughout the testing, close watch was kept on the temperature and flow rate of the aerosol stream. Any discrepancies were quickly corrected, and readings of all temperatures were recorded periodically. Therefore repeatability of the tests and test results was insured.

After each test, the cyclone and filter substrates were washed to dissolve and rinse off all the aerosol particles. The wash solutions used were 0.1 N NH_4OH for ammonium fluorescein and a sodium bicarbonate solution for turquoise dye.

A Bausch and Lomb Spectronic 88 Spectrophotometer, calibrated with solutions of known concentration of the aerosol solute (turquoise dye or ammonium fluorescein) was used to measure the absorbance of the wash from the cyclone and the filter. From knowledge of the amount of wash solution, the dilution factor, if any, and the absolute concentration, the mass of particles in the cyclone and on the filter was calculated. With these two masses known, the collection efficiency of the cyclone for that particular particle size was calculated.

Results

Table XI lists the D_{50} cut points of the cyclone at various conditions. Figure 48 shows the collection efficiency curves of the cyclone when calibrated with ammonium fluorescein particles at 70°F, 200°F, and 350°F. The D_{50}'s obtained from these curves and plotted in Figure 49 indicate that the D_{50}-gas viscosity relationship is linear. This does not correspond to Lapple's[13] prediction that D_{50} would vary directly with the change in the square root of the gas viscosity.

Figure 50 shows the collection efficiency of the cyclone for ammonium fluorescein particles and turquoise dye particles when collected under similar conditions. The relative differences between the two aerodynamic D_{50} cut points derived from the two curves differ from the prediction of Lapple's equation by only 7%.

Table XII

SASS Middle Cyclone Calibration Data

Material	Vortex Buster	Temperature	Flow Rate ft.^{3}/min Actual/Standard	D_{50} Physical Micrometers	D_{50} Aerodynamic Micrometers
Ammonium Fluorescein	IN	Ambient	5.37/——	2.8	3.3
Ammonium Fluorescein	IN	200°F	5.41/——	3.5	4.0
Ammonium Fluorescein	IN	350°F	5.46/——	4.2	4.9
Turquoise Dye	IN	Ambient	5.42/——	2.2	3.1
Turquoise Dye	OUT	400°F	6.50/4.00	2.5	3.5
Turquoise Dye	IN	400°F	6.50/4.00	3.4	4.9

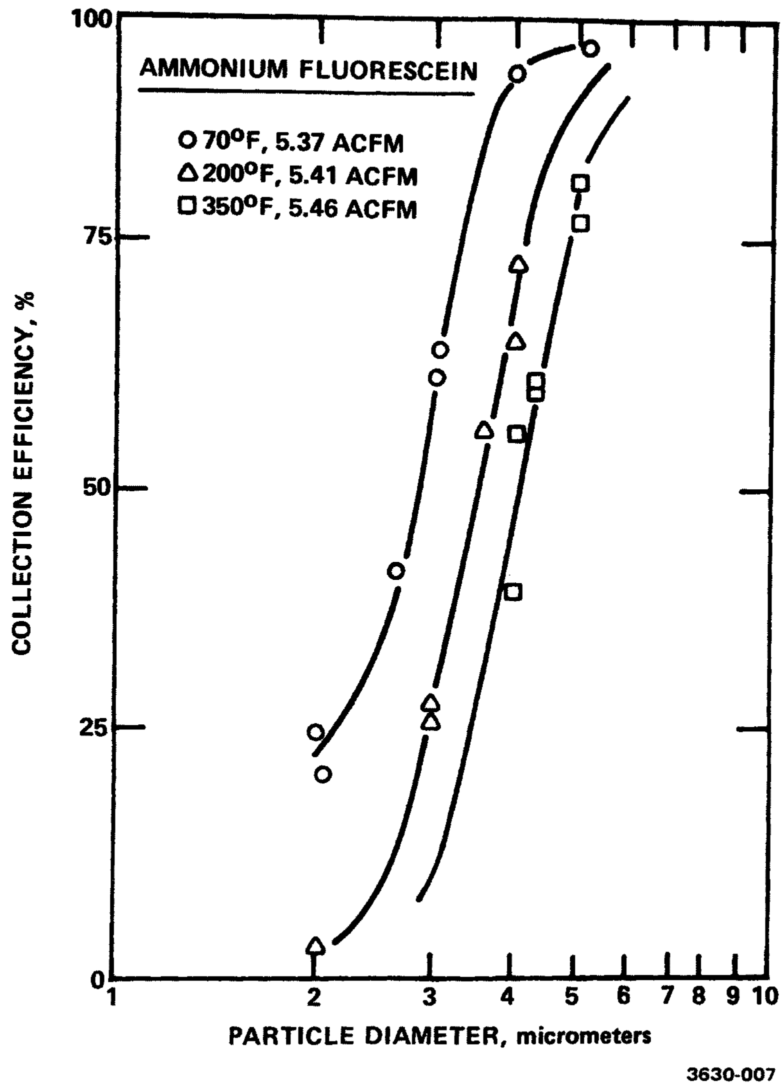


Figure 48. Collection efficiency - temperature relationship SASS middle cyclone. Ammonium fluorescein particle density = 1.35 gm/cm^3.

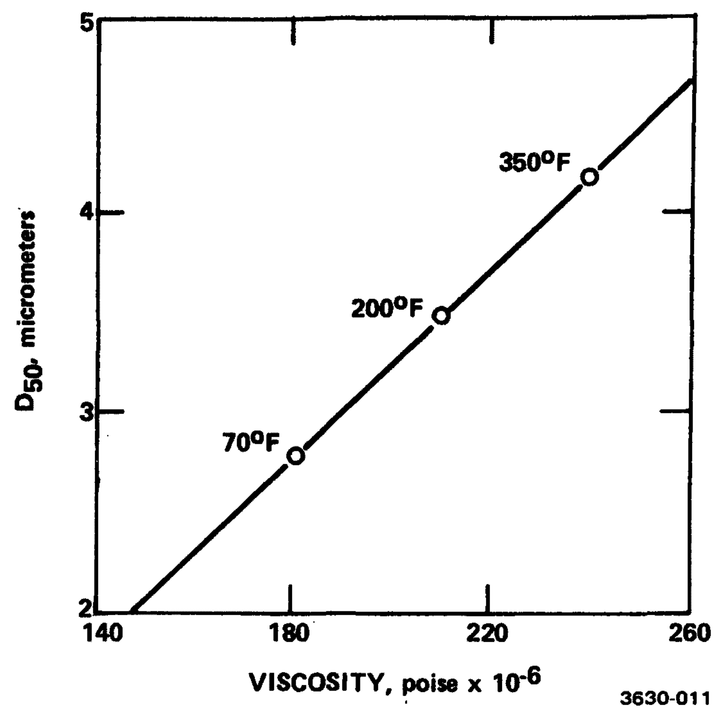


Figure 49. D_{50} - viscosity relationship SASS middle cyclone. Ammonium fluorescein particle density = 1.35 gm/cm^3.

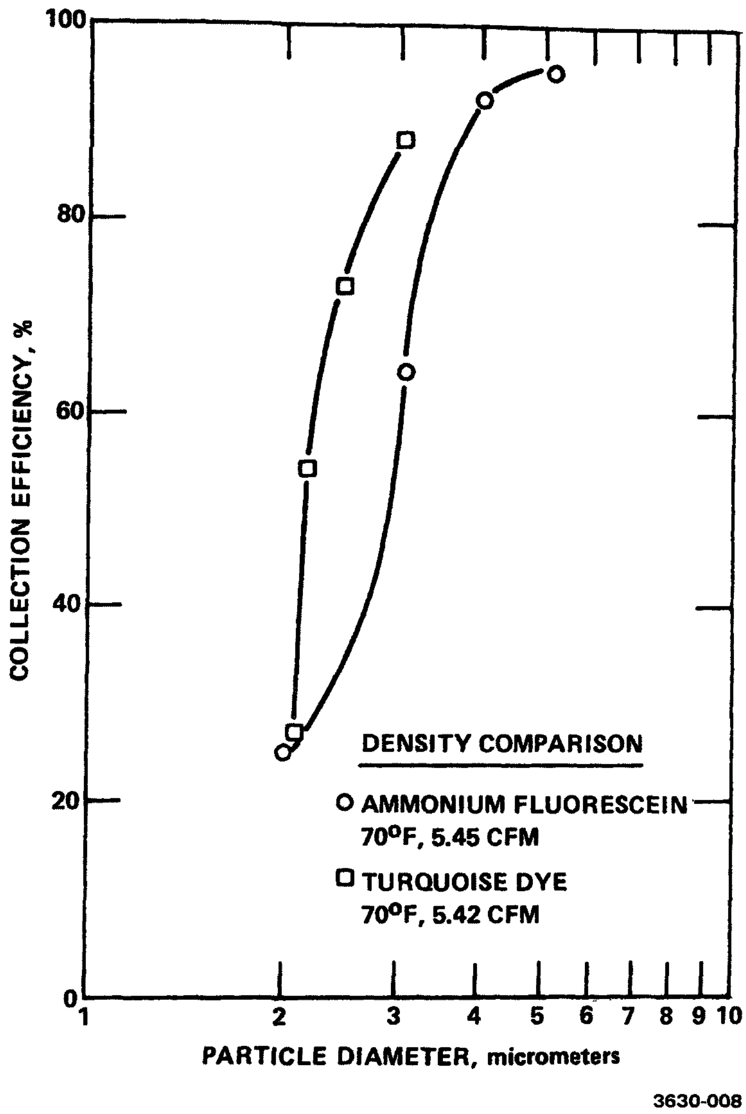


Figure 50. Collection efficiency - particle density relationship SASS middle cyclone. Ammonium fluorescein particle density = 1.35 gm/cm^3. Turquoise dye particle density = 2.04 gm/cm^3.

Figure 51 shows the collection efficiency curves of the cyclone when calibrated with turquoise dye particles with and without the vortex buster in place. It was determined using Lapple's equation that the D_{50} cut point of the cylcone with the vortex buster removed is 3.5 μm for 1.00 gm/cm^3 particles, which is within the acceptable range.

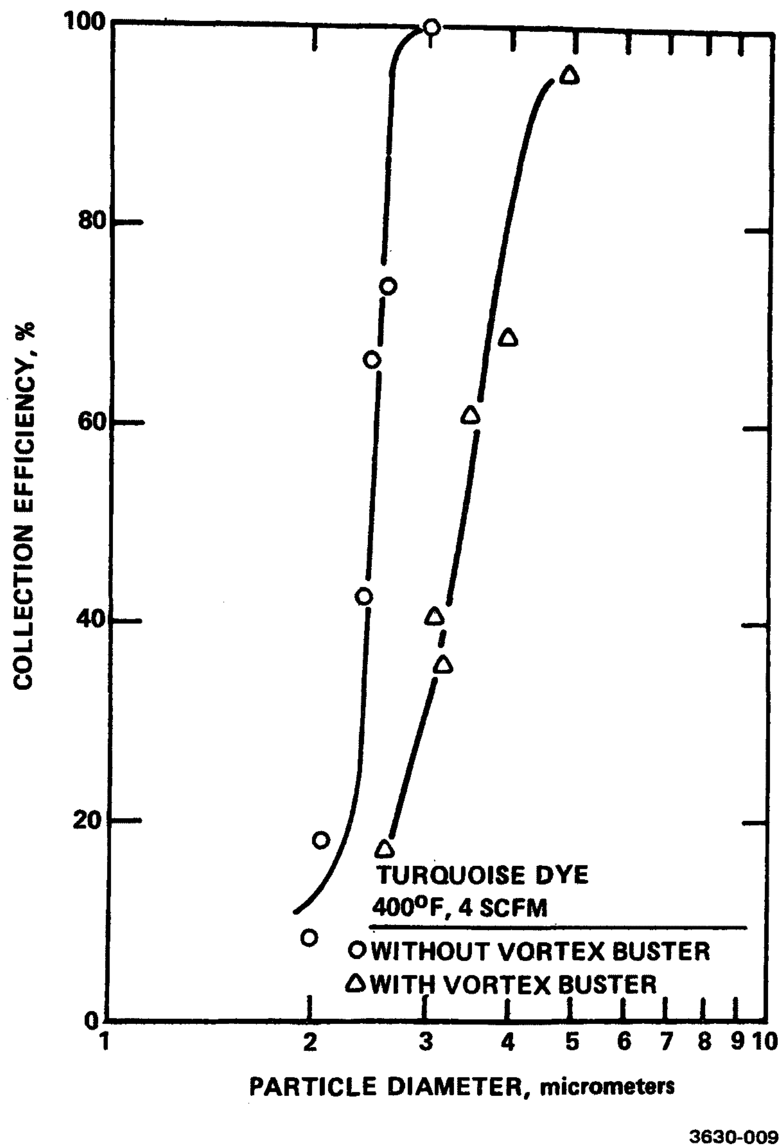


Figure 51. Collection efficiency at 400°F, 4 SCFM SASS middle cyclone. Turquoise dye particle density = 2.04 gm/cm^3.

PROCEDURES MANUAL FOR ELECTROSTATIC PRECIPITATOR EVALUATION

A manual entitled "Procedures Manual for Electrostatic Precipitator Evaluation," EPA-600/7-77-059, June 1977 (NTIS PB 209 698/7BE) has been written. The purpose of this procedures manual is to describe methods to be used in characterizing the performance of electrostatic precipitators for air pollution control. A detailed description of the mechanical and electrical characteristics of precipitators is given. Procedures are described for measuring the particle size distribution, the mass concentration of particulate matter, and the concentrations of major gaseous components of the flue gas-aerosol mixture. Procedures are also given for measuring the electrical resistivity of the dust. A concise discussion and outline is presented which describes the development of a test plan for the evaluation of an industrial precipitator. Several appendixes contain detailed information on testing methods as well as a listing of the Federal Stationary Source Performance Standards and Federal Source Testing Reference Methods.

To give a better idea of the scope of this document the contents listing is reproduced below.

INTRODUCTION
- ELECTROSTATIC PRECIPITATOR INSTALLATIONS
  - Types of Electrostatic Precipitators
  - Characteristics of Typical Precipitator Installations
  - Parameters Which Govern Electrostatic Precipitator Operation
- PARTICULATE SAMPLING FOR ELECTROSTATIC PRECIPITATOR EVALUATION
  - General Problems
  - Particulate Mass Measurements
  - Particle Sizing Techniques
  - Particulate Resistivity Measurements

TECHNICAL DISCUSSION
- ELECTRICAL AND MECHANICAL CHARACTERIZATION OF AN ELECTROSTATIC PRECIPITATOR
  - Electrical and Mechanical Design Data
  - Collecting Electrode System
  - Discharge Electrode System
  - Electrical Power Supplies
  - Rapping Systems
  - Dust Removal Systems
- MASS EMISSION MEASUREMENTS
  - General Discussion
  - EPA-Type Particulate Sampling Train
  - ASTM-Type Particulate Sampling Train
  - ASME-Type Particulate Sampling Train
  - General Sampling Procedures

PARTICLE SIZE MEASUREMENT TECHNIQUES
General Discussion
Inertial Particle Sizing Devices
Optical Measurement Techniques
Ultrafine Particle Sizing Techniques
PARTICULATE RESISTIVITY MEASUREMENTS
General Discussion
Laboratory Determination of Particulate Resistivity
In Situ Particulate Resistivity Measurement
PROCESS EFFLUENT GAS ANALYSIS
General Discussion
Qualitative Gas Analysis
Quantitative Gas Analysis
DEVELOPMENT OF TEST PLANS FOR ELECTROSTATIC PRECIPITATOR EVALUATION
General Discussion
Level A Evaluation
Level B Evaluation
Level C Evaluation

Appendix A - AEROSOL FUNDAMENTALS, NOMENCLATURE, AND DEFINITIONS

Appendix B - PARTICULATE MASS CONCENTRATION MEASUREMENTS

Appendix C - CASCADE IMPACTOR SAMPLING TECHNIQUES

Appendix D - SIZE DISTRIBUTIONS OF SUBMICRON AEROSOL PARTICLES

Appendix E - LABORATORY DETERMINATION OF PARTICULATE RESISTIVITY

Appendix F - IN SITU PARTICULATE RESISTIVITY MEASUREMENTS

Appendix G - FEDERAL STATIONARY SOURCE PERFORMANCE REFERENCE METHODS

Appendix H - FEDERAL STATIONARY SOURCE PERFORMANCE STANDARDS

REVIEW OF DOCUMENTS AND REPORTS FURNISHED BY EPA

During the course of this contract two documents furnished by our Project Officer were critically reviewed. Criticisms, comments, and suggestions for improvement were returned to the Task Officer in charge. These documents were:

IERL-RTP Procedures Manual: Level 1 Environmental Assessment by J. W. Hamersma, S. L. Reynolds, and R. F. Maddalone, EPA-600/2-76-160a, June 1976.

Procedures For Cascade Impactor Calibration and Operation in Process Streams by D. Bruce Harris, EPA-600/2-77-004, January 1977.

U.S.A.-U.S.S.R. SCIENTIFIC INFORMATION EXCHANGE PROGRAM

Under this task Southern Research Institute personnel participated as consultants on particle sizing in a program of technical information exchange with scientists in the Soviet Union. During July, 1976 particle sizing equipment was prepared and shipped to the Soviet Union for a field testing program at a scrubber installed on a metallurgical plant. Mr. J.D. McCain of the Southern Research Institute staff accompanied several EPA staff scientists to the test site. The actual field test took place during August, 1976. No results have been published as of this date.

EPA/IERL/PMB EXHIBIT BOOTH AT THE 1977 APCA ANNUAL MEETING

On June 21, 22, 23, 1977, the Process Measurements Branch of IERL/RTP supported an exhibit booth at the 70th Annual Air Pollution Control Association Meeting in Toronto, Ontario, Canada. This 10' x 20' booth used a color scheme of dark blue booth back wall and side walls, light blue carpet, and green draped tables. Three tables along the back wall were used for document display. Two tables, one on each side, were used to display hardware. On the white 1' x 20' header board in black letters was printed the following title:

United States Environmental Protection Agency
Industrial Environmental Research Laboratory - RTP
Process Measurements Branch

On either side of the title was an EPA LOGO in color.

On the back wall were hung six 3' diameter discs which briefly described the research and development efforts of the six 1977 Task Level of Effort contractors for the PMB. These six contractors were Acurex/Aerotherm, Arthur D. Little, Inc., Research Triangle Institute, Southern Research Institute, The Research Corporation of New England, and TRW, Inc. Representatives from each of the contractors were at the booth on a rotating basis to answer technical questions.

The hardware on display included a complete Source Assessment Sampling System, a KLD Droplet Analyser, and a Five Stage Series Cyclone and IERL/PMB Advanced Sampling System.

Approximately 200 copies each of twenty-one EPA Research and Development Reports were distributed on a first-come, first served basis to the 4200 registrants at the meeting.

The following is a list of the documents which were distributed:

HP-25 Programmable Pocket Calculator Applied to Air Pollution Measurement Studies: Stationary Sources. EPA-600/7-77-058, June 1977

Procedures Manual for Electrostatic Precipitator Evaluation, EPA-600/7-77-059, June 1977

Industrial Environmental Research Laboratory - RTP Annual Report 1976

Flow and Gas Sampling Manual. EPA-600/2-76-203, July 1976

IERL-RTP Procedures Manual: Level 1 Environmental Assessment. EPA-600/2-76-106a, June 1976

Selection and Evaluation of Sorbent Resins for the Collection of Organic Compounds. EPA-600/7-77-044, April 1977

Technical Manual for Measurement of Fugitive Emissions: Upwind/Downwind Sampling Method for Industrial Emissions. EPA-600/2-76-089a, April 1976

Technical Manual for the Measurement of Fugitive Emissions: Roof Monitor Sampling Method for Industrial Fugitive Emissions. EPA-600/2-76-089b, May 1976

Technical Manual for Measurement of Fugitive Emissions: Quasi-Stack Sampling Method for Industrial Fugitive Emissions. EPA-600/2-76-089c, May 1976

Technical Manual for Process Sampling Strategies for Organic Materials. EPA-600/2-76-122, April 1976

Technical Manual for Analysis of Organic Materials in Process Streams. EPA-600/2-76-072, March 1976

Particulate Sizing Techniques for Control Device Evaluation: Cascade Impactor Calibrations. EPA-600/2-76-280. October 1976

Inertial Cascade Impactor Substrate Media for Flue Gas Sampling. EPA-600/7-77-060, June 1977

Operating and Service Manual: Source Assessment Sampling System. Acurex/Aerotherm Report UM-77-81, March 1977

Environmental Assessment Sampling and Analysis: Phased Approach and Techniques for Level 1. EPA-600/2-77-115, June 1977

Procedures for Cascade Impactor Calibration and Operating in Process Streams. EPA-600/2-77-004, January 1977

Technical Manual for Inorganic Sampling and Analysis. EPA/2-77-024, January 1977

Development and Trial Field Application of a Quality Assurance Program for Demonstration Projects. EPA-600/2-76-083, March 1976

HP-65 Programmable Pocket Calculator Applied to Air Pollution Measurement Studies: Stationary Sources. EPA-600/8-76-002, October 1976.

Process Measurements Branch: Report Listing, June 1, 1977

Pollution Control Technology and Environmental Assessment: Brochure Describing the Research and Development Efforts of the Six PMB Contractors

At the conclusion of the exhibit all of the reports had been given out, except for a few HP-65 booklets. Reaction to the exhibit by the attendees at the meeting was quite favorable.

CALIBRATION OF A SASS MIDDLE CYCLONE FOR THE HEALTH EFFECTS RESEARCH LABORATORY/RTP

Exxon Research and Engineering Corporation used a Source Assessment Sampling System at a coal-fired power plant in Paducah, Kentucky early in 1977. This work was performed for the Health Effects Research Laboratory of the National Environmental Research Center/RTP. The SASS was used to size and sample the particulate effluent. In order to determine the actual Middle Cyclone D_{50} as run Southern Research Institute was requested to calibrate the actual SASS Middle Cyclone used by Exxon at the actual sampling conditions.

Exxon used the following sampling conditions.

- 600°F inlet gas temperature to the oven
- Oven temperature 375°F
- No filter element in the filter housing in the heated oven
- Pump flow wide open with filter on pump inlet and muffler on pump outlet
- Vacuum measured ahead of pump filter - 14 inches H_2O vacuum under sampling conditions
- Stack moisture 8%
- Gas temperature in middle cyclone unknown
- Vortex busters in the collection cups of the Large and Middle cyclones

These conditions and those of the calibration system were not completely compatible. The inlet gas temperature was 450°F, the constraint being the temperature limit of the calibration aerosol. The oven temperature was 375°F. The humidity of the air was not measured.

No probe was supplied with the cyclones; however, a telephone conversation revealed that Exxon used an Aerotherm probe which was twelve feet long. The sampling line of this probe is one-half inch O.D. Stainless Steel tube. The heat loss through this probe in our lab was unacceptable, and the particle loss would probably be quite high. Also a filter had to be used in the filter holder so that all the mass would be caught for collection efficiency determinations. Therefore, the flow rate at the inlet of the large cyclone had to be determined. The field set-up was duplicated as closely as possible and the flow was measured to be 13 ACFM at an oven inlet temperature of 399°F. Then the probe was removed and a glass fiber filter was added to the filter holder. The flow was adjusted so that the inlet flow to the cyclones was 13 ACFM. There was a definite but unknown amount of water in the air.

A note should be made as to the conditions of the cyclones when they arrived. There were a few dents in the cup and the inlet of the Middle cyclone was bent such that the air stream did not enter the cyclone strictly tangentially. The only modification made to the cyclones by SoRI was replacement of some teflon gaskets which were badly deformed.

The calibration system used was a Vibrating Orifice Aerosol Generator with du Pont "Pontamine" Fast Turquoise 8 GLP dye as an aerosol. The collected particles were washed off the cyclones and filter with a sodium bicarbonate solution, and their mass was determined with a spectrophotometer.

For a temperature of 450°F, a flow of 13 cfm, and a particle density of 2.04 gm/cm^3, the D_{50} cut points of the large and middle cyclones were 7.6 μm and 2.13 μm, respectively (see Figure 52). For a particle density of 1.00 gm/cm^3 and the same conditions, the D_{50} cut point of the large and middle cyclones would be 11 μm and 3.0 μm, respectively.

Estimation of D_{50} of Middle Cyclone at 600°F

The D_{50} cut point for the Middle cyclone is 3.0 μm for a temperature of 450°F, a flow rate of 13 CFM, and a particle density Of 1.00 gm/cm^3, with the vortex buster in place. Experimental work with the middle cyclone has indicated the following may be obtained by extrapolating the D_{50} vs. viscosity curve.

Flow Rate	D_{50}	Temperature	Particle Density
5.4 CFM	5.0 μm	375°F	1.00 gm/cm^3
5.4 CFM	5.8 μm	450°F	1.00 gm/cm^3
5.4 CFM	6.2 μm	600°F	1.00 gm/cm^3

Assuming that the D_{50} cut point will increase at the same rate with increasing temperature at flow rates of 5.4 and 13.0 CFM, the following relationships are obtained.

$$\frac{D_{50}\ (600°F;\ 13\ CFM)}{D_{50}\ (450°F;\ 13\ CFM)} = \frac{D_{50}\ (600°F;\ 5.4\ CFM)}{D_{50}\ (450°F;\ 5.4\ CFM)}$$

and

$$\frac{D_{50}\ (375°F;\ 13\ CFM)}{D_{50}\ (450°F;\ 13\ CFM)} = \frac{D_{50}\ (375°F;\ 5.4\ CFM)}{D_{50}\ (450°F;\ 5.4\ CFM)}$$

Thus,

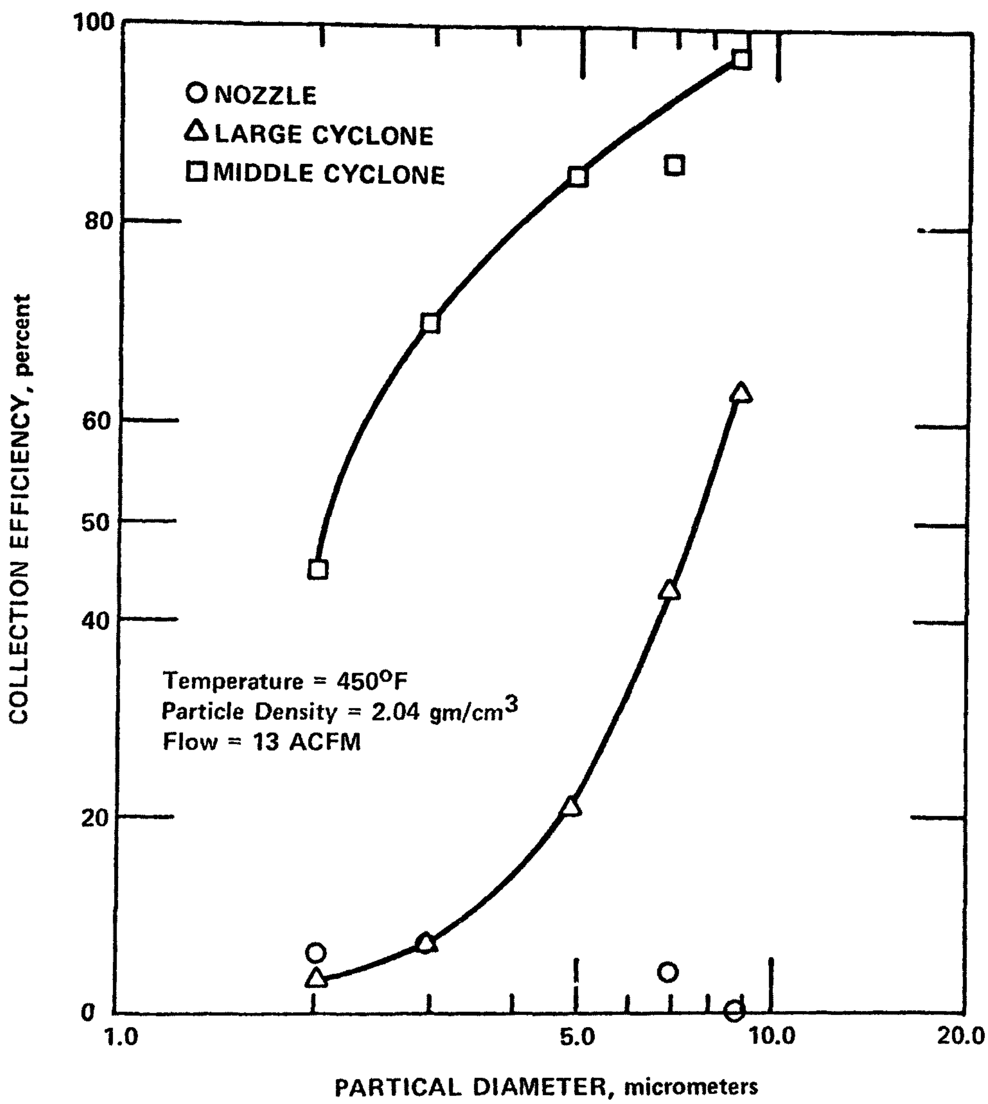


Figure 52. Exxon SASS cyclones.

$$D_{50}\ (600°F,\ 13\ CFM) = 3.0 \times \frac{6.2}{5.8} = 3.2\ \mu m.$$

and

$$D_{50}\ (375°F;\ 13\ CFM) = 3.0 \times \frac{5.0}{5.8} = 2.6\ \mu m.$$

Therefore, the D_{50} cut points of the middle cyclone for a flow rate of 13 ACFM were estimated to be 2.6 μm for a temperature of 375°F, and 3.2 μm for a temperature of 600°F.

Estimation of D_{50} of Small Cyclone at 600°F

The small cyclone has previously been calibrated at two flows:

Flow	D_{50}	Temperature	Particle Density
1.8 ACFM	1.88	77°F	1.00 gm/cm^3
3.1 ACFM	1.11	77°F	1.00 gm/cm^3

Using this relationship $D_{50} = KQ^N$ from Chan and Lippmann[17]

$$\frac{D_{50}\ (1.88)}{D_{50}\ (1.11)} = \frac{K\ (1.8)^N}{K\ (3.1)^N}$$

$$N = -0.97$$

So

$$D_{50} = KQ^{-0.97}$$

or

$$1.88 = K\ (1.8)^{-0.97}$$

$$K = 3.32$$

Assuming the D_{50} vs. Q relationship above holds at Q = 13 ACFM,

$$D = 3.32Q^{-0.97}$$

$$= 3.32(13)^{-0.97}$$

$$= 0.277\ \mu m.$$

Recent experimental work with the Five Stage Series Cyclone II (which has identical dimensions as the SASS small cyclone except for the width and depth of the cup) has indicated the following

Flow	D_{50}	Temperature	Particle Density
1 CFM	2.30 μm	77°F	1.00 gm/cm^3
1 CFM	5.21 μm	600°F	1.00 gm/cm^3
1 CFM	4.11 μm	375°F	1.00 gm/cm^3

Assuming that the D_{50} cut point will increase at the same rate with increasing temperature at flows of 1 and 13 CFM, we obtain the following relationships:

$$\frac{D_{50}\ (600°F;\ 13\ CFM)}{D_{50}\ (77°F;\ 13\ CFM)} = \frac{D_{50}\ (600°F,\ 1\ CFM)}{D_{50}\ (77°F,\ 1\ CFM)}$$

and

$$\frac{D_{50}\ (375°F;\ 13\ CFM)}{D_{50}\ (77°F;\ 13\ CFM)} = \frac{D_{50}\ (375°F;\ 1\ CFM)}{D_{50}\ (77°F;\ 1\ CFM)}$$

Thus, the D_{50} cut points of the small cyclone for a flow of 13 ACFM were estimated to be 0.49 μm for a temperature of 375°F and 0.63 μm for a temperature of 600°F.

PROCEDURES MANUAL FOR FABRIC FILTER EVALUATION

The procedures manual for the evaluation of fabric filters (baghouses) has been published under the title "Procedures Manual for Fabric Filter Evaluation." EPA-600/7-78-113, June 1978 (NTIS-PB 283 289).

The purpose of this procedures manual was to describe methods to be used in experimentally characterizing the performance of fabric filters for pollution control. A detailed description of the mechanical characteristics of fabric filters is presented. Procedures are described for measuring the particle size distribution, the mass concentration of particulate matter, and the concentration of major gaseous components of the flue gas-particle mixture. A concise discussion and outline is presented which describes the development of a test plan for the evaluation of a fabric filter installation. By following this outline useful tests may be performed which range in complexity from qualitative and relatively inexpensive to rather elaborate research programs.

In order to detail the scope of this document the Table of Contents is reproduced below.

INTRODUCTION
- FABRIC FILTER INSTALLATIONS
  - Particle Filtering Mechanisms
  - Factors Affecting Filter Performance
  - Filter Fabrics
  - Types of Fabric Filters
- PARTICULATE SAMPLING FOR FABRIC FILTER EVALUATION
  - General Considerations
  - Particulate Mass Measurements
  - Particle Sizing Techniques

TECHNICAL DISCUSSION
- MECHANICAL CHARACTERIZATION OF A FABRIC FILTER INSTALLATION
  - Mechanical Design and Operating Data
  - The Fabric Filter Bags
  - Filter Fabrics
  - Dust Removal Systems
  - Baghouse Operation-General Maintenance Considerations
- MASS EMISSION MEASUREMENTS
  - General Discussion
  - EPA-Type Particulate Sampling Train (Method 5)
  - ASTM-Type Particulate Sampling Train
  - ASME-Type Particulate Sampling Train
  - General Sampling Procedures

PARTICLE SIZE MEASUREMENT TECHNIQUES
General Discussion
Inertial Particle Sizing Devices
Optical Measurement Techniques
Ultrafine Particle Sizing Techniques

PROCESS EFFLUENT GAS ANALYSIS
General Discussion
Qualitative Gas Analysis
Quantitative Gas Analysis

DEVELOPMENT OF TEST PLANS FOR FABRIC FILTER EVALUATIONS
OBJECTIVES OF CONTROL DEVICE TESTS
TYPE AND NUMBER OF TESTS REQUIRED
Fabric Filter Level A Evaluation
Plant Operating Data
Baghouse-Fabric Filter Design Data
Flue Gas Characteristics, Baghouse ΔP, Maintenance Data
Fabric Filter Level B Evaluation
Quantitative Gas Analysis
Inlet and Outlet Mass Concentration Measurements Total Mass Collection Efficiency
Fabric Filter Level C Evaluation

GENERAL PROBLEMS AND CONSIDERATIONS

APPENDICES

Appendix A - AEROSOL FUNDAMENTALS, NOMENCLATURE, AND DEFINITIONS

Appendix B - PARTICULATE MASS CONCENTRATION MEASUREMENTS

Appendix C - CASCADE IMPACTOR SAMPLING TECHNIQUES

Appendix D - SIZE DISTRIBUTIONS OF SUBMICRON AEROSOL PARTICLES

Appendix E - SUMMARY OF SOURCE PERFORMANCE METHODS

Appendix F - FEDERAL STATIONARY SOURCE PERFORMANCE STANDARDS

ADVANCES IN PARTICLE SAMPLING AND MEASUREMENT SYMPOSIUM

Southern Research Institute coordinated a symposium for the Process Measurements Branch/IERL-RTP on May 15-17, 1978 at the Grove Park Inn and Country Club, Asheville, North Carolina. The number of attendees was 176. There were five sessions with a total of seventeen speakers. The symposium had morning and evening sessions with the afternoons free for recreation. A proceedings from this technical meeting has been published. The scope of the meeting can be seen in the following reprint of the technical program.

TECHNICAL PROGRAM

ADVANCES IN PARTICLE SAMPLING AND MEASUREMENT

A Symposium Sponsored by The Process Measurement Branch,
Industrial Environmental Research Laboratory,
U.S. Environmental Protection Agency,
Research Triangle Park, North Carolina.

MONDAY MORNING, MAY 15

SESSION I: INSTRUMENTS AND TECHNIQUES FOR PARTICLE-SIZE ANALYSIS

8:30 am	Welcome Address - John K. Burchard (EPA), Director, Industrial Environmental Research Laboratory - RTP
8:40	Opening Remarks - Symposium Chairman, D. Bruce Harris (EPA/IERL-RTP)
8:55	Opening of Technical Program - Session Chairman, A. McFarland (Texas A & M)
9:00	First Paper - "Inertia Effects in Sampling Aerosols", C. N. Davies and M. B. Subari (U. of Essex, England)
9:45	Break
10:05	Second Paper - "Cyclone Sampler Performance", M. Lippmann (NYU) and T. L. Chan (Gen. Motors Res. Lab.)
10:50	Third Paper - "Research on Dust Sampling and Measurement in Our Laboratory", K. Iinoya (Kyoto U., Japan)
11:35	First Session Adjourns

MONDAY EVENING

SESSION II: INSTRUMENTS AND TECHNIQUES FOR PARTICLE-SIZE ANALYSIS (CONTINUED)

7:30 pm	Call to Order - Session Chairman, D. Lundgren (U. of Florida)
7:35	First Paper - "Sizing Submicron Particles with a Cascade Impactor", M. Pilat (U. of Washington)
8:20	Second Paper - "Experience in Sampling Urban Aerosols with the Sinclair Diffusion Battery and Nucleus Counter", D. Sinclair and E. Knutson (Dept. of Energy)
9:05	Third Paper - "Selecting Laboratory Instruments for Particle Sizing", R. Draftz (IITRI)
9:50	Second Session Adjourns

TUESDAY MORNING, MAY 16

SESSION III: REAL-TIME MEASUREMENTS OF PARTICLE CONCENTRATION AND SIZE

8:30 am	Call to Order - Session Chairman, W. Kuykendal (EPA/IERL-RTP)
8:35	First Paper - "Long-Term Field Evaluation of Continuous Particulate Monitors", A. W. Gnyp, S. J. W. Price, C. C. St. Pierre, and D. S. Smith (U. of Windsor, Canada)
9:20	Second Paper - "An In-Situ Stack Fine Particle Size Spectrometer - A Discussion of Its Design and Development", R. Knollenberg (Particle Meas. Systems)
10:05	Break
10:25	Third Paper - "Optical Measurements of Particulate Size in Stationary Source Emissions", A. L. Wertheimer, W. H. Hart, and M. N. Trainer (Leeds & Northrup)
11:10	Fourth Paper - "Studies of Relating Plume Appearance to Emission Rate and Continuous Particulate Mass Emission Monitoring", K. T. Hood and H. S. Oglesby (NCASI)
11:55	Third Session Adjourns

TUESDAY EVENING

SESSION IV: DATA REDUCTION, ACCURACY AND QUALITY CONTROL

7:30 pm	Call to Order Session Chairman, T. T. Mercer (U. of Rochester)
7:35	First Paper - "A Data Reduction System for Cascade Impactors", J. D. McCain, G. I. Clinard, L. G. Felix, and J. W. Johnson (Sou. Res. Inst.)
8:20	Second Paper - "Aerosol Generation and Calibration of Instruments", D. Y. H. Pui and B. Y. H. Liu (U. of Minnesota)
9:05	Third Paper - "Collection Substrates for Cascade Impactors", D. B. Harris (EPA), G. I. Clinard, L. G. Felix, G. E. Lacey, and J. D. McCain (Sou. Res. Inst.)
9:50	Fourth Session Adjourns

WEDNESDAY MORNING, MAY 17

SESSION V: CONTROL DEVICE EVALUATION

8:30 am	Call to Order Session Chairman, G. B. Nichols (Sou. Res. Inst.)
8:35	First Paper - "Particle Size Measurement for Evaluation of Wet Scrubbers", S. C. Yung, R. Chmielewski, G. Monahan, and S. Calvert (APT, Inc.)
9:20	Second Paper - "Evaluation of Performance and Particle Size Dependent Efficiency of Baghouses", D. S. Ensor, R. C. Hooper, G. Markowski (MRI), and R. D. Carr (EPRI)
10:05	Break
10:25	Third Paper - "Evaluation of the Efficiency of Electrostatic Precipitators", W. B. Smith, J. P. Gooch, J. D. McCain, and J. E. McCormack (Sou. Res. Inst.)
11:10	Fourth Paper "Some Studies of Chemical Species in Fly Ash", L. D. Hulett, R. R. Turner, J. M. Dale, A. J. Weinberger, H. W. Dunn, C. Feldman, E. Ricci (Oak Ridge Nat. Lab.) and J. O. Thompson (Consultant)
12:00 noon	Symposium Adjourns

PRESENTATION TO FEDERAL REPUBLIC OF GERMANY

Under this technical directive Mr. J.D. McCain of Southern Research Institute wrote and presented a paper on manual particulate mass and size measurements at a workshop held in Julich, Federal Republic of Germany on March 16 and 17, 1978.

PARTICULATE SIZING INSTRUMENT EVALUATION

Criteria were developed for the evaluation of three real-time particle sizing instruments. The instruments are:

1. a light scattering instrument--Particle Measuring Systems, Inc., Boulder, CO
2. a light sensing virtual impactor--Meteorology Research, Inc., Altadena, CA
3. an acoustic instrument--KLD Associates, Huntington Station, NY

The suggested evaluation program is based on the operational principle of each instrument. The evaluation criteria based on measurable parameters that are of greatest interest to EPA/IERL/RTP have been developed to allow comparisons of the three instruments.

The test plan is entitled "Particulate Sizing Instrument Evaluation," Southern Research Institute Report Number SORI-EAS-78-595, October 6, 1978.

References

1. Cooper, Douglas W. and John W. Davis, "Cascade impactors for aerosols: Improved data analysis," Amer. Ind. Hyg. Assoc., p. 79, 1972.

2. Cooper, Douglas W. and Lloyd A. Spielman, "Data inversion using nonlinear programming with physical constraints: Aerosol size distribution measurement by impactors," Atmospheric Environment, Vol. 10, pp. 723-729, 1976.

3. Picknett, R. G., "A new method of determining aerosol size distributions from ministage sampler data," Aerosol Science, 1972.

4. McCain, J. D., K. M. Cushing, and W. B. Smith, "Methods for determining particulate mass and size properties: Laboratory and field measurements," J. APCA 24(12): 1172-1176, December 1974.

5. Rao, A. K., "An experimental study of inertial impactors," Ph.D. Dissertation, University of Minnesota, Minneapolis, Minnesota, 1975.

6. Dzubay, T. G., L. E. Hines and R. K. Stevens, "Particulate bounce errors in cascade impactors," Atmospheric Environment, Vol. 10, pp. 229-234, 1976.

7. Natusch, D. F. S. and J. R. Wallace, "Determination of air-borne particle size distributions: Calculation of cross-sensitivity and discreteness effects in cascade impaction," Atmospheric Environment, Vol. 10, pp. 314-324, 1976.

8. Cushing, K. M., J. D. McCain, and W. B. Smith, "Experimental Determination of sizing parameters and wall losses of five commercially available cascade impactors," in Proceedings of the 69th Annual Meeting of the Air Pollution Control Association, Portland, Oregon, 1976, paper No. 76-374.

9. Lundgren, D. A. (1967). "An aerosol sampler for determination of particle concentration as a function of size and time," J. APCA 17, pp. 225-229.

10. Smith, W. B., K. M. Cushing, and G. E. Lacey, Andersen Filter Substrate Weight Loss Study. EPA-650/2-75-022, U.S. Environmental Protection Agency, Research Triangle Park, N.C., 1975.

11. McCain, J. D., J. E. McCormack, and D. B. Harris. Non-Ideal Behavior in Cascade Impactors. 70th Annual Meeting, APCA, Toronto, Ontario, Canada, 1977. Paper 77-35.3.

12. Felix, L. G., G. I. Clinard, G. E. Lacey, and J. D. McCain. Inertial Cascade Impactor Substrate Media for Flue Gas Sampling. EPA-600/7-77-060, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1977, 89 pp.

13. Lapple, C. E. Processes Use Many Collector Types. Chemical Engineering, 58: 144-151, 1951.

14. Sproull, W. T. Air Pollution and Its Control. Exposition Press, New York, 1970.

15. Muschelknautz, E. Design of Cyclone Separators in the Engineering Practice. Staub-Reinhalt. Luft, 30(5): 1, 1970.

16. Leith, D. and W. Licht. The Collection Efficiency of Cyclone Type Particle Collectors-A New Theoretical Approach, A.I.Ch.E. Symposium Series, New York, New York, 1971, pp. 196-206.

17. Chan, T., and M. Lippmann. Particle Collection Efficiencies of Air Sampling Cyclones: An Empirical Theory. Environmental Science and Technology, 11(4): 377-382, 1977.

18. Ranz, W. D., and J. B. Wong. Impaction of Dust and Smoke Particles, Ind. and Eng. Chem., 50, No. 4 (April, 1958).

19. Marple, V. A. A Fundamental Study of Inertial Impactors. Ph.D. Thesis, Mechanical Engineering Department, University of Minnesota, Minneapolis, Minnesota 55455, 1970.

20. Willeke, K. Performance of the Slotted Impactor. Am. Ind. Hygiene Assoc. J., 683-691, September 1975.

APPENDIX

A List of Reports Written under Contract No. 68-02-2131

Particulate Sizing Techniques For Control Device Evaluation: Cascade Impactor Calibrations
Kenneth M. Cushing, George E. Lacey, Joseph D. McCain, Wallace B. Smith
EPA-600/2-76-280, October 1976, NTIS (PB 262 849/3BE)
(Original work supported by EPA Contract No. 68-02-0273.)

HP-65 Progammable Pocket Calculator Applied To Air Pollution Measurement Studies: Stationary Sources
James W. Ragland, Kenneth M. Cushing, Joseph D. McCain, Wallace B. Smith
EPA-600/8-76-002, October 1976, NTIS(PB 264 284/1BE)

HP-25 Programmable Pocket Calculator Applied To Air Pollution Measurement Studies: Stationary Sources
James W. Ragland, Kenneth M. Cushing, Joseph D. McCain, Wallace B. Smith
EPA-600/7-77-058, June 1977, NTIS(PB 269 666/4BE)

Procedures Manual for Electrostatic Precipitator Evaluation
Wallace B. Smith, Kenneth M. Cushing, Joseph D. McCain
EPA-600/7-77-059, June 1977, NTIS(PB 269 698/7BE)

Inertial Cascade Impactor Substrate Media For Flue Gas Sampling
Larry G. Felix, George I. Clinard, George E. Lacey, Joseph D. McCain
EPA-600/7-77-060, June 1977, NTIS(PB 276 583/2BE)

Development and Laboratory Evaluation of a Five-Stage Cyclone System
Wallace B. Smith, Rufus Ray Wilson, Jr.
EPA-600/7-78-008, January 1978, NTIS(PB 279 084/8BE)

Particulate Sampling Support: 1977 Annual Report
Kenneth M. Cushing, William E. Farthing, Larry G. Felix, Joseph D. McCain, Wallace B. Smith
EPA-600/7-78-009, January 1978, NTIS(PB 279 170/5BE)

A Computer-Based Cascade Impactor Data Reduction System
Jean W. Johnson, George I. Clinard, Larry G. Felix, Joseph D. McCain
EPA-600/7-78-042, March 1978, NTIS (PB 285 433)

Technical Mannual: A Survey of Equipment and Methods for Particulate Sampling in Industrial Process Streams
Wallace B. Smith, Paul R. Cavanaugh, Rufus Ray Wilson
EPA-600/7-78-043, March 1978, NTIS (PB 282 501)

Procedures Mannual For Fabric Filter Evaluation
Kenneth M. Cushing, Wallace B. Smith
EPA-600/7-78-113, June 1978, NTIS (PB 283 389)

An Electrostatic Precipitator Backup for Sampling Systems
P. Vann Bush, Wallace B. Smith
EPA-600/7-78-114, June 1978, NTIS (PB 283 660)

Evaluation of the PILLS-IV
William E. Farthing, Wallace B. Smith
EPA-600/7-78-130, July 1978, NTIS (PB 283 173)

A Data Reduction System for Cascade Impactors
Joseph D. McCain, George I. Clinard, Larry G. Felix, Jean W. Johnson
EPA-600/7-78-132a, July 1978

Design a Particle Sampling Test Facility
Norman L. Francis, Kenneth M. Cushing
SORI-EAS-78-560, September 22, 1978

Particulate Sizing Instrument Evaluation
William E. Farthing
SORI-EAS-78-595, October 6, 1978

Sampling Charged Particles With Cascade Impactors
William E. Farthing, David H. Hussey, Wallace B. Smith,
Rufus Ray Wilson, Jr.
EPA-600/7-79-027, January 1979

Guidelines For Particulate Sampling In Gaseous Effluents From
Industrial Processes
Rufus R. Wilson, Jr., Paul R. Cavanaugh, Kenneth Cushing,
William E. Farthing, Wallace B. Smith
EPA-600/7-79-028, January 1979

Proceeding: Advances in Particle Sampling and Measurement
(Asheville, North Carolina, May, 1978)
Wallace B. Smith, Compiler
EPA-600/7-79-065, February 1979

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16. ABSTRACT The report summarizes results of research, development, and support tasks performed during the 3-year period of the contract (11/75-11/78). The tasks encompassed many aspects of particulate sampling and measurement in industrial gaseous process and effluent streams. Under this contract: cascade impactors were calibrated and evaluated; novel particle sampling cyclones were designed and evaluated; technical and procedures manuals were prepared for control device evaluation and particle sampling methods; an electrostatic precipitator backup was designed for high flow rate systems; and advanced concepts in monitoring particle mass and size, using optical systems, were evaluated. A number of smaller tasks, involving lower levels of effort, are also discussed. The appendix lists technical documents published under the contract.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Impactors	Pollution Control	13B	13I
Dust	Cyclone Separators	Stationary Sources	11G	07A
Sampling	Electrostatic Pre-	Particulate	14B	
Measurement	cipitators	Cascade Impactors		
Optical Measurement				
Industrial Processes			13H	

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