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WIND TUNNEL EVALUATION OF PARTICLE SIZING INSTRUMENTS

Industrial Environmental Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, North Carolina 27711

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WIND TUNNEL
EVALUATION OF
PARTICLE SIZING INSTRUMENTS

by

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Mr. W. B. Kuykendal of the EPA Industrial Environmental Research Laboratory (Research Triangle Park, N. C.) provided overall direction for this work in his capacity as Project Officer.

CONCLUSIONS

The conclusions derived from this experimental work and subsequent data analysis are as follows:

1) Although the particulate aerodynamic test facility is equipped with 8 sampling ports, simultaneous sampling with more than one instrument in the tunnel did not yield reliable data. The concentration of particulate across the wind tunnel was not uniform, and instruments placed in upstream ports created a disturbance which was detected over the length of the tunnel. For instrument comparison, more consistent results were obtained by operating the wind tunnel continuously with steady state conditions and sampling with the instruments one at a time in the same port.

2) The Brink and Andersen Impactors and the Southern Series Cyclones yielded comparable results when measuring the particle size distribution of fly ash.

3) The Celesco Piezoelectric Microbalance Impactor yielded results consistent with those obtained using the Brink and Andersen Impactors and Series Cyclones. However, the extractive testing procedure resulted in an absence of data from the first three of the ten stages of the impactor due to sample line losses. Data from the last three of the ten stages were also lost because a measurable mass of particulate could not be collected on these stages without overloading the middle stages.

4) The GCA In-Stack Beta Impactor appeared to classify particles, but the distribution calculated from the data did not agree well with the Brink and Andersen results. More study is needed to clarify and perhaps improve on the conversion from beta attenuation to collected mass. The zero fluctuation problem must be eliminated before the instrument can be used with confidence. The amplifer gains should also be optimized to provide a detectable signal from the lower stages and to avoid pegging of the chart readout on the upper stages.

5) The differential particle size distributions obtained with the PILLS IV instrument did not agree at all with those obtained from the inertial classification devices. This result was not unexpected since the PILLS IV is an optical single-particle

counter. For the two types of instruments to be comparable, all of the particles should be spherical and of the same density. Neither of these conditions exists with fly ash.

6) No conclusions could be reached concerning the operation of the Thermo-Systems Electrical Aerosol Size Analyzer because erratic results were obtained. The problem was postulated to be inadequate static charge neutralization of the particles prior to entry into the instrument.

RECOMMENDATIONS

This project was a first effort to evaluate and compare the results of several particle sizing instruments which operate on various theoretical principles. Expanded studies that include other instruments as well as other industrial dusts are obviously needed to extend the value of existing experimental data and to better define the options available to the researcher faced with instrument selection for particle sizing studies.

Specific recommendations related to the equipment and instruments utilized in this study are enumerated below.

1) The EPA particulate aerodynamic test facility has been equipped with a new dust feed system since the completion of this study. Before particulate studies similar to this one are undertaken, the modified system should be thoroughly tested to characterize the stratification and upstream disturbance phenomena identified in this work. If these phenomena still exist, both total particulate mass and particle sizing measurements should employ duct traversing techniques or at least identical-point-sampling by all instruments to be compared.

2) The Brink and Andersen Impactors and the Southern Series Cyclones may be assumed to give equivalent particle size distribution data when operated under conditions similar to this study. Use of the Andersen cyclone precollector at a sample rate more than a few percent greater or less than 21.2 ℓ/min is not recommended until more extensive calibration tests are performed at other flow rates to determine the D_{50} and the shape of the collection efficiency curve in relation to the efficiency curves of the upper cascade stages.

3) The "brush" technique now employed to remove particles deposited in the cyclones and on impactor walls can lead to significant errors due to particles sticking to the brush and brush hairs contaminating the sample. A reasonable alternative might be washing of the surfaces with small volumes of a volatile solvent, followed by evaporation, dessication, and weighing. This and other possible alternative techniques should be investigated.

4) The PILLS IV instrument should not be used in a comparative situation with inertial separation devices until a method is established to correlate the results. Such a correlation would likely involve, as a minimum, the expression of particle shape and density as a function of size.

5) If the development of the GCA In-Stack Beta Impactor is to continue, the source of the zero fluctuation must be identified and eliminated. The correlation between beta attenuation and mass of particles on the substrates should be verified, and the gain of the individual stages should be optimized to allow data retrieval from the lower stages and to avoid pegging of the chart readout on the upper stages.

6) Consideration should be given to the development of an in-stack cascade impactor using piezoelectric crystals as stage substrates. Such an instrument could offer the advantages of near real-time operation and reasonably small physical size. The primary obstacle to overcome will be the low mass capacity of the crystals. An integrated, in-stack dilution system could possibly be developed to alleviate this limitation.

1.0 INTRODUCTION

In the last few years, particulate control technology has been developed to the extent that several methods are now available to collect large particles with an efficiency of greater than 99 percent. Emphasis on particulate control has now shifted toward the fine particle size range, particularly to particles which have diameters between 0.3 and 3 micrometers. These particles are of particular interest because they tend to remain in the atmosphere for long periods of time, thus contributing to atmospheric haze. They also tend to deposit in the human respiratory system when inhaled.

Many instruments have been developed to classify airborne particulate according to size. This research project was undertaken to evaluate and compare several particle sizing devices in a wind tunnel. Particulate concentrations more typical of stack conditions rather than atmospheric conditions were used. The scope of the project was originally intended to encompass three different types of particulate with different properties; however, because of unexpected complications with the dust dispersion system, the project was limited to a comparison of the instruments with fly ash from a coal-fired power plant at two concentration levels.

Two experimental approaches were utilized. In the first, three or more instruments were tested simultaneously in different ports of the wind tunnel. Replicate runs were made, alternating ports and instruments to average out any port bias. In the second experimental approach, which yielded more consistent data, particular care was taken to operate the wind tunnel at steady state conditions and the instruments were tested successively, one at a time, in the same port. Analysis of the data obtained by both approaches resulted in an evaluation of wind tunnel performance characteristics as well as a comparison of the particle sizing instruments.

2.0 CHARACTERISTICS OF THE WIND TUNNEL AND TEST CONDITIONS

The experimental portion of this project was conducted at the particulate aerodynamic test facility located at EPA, Environmental Research Center, Research Triangle Park, N. C. This facility, is basically a low speed wind tunnel. The lower leg of the tunnel is a modular 61 cm diameter duct, 12.2 m in length. Each of four test sections located in this leg is equipped with two opposing 15 cm test ports. Dust is injected just upstream of the first test section and is removed in a baghouse dust collector located at the end of the return air loop. The tunnel is thus closed-loop with respect to gas flow but open-loop with respect to particulate. Figure 1 is an isometric sketch of the wind tunnel showing the port designations utilized in this report.

Table 1 summarizes the operating conditions for the test program. The low concentration is a reasonable approximation of clean stack emissions and the high concentration is approximately an order of magnitude higher. The velocities are higher than those normally encountered in a stack test, but were necessary in order to minimize settling of large particles and to achieve the desired concentrations. A moderate temperature was chosen to avoid the complications of preheating and condensation devices in the sample trains.

Initially the experimental program was begun with the assumptions that the wind tunnel provided a uniform cross-sectional particulate concentration at all ports as indicated in the design manual (ref.1), and that upstream particulate sizing instruments would present a negligible disturbance to downstream positions. After several series of simultaneous tests were completed and the data were analyzed, it was apparent that these assumptions were invalid. A special test was designed to evaluate the constancy of total mass particulate concentrations across a chosen cross-section of the wind tunnel and to determine the effect of an upstream obstruction on the particulate distribution across the cross-section. An IKOR model 206 portable air quality monitor, which is a real-time instrument, was utilized for this test.

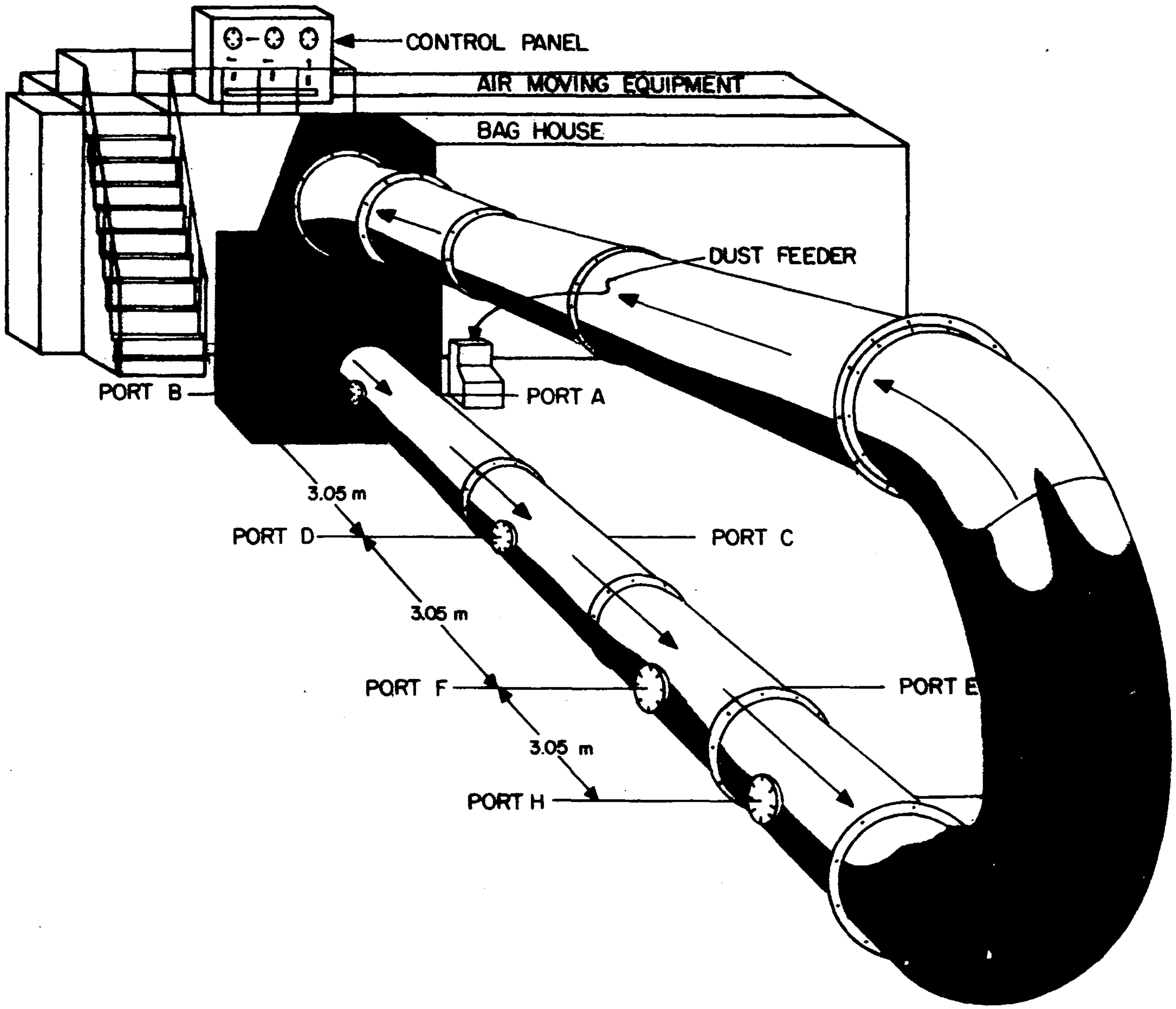

Figure 1. Isometric sketch of the particulate aerodynamic test facility.

Table 1. WIND TUNNEL OPERATING CONDITIONS

	High Concentration	Low Concentration
Velocity (m/s)	9.1	27.4
Temperature (°C)	27	27
Relative Humidity	50-60%	50-60%
Gas Composition	Air	Air
Fly Ash Feed (kg/hr)	8.3	2.3
Concentration (g/Nm^3)	0.955	0.089

In the IKOR model 206 a sample is continuously drawn through an electronic sensing head where the particulate generates an electric current by charge transfer. The current is proportional to total mass concentration. The IKOR was placed in port H to run horizontal traverses across the tunnel. The bottom portion of Figures 2 and 3 show the results of traverses with no upstream obstructions at velocities of 9.1 m/s and 27.4 m/s, respectively. These data indicate that the profile is definitely not uniform, and is possibly assymmetric with respect to the horizontal centerline of the wind tunnel.

To evaluate the effect of upstream obstructions, a section of 3.3 cm O.D. pipe was placed in the center of the flow stream, extending from top to bottom of the tunnel. The diameter of this pipe was approximately the same as that of a Brink Impactor. Horizontal traverses were then run at each velocity with the IKOR in port H and the pipe 3, 6, and 9 m upstream, corresponding to the upstream port locations. The results are plotted in Figures 2 and 3. The general tendency at both velocities is for the obstruction to depress the particulate concentration in the center and create peaks on each size between the vertical centerline and the wall. This effect is noticeable even when the obstruction is 9 m upstream.

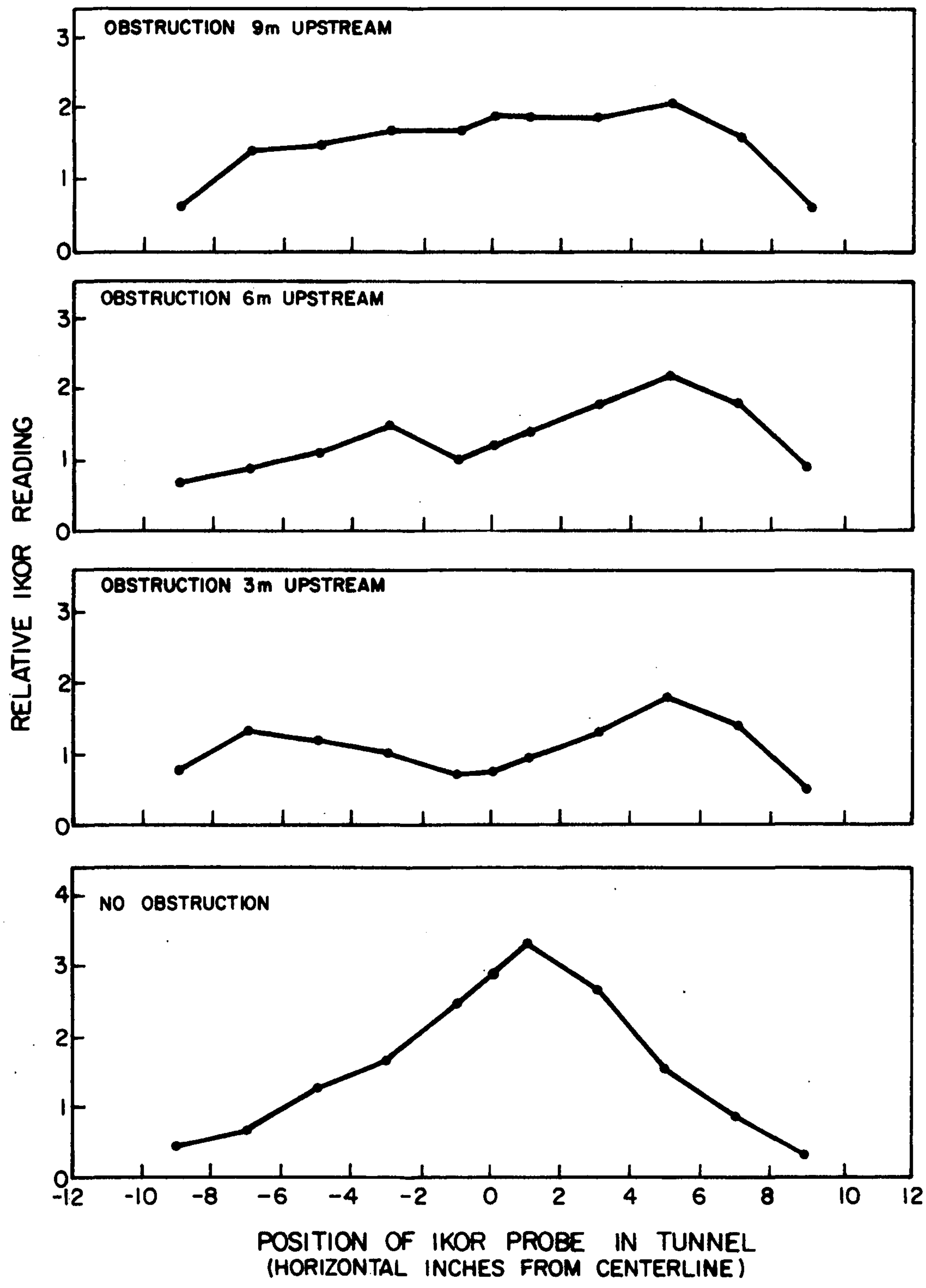

Figure 2. Dust concentration profiles with and without an upstream obstruction (velocity = 9.1 m/s).

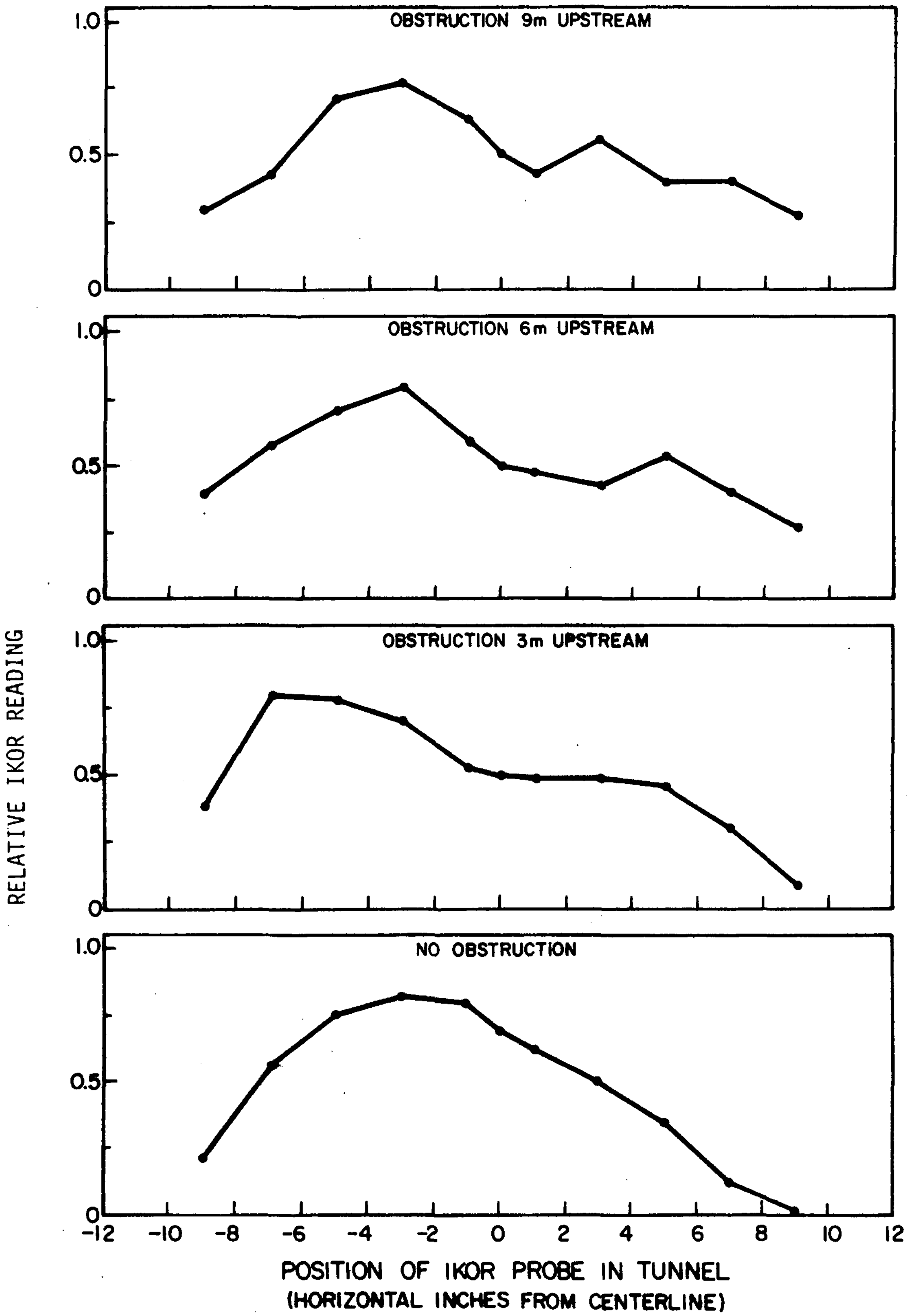

Figure 3. Dust concentration profiles with and without an upstream obstruction (velocity = 27.3 m/s).

Since the scope of the project did not include a thorough evaluation of the wind tunnel's characteristics, no additional tests were conducted to determine the severity of interference created by instruments in opposing ports or to compare the profiles in different test sections with no obstructions or to run vertical traverses. The results discussed above and shown in Figures 2 and 3 were sufficient to cast serious doubt on the validity of the data obtained with more than one instrument in the tunnel at the same time. The results also suggested that comparative instrument runs should be made with all of the instruments sampling at identically the same point inside the wind tunnel.

In addition to the fly ash evaluation, comparison of the instruments with dusts from a basic oxygen furnace and from a cement kiln was originally planned. Neither of these dusts could be utilized, however, because of severe plugging which occurred in the dust feeder and in the tubes that transport the redispersed dust to the wind tunnel. Several minor modifications to the dust feed system were attempted with no success. The system provided a satisfactory feed stream of fly ash, which generally has better flow properties than either the BOF or cement kiln dust. Since the completion of this project, the dust feeder has been replaced by a system of more sophisticated design.

3.0 OPERATING PROCEDURES FOR THE PARTICLE SIZING INSTRUMENTS

The seven particle sizing instruments listed in Table 2 were tested during this study. Specifications of these instruments are summarized in Table 3. The operating and sample analysis procedures utilized for each instrument are described in the following paragraphs.

3.1 BRINK IMPACTOR

The modified Brink impactor used by EPA is a low flow rate impactor consisting of seven stages numbered 0 through 6. In this study, a cyclone precollector designed and fabricated by Southern Research Institute was also utilized.

An aluminum foil substrate, coated with a 20 percent solution of Dow Corning High Vacuum Grease in benzene, was used on each of the seven stages of the cascade. The aluminum foil substrates were initially fitted to the shape of the collection plates. An eye dropper was then used to place two or three drops of the benzene-grease solution on each foil. The foils were baked overnight at 110°C and desiccated for at least 12 hours prior to weighing. Tare weights were also determined for an aluminum foil cup prepared for the cyclone catch and a backup filter used to collect the material that passed through the last impaction stage. All of the foils and filters were handled with tweezers to avoid contamination.

Before each run, the Brink was assembled from the bottom up; first placing a teflon washer and a support filter disc behind the actual filter, then following with the 6 to 0 stages in series, and finally placing the cyclone and sample nozzle in position. Because of the high gas velocities, it was necessary to use nozzles of 1.2 and 1.7 millimeter diameter at the low and high concentrations, respectively, to achieve isokinetic sampling. These nozzle diameters are smaller than the recommended 2 millimeter minimum, but no experimental problems attributed to the nozzle diameter were identified during the data analysis.

To take a sample, the Brink was placed horizontally in the chosen port, taking special care not to bump the Brink against the side of the wind tunnel and thus dislodge the aluminum foil substrates. A vacuum

Table 2. PARTICLE SIZING INSTRUMENTS TESTED

Instrument	Company	Status
Brink Impactor	Monsanto Envirochem, Inc. St. Louis, Mo.	Commercially Available
Andersen Impactor	Andersen 2000, Inc. Atlanta, Ga.	Commercially Available
Series Cyclones	Southern Research Institute Birmingham, Ala.	Research and Development
PILLS IV	Environmental Systems Corp. Knoxville, Tenn.	Commercially Available
In-Stack Beta Impactor	GCA Corp. Bedford, Mass.	Research and Development
Piezoelectric Microbalance Impactor	Celesco, Inc. Irvine, Ca.	Commercially Available
Electrical Aerosol Size Analyzer	Thermo-Systems, Inc. St.Paul, Minn.	Commercially Available

Table 3. INSTRUMENT SPECIFICATIONS

Instrument	Brink Impactor	Andersen Impactor	Southern Series Cyclone	ESC PILLS IV	GCA Beta Impactor	Celesco Piezoelectric Impactor	Thermo-Systems Model 3030 Electrical Aerosol Size Analyzer
Operating Principle	Manual Impactor with Cyclone	Manual Impactor with Cyclone	Manual Cyclone	Single Particle Dual angle Light Scattering	Impactor with Beta Detection of Mass	Impactor with Piezoelectric Detection of Mass	Electrostatic Charging and Mobility Analysis
Mode of Operation	In Stack	In Stack	In Stack	In Stack	In Stack	Extractive	Extractive
Size Range (μm) (Unit density)	<0.4 to >14	<0.4 to >8.3	<0.7 to>3.5	0.3 to 3.0	0.3 to >6.5	0.09 to >35	0.0032 to 1.0
Number of Size Intervals	9	10	4	10	7	10	10
Mass Concentration Range (g/m^3)	0.1 to 6	0.02 to 3	0.1 to 25	10^3 to 10^6*	0.3 to 20	50×10^{-6} to 0.08	10^{-6} to 10^{-3}
Nominal Instrument Flow Rate (ℓ/min)	1.4	20	20	NA	9	0.2	4
Data Rate	Manual	Manual	Manual	Batch (5-60 min)	Real time (5 min lag)	Batch (10-15 min)	Near real time (~2 min scan)
Approximate Cost	$2.5K	$3K	R&D	$35K	R&D	$15K	$12K

*Particles/cc

pump was used to draw the sample and a calibrated orifice was used to determine the sample flow rate. Sample rates of 1.25 and 1.86 ℓ/min were utilized at the high and low concentrations, respectively. During each run, the sample rate was held constant by manual adjustment of a needle valve as necessary. Sample times were 90 minutes for the low concentration runs and 30 minutes for the high concentration runs.

After each test run the Brink was carefully removed from the duct and returned to the laboratory. Disassembly proceeded from the cyclone down. All materials from the cyclone and nozzle were carefully brushed into the tared aluminum foil cup. The aluminum foil substrates and backup filter were then removed sequentially and placed in a desiccator along with the cyclone cup. The samples were desiccated overnight and weighed to a precision of 1 microgram on a Cahn Model G2 electrobalance. The cyclone generally contained 80 to 90 percent of the total mass. Stage weights ranged from approximately 10 micrograms to 10 milligrams. Occasionally negative weights were observed on the number 5 and 6 stages and the filter. These anomalous results were attributed to handling problems and weighing inaccuracies and were deleted prior to data reduction.

In several of the early runs, unusually high and inconsistent cyclone catches were noted. This problem was attributed to leakage detected around the nozzle flange of the cyclone. Apparently large particles impacted on the surface of the cyclone were being sucked in through the leak. A gasket was fitted between the flange and cyclone (and one also between the two lower parts of the cyclone as a precaution), and the problem was corrected. Data from the previous runs were discarded.

3.2 ANDERSEN IMPACTOR

The Andersen is a high flow rate impactor containing 8 stages in series with an optional cyclone precollector and backup filter. The Andersen uses preformed glass fiber filter substrates purchased from the manufacturer. Handling of the substrates was simplified by cutting aluminum foil squares slightly larger than the substrates and inscribing identifying numbers. Tweezers and surgical gloves were used to prevent contamination of the foils or substrates.

Each substrate was desiccated overnight and weighed as a unit with its foil square. An aluminum foil cup was also cut, desiccated, and weighed to receive the cyclone catch. The Andersen was carefully assembled from the filter up according to the manufacturer's instructions. Nozzles of 3.0 to 7.0 millimeters were employed with the cyclone precollector to allow isokinetic sampling.

For each run, the Andersen assembly was horizontally positioned in the appropriate port. The sample was drawn with a vacuum pump and a calibrated orifice and needle valve were utilized to maintain an isokinetic sample rate. Sample rates of 3.9 and 21.1 ℓ/min with a sample time of 30 minutes were used for high concentration runs, and sample rates of 15.8 and 20.7 ℓ/min with a sample time of 90 minutes were used for low concentration runs. As discussed further in sections 5.0 and 6.0, the higher sample rates yielded more reproducible results in each case.

When each test run was completed, the Andersen was returned to the laboratory and disassembled from the cyclone down. The material in the nozzle and cyclone was carefully brushed into the tared aluminum foil cup. The substrates were then removed and placed on the appropriate foil square using tweezers and gloves to minimize loss or contamination of the samples. Difficulty was consistently experienced with the filters sticking to the stainless steel O-rings and plates. Occasionally particulate was also found on the steel plates rather than the substrates. In all of these cases, the material was carefully brushed or scraped onto the appropriate foil square. The squares were then loosely folded over the substrates to prevent spillage, and the samples were desiccated overnight.

Weighing was accomplished on a Mettler balance to a precision of 0.1 milligram. The cyclone generally contained about 90 percent of the total mass. Stage weights ranged from less than 1 milligram to about 40 milligrams. The low and occasionally negative weights observed on the last three stages and filter resulted in some loss of consistency at the smaller particle sizes. As noted above, particulate scouring and spillage on the steel plates were occasionally observed with the highest stage weights. Obviously, in any sampling situation a compromise must be reached between overloading of the upper stages and a reduction of weighing accuracy on the lower stages. Use of the Cahn electrobalance can partially solve this problem, but it is extremely difficult because of the large size of the Andersen substrates. A balance of comparable precision to the Cahn but larger weighing pans would remedy some of these difficulties.

3.3 SOUTHERN SERIES CYCLONES

The series cyclone system tested during this study was developed by Southern Research Institute to satisfy the specific objectives of allowing longer sample times in high dust load situations and of allowing larger quantities of size-fractionated particulate to be collected for chemical analysis. The system consists of three cyclones in series, each with a different cut point, and a Gelman backup filter. No internal substrates are required. To prepare this system, the cyclones are simply assembled with a tared filter in the filter holder and a nozzle fitted to the inlet of the largest cyclone. The cyclones were designed for a nominal flow rate of 1 actual cubic foot per minute. During these tests they were utilized with the same sampling system as the Andersen Impactor. For high concentration runs, 30 minute samples were drawn at a flow rate of 21.1 ℓ/min (0.746 acfm) using a 7 mm nozzle. Low concentration samples were obtained in a 90 minute sample period using a rate of 20.7 ℓ/min (0.730 acfm) and a 4.0 mm nozzle. The cyclones had a vertical orientation while they were in the wind tunnel.

When each test run was completed, the cyclones were returned to the laboratory and disassembled. The material in the nozzle and first cyclone was carefully brushed into a tared aluminum foil cup. Similar cups were used to receive the catch from the second and third cyclones and the filter. The samples were then desiccated overnight. A Mettler balance was used to weigh the particulate with a precision of 0.1 milligram. The first cyclone generally contained about 98 percent of the total particulate catch, leaving only a few milligrams for the second and third cyclones and filter.

3.4 ENVIRONMENTAL SYSTEMS CORPORATION PILLS IV

The PILLS IV is an optical, single particle counter. Particles are counted and sized as they pass through a small viewing volume through which a laser is focused. Light is scattered by each particle into two cones at near-forward angles. The light is collected and the size of particles greater than 0.6 micrometer is determined from a ratio of the collected light intensities. Small angle scatter is used directly to determine the size of particles smaller than 0.6 micrometers. For these tests, the PILLS IV was set up to yield particle counts in 10 increments from 0.3 to 3.0 micrometers.

The PILLS IV operates with an in-stack probe, approximately 10 cm in diameter and 2 m long, which contains the viewing volume. The optics are protected by a purge air system. At the beginning of each run, the limits were set and checked and the probe was inserted. The "count enable" switch was then manually thrown. The length of time over which particles were counted was also manually controlled. At the end of the count, the number of particles counted in each size increment was printed out on tape. The number of laser pulses was also printed to give a precise time reference. During the low concentration runs a minimum count time of one hour was required to insure that at least 5 to 10 particles were counted in each size increment.

3.5 GCA IN-STACK BETA IMPACTOR

The GCA In-Stack Beta Impactor consists of seven cascade stages and operates on the same classification principle as the Brink and Andersen impactors. Unlike the Brink and Andersen, the GCA is a real-time instrument, and manual weighing of the collected particulate is not necessary. Instead the collection substrate of each stage is a Mylar film coated with petroleum jelly. In operation the film rolls at a predetermined rate between two cassettes, passing under the stage jet. On each side of the stage jet the film passes between a beta source and a Geiger-Mueller tube. The increased beta attenuation observed on the dirty side of the stage jet is, in principle, proportional to the mass of particulate collected. The difference in upstream and downstream beta attenuation for each stage is compared internally and displayed on a strip chart. Periodically, by manual control, a reverse flow of air is directed through the cascade to prohibit entry of particulate and allow for zero check and adjustment.

Since the Beta Impactor is a recently developed instrument and had not been tested previously, time was devoted to establishing an operating procedure, studying the zero fluctuations apparently caused by inconsistencies in the film or petroleum jelly coating, and adjusting the sensitivity of the output of each stage to give a reasonable response. It was not possible to operate the Beta Impactor at the low concentration used for the other instruments because of the sensitivity limitation or to accomplish port switching since an oversized port was required.

Comparative runs were made simultaneously with the Brink Impactor at the nominal high concentration and at a lower concentration three times that of the nominal low concentration runs. (This particular concentration was used for convenience since it resulted from a simple combination of the low dust feed rate and the low velocity used in other runs).

3.6 CELESCO PIEZOELECTRIC MICROBALANCE IMPACTOR

The Celesco Impactor is based on the same particle classification principle as the Brink and Andersen. In this instrument, however, the collection substrate of each stage is a piezoelectric quartz crystal. The mass collected on each stage is determined by the vibration frequency shift observed in the crystal (See electronic schematic in Figure 4).

The Celesco Impactor was developed for low concentration particle sizing. Without dilution it has a nominal operating range of 50 to 6,000 $\mu g/m^3$ total mass concentration. At higher concentrations, the crystals will overload quickly invalidating the linear relationship between frequency shift and mass. A dilution system could be used to control mass concentration, but one was not available for this test program. Instead, for this first attempt to utilize the Celesco at a "clean stack concentration" of 0.089 g/Nm^3, the sample time was reduced to 5 seconds. No attempt was made to sample at the higher concentration. Extractive samples were drawn through a 1/4-inch O.D. tube approximately 40 cm long. A 1 mm nozzle was used since it was the smallest available. (For the Celesco's standard 200 mℓ/min sample flow, a 0.4 mm nozzle would have been required for isokinetic sampling.)

At the beginning of each test, a filtered air flow of 200 mℓ/min was started through the Celesco using its integral pump and a detachable rotameter (See flow schematic in Figure 4). At the end of a one-hour warmup, the flow was adjusted back to 200 mℓ/min, and repetitive crystal scans were run to determine the baseline frequency of each crystal. When all crystals had stabilized (frequency drift less than 10 Hz in a 10 minute interval), the sample was drawn. A manually operated, quick-opening, three-way valve was used to switch from the filter purge to the sample mode. At the end of seven seconds, the valve was switched back to purge. To allow for the dead space in the sample line, the sample time was treated in the calculations as if it were 5 seconds rather than 7 seconds.

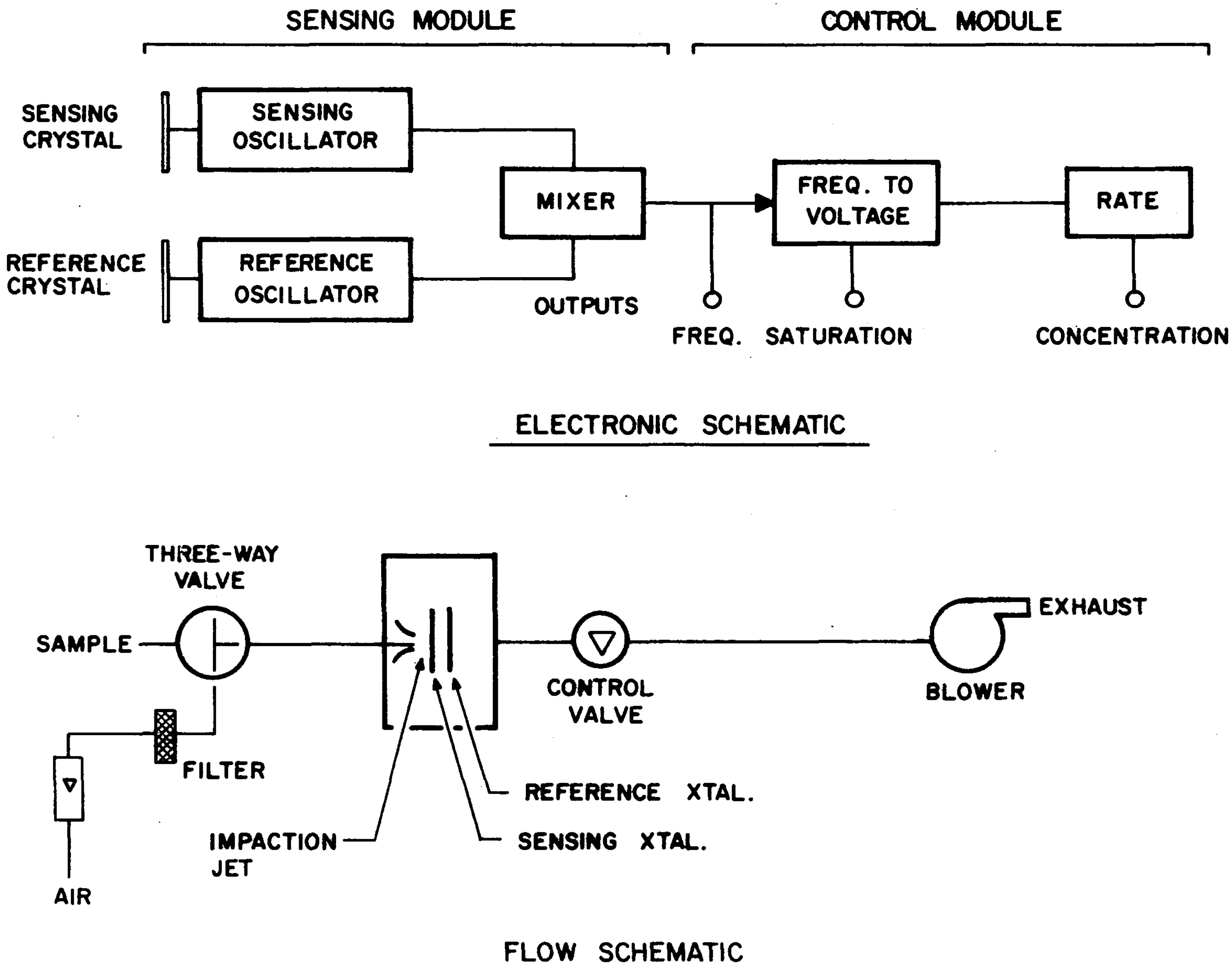

Figure 4. Electronic and flow schematics of Celesco impactor.

After the sample was drawn, a repetitive scan of the crystal frequency was initiated and continued until the drift criterion was again achieved. The frequency shift in each crystal was then recorded, and a check was made to ensure that no crystal had exceeded the manufacturer's recommended allowable frequency shift. When any crystal approached the allowable shift after several runs, it was replaced with a fresh crystal.

3.7 THERMO-SYSTEMS MODEL 3030 ELECTRICAL AEROSOL SIZE ANALYZER

The Thermo-Systems Electrical Aerosol Size Analyzer operates on the principle of electrostatic charging and mobility analysis to determine particle size. Particles may be classified in ten size increments between 0.0032 and 1.0 micrometers. The instrument is primarily for laboratory and ambient use with a nominal concentration range of 1 to 1,000 $\mu g/m^3$ when used with typical atmospheric aerosols. Since the redispersed fly ash utilized in this study was expected to have a smaller fraction of small particles than a normal atmospheric aerosol, operation of the EASA without dilution was attempted.

A sample tube was affixed to the aerosol inlet for extractive sampling, ignoring isokinetic conditions since no particles greater than 1 micrometer could be detected by the instrument. During several days of testing the results were quite erratic and the digital readout was always of negative sign. These problems were described to a manufacturer's representative by telephone and he suggested that the particles were probably highly negatively charged. A 10 millicurie Krypton-85 source was incorporated in the sample line, but no appreciable change in the results could be determined. The instrument was removed from the wind tunnel to a laboratory where ambient air samples were drawn and normal results were obtained. Since the erroneous results thus seemed to be related to the condition of the particles rather than a malfunction of the instrument and no other particle conditioning equipment was available, operation of the EASA was discontinued.

4.0 DATA REDUCTION

Several techniques can be used to analyze and present particle size distribution data obtained with cascade impactors and other sizing instruments. The method utilized in this project is frequently used by EPA and involves the presentation of data as differential particle size distributions using the D_{50} concept. The standard calculations and all exceptions applied in this project are described in the following paragraphs. Further information can be obtained in Reference 2.

4.1 DIFFERENTIAL PARTICLE SIZE DISTRIBUTIONS-D_{50} METHOD

The D_{50} method is presently used for the majority of cascade impactor data reduction. It is also applicable to cyclones. The method is fairly straightforward and can be hand-calculated, but it is recognized as a considerably simplified picture of the real distribution and can cause some loss of information (ref.2).

The D_{50} of a stage in a cascade impactor or of a cyclone is the particle diameter at which the device achieves 50 percent efficiency; one half of the particles of that diameter are captured and one half are not. Larger particles are captured with greater than 50 percent efficiency, and smaller particles with less than 50 percent efficiency. The D_{50} at a particular set of conditions is determined by experimental tests or from theoretical and semi-empirical equations based on previous experimental work. The latter approach was used in this work.

The D_{50} reported can be either aerodynamic diameter (that is, diameter based on the behavior of unit density particles) or approximate physical diameter, which is based on an estimate of the true particle density. In either case, the particles are assumed to be spherical. In this project all calculations were based on an assumed fly ash particle density of 2.5 g/cm^3.

The D_{50} analysis method simplifies calculations by assuming that a given stage captures all of the particles with a diameter equal to or greater than the D_{50} of that stage and less than the D_{50} of the preceding stage. For the first stage (or cyclone), it is assumed that all of the particles caught have diameters greater than, or equal to, the D_{50} for that stage (or cyclone), but less than the maximum particle size. If the maximum particle size is not known, some arbitrary large value is used. In these tests a maximum of 100 μm was assumed.

With these simplifications, the mass collected on a given stage is assigned to a particular diameter; usually the geometric mean of the stage D_{50} and the preceding stage D_{50} is used.

If the true particle-size distribution constituted a continuum, the amount of material having diameters between D and D+dD could be represented by dM. Then the integral

$$\int_{D_1}^{D_2} \frac{dM}{dD}\, dD$$

would yield the total mass having diameters between D_1 and D_2. In this integral the term dM/dD is referred to as the differential particle size distribution.

Because the intervals between the stage D_{50}'s are in most instruments logarithmically related, the differential particle size distribution is normally calculated as dM/d(log D) rather than dM/dD. This modification also minimizes scaling problems when the data are plotted in the usual manner on log-log or semi-log paper with dM/d(log D) as the ordinate and log D as the abscissa.

To calculate the differential distribution, the mass on stage "n" is designated by ΔM_n and is, in approximation, the mass of particulate with diameters between $(D_{50})_n$ and $(D_{50})_{n+1}$. The $\Delta(\log D)$ associated with ΔM_n is $\log (D_{50})_{n+1} - \log (D_{50})_n$. Using these approximations, the derivative term associated with stage "n" is

$$dM/d(\log D)\big|_n \simeq \frac{\Delta M_n}{\Delta(\log D_{50})\big|_n} = \frac{\text{Mass on Stage "n"}}{\log(D_{50})_{n+1} - \log(D_{50})_n} \, .$$

The diameter corresponding to stage "n" is

$$D_{geo} = \left[(D_{50})_n \cdot (D_{50})_{n+1}\right]^{1/2}$$

Plotting this approximation of dM/d (log D) versus log D_{geo} results in a histogram. If an impactor with an infinite number of stages were available, the histogram would approach a continous curve of differential distribution, dM/d(log D), as a function of particle diameter. Such an impactor does not exist, but the histogram is usually plotted as a smooth curve by connecting the available data points. This curve is then a continuous function approximating the actual particle size distribution. The accuracy of the approximation is limited by the number of points, and by the basic inaccuracy of neglecting the non-ideal behavior of the impactors, especially overlapping collection efficiencies for adjacent stages or cyclones.

Despite its limitations, the differential distribution method of data analysis offers several advantages over cumulative distribution representations. Experimental errors associated with one stage of the sizing device are not propagated to other points of the distribution. Also since the method does not involve the use of total mass concentration or total size distribution from diameters of zero to infinity, it is especially useful in comparing instruments with overlapping but different size fractionation ranges and different stage cut points. To normalize the differences in mass of sample collected by various instruments, the mass on each stage is usually divided by the standard volume of the sample, yielding concentration units, i.e., dC/d(log D) in g/Nm^3.

A sample calculation using Brink Impactor data is presented in the Appendix of this report.

4.2 BRINK IMPACTOR

To reduce the Brink data, D_{50}'s of the impactor stages and cyclone were obtained for the operating conditions described previously from a computer program which EPA has on file. The calculated D_{50}'s for the various sample rates are shown in Table 4. No exceptions to the general calculational scheme explained in Section 4.1 and the Appendix were required.

4.3 ANDERSEN IMPACTOR

To reduce the Andersen data, D_{50}'s of the impactor stages were obtained from the EPA computer program. To determine the D_{50} of the cyclone, RTI contacted the manufacturer and was referred to a consultant

Table 4. D_{50}'S OF BRINK STAGES AND CYCLONE

Stage	D_{50}(μm) @1.25 ℓ/min	D_{50}(μm) @1.86 ℓ/min
Cyclone	9.39	7.69
0	5.73	4.68
1	3.25	2.65
2	1.93	1.56
3	1.32	1.07
4	0.71	0.56
5	0.46	0.36
6	0.28	0.21

Table 5. D_{50}'S OF ANDERSEN STAGES AND CYCLONE

Stage	D_{50}(μm) @21.1 ℓ/min	D_{50}(μm) @20.7 ℓ/min	D_{50}(μm) @15.8 ℓ/min	D_{50}(μm) @3.9 ℓ/min
Cyclone	5.30	5.35	6.08	12.3
1	7.27	7.31	8.36	17.0
2	4.50	4.54	5.20	10.6
3	3.04	3.07	3.52	7.20
4	2.06	2.08	2.39	4.91
5	1.32	1.33	1.53	3.17
6	0.64	0.65	0.75	1.60
7	0.39	0.39	0.46	0.99
8	0.24	0.25	0.29	0.68

(ref.3). The consultant stated that the cyclone has been calibrated only at a flow rate of 21.2 ℓ/min (0.75 cfm). For other sample rates, it was assumed that the D_{50} was inversely proportional to the square root of the flow rate. The calculated D_{50}'s of the cyclone and stages for the various sample rates are shown in Table 5.

The design of the Andersen cyclone presents an anomaly in that the D_{50} at the calibrated flow rate is less than the D_{50} of the first stage at the same flow. To handle this irregularity, the mass of the cyclone and first stage were added in the calculations and assigned to the smaller D_{50}. The consultant concurred with this approach. No other deviations from the standard calculations shown in the Appendix were encountered.

4.4 SOUTHERN SERIES CYCLONES

The D_{50}'s of the Series Cyclones were determined from a set of equations derived by Southern Research Institute from calibration data.

Cyclone 1 $\quad D_{50}(\mu m) = 225.1\sqrt{\mu/\rho F}$

Cyclone 2 $\quad D_{50}(\mu m) = 88.25\sqrt{\mu/\rho F}$

Cyclone 3 $\quad D_{50}(\mu m) = 43.29\sqrt{\mu/\rho F}$

where μ = gas viscosity, poise

ρ = particle density, g/cm^3

F = sample flow rate, ft^3/min

No deviations from the standard calculations shown in the Appendix were necessary.

4.5 CELESCO PIEZOELECTRIC MICROBALANCE IMPACTOR

The D_{50}'s of the Celesco stages were provided by the manufacturer for a particle density of 2.0 g/cm^3. To correct these values to a particle density of 2.5 g/cm^3, a simple ratio was used, assuming that D_{50} is inversely proportional to the square root of particle density. The D_{50}'s of the stages on which data were obtained were as follows:

Stage 4	D_{50} = 2.87 μm
Stage 5	D_{50} = 1.42 μm
Stage 6	D_{50} = 0.71 μm
Stage 7	D_{50} = 0.35 μm

To convert from frequency shift on each stage to incremental mass concentration with the standard sample rate and a five-second sample, the following equation was used:

$$C = 1.02 \times 10^{-4} \times \Delta F$$

where C = mass concentration, g/m^3

ΔF = frequency shift, Hz

The remainder of the data reduction was similar to the example shown in the Appendix.

4.6 GCA IN-STACK BETA IMPACTOR

The D_{50}'s of the Beta Impactor were provided by GCA for a particle density of 1.0 g/cm^3 and were corrected to a density of 2.5 using the same relationship employed with the Celesco. The results were as follows:

Stage 1	D_{50} = 4.1 μm
Stage 2	D_{50} = 2.5 μm

Stage 3 $D_{50} = 1.5$ μm

Stage 4 $D_{50} = 0.89$ μm

Stage 5 $D_{50} = 0.54$ μm

Stage 6 $D_{50} = 0.33$ μm

Stage 7 $D_{50} = 0.19$ μm

Raw data were obtained from the Beta Impactor in the form of seven pen traces on a strip chart, corresponding to the seven stages. Scale factors were provided by GCA to convert from pen displacement to mg/m^3. Since the continuous output of each stage showed considerable fluctuation, a graphical integration was performed over the sample period to determine the time-averaged particle concentration in each size increment. Figure 5 is a reproduction of the typical response of two adjacent stages, illustrating the selection of zero and the graphical integration procedure. Once the average incremental concentration was determined for each stage, the remainder of the calculational procedure was similar to that shown in the Appendix.

4.7 ENVIRONMENTAL SYSTEMS CORPORATION PILLS IV

Since the PILLS IV counts individual particles in a given size increment rather than collecting an agglomerate of particles for mass determination, a different technique is required to obtain the differential particle size distribution in mass concentration terms. The data printout from the PILLS IV gives the total number of times that the laser fired and the number of particles counted in each of the ten size increments. (The sample time can be accurately determined from the number of laser pulses since the pulse rate is 1000 times per second.) The incremental number concentration is then determined by

$$\frac{\Delta n_i}{V_s} = \frac{n_i}{K \cdot V}$$

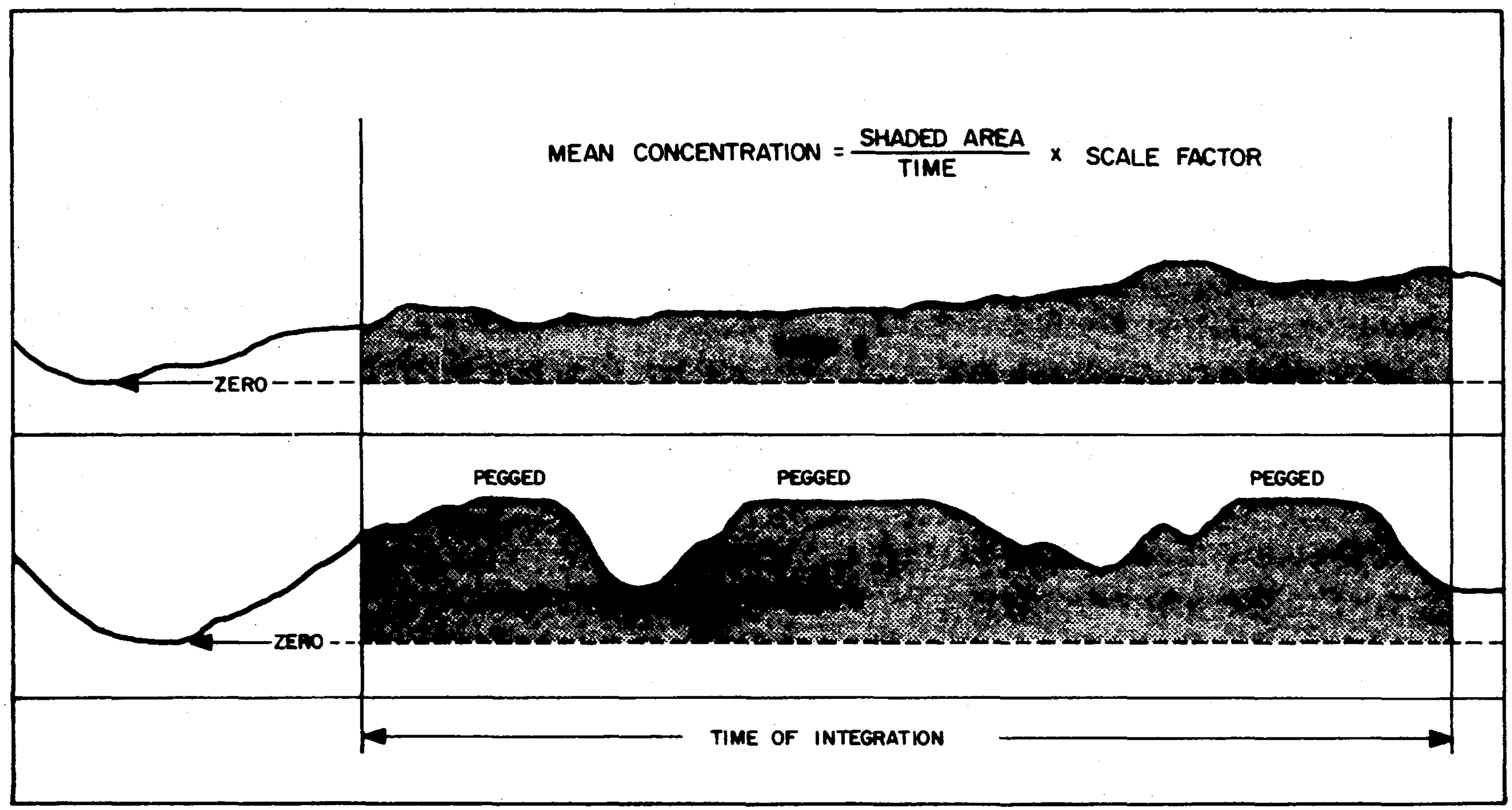

Figure 5. Determination of mean concentration for stages of the GCA In-Stack Beta Impactor.

where $\frac{\Delta n_i}{V_s}$ = incremental number concentration, particles/m^3

n_i = number of particles in increment i

K = number of laser pulses

V = viewing volume = $2 \times 10^{-13} m^3$

In each set of calculations the viewing volume was corrected to standard conditions as shown in the Appendix.

Assuming that all particles were spherical and of equal density, the incremental mass concentration was then determined by

$$\Delta C_i = \frac{\Delta n_i}{V_s} \times \frac{\rho\pi(d_i^*)^3}{6} \times 10^{-12}$$

where ΔC_i = incremental mass concentration, g/m^3

ρ = assumed particle density, g/cm^3

d_i^* = geometric mean of the upper and lower boundaries of the increment, μm.

A differential particle size distribution equivalent to those calculated by the procedure described in the Appendix was then calculated by

$$dC/d(\log D) = \frac{\Delta C_i}{\Delta \log(d_i)}$$

where

dC/d(log D) = differential particle size distribution, g/m^3

$\Delta\log(d_i)$ = difference of the common logarithms of the upper and lower boundaries of the increment.

The size increments of the PILLS IV used in this project are presented in Table 6.

Table 6. SIZE INCREMENTS OF PILLS IV

Channel	Size Range, μm	Mean Diameter, μm	$\Delta \log(d_i)$
5	0.35 - 0.38	0.365	0.036
6	0.38 - 0.48	0.42	0.1
7	0.48 - 0.60	0.53	0.1
8	0.60 - 0.75	0.67	0.1
9	0.75 - 0.95	0.85	0.1
10	0.95 - 1.19	1.06	0.1
11	1.19 - 1.50	1.34	0.1
12	1.50 - 1.89	1.69	0.1
13	1.89 - 2.38	2.12	0.1
14	2.38 - 3.00	2.67	0.1

5.0 COMPARISON OF INSTRUMENTS BASED ON PRIMARY DATA

5.1 PROCEDURE FOR SUCCESSIVE RUNS

As discussed previously in this report, it was originally assumed that the most valid approach to instrument comparison was to operate the instruments simultaneously in different ports of the wind tunnel. This approach required that the particulate concentration in the wind tunnel be uniform and that upstream instruments had a negligible effect on the particle concentration and distribution arriving at downstream sample points. When the problems of analyzing the data obtained in this manner became apparent, additional runs were made operating the instruments one at a time in succession in the same port. Although the remaining authorized time for project completion allowed only two runs with each instrument at each concentration, the limited data proved to be of primary use in comparing the particle sizing instruments.

During the successive runs, frequent checks were made of wind tunnel operating parameters to ensure steady state operations. The IKOR was also used in port H as an additional check of steady state conditions. In general, the IKOR indicated a "steady periodic" dust concentration in the tunnel during any run, oscillating within about 10 percent of the mean value with a frequency on the order of one cycle per minute. All of the instruments with the exception of the GCA, which is discussed in Section 5.3, were operated in port D with their respective sample nozzles positioned as closely as possible to the same point. Table 7 shows the variation of sample points among the instruments and the total mass concentration measured by each.

At both the high and low concentrations the Brink, Andersen and Series Cyclones all indicated a significantly higher total mass loading than the homogenous mass loading calculated from the dust feeder calibration. Wide disparity between dust loadings obtained with mass trains and with cascade impactors is not uncommon (ref. 4), and is frequently attributed to stratification of dust in the duct. Stratification is the likely cause in this case also. At the higher concentration stratification of the dust streams from the individual feed nozzles could be observed with a flashlight shining into the sample ports.

The total mass concentration indicated by the Brink measurements differs markedly from the Andersen and Series Cyclone measurements. Part of this difference might also be attributed to dust stratification in the wind tunnel since the sample points did not coincide identically. Another credible explanation is the presence of a relative error in the flow rate measurements of the Brink sample train and the separate sample train used for the Andersen and Series Cyclones. These two sample trains were calibrated with different flow standards since the flow rates differed by approximately an order of magnitude.

Duplicates were run with all instruments at both concentrations. From these duplicates a normalized variance of the differential distribution at each stage was calculated for both the high and low concentrations according to the following equation.

$$v = \frac{1}{n-1} \sum_{i=1}^{n} \left(\frac{x_i - \bar{x}}{\bar{x}} \right)^2$$

where v = normalized variance at a specified stage

n = number of runs

x_i = differential distribution of run i

$\bar{x}$ = mean differential distribution of all runs, specified stage

In general, a higher variance indicates a lower level of repeatibility. The variance in selected size intervals is tabulated for each of the instruments in Tables 8 and 9. These tabulations are useful as an indication of the relative variance of the instruments, but must be viewed with some caution since they were calculated from only two duplicate runs. Part of the variance might also be attributed to wind tunnel variations and not to instrument performance. The conclusions from Tables 8 and 9 are included in the following discussion of instrument comparison.

5.2 COMPARISON OF INSTRUMENTS IN SUCCESSIVE RUNS

Figures 6 and 7 are plots of differential distribution versus particle size as calculated from the Brink and Andersen data at low and high concentrations, respectively. The curves on each plot represent a least square fit to the experimental data of both instruments in the

Table 7. POSITION OF INSTRUMENTS IN THE WIND TUNNEL AND MEASURED TOTAL MASS CONCENTRATION

Instrument	Horizontal Position	Vertical Position	Indicated Total Mass Concentration, g/Nm^3	
			Low Runs	High Runs
Brink	23 cm into port D	1.3 cm below centerline	0.577 and 0.660	1.841 and 1.867
Andersen	23 cm into port D	2.5 cm above centerline	0.376 and 0.386	2.200 and 2.384
Cyclones	23 cm into port D	5.1 cm below centerline	0.376 and 0.377	2.373 and 2.765
PILLS IV	23 cm into port D	On centerline	--	--
Celesco	15 cm into port D	On centerline	--	--
Dust feeder Calibration	--	--	0.089	0.955

Table 8. NORMALIZED VARIANCE FOR LOW CONCENTRATION RUNS-PRIMARY DATA

Particle Size Range, μm	Brink	Andersen	Cyclones	PILLS IV	Celesco	GCA*
>10	0.004	0.0004	9×10^{-7}	--	--	0.02
5-10	0.001	--	--	--	--	--
2-5	0.03	0.002	--	0.04	0.05	3
1-2	--	0.009	0.0005	0.09	0.02	1
0.5-1	0.02	0.5	<0.005	0.3	0.1	--
0.2-0.5	--	--	--	0.4	--	--

*GCA variance calculated from three special comparative runs with Brink at a concentration of 0.267 g/Nm^3.

Table 9. NORMALIZED VARIANCE FOR HIGH CONCENTRATION RUNS-PRIMARY DATA

Particle Size Range, μm	Brink	Andersen	Cyclones	PILLS IV	Celesco	GCA*
>10	0.005	0.004	0.01	--	--	0.004
5-10	0.5	--	--	--	--	--
2-5	0.06	0.008	--	0.0003	--	0.03
1-2	0.03	0.0003	0.02	0.03	--	0.03
0.5-1	0.02	0.1	0.02	0.02	--	0.06
0.2-0.5	0.7	3	--	0.01	--	8

*GCA variance calculated from two special comparative runs with Brink at same concentration as successive runs.

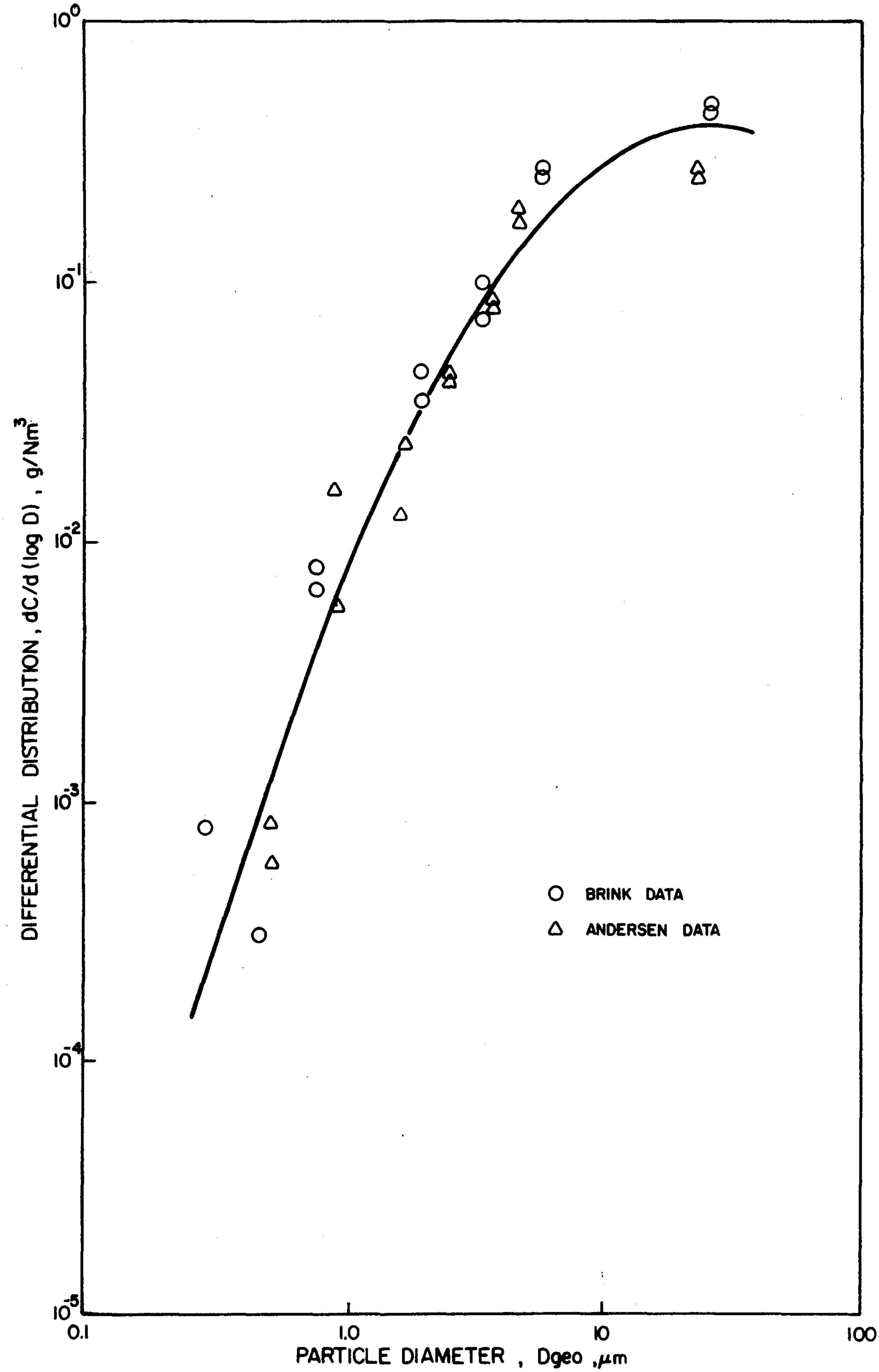

Figure 6. Comparison and curve fit of Brink and Andersen Impactor data (concentration = 0.089 g/Nm^3).

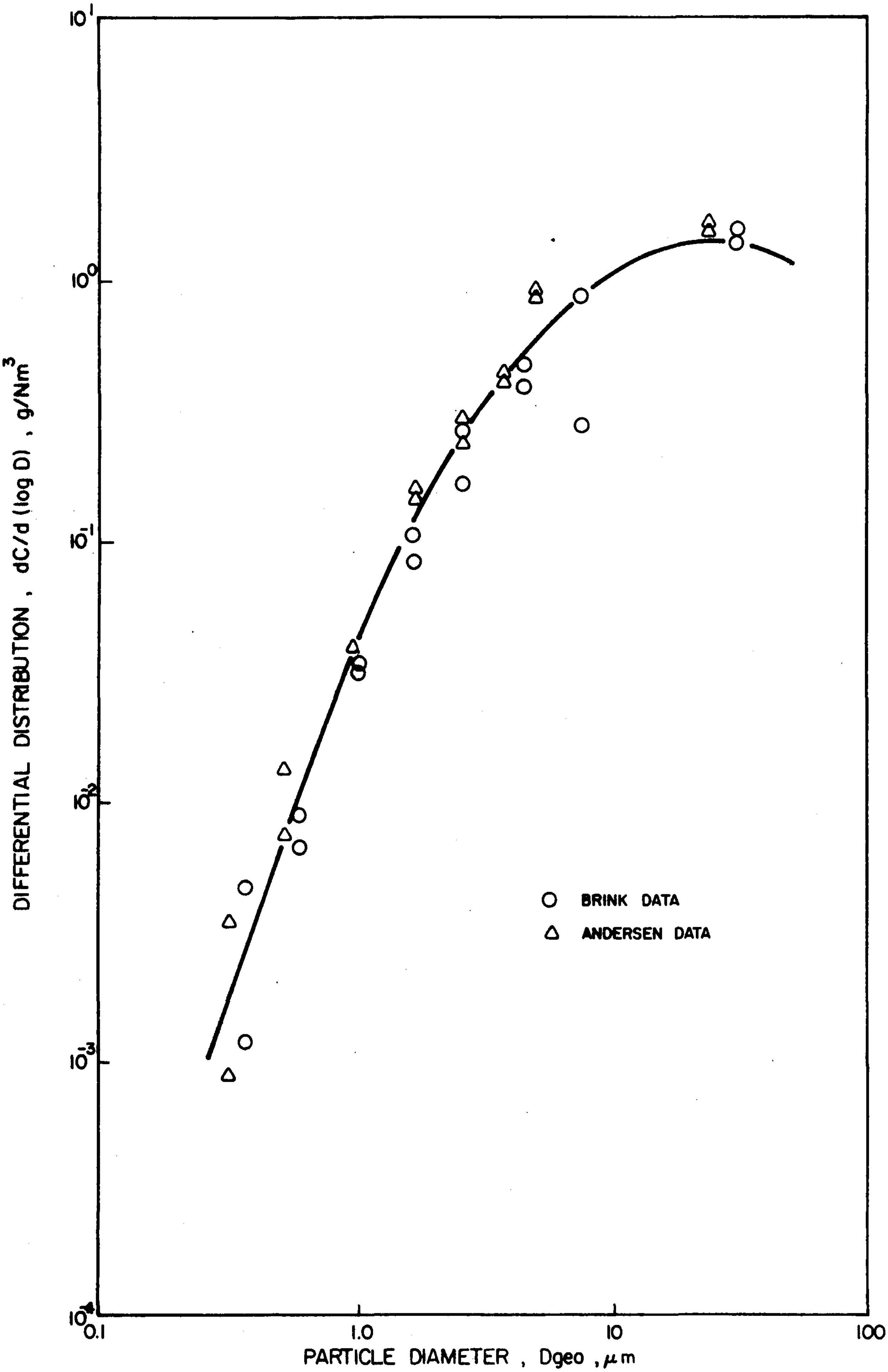

Figure 7. Comparison and curve fit of Brink and Andersen Impactor data (concentration = 0.955 g/Nm^3).

form

$$\log[dC/d(\log D)] = a_0 + a_1(\log D_{geo}) + a_2 (\log D_{geo})^2$$

where a_0, a_1 and a_2 are constants determined by the least square procedure.

The Brink and Andersen data were treated together because these instruments have been shown by EPA to yield comparable particle size distributions in past experiments. The agreement was good in these tests also. The figure "(2)" beside a data point indicates that two individual runs yielded data points so close together as to be indistinguishable on the plot.

The Brink Impactor showed a large variation in the results obtained with the zero stage at high concentration. This discrepancy was noticed throughout the test (see also Section 6). The effect apparently results from a difference in the shape of the particle collection efficiency curves of the cyclone precollector and the zero stage. The cyclone efficiency curve overlaps with the zero stage curve (ref. 2), which leads to a particle collection phenomenon not well handled by the D_{50} data reduction technique. The effect is apparently more pronounced at the lower sample rate used with the high concentration results. The Andersen runs shown in these figures were made with sample flow rates within 3 percent of the calibration flow rate of the cyclone precollector. The variance of the Andersen (Tables 8 and 9) appears to be slightly less than that of the Brink.

In Figures 8 through 12 the experimental data obtained with the Series Cyclones, Celesco and PILLS IV are compared with the appropriate least square curve of the Brink and Andersen data. Figures 8 and 9 show this comparison for the Series Cyclones at the low and high concentrations respectively. The Series Cyclone data are in good agreement with the Brink and Andersen curves. At both the low and high concentrations the cyclone data are actually within the scatter band exhibited by the Brink and Andersen data used to calculate the least square fit. At the high concentration, the cyclone seems to have a slight tendency toward higher readings relative to the Brink and Andersen. This effect would be in agreement with the usual observation that cyclone collection efficiency increases with increasing dust load, but a definite conclusion would be presumptious due to the limited amount of data in this

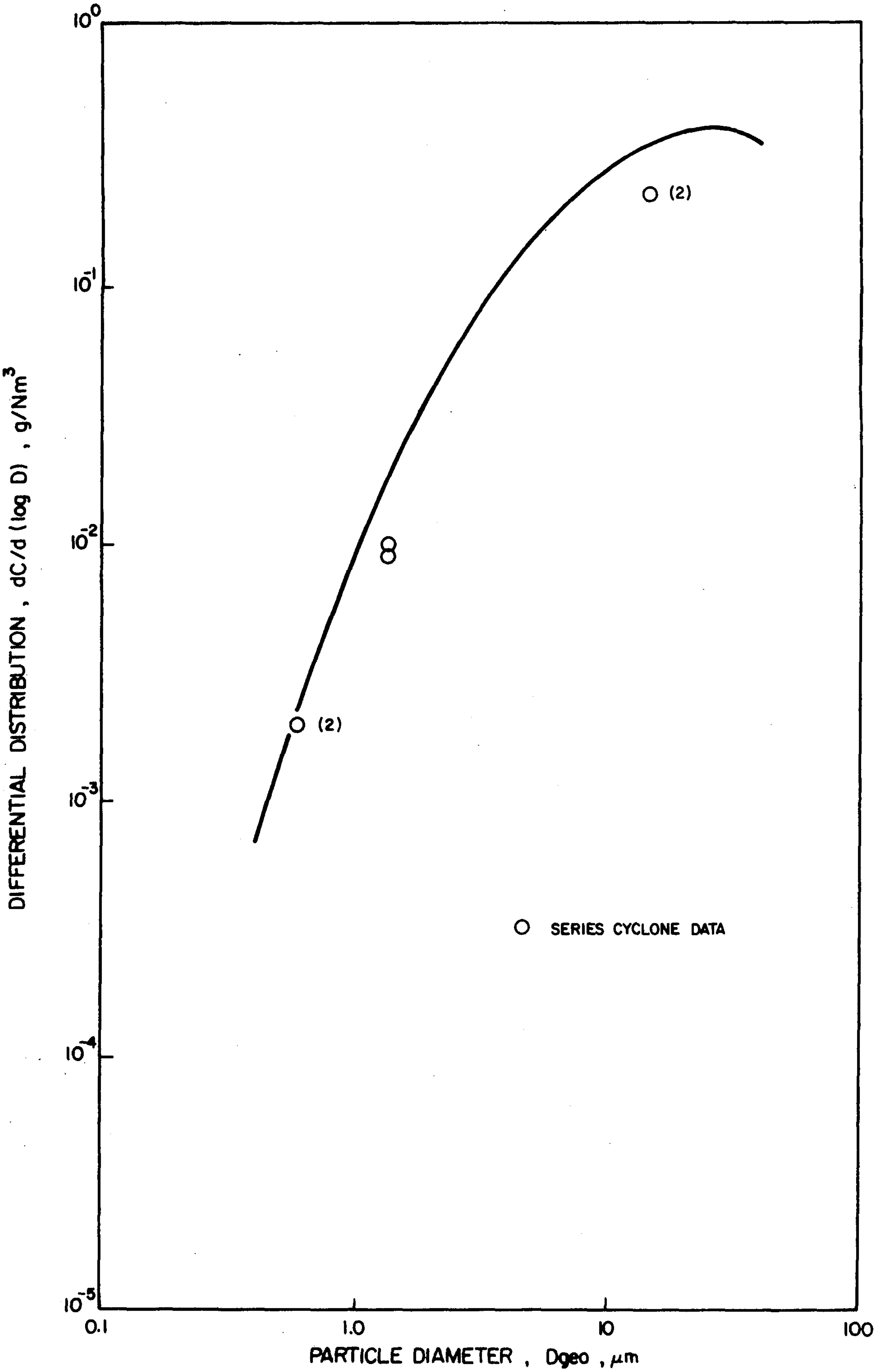

Figure 8. Comparison of Southern Series Cyclone data with impactor curve (concentration = 0.089 g/Nm^3).

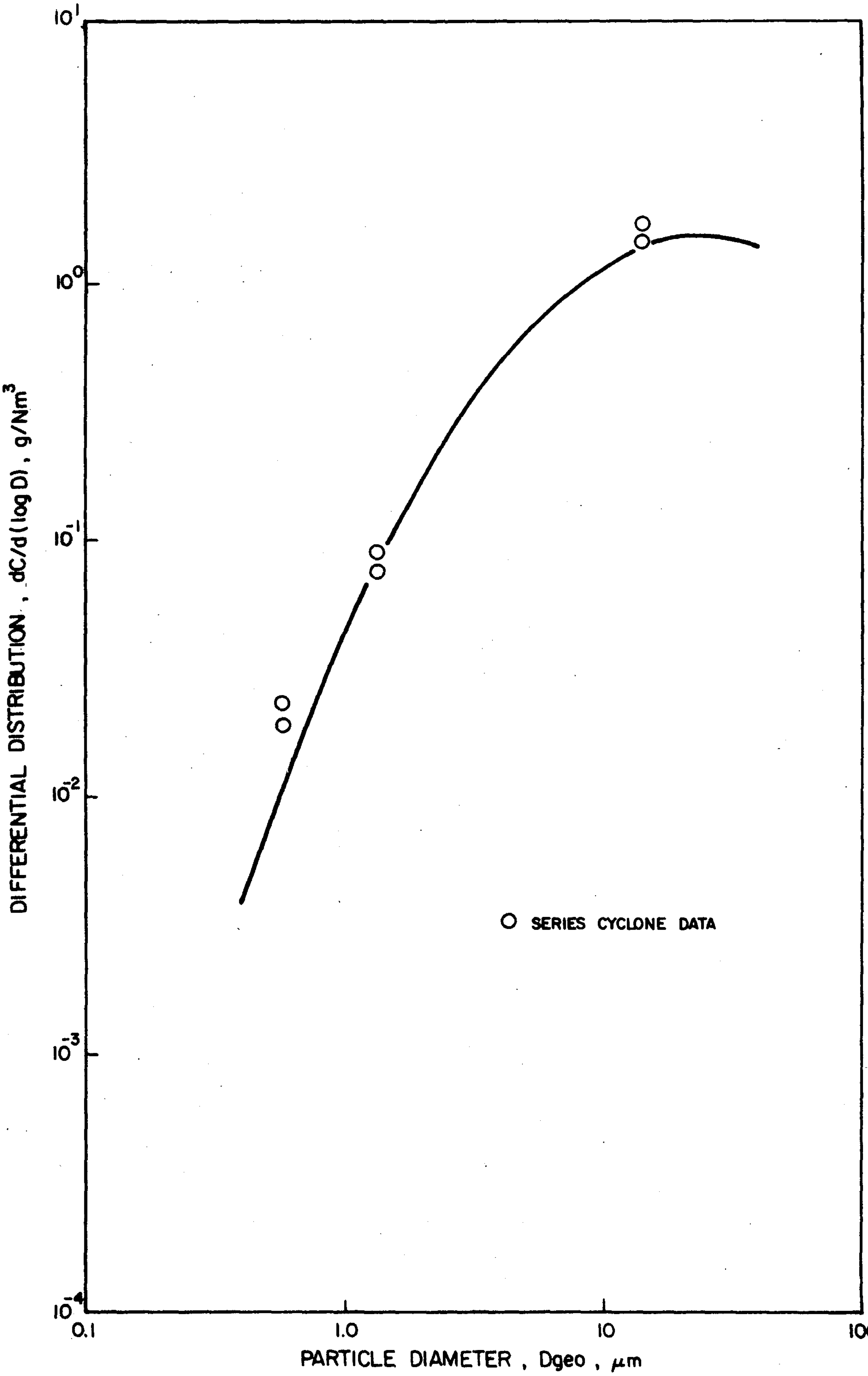

Figure 9. Comparison of Southern Series Cyclone data with impactor curve (concentration = 0.955 g/Nm^3).

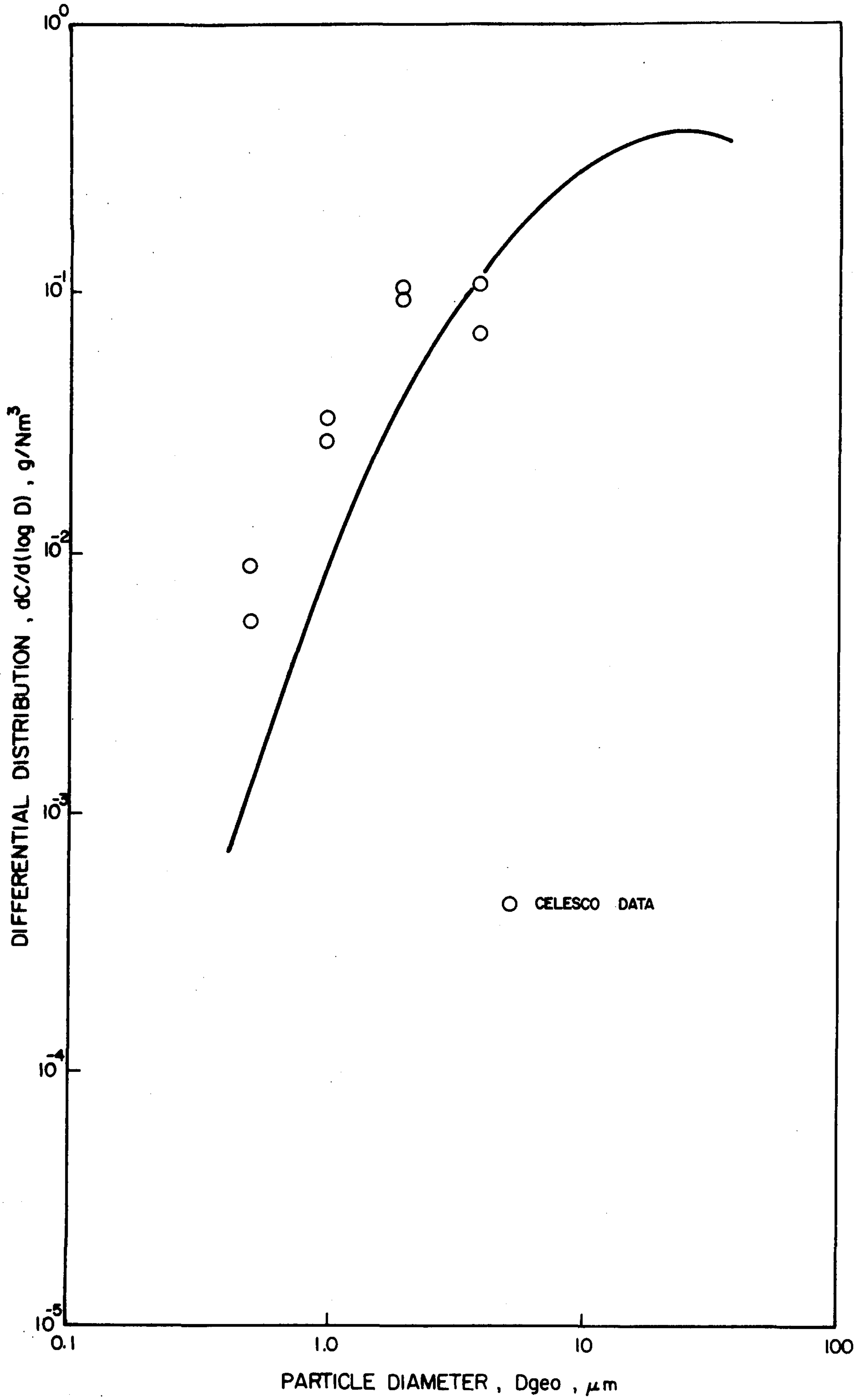

Figure 10· Comparison of Celesco Piezoelectric Microbalance Impactor with impactor curve (concentration = 0.089 g/Nm^3).

case. The variance of the Series Cyclone data is comparable to that of the Brink at the high concentration and is considerably lower than the variance of the Brink or Andersen at the lower concentrations.

Figure 10 compares the Celesco data with the Brink/Andersen curve fit at low concentration. Data were obtained only from the fourth, fifth, sixth and seventh stages of the ten stage cascade in the Celesco instrument. The loss of data at the top and bottom of the cascade was not unexpected with the given conditions and sampling apparatus. The first three stages correspond to D_{50}'s of 22.3, 11.5, and 5.6 microns, respectively. With a lag time of 2 seconds in the 1/4-inch extractive sample line, a simple settling velocity calculation shows that no particles of 5.6 microns or greater would ever reach the cascade. The same calculation partially explains the low tendency of the fourth stage data (D_{50} = 2.9 micrometers). Data were lost from the last three stages of the cascade because of the short sample time. The sample time was limited to 5 seconds to prevent overloading of the middle stages of the cascade. With this short sample time and the given particle size distribution, one would expect a frequency shift on the eight stage of less than 3 Hz. Since the drift criterion was 10 Hz or less in ten minutes, a 3 Hz shift could obviously not be detected.

The data points corresponding to the fifth, sixth and seventh stages of the cascade are significantly higher than the Brink/Andersen curve but show a similar slope. At least three experimental factors may have bearing on this effect.

1) Anisokinetic sampling was necessary because a sample nozzle small enough to allow isokinetic sampling was not available. The slow sampling would tend to oversample larger particles and shift the distributions upward. However, this effect is probably not too significant since particles of approximately 1 micron diameter and smaller are usually sampled correctly regardless of the anisokinetic conditions (ref. 5).

2) Sample time and rate were determined with a stop watch and rotameter supplied by the instrument manufacturer. Errors in either or both of these measurements could bias the differential distribution curve, but the combined error would have to be on the order of 100 percent to fully account for the discrepancy between the Celesco data and the Brink, Andersen curve.

3) As shown in Table 7, the Celesco sample point was several cm away from the Brink and Andersen sample points, and thus dust stratification in the tunnel could have contributed to the error.

The variance of the data that were obtained with the Celesco is slightly higher than the variance of the Brink Impactor data.

Figures 11 and 12 compare data obtained with the PILLS IV to the Brink/Andersen curves. The pronounced disagreement was not unexpected since the instruments operate on completely different theoretical principles. Coincidence of the PILLS IV data and the Brink/Andersen curves would only be expected if all of the particles were spherical and of the same density. There is no known explanation for the indicated increase in the differential distribution as the particle diameter decreases from about 0.5 microns. The variance of the PILLS IV data appears to be slightly less than that of the Brink data.

5.3 COMPARISON OF THE GCA IN-STACK BETA IMPACTOR WITH THE BRINK IMPACTOR

Special tests were arranged for the GCA In-Stack Beta Impactor so that it could be operated and adjusted by a GCA engineer. To obtain a comparison with the Brink Impactor, the two instruments were operated simultaneously with the Brink in port D and the GCA in port F. The GCA instrument did not show sufficient sensitivity to use the low concentration used with the other instruments. Therefore runs were made at a medium concentration three times the normal low concentration and at the normal high concentration. The results of these two comparisons are shown in Figures 13 and 14. In both figures a least-square curve of the same form used previously has been calculated from the Brink data and the GCA data are plotted for comparison.

At both concentrations, the data points corresponding to the first stage of the GCA Impactor are more than an order of magnitude lower than the Brink curve and appear to be inconsistent with the remainder of the GCA data. This effect was probably caused in part by the heavy dust accumulations observed on the inside walls of the upper stages and the inlet nozzle and cone of the GCA probe. Accumulations of dust were also noted on the interior walls of the lower stages, but were not nearly as pronounced as at the inlet. Furthermore, the graphical integration for first stage was biased by the occasional pegging of the chart pen (see Figure 5).

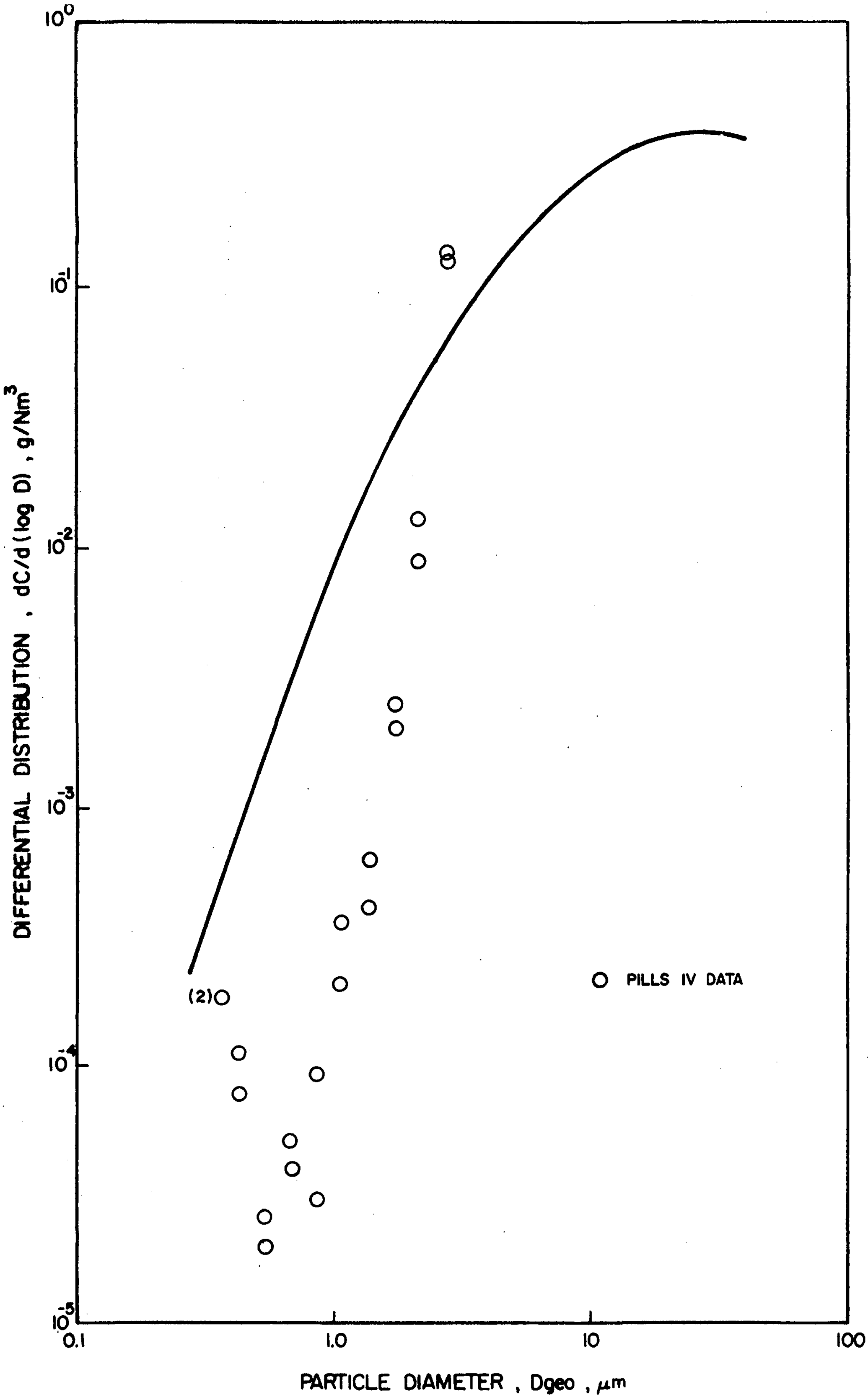

Figure 11. Comparison of Environmental Systems Corporation PILLS IV data with impactor curve (concentration = 0.089 g/Nm^3).

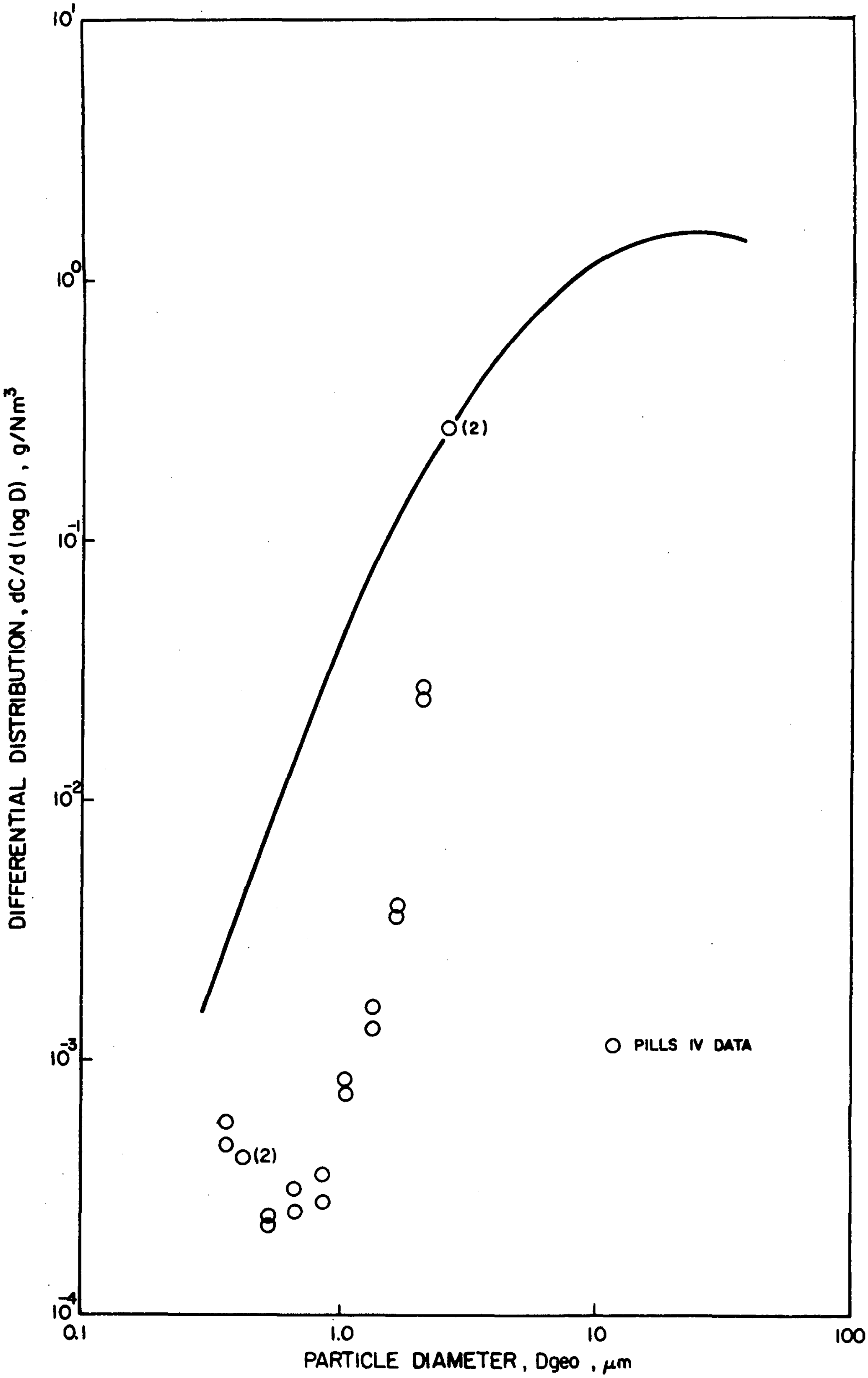

Figure 12. Comparison of Environmental Systems Corporation PILLS IV data with impactor curve (concentration = 0.955 g/Nm^3).

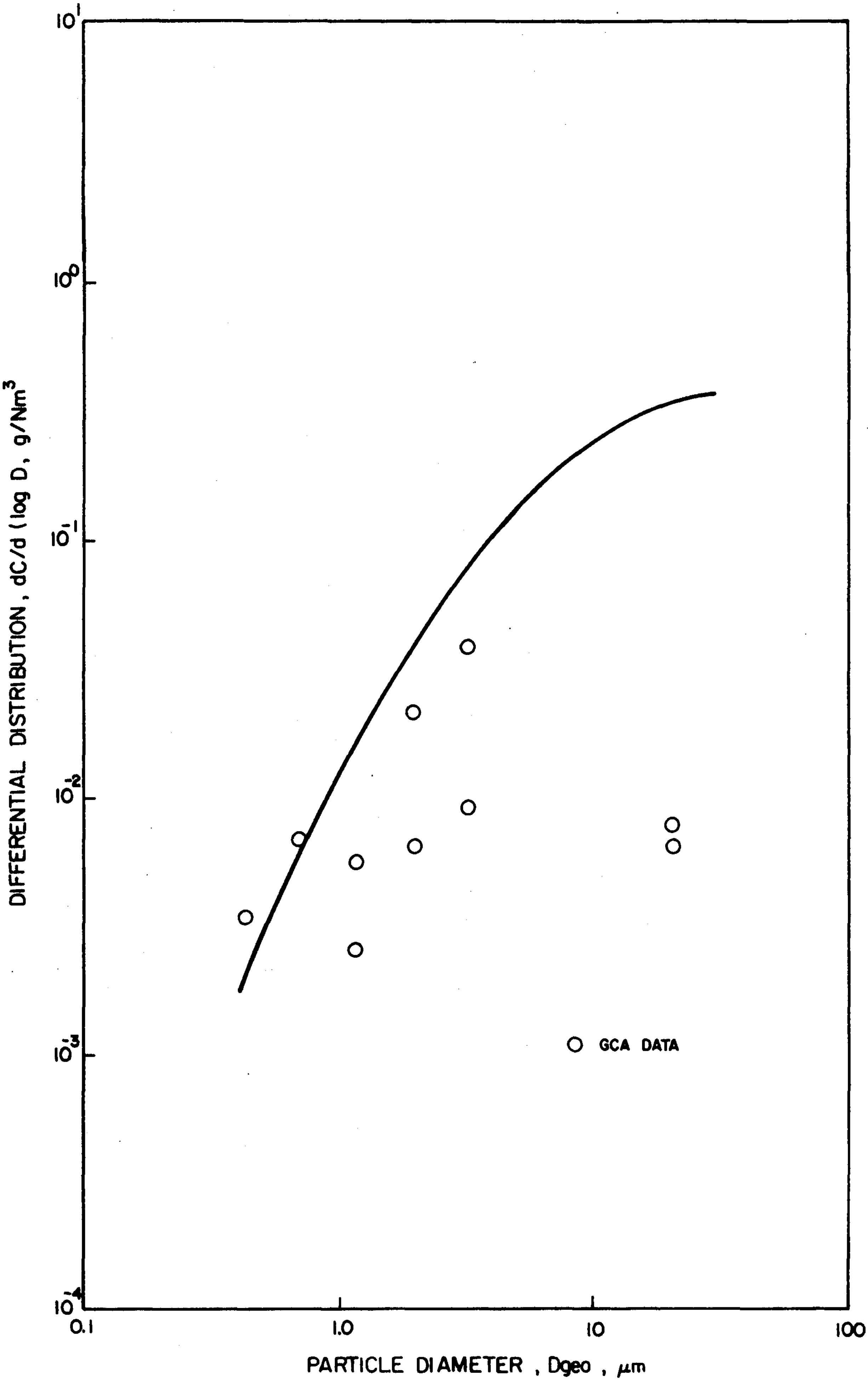

Figure 13. Comparison of GCA In-Stack Beta Impactor data with corresponding Brink curve (concentration = 0.267 g/Nm^3).

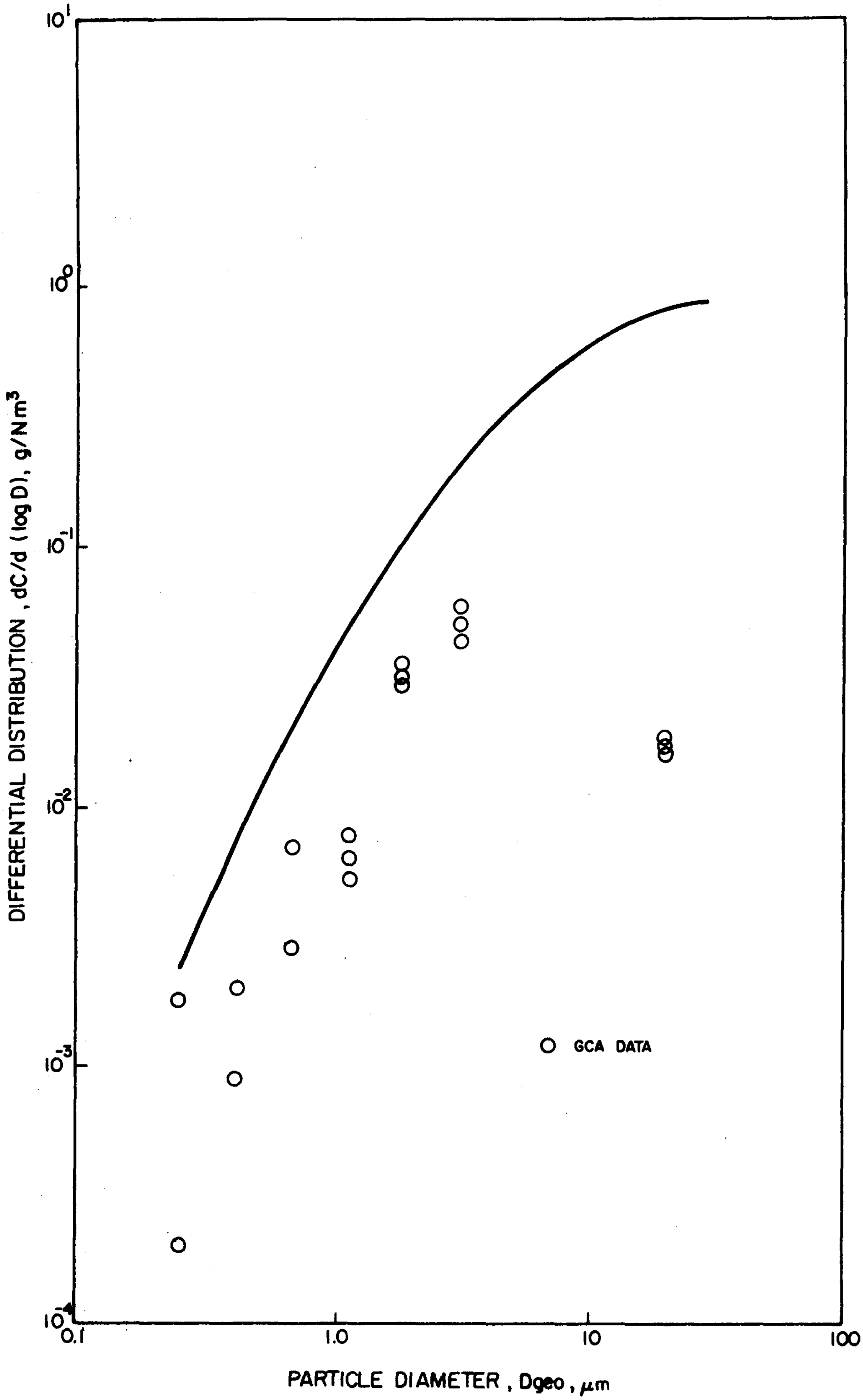

Figure 14. Comparison of GCA In-Stack Beta Impactor data with corresponding Brink curve (concentration = 0.955 g/Nm^3).

At the high concentration the remainder of the GCA data falls in a line roughly parallel to the Brink curve. The differential distribution indicated by the GCA is roughly 30 to 50 percent lower than the Brink curve at corresponding particle diameters. Part of this discrepancy can certainly be attributed to the obstruction effect and to the dust stratification in the wind tunnel. The Brink sample nozzle was inserted 23 cm into port D (corresponding to the "-3" position in Figure 2), while the GCA sample nozzle was at the center of the port and approximately 2 m downstream from the Brink. Figure 2 indicates that a 50 percent variation in mass concentration, which would lead to a comparable variation in the differential distribution curve, could possibly be attributed to the stratification and obstruction effects alone. Additional tests will have to be run under more ideal conditions to determine if the scale factors used to convert beta attenuation to particle mass also need correction.

At the high concentration the variance of the GCA data is comparable to that of the Brink data for particle diameters greater than 1 micron, but increases sharply on the lower stages. At the medium concentration, the variance is consistently greater than any of the other instruments.

The fluctuation of the GCA response with time has already been illustrated in Figure 5. Since no other instrument except the IKOR operated in real time, it could not be determined whether or not these fluctuations reflected actual time variations in the total mass concentration of particle size distribution. The IKOR did show oscillations of smaller magnitude than the GCA, but the GCA also showed significant fluctuations in the zero, which would tend to indicate an inconsistency in the grease coating of the substrate or in the substrate itself.

6.0 RESULTS OF SIMULTANEOUS RUNS

In the early part of the experimental program, tests runs were made with several instruments operating simultaneously in different ports of the wind tunnel. At each operating condition, runs were repeated until each instrument was tested twice in each port in which it could be operated. The PILLS IV instrument was operated only in ports D and F because of the physical size of the probe. All of the data which were recoverable from these simultaneous runs are presented in Figures 15 through 23, with appropriate port identifications. In each figure the curve drawn is a second-order, least-square fit, not of the data shown, but of the data obtained under equivalent conditions with the same instrument during the successive runs; i.e., the data presented in Figures 6 through 12.

Analysis of these figures reveals four important effects which support and extend the conclusions drawn from the primary data and profile studies.

1) With each instrument, excluding the Andersen Impactor which is discussed below, the data are in reasonable agreement with the least-square fit of the successive test run results. This agreement tends to support the conclusions drawn from the limited number of primary data runs.

2) The spread of the experimental data at individual particle diameter is much greater than that obtained in the successive runs, indicating port variations and the detrimental effect of instruments interferring with other instruments downstream.

3) Although it does not appear in each of the figures, there is a definite overall trend of decreasing particle concentration as one moves downstream in the wind tunnel; i.e., the differential distribution measured at port B > ports C and D > ports E and F. This trend is another indication of the interference and dust stratification created by upstream instruments in relation to downstream sampling ports. It might also indicate particle

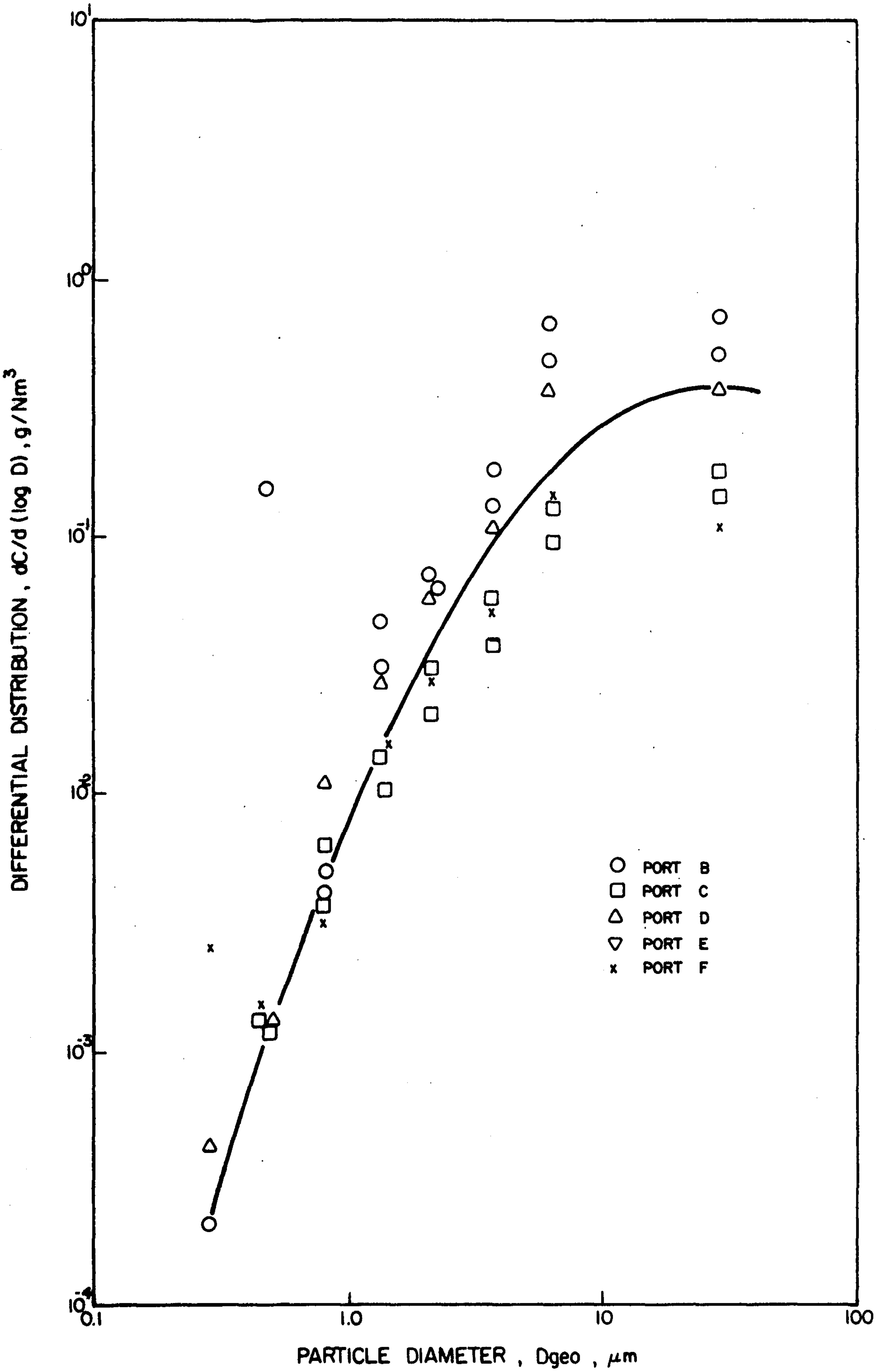

Figure 15. Comparison of simultaneous Brink data with primary Brink data curve fit (concentration = 0.089 g/Nm^3).

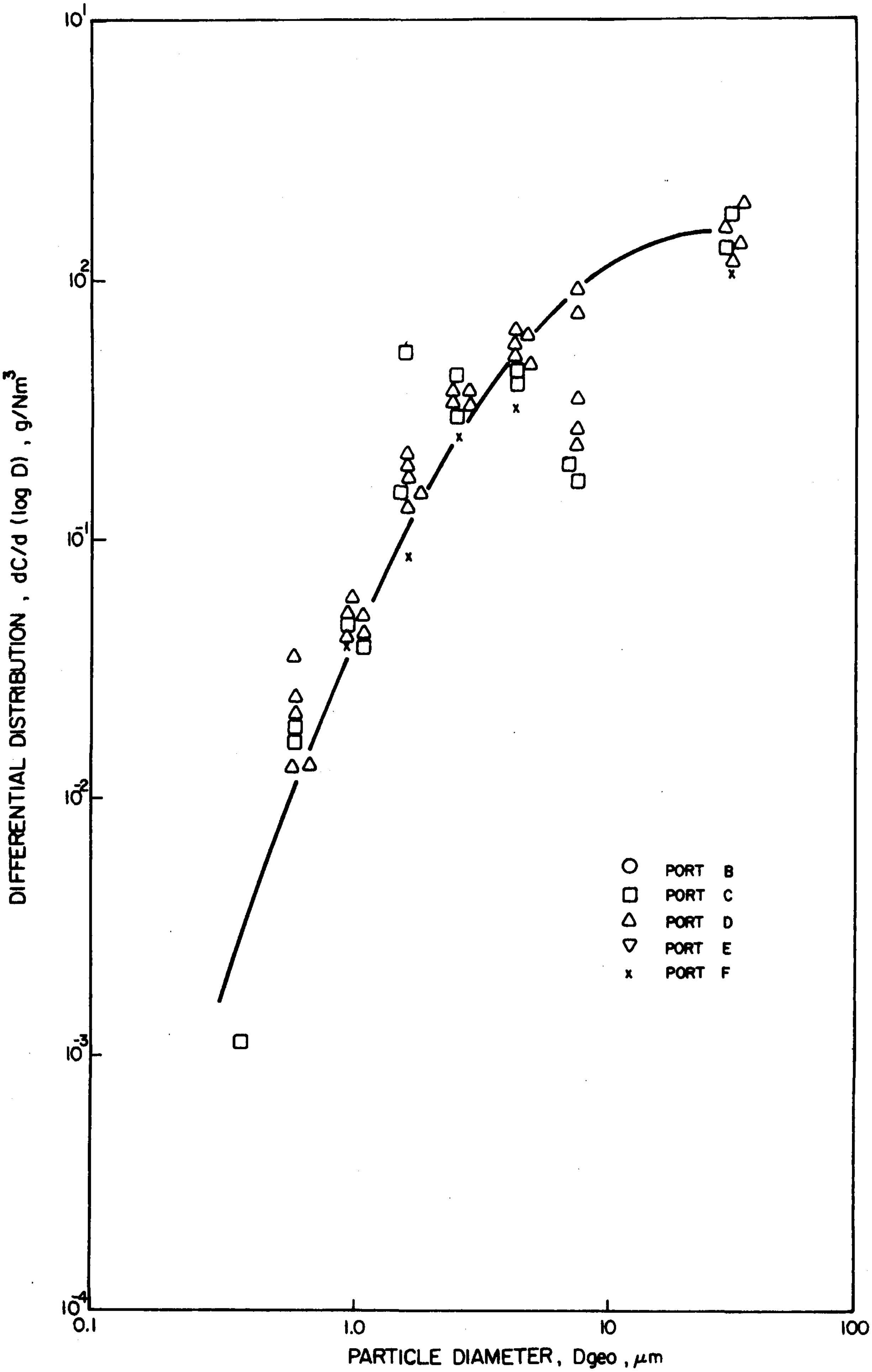

Figure 16. Comparison of simultaneous Brink data with primary Brink data curve fit (concentration = 0.955 g/Nm^3).

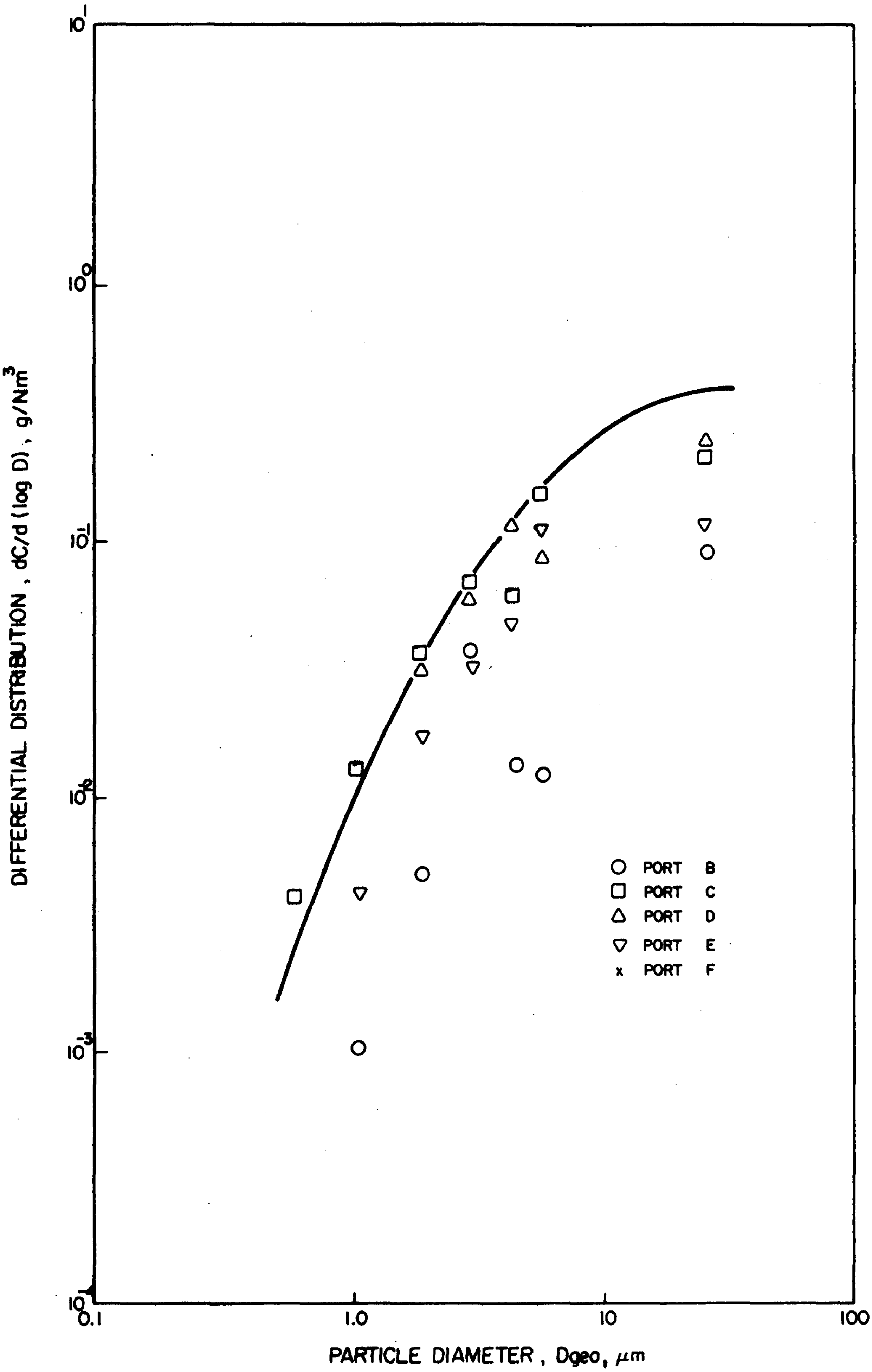

Figure 17. Comparison of simultaneous Andersen data with primary Andersen data curve fit (concentration = 0.089 g/Nm^3).

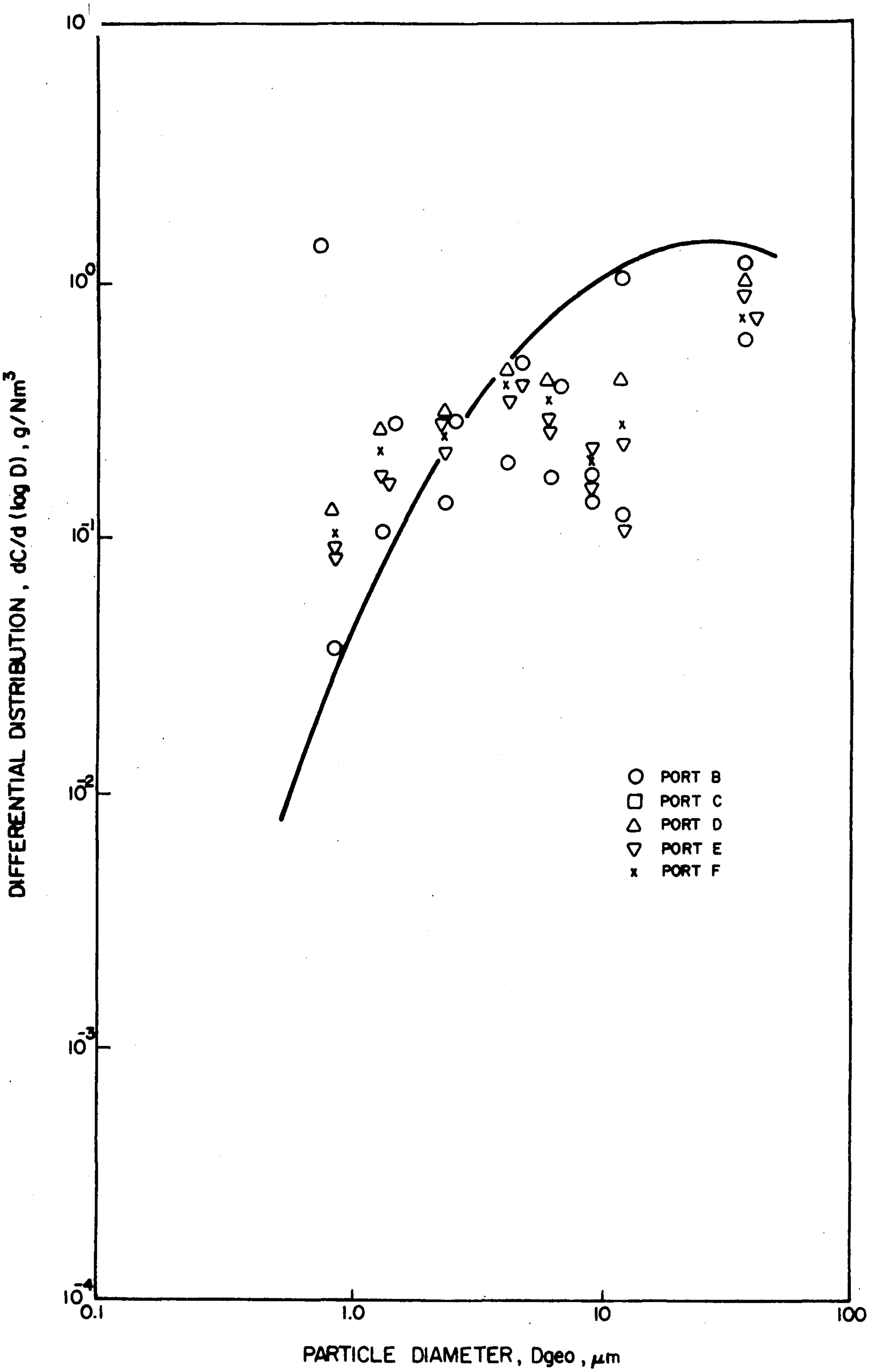

Figure 18. Comparison of simultaneous Andersen data with primary Andersen data curve fit (concentration = 0.955 g/Nm^3).

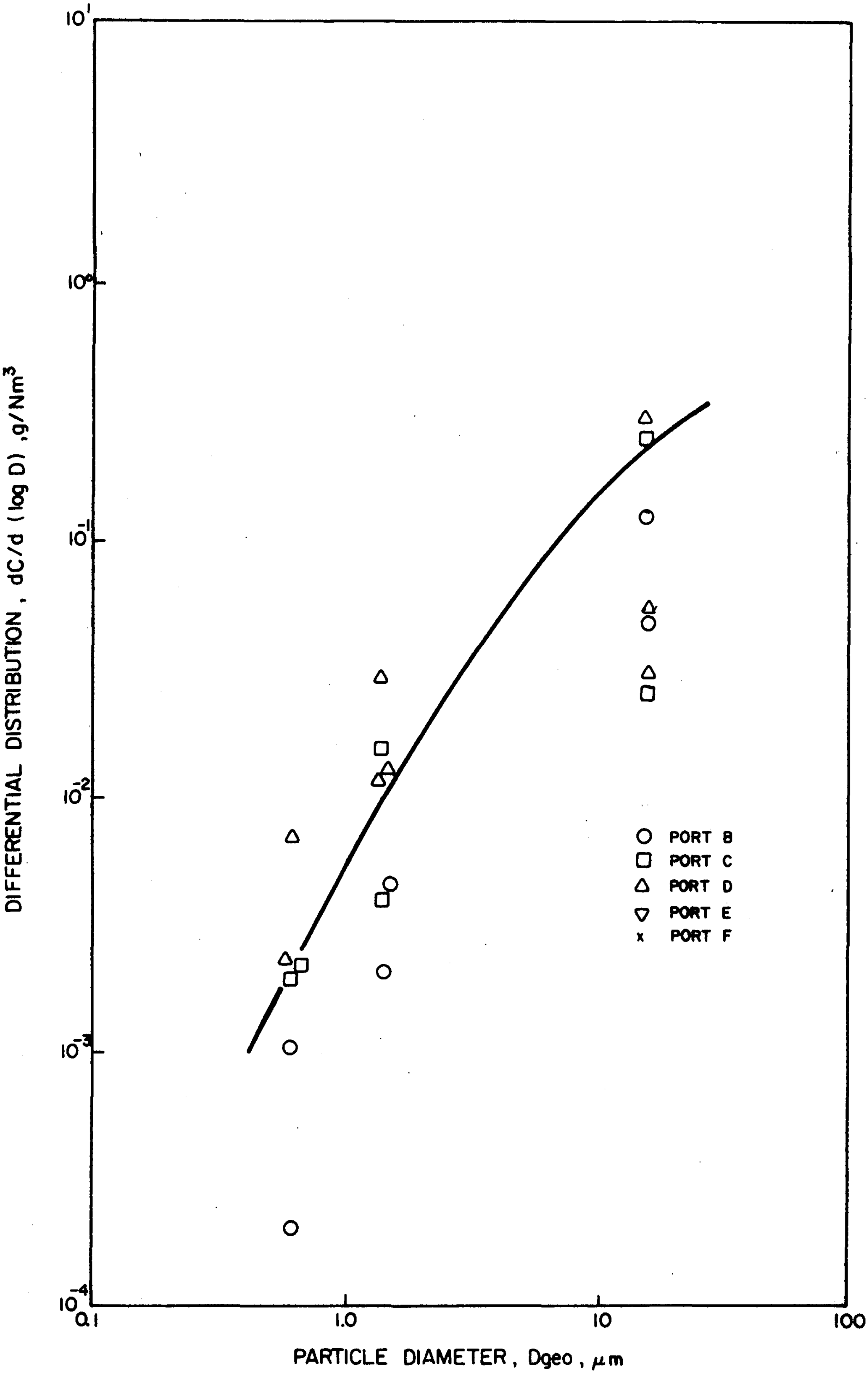

Figure 19. Comparison of simultaneous Southern Series Cyclone data with primary Cyclone data curve fit (concentration = 0.089 g/Nm^3).

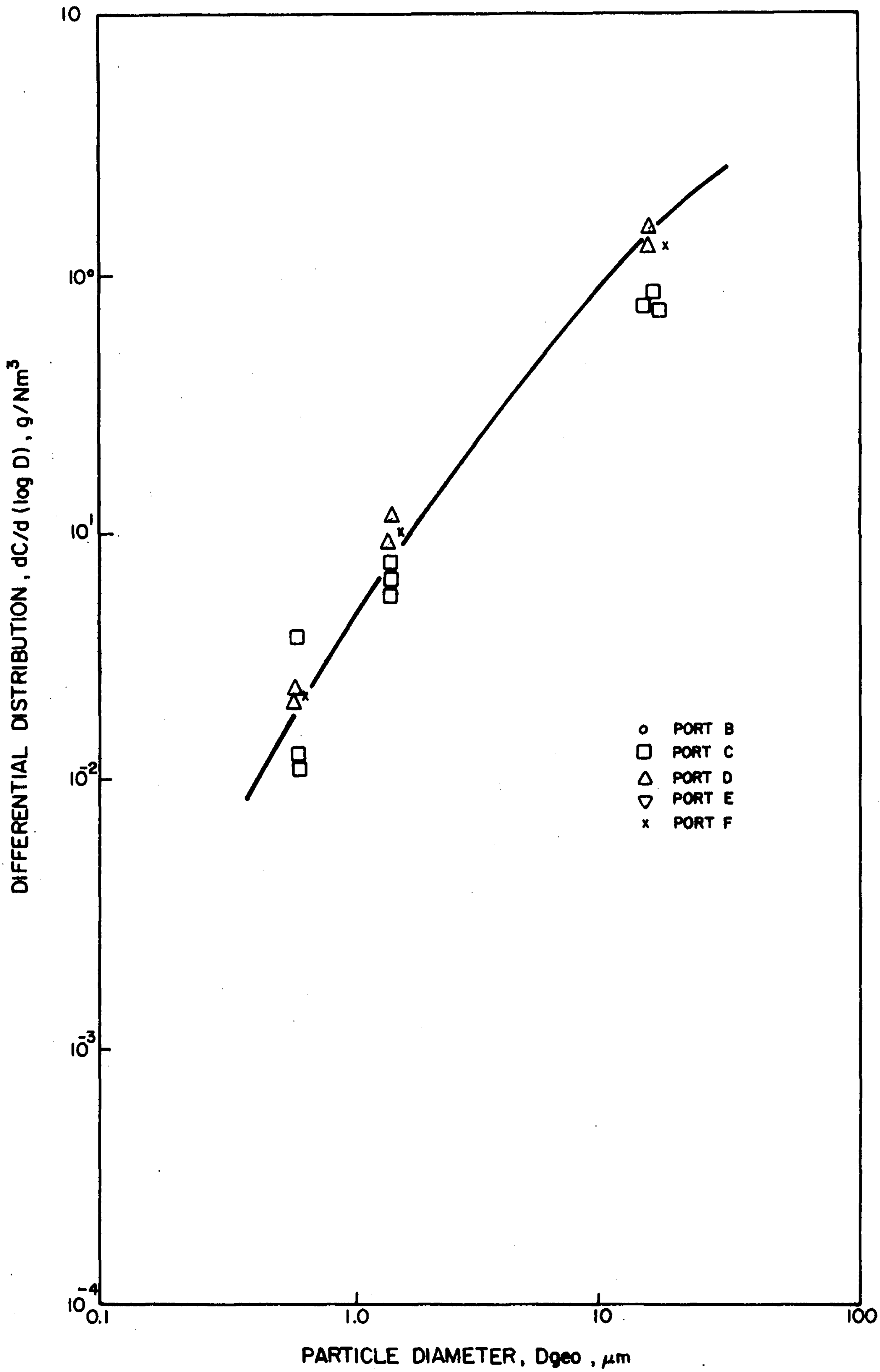

Figure 20. Comparison of simultaneous Southern Series Cyclone data with primary Cyclone data curve fit (concentration = 0.955 g/Nm^3).

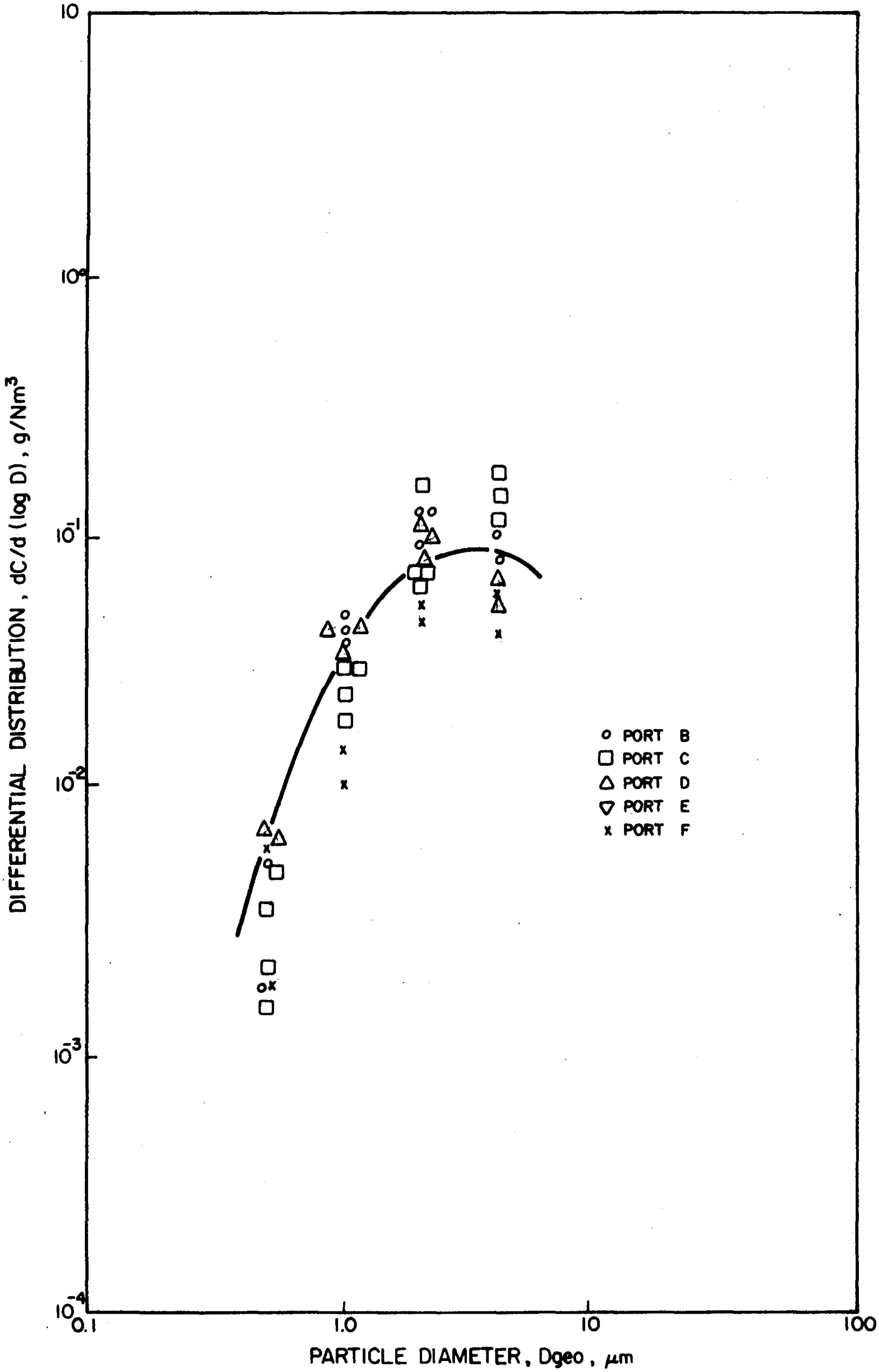

Figure 21. Comparison of simultaneous Celesco data with primary Celesco data curve fit (concentration = 0.089 g/Nm^3).

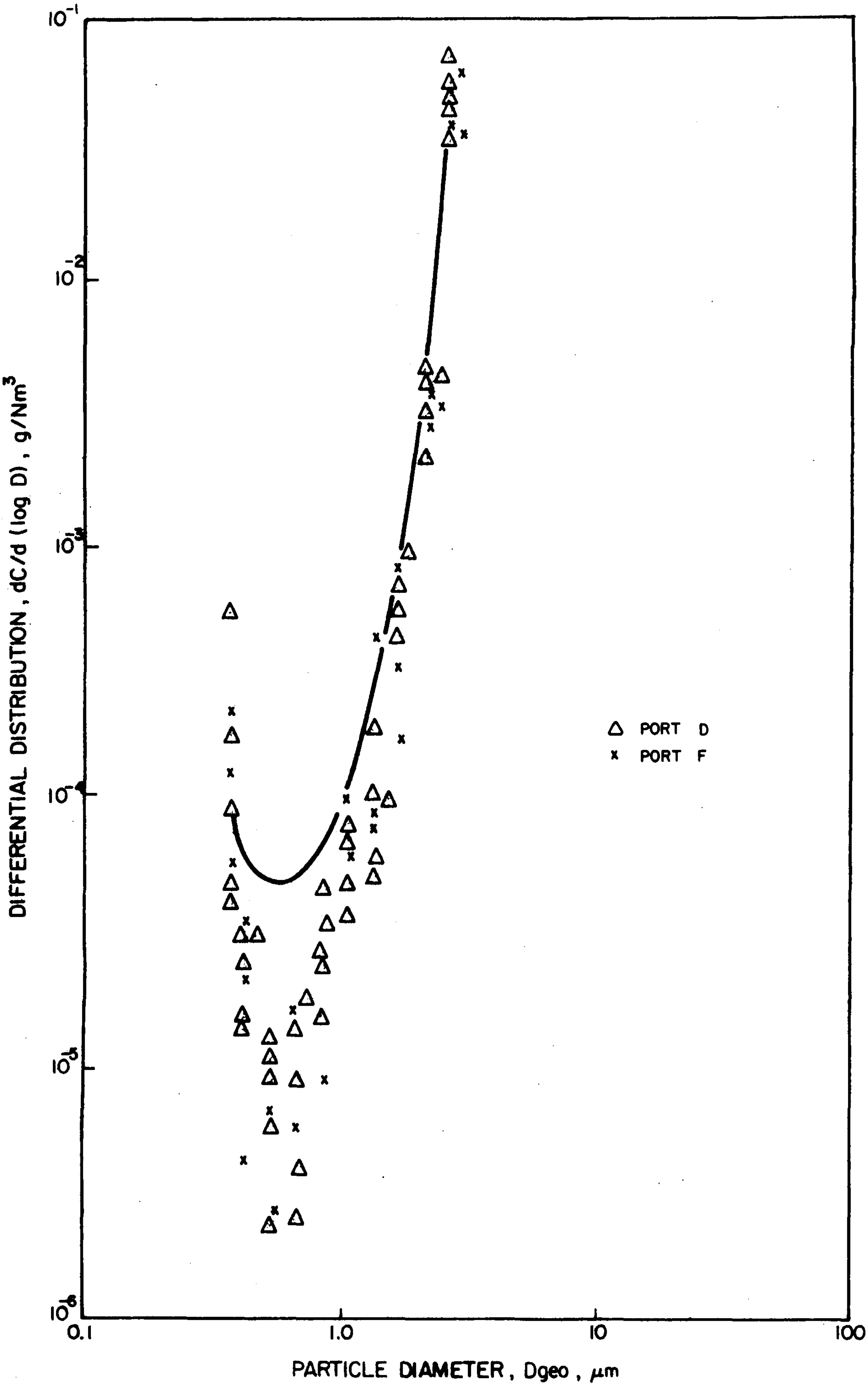

Figure 22. Comparison of simultaneous PILLS IV data with primary PILLS IV data curve fit (concentration = 0.089 g/Nm^3).

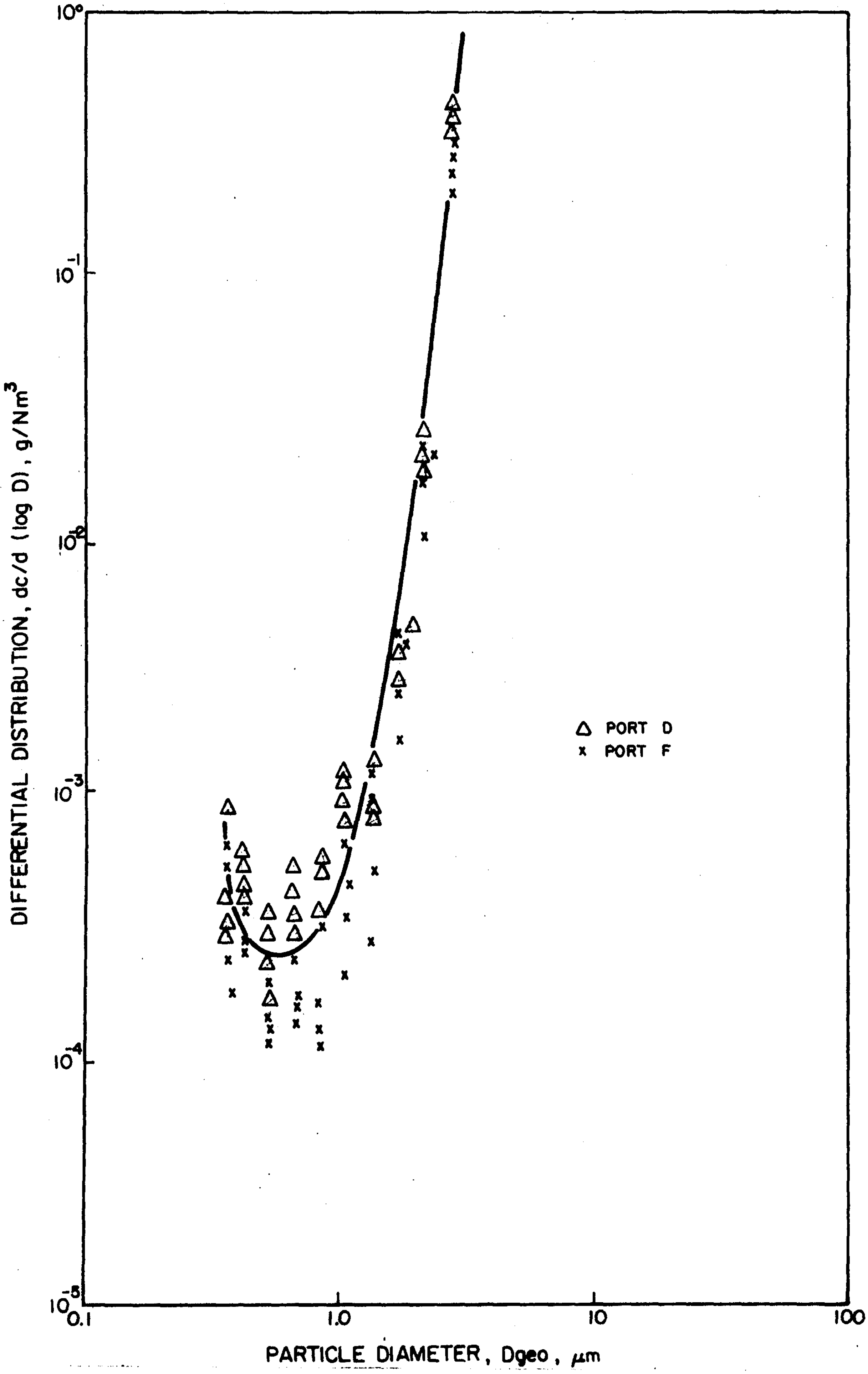

Figure 23. Comparison of simultaneous PILLS IV data with primary PILLS IV data curve fit (concentration = 0.955 g/Nm^3).

settling. Terminal velocity calculations indicate that settling could have been significant for particles of greater than 50 microns diameter, particularly in the high concentration--low velocity runs. No experimental evaluation of vertical stratification was attempted.

4) Figure 18 for the Andersen Impactor at high concentration exhibits a flattening of the differential distribution curve. This effect is believed to be related to the sample flow rate of 3.9 ℓ/min used in these early runs. This sample rate is much lower than the calibration flow rate of the cyclone precollector, and it is likely that the cyclone efficiency curve at this flow rate is distorted to such an extent that it interferes with the behavior of several stages in the cascade. The data shown in Figure 17 at low concentration were obtained at a flow rate of 15.8 ℓ/min and the effect is not as pronounced although considerable scatter is evident. There was no explanation for the extremely low results obtained in the port B test runs in this particular case.

APPENDIX

CALCULATION OF DIFFERENTIAL SIZE DISTRIBUTION

The procedure for reducing the data from stage weights to a differential distribution is illustrated in the following sequence of equations. Table A-1 is a table of reduced data taken from a run with the Brink Impactor. These data are plotted in Figure 7.

STEP 1: Calculate the standard volume of the sample.

$$V_N = V_m \left[\frac{P_a - \Delta P_T - \Delta P_m}{760} \times \frac{273}{T_m} \times \frac{1}{1 + y} \right]$$

where V_N = standard volume, Nm^3

V_m = measured volume, m^3

P_a = atmospheric pressure, mm Hg

ΔP_T = pressure drop from atmosphere to the tunnel, mm Hg

ΔP_m = pressure drop from tunnel to the flow measuring device mm Hg

T_m = temperature of the flow measuring device, °K

y = volume fraction of water at the flow measuring device

STEP 2: Calculate the incremental concentration on the stage.

$$\Delta C_i = \frac{M_i}{V_N} \times 10^{-3}$$

ΔC_i = incremental concentration on stage i, g/Nm^3

M_i = mass collected on stage i, mg

STEP 3: Calculate the difference in logarithms of the D_{50}'s of two adjacent stages.

$$(\Delta \log D_{50})_i = (\log D_{50})_{i+1} - (\log D_{50})_i$$

where D_{50} is expressed in μm.

STEP 4: Calculate the geometric mean of two adjacent stages.

$$(D_{geo})_i = \left[(D_{50})_{i+1} \times (D_{50})_i\right]^{1/2}$$

where $(D_{geo})_i$ is the particle diameter associated with the mass collected on stage i, expressed in μm.

STEP 5: Calculate the point on the differential distribution corresponding to $(D_{geo})_i$.

$$[dC/d(\log D)]_i = (\Delta C_i)/(\Delta \log D_{50})_i$$

where $[dC/d(\log D)_i]$ is a point on the differential curve, expressed in g/Nm^3.

Table A-1. REDUCED DATA TABLE FOR BRINK RUN NO. 905-2

Stage	D_{50}, μm	$\log D_{50}$	$\Delta \log D_{50}$	D_{geo}, μm	M, mg	ΔC_i, g/Nm^3	dC/d(logD)
Arbitrary maximum	100	2.0	--	--	--	--	--
Cyclone	9.39	0.973	1.027	30.6	47.840	1.454	1.416
0	5.73	0.758	0.215	7.34	6.336	0.193	0.896
1	3.25	0.512	0.246	4.32	3.848	0.117	0.475
2	1.93	0.286	0.226	2.50	1.992	0.0605	0.268
3	1.32	0.121	0.165	1.60	0.576	0.0175	0.106
4	0.71	-0.149	0.270	0.97	0.296	0.0090	0.0333
5	0.46	-0.337	0.188	0.57	0.056	0.0017	0.0090
6	0.28	-0.553	0.216	0.36	0.008	0.00024	0.0011
Filter	--	--	--	--	0.280	--	--

Additional Data

P_a = 765.8 mm Hg

ΔP_T = 1.0 mm Hg

ΔP_m = 17.8 mm Hg

T_m = 300°K

y = 0.019 (54% relative humidity)

V_m = 0.0374 m^3

$\therefore V_N$ = 0.0329 Nm^3

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16. ABSTRACT The report gives results of an experimental study, undertaken to evaluate and compare several particle sizing instruments. Fly ash from a coal-fired power plant was redispersed and fed into a wind tunnel at concentrations corresponding roughly to clean and dirty stack conditions. Data were obtained with two standard cascade impactors (using gravimetric mass determination), a set of series cyclones, a cascade impactor with piezoelectric crystal sensors, a cascade impactor using beta attenuation to determine collected mass, and an optical single-particle counter using a laser light source. The standard impactors and the series cyclones yielded comparable results. Data from the piezoelectric cyrstal cascade were in reasonable agreement with the standard impactors but were limited because of the required extractive sampling mode and the mass capacity limitation of the crystals. The beta impactor showed general agreement but needs further development in the areas of zero stability, sensitivity, signal-to-noise ratio, and scale conversion from beta attenuation to collected mass. No simple correlation could be established between the results of the optical instrument and those of the inertial classification devices, due to the probable nonuniformity of particle shape and density.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Fly Ash	Air Pollution Control	13B	21B
Size Determination	Impactors	Stationary Sources	14B	13I
Particles	Cyclone Separators	Cascade Impactors		07A
Instruments	Piezoelectricity			20C
Evaluation	Beta Particles		14A	20H
Wind Tunnels	Lasers			20E

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