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PHASE I CHARACTERIZATION OF THE HEPA FILTER MEDIA USED IN THE AIRBORNE ACTIVITY CONFINEMENT SYSTEM AT THE SAVANNAH RIVER SITE (U)

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

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1.0 Introduction

The Airborne Activity Confinement System (AACS) is used in the production reactors of the Savannah River Site to provide for the capture and confinement of accidentally released radioisotopes. Figure 1.1 presents a schematic description of the AACS.[1] Outside air is continuously drawn through the building by fans and exhausted out of a stack. The exhaust fans maintain the reactor room and other areas of the building at a negative pressure so that any material released inside of the building cannot exit to the outdoor environment without first passing through a series of filters. The first filter in the filter compartment is designed primarily to address accident scenarios where steam is released. As the steam cools in the reactor building, it will condense and form a fog of water droplets. The purpose of the moisture separator (first filter) is to remove the water droplets and any other large aerosol particles before they can be deposited in the High Efficiency Particulate Air (HEPA) filter. The HEPA filters comprise the second filter in the series. The HEPA filter is designed to remove all particles from the gas stream with efficiencies of at least 99.97%.[2] The final component of the filter compartment is a carbon bed. The purpose of the carbon bed is to remove more than 99.9% of the elemental iodine vapors from the exhaust gas.[3]

The purpose of this report was to characterize the HEPA filter media material. This work consisted of two major tasks. First, the pressure drop characteristics of the HEPA filter material were measured as a function of the aerosol mass loading. Particle size effects were studied by using three different particle size distributions to load the filter material. The second task was to determine the filtration efficiency spectrum for solid particles as a function of particle diameter. The filtration efficiency was measured at two different media velocities, one corresponding to the equivalent flow rate under normal operating conditions, the other corresponding to the minimum equivalent flow rate expected through the filter compartments. These tests were conducted at the Argonne National Laboratory between September 1988 and February 1989.

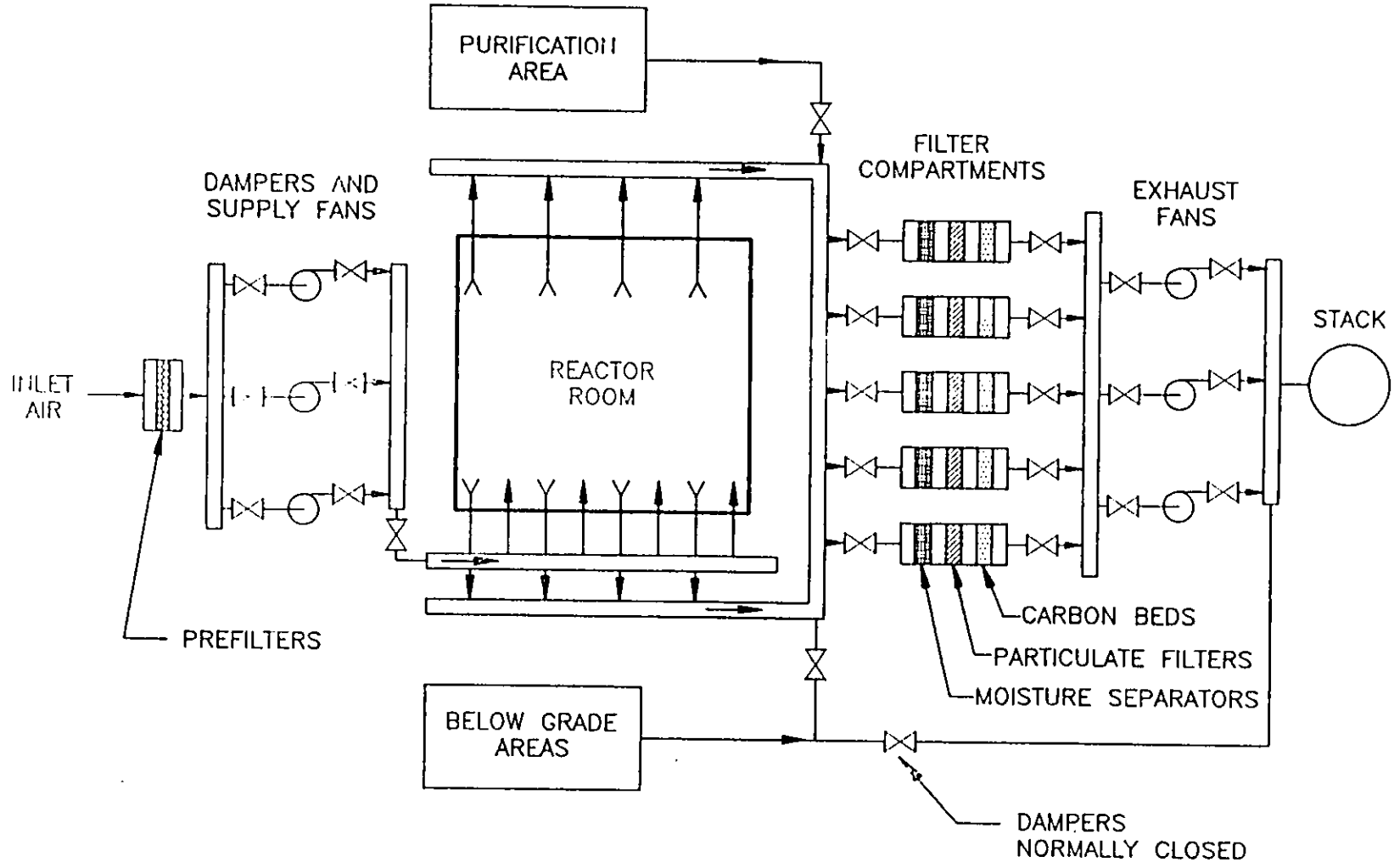

Figure 1.1 Schematic of the Airborne Activity Confinement System (AACS)

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2.0 Background

In 1966, the Savannah River Laboratory completed a series of tests on various filter media to select the best candidate for the AACS.[4] The filters were subjected to a variety of stress tests involving air, water and steam at normal and up to 10 times normal flow velocities. The efficiencies of these filters were measured before and after each test using 0.3 μm DOP particles. One filter, military specification MIL-F-51079, successfully completed the test sequence with less than a 1% difference in measured efficiency.

Savannah River purchases assembled 2 ft x 2 ft x 1 ft filter units from the Cambridge Filter Corp. The HEPA filter, Model 1E-242412-1S, is manufactured according to DPSOP 40-2 specification 4. The filter media is supplied to Cambridge by Hollingsworth and Vose and meets the above military specification. ANL purchased, from Cambridge Filter Corp., filter media identical to that supplied by Cambridge to the Savannah River Plant (SRP). A number of 47 mm filter disks were cut from lot No. 55855 Roll 3-A. This filter size was chosen for testing in order to minimize the time required for each test, to conform to existing equipment and to simplify the analysis.

Experimental apparatus was set up based on filter characterization work discussed in the aerosol science literature.[5,6] Sodium chloride was chosen as the challenge aerosol based on a number of considerations:

- Solid aerosol particles were desired to challenge the filters
- Solids are desirable for measuring the minimum efficiency characteristics because of reentrainment and particle bounce effects.
- Sodium chloride is used as a standard in filter testing -- British Standard 3928: 1969

- Sodium Chloride aerosol shape characteristics might be similar to aerosols released during accidents where steam would condense in colder regions of the building but then evaporate upon mixing with drier dilution air in the plenum before reaching the filters.

- The use of sodium chloride allowed the filtered particle mass to be determined by conductivity analysis as well as weighing, providing increased accuracy and confidence in the results.

- Sodium chloride is non-toxic and can easily be cleaned from the equipment used in the tests.

3.0 Experimental Description

Prior to designing the laboratory test apparatus for the 47 mm filter, key scaling relationships must be determined. The filtration process depends on the filter characteristics such as fiber size, filter depth and filter porosity and the aerosol mechanisms of impaction, interception and diffusion. Furthermore, these aerosol collection mechanisms depend on particle size, gas viscosity and gas velocity. The filter media was chosen to be identical with the SRP filter material. The gas viscosity is expected to be similar to that encountered at SRP by using air at 25°C. The particle size is an experimental variable since there is uncertainty in the expected particle size distribution. This leaves the gas velocity through the filter media as the key parameter that must be determined in order to conduct relevant scaled tests.

3.1 Calculation of Filtration Velocity

To calculate filtration velocity for the Savannah River AACS HEPA filters, the effective filter area for one unit must first be found. Some filtration area is lost due to contact with the corrugated aluminum separators used to pleat the filter media and filter edges where it is sealed to the housing. Given that the area of the unpleated filter is 200 ft^2 and the

filter media is 2 ft wide, the length must be 100 ft. With a pleat length of 10.5 in., there must be approximately 114 pleats per unit. Two assumptions are made concerning the filtration area lost at each pleat.

1. The edge of the filter is sealed to the container resulting in loss of 1/4" across the top and bottom of each pleat.

2. There are 20 corrugations per separator, each contacting the length of the pleat in a 1/4" wide strip.

Summing the area lost in sealing the filter to the housing with the area lost due to contact with the aluminum separators gives:

$$\begin{aligned}\text{Lost Filtration Area} &= (0.25\text{ inch})(12\text{ inch top surface} + \\ &\quad 12\text{ inch bottom surface})(114\text{ pleats}) \\ &+ (0.25\text{ inch})(10.5\text{ inches between pleats}) \\ &\quad (20\text{ corrugations per separator})(114\text{ pleats}) \\ &= 6670\text{ in}^2\end{aligned}$$

or approximately 50 ft^2. Therefore, the effective filtration area per unit is 200 ft^2 - 50ft^2 or approximately 150 $ft.^2$

Since each filter bank normally operates with a volumetric flow of 20000 to 28000 CFM, each of the 32 filter units that make up one filter bank draws 625 to 875 CFM. Under normal operating conditions, then, the filtration velocity for the AACS filters is,

$$\begin{aligned}\text{Filtration velocity} &= (625\text{ to }875\text{ CFM})/150\text{ ft}^2 \\ &= 4.17\text{ to }5.83\text{ ft./min} \\ &= 2.12\text{ to }2.96\text{ cm/s}\end{aligned}$$

In the case where the volumetric flow through each bank is 8000 CFM, which is the minimum expected operational flow, the filtration velocity is calculated to be 0.85 cm/s. The ANL test apparatus was designed to operate at both normal and minimum SRL gas velocities using the 47 mm filter disks.

The flow control devices used in the bench-scale test apparatus were either constant flow rate mass flow meters or critical orifices. Therefore, in order to vary the filtration velocity, it was most convenient to hold the volumetric flow rate constant and vary the effective filtration area to produce the desired velocity. Table 3.1 summarizes the various filtration velocities tested and equivalent flow rates for each AACS filter bank.

Table 3.1 Filtration Velocities Tested and AACS Equivalent Flow Through One Filter Bank

Test Type	Test Parameters			ACCS Equivalent
	Volumetric Flow (liter/min)	Filtration Area (cm^2)	Filtration Velocity (cm/s)	Volumetric Flow (CFM)
Mass Loading	1.415	9.62	2.45	23100
Efficiency	1.415	7.92	2.98	28200
Efficiency	1.415	26.4	0.89	8440

3.2 Apparatus For the Pressure Drop vs Mass Loading Tests

Figure 3.1 shows the basic elements of the test apparatus as arranged for the mass loading tests. A Balston air purifier was used to clean and dehumidify the laboratory compressed air. A General Eastern model 1100DP dewpoint hygrometer indicated the relative humidity of the resulting source air was lower than 10%. Tests with a TSI model 3020 condensation nucleus counter (CNC) showed fewer than 0.01 particles/cm^3 in the air supplied by the Balston purifier. However, immediately following the pressure regulator, an inline HEPA filter was installed because the history of the regulator was unknown. The resultant gas stream was retested and particle concentrations were still below 0.01 particles/cm^3. The regulated output of the air purifier was then split with a tee, one line coupled to the aerosol generator and one line bypassing the generator through a rotameter for dilution of the wet polydisperse aerosol.

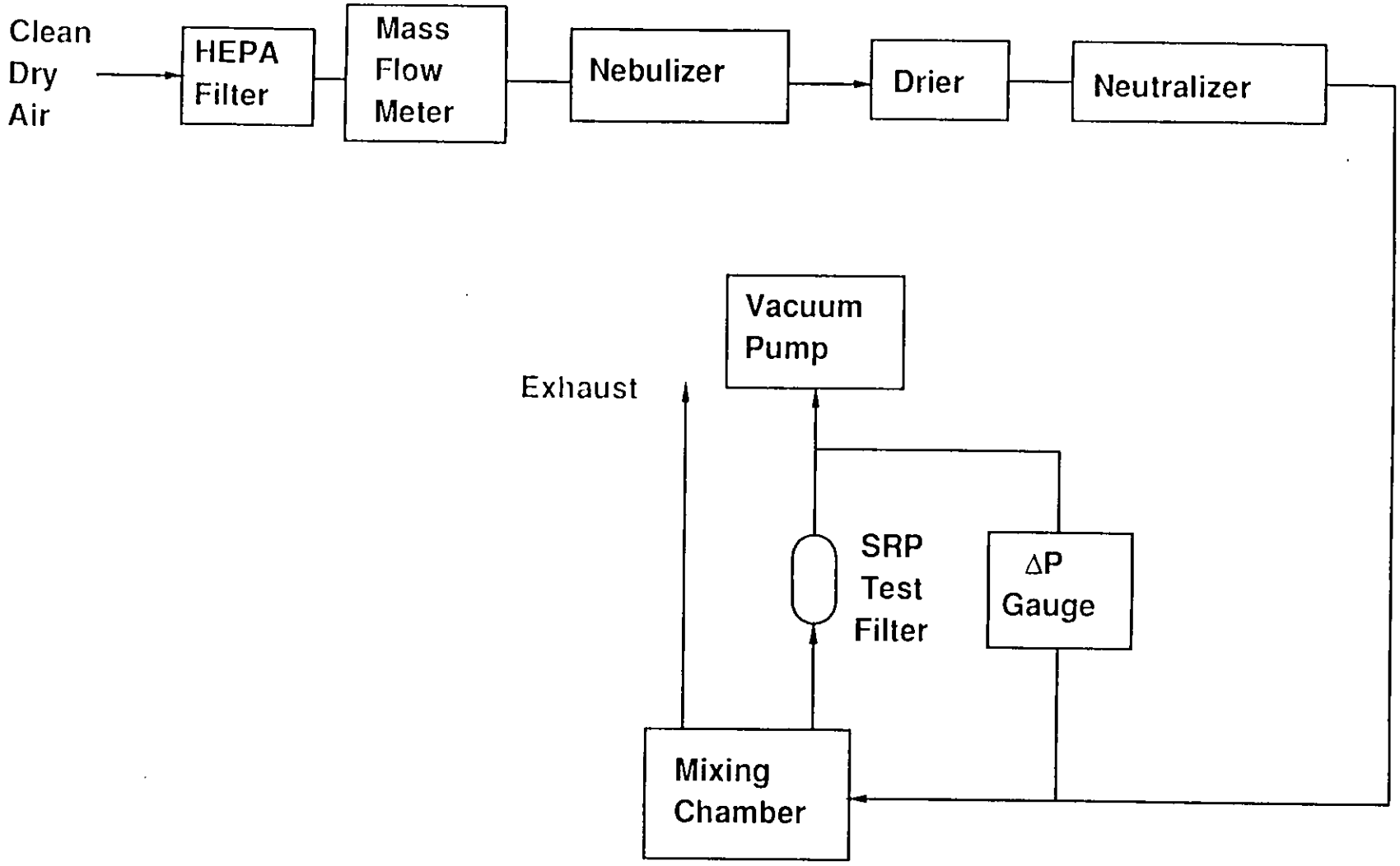

Figure 3.1 Experimental Configuration for Pressure Drop vs Mass Loading Tests

3.2.1 Aerosol Generation

Two different aerosol generators were necessary to provide the desired span of particle sizes for the mass loading tests. A TSI model 3076 constant output atomizer was used to generate the smallest size distribution and a Retec nebulizer for the two largest size distributions. Both generators produce a polydisperse aerosol of liquid droplets by directing a high velocity air jet across the end of a tube, the other end of which is inserted in a liquid reservoir. The liquid is drawn up the tube by pressure difference and atomized by the air jet. To generate aerosols of solid particles, a solid material is dissolved in a volatile solvent, typically water, and the solution is atomized. The solvent then evaporates leaving a polydisperse aerosol of solid particles. The initial droplet size and the solution concentration determines the size of these solids.

Sodium chloride was chosen as the solute for a number of reasons as discussed earlier. Sodium chloride particle produced in this manner are irregularly shaped. In comparison to spherical particles, they may simulate more closely the shape of particles likely to be produced in the Savannah River Reactor. Additionally, sodium chloride is highly soluble in water, is non-toxic, and allows a precise means of mass analysis by conductivity.

To insure complete evaporation of the water, a diffusion drier is incorporated immediately after the aerosol generator. The drier consists of a cylindrical wire screen providing an unobstructed flow path for the wet aerosol surrounded by silica gel desiccant. The desiccant changes color as water is absorbed and is regenerated by heating after approximately 10 to 15 hours of aerosol flow.

Solid aerosols formed in this way can be highly charged and losses to the tubing walls may be significant. For this reason, a TSI model 3054 bipolar aerosol neutralizer is inserted downstream of the drier. A small amount of radioactive Kr-85 gas is used to ionize air molecules inside the neutralizer volume. The aerosol particles passing through the neutralizer acquire charge to rapidly attain a Boltzman equilibrium charge distribution.

3.2.2 Aerosol Sampling

Because it was frequently necessary to sample the aerosol with more than one instrument simultaneously, a cylindrical mixing chamber was constructed having six ports from which the aerosol could be sampled with equal preference. A single standard 47 mm diameter in-line filter holder was used to hold the filter media samples for the mass loading tests. Two Dwyer Magnehelic differential pressure gauges, measuring from 0 to 1 and 0 to 10 inches of water respectively, monitored the pressure drop across the filter media. These gauges measured the pressure differential between the mixing chamber and a tee immediately behind the filter holder(s). Other pressure drops through the connective tubing, drier, neutralizer and mixing chamber, transporting the aerosol, were negligible.

3.2.3 Particle Size Measurements

The polydisperse aerosols used in the mass loading tests were sized with a seven-stage inertial cascade impactor. Each stage increases the aerosol velocity, causing successively smaller particles to impact on a collector plate due to the inability to follow the gas stream lines. Small particles able to follow the stream lines around the final collection substrate are captured on an absolute final filter. Mass analysis of the stages and final filter produces a frequency versus aerodynamic diameter mass distribution. Knowledge of the particle density can be used to calculate the mass distribution of physical diameters.

3.2.4 Calibration and Performance Verification Tests

Devices used in these tests were calibrated against standard equipment or the performance was verified as accurate when compared to similar devices. The performance characteristics of the experimental components were found to be as follows:

- The volumetric flow rate through the filter was controlled by a critical orifice in the model 3760 CNC. This volumetric flow rate was verified to be within 1% of 1.415 liter/min using a standard wet test meter.

- All other flowmeters, such as that used for dilution of wet aerosol, were found to agree to within ±5% of the wet test meter reading.

- The mass of sodium chloride on the filter was measured by weighing and by conductivity. An analytical balance (Mettler Gram-atic) was used for gravimetric analyses, providing a sensitivity of 0.0001 g. A calibration curve for sodium chloride in water was generated using a Horizon model 1484 conductivity meter. A reference solution was accurately prepared and diluted by decades in volumetric flasks. Sodium chloride from the same stock and distilled water from the same source were used in the actual mass loading tests. Using 25 ml of distilled water, the conductivity measurements were subject to a minimum sensitivity of approximately 2.5×10^{-5} g of NaCl.

- Particle size measurements using the inertial cascade impactor are at least accurate to within ±10%, based on past laboratory experience and manufacturer's literature.

Several preliminary tests of the equipment and the filter media were performed before acquiring data. First, the system was pressurized to 16 psi and then sealed to check for leakage. After 28 minutes the pressure was 8 psi, which was considered acceptable because less leakage would occur under actual test conditions as the system pressure would then be at most approximately 1 psi.

Two modes of operation of the TSI atomizer were tested. In the recirculating mode, liquid is drawn up from the reservoir to the atomizing jet. Larger droplets impact on the atomizer surfaces and the excess liquid then drains back into the reservoir. Eventually, the stock solution becomes more concentrated, increasing the output particle size. Therefore, a non-recirculating mode was tested where the solution is fed to the atomizing jet using a syringe pump. However, this feed mechanism proved to be much less stable than the aspiration method of the recirculating mode. Measurements using the model 3020 CNC showed regular oscillations of at least a factor of

ten in the aerosol particle concentration when using the non-recirculating mode. For this reason, the recirculating mode was used, taking care to change the stock solution frequently to insure that the output particle size would increase by no more than 5%.

A dewpoint hygrometer was used to measure the relative humidity of the gas transporting the aerosol particles downstream from the diffusion drier. This measurement was necessary to determine if the diffusion driers were sufficiently reducing the moisture content of the wet aerosol stream. Pure distilled water was atomized and the system was allowed to stabilize for 20 to 30 minutes to insure an accurate measurement. The relative humidity was measured to be 35% when using the TSI atomizer. For the Retec nebulizer, the relative humidity was found to be 44%. A second diffusion drier was installed in series with the first and the measurement repeated. With the Retec nebulizer, this configuration resulted in a decrease in the relative humidity to only 42%. These measurements were consistent with the TSI literature describing the operation of the drier. Therefore, it was concluded that the diffusion driers would remove sufficient water vapor to dry the wet aerosol particles.

Three 47 mm diameter filter samples were weighed before and after overnight desiccation to determine retained water content. Table 3.2 summarizes these weights, showing the hydrophobic quality of the filter media. Based on these results, it was concluded that the filter samples need not be desiccated prior to the mass loading tests. Also listed in the table are the masses of dissolved solids measured by conductivity in samples of distilled water used to rinse two of the filters. These figures indicate that very little residue exists on the clean filter media, supporting the suitability of measuring sodium chloride mass by conductivity.

Table 3.2 Hydrophobic and Residue Characteristics of HEPA Filter Media

Filter#	Mass before Desiccation (g)	Mass after Desiccation (g)	Equivalent Mass Washed From Clean Filter (g)
1	0.1601	0.1601	7.7×10^{-5}
2	0.1670	0.1670	6.0×10^{-5}
3	0.1674	0.1673	

The two rinsed filter samples were again desiccated and all three samples sequentially placed in the filter holder and subjected to a clean air flow producing a filtration velocity of 3.30 cm/s. In accordance with Savannah River requirements, each filter showed a pressure drop of less than 1.0 inch of water. Table 3.3 lists these results as well as the average measured pressure drops for all filter samples tested. The arithmetic standard deviations associated with these averages are listed in the last column. The measured pressure drop across a holder with no filter installed is shown in the last row.

Table 3.3 Pressure Drop Characteristics of Clean HEPA Filter Media

Number of Filters Tested	Filtration Velocity (cm/s)	Average ΔP (In of H_2O)	Standard Deviation
9	0.89	0.29	0.003
18	2.45	0.64	0.03
10	2.98	0.82	0.05
3	3.30	0.98	0.02
Holder Only	3.30	0.04	--

3.3 Apparatus for the Filter Efficiency Tests

A schematic of the apparatus used in the filter efficiency tests is shown in Fig. 3.2. The air supply, nebulizer, neutralizer, drier and aerosol sampling chamber are identical to those described in Section 3.2. This section will concentrate on the additional apparatus used for the filter efficiency tests.

3.3.1 Aerosol Generation

The Savannah River HEPA Filter Material

Typically, filter efficiency spectra are obtained using monodisperse challenge aerosols. In addition, the characterization of the filter efficiency using monodisperse particles would be more useful for later code input for calculating probable scenario dependent releases. A proven method of generating monodisperse aerosols is to use an electrostatic classifier.[7,8] The classifier uses the output from a polydisperse aerosol generator, brings the aerosol to a Boltzman equilibrium, then selects only particles within a narrow electrical mobility range to remain entrained in the gas stream. Since the particle diameter is directly related to the electrical mobility, the output particles are monodisperse to within 2%. Different electrical mobilities, hence particle diameters, can be selected by adjusting the gas flow rate through the classifier and the voltage on the collection rod. The classifier used in this work is the Model 3071, manufactured by TSI Inc. of St Paul, Minnesota, capable of producing monodisperse particles ranging from 0.01 μm to 1 μm in diameter.

3.3.2 Aerosol Sampling

For the filter efficiency tests, the aerosols were sampled through the filter media at two different velocities. Two filter holders were used in parallel for the low filtration velocity efficiency test. One filter holder with an area restrictor placed immediately before the filter media was used to attain the high filtration velocity for the other efficiency test. The area restrictor was simply a 47 mm diameter piece of 1 mm thick Teflon

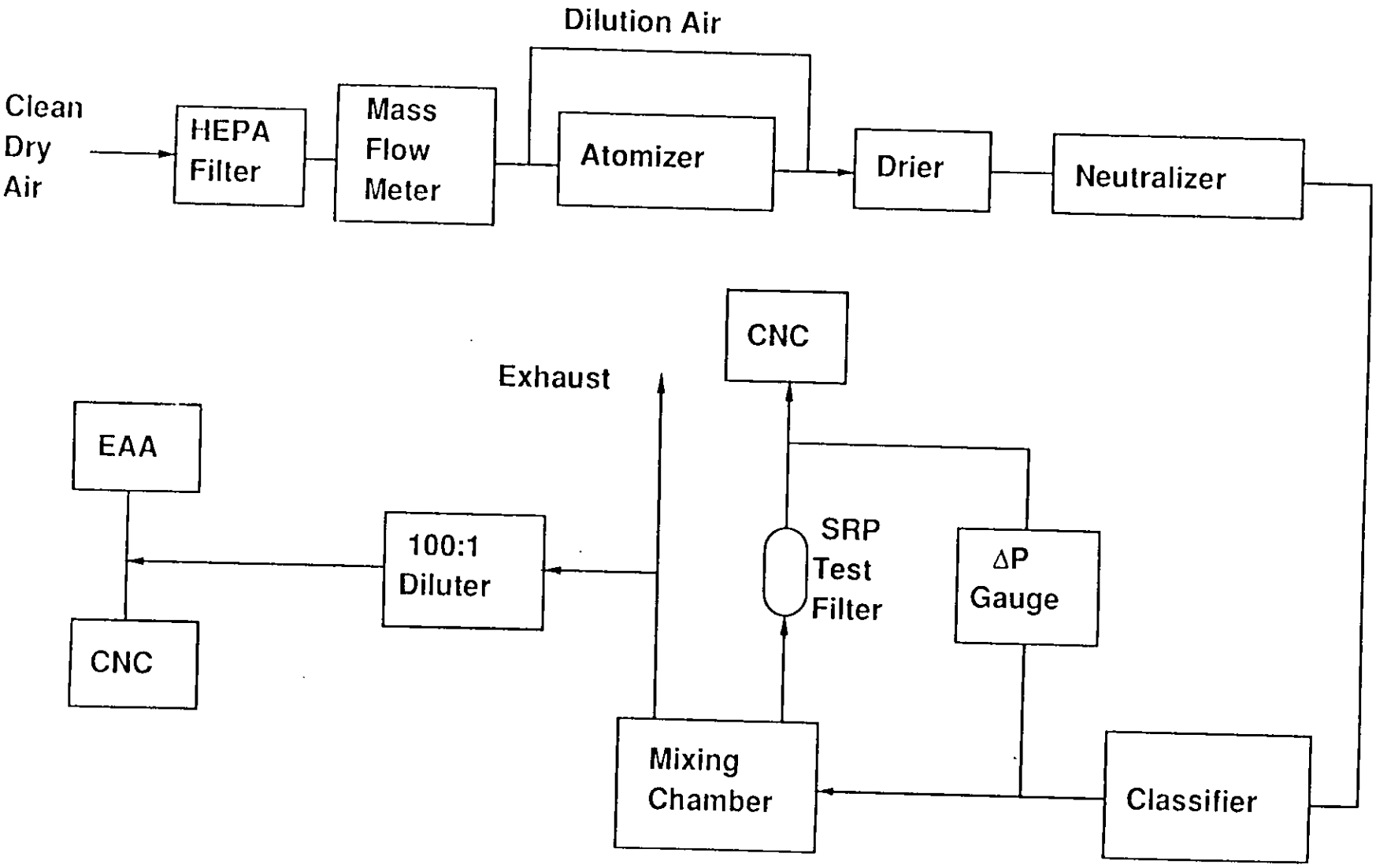

Figure 3.2 Experimental Configuration for Efficiency Tests

sheeting punched with a 1.25 in. concentric hole. As described earlier, this method of changing the filtration area while maintaining a constant volumetric gas flow rate was found to be the easiest and fastest method of obtaining data.

Data was acquired during the efficiency test, by simultaneously using TSI condensation nucleus counters (CNC's) to measure the filtered and unfiltered particle concentrations from the sampling chamber. A CNC draws submicron-size particles through a supersaturated alcohol vapor. The vapor condenses on the particles forming droplets approximately 12 μm in diameter. These droplets are then large enough to be counted with a white light photodetector.

The CNC used to measure the unfiltered particle concentration (model 3020) has an internal mass flow controller, factory set to sample the aerosol at a rate of 0.30 liters/min. The instrument has two particle counting modes, providing a dynamic measurement range of 10^{-2} to 10^{7} particles/cm^3. In the single-particle mode, concentrations below 10^{3} particles/cm^3, the instrument counts individual particles for a known time and divides the total by the volume of aerosol sampled. In the photometric mode, concentrations between 10^{3} and 10^{7} particles/cm^3, the total scattered light intensity is measured. Particle concentration is computed from a factory calibration of the photodetector.

The CNC used to measure the filtered particle concentration (model 3760) operates in only the single-particle mode. Aerosol flow through this CNC is controlled by a critical orifice and an external vacuum pump, providing a constant gas flow rate of 1.415 liters/min. The range of particle concentrations measurable by the Model 3760 extends from 10^{-3} to 10^{3} particles/cm^3.

3.3.3 Particle Size Measurements

Since the electrostatic classifier is a primary standard for supplying monodisperse particles, particle size measurements of the classifier output were made not to determine the particle size distribution, but to

provide confirmation that all equipment was functioning properly. Depending on the absolute size distribution of aerosol particles, different size measurement devices were employed. A TSI model 3030 electrical aerosol analyzer (EAA) is designed to measure the smaller aerosols (0.05 to 1.0 μm). This device operates much like the classifier, using a variable electrical field to sort particles according to their electrical mobility. It also incorporates an aerosol electrometer which measures the number concentration for the selected size. Thus, a complete number, area, or mass frequency distribution can be computed. Past and recent experience, though, has shown measurement errors up to 25% for typical polydisperse aerosols. Due to inherent instrument limitations, particle distributions cannot be resolved with geometric standard deviations of less than 1.3. In addition, the largest monodisperse particles that can be sized accurately with the EAA were found to be approximately 0.2 μm in diameter. This is consistent with limitations due to multiple changing effects in the EAA found by other researchers.

To verify the larger monodisperse particle sizes, a Particle Measuring Systems model LAS-X laser aerosol spectrometer (LAS) was used. Here, the aerosol is drawn through the open cavity of a low-power helium-neon laser, providing the high intensity needed for optical detection of submicron particles. Light scattered in nearly all directions is collected and focused onto a photodetector. Particles are counted singly and sized in direct proportion to the intensity of the scattered pulse. Three measurement ranges are provided, covering 0.09 to 3.0 μm. However, tests with sodium chloride particles showed consistent accuracy only for particle diameters larger than 0.2 μm. Thus, the LAS and EAA provided secondary verification of proper classifier operation over the entire range of particle sizes generated for the efficiency tests.

3.3.4 Calibration and Performance Verification Tests

A number of additional calibration checks were performed for the efficiency tests, focusing on the CNC's and the electrostatic classifier. The model 3020 CNC was adjusted internally according to manufacturer's procedures for agreement within 25% between the photometric and single-particle counting modes. The photometric mode was factory-calibrated using monodisperse sodium

chloride aerosols 0.05 μm in diameter, from an electrostatic classifier, and measuring the concentration with an aerosol electrometer. No calibration of the single-particle mode is necessary for either CNC. For aerosol concentrations below 10^3 particles/cm^3, measured simultaneously, the model 3020 and the model 3760 agreed to within 15%. To balance diffusion losses in the sampling lines leading to each CNC, the length of each line was adjusted in direct proportion to the volumetric flow through each CNC. For aerosol concentrations above 10^3 particles/cm^3, measured simultaneously, the model 3020 CNC and the EAA were found to agree to within 20%.

The electrostatic classifier's three mass flowmeters were compared against a standard wet test meter. Agreement within 12% was found over the normal ranges of operation of the classifier. The monodisperse aerosols generated by the electrostatic classifier were, analyzed by other size-measuring instruments described earlier. The results should only be considered to indicate consistency in measurement since the classifier itself often serves as a reference against which other aerosol equipment is calibrated (for example, the EAA and the CNC's photometric mode). Figure 3.3 shows a general agreement within 7% between the classifier and the EAA for particle sizes less than 0.2 μm. For larger particles, the LAS gave better results than the EAA. Measurements agreed to within 4% for particles 0.2 to 0.4 μm in diameter. For the 0.5 μm particle size the LAS measures only 0.42 μm or a 16% difference. A possible explanation may be that the LAS assumes a single valued intensity response as a function of particle diameter, whereas the theoretical Mie response function is multivalued.

4.0 Test Conditions and Procedures

4.1 Pressure Drop vs Mass Loading Test

4.1.1 Aerosol Generation

Three different polydisperse particle size distributions were generated by atomizing water solutions containing various concentrations of sodium chloride. To generate the smallest polydisperse particle size, the TSI atomizer was used with a sodium chloride/water concentration of 0.1 g/cm^3.

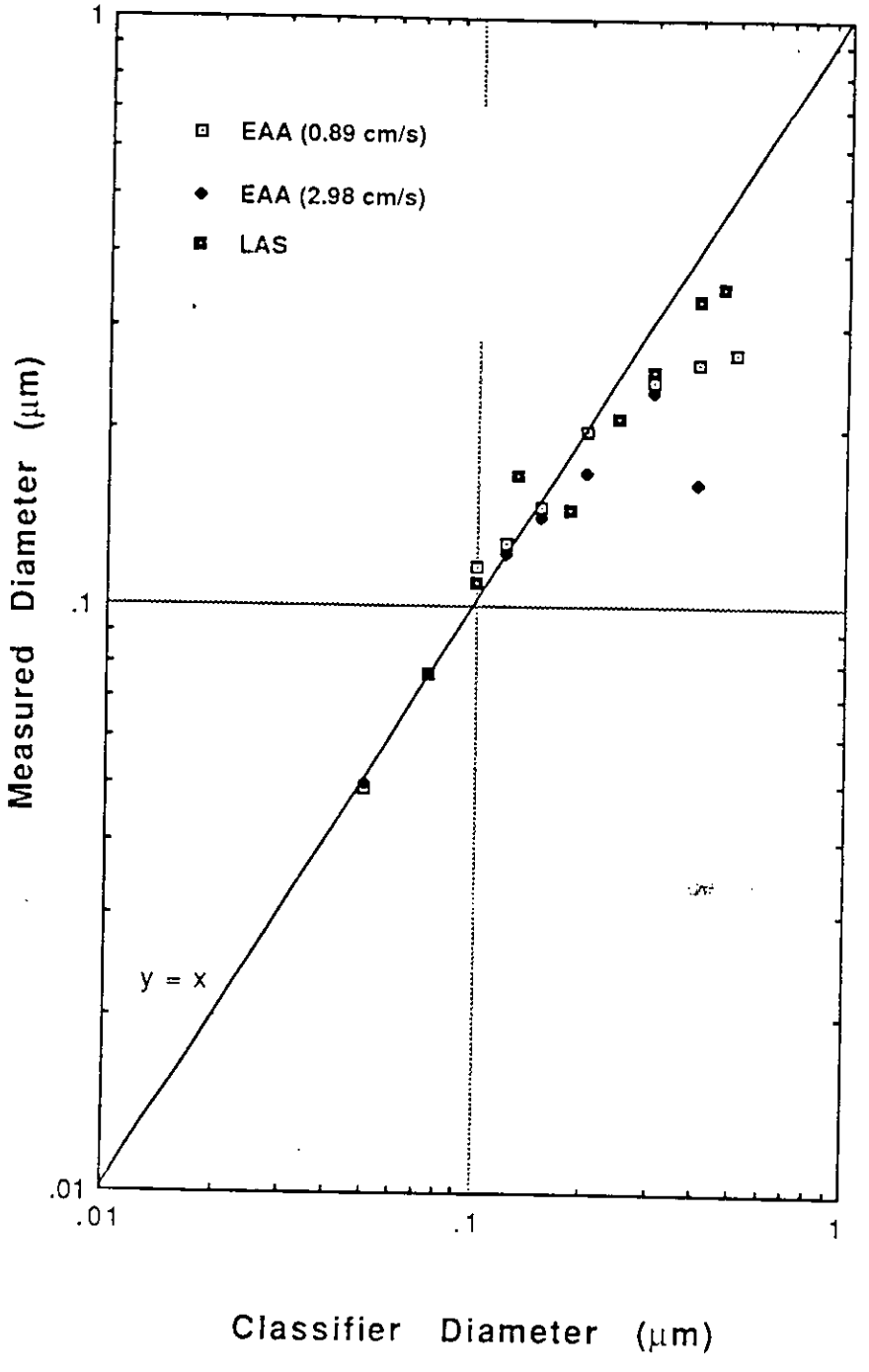

Figure 3.3 Particle Size Comparison Between Calculated Electrostatic Classifier Output and Measurements Using the Electrical Aerosol Analyzer (EAA) and the Laser Aerosol Spectrometer (LAS)

The atomizing jet (critical orifice) of the TSI atomizer was operated at 35 psi and the wet output aerosol was diluted with 4 liters/min of dry, clean air. For the larger two particle sizes, solution concentrations of 0.01 g/cm^3 and 0.1 g/cm^3 were atomized with the Retec nebulizer. The Retec atomizing jet was operated at a constant volumetric flow of 3 liters/min. Because the primary droplet size from this generator is larger than that from the TSI generator, a second diffusion drier and 2 liter/min of clean, dry dilution air were incorporated during the tests with the Retec nebulizer to assure dry challenge aerosols.

4.1.2 Experimental Procedures and Analysis

After preparing the solutions to be atomized and the aerosol generation equipment, a typical experiment to measure the pressure drop across the filter as a function of the mass loading on the filter, proceeded according to the following steps:

- A 47 mm disk was punched from the filter media stock, cleaned with a high-velocity jet of bottled nitrogen gas, and weighed in the analytical balance before installing in the filter holder.

- The selected aerosol generator was filled with the appropriate solution. Pressurized gas was supplied to the generator inlet causing the solution to be atomized and test particles to be transported to the mixing chamber. Two to three minutes were necessary to attain a constant particle concentration throughout the system. Excess aerosol was vented through the exhaust.

- A particle size measurement was made using a cascade impactor.

- The valve in line with the filter holder was opened, the vacuum pump switched on, a stopwatch started, and the initial filter pressure drop recorded. As aerosol mass accumulated on the filter, time and pressure drop were recorded at intervals of approximately 0.3 inches of water.

- When the pressure drop reached the desired value (2,4,6 or 8 inches of water), the vacuum pump was switched off and the filter holder valve was closed. The aerosol generator was switched off, however, the clean dilution air continued to flow, flushing the particles from the system.

- The filter was removed from the holder and weighed in the analytical balance. The mass of sodium chloride was found by the difference between the weight of the filter and collected particles and the clean filter weight.

- The filter was then rinsed in a known volume of distilled water and conductivity at the resulting solution was measured. The mass of sodium chloride dissolved in the water was determined from the calibration curve.

- When the Retec nebulizer was used, the larger primary droplets and resulting larger solid particles deposit more readily in the transport line. These deposits were not large enough to increase the pressure drop across the system or to change the inner diameter of the tubing. However, there was some concern that a fraction of the deposited particles might be re-entrained or that the deposit may affect the transported particle size distribution between tests. Therefore, the aerosol lines were cleansed of aerosol deposits before the next filter was tested. This was done by opening both ends of the system and connecting a 35 psi source of clean, dry air. Since the TSI atomizer produced smaller droplets and particles, no significant deposition was observed, hence, the periodic cleaning was not necessary.

- The procedure was then repeated for the next data point in the pressure drop vs mass loading curve for each of the three particle size distributions.

4.2 Efficiency Tests

4.2.1 Aerosol Generation

Because the classifier selects a very narrow particle size range from the polydisperse output of the TSI atomizer, the monodisperse particle size output from the classifier is independent of the solution concentration. A small change in solution concentration only slightly affects the number concentration of the monodisperse aerosol. For these reasons, a solution concentration of 0.2 g/cm^3 was used in conjunction with the TSI atomizer for all efficiency tests. The wet aerosol was dried and neutralized, as in the mass loading tests, before entering the classifier. The voltages and gas flow rates were adjusted to give the desired particle size output. A minimum of six different monodisperse particle diameters were generated using the TSI electrostatic classifier and the apparatus described in Section 3.

4.2.2 Experimental Procedures and Analysis

The specific data acquisition steps for the efficiency measurements are outlined as follows:

- A 47mm filter disk was punched and cleaned before being installed in the filter holder. In comparison to the mass loading tests, the number concentration of the test aerosol exiting the classifier was less approximately by a factor of 100. The collection time was only 15 minutes because the minimum efficiency of a filter occurs when the filter is clean. Therefore, the mass of collected aerosol was lower than measurable by the analytical balance, eliminating the filter weighing procedure before and after each test.

- The model 3020 CNC, measuring the unfiltered particle concentration and the model 3760 CNC measuring the filtered particle concentration were switched on and allowed to warm up for at least 20 minutes. Instrument readings of zero particles/cm^3, using the clean, dry supply gas, were required before starting the experiment.

- The classifier flow rates and voltages were adjusted to produce the desired monodisperse particle size. Approximately five minutes were necessary for the system to reach constant particle concentration.

- When a relatively constant reading was observed on the 3020 CNC, the valve in line with the filter holder was opened, the stopwatch was started, and the initial pressure drop recorded. The filtered and unfiltered particle concentrations were recorded each minute for 15 minutes. In addition, a continuous record of both CNC readings was made with a strip chart recorder to observe short and long term concentration changes.

- After 15 minutes, the CNC's and the strip chart recorder were switched off and a particle size measurement was made using the EAA.

- Finally, the filter was removed and a mass analysis by conductivity was performed. Although the mass of collected aerosol was not of primary concern to the efficiency measurements, such information may be useful when considering possible future investigations of mass loading using monodisperse aerosols.

- The sequence was repeated for the next particle size in the test matrix.

5.0 Results

5.1 Mass Loading Tests

5.1.1 Laboratory Scale Results

Figures 5.1, 5.2 and 5.3 show the frequency distribution of particle diameters as measured by the cascade impactor for the mass loading experiments. Table 5.1 lists measured size distribution statistics for the three polydisperse particle sizes tested. Analysis of the mass accumulation on the impactor stages results in a mass distribution according to aerodynamic particle diameter. From a plot of cumulative mass versus particle size, the

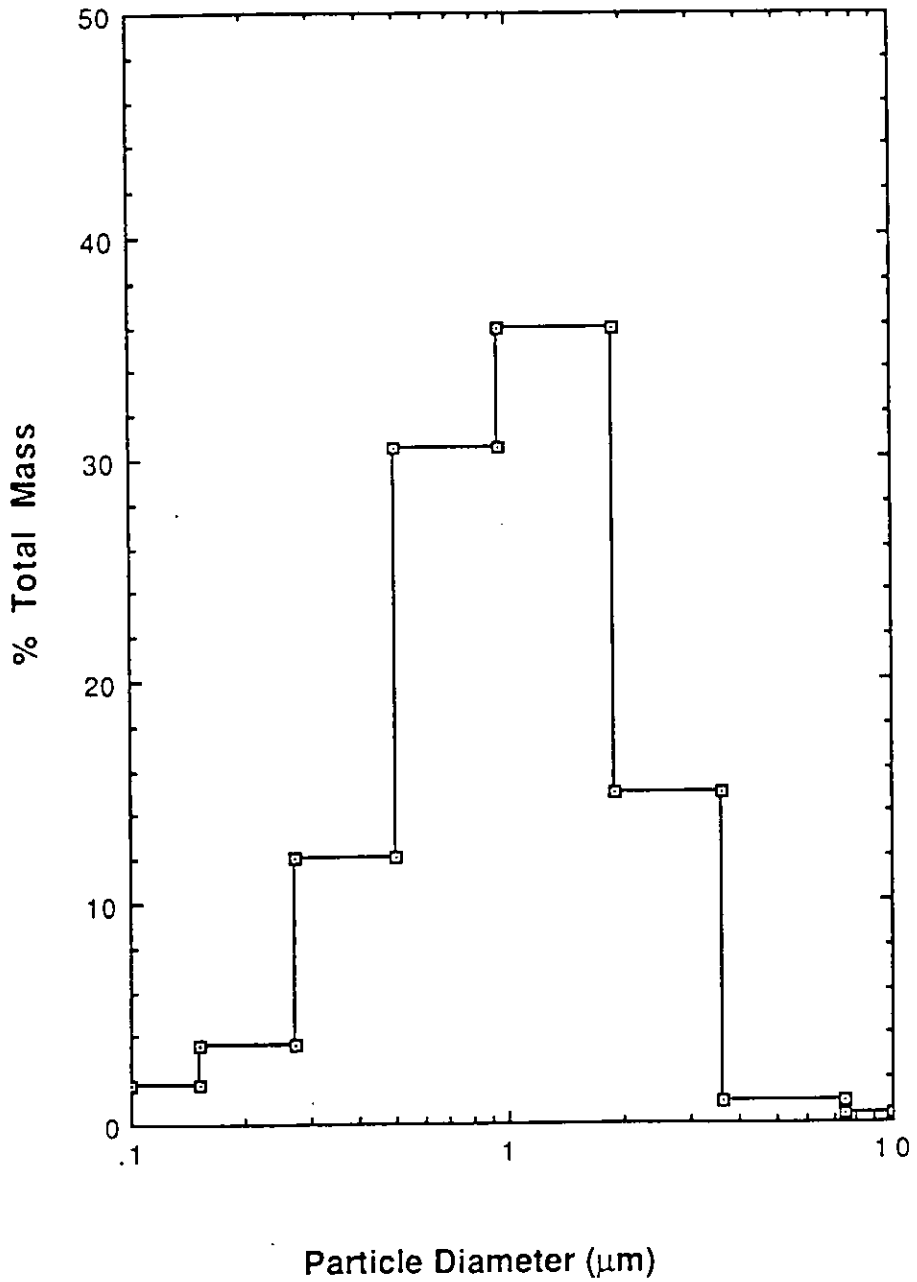

Figure 5.1 Size Distribution from TSI Atomizer (10% Solution) Measured by Cascade Impactor

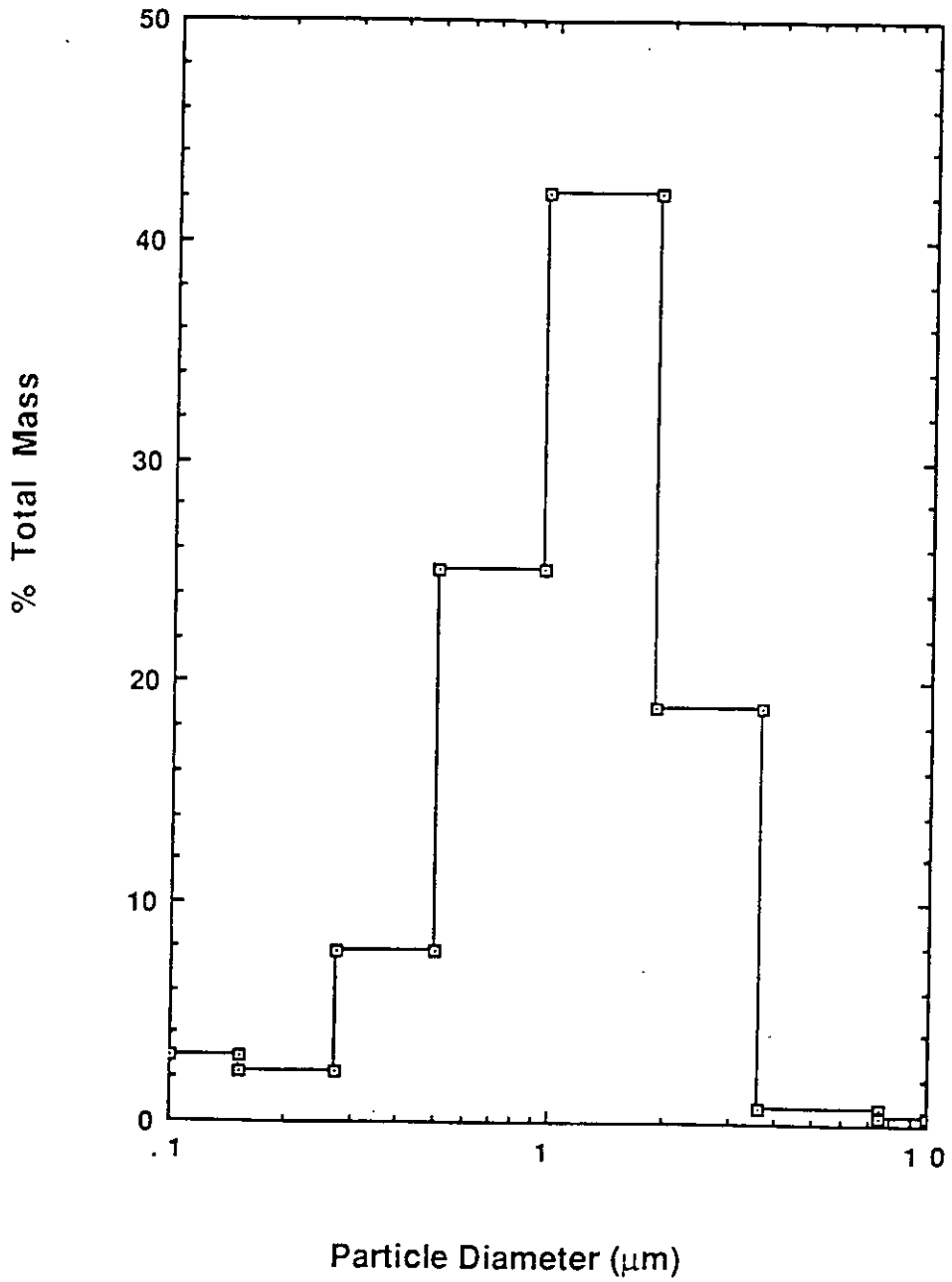

Figure 5.2 Size Distribution from Retec Nebulizer (1% Solution) Measured by Cascade Impactor

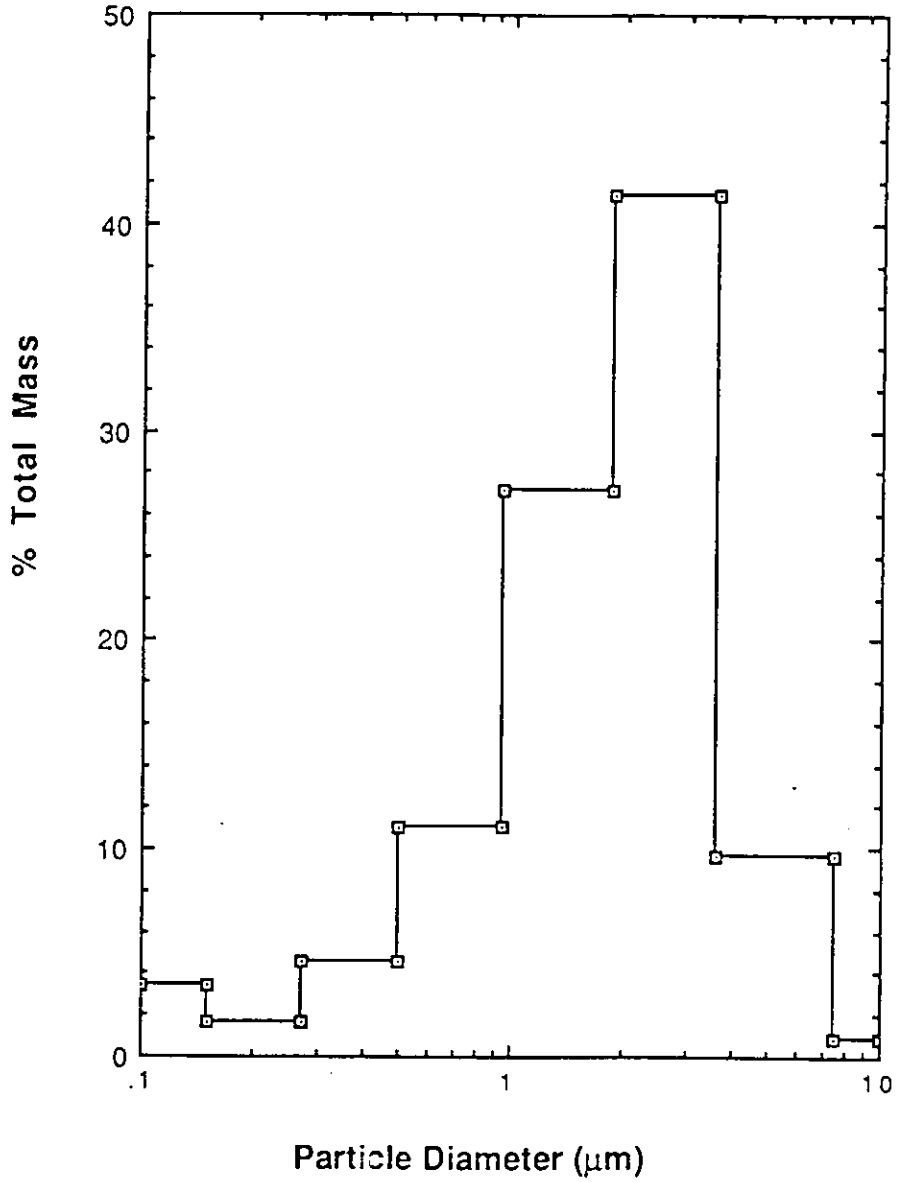

Figure 5.3 Size Distribution from Retec Nebulizer (10% Solution) Measured by Cascade Impactor

Table 5.1 Impactor Measurements of Polydisperse NaCl Aerosols Used in Mass Loading Tests

Atomizer	Solution Conc. (g/cm^3)	Measured MMAD (μm)	Measured σ_g	Calculated MMD (μm)	Calculated NMD (μm)
TSI	0.1	0.99	2.11	0.65	0.12
		1.09	2.14	0.72	0.13
	Mean $\pm \sigma_x$:	1.04$\pm$.07	2.13$\pm$.02	0.69$\pm$.05	0.13$\pm$.007
Retec	0.01	1.07	2.06	0.70	0.15
		1.42	2.12	0.94	0.17
		1.18	2.11	0.78	0.15
		1.27	2.02	0.84	0.19
	Mean $\pm \sigma_x$:	1.24$\pm$.15	2.08$\pm$.05	0.82$\pm$.10	0.17$\pm$.02
Retec	0.1	1.96	2.07	1.31	0.27
		1.76	2.41	1.17	0.11
		1.87	2.47	1.25	0.11
		2.15	2.03	1.44	0.32
		1.97	2.19	1.31	0.21
	Mean $\pm \sigma_x$:	1.94$\pm$.14	2.23$\pm$.20	1.30$\pm$.10	0.20$\pm$.09

mass median aerodynamic diameter (MMAD) is defined as the diameter corresponding to the 50% cumulative mass point. A common practice when making aerosol measurements, is to assume that the particles are log-normally distributed especially when the source of particles is a spray atomizer. Impactor measurements are typically skewed from log-normal due to effects such as sampling line losses and particle bounce effects inside the impactor. For the purpose of estimating other moments of the aerosol size distribution, specifically the number median diameter (NMD), the measured data is fit to a log-normal distribution. The geometric standard deviation (σ_g) of the distribution can then be found from the cumulative mass vs particle diameter curve as follows:

σ_g = (Diameter at the 84th percentile/diameter at the 16th percentile)$^{1/2}$

The mass median diameter (MMD) and number median diameter (NMD) are calculated using the following relationships:

$$NMD = MMD \exp(-3 \ln^2 \sigma_g)$$

and

$$C_{ar} D_{ar}^2 = C \rho D^2$$

where

D_{ar} - Aerodynamic diameter
D - Physical diameter
C_{ar} - Cunningham slip correction for particle with diameter D_{ar}
C - Cunningham slip correction for particle with diameter D
ρ - Particle density

The slip correction factor is defined by:

$$C = 1 + \lambda/D \ (2.514 + 0.8 \exp (-0.55 \ D/\lambda))$$

where

λ = mean free path of air = 0.066 μm

The first equation uses the slip correction factor and particle density to convert aerodynamic quantities, on the left side of the equation, to physical quantities, on the right side. This is a recursive relationship and a new estimate of the slip correction factor, C, must be calculated after each iteration. Finally, all measured and calculated quantities are averaged, the error tolerances shown are the arithmetic standard deviation of the means ($\sigma_{\bar{x}}$).

Sodium chloride mass deposition on the filters as measured by weighing and by conductivity is summarized in Table 5.2. As shown in the seventh column, these two methods produced results differing by no more than 6%; the average magnitude of difference was 3.1%. The average of the two measurements was then used in generating a mass loading curve for each particle size.

A mass loading curve was generated by plotting the pressure drop across the filter as a function of total sodium chloride mass per unit of filtration area. The effective area of filtration for all mass loading tests was measured as 9.62 cm^2. Figures 5.4, 5.5, and 5.6 illustrate the pressure drop versus mass loading characteristics of the HEPA filter media for the three polydisperse particle sizes tested. For each set of points, a computer curve fit and equation are shown.

Figure 5.4, corresponding to measurements taken with a TSI nebulizer with a 10% NaCl solution resulting in a MMAD of 1.04 μm, and Figure 5.2, corresponding to measurements taken with the Retec nebulizer with a 10% NaCl solution resulting in a MMAD of 1.94 μm, are best fit with linear expressions describing the pressure drop as a function of mass loading. On the other hand, Figure 5.3, corresponding to measurements taken with the Retec nebulizer and a 1% NaCl solution resulting in a MMAD of 1.24 μm, is best fit by an exponential expression. Both exponential and linear functions describing the pressure drop increase with mass loading, have been reported in the literature.[9,10,11,12] Most of this research was concerned only with variations between filter types, different materials or gas mixtures used. The only known research demonstrating both linear and exponential behavior of

Table 5.2 Mass of NaCl Collected on 47 mm Filter Media Samples For Three Polydisperse Particle Sizes. The Filtration Velocity is 2.45 cm/s.

Atomizer	Solution Conc. (g/cm^3)	MMD (μm)	Final ΔP (in of H_2O)	Mass of NaCl (by Cond.) (g)	Mass of NaCl (by Weight) (g)	Percent Difference (%)	Average Mass (g)
TSI	0.1	0.69	2	0.0132	0.0125	-5.3	0.0129
			4	--	0.0392	--	0.0392
			6	0.0611	0.0616	+0.8	0.0614
			8	0.0854	0.0817	-4.3	0.0836
Retec	0.01	0.82	2	0.0095	0.0096	+1.1	0.0096
			4	--	0.0153	--	0.0153
			6	0.0184	0.0179	-2.7	0.0182
			8	0.0217	0.0206	-5.1	0.0212
Retec	0.1	1.30	2	0.0259	0.0256	-1.2	0.0258
			4	0.0599	0.0621	+3.7	0.0611
			5	0.0757	0.0785	+3.7	0.0771
			6	0.1288	0.1240	-3.7	0.1264
			8	0.1411	0.1440	+2.1	0.1426
				Average magnitude of error:		3.1	

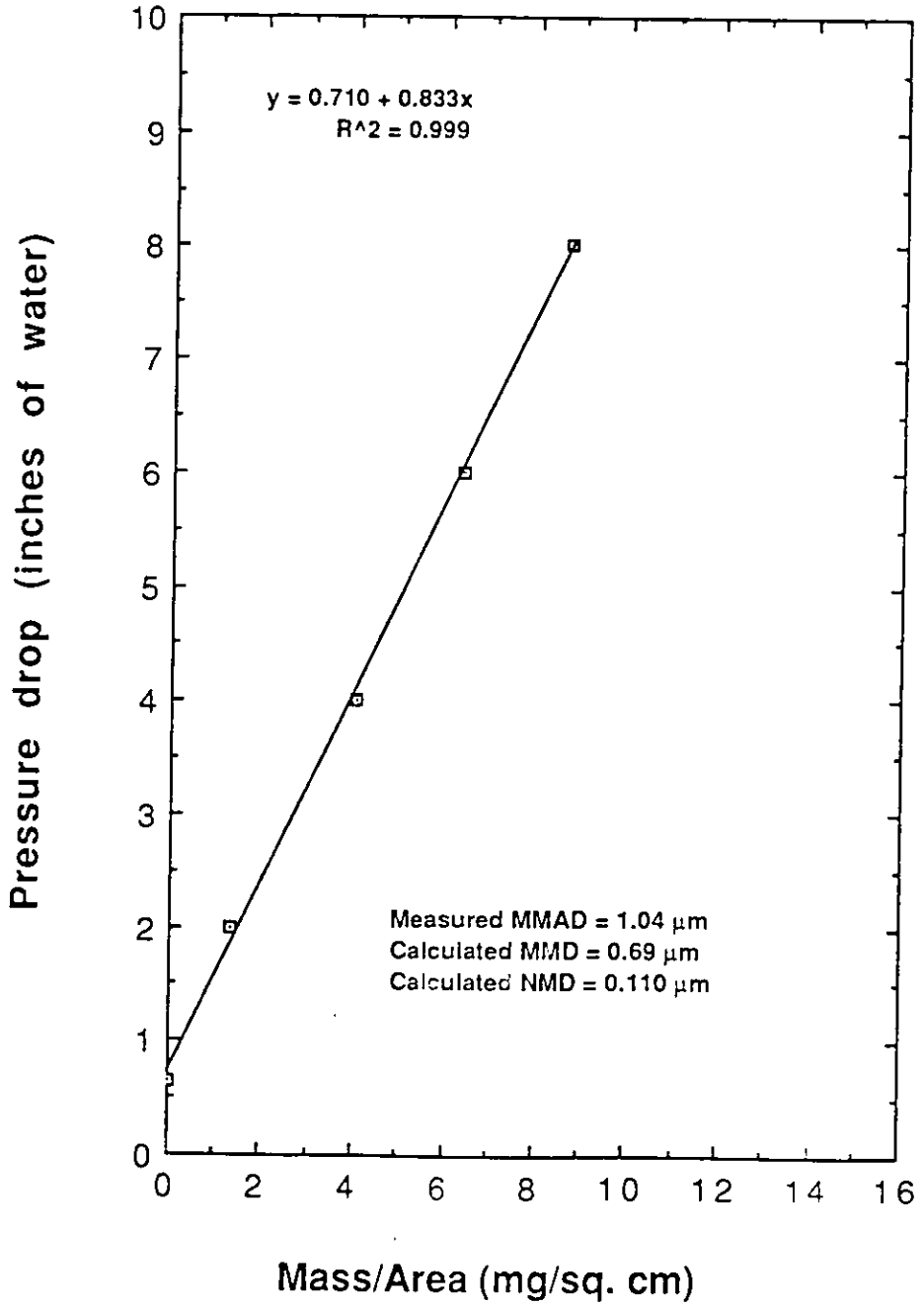

Figure 5.4 Pressure Drop vs Mass Loading for Polydisperse NaCl Aerosols Using the TSI Atomizer (10% Solution)

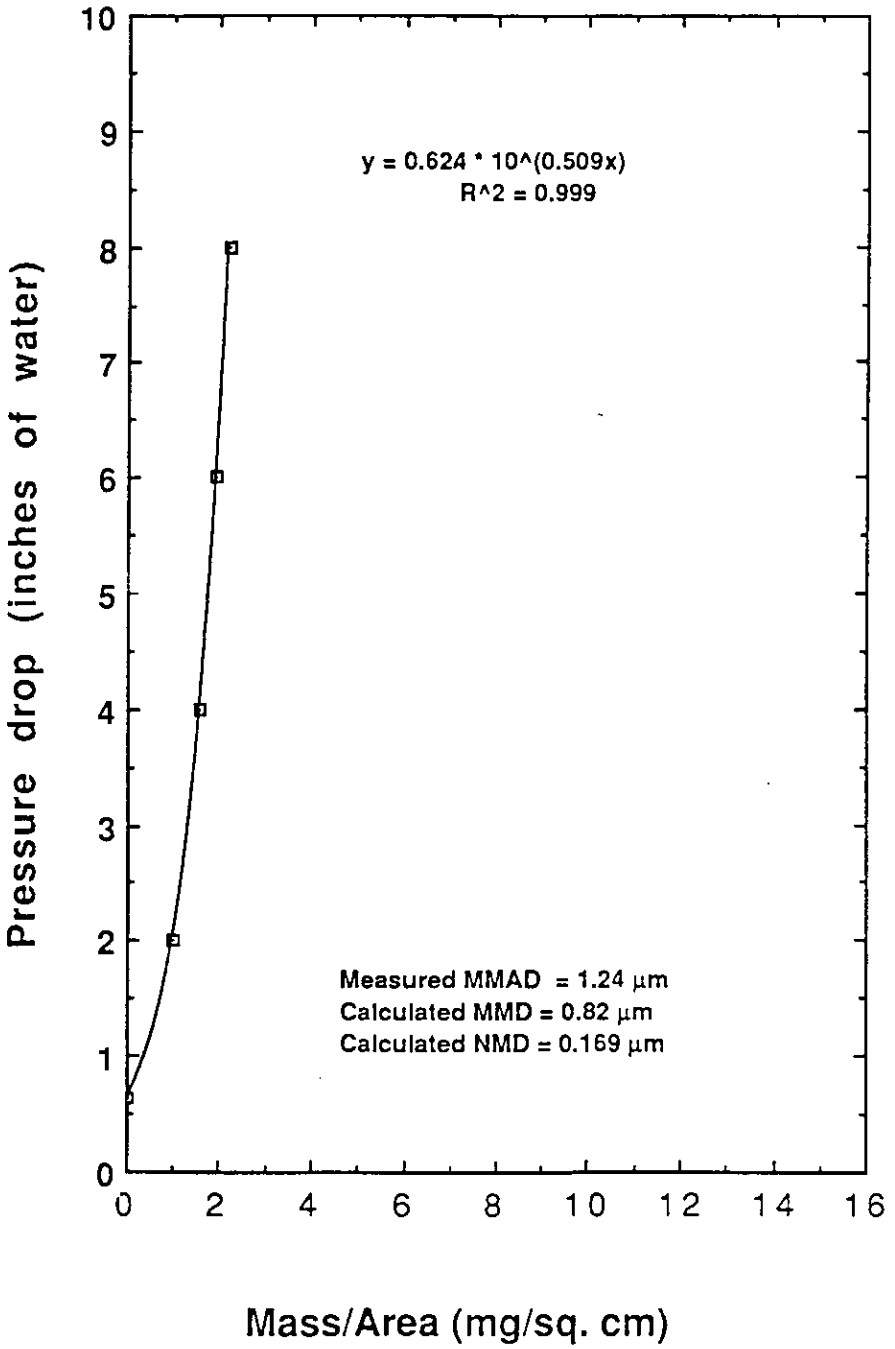

Figure 5.5 Pressure Drop vs Mass Loading for Polydisperse NaCl Aerosols Using the Retec Atomizer (1% Solution)

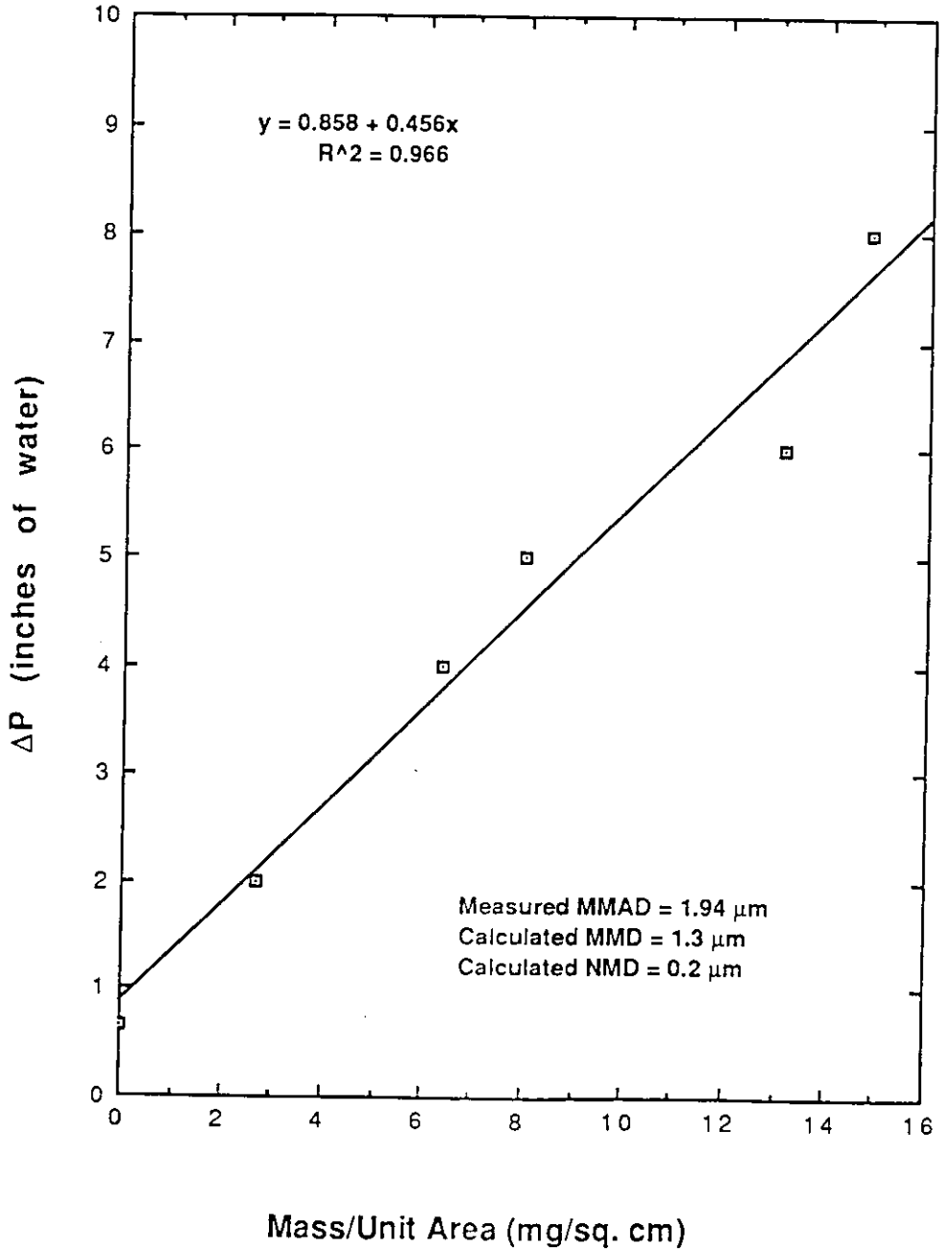

Figure 5.6 Pressure Drop vs Mass Loading for Polydisperse NaCl Aerosols Using the Retec Atomizer (10% Solution)

pressure drop with mass loading, using one type of filter and one type of material but different mean particle diameters is given in Appendix A. It appears that the exponential increase in pressure drop as a function of mass loading occurs at a particle diameter (NMD) which is very near the same particle size that produces minimum filtration efficiency. Whether or not there is a strict correlation between these two phenomena cannot be determined conclusively due to the small data set available and since polydisperse aerosols were used in the mass loading tests and monodisperse aerosols in the efficiency tests.

Even though every attempt was made to vary one parameter at a time, in this case the particle diameter, there may have been other factors contributing to the transformation between linear and exponential results. As noted earlier, the relative humidity of the gas stream was not precisely controlled and ranged from below 35% to 45% depending on the nebulizer used and the adsorptivity of the silicon gel. Since the deliquescent point for NaCl is above 70% relative humidity,[13] all of the aerosols generated for these tests should have retained their crystalline structure. Another variable was the change in concentration of the nebulized solution necessary to change the particle diameter. Leong[14,15] noted a change in the structure of the NaCl aerosol as the solute concentration was varied. For low concentrations, the particles were simple cubical crystals, for higher concentrations, the particles became nearer to a spherical assembly of a number of crystals. In order to investigate possible solution concentration effects, a fourth mass loading experiment was conducted with a 1% solution of NaCl using the TSI nebulizer, since it was the 1% solution that generated the exponential response as opposed to the linear response measured for the 10% solution with either nebulizer. The pressure drop response to the mass loading was found to be linear ($y = .84 + .825\ x$, $R^2 = .956$). The measured MMAD was 0.67 μm and the calculated NMD was 0.076 μm. The mass loading curve is nearly identical to Figure 5.4. This implies that, while the solution concentration can account for a change in shape of the resulting solid aerosol, a change in solution concentration, by itself, does not account for the observed exponential response.

The degree of reproducibility of filter pressure drop characteristics over time is shown in Figures 5.7, 5.8, and 5.9. These graphs track the time history of the same filter loadings described previously. All filter loadings for a given particle size are seen to behave in a similar manner but are not perfectly reproducible. This could be attributable to variations between individual filters. As in the case of the pressure drop versus mass loading curves, the intermediate particle size causes an exponential increase in pressure drop with time. Likewise, the larger and smaller particle sizes increase in a more linear manner.

5.1.2 Scale-Up of Results to Savannah River Reactor

Given an effective filtration area of 150 $ft.^2$ for one SRS, HEPA filter unit, a sodium chloride aerosol deposition of 1 mg/cm^2 equates to,

$$(1\ mg/cm^2)(150ft^2)(12\ in/ft)^2(2.54\ cm/in)^2(1\ g/1000\ mg) = 129g$$

or 4.45 kg per 32 unit filter bank. Scaling the previously described mass loading curves with this factor, Figure 5.10 shows the pressure drop expected across one 32 unit HEPA filter bank for a given mass of aerosol evenly deposited over the filtration area of the media. Table 5.3 lists the empirical equations now describing pressure drop as a function of total aerosol mass deposited on a filter bank.

Table 5.3 Equations Describing Pressure Drop As A Function of Total Aerosol Mass Deposited on One Savannah HEPA Filter Bank. The Equations Were Determined Empirically From Tests of Polydisperse NaCl Aerosols. (ΔP in Inches of Water, Mass in Kilograms)

MMAD μm	MMD μm	NMD μm	ΔP = f(Total Mass)
1.04	0.69	0.13	$\Delta P = 0.710 + 0.817$ Mass
1.24	0.82	0.17	$\Delta P = 0.624 \times 10^{0.114}$ Mass
1.94	1.30	0.20	$\Delta P = 0.858 + 0.102$ Mass

Note that this calculated mass loading scaled up to a full sized HEPA filter unit may be considered conservative because the filtration area is assumed to be 150 ft^2 rather than 200 ft^2. However, based on the arguments in Section

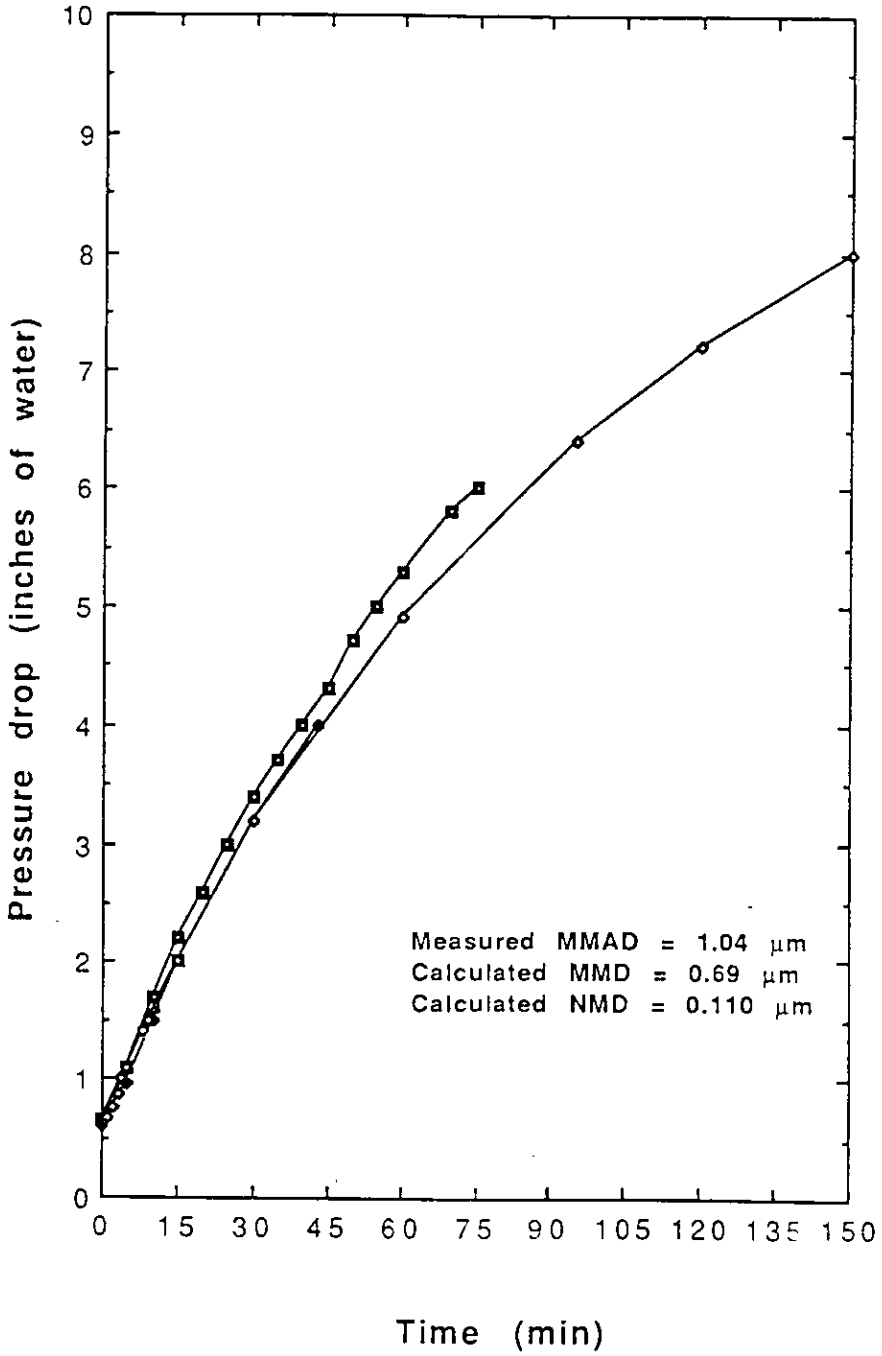

Figure 5.7 Time History of Filter Loadings for Polydisperse NaCl Aerosols Using the TSI Atomizer (10% Solution)

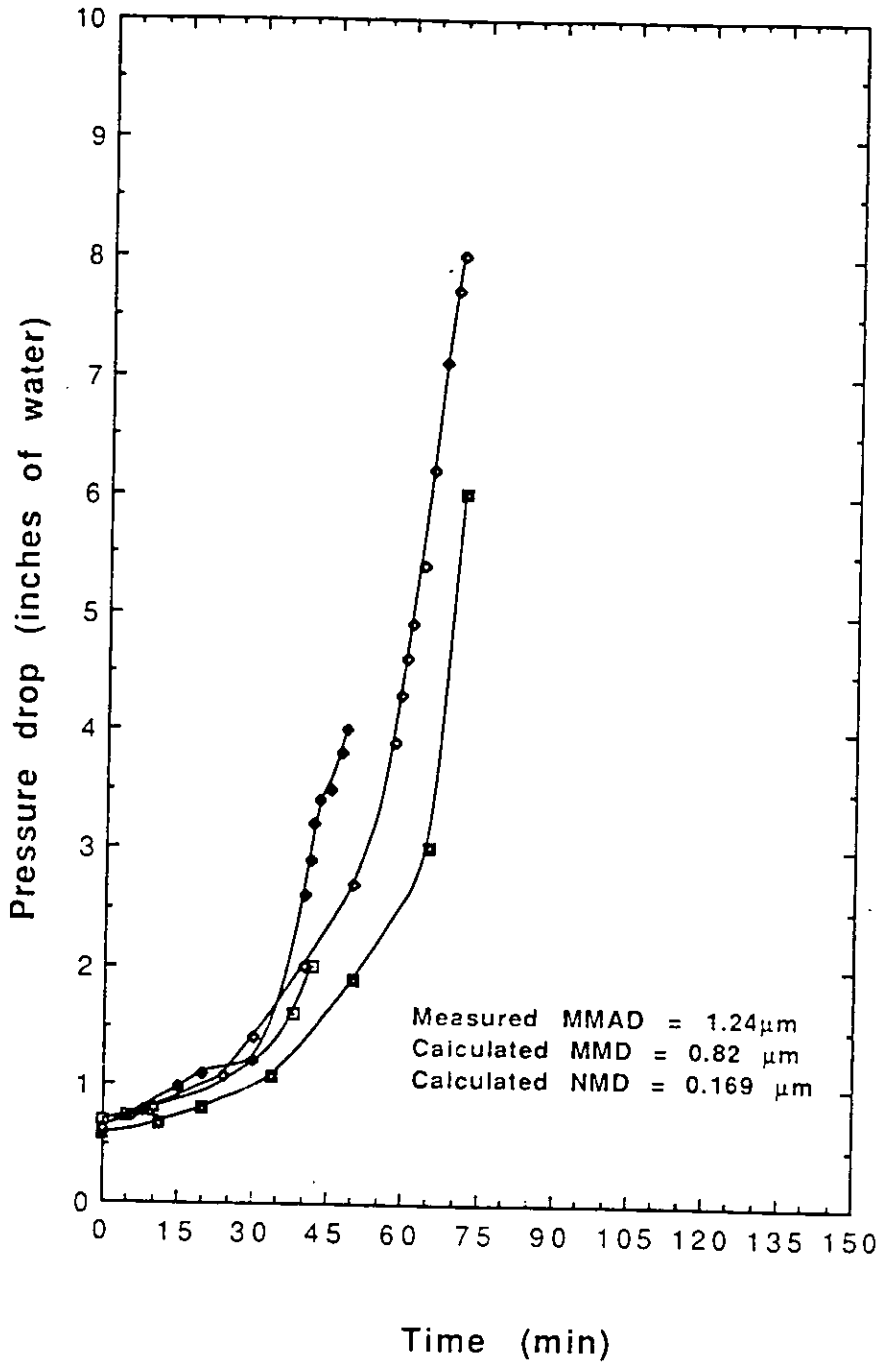

Figure 5.8 Time History of Filter Loadings for Polydisperse NaCl Aerosols Using the Retec Atomizer (1% Solution)

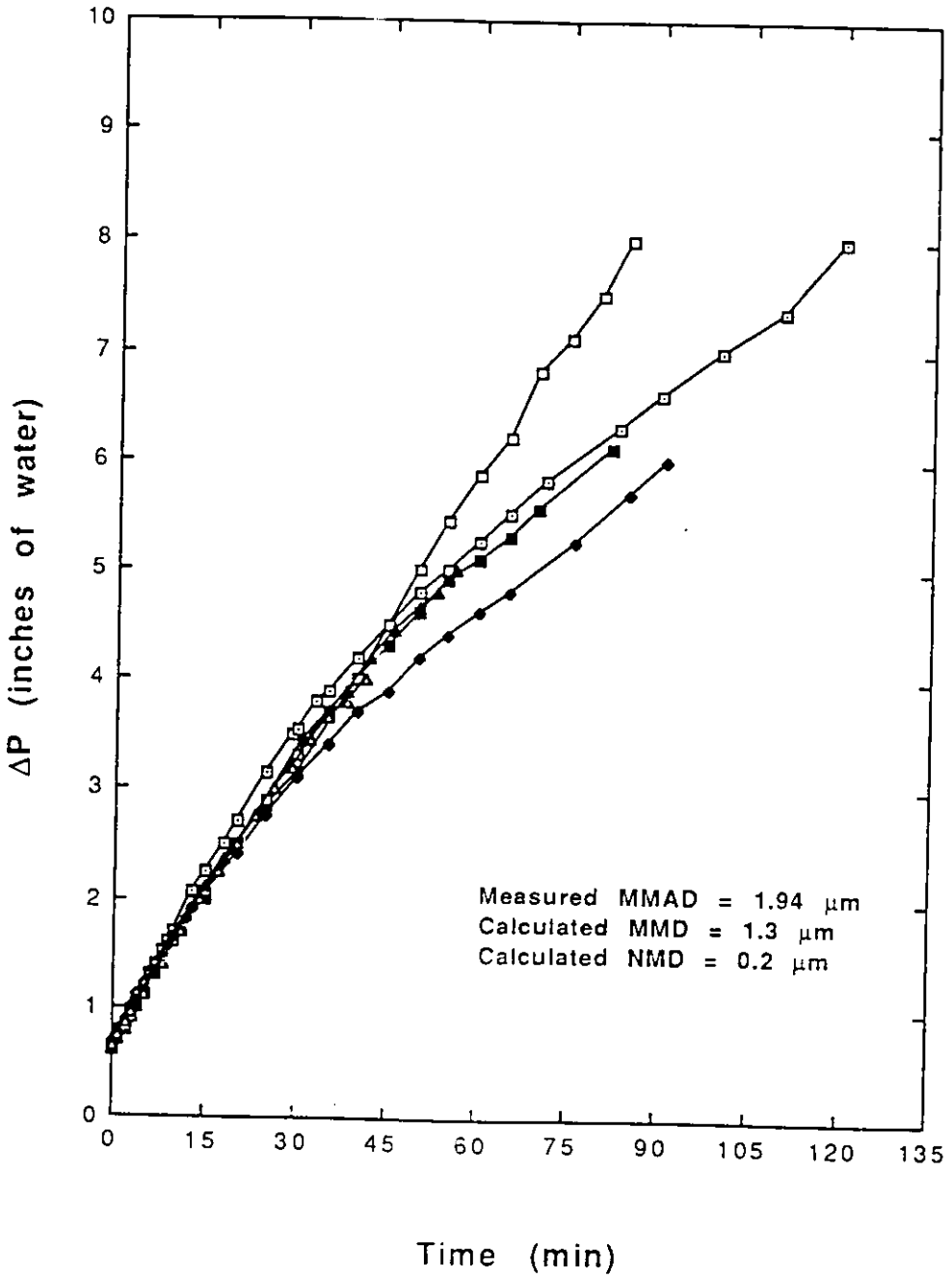

Figure 5.9 Time History of Filter Loadings for Polydisperse NaCl Aerosols Using the Retec Atomizer (10% Solution)

3.1, the data presented in Figure 5.10 and Table 5.3 based on 150 ft^2 scale factor, is considered to be more reasonable. It also appears to be consistent with results reported by McCormack et al who measured filter loading capacity with and without the corrugated aluminum separators. They found that the mass loading increased by an average of 23% when the separators were removed.[9]

5.2 Efficiency Tests

Table 5.4 lists the sodium chloride particles sizes generated by the classifier and as measured by the LAS and the EAA. Figures 5.11 through 5.19 provide the detailed particle size distribution spectra as measured by the EAA and LAS instruments. As described earlier, the measured size distributions are slightly broader than monodisperse (σ_g = 1). Because, like all measuring instruments, the EAA and LAS have their own associated measurement errors causing the measured distribution to appear broader than it is in reality. In fact, the electrostatic classifier is used to calibrate the EAA and LAS as well as the CNC.[16,17,18] Therefore, Figures 5.11 through 5.19 should only be used as an internal check of component performance and as a graphical comparison to the polydisperse distributions from the mass loading tests.

Table 5.4 Monodisperse NaCl Particle Sizes Generated for Efficiency Measurements

Calculated Classifier Diameter (μm)	Measured Diameter (μm)
0.05	.049
0.075	.077
0.1	.116
0.12	.128
0.15	.147
0.199	.198
0.3	.31
0.4	.40
0.5	.42

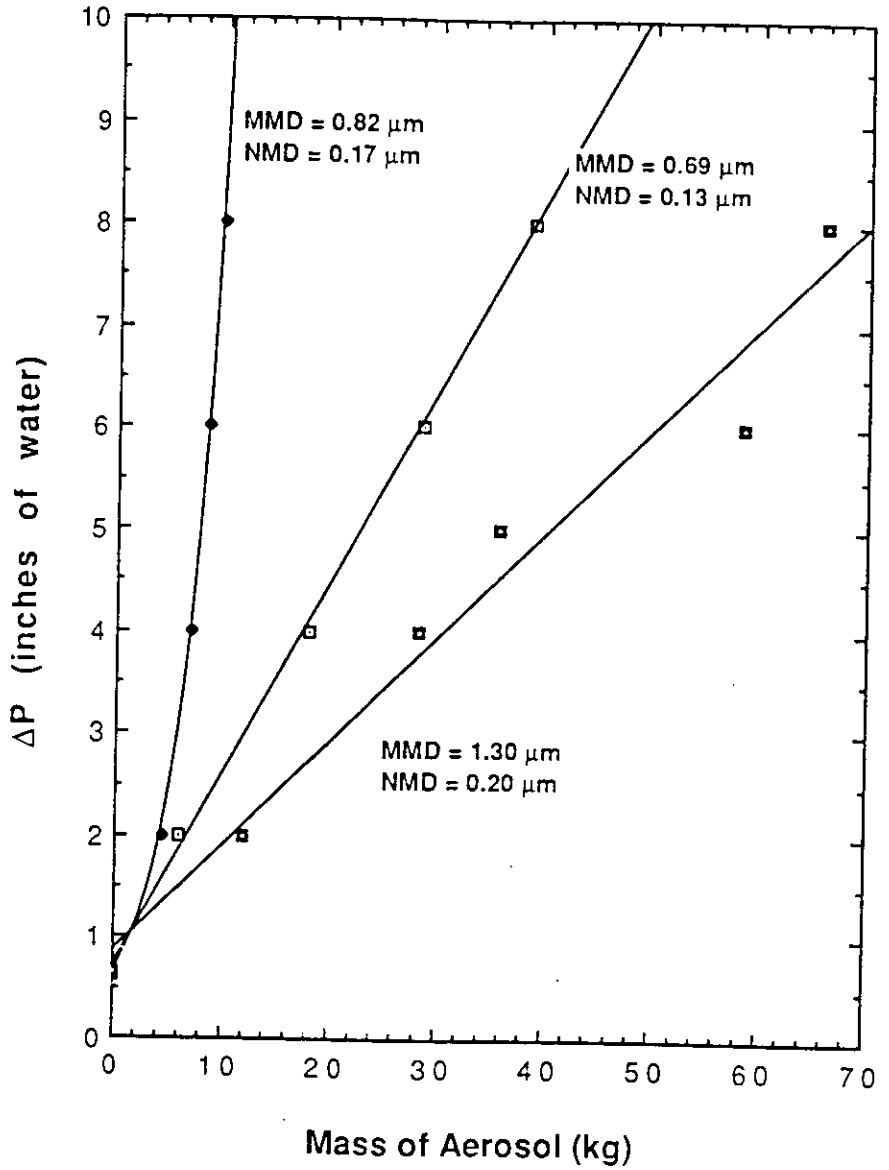

Figure 5.10 Pressure Drop as a Function of Mass Loading for One 32 Unit Savannah River HEPA Filter Bank

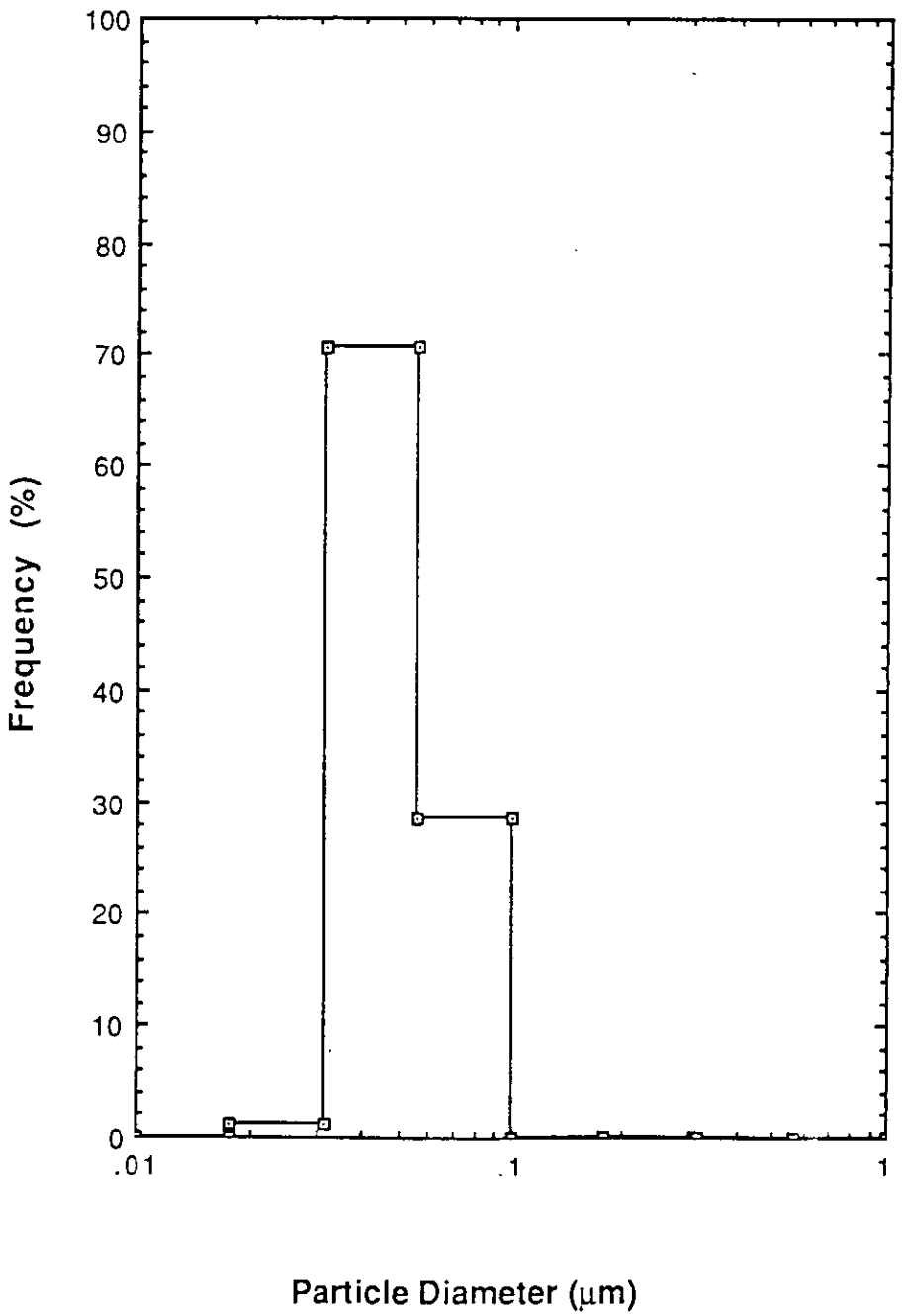

Figure 5.11 Classifier Output 0.05 μm Measured With EAA 0.049 μm

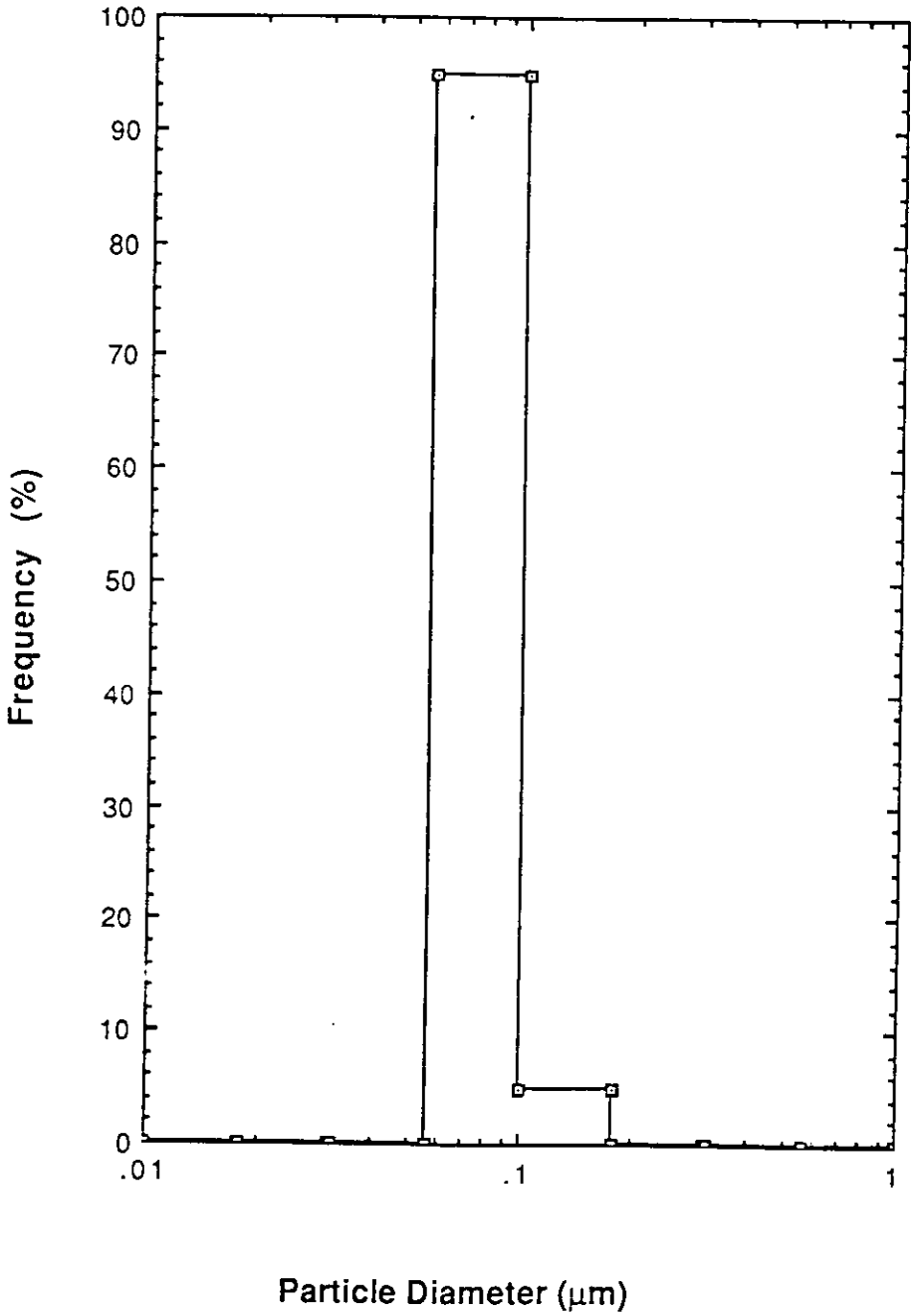

Figure 5.12 Classifier Output 0.075 μm Measured With EAA 0.077 μm

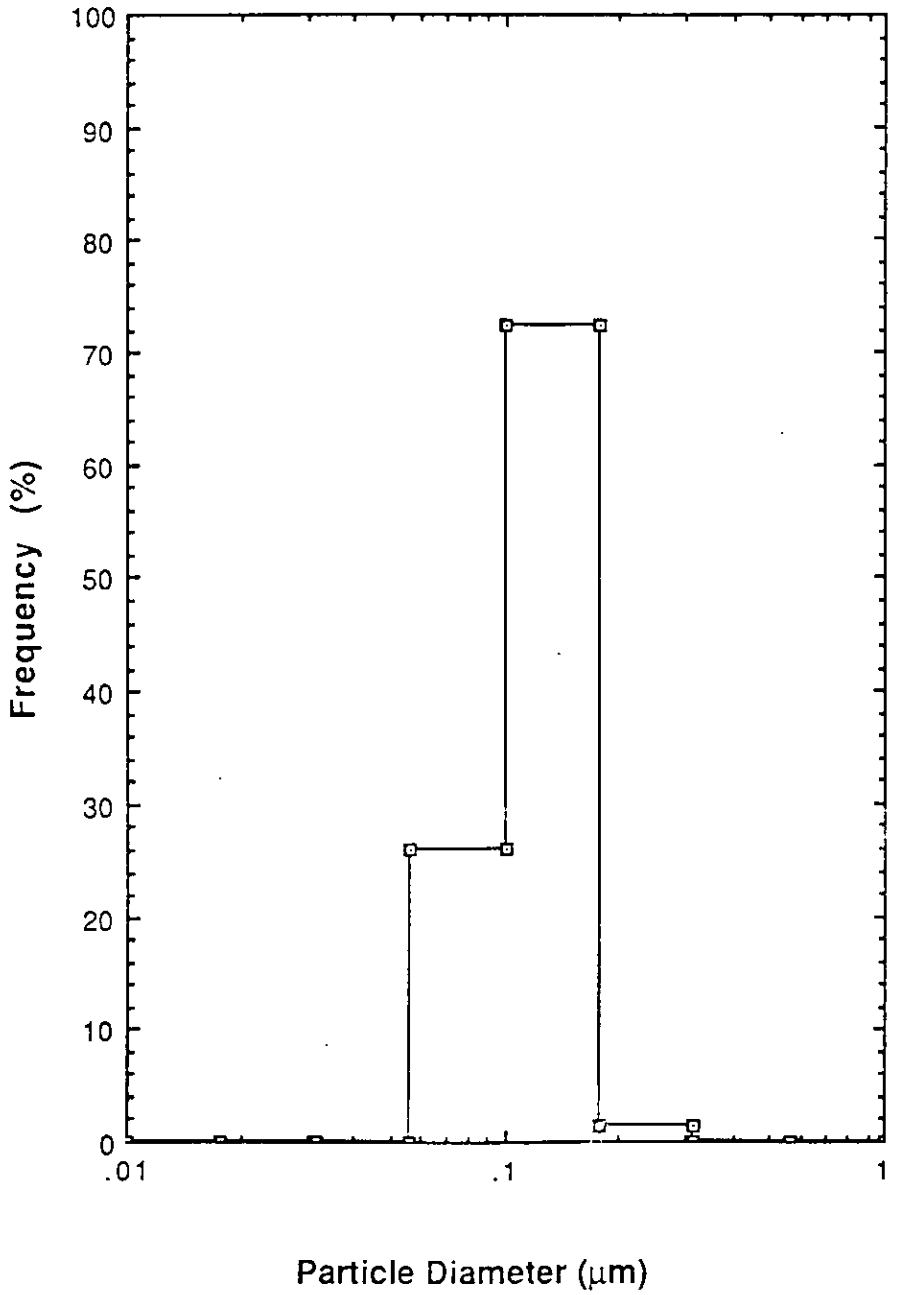

Figure 5.13 Classifier Output 0.1 μm Measured with EAA 0.116 μm

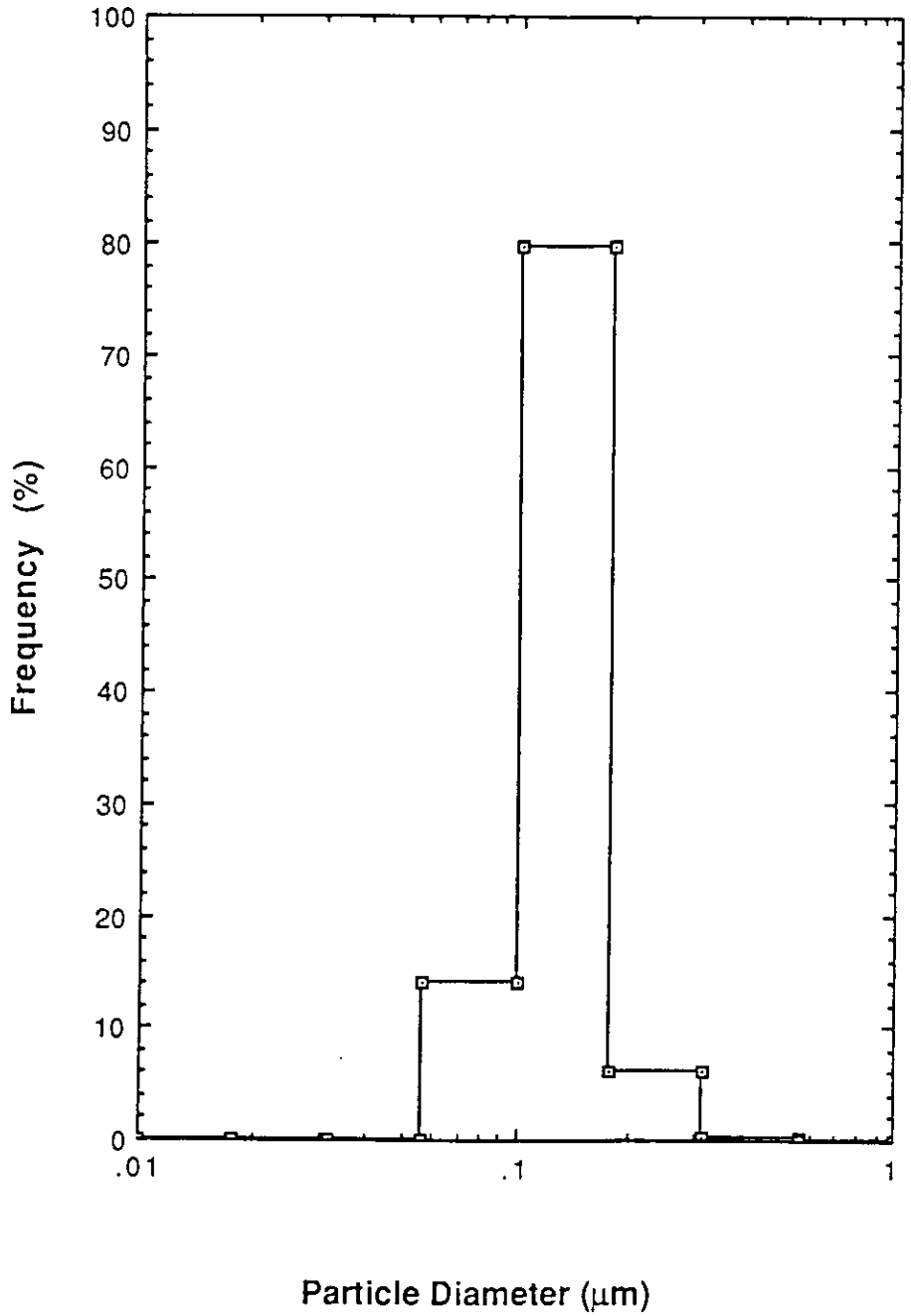

Figure 5.14 Classifier Output 0.12 μm Measured with EAA 0.128 μm

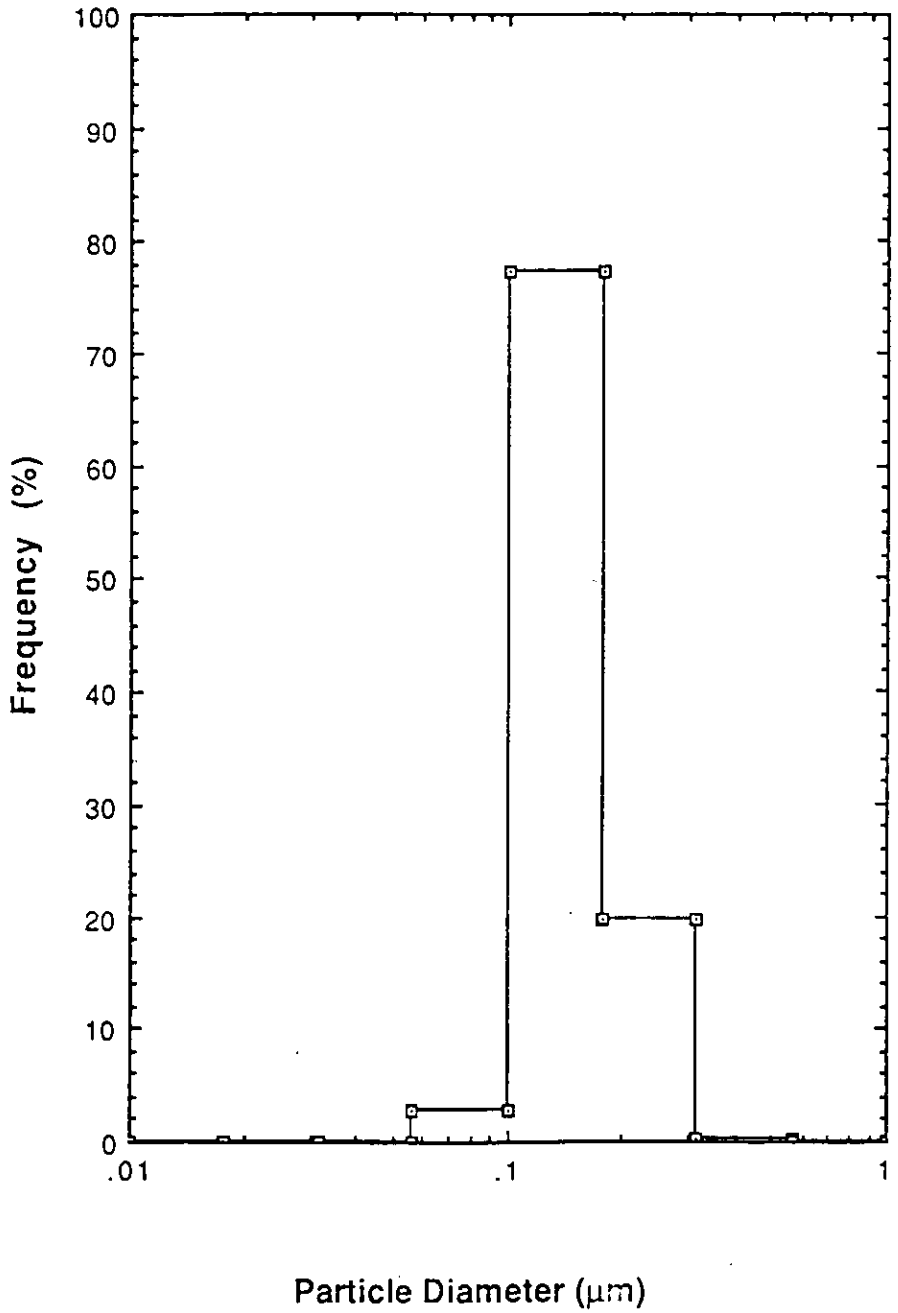

Figure 5.15 Classifier Output 0.15 μm Measured with EAA 0.147 μm

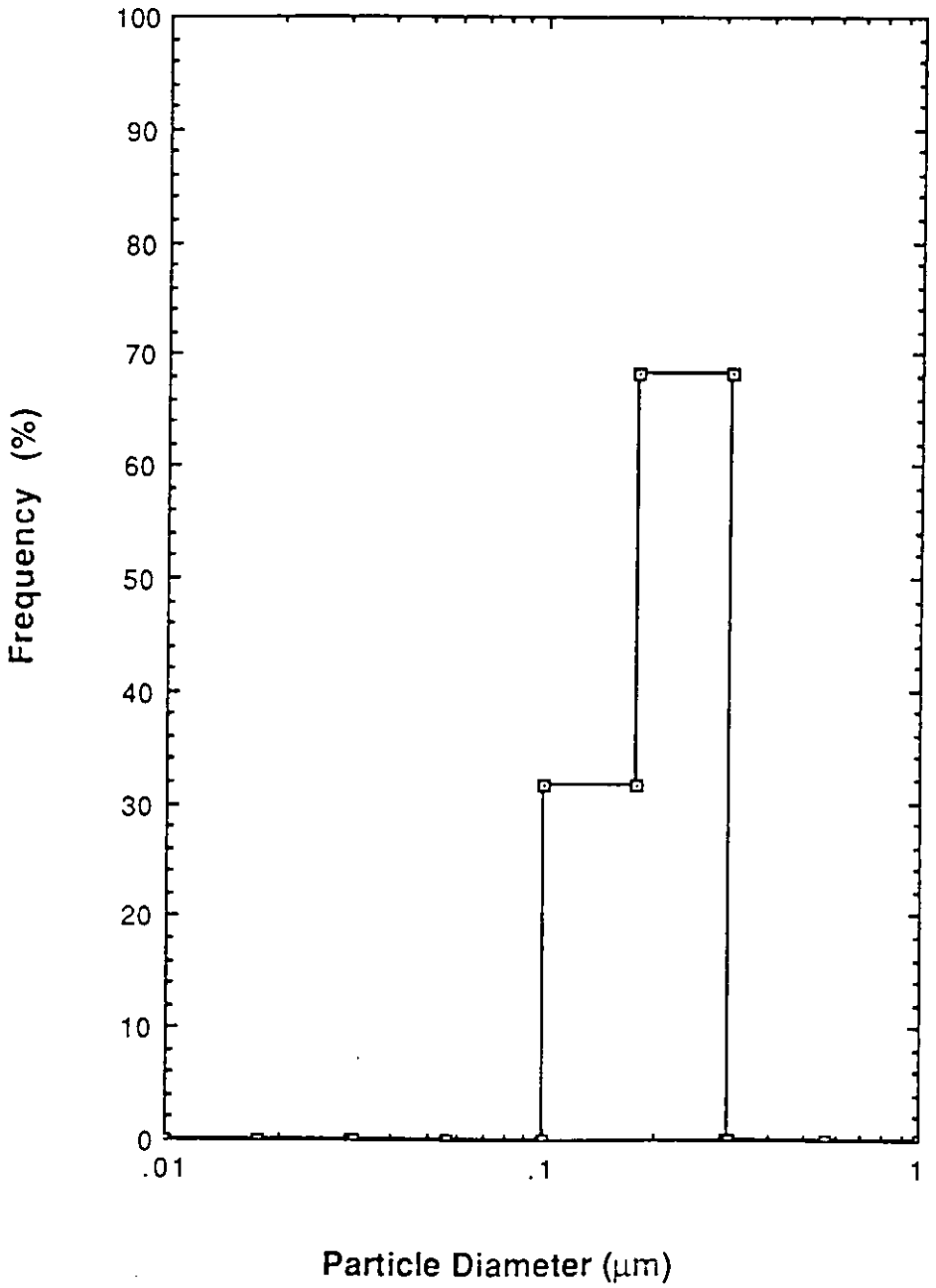

Figure 5.16 Classifier Output 0.199 μm Measured with EAA 0.198 μm

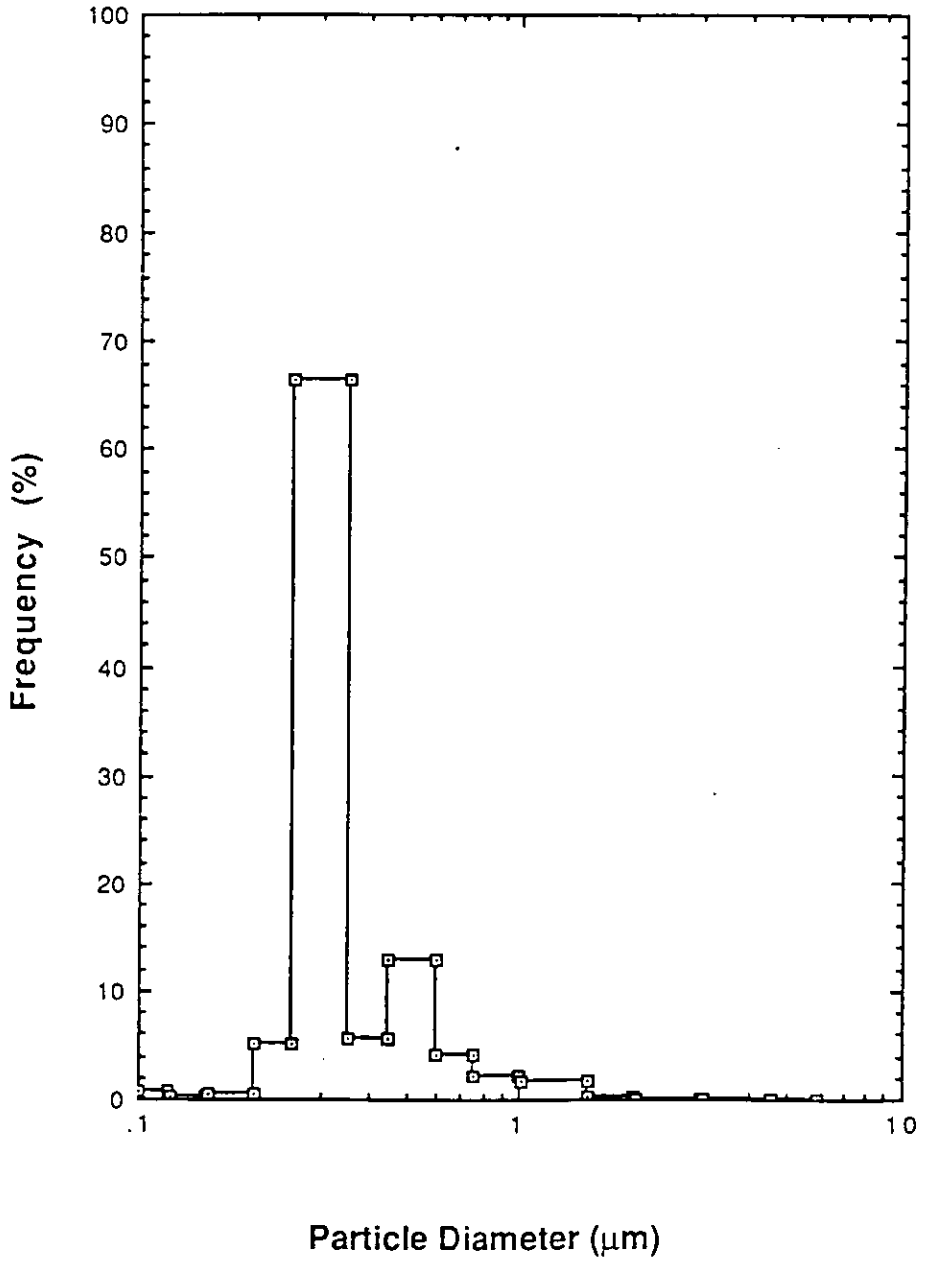

Figure 5.17 Classifier Output 0.3 µm Measured with LAS 0.31 µm

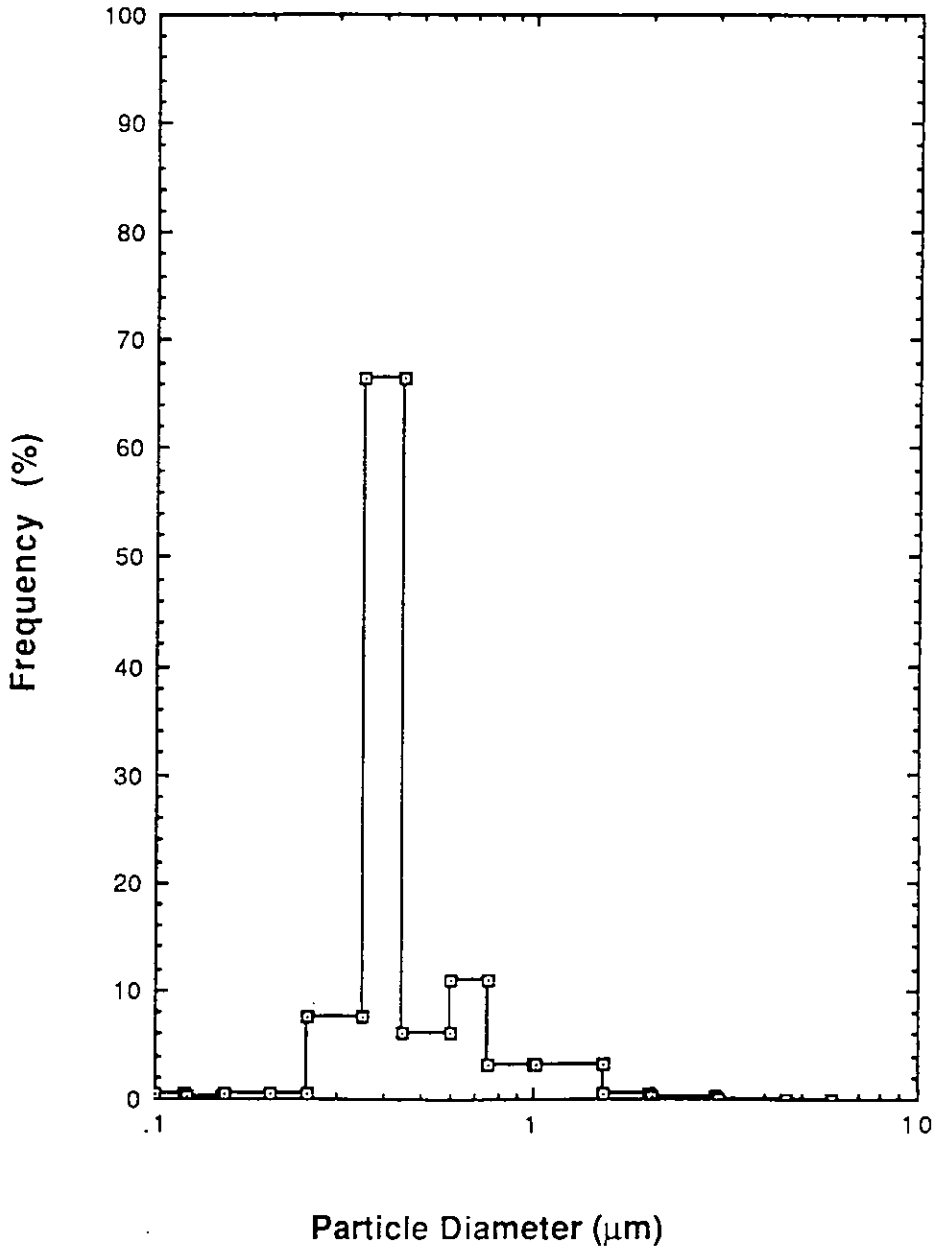

Figure 5.18 Classifier Output 0.4 μm Measured with LAS 0.40 μm

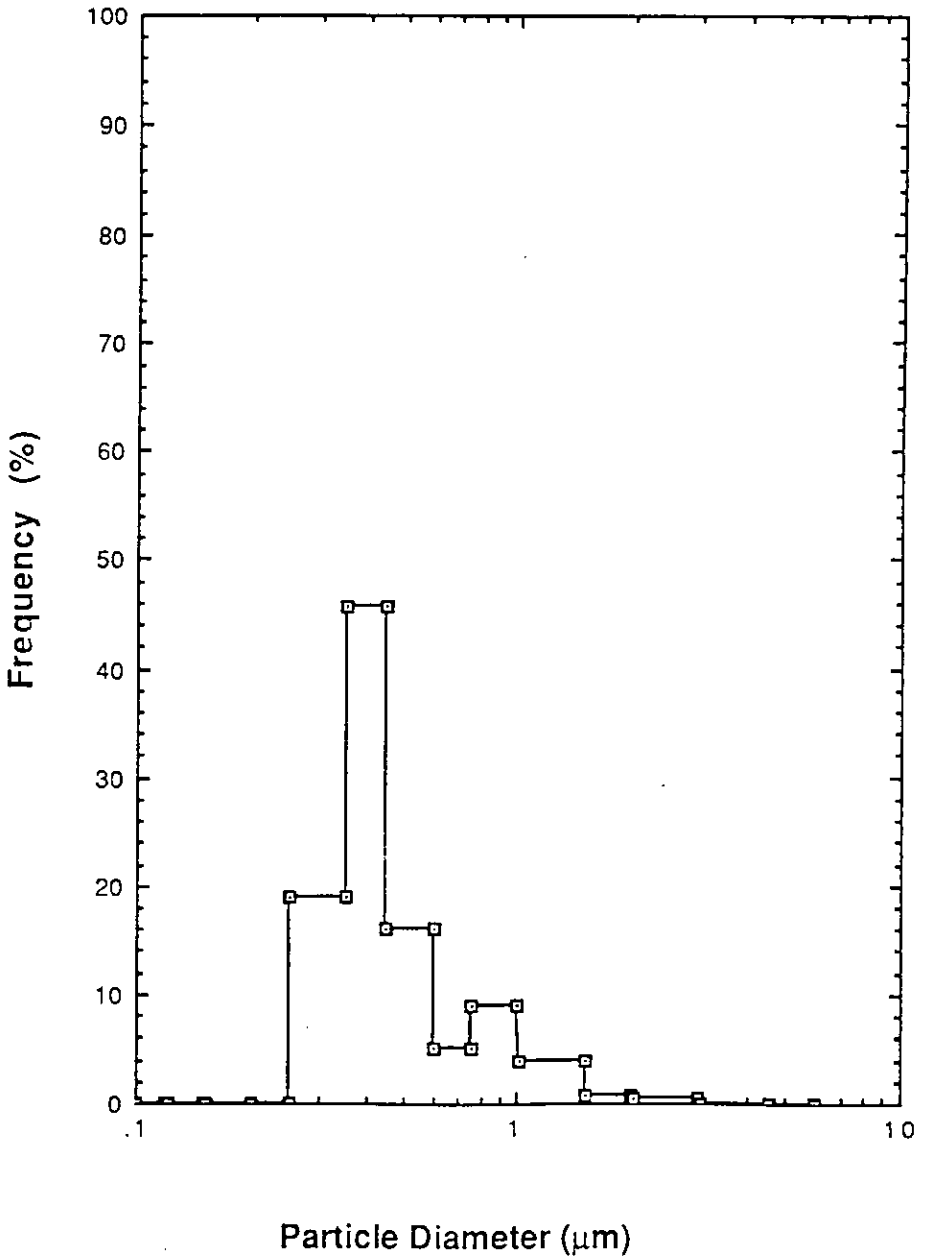

Figure 5.19 Classifier Output 0.5 µm Measured with LAS 0.42 µm

As described in the procedure in Section 3, the number concentration of particles was monitored both upstream (unfiltered) and downstream (filtered) of the HEPA filter media. Figure 5.20 shows a strip chart record of the filtered and unfiltered particle concentrations for a typical efficiency measurement. The traces are a real-time record of particle concentrations measured by the CNC's. For some experiments, the number concentration was not as stable as that shown in Figure 5.20. However, the downstream concentration followed the upstream concentration with time. This indicates that there is minimal lag time in the system and that the same particle concentration challenging the filter is being sampled by the model 3020 CNC.

The quotient of the absolute filtered divided by unfiltered particle concentrations for each minute of the test were plotted against time. The filtration efficiency for a given particle size and filtration velocity was usually found to be relatively constant over the time interval during which measurements were recorded. Figures 5.21 and 5.22 illustrate the results for filtration velocities of 0.89 cm/s and 2.98 cm/s, respectively. To fit the data to a logarithmic scale, absolute number penetration was plotted instead of efficiency. The absolute number penetration and efficiency are related by,

Penetration = 1 - Fractional Efficiency

The observed penetrations for most of the particle sizes tested, are generally flat due to the relatively low aerosol concentration, typically around 10^5 particles/cm^3, and the short measurement time, 15 minutes. If a significant amount of mass were allowed to accumulate on the filter, the penetration would be expected to decrease with time for all particle sizes tested.

All penetration measurements for a given filtration velocity and particle size were averaged in order to plot the efficiency curves. Figures 5.23 and 5.24 show the average number penetration as a function of particle size for the two filtration velocities. Figure 5.23 shows that for a filtration velocity of 0.89 cm/s the maximum penetration occurs near 0.3 μm.

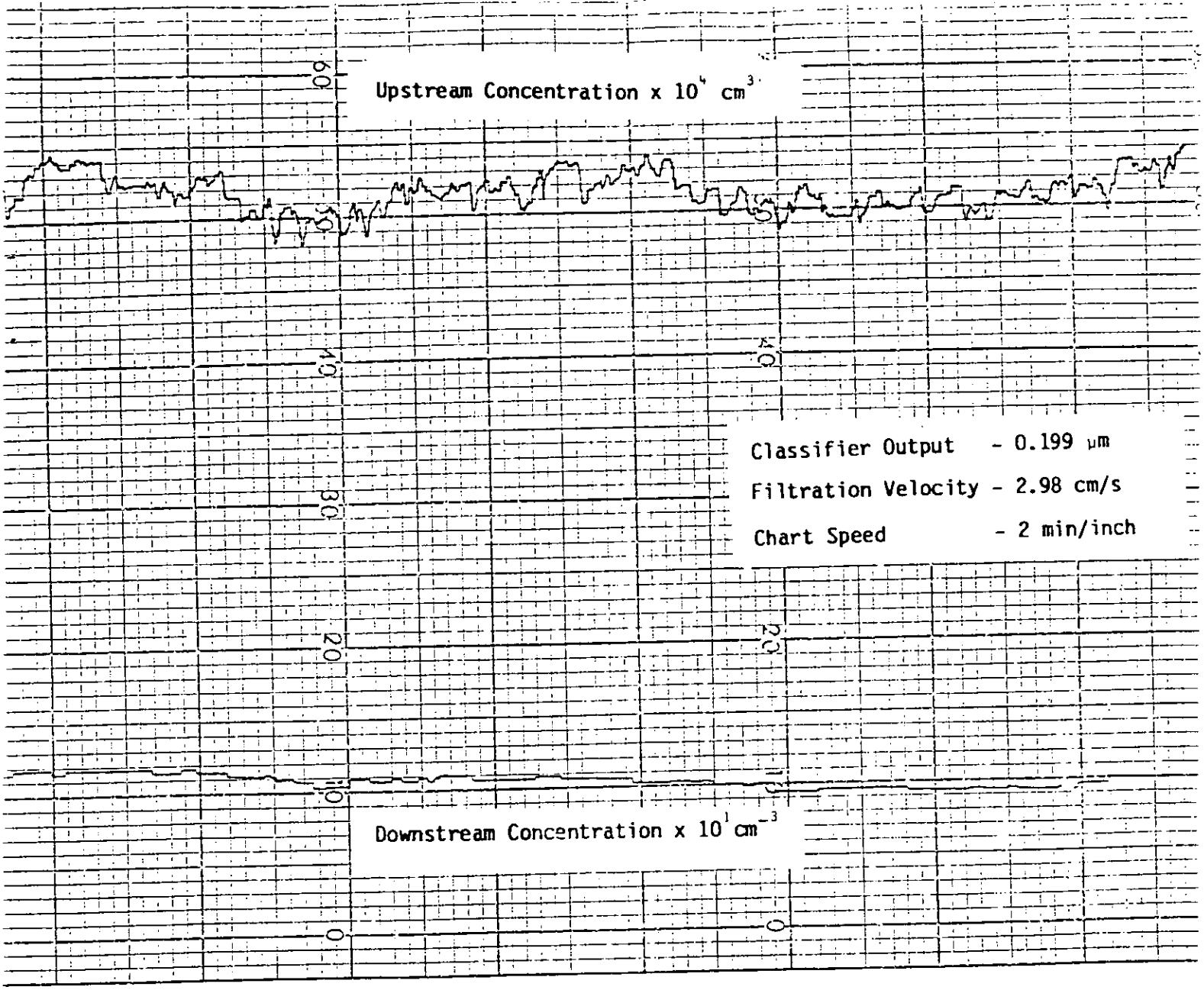

Figure 5.20 Typical Strip Chart Record of Upstream (Unfiltered) and Downstream (Filtered) Particle Number Concentrations as a Function of Time.

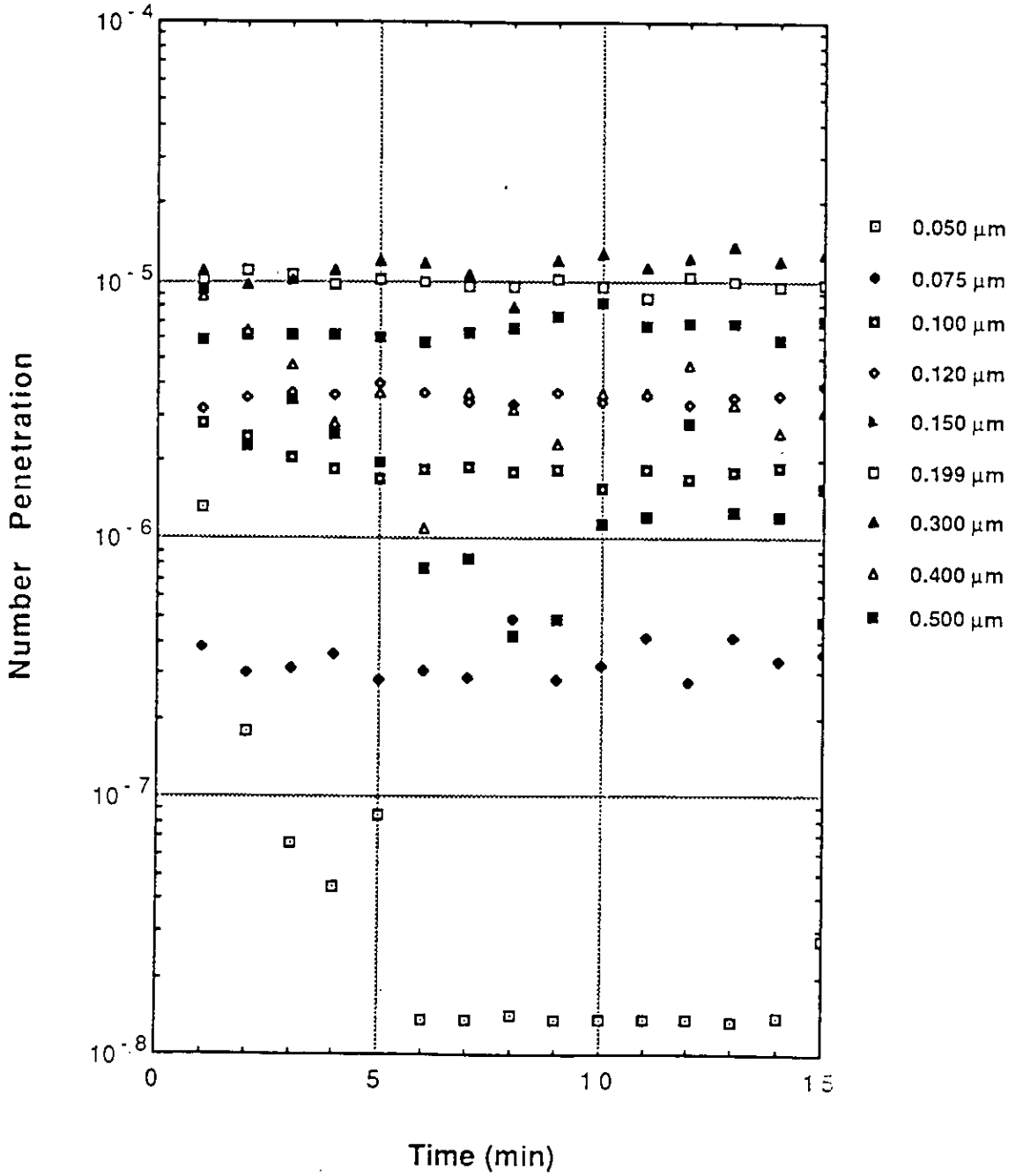

Figure 5.21 Number Penetration vs Time Using Monodisperse NaCl Aerosols For the Electrostatic Classifier, Filtration Velocity = 0.89 cm/s

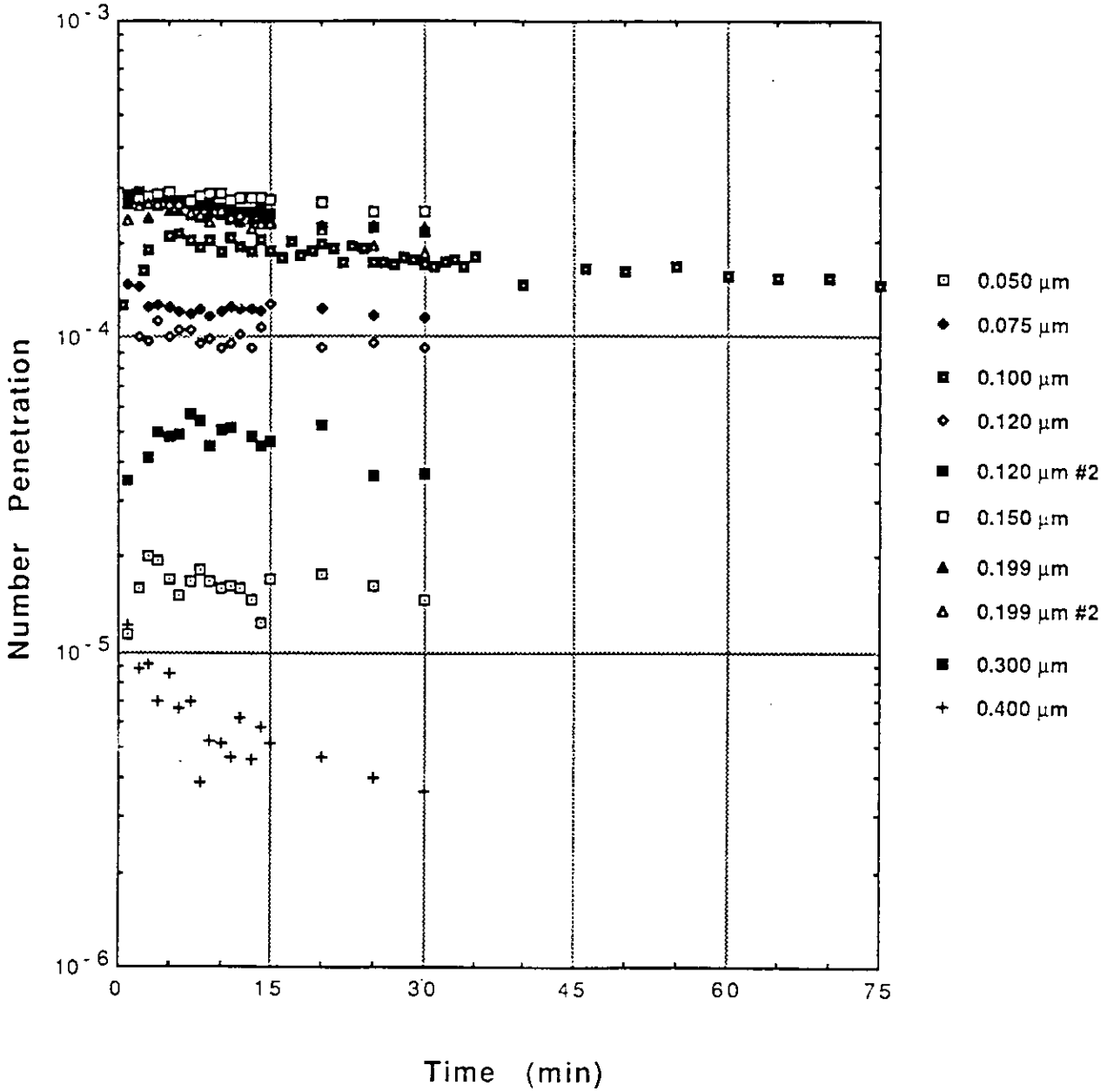

Figure 5.22 Number Penetration vs Time Using Monodisperse NaCl Aerosols from an Electrostatic Classifier, Filtration Velocity = 2.98 cm/s

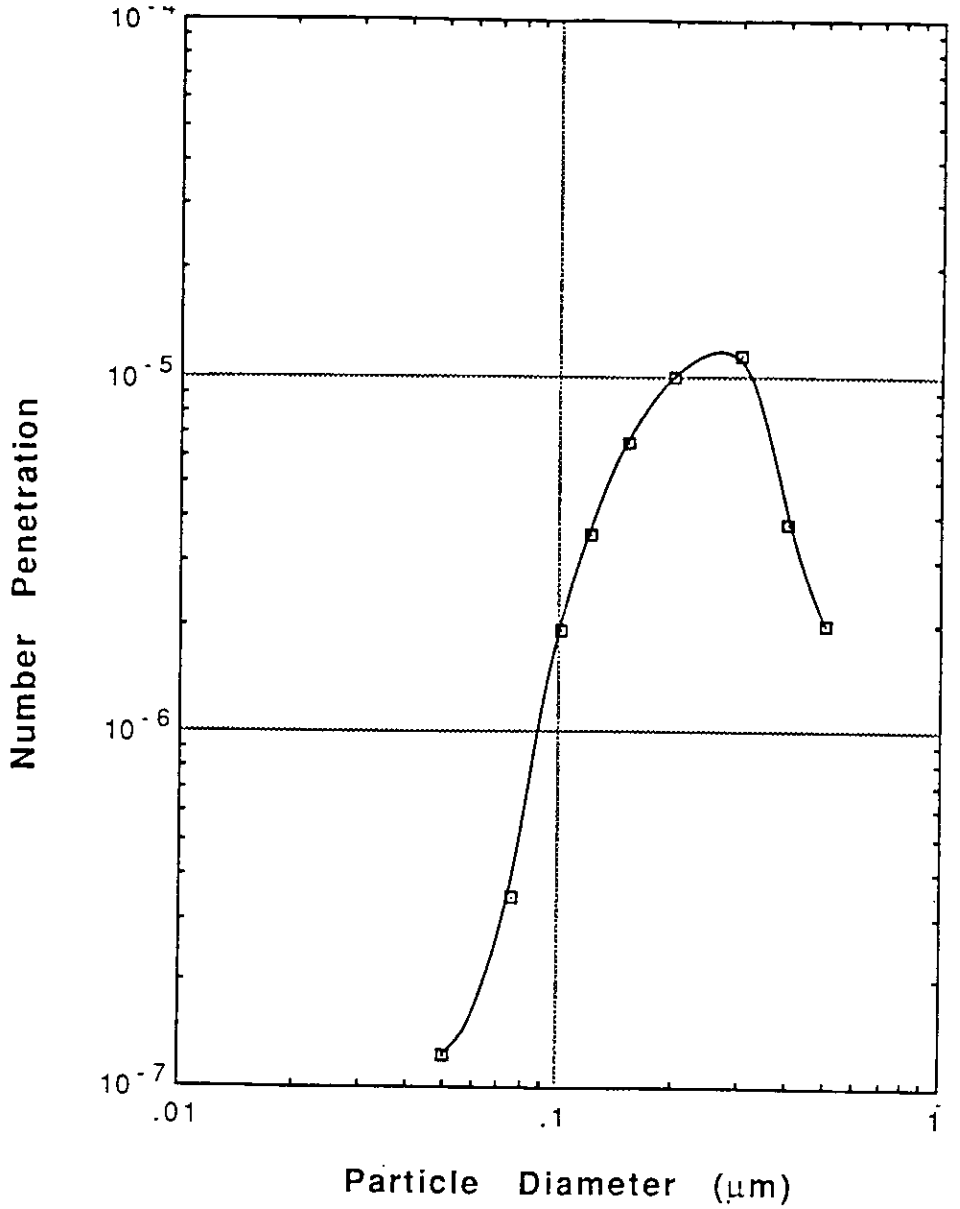

Figure 5.23 Number Penetration vs Particle Diameter for Monodisperse NaCl Aerosols Using an Electrostatic Classifier, Filtration Velocity = 0.89 cm/s

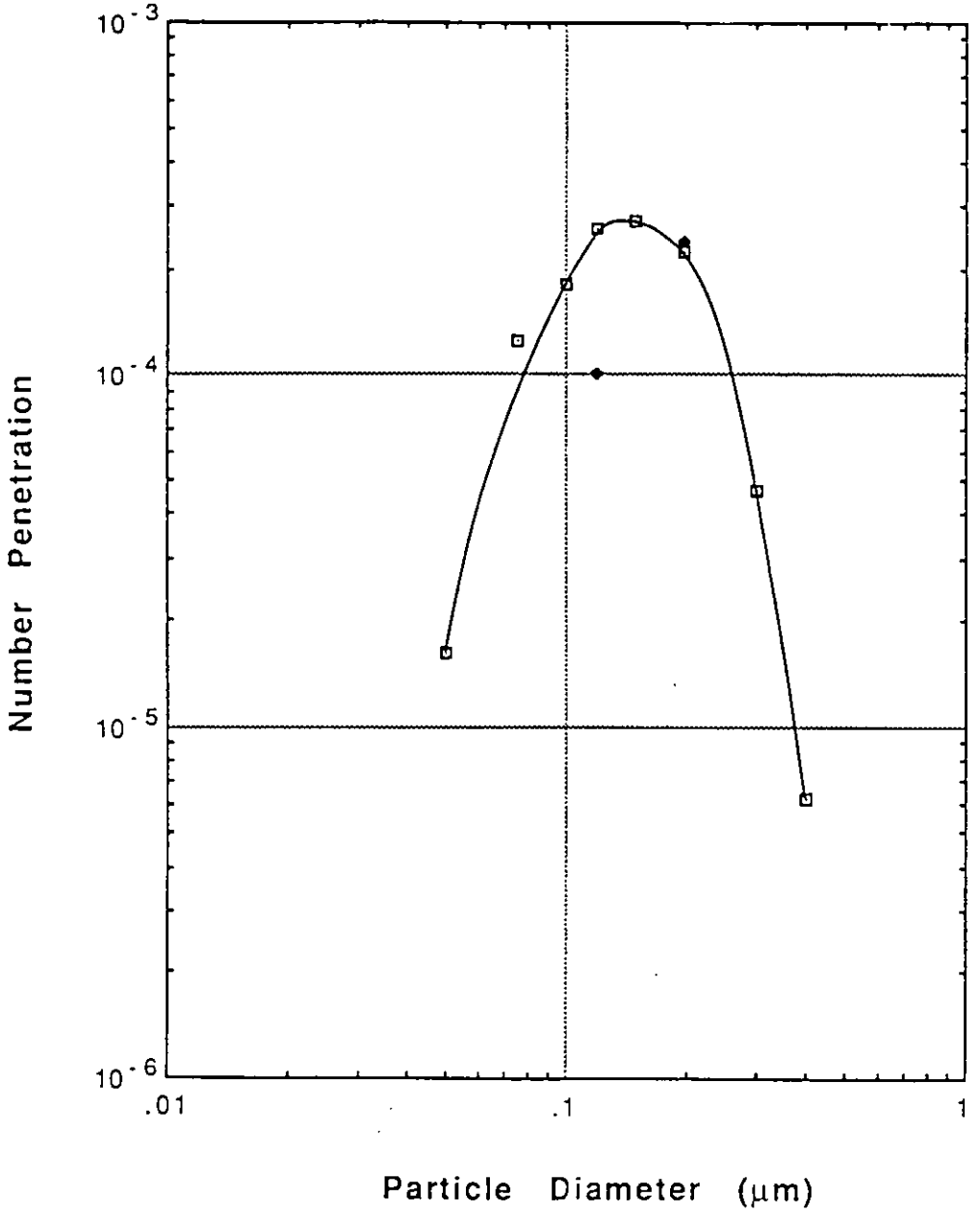

Figure 5.24 Number Penetration vs Particle Diameter for Monodisperse NaCl Aerosols Using an Electrostatic Classifier, Filtration Velocity = 2.98 cm/s

This maximum penetration corresponds to a minimum filtration efficiency of 99.99886%. As expected from filtration theory, the efficiency is seen to increase for both larger and smaller particle sizes. This is because the mechanism of filtration for smaller particles is diffusion which varies inversely with particle size. For particles larger than that producing minimum efficiency, impaction and interception with the fibers increases directly as function of particle size.

For the higher filtration velocity of 2.98 cm/s, Fig. 5.24, the overall penetration increased approximately by a factor of ten and shifted toward smaller particle diameters. In this case, the minimum penetration occurred at approximately 0.15 μm, corresponding to a filtration efficiency of 99.9727%. Two additional points are included on this graph. When the efficiency for 0.12 μm particles was first measured, it was noticed that this point did not fall on a smooth curve joining the other points. The efficiency measurement was repeated for this particle size and this time the point did fall very close to the curve defined by the other data points. To investigate repeatability, another test was rerun at 0.199 μm. This time the second measurement was consistent with the first and with the majority of the other data points. Since no procedural error was evident, the error in the first measurement at 0.12 μm was attributed to filter variation. Out of 10 total filters tested at 2.98 cm/s, only this one produced results inconsistent with the others. No inconsistencies were observed at 0.89 cm/s.

6.0 Conclusions and Recommendations

Based on the data from these experiments, the following conclusions can be made concerning the Savannah River HEPA filter media:

- The maximum aerosol mass that can be collected by one filter bank without exceeding a pressure drop of 6 inches of water and drawing a volumetric flow of 23100 CFM, depends on the particle size distribution of the aerosol. This work has demonstrated that a mass range between 8kg and 12kg can produce a pressure drop of 6 inches of water across a SRS HEPA filter bank (36 units). These values are consistent with those measured by McCormack et al when adjusted for

a pressure drop of 6 inches of water.[9] Additional work is needed in this area to address concerns such as repeatability, shape factor effects and humidity or liquid aerosol effects.

- The HEPA filter media is at least 99.99886% efficient for all dry particles sizes and a volumetric flow of 8440 CFM through one bank and at least 99.9727% efficient for a volumetric flow of 28200 CFM. These measured efficiencies exceed current specifications. Efficiency spectra were determined for both flow rates allowing the release to the environment to be calculated for a given particle size distribution. Measurements should be repeated for liquid or liquid-coated aerosols.

- The prefilter/demister is an integral part of the SRP confinement system and needs to be tested to determine its collection efficiency and mass loading characteristics. The prefilter/demister may significantly improve the total AACS mass loading capacity.

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APPENDIX A

METAL FIBER FILTER CHARACTERISTICS

The work presented here is a summary of data collected at the Idaho National Engineering Laboratory in 1984. The objective was to design a high efficiency filter that would be able to collect a quantity of aerosol material from a high temperature gas consisting of steam and hydrogen. These constraints led to the investigation of stainless steel fiber felt filter materials. These materials are available from Michigan Dynamics and manufactured by Bekaert.

The 5AL2 filter material was chosen for testing. In addition to the published specifications, important parameters were obtained from the manufacturer or experimentally.

	MFG Data	Experimental Data
Fiber diameter (d_f)	10 μm	12.5 μm (average) 8-16 μm (absolute)
Porosity (p)	.67	.59
Solidity (α = 1-p)	.33	.41
Thickness (t)	.25 mm	.17 mm

The test procedure was to collect NaCl aerosols on a 25 mm diameter metal filter and a 47 mm millipore 0.8 μm backup filter (collection efficiency greater than 99%). The effective area of the metal filter in its housing was 3.7 cm^2. The NaCl aerosols were generated with a TSI model 3076 atomizer. Published experimental data from Liu and Lee (1975) were used to determine the output number median particle size and geometric standard deviation as a function of solution concentration. Metal filter efficiencies were determined by flowing the NaCl aerosol past both filters in series and determining the mass collected by each filter by washing the filters and measuring the conductivity of the resultant solutions. Table A provides efficiency data as a function of polydisperse particle size for face flow velocities of 8.9 cm/s.

Table A

Solution Concentration	Number Median Diameter	Mass Median Diameter	Mass Efficiency
.001%	.012	.053	82%
.01%	.0185	.082	87%
.05%	.025	.110	81%
.1%	.029	.128	61%
.5%	.039	.172	86%
1.0	.045	.198	90%
5.0%	.061	.267	99.1%
10.0%	.070	.306	99.3%

Table B provides the efficiency of the 5AL2 filter as a function of polydisperse particle size for face flow velocities of 26.1 cm/s.

Table B

Mass Median Diameter	Efficiency
.071	64%
.128	38%
.185	79%
.30	95%

The measured efficiencies were compared to theoretical efficiencies calculated from Hinds (1982).

$$E = 1 - \exp [- 4 \alpha E_S t/\pi d_f]$$

where E_S is the single fiber collection efficiency. Figure A shows that the theoretical calculation overestimates the amount of material transported through the filter material.

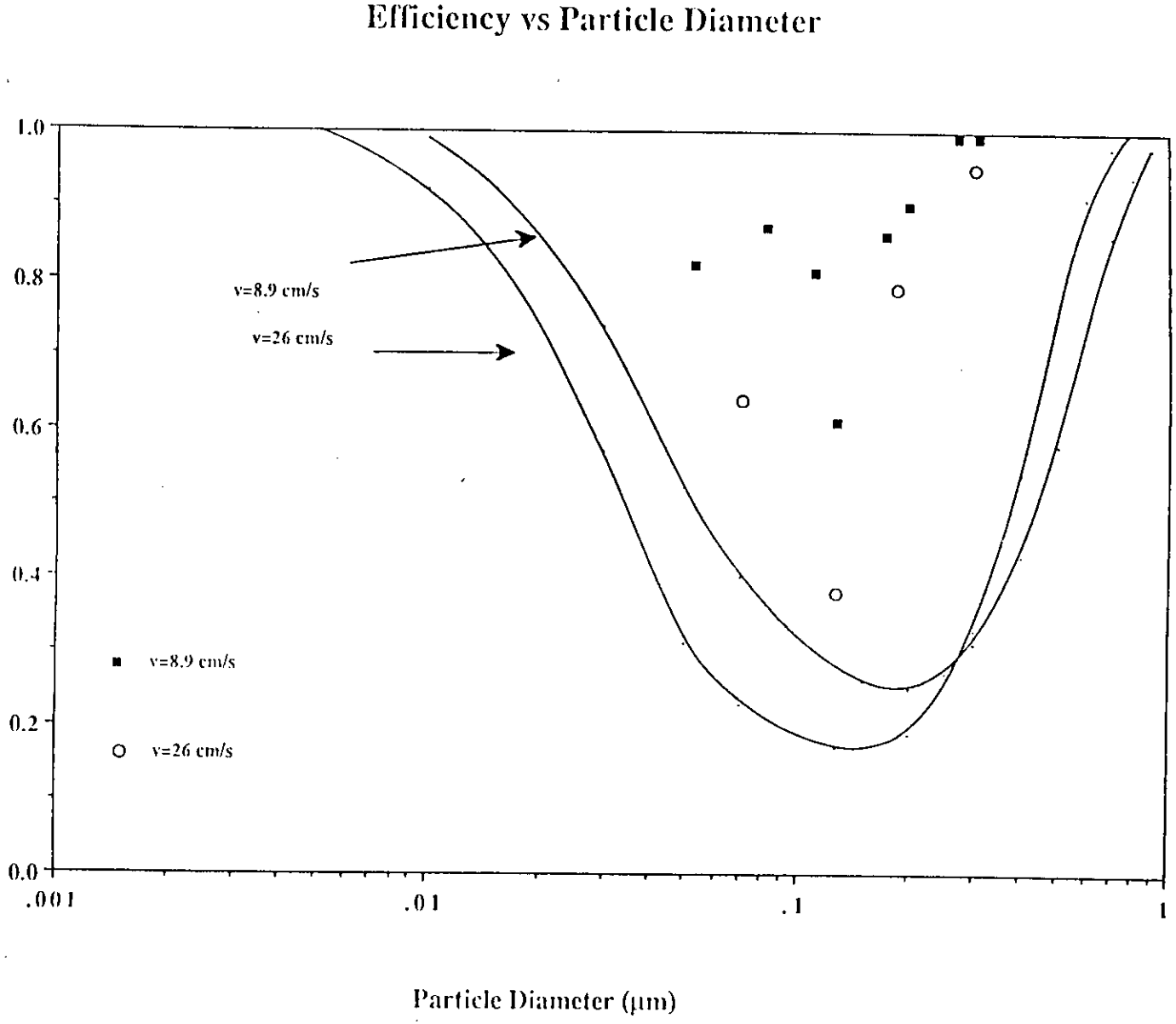

Figure A Efficiency as a Function of Particle Diameter For the Type 5AL2 Metal Fiber Filter

In addition to filter efficiencies, the amount of material that can be collected on a filter that will increase the pressure differential across the filter by a given ΔP, is also a function of the particle size. A particle size distribution with a mass medium of 0.11 μm was produced using a .05% NaCl solution in the TSI atomizer. Larger particle size distributions were generated using an In-Tox products nebulizer and solution concentrations of 0.12% and 9.1% yielding mass medium diameters of 0.5 μm and 2.1 μm respectively. Figure B, plots the measured ΔP across the filter as a function of the mass loading for face velocities of 8.9 cm/s and submicron mass median particle sizes of 0.11 μm and 0.5 μm. Figure C, plots the same parameters of a 2.1 μm mass median particle size. Finally, the amount of material per unit area of filter material is listed as a function of particle size for a factor of five and a factor of ten increase in pressure drop from a clean filter. This results in a ΔP of 15 mm Hg and 30 mm Hg.

Table C

Mass Median Diameter	Mass Loaded/Unit Area	
	ΔP = 15 mm Hg	ΔP = 30 mm Hg
2.1 μm	2.57 mg/cm^2	5.54 mg/cm^2
0.5 μm	0.84 mg/cm^2	0.95 mg/cm^2
0.11 μm	0.46 mg/cm^2	0.61 mg/cm^2

These data led to a pleated metal filter design to increase the total surface area available for collection and the use of four layers of material to increase the minimum efficiency at 8.9 cm/s to over 95%.

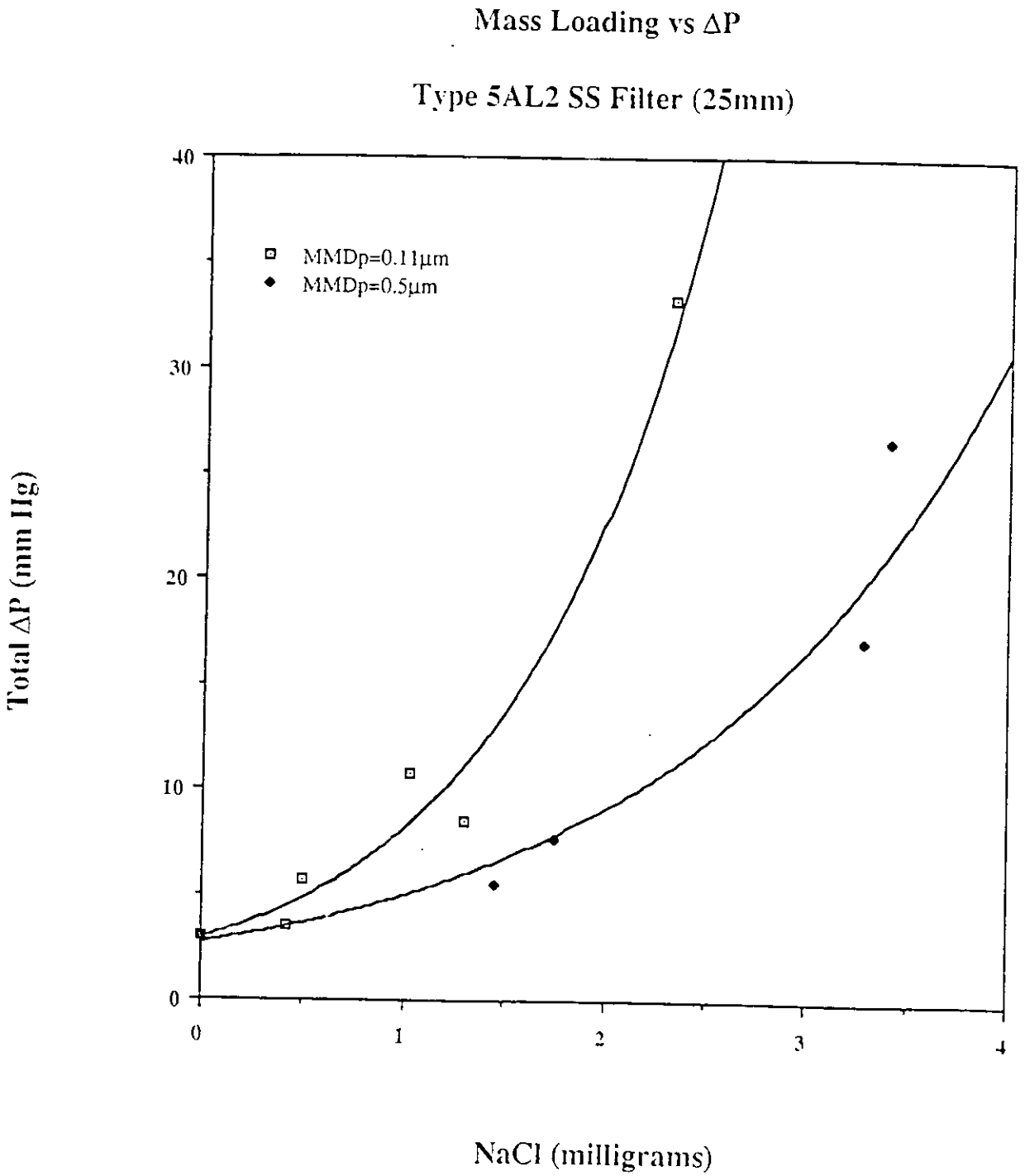

Figure B Pressure Drop as a Function of Mass Loading for Two Different Particle Size Distributions, MMD = .11 µm and .5 µm

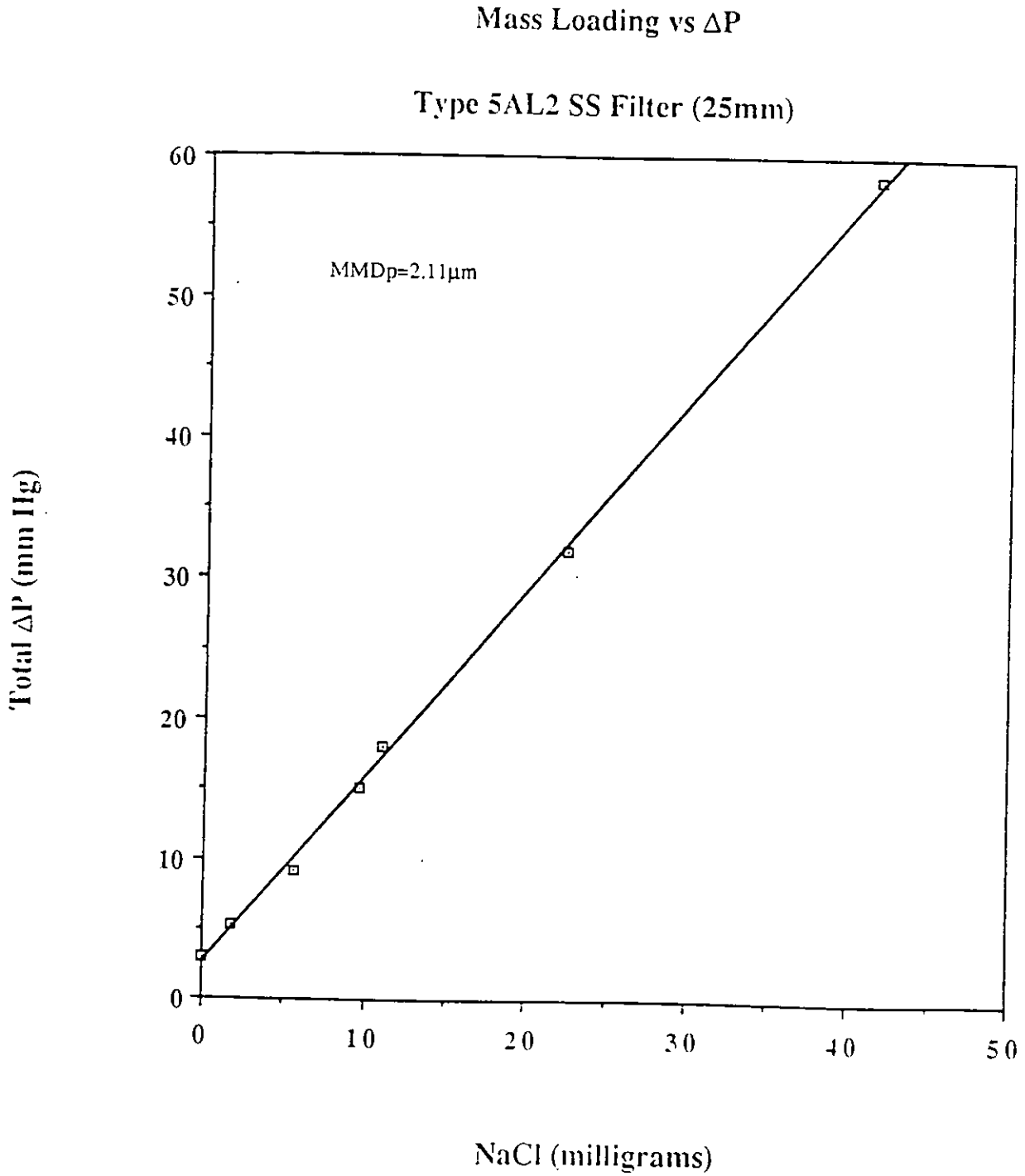

Figure C Pressure Drop as a Function of Mass Loading for a Third Particle Size Distribution, MMD = 2.11 µm

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