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# DEVELOPMENT OF A LOW PRESSURE IMPACTOR

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# DEVELOPMENT OF A LOW PRESSURE IMPACTOR

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## ABSTRACT

A Low Pressure Impactor aerosol sampler was designed fabricated and tested. The system injects a fixed aerosol flow rate of 1 cfm at inlet conditions and causes the particulate matter to be separated and collected on four atmospheric pressure and three reduced pressure impaction stages and an after-filter. Cutpoint sizes of the stages are 9.7, 5.0, 2.46, 1.21, 0.355, 0.141, and 0.05 micrometers for spherical particles with a density of 2 gm/cm$^3$. Each of the impaction stages is fitted with a glass fiber media collection substrate to facilitate gravimetric analysis of the collected samples.

Experiments conducted with laboratory aerosols show the system to have wall losses less than 6 percent when the mass median diameter of the aerosol is 0.6 micrometers. For particles 6.1 microns in size, the wall losses on the upper stages are less than 11 percent. Both particle rebound and re-entrainment from the collection surfaces are shown to be negligible. Each low pressure stage can be loaded with more than 10 mg of deposited aerosol without re-entrainment occurring.

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| | | |
|---|---|---|
| $A$ | = | 1.23, a constant |
| $C$ | = | Cunningham's Correction |
| $D_j$ | = | Jet Diameter |
| $D_p$ | = | Particle Diameter |
| $D_{p.5}$ | = | Particle Diameter for which Stage Efficiency is 50 percent |
| $K$ | = | Inertial Parameter |
| $K_{.5}$ | = | Value of Inertial Parameter for which Stage Efficiency is 50 percent |
| $K_T$ | = | Value of Inertial Parameter Corresponding to Conditions Employed in a Particular Test |
| $L$ | = | Distance from Jet Exit Plane to Collection Plate |
| $P$ | = | Air Pressure at Jet Exit Plane |
| $Q$ | = | 0.41, a constant |
| $Re_j$ | = | Jet Reynolds Number |
| $T$ | = | Air Temperature at Jet Exit Plane |
| $V_o$ | = | Air Velocity at Jet Exit Plane |
| $b$ | = | 0.44, a constant |
| $\eta$ | = | Stage Efficiency |
| $\eta_T$ | = | Value of Efficiency Obtained Experimentally |
| $\lambda$ | = | Mean Free Path of Air Molecules |
| $\mu$ | = | Dynamic Viscosity of Air |
| $\rho_p$ | = | Density of Particulate Matter |

# INTRODUCTION

## Background

The deleterious effects of atmospheric particulate matter are numerous and varied. These include:

Reduction of solar radiation (which causes a decrease in seasonal temperatures) Landberg[1] reported that urban areas receive up to 20% less insolation than rural areas. Robinson[2] and Holzworth[3] demonstrated that there is a relationship between visibility and the amount of particulate matter in the atmosphere.

Corrosion of metals Hudson[4] observed that industrial locations with high concentrations of particles and oxides of sulfur are more corrosive to steel and zinc than less industrialized ares.

Interference with photosynthesis Particles settling on vegetation interfere with light required for photosynthesis thereby lowering starch production by the plant (Czaja[5] and Bohne[6]).

Human health hazard Atmospheric particles are suspect as being a threat to human health[7] since these may be intrinsically toxic, may carry an adsorbed toxic material or may interfere with the clearance mechanisms in the in the respiratory tract.

In all of the above areas the knowledge of the size of the particle is vital to understanding its effects and determining the best methods to control particulate emissions from man made sources.

In the case of examining the role of aerosols as public health hazards, the Task Group on Lung Dynamics[8] noted the utility of a sampler which can be used to determine the size of particles in aerodynamic terms. The degree of penetration and retention of particles in the respiratory system is a function of aerodynamic size[9]. Particles are, to a large extent selectively deposited by aerodynamic size in the nasopharyngeal, tracheobronchial, and pulmonary areas of the respiratory system. Final deposition site also depends on variations in the respiratory air flowrate, and on physiological considerations.

The use of aerodynamic sizing is of interest not only because it allows simulation of the important size parameter in lung deposition but also because it renders itself to the measurement of the aerosol mass-size distribution. Although there are various types of apparatus which could be used to acquire size distribution data based upon aerodynamic size, the most widely used are cascade impactors. With reference to Figure 1 the cascade impactor draws an aerosol sample through a series of two or more stages made up of a jet or orifice plate and a collection surface. As the air flows through the jet it is accelerated to a specific velocity and directed towards the

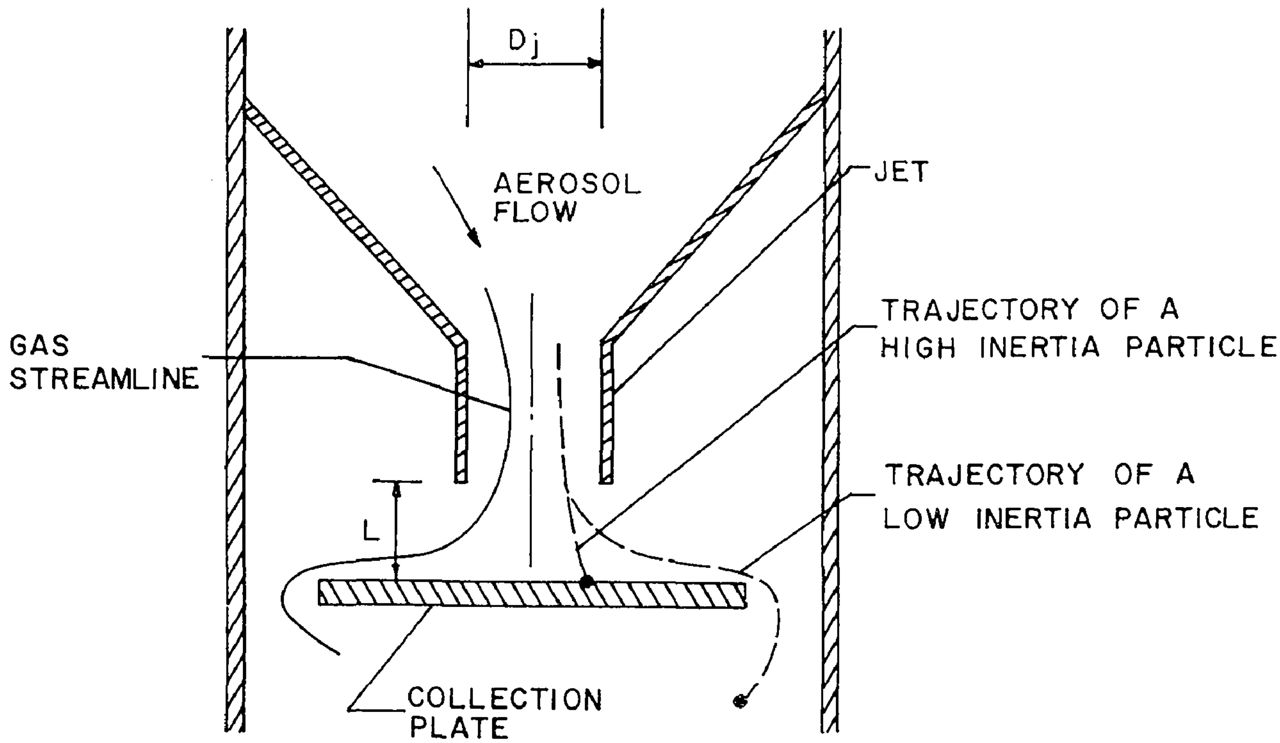


FIGURE 1 - IMPACTOR STAGE - SINGLE JET TYPE

collection surface and through the following jet stage. Particles with sufficient inertia cross the air flow stream lines and impact on the collection surface. The smaller particles, which have insufficient inertia, follow the stream lines into the next impactor stage. By employing several stages in series it is possible to separate an aerosol into size groupings. Samplers which characterize atmospheric particles in this manner have been available since 1945 when May[10] developed a four stage cascade-type inertial impactor.

May's first impactor employed rectangular jets, however, Ranz and Wong[11] found better efficiency characteristics and sharper cuts could be obtained with round jet impactors. In 1958, A. A. Andersen[12] developed a cascade inertial impactor for bacterial sampling which employed multiple jets on each stage. Subsequently developed versions of the apparatus have found application in atmospheric and stack sampling.

Inertial impactors commonly used up to the present time have had the capability of sizing particles to a lower limit of approximately 0.4 micrometers. This operational characteristic has limited the study of the submicron components of aerosols such as motor vehicle exhaust (which at cruising speeds consists of particles of carbon, motor oil, aldehydes, ketones and lead) approximately 70 percent of which have an equivalent size for unit density particles of less than 2 microns.[13] Indeed, ninety percent of the lead by weight is associated with particles of sizes less than 0.5 micrometers.[14] Other important submicron aerosols include, stationary source combustion products, photochemical aerosols, oil mists and metallic fumes.

The limitation on particle size can be extended to much smaller diameters if the impactor is operated at a reduced pressure. Basic investigations by Stern and Zeller[15] demonstrated the feasibility of such an approach. Subsequently, McFarland and Zeller[16] conducted in-depth studies to determine the operational characteristics of a low pressure impactor and, recently, Bucholz[17] conducted tests with an impactor operating at reduced pressure for separating particles of 0.1 micrometers and smaller.

Purpose of Study

Although the feasibility of particle collection by low pressure impaction has been demonstrated, the concept has not been extensively used in air sampling. The reason is principally due to the lack of specially designed apparatus.

The purpose of the present study was to design, construct and test a prototype cascade impactor which can be used to determine the mass-size distribution of atmospheric aerosols as small as 0.05 micrometers for a density of 2 $gm/cm^3$. The basic design of the resulting device, which is shown schematically in Figure 2 and photographically in Figure 3, incorporates the configuration of a conventional Andersen non-viable impactor* in four stages of a high pressure section

*Andersen-2000 Inc. Atlanta, Georgia

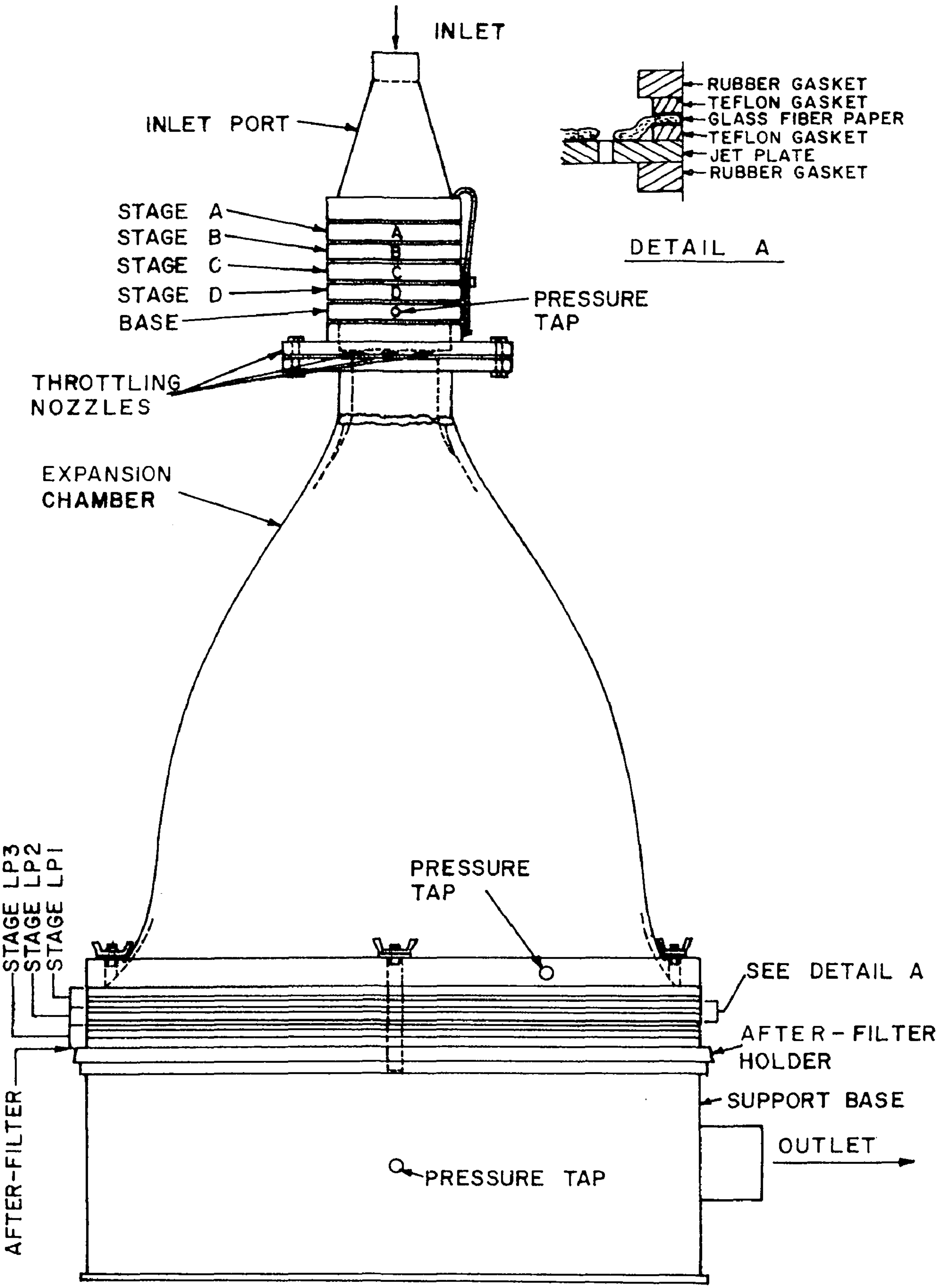


FIGURE 2 - LOW PRESSURE IMPACTOR UNIT

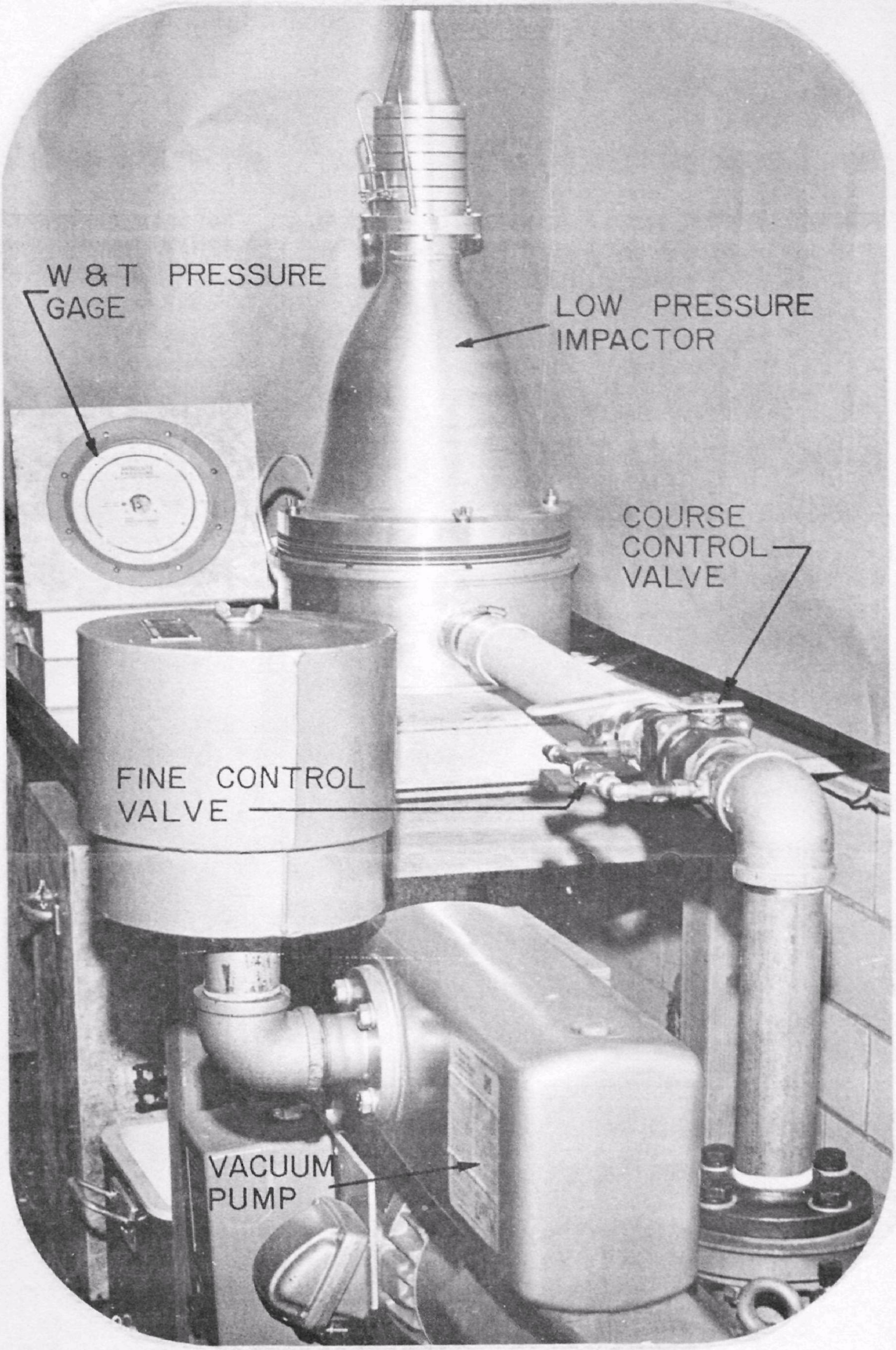


FIGURE 3 - LOW PRESSURE IMPACTOR SYSTEM

(to separate particles larger than 1.21 μm) followed by three stages in the low pressure section which effect separation of particles down to 0.05 micrometers. The first four stages operate at atmospheric pressure and the low pressure stages operate at approximately 1/30 atmosphere.

The unit has been laboratory tested to determine efficiency characteristics and to evaluate the performance limiting characteristics of (1) the loss of particles to internal surfaces other than the collection plate (wall losses), (2) the particle rebound or bounce characteristics for the stage which has the highest air velocity, and (3) the mass loading capability of the low pressure stage which should be most susceptible to re-entrainment of a deposited sample.

# INERTIAL IMPACTOR PERFORMANCE

The size selection characteristics of an inertial impactor stage are reflected by the efficiency with which the stage collects variously sized particles. In turn, the efficiency, which is commonly called the impaction efficiency, $\eta$, is a function of three dimensionless parameters:

$$\eta = f(K, L/D_j, Re_j)$$

where:

$K$ = Inertial Parameter

$L/D_j$ = Aspect Ratio

$Re_j$ = Jet Reynolds Number

Of these dimensionless groups, $K$ has the most significant influence upon $\eta$ - - the other two may be considered to be second order variables.

Ranz and Wong[11] carried out studies with impactors which had single circular or slit jets on each stage and related the collections efficiency to the inertial parameter. Later an experimental investigation by McFarland and Zeller[16] showed the relationship between $K$ and $\eta$ for a stage with multiple circular jets. A typical curve relating these two variables is shown in Figure 4.

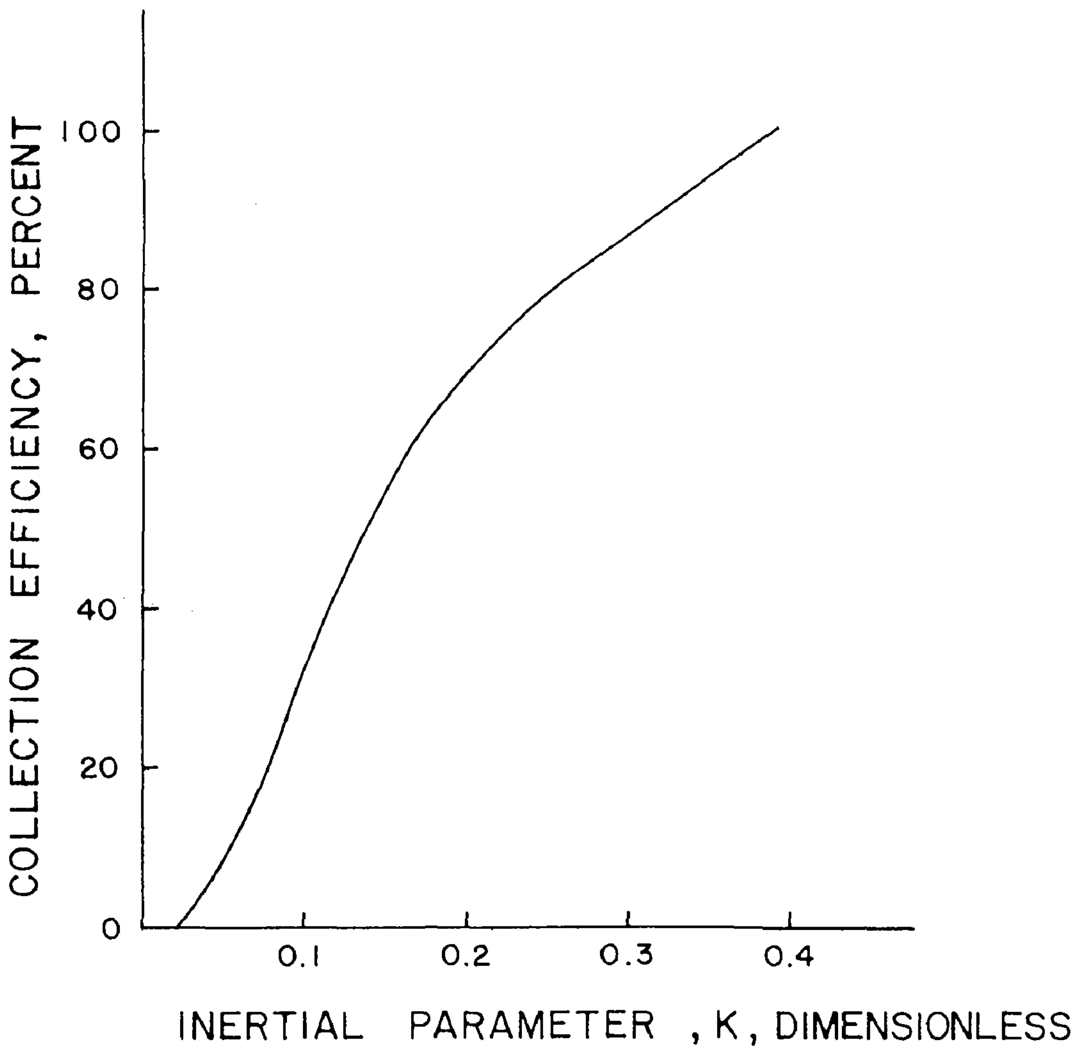


FIGURE 4 – COLLECTION CHARACTERISTICS OF MULTI-JET INERTIAL IMPACTOR FOR $Re_j \geq 100$

In this work, the inertial parameter is defined as:

$$K = \frac{C\rho_p V_o D_p^2}{18\mu D_j}$$

where:

$C$ = Cunningham's slip correction factor

$\rho_p$ = particle density

$V_o$ = jet exit velocity

$D_p$ = particle diameter

$\mu$ = air viscosity

$D_j$ = jet exit diameter

It is customary to attempt to represent the $\eta$ vs. K curve by a single value, namely that of the inertial parameter which corresponds to 50 percent efficiency, $K_{.5}$. For a given stage operating with fixed values of all variables involved in K other than particle size, the $\eta$ vs. K curve can also be represented by the diameter of a spherical particle which would be removed with 50 percent efficiency. This parameter is called the stage cutpoint and is denoted by $D_{p.5}$.

In the design of an inertial impactor stage it would appear possible to achieve small values of the stage cutpoint through either increasing the jet velocity or reducing the jet size. However, this approach does have its limitations. When velocities much greater than 3000-4000 cm/sec are used, small particles may tend to either rebound or become re-entrained from the collection surface. In addition, it is presently not practical to use jet diameters smaller than approximately 0.01 inch. As a consequence, the smallest cutpoint which can be reliably achieved through varying the jet velocity and diameter is approximately 0.5 micrometers.

Closer observation of the impaction parameter reveals that if the value of Cunningham's correction, C, can be increased, it may be possible to achieve a cutpoint diameter without resorting to high jet velocities or extremely small jet diameters.

Cunningham's correction, C, takes into account the non-continuum nature of gas flow about the particle. The factor C increases directly with the increase in the mean free path length of the molecules while increasing inversely with particle size.

Milliken[18] has shown C to accurately be represented by:

$$C = 1 + \frac{2\lambda}{D_p}\left(A + Q e^{-bD_p/\lambda}\right)$$

$\lambda$ = mean free path of gas molecules

= 0.0685 micrometers at standard atmospheric temperature and pressure

A = 1.23

Q = 0.41

b = 0.44

For small values of $\frac{\lambda}{D_p}$, $C \approx 1$, where as for large values of $\frac{\lambda}{D_p}$, $C \approx \frac{2\lambda}{D_p}(A+Q)$. For a perfect gas, the mean free path $\lambda$ can be represented by:

$$\lambda = 1.70 \times 10^{-5} T/P$$

$T$ = temperature, $^{\circ}K$

$P$ = pressure, mm Hg

It may be noted that $\lambda$ is inversely proportional to pressure. Reference to the definition of the inertial parameter indicates that a reduction in pressure will increase C thereby giving a larger values for K and thus allowing for collection of smaller aerosols with a given stage.

The effect of pressure upon C may be noted by the example that the value is 1.6 for a 0.3 micron particle at atmospheric pressure whereas it is 23.1 for the same particle at 1/30 atmosphere.

While the influence of the aspect ratio, $L/D_j$, and the jet Reynolds numbers, $Re_j$, are of second order importance, they do somewhat affect the collection efficiency of an impactor. The air jet effluxing from the nozzle remains relatively intact, independent of aspect ratio, as it approaches the collection plate. There is, however, a small change in streamline curvatures as the aspect ratio is varied and, as a consequence, a variation in collection efficiency. For values of $L/D_j$ between 0.55 and 5, Marple[19] shows that the shift in $K_{.5}$ is less than 3 percent.

Both the velocity profile at the jet exit plane and the boundary layer on the collection plate are affected by the jet Reynolds number. As $Re_j$ is decreased the value of $K_{.5}$ increases. McFarland and Zeller,[16] in their study with multiple-jet stages, made a linear interpolation of experimental data to show this effect. A plot of their results, adjusted to show $K_{.5} = 0.14$ for large values of the Reynolds number, is presented in Figure 5. In the design of an inertial impactor, it is possible to take into account the shift in $K_{.5}$ caused by the Reynolds number effect, thus a well defined $D_{p.5}$ exists for a given impactor stage operated under fixed conditions.

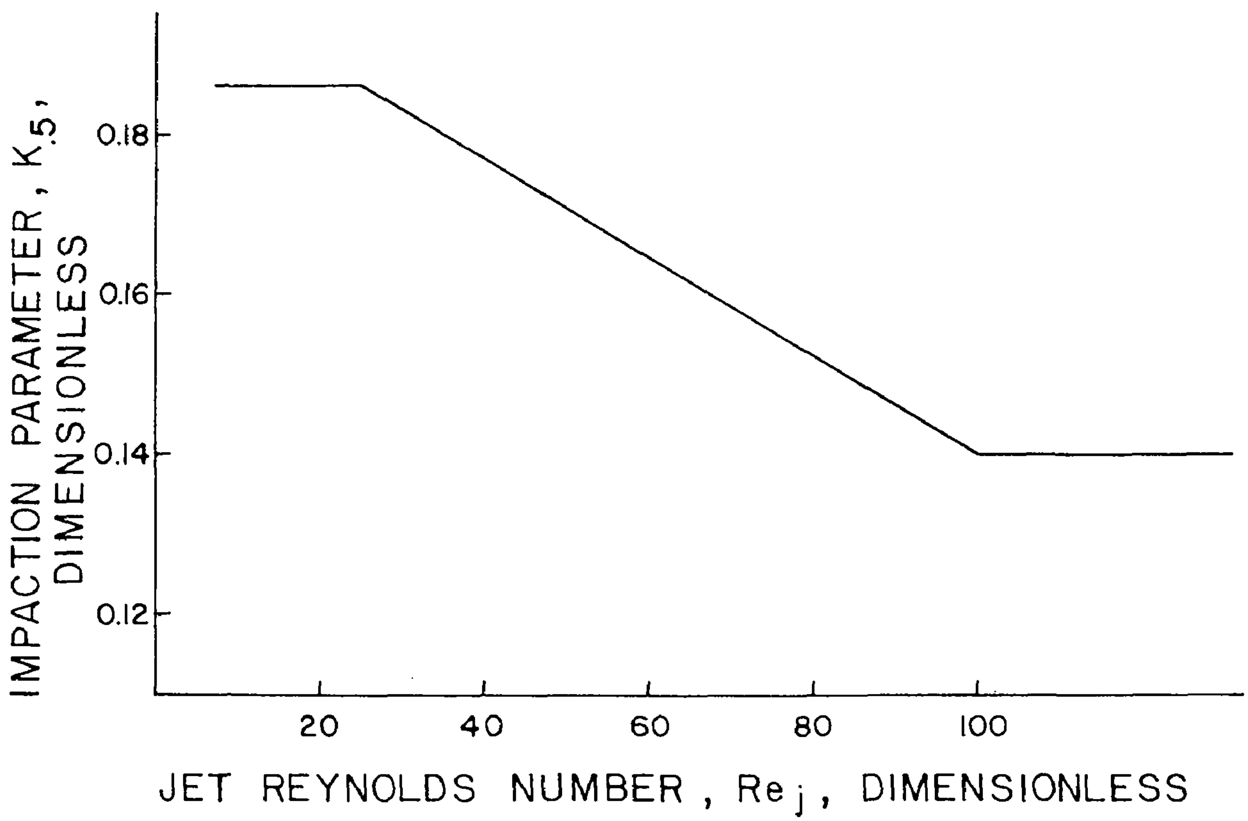


FIGURE 5 – EFFECT OF JET REYNOLDS NUMBER UPON $K_{0.5}$

# LOW PRESSURE IMPACTOR DESIGN

The fundamental criteria employed in the development of the Low Pressure Impactor were that the system should sample at a flow rate of 1.0 cfm, that the cutpoints of the first and last stages should be approximately 10 and 0.05 micrometers, respectively, and that the collected samples should be compatible with gravimetric analysis.

The approach selected was to use a system which is divided into two sections-- a set of four impactor stages which operates at atmospheric pressure and a set of three impactor stages together with an after-filter which operates at reduced pressure (See Figure 2) The two sections are separated by a throttling plate which serves not only to create a pressure drop but also limit the flow through the system to an equivalent of 1 cfm at inlet conditions. To minimize aerosol losses from jets effluxing from the throttling nozzles, an expansion chamber with an axial length of over 1 ft. has been employed.

Basically, the upper four stages of the system are similar to the Andersen non-viable sampler, however the unit has been modified to the extent that the jets of the first two stages are few in number (only 36 per stage) and have tapered inlets. Also, the collection plates of these two stages are designed to permit air to flow both around the edges and through one-inch holes in the collection plate centers. Collection in the upper stages is effected upon 81 mm diameter substrates composed of glass fiber filter media.

The principal elements in low pressure stages of the unit are three jet plates, a collection plate, an after-filter support and gaskets. The stages are arranged such that air is passed through the jet plate of the first stage and directed towards the second stage jet plate. The holes in the two plates are offset to permit the second stage jet plate to serve as the collection plate for the first stage. Particles are deposited on a special glass fiber filter media collection substrate. Proper values of the aspect ratio are obtained through the use of a neoprene gasket to separate the jet plates. To preclude the glass fiber media from adhering to either the gasket or the jet plate, thin teflon gaskets are placed on either side of the media.

The air from the first stage impaction process is directed through the jets of the second stage (which are situated under opening in the first stage collection substrate) and the process is repeated. For the third stage, impaction takes place upon a surface designed to serve only the purpose of holding a collection substrate. After passing the third stage, the air flows through a glass fiber filter and is discharged from the system.

The system is setup such that the only variable that need be controlled during sampling is the pressure level in the expansion chamber. This value is measured with the aid of a percision Wallace and Tiernangage and is to be maintained at 24.3 mm of mercury.

Stage cutpoints for the system were calculated using the data shown in Figures 4 and 5. The resulting design specifications for the system are presented in Table 1. The four atmospheric pressure-stages are denoted by A, B, C and D whereas the low pressure stages are listed as LP-1, LP-2 and LP-3. Selection of cutpoints was set to provide a ratio of approximately two between successive stages in the high pressure section and a ratio of approximately three between successive low pressure stages.

TABLE 1. Low Pressure Impactor Design and Operational Parameters - 1 cfm Inlet Flow Rate
- 24.3 mm Hg Pressure in Expansion Chamber

| Stage | Number of Jets | Diameter (inches) | Aspect Ratio $L/D_j$ | Jet Velocity cm/sec | Jet Reynolds Number $Re_j$ | Stage Cutpoints ($D_{p.5}$ μm) |
|---|---|---|---|---|---|---|
| A (Modified) | 36 | 0.161 | 0.55 | 100 | 254 | 9.7 |
| B (Modified) | 36 | 0.104 | 0.9 | 240 | 393 | 5.0 |
| C | 400 | 0.0295 | 3 | 269 | 127 | 2.46 |
| D | 400 | 0.0187 | 5 | 668 | 200 | 1.21 |
| LP-1 | 600 | 0.0547 | 2.2 | 1606 | 45.9 | 0.355 |
| LP-2 | 600 | 0.0398 | 3.0 | 2886 | 61.4 | 0.141 |
| LP-3 | 1762 | 0.0208 | 2.9 | 4158 | 40.5 | 0.050 |

# EXPERIMENTAL PROGRAM

A set of laboratory tests was conducted with the prototype Low Pressure Impactor to verify the design stage cutpoints and to quantify the performance limiting factors of: losses to internal surfaces of the impactor other than the collection surface (wall losses), particle bounce and re-entrainment, and the mass loading characteristics. Basically, these tests involved subjecting the sampler to an aerosol which has known (or easily measurable) properties and which is readily identifiable. The aerosols were generated with two types of apparatus: a spinning disc atomizer and a nebulizer,[19] with the first device serving the purpose of forming large (> 1 micrometer diameter) particles and the latter device being used to generate the smaller aerosols. For both systems, the aerosol generators formed a spray from a solution of 70 percent uranine dye and 30 percent methylene blue dye dissolved on a solution of 67 percent ethyl alcohol and 33 percent water. Evaporation of the spray droplets produced the actual test aerosol. Particle size was varied by changing the concentration of the dye solutions.

The basic layout of apparatus employed in the testing is shown schematically in Figure 6. Aerosol from either the spinning disc or air blast atomizer was passed through an 8-inch diameter duct. One sample stream of the aerosol was drawn at a flow rate of 1 cfm

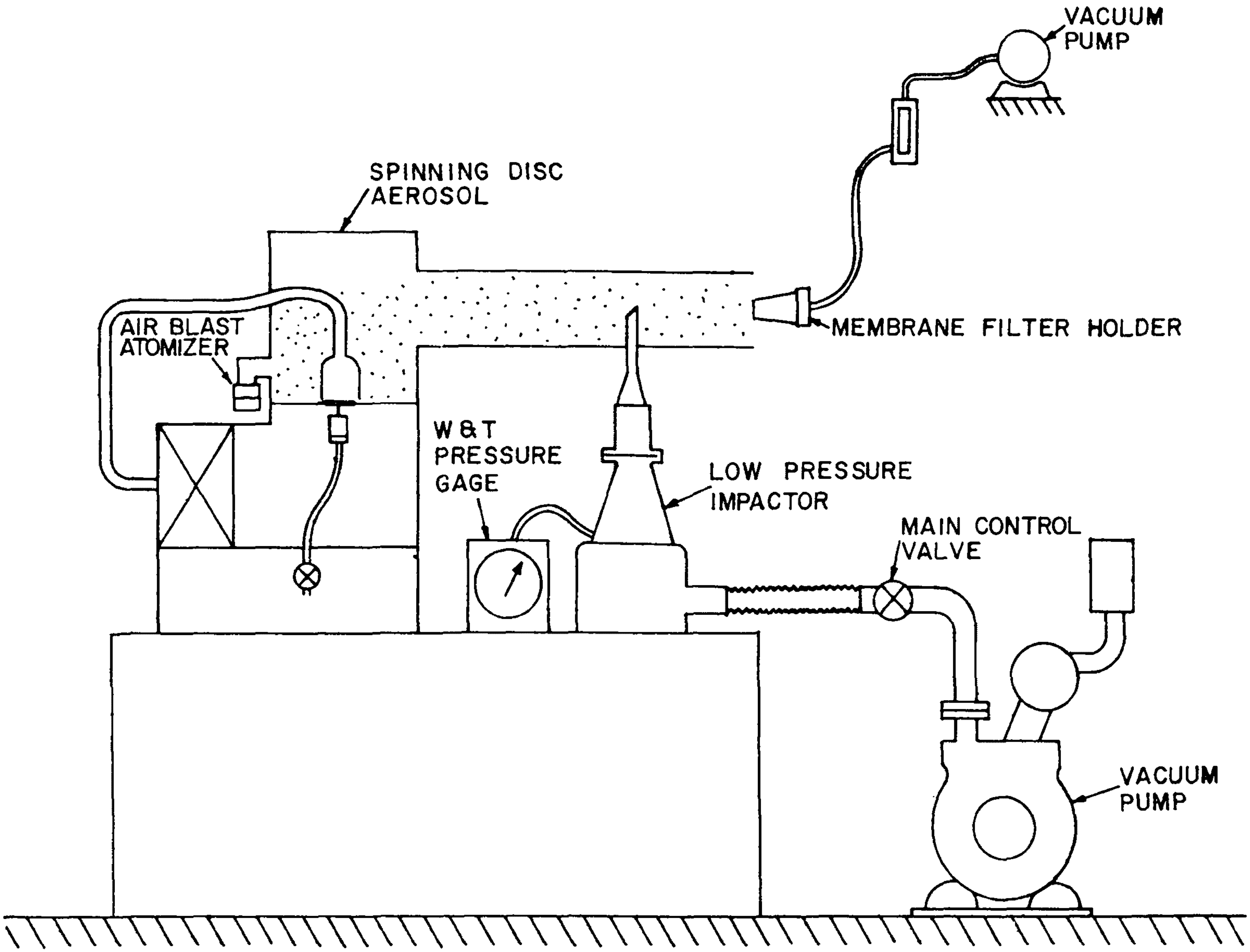


FIGURE 6 – APPARATUS EMPLOYED IN AEROSOL TESTS

into the Low Pressure Impactor and a second sample stream, also at a flow rate of 1 cfm, was drawn through a 47 mm glass fiber filter mounted in a membrane filter holder. The purpose of the latter sample was to monitor the constancy of aerosol output.

For each test performed with the spinning disc generator, a sample of aerosol was collected on a membrane filter and a microscopic size distribution was made. Figure 7 shows the results obtained from such a determination. The characteristic aerosol size was represented by a mass-average size which was obtained by converting the microscopic data to a mass basis and calculating the average value.

The nebulizer used to generate the submicron aerosols was a Model 099 Dispos-A-Neb manufactured by Bio-Logics, Incorporated. For determination of the particle sizes created with this device, samples were collected on electron microscope grids using a Thermosystems, Incorporated electrostatic sampler. These were subsequently sized from photomicrographs taken with the aid of a Hitachi HU-11 transmission electron microscope. Figure 7 shows results obtained from sizing a typical submicron aerosol.

Stage Cutpoint Sizes

To obtain the desired cutpoint of 0.05 micrometers for the final stage, LP-3, of the Low Pressure Impactor, it is necessary that the pressure level at the jet discharge plane be 22.1 mm Hg.

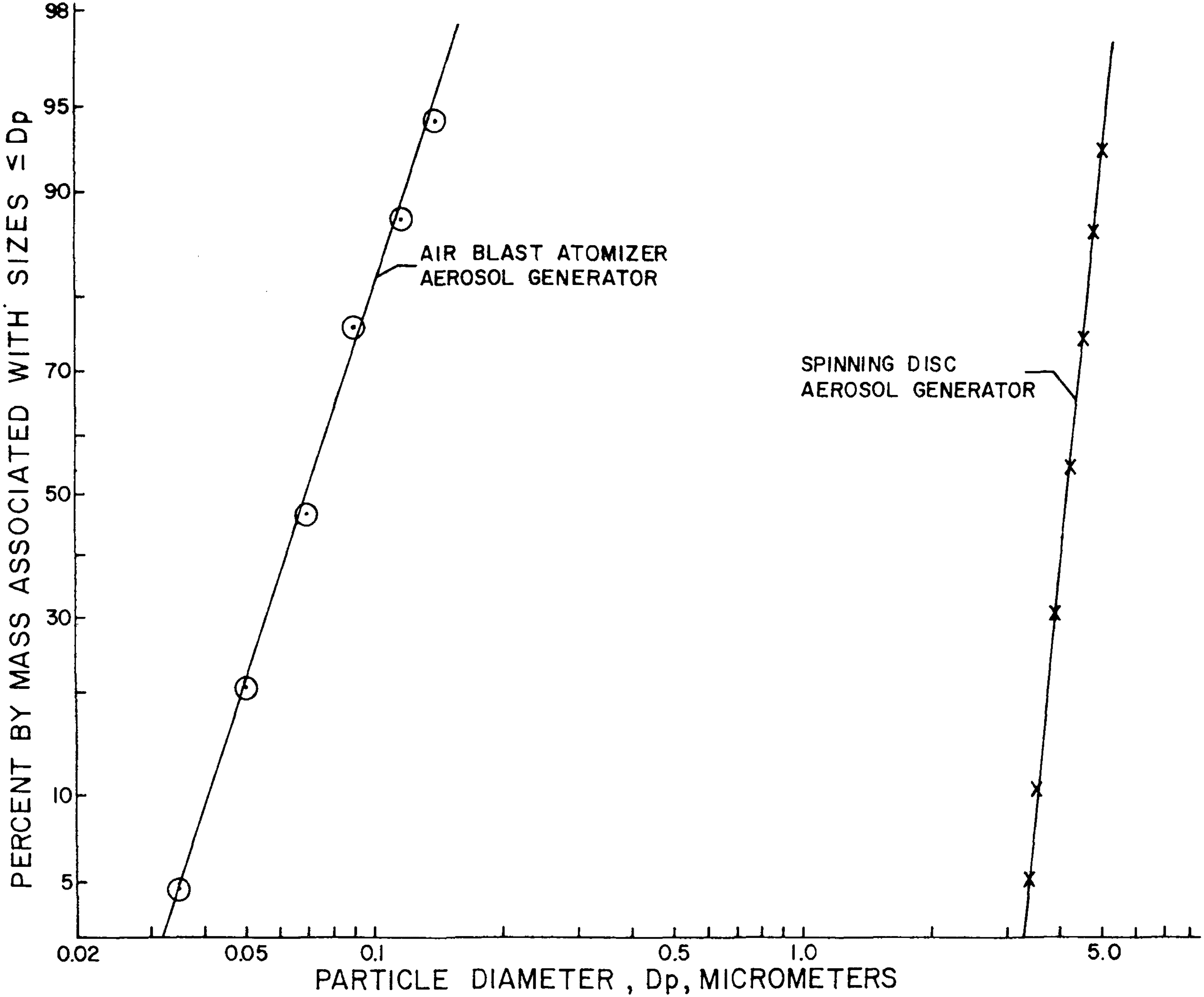


FIGURE 7 - SIZE DISTRIBUTIONS-TYPICAL TEST AEROSOLS

Since the pressure level for the system is sensed at the expansion chamber and there are pressure losses as the air flows through each impaction stage, it was necessary to determine pressure variations in the low pressure system. The results of such a check show:

| LOCATION | PRESSURE |
|---|---|
| Jet Exit Plane of Stage LP-3 | 22.1 mm Hg |
| Jet Exit Plane of Stage LP-2 | 23.6 |
| Jet Exit Plane of Stage LP-1 | 24.2 |
| Expansion Chamber | 24.3 |

Design cutpoints for stages LP-1, LP-2 and LP-3, which are shown in Table 1, are based upon these pressure levels. The predicted cutpoints are also shown graphically in Figure 8 wherein the cutpoints are presented not only for a particle density of 2 $gm/cm^3$ but also for 1 and 4 $gm/cm^3$. Operation of the impactor with the predicted cutpoints is obtained when the expansion chamber pressure is set at 24.3 mm Hg. Use of lower pressure levels will shift the cutpoints of the low pressure stages to smaller values.

In order to verify the design cutpoint particle sizes of the low pressure stages, detailed tests were conducted with stage LP-3. Since this stage has the smallest jets, largest value of $L/D_j$, and smallest value of $Re_j$ of the low pressure stages, it is anticipated

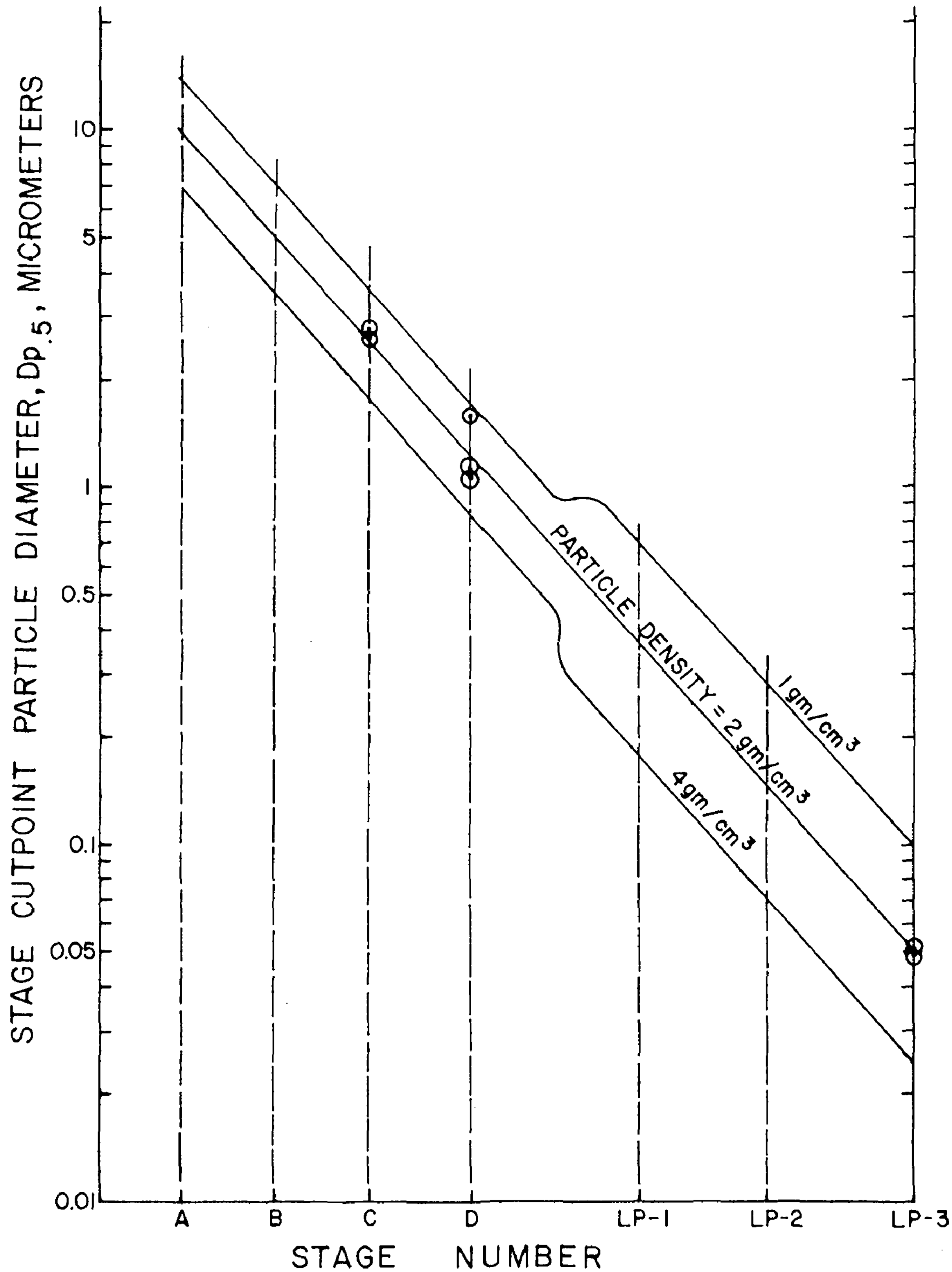


FIGURE 8 – SIZE CALIBRATION OF LOW PRESSURE IMPACTOR

that any deviations from design predictions would be most easily observed by testing this stage.

The tests were conducted using the apparatus arrangement shown in Figure 6 with the aerosol generated by the nebulizer. The high pressure stages of the impactor were left in place during these tests in order to strip the largest particles from the distribution. The low pressure stages were re-arranged such that LP-3 was placed above LP-1 and LP-2. During operation, aerosol was drawn through the impactor system for a time sufficient to collect an easily measurable quantity of uranine dye. The amount of uranine collected by stage LP-3 and the remaining components of the low pressure section of the impactor was determined by washing the parts in distilled deionized water to extract the uranine dye and subsequently analyzing the wash water with a Turner Model 110 Fluorometer. From the resulting data, the test efficiency $\eta_T$, of stage LP-3 was determined. Next, a value of the inertial parameters, $K_T$, which corresponds to the test efficiency was taken from Figure 4 and the following equation employed:

$$\frac{K_{.5}}{K_T} = \frac{(C\rho_p D_p^{\,2})_{.5}}{(C\rho_p D_p^{\,2})_T}$$

This expression was solved for $D_{p.5}$ based upon knowledge of the size and density of the test particles and upon an assumed value of two for the density of the cutpoint size particles.

This method was chosen because the cutpoint size can be determined from a minimal number of tests. Reliance is placed upon the impaction efficiency curve only to the extent that the slope is utilized.

The results for triplicate tests with stage LP-3 are shown in Figure 8 superimposed upon the curve which gives the predicted cutpoint size for the system. It should be noted the experimental data verifies the calculated cutpoint of 0.05 micrometers for the last stage.

Similar tests were performed on stages C and D of the high pressure section using particles produced by the spinning disc aerosol generator. In this case the impaction stage to be tested was placed first in the impactor and its efficiency determined. Following the prodecure given above the values of $D_{p.5}$ were computed. These results, which are also shown in Figure 8, support the predicted cutpoint sizes.

## Wall Losses

Wall losses in cascade impactors can be attributed to the following factors; high jet and other internal velocities, close spacing of internal components and abrupt changes in air direction at locations other than collection surfaces. Use of an impactor with any of these design deficiencies may result in a high ratio of internal wall losses to sample collected. The relatively large geometric scale of the low pressure impactor together with the multi-jet principle renders it a device which has inherently low wall losses.

At the present time, the only method to reliably quantify wall losses is through the use of controlled laboratory experiments. The approach used to acquire these data for the low pressure impactor involved the following procedure.

Prior to the onset of each test run, the entire impactor was washed with a laboratory grade detergent and rinsed with distilled, deionized water. The unit was then subjected to a heterogenous uranine-methylene blue aerosol created by the nebulizer (geometric standard deviation of approximately three). At the completion of each test run, the individual collecting surfaces and the internal wall surfaces were again washed with a measured volume of distilled, deionized water to extract the dye. The wash water was then subjected to fluoroscopic analysis to quantify the uranine mass which has been deposited on the impactor surfaces.

The results obtained for aerosols with mean sizes of 0.3 and 0.6 micrometer are shown in Table 2. It may be noted that totally the losses were less than 6 percent in each case.

TABLE 2. Wall Losses for Individual Impactor Components

| Impactor Components | Percent Wall Losses for given Aerosol Size | |
|---|---|---|
| | 0.3 micrometers | 0.6 micrometers |
| Inlet | 0.053 | 0.031 |
| Jet Plate A (Modified) | 0.160 | 0.170 |
| Jet Plate B (Modified) | 0.193 | 0.230 |
| Jet Plate C | 0.226 | 0.190 |
| Jet Plate D | 0.206 | 0.230 |
| Interface | 0.034 | 0.015 |
| Throttling Plate | 0.866 | 0.860 |
| Expansion Chamber | 1.545 | 1.530 |
| Jet Plate LPI-1 | 0.499 | 1.990 |
| Jet Plate LPI-2 | 0.293 | 0.460 |
| Jet Plate LPI-3 | 0.149 | 0.090 |
| All other extraneous surfaces | 1.307 | .058 |
| Total Wall Losses | 5.43 | 5.85 |

Early in the experimental testing phase of the program it was noted that stage A and B had inordinately high wall losses (Table 3). To reduce this phenomenon a design change was undertaken. For both stages A and B the number of jets was reduced from 400 to 36 and, correspondingly the diameter of the jets was increased (to 0.161 inches for stage A and 0.104 inches for stage B). In addition the intake sides of jets were chamfered $60^{\circ}$. A one inch diameter circle was cut in the center of the collection plates of both stages A and B to reduce the volumetric flow rate (and hence the velocity) of gas passing around the periphery of the collection plate. These modifications provided a drastic reduction in wall losses when tested with a monodisperse 6.1 micrometers diameter uranine aerosol (Table 4).

Wall loss data for the remaining upper stages, C and D, were also acquired. Here it may be noted that the losses for each stage are approximately 2 percent when the stage is tested with particles of size similar to the stage cutpoint size.

Particle Bounce

Particle bounce can greatly reduce the efficiency of an inertial impactor. If the collection surface is a smooth plate, as the jet velocities are increased beyond 3200 cm/sec[16] in the lower stages of the impactor an increase in particle bounce and re-entrainment can be expected. The problem may be partially

TABLE 3. Wall Loss Characteristics of Original Stages "A" and "B"

| Jet Stages | Sampler Flow Rate (cfm) | Test Aerosol Size (μm) | Wall Losses Percent |
|---|---|---|---|
| A and B | 1.3 | 6.1 | 32.4 |
| A and B | 1.0 | 6.3 | 40.0 |

TABLE 4. Wall Loss Characteristics of Upper LPI Stages ("A" & "B" Modified) - Flow Rate = 1 cfm

| Jet Stages | Test Aerosol Size (μm) | Wall Losses Percent |
|---|---|---|
| A and B (Modified) | 6.10 | 10.7 |
| C | 3.44 | 2.2 |
| D | 1.02 | 2.2 |

controlled by employing thin viscous coatings on the collection surfaces, since the coating will both create a condition of inelastic impact and at the same time provide an adhesive force to retain the particles on the collection surface. An alternate approach, which serves to increase adhesion, is to employ glass fiber filters as the collection substrates. This method offers a considerable advantage over the use of viscous coatings in that less substrate preparation is required and the substrates render themselves better to standard analysis procedures.

To determine if the glass fiber filters used in the low pressure section of the system were effectively preventing rebound of impacted particles, a set of tests was conducted with stage LP-3. This particular stage was chosen for detailed study because it has the highest jet velocity, 4160 cm/sec. In conducting these tests, the stage was operated in a manner in which the velocity could be varied yet the predicted efficiency could be held constant.

If particle bounce were a problem, the expected result of a plot of efficiency vs. velocity would show a decrease in efficiency with increasing velocity as the particle bounce phenomenon comes into play. The results of the tests, which are presented in Figure 9, show the efficiency of the stage increases slightly with increasing jet velocity (due to a jet Reynolds number effect not adequately compensated for in the test conditions). The efficiency curve in the

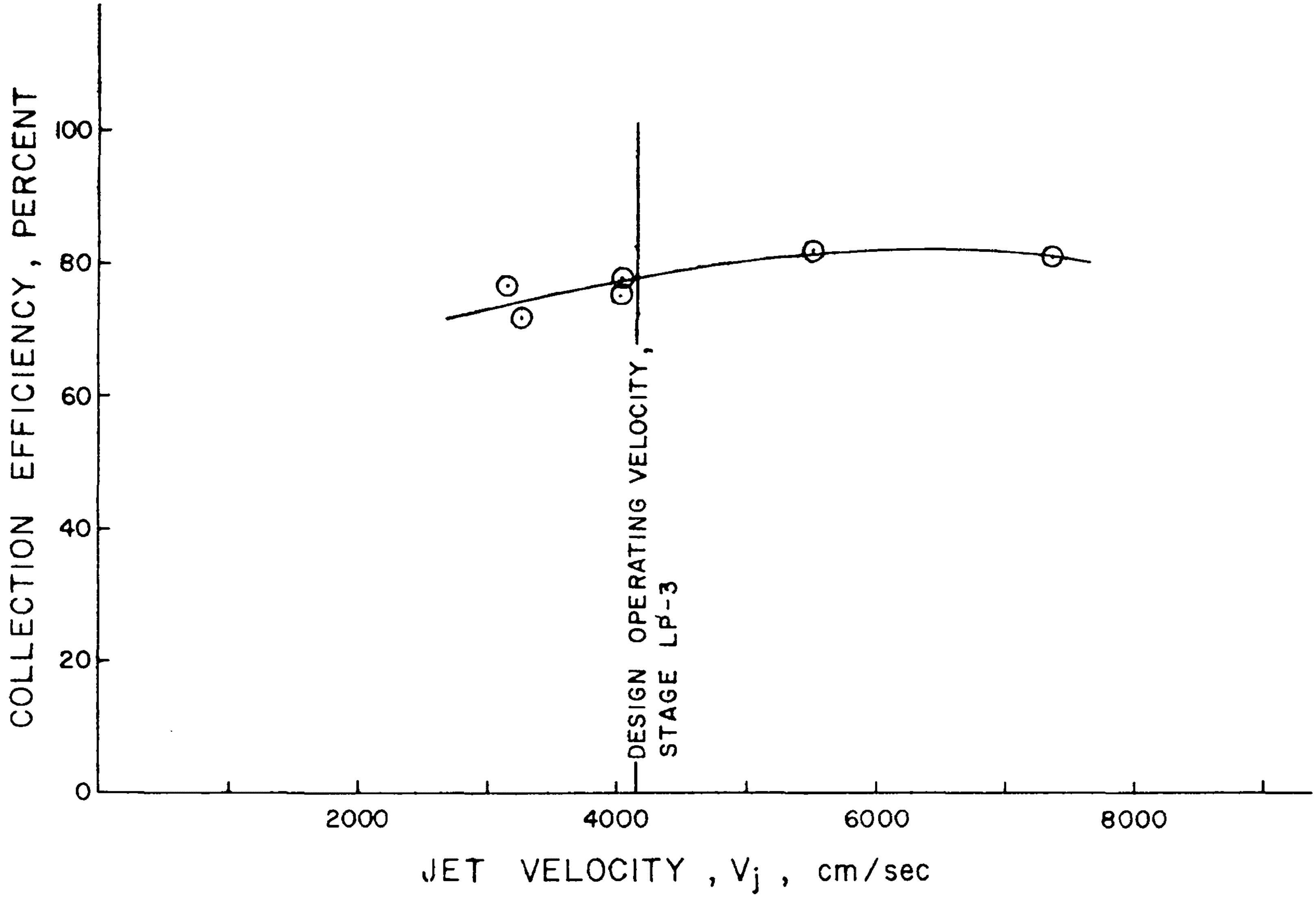


FIGURE 9 - PARTICLE BOUNCE CHARACTERISTICS OF STAGE LP-3
(0.05 μm CUTPOINT)

vicinity of the design velocity did not drop which gives evidence that particle bounce is not a significant problem with the low pressure section of the impactor.

With respect to the high pressure stages, McGregor[20] conducted bounce tests with a standard Andersen non-viable sampler and found that a stage with a cutpoint of 1.1 micrometers (for unity density particles) could be operated at a velocity five times as large as the velocity encountered in stage D of the present system without a rebound phenomenon being noticeable. Based upon this result it would be expected that the upper stages of the present design would not be subject to a limitation caused by particle bounce.

Loading Characteristics

When substantial quantities of aerosol are deposited on the collection plate of a given stage, it is possible that portions of the collected material could be re-entrained by the air stream and be subsequently re-deposited on lower stages. Under such circumstances, misleading size distribution data would be obtained.

The tendency of an impactor stage to be susceptible to re-entrainment problems can be tested experimentally by subjecting the stage to a known aerosol and studying the relationship between the mass of material sampled and the collection efficiency. Should re-entrainment occur, the efficiency would show an apparent drop as the mass loading is increased. Tests of this type have been conducted with a standard Andersen non-viable sampler by McGregor.[20] His results, when applied to the upper stages of the low pressure impactor system, indicate that the permissible mass loadings of Stage A would be approximately 2 mg, that of Stage C would be about 13 mg and that of Stage D should be approximately 8 mg. Loadings above these values do not show abrupt re-entrainment effects, but rather a gradual decrease in efficiency of the stage. In addition for the stages with smaller cutpoints, the loadings limitation is more pronounced as the jet diameter is decreased and the velocity increased. Since Stage LP-3 has both the highest velocity and the smallest jet sizes of the low pressure stages, it was selected for an investigation of the loading characteristics. It was assumed that if the loading limitations of stage LP-3 were acceptable, so would be those of stages LP-1 and LP-2.

The tests were conducted by exposing stage LP-3 for varying times to a dye aerosol generated by the nebulizer. After each run, the efficiency of the stage as well as the total quantity of uranine aerosol collected by the impactor was determined for each test. The results, shown in Figure 10 demonstrate that the efficiency of stage LP-3 is constant up to a sample load of over 10 mg, indicating that overloading is not a problem.

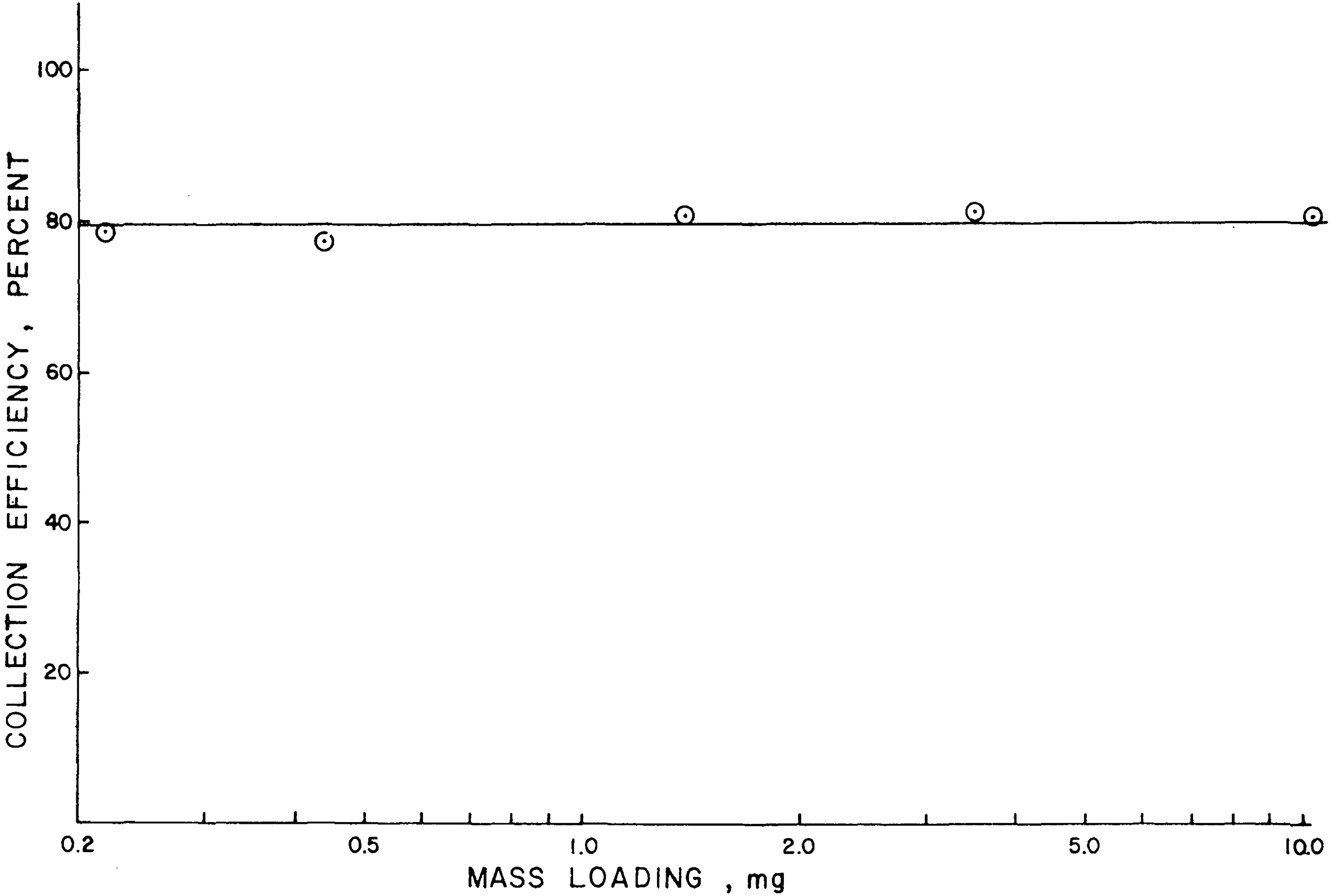


FIGURE 10 - LOADING CURVE FOR STAGE LP-3 (0.05 μm CUTPOINT) OF LOW PRESSURE IMPACTOR

# FIELD TESTS

The Low Pressure Impactor system was setup to simultaneously sample aerosol in parallel with a standard Andersen non-viable unit. For the first experiments the two devices were exposed to a well-mixed and diluted cigarette smoke. The mass collected on the various stages of both impactors was determined through measurement of the weight change of the glass fiber collection substrates using a semi-micro analytical balance. All collection substrates were conditioned for several hours to the laboratory environment before the weight measurements were made. The resulting data, which has been converted to cumulative distributions, is shown in Figure 11. In this case the particle size parameter represents that of equivalent spheres of unit density. It may be noted that there is good agreement between the data obtained from use of the two devices for sizes larger than approximately 0.6 micrometers. Below this size the Low Pressure Impactor tends to show a greater relative abundance of small particles.

With respect to the mass of aerosol collected by each unit, the sum of all differential weights for the Low Pressure Impactor was 78.9 mg whereas that of the standard non-viable sampler was 79.5 mg.

Both units were exposed to atmospheric aerosol for times sufficient to collect several tens of milligrams in each unit. The

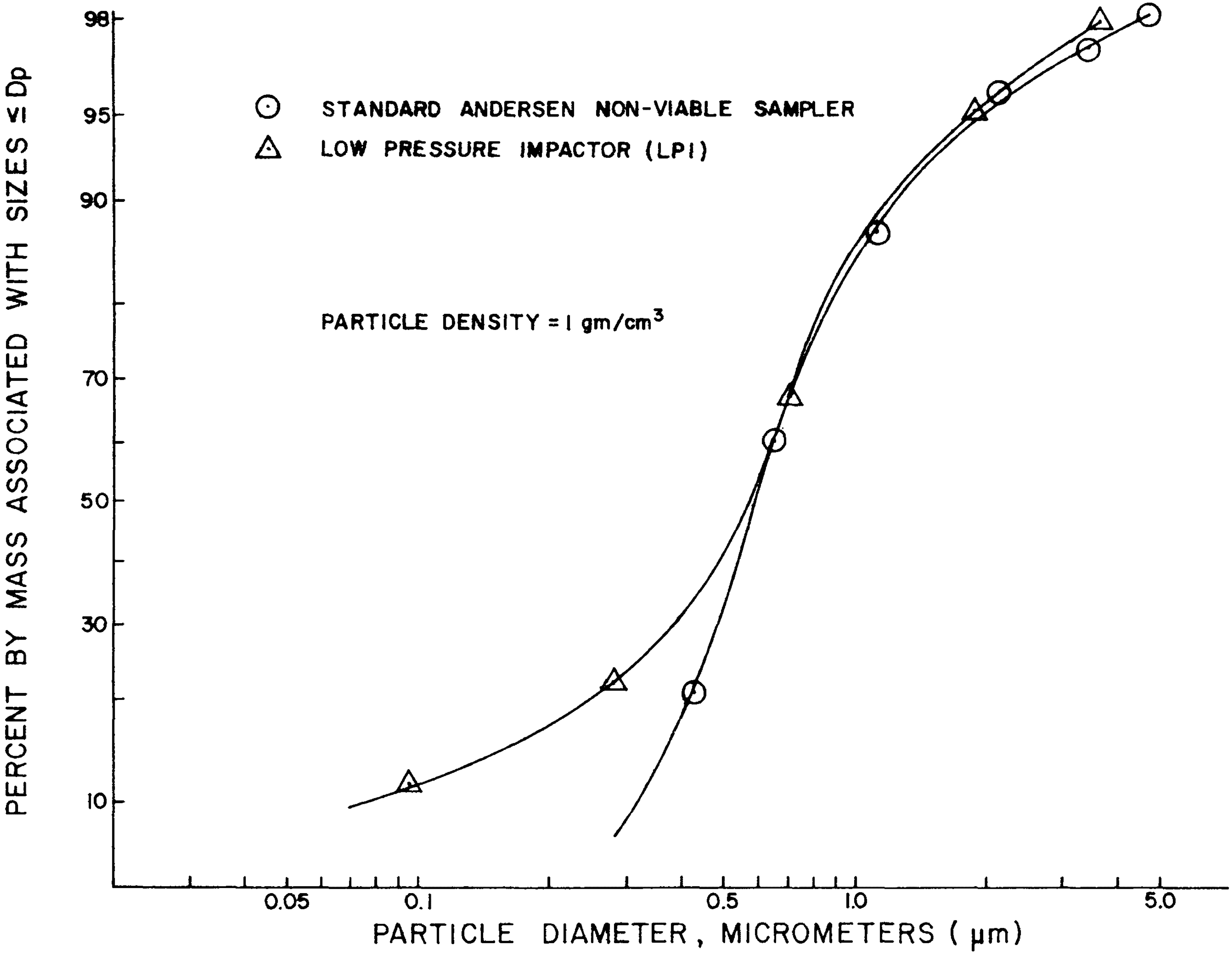


FIGURE II - SIZE DISTRIBUTION OF CIGARETTE SMOKE purpose of collecting these substantial quantities of mass was to minimize any errors associated with the process of measuring differential weights of the substrates. Results for two separate atmospheric aerosol runs are represented in Figures 12 and 13. In both runs the Low Pressure Impactor yielded data which indicates greater percentages of particles of size less than 0.6 micrometers. Additionally, the data presented in Figure 12 shows that the Low Pressure Impactor collected substantially greater fractions of the very large particles. Nineteen percent of the aerosol mass was associated with sizes larger than 16 micrometers. With reference to Figure 13, it would appear that the Low Pressure Impactor collected less material of large sizes than did the standard non-viable unit. However, the cumulative distribution curve is misleading for this test since it presents percentages rather than actual mass values. The raw data showed nearly identical quantities of large particles were collected by the two devices (for example the total mass of all particles larger than 7 micrometers in size collected by the Low Pressure Impactor was 3.79 mg whereas that of the standard non-viable unit was 4.13 mg). But, the Low Pressure Impactor System collected more total mass (41.99 mg versus 31.04 mg) therefore the cumulative distribution of the Low Pressure Impactor is shifted to the left.

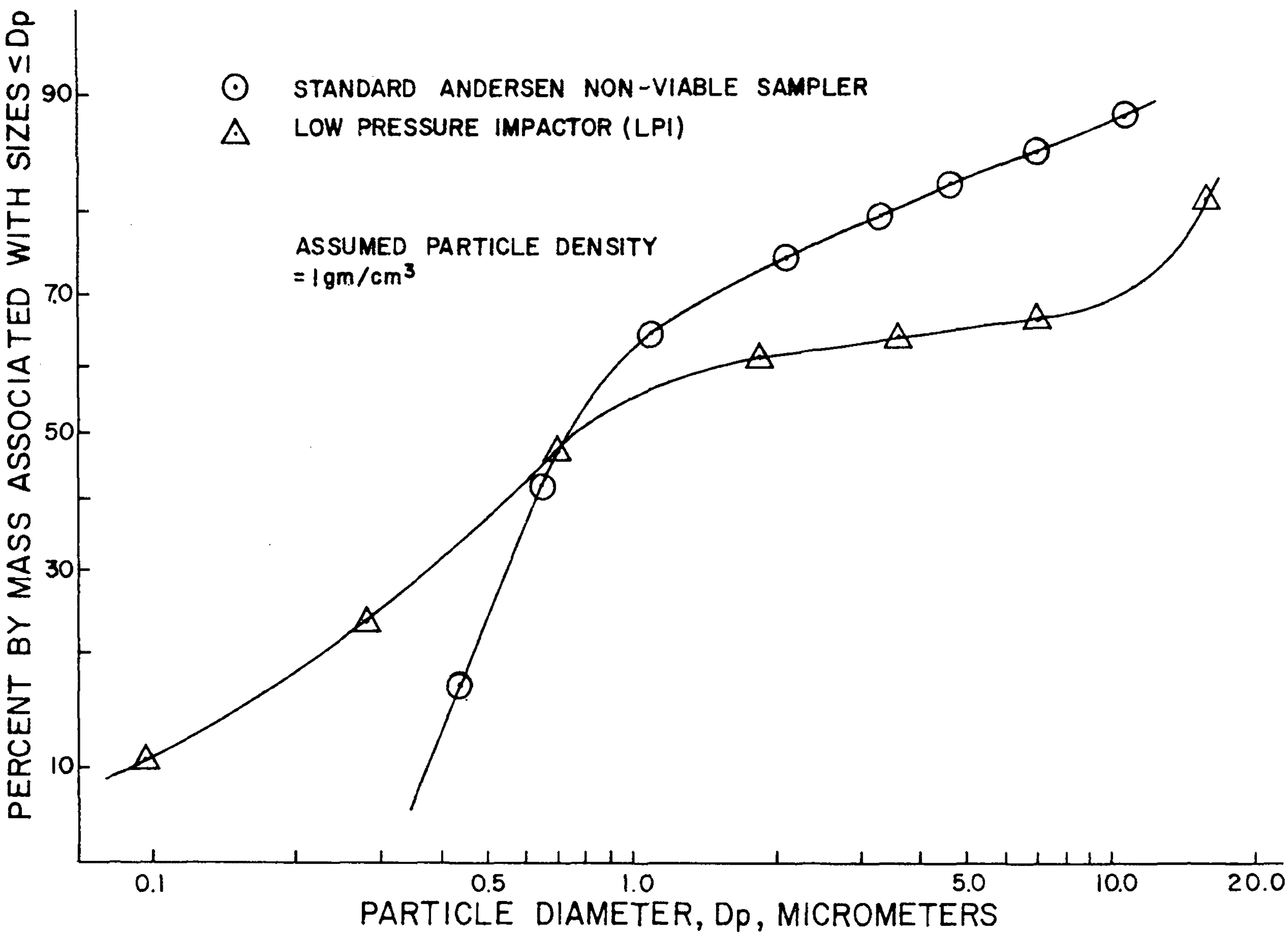


FIGURE 12 – SIZE DISTRIBUTION OF ATMOSPHERIC AEROSOL JUNE 30 – JULY 20, 1973 AT URBANA, ILLINOIS

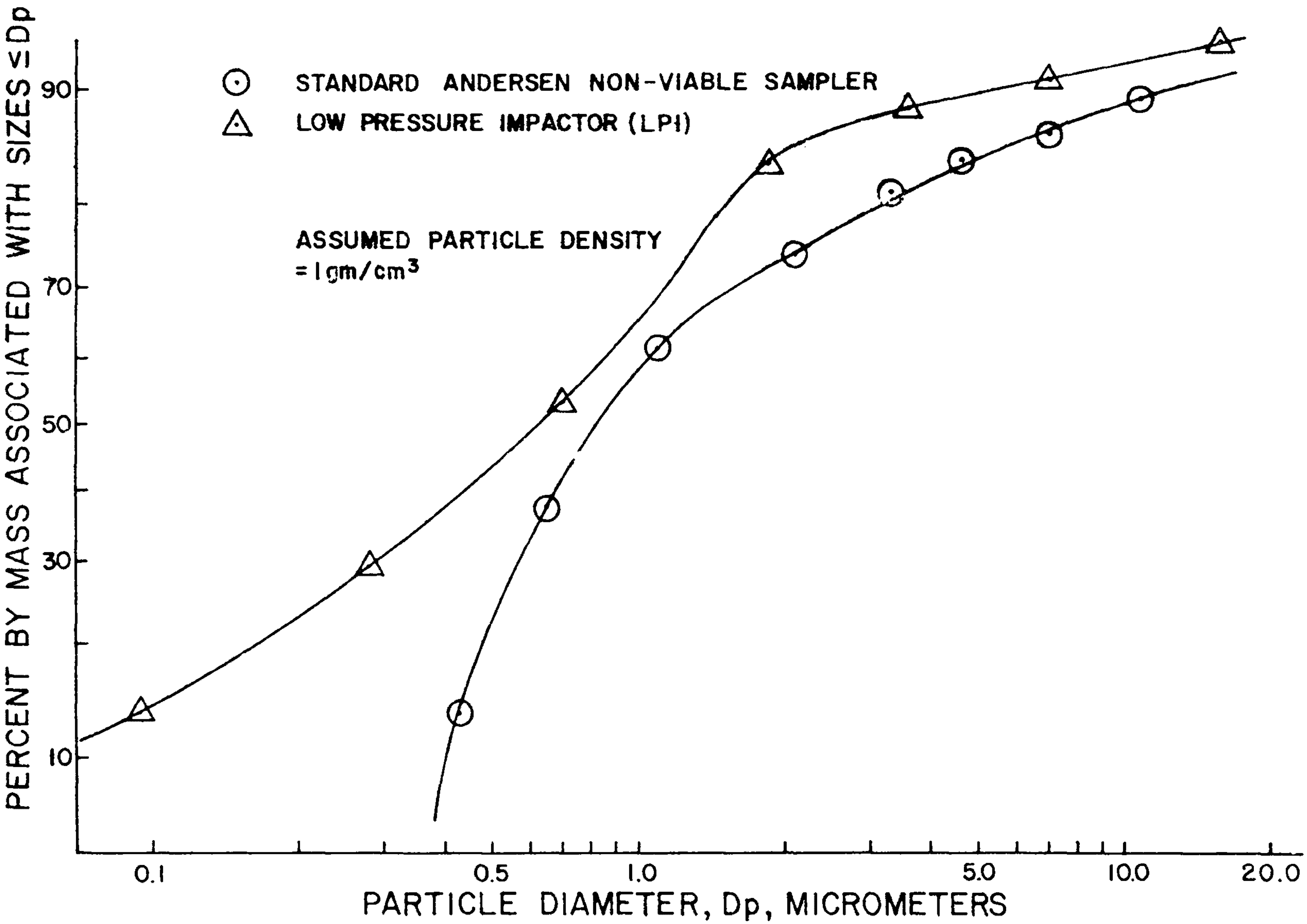


FIGURE 13 – SIZE DISTRIBUTION OF ATMOSPHERIC AEROSOL JULY 21 – AUGUST 15, 1973 AT URBANA, ILLINOIS

In addition to determinations of the aerosol size distribution, comparative values of average aerosol concentrations were calculated. These results, presented in the following table, show that

| Test | Average Concentrations Std. Non-Viable Unit | Low Pressure Impactor |
|---|---|---|
| June 30 - July 20 | 39.0 $\mu g/m^3$ | 86.2 $\mu g/m^3$ |
| July 21 - Aug. 15 | 30.3 | 42.9 |

the Low Pressure Impactor yields higher values of mass concentration. This is due, at least in part, to the better collection characteristics of the Low Pressure Impactor for large particles.

# SUMMARY AND CONCLUSIONS

Although the cascade impactor has been a useful tool in the measurement of aerosol mass-size distribution, most systems in current use are limited to a usable lower particle size limit of approximately 0.4 micrometers. However, operation of specially designed impactors at reduced pressures can extend this lower limit. In the present study a Low Pressure Impactor system has been designed, fabricated and tested which has a particle cutpoint size for the last stage of 0.05 micrometers for particles of density = 2 gm/cm$^3$.

The impactor has four stages which operate at atmospheric pressure and separate particles into fractions with size ranges of $>$ 9.7, 5.0-9.7, 2.46-5.0 and 1.21-2.46 micrometers. These are followed by three stages and an after-filter which separate the aersol into size intervals of 0.36-1.21, 0.14-0.36, 0.05-0.36 and $<$ 0.05 micrometers.

Laboratory testing was performed to verify the predicted cutpoints and to evaluate the performance-limiting characteristics of a) wall losses b) particle rebound from collection surface and c) collected deposit re-entrainment (mass loading limitation). The results of these experiments confirmed the predicted cutpoints of the stages which were tested. Data points for the tests are shown in Figure 8 superimposed upon a curve which represents the calculated cutpoint values.

Wall losses for the entire system were shown to be less than 6 percent when tested with aerosols of 0.3 and 0.6 micrometers median diameter which had geometric standard deviations of 3. Initial tests with the upper stages indicated that substantial wall losses resulted when the stages were used to sample large particles. A re-design of the first two stages reduced these losses by 2/3; the total loss for these stages, when tested with 6.1 micrometer diameter aerosol, is now 10.7 percent.

Tests with the last stage of the low pressure section, a stage which has a normal jet velocity of 4160 cm/sec, indicate that particle rebound from the collection surface is not a significant problem. In these tests, the jet velocity was increased to over 7000 cm/sec while the other impaction parameters were adjusted in such a manner that the predicted collection efficiency with the test aerosol would remain nearly constant. Even at this high value of velocity, there was no reduction in the efficiency of the stage which demonstrates that a substantial fraction of the particulate matter did not bounce off of the collection media during the impaction process.

The last impaction stage of the low pressure section has design parameters (high velocity and small jet sizes) which make it the most vulnerable of the low pressure stages to re-entrainment of collected deposits. This phenomenon is observed to occur in impactors when substantial deposits are collected on a given stage. Portions of the deposits are subsequently eroded away during further sampling. Tests with the last low pressure stage showed no tendency for re-entrainment for deposits as large as 10 mg.

The Low Pressure Impactor system was operated in parallel with a standard Andersen non-viable cascade impactor and used to sample cigarette smoke and atmospheric aerosol. For cigarette smoke, which has few large particles, the agreement between data obtained from the two devices was excellent for particles larger than 0.6 micrometers. The Low Pressure Impactor showed a greater mass fraction for the smaller sizes. Tests with atmospheric aerosol showed the Low Pressure Impactor to yield larger fractions of small ($<$ 0.6 micrometer) particles and higher overall values of aerosol concentration. In one case the Low Pressure Impactor collected a substantially greater quantity of larger ($>$ 7 micrometers) particles.

## REFERENCES


1. Landsberg, H., "Physical Climatology." 2nd edition, Gray, DuBois, Pennsylvania, pp. 317-326 (1958).

2. Robinson, E., "Effects of Air Pollution on Visibility." Air Pollution, Chapter 11, Vol. 1, 2nd edition, A.C. Stern (ed.), Academic Press, New York, 349-400 (1968).

3. Holzworth, G.C., "Some Effects of Air Pollution on Visibility in and near Cities." Air Over Cities Symposium, U.S. Dept. of Health, Education and Welfare, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio, Technical Report A62-5, 69-88 (1961).

4. Hudson, J.D., "Present Position of the Corrosion Committee's Field Tests on Atmospheric Corrosion (Unpainted Specimens)." J. Iron Steel Institute, Vol. 148, 161-215 (1943).

5. Czaja, A.T., "Uber das Problem der Zementstaubwirkungen auf Pflanzen." Staub, Vol 22, 228-232, (1962).

6. Bohne, H., "Schadlichkeit von Staub aus Zimentwerken fur Waldbestande." Allgem. Forstz, Vol. 18, 107-111 (1963).

7. "Air Quality Criteria For Particulate Matter." U.S. Department of Health, Education and Welfare, Public Health Service, Environmental Health Service, National Air Pollution Control Administration Publication No. AP-49, 129-144 (1969).

8. "Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract." Task Group on Lung Dynamics Health Physics, Vol. 12, 173-207 (1966).

9. Findeisen, W., "Uber das Absetzen Kleiner in der Luft suspendierten Leilchen in der menschlichen Lunge bei der Atmung." Arc. Ges. Physiol., Vol. 236, 367-379 (1935).

10. May, K.R., "The Cascade Impactor: An Instrument for Sampling Coarse Aerosols," Journal of Scienctific Instruments, Vol. 22, 187-195 (1945).

11. Ranz, W.E. and Wong, J.B., "Impaction of Dust and Smoke Particles on Surface and Body Collectors," Industrial and Engineering Chemistry, Vol. 44, 1371-1381 (1952).

12. Andersen, A. A., "A Sampler for Respiratory Health Hazard Assessment," American Industrial Hygiene Association Journal, Vol. 27, 11. 160-165, 1966.

13. Mueller, P.K., Helwig, H.L., Alcocer, A.E., Gong, W.K., and Jones, E.E., "Concentration of Fine Particles and Lead in Car Exhaust." American Society for Testing and Materials, Special Technical Publication 352, pp. 60-73, 1964.

14. Lee, R.E., Jr., Patterson, R.K., Crider, W.L., and Wagman, J., "Concentration and Particle Size Distribution of Particulate Emissions in Auto Exhaust,", Atm. Env. 5, 225-237 (1971).

15. Stern, S.C., Zeller, H.W., Shekman, A.I., "Collection Efficiency of Jet Impactors at Reduced Pressures," Industrial and Engineering Chemistry Fundamentals, Vol. 1, No. 4 pp. 273-277, 1962.

16. McFarland, A.R., Zeller, H.W., "Study of a large volume impactor for high altitude aerosol collection." Report of the Division of Technical Information Extension of the USAEC, TID-18624, 1963.

17. Buchholz, H., "An Underpressure Impactor." Staub-Reinhalt, Luft, Vol. 30, No. 4, 1970.

18. Millikan, R.A., "The general law of fall of a small spherical body through a gas and its bearing upon the nature of molecular reflection from surfaces." Phys. Rev. 22, 1-23 (1923).

19. Marple, V.A., "A Fundamental Study of Inertial Impactors." Ph.D. Thesis, Univ. of Minn. (1970).

20. McGregor, F.R., "Development of a Modified Andersen Impactor," M.S. Thesis, Univ. of Notre Dame, (1971).

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16. ABSTRACT


A Low Pressure Impactor aerosol sampler was designed fabricated and tested. The system injects a fixed aerosol flow rate of 1 cfm at inlet conditions and causes the particulate matter to be separated and collected on four atmospheric pressure and three reduced pressure impaction stages and an after-filter. Cutpoint sizes of the stages are 9.7, 5.0, 2.46, 1.21, 0.355, 0.141, and 0.05 micrometers for spherical particles with a density of 2 gm/cm$^3$. Each of the impaction stages is fitted with a glass fiber media collection substrate to facilitate gravimetric analysis of the collected samples.

Experiments conducted with laboratory aerosols show the system to have wall losses less than 6 percent when the mass median diameter of the aerosol is 0.6 micrometers. For particles 6.1 microns in size, the wall losses on the upper stages are less than 11 percent. Both particle rebound and re-entrainment from the collection surfaces are shown to be negligible. Each low pressure stage can be loaded with more than 10 mg of deposited aerosol without re-entrainment occurring.


17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Aerosol Sampler<br>Low Pressure Impactor<br>Re-Entrainment<br>Particle Sizing<br>Sub-Micron | | |

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