EPA-660/3-74-004a
March 1974

Ecological Research Series

Turbulent Diffusion In Liquid Jets: Part I

Office of Research and Development
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TURBULENT DIFFUSION IN LIQUID JETS: PART I

Measurement of Particle Concentration By a Light Scattering Probe

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OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

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ABSTRACT

A technique for measuring particle concentrations in turbulent flows was investigated. This technique is the measurement of the light scattered from an incident beam by the solid contaminants present.

The results show that for moderate concentrations the scattering system gives proportional increases in count to increases in particle concentration. The limitations of this system are the signal to noise ratio and the condition of singular scattering by the particles.

Suggestions on refinements on the correlation technique used are made and observed phenomena which require further investigation are discussed.

This report was submitted in (partial) fulfillment of Contract 16070 DEP under the (partial) sponsorship of the U.S. Environmental Protection Agency.

CONTENTS

FIGURES

TABLES

SECTION I

CONCLUSIONS

It was found in this investigation that light scattering can be used to measure concentration profiles in internal turbulent flows in regions not adjacent to the wall.

Other important conclusions reached in this investigation are presented below.

1. Changes in concentration levels resulted in proportional changes in counts per second at the sampler.

2. For low concentrations of solids with specific gravity close to one, the concentration profiles closely approximated that of the velocity. However, for higher concentrations the similarity becomes increasing less pronounced.

3. For a given alignment the scattering system seemed insensitive to changes of particle size and real index of refraction.

4. The use of a Coulter counter was not feasible as a check of concentration levels. A more practical system would be to use a fiber optic probe.

SECTION II

RECOMMENDATIONS

This study was limited to the investigation of the possible use of a light scattering probe as a particle concentration sampler.

1. The use of alternate sampling methods might be considered when applicable. For instance, when sampling droplets or bubbles the use of a modified hot wire or hot film anemometer may well be more convenient and reliable.

2. The actual sampling volume of the light scattering probe has to be selected to eliminate multiple particle scattering signals, as well as to permit a dependable calibration of the samples.

3. Techniques for signal to noise optimization should be studied in future tests if a device of the type described is to be employed.

4. Additional studies are necessary to determine the exact count per second and particle number density relationships. These studies should follow the direction taken by M.J. Fischer and F.R. Kause (1967) or that suggested by H.L. Morse et al. These authors used a two point correlation method by either using two beams or two detectors. This allows correlation to help eliminate unwanted noise.

SECTION III

INTRODUCTION

SCOPE OF PROJECT

The stated objectives of the work sponsored under Contract #16070DEP, were twofold. One to establish an effective method of tracking contaminants in a liquid jet, including the use of a laser system. Two to determine the diffusion due to turbulence of contaminants of different size and density. The second objective was fully met. An earlier report "Turbulent Diffusion in Liquid Jets" dealt directly with it. On the other hand the first objective was only partly met. It is now discussed in this report. The second objective was met through the research of Dr. Strong C. Chuang. His doctoral thesis was completed on August 1970. The research into the use of a laser as a sampling device was conducted by Mr. Charles H. Tinsley as part of his M. S. studies at Purdue University.

PROJECT BACKGROUND

Knowledge of the properties of two phase flow systems, such as solid-gas, solid-liquid and liquid-gas, is important in many aspects of engineering. In recent years applications in nuclear reactor development, chemical processes, dispersion of contaminants in waterways, and the dispersion of particulate matter into the atmosphere have called for knowledge of the concentration and concentration gradient of the dispersed phases.

Several techniques for the experimental evaluation of the distributions of dispersed phases have been proposed. One is the hot wire impact method developed by Goldschmidt and Eskinazi (1966). This has been used to measure aerosol particle concentrations (Householder (1968)) and Lee (1970) and to measure bubble concentrations (Chuang (1969)), all in free turbulent jets. This method consists of inserting a hot wire probe into the flow and measuring the signal resulting from the impact of bubbles or liquid droplets on the wire. Soo et al (1964) investigated several different methods for measuring concentration distribution and mass flow. The more successful of these was the light attenuation method. In this method light is projected perpendicular to the flow stream and the transmitted (unattenuated) light is measured on the other side. The amount of light received by the detector can be related to the size and the concentration of particles in the flowing medium. Phelps (1968) evaluated this dependence of light transmitted on the average concentration, particle diameter and particle properties. The experimental arrangement is shown in Figure 1. Soo et al (1964) used a modification of this method employing a fiber optic probe. This has the same dependency on particle size and properties and particulate concentration as shown by Phelps for the amount of light received. The primary difference between these two methods is that the test section for the experiments of Soo et al is defined by the geometry of the probe, and the test section for Phelps is defined by the cross-section of the flow. Consequently, Soo et al are able to obtain a gradient and Phelps is only able to obtain an average concentration. The disadvantage in the method of Soo et al is that a probe must be inserted into the flow field. An example of the type of probe used by Soo et al is shown in Figure 2. This probe was used by Peskin and Baw to obtain concentration profiles in pipe flow with solids and air as the two constituents.

The method used for the measurements reported herein was light scattering. In this method no physical probe is inserted into the flow. The concentration is measured in a finite volume which is determined by the geometry of the optics. This method has been used previously by Rosensweig, Hottel and Williams 1961, while studying the concentration gradient in free turbulent flows of a gas-solid mixture. In this study the phases are solid-liquid and the turbulent flow under consideration is an internal flow. The object of this study was to evaluate the feasibility of using a light scattering system to determine the concentration and concentration gradient of the solid particles in a turbulent internal flow.

A. Spectra-Physics model 124
Stabilite gas laser λ = 6328 A

L_1 Condensing lens

L_2 Collimating lens

B. Test cell

C. Interference filter

D. RCA IP-28 photomultiplier tube

E. PPI Laboratory photometer

F. Leeds & Northrup Speedomax
strip recorder

G. D.C. power supply

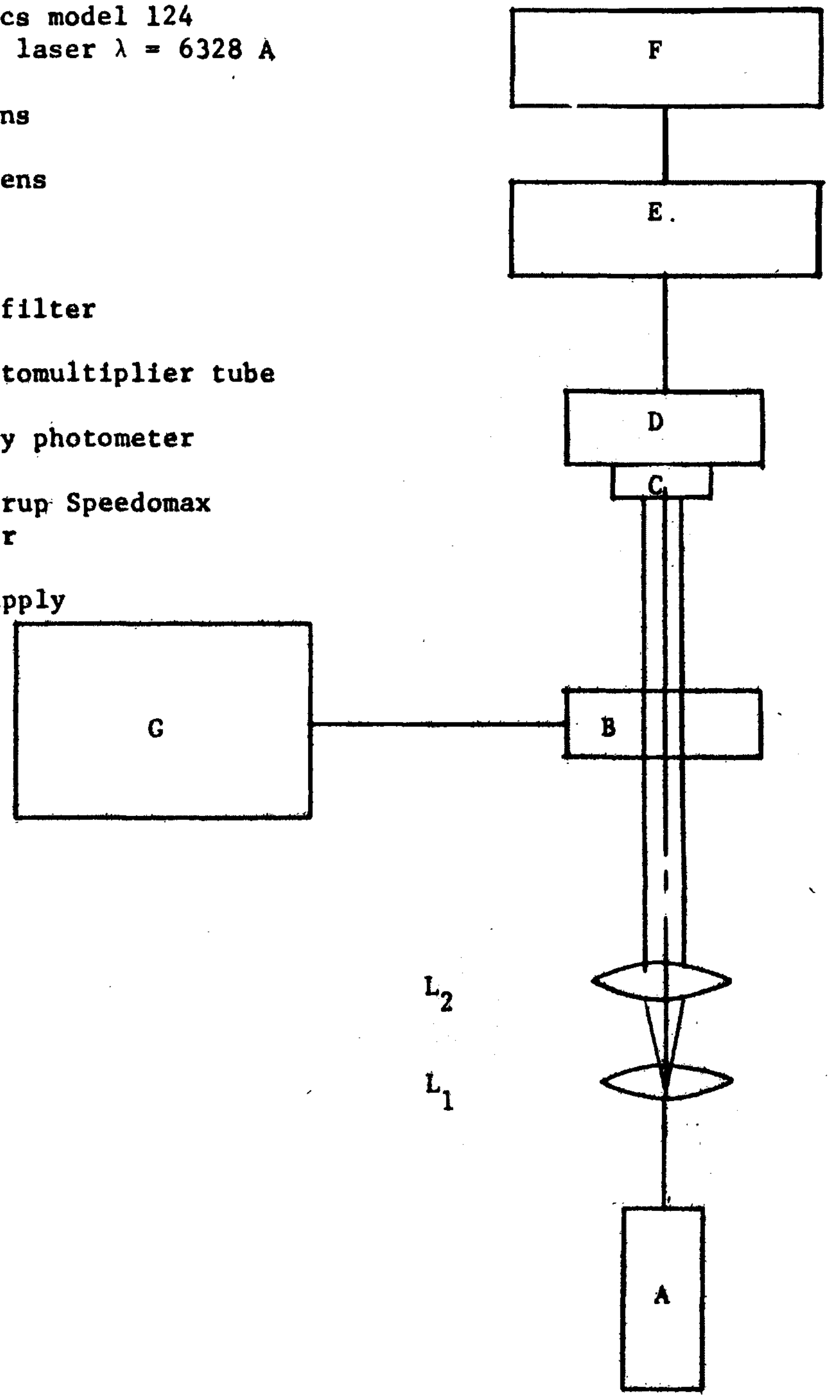


FIGURE 1 - OPTICAL SYSTEM USED FOR

LIGHT TRANSMISSION MEASUREMENTS (PHELPS (20))

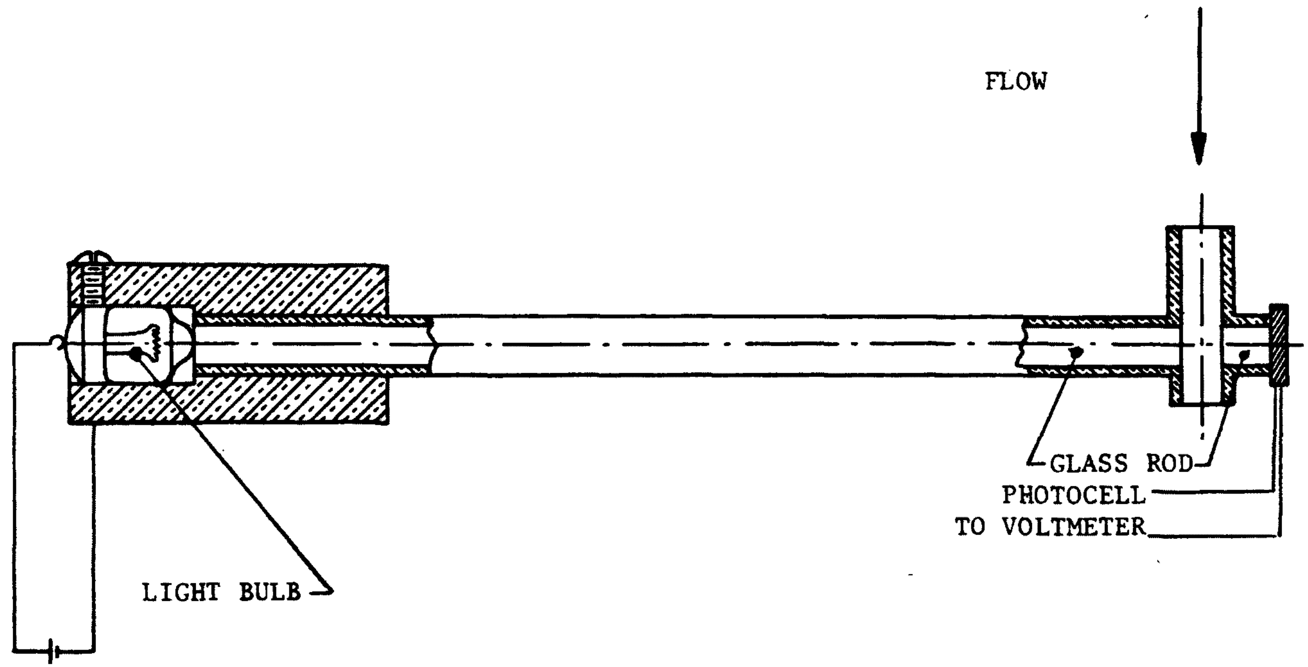


FIGURE 2 PROBE WITH MINIATURE PHOTOCELL

PESKIN AND BAW (18)

THEORETICAL BACKGROUND

Scattering Parameters and System Response

Light that traverses a medium may be transmitted, absorbed or scattered. There are certain parameters of the medium and of the incident light that determine to what degree transmission, absorption, and scattering occur. These phenomena are related such that the amount of light not transmitted (extinction) is equal to the sum of losses due to scattering and absorption.

In equation form:

$$\text{Extinction} = \text{Absorption} + \text{Scattering} \qquad (1)$$

A brief summary of these parameters and their effect on extinction, primarily taken from Green and Lane (1957), is given here.

The relative index of refraction of a particle suspended in a medium affects extinction. The relative index of refraction is given by:

$$n' = \frac{n_{\text{particle}}}{n_{\text{fluid}}} \qquad (2)$$

where n = real part of the complex index of refraction $(n - ik_o)$

$i = -1$

$k_o = \frac{\alpha \lambda}{4\pi}$

with α = absorption coefficient, and λ = wavelength of the incident beam

Scattering systems generally utilize particles which have a zero absorption coefficient, thereby maximizing the amount of the signal obtained by scattering alone. The effect of the index of refraction on the angular distribution of scattered light is shown in Figure 3 for the two types of particles studied.

Two other important parameters for scattering systems are the angle θ subtended between the beam and the detector, and the solid angle, α viewed by the detector. These angles help determine the length of the scattering volume. When the angle, θ, is zero the scattering system reduces to a transmission system and the scattering volume is maximum. For angle, θ,

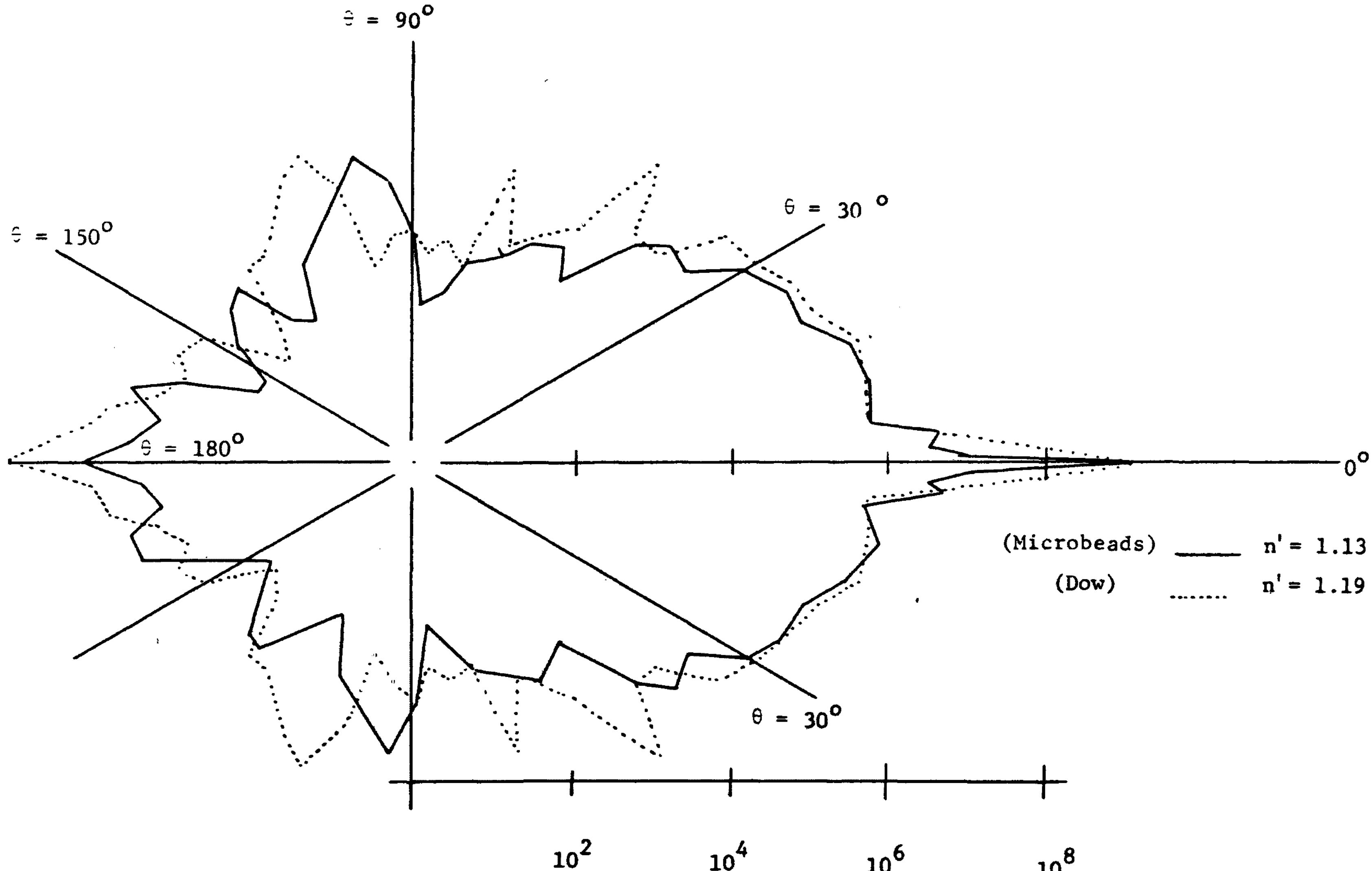


FIGURE 3 - ANGULAR DISTRIBUTION OF SCATTERED LIGHT FOR PARTICLES USED

equal to ninety degrees the scattering volume is minimum. These angles are shown in Figure 4.

Another important parameter in scattering studies is the ratio of the incident light. This parameter is the size parameter defined by:

$$q = 2\pi r/\lambda \tag{3}$$

where

r = radius of the particle

λ = the wavelength of the incident light

Theoretical angular distributions of scattered light were obtained for particles used in this study from an I.B.M. computer program called Dame. This program has the capability of calculating scattering distributions for a size parameter up to 5000. The distributions obtained are presented in Figure 5 as a function of size parameter.

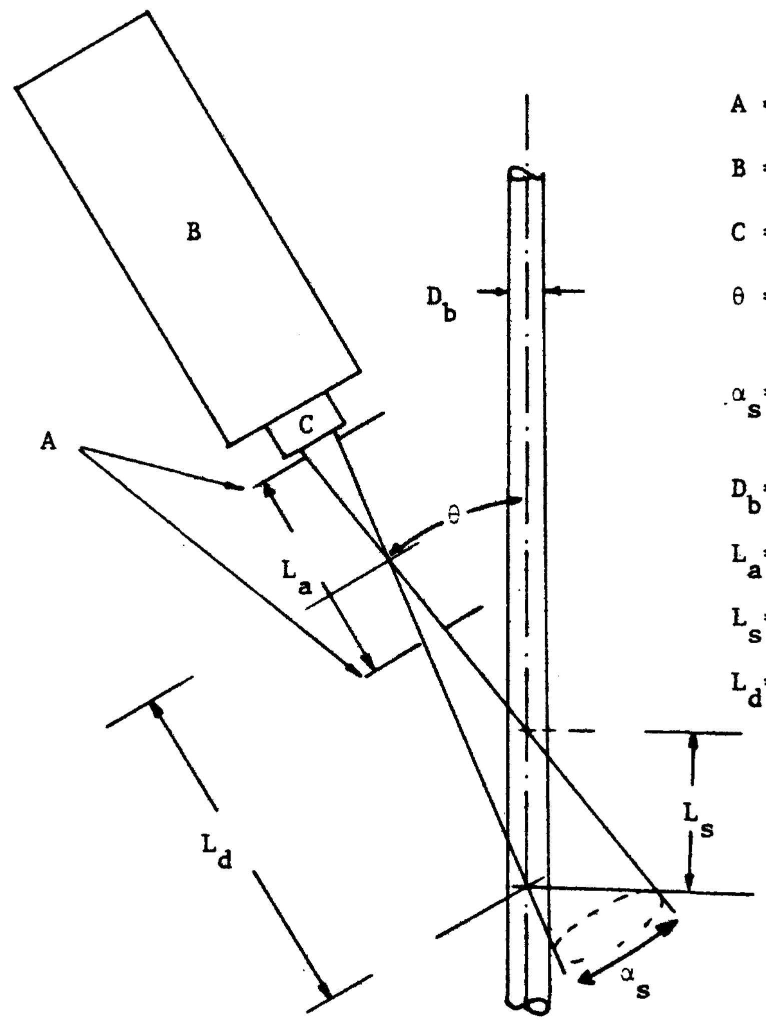
There have been several theories proposed to explain the relationship between the incident beam and losses associated with the scattering and absorption. For the size range of particles used the appropriate theory is that developed by Mie. A detailed explanation of this theory is given by Van de Hulst (1957). For the type of scattering experiments conducted in this study a detailed examination of Mie's theory is not needed. The underlying assumption of this study is that the light scattered is directly proportional to the number of scatterers in the control or scattering volume. This is true as long as single or independent scattering is the only type present. Sinclair (1950) has stated that this assumption is valid as long as the distance between particles is ten or preferably a hundred times the radius of the particle.

The single scattering assumption has been used by many investigators; Green and Lane (1957) give the following simplified scattering expression:

$$I = kr^{P}\bar{n} \tag{4}$$

where

I = the scattered light intensity
r = the radius of the scatterers
$\underline{P}$ = parameter determined experimentally
$\bar{n}$ = number of scatterers



A = Pinhole apertures (394 microns)

B = Photomultiplier Tube (detector)

C = Bandpass Filter for 6328 A°

θ = Angle between detector and beam (30°)

α_s = Solid angle formed by detector (0.4° planar angle)

D_b = Diameter of incident beam (2mm)

L_a = Distance between apertures (2inches)

L_s = Length of scattering volume

L_d = Distance of the scattering volume from origin of α_s (5 inches)

FIGURE 4 - OPTICAL GEOMETRY DEFINING THE SCATTERING VOLUME

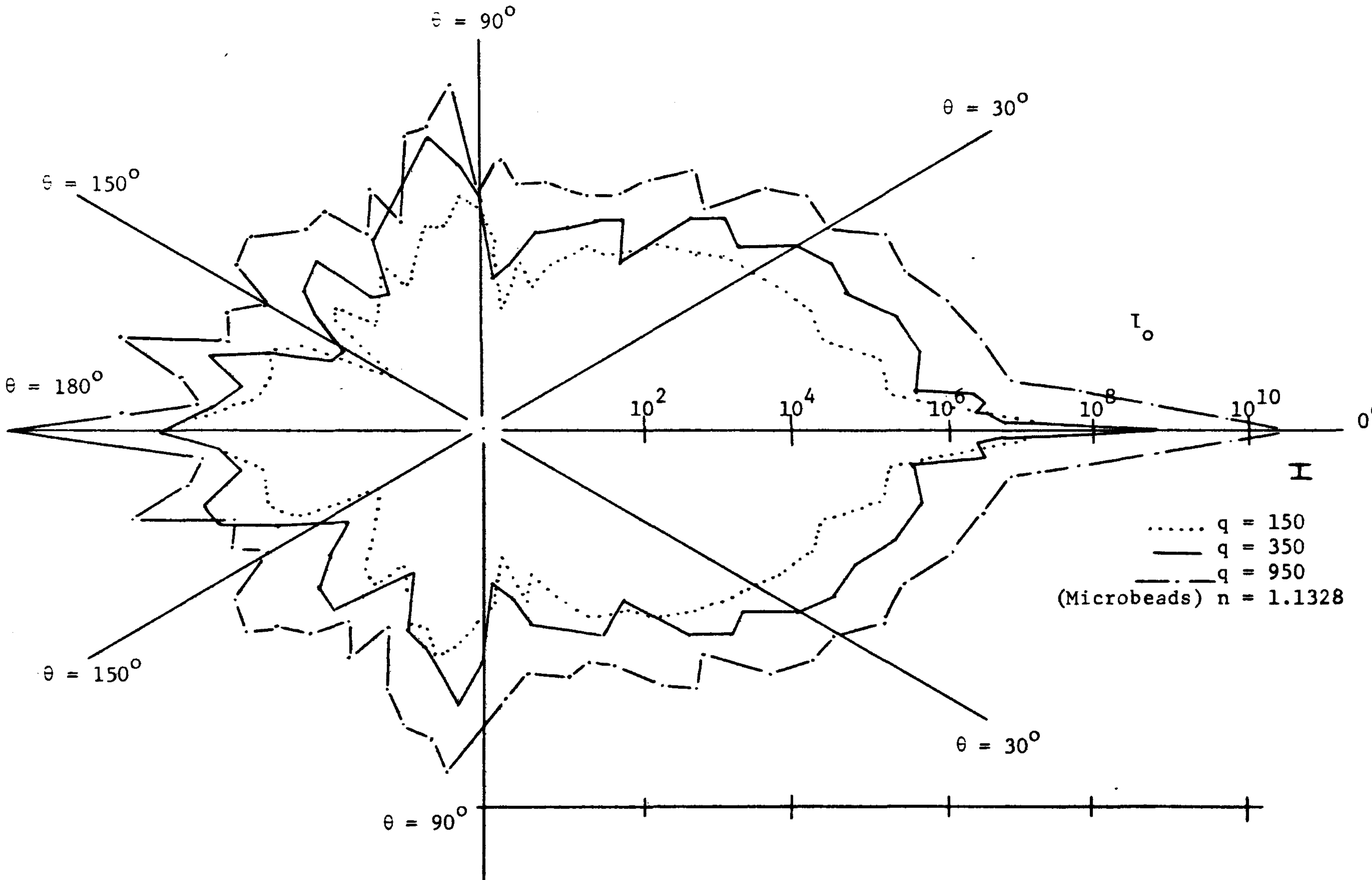


FIGURE 5 - ANGULAR SCATTERING DISTRIBUTIONS FOR VARIOUS VALUES OF SIZE PARAMETER

Rosensweig, Hottel and Williams (1961) extended this simplified expression to the signal (current) produced by the phototube which is given by:

$$\bar{I}_s = \frac{S}{V_s} \int_{V_s} \Gamma^* \, dV_s \qquad (5)$$

where

$\bar{I}_s$ is the phototube signal

S is the overall system sensitivity and is constant for a given optical arrangement and alignment

$\bar{\Gamma}^*$ is given by $\lim_{V_s \to 0} \frac{N}{V_s}$ and is defined as the average particle density contained within the control volume.

N is the average number of particles contained in V_s

The desirable relation between I_s, S and $\bar{\Gamma}^*$ is

$$I_s = S\bar{\Gamma}^* \qquad (6)$$

Rosensweig et al (1961) state that clearly V must be small. However, decreasing V increases all noise levels of the system. Therefore an optimization is needed. They also show that if a point concentration is to be obtained from equation (5) the concentration profile must not have large curvature. These conditions are controlled by the geometry of the optics and by the velocity profile in the medium.

The relation between the count from an electronic counter, monitoring the phototube output, and the number of particles per unit volume can now be obtained. Under the assumption of homogenous flow, the total number of particles counted is attributed to the passage of a frozen concentration pattern through the scattering volume V_s. The pattern passes at a velocity U - the local mean velocity of the flow field. The average time for one particle to pass through the scattering volume is given as:

$$\Delta t = \frac{D_{b/2}}{U} \qquad (7)$$

where

D_b = diameter of the beam
U = stream velocity

The length D/2 represents an average cross-sectional length for the circular beam. The time it takes for a length V_s/A_s to pass through the scattering volume is:

$$\frac{V_s}{UA_s} = \Lambda t \tag{8}$$

where

V_s = scattering volume

A_s = cross-sectional area of the scattering volume defined as $L_s D_b$.

L_s = the length of the volume formed by the interception of the solid angle and the beam. (shown in Figure 4)

If the average number of particles per unit scattering volume is given by:

$$\Gamma^* = \frac{\tilde{N}}{V_s} \tag{9}$$

where

$\tilde{N}$ = total number of particles contained in V_s

V_s = scattering volume

and the total number of particles contained in the system volume is N then the particle density is given by:

$$\Gamma = \frac{N}{V} \tag{10}$$

and for homogenous flow

$$\frac{N}{V} = \frac{\tilde{N}}{V_s} \tag{11}$$

The number of counts per second is then given by the number of particles per unit scattering volume divided by the time for one scattering volume to be convected through the volume. In equation form this is:

$$\delta = \frac{\Gamma^* V_s}{\Lambda t} \tag{12}$$

where

δ = count/second
V_s = Scattering volume

or substituting for Γ^* from equation 9 and for Λt from equation 8

$$\delta = \frac{\tilde{N}}{V_s} A_s U$$

But $\frac{\tilde{N}}{V_s} = \frac{N}{V}$ so

$$\delta = \frac{N}{V} A_s U \tag{13}$$

For a desired count the number of particles and ultimately the weight of the particles were determined by the relationship expressed by equation 13.

Resolution of the Scattering Volume

The length of the scattering volume may be determined directly from the geometry of the optics. The angle α_s is determined by the diameter of the pinhole apertures which limit the field of view of the photomultiplier tube. The angle θ is the angle between the photomultiplier tube and the incident beam. These variables are all shown in Figure 4. The equation that describes the dependence of the scattering length upon the geometry is given by:

$$L_s = Ld \frac{\sin \alpha_s}{\cos (\theta + \alpha_s)} + \frac{\sin \alpha_s}{\sin (\theta - \alpha_s)} \tag{14}$$

where

Ld is the distance of the center of the apertures to the center of the beam

L_s is the length of the scattering volume at the center of the beam

The effect of different values of α and θ on the length L_s is shown in Figure 6.

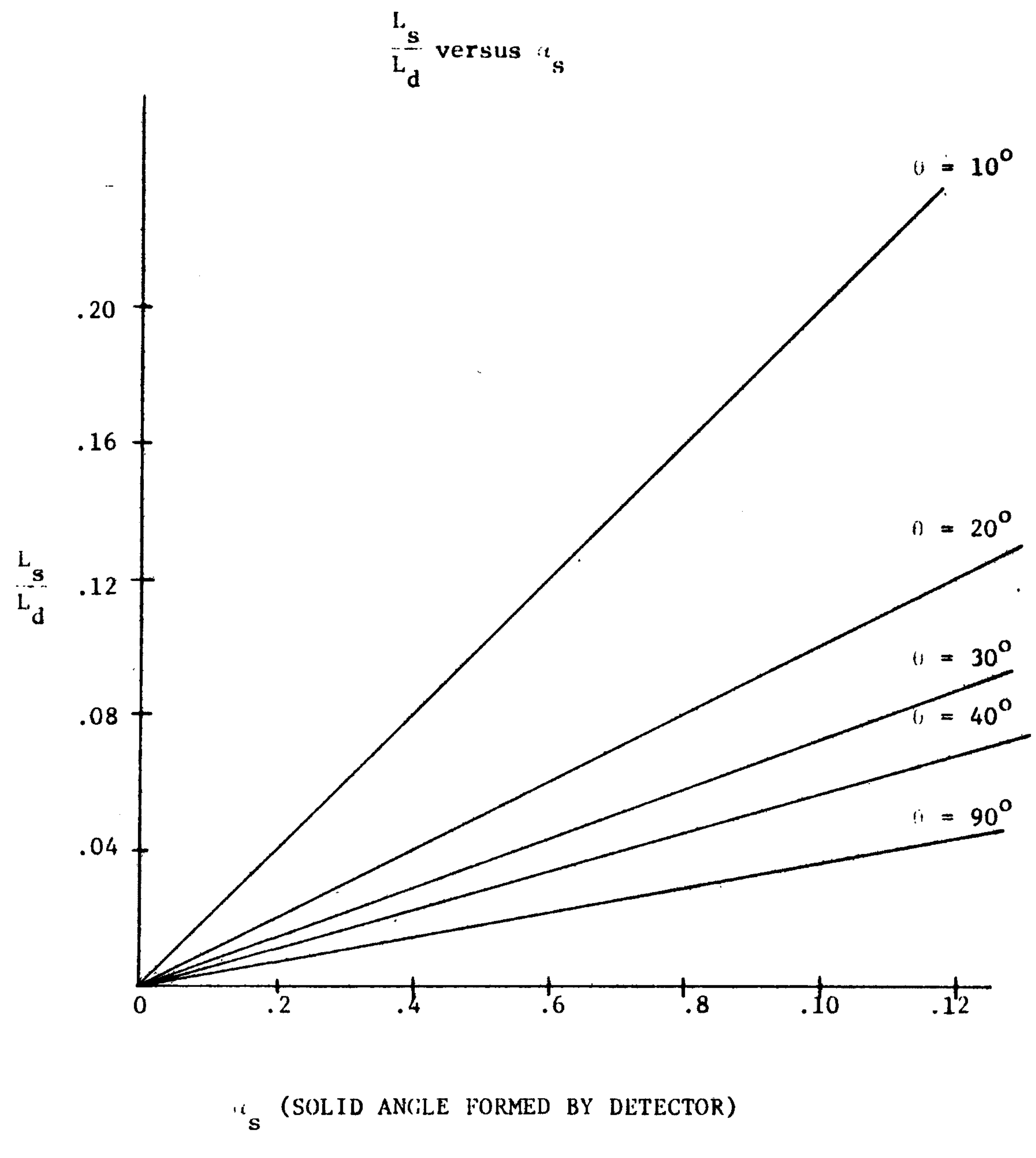


FIGURE 6 - VARIATION OF DIMENSIONLESS LENGTH WITH SOLID ANGLE α_s

The effective length for transversing the test section is longer than L_s by a Length equal to AL_1 and AL_2. The lengths AL_1 and AL_2 are shown in Figure 7 and are given by:

$$AL_1 = \frac{D_b}{2} \tan(\theta + \alpha) \tag{15}$$

$$AL_2 = \frac{D_b}{2} \tan(\theta - \alpha) \tag{16}$$

This total length is the dimension which limits the ability to make measurements close to the wall.

The conditions that are necessary in order that the volume be small are:

a. large values of θ (Max. = 90°)

b. small diameter pinholes

c. large distance between apertures

d. small distance between the center of the aperture and the beam

Equation 14 is derived neglecting the effects of refraction at the walls of the test section. This effect is generally negligible provided angle α is very small.

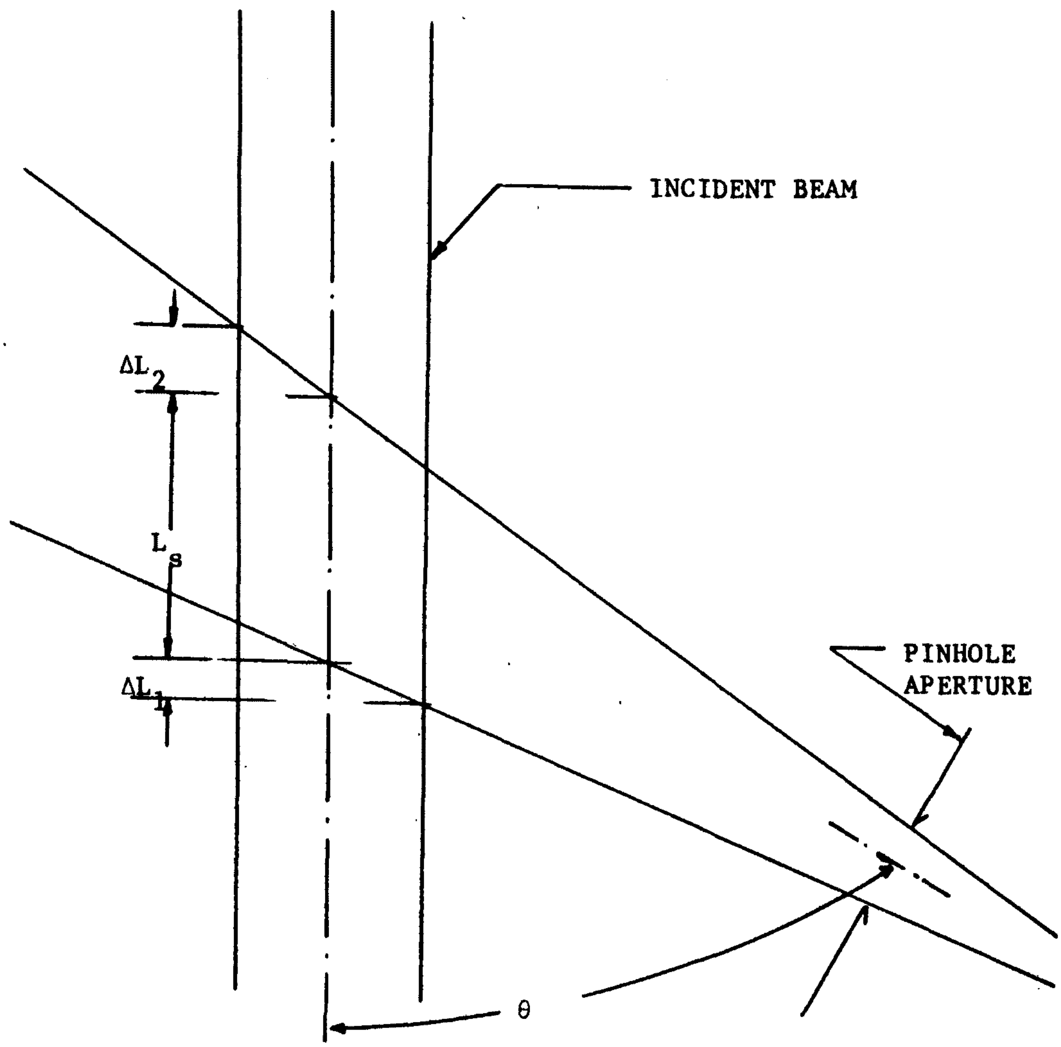


FIGURE 7 - EFFECTIVE TRAVERSING LENGTH

SECTION IV

EXPERIMENTAL APPARATUS DESCRIPTION

The experimental apparatus may be divided into various subsystems - the fluid flow system, optical system, particle measuring system, and the electronic system.

Description of the Fluid Flow System

A schematic of the fluid system is shown in Figure 8. The system consists of a plenum chamber, a reservoir, a one-third horsepower centrifugal pump with a bronze head and an Aqua-Pure water filter. All piping used was made of Polyvinyl Chloride (plastic pipe) to insure that the system remained as rust free as possible. The plenum chamber was made of Plexiglass and had dimensions of 1' x 1' x 2.5'. The inlet section from the plenum to the test section was constructed from a cylindrical Plexiglass piece cut at 45° angles in such a manner that when it was reunited, it formed a bell shape inlet section for a square channel as shown in Figure 9. The plenum chamber also had an overflow weir that consisted of a 3/4 inch diameter pipe. The reservoir was constructed from a fifty-five gallon drum that had been treated to prevent rust. The reservoir had four holes located in its bottom, leading to valves 3, 4, 5, 6. Valve No. 5 is used to help control the amount of flow going to the reservoir from the constant speed pump. All four valves allowed the separation of the reservoir from the rest of the system. Valve 4 is between the reservoir and the drain. Valves 7, 8, 9, are for further flow control. They allow either complete, partial, or no flow through the filter. Valve 11 is to control the weir draining rate and valve 12 is to control the plenum draining rate. The remaining valves (1, 2) were to allow collection of a flowing sample from the test region.

The test section located immediately downstream of the inlet nozzle was made of Plexiglass and designed in such a manner that it could be detached from this position and interchanged with another section of the channel. The test section is shown in Figure 9.

The velocity profiles were measured with the device shown in Figure 9. The measuring instrument was a Pace differential

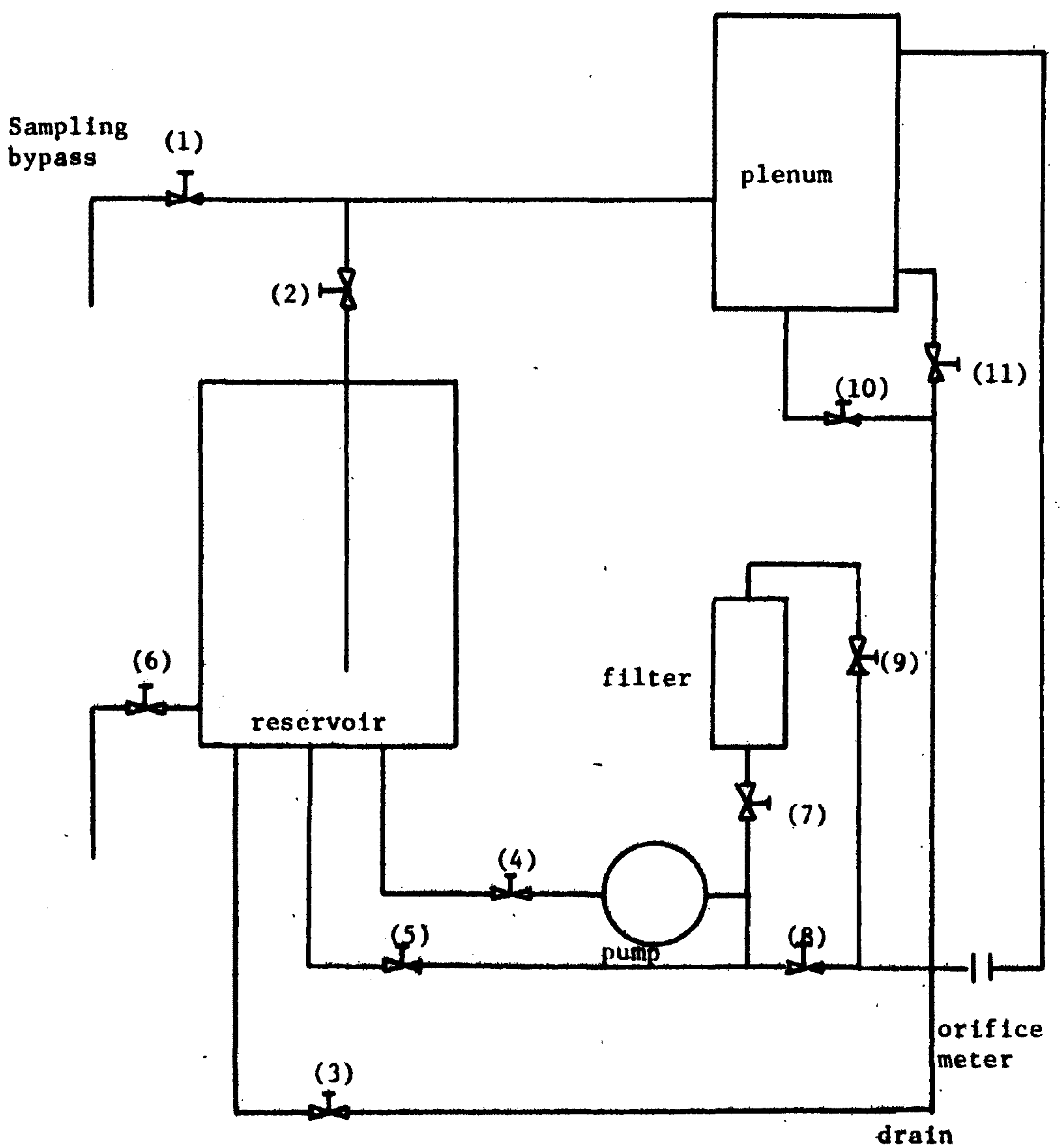
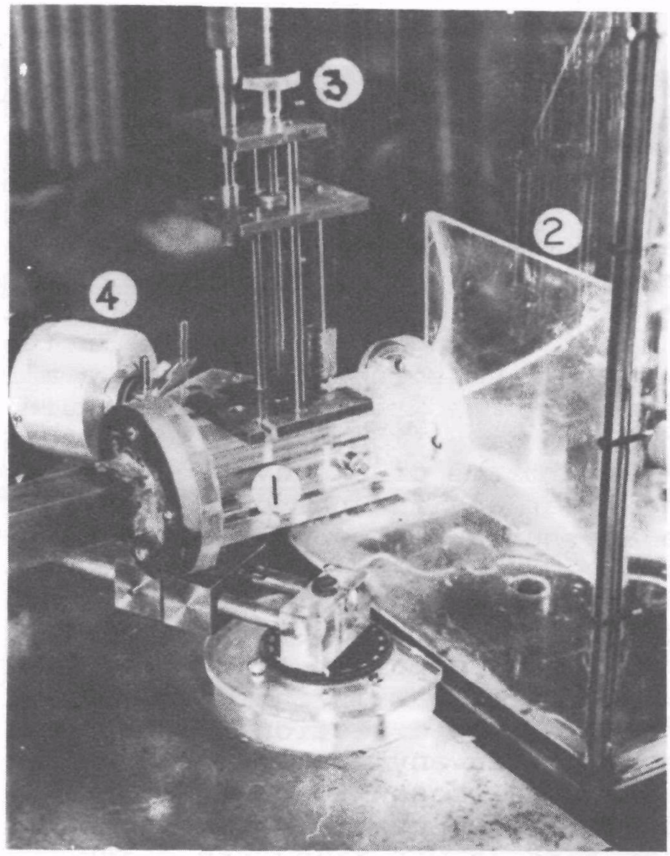


FIGURE 8 - SCHEMATIC-FLUID FLOW SYSTEM



(1) Test section
(2) Inlet nozzle

(3) Pilot tube with traversing device

(4) Photomultiplier tube

FIGURE 9 - INLET SECTION AND TEST REGION

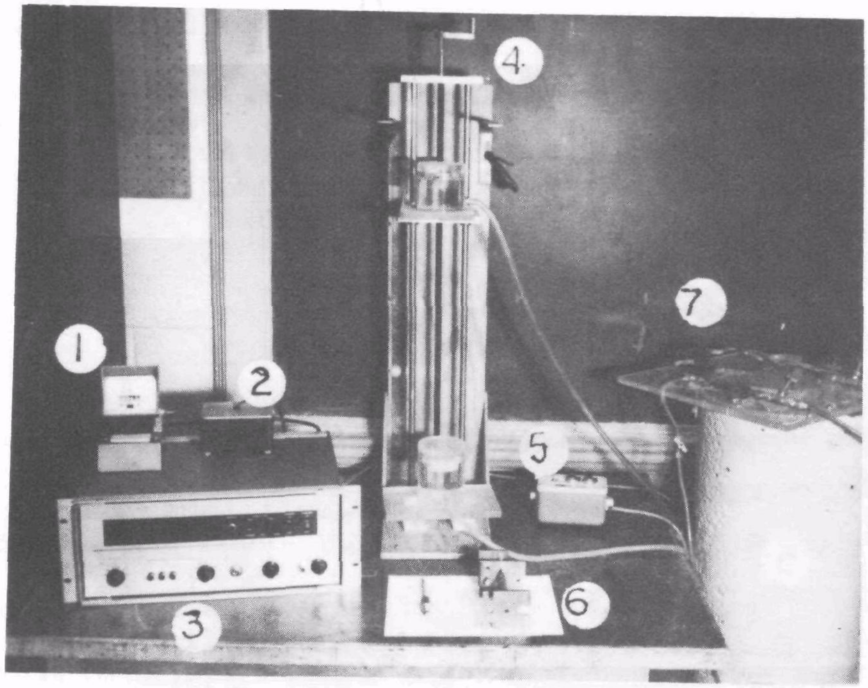
transducer and the probe was made from 0.035" I.D. wire tubing. The traversing mechanism used a micrometer to position the probe. The electronics used for velocity measurement are also shown in Figure 10. The electronics consisted of a carrier demodulator and a VIDAR digital voltmeter with external controls allowing time averaging of the velocity profile.

Optical System

The optical system consisted of a helium-neon laser, a photomultiplier tube, a narrow band filter, and two pinhole apertures. The system is as shown in Figure 11. This arrangement was chosen as a compromise between scattering volume size and signal to noise ratio. In general as the angle between the beam and the photomultiplier was decreased, the scattering volume length increased and the signal to noise ratio decreased reaching a minimum at the zero degree angle. The prism shown in Figure 11 was used just to change the direction of the beam and has no effect on the performance of the overall system. The wavelength of the laser and the narrow band filter used was 6328 A. The apertures were approximately 310 microns in diameter.

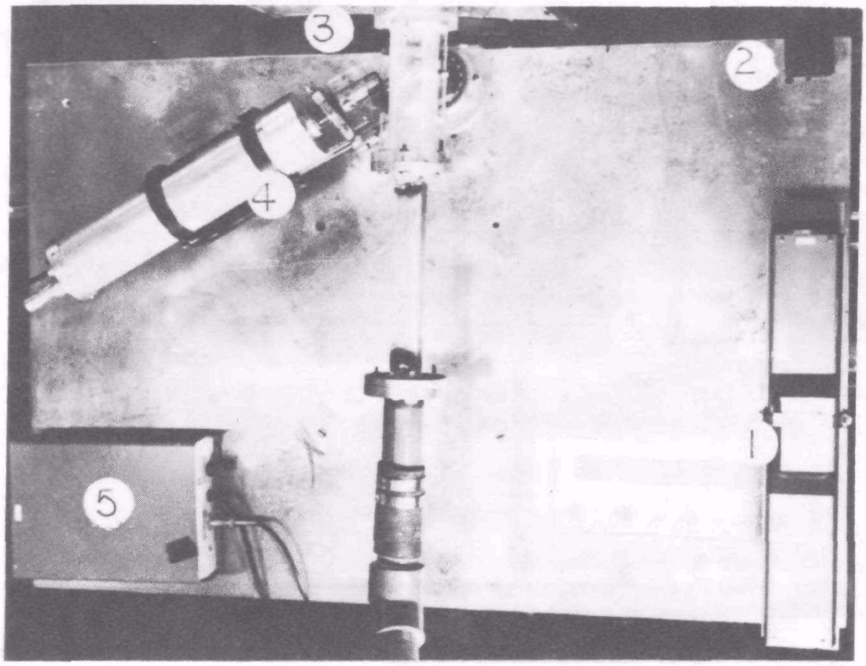
To aid in understanding the operation of the system and the purposes of each component a detailed explanation is presented. A uniform beam is incident upon the test section normal to the flow direction. The normal condition was chosen to minimize any aberrations due to refraction. The test section was chosen to have flat walls to eliminate the need for a compensator box to compensate for the effect of curvature as was found necessary in work done in internal flows with a Doppler system by Denison (1969). A system that involved the use of a lens that would focus the collimated beam down to a particular point was tried. It was discovered that with such a system, it would be necessary to refocus the system at each point in the flow field as the concentration gradient was taken. This was due to the change in optical path and consequently the change in effective focal length of the lens.

If small particles are seeded into the flow system, they will scatter radiation in all directions. The pinhole apertures that are placed between the photomultiplier tube and the flow field, together with the geometrical relationship between the incident beam and the photomultiplier tube, define the cone that intercepts the beam. The common region between the cone and the incident beam defines the scattering volume. The particles entering the scattering volume will scatter light in all directions,



(1) External timer
(2) External start and stop
(3) Vidar digital voltmeter
(4) Calibration mechanism
(5) Carrier demodulator
(6) Probe and transversing mechanism
(7) Transducer

FIGURE 10- VELOCITY MEASUREMENT INSTRUMENTATION



(1) Laser

(2) Prism

(3) Apertures and bandpass filter

(4) Photomultiplier tube

(5) Laser power supply

FIGURE 11 - OPTICAL SYSTEM

some of which is received by the photomultiplier tube. The narrow band filter, which is placed directly in front of the photomultiplier tube, limits the wavelength of light that reaches the tube. Therefore, only radiation that is the same wavelength as the filter bandpass excites the tube. The signal received by the tube is then proportional to the scattered radiation from the particles, from scattering due to turbulence of the water (Gurvich, (1968)) and from background radiation from the room within the filter bandpass. Both of the latter effects were found to be negligible in this study.

The entire optical system was mounted on a large aluminum plate which was in turn mounted on a lathe bed in such a manner as to allow the scattering volume to be traversed across the flow. Mounting the optics in this manner limited vibrations and allowed the whole optics to move normal to the section where concentration gradients were taken.

Electronic System

The electronic system used in the analysis of the signal from the photomultiplier tube is shown in Figures 12 and 13. This system consisted of an oscilloscope, bandpass filter, an a.c. amplifier, an oscillator, a visicorder and an electronic counter.

The signal from the photomultiplier tube was first channelled to the oscilloscope, and simultaneously to the a.c. amplifier from which it entered the bandpass filter. The signal was amplified to enable it to trigger the electronic counter. The amplification factor was ten times the input signal. The bandpass filter was used to improve the signal to noise ratio. After passing through the bandpass filter, the signal was simultaneously sent to the oscilloscope and to the electronic counter. Since the signal had the appearance of shot noise, the filtered and unfiltered signals were observed on the oscilloscope to insure that the basic form of the signals was not changed.

The purpose of the oscillator was to serve as a standard when in connection with the oscilloscope, by which the electronic counter could be calibrated for sensitivity versus accurate count setting.

The visicorder was used to double check the effect of the bandpass filter, to compare the intensity of light received from the different types of particles used, and also to check on the count received from the counter at various locations.

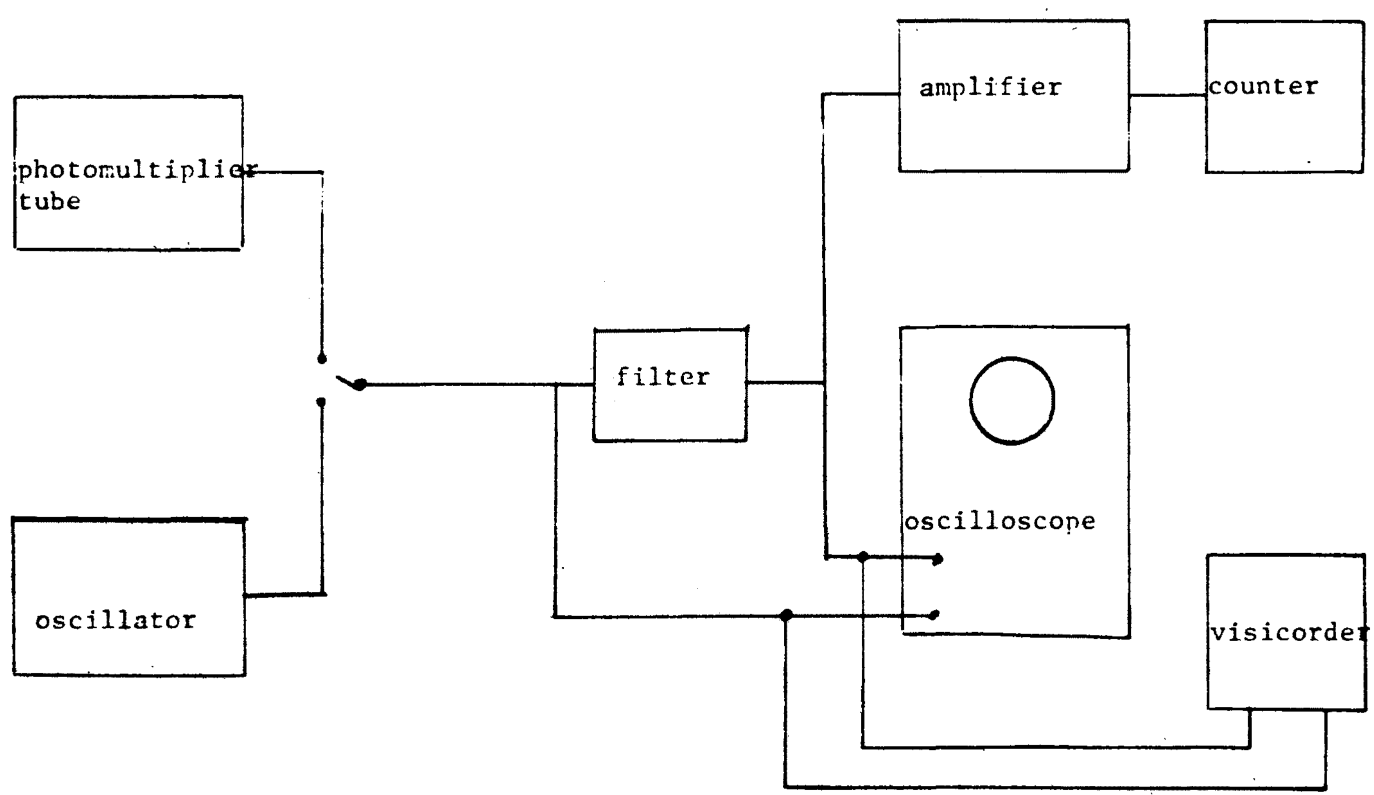
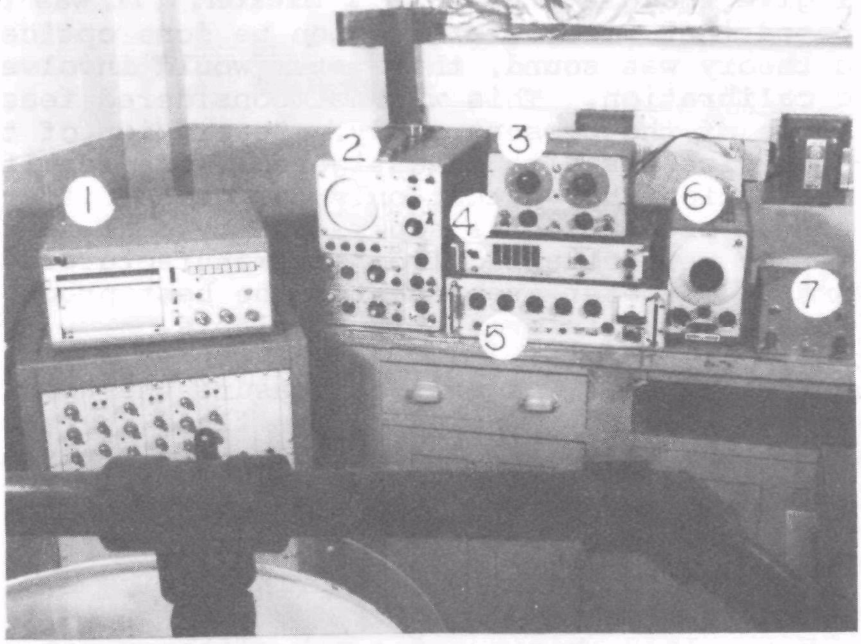


FIGURE 12 - SCHEMATIC OF THE ELECTRONIC SYSTEM USED



(1)	Viscorder	(5)	Photomultiplier tube voltage power supply
(2)	Oscilloscope	(6)	Oscillator
(3)	Narrow band filter	(7)	A.C. amplifier
(4)	Electronic counter		

FIGURE 13- ELECTONICS USED IN SIGNAL ANALYSIS

Particle Measuring System

This system consisted of only a microscope and an analytical balance. The size distribution of the particles was determined by measuring a sample of the particles used under the microscope. The microscope at high magnification will give the diameter to $\pm$ 1 micron. It was originally proposed that size determination be done optically. While the theory was sound, the system would involve an extensive calibration. This was not considered feasible for the scope of the present study. Separation of the particles by size was also investigated. The results of this investigation showed that only for gross differences in diameter or properties is separation by size feasible. Particles that were obtained from the manufacturers though not uniform in diameter, represented the best practical size separation that is presently available.

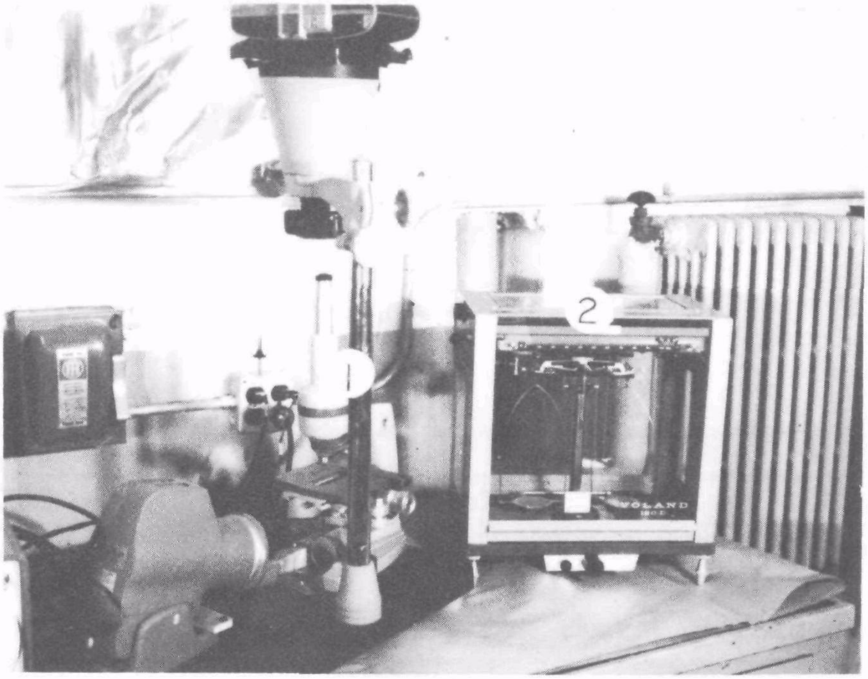
The analytical balance was used to measure the amount of particles that were to be added to the fluid system. The balance was accurate to 1/100 milligram. This system is shown in Figure 14.

Average Concentration Measuring Device

In order that values obtained from the light scattering experiments could be verified, a Coulter counter was used. The Coulter counter works on the principle that the presence of particles passing through a small orifice changes the electrical path through the orifice. This device is thereby able to determine the particle size and concentration that is present in a small sampling vessel.

Concentration measurements from this device were determined from small samples taken at each concentration level that was used. The samples were taken with a bypass arrangement from the reservoir that can be seen in Figure 8 and was controlled by valves (1) and (2).

The results obtained from this instrument proved to be unreliable for the fluid (deionized water) and concentrations used.



(1) Microscope (2) Analytical Balance

FIGURE 14 - PARTICLE SIZE AND NUMBER MEASUREMENT SYSTEM

SECTION V

MEASUREMENTS AND RESULTS

Particle Size Measurements

The particle size was determined by measurement with a microscope. The standard deviation and average were calculated from the following equations:

$$\bar{D} = \frac{1}{\underline{N}} \sum_{d=1}^{N} f_j \, x_j \qquad (17)$$

$$\tau = \frac{1}{\underline{N}-1} \sum_{j=1}^{N} f_j \, (x_j - \bar{D})^2 \qquad (18)$$

where

$\underline{N}$ = Number of particles sampled

x_j = Diameter of a given particle

f = Frequency of occurrence for that particle diameter

τ = Standard deviation of the particle diameter

$\bar{D}$ = Average diameter

The results obtained are given in the following table:

Table I

TYPE OF PARTICLE	D	τ	n
Lycopodium Spores	31.66 μ	2.23 μ	Unavailable
Microbeads	34.3 μ	4.74	1.51
Dow Beads	45.4 μ	8.9	1.587

The frequency of occurrence of sizes for Lycopodium and for microbeads can be found in Figures 15 and 16. The density and other properties of Lycopodium were taken from Rouhiainen and Stachiewicz (1970). The other particle properties were taken from manufacturer's data and can be found in Table II.

TABLE II

PARTICLE SUPPLIERS AND PROPERTIES

MANUFACTURER OR SUPPLIER	MATERIAL	DIAMETER	INDEX OF REFRACTION	SPECIFIC GRAVITY
Carolina Biological Supplies	Lycopodium Spores	32.2 μ	-	0.621
Dow Chemical	Styrene divinyl-benze	34.3 μ	1.587	1.05
Microbeads	Soda-lime silca glass		1.51	1.5
Minnesota Mining Reflective Products	Glass		1.5	1.5

Velocity Measurement

The measurement of the velocity was done prior to any of the concentration runs. The nozzle and flow field is shown in Figure 16. The mean velocity in the test section was found to be 8 feet per second. The corresponding Reynolds number based on the hydraulic diameter is 5.76×10^5. Velocity profiles were found to be flat over most of the test section in both horizontal and vertical directions. A typical profile is shown in Figure 17.

Concentration Measurements

The particles were injected into the plenum chamber and

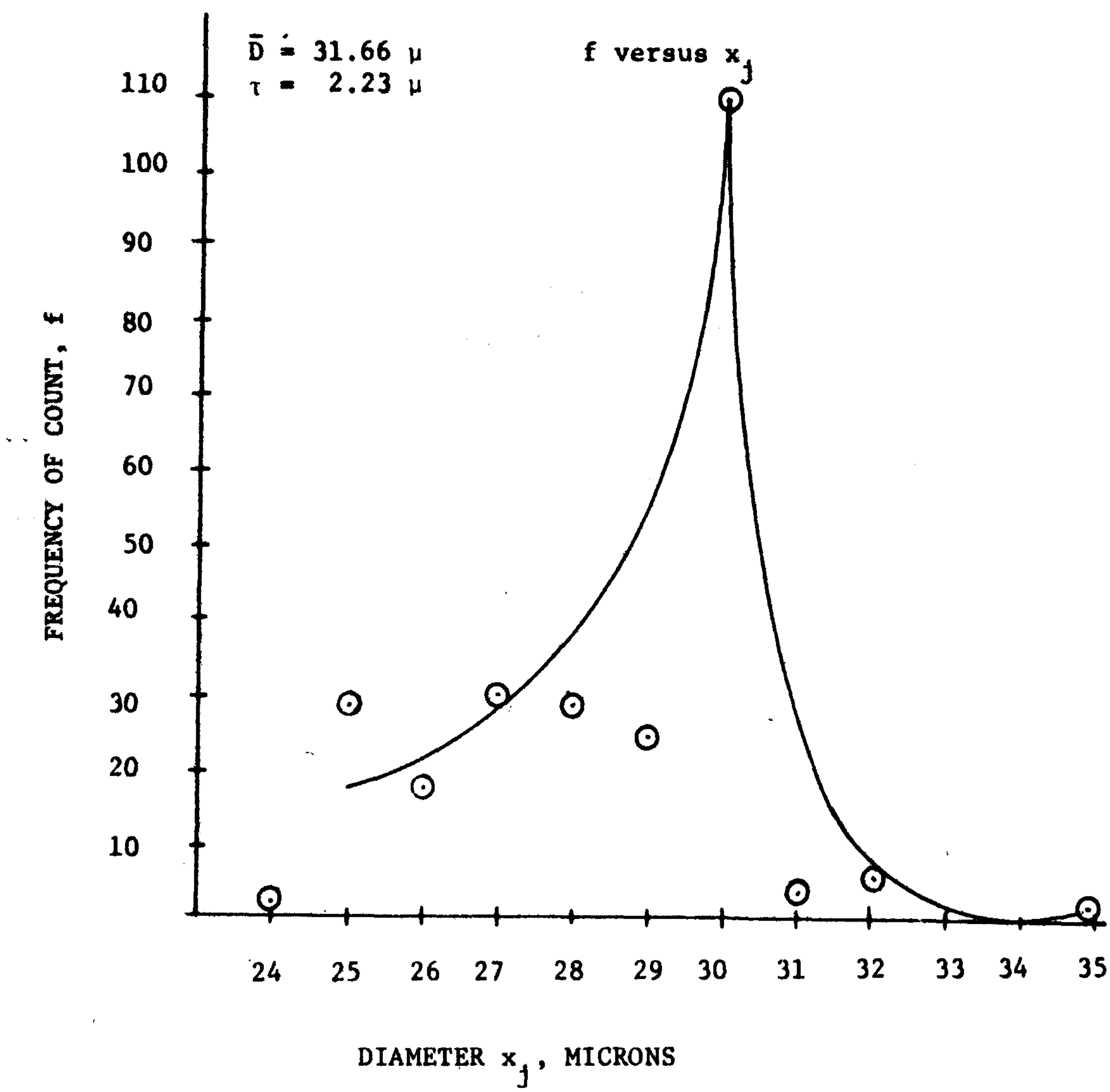


FIGURE 15 - FREQUENCY VERSUS DIAMETER FOR LYCOPODIUM SPORES

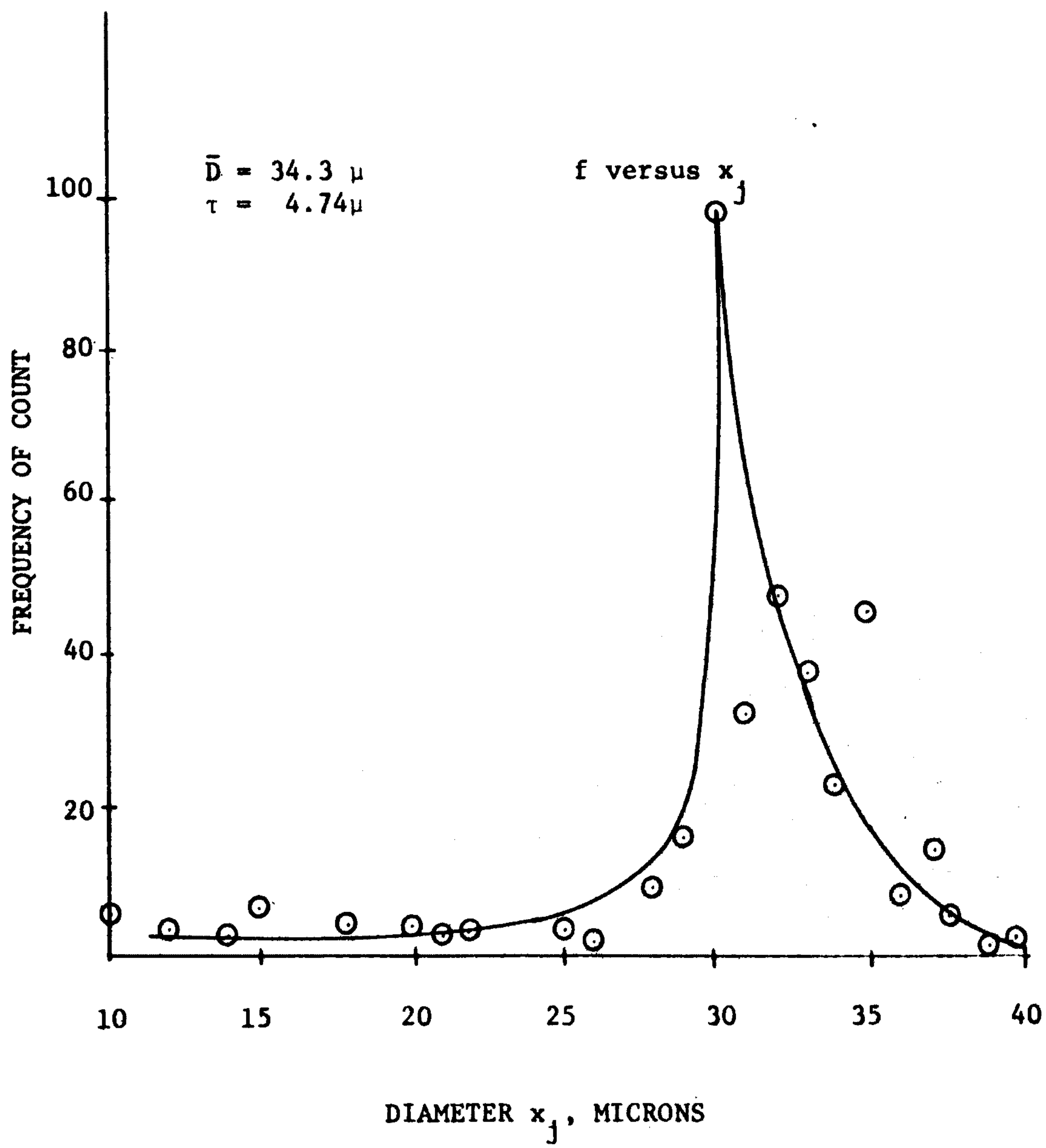


FIGURE 16 - FREQUENCY VERSUS DIAMETER FOR MICROBEADS

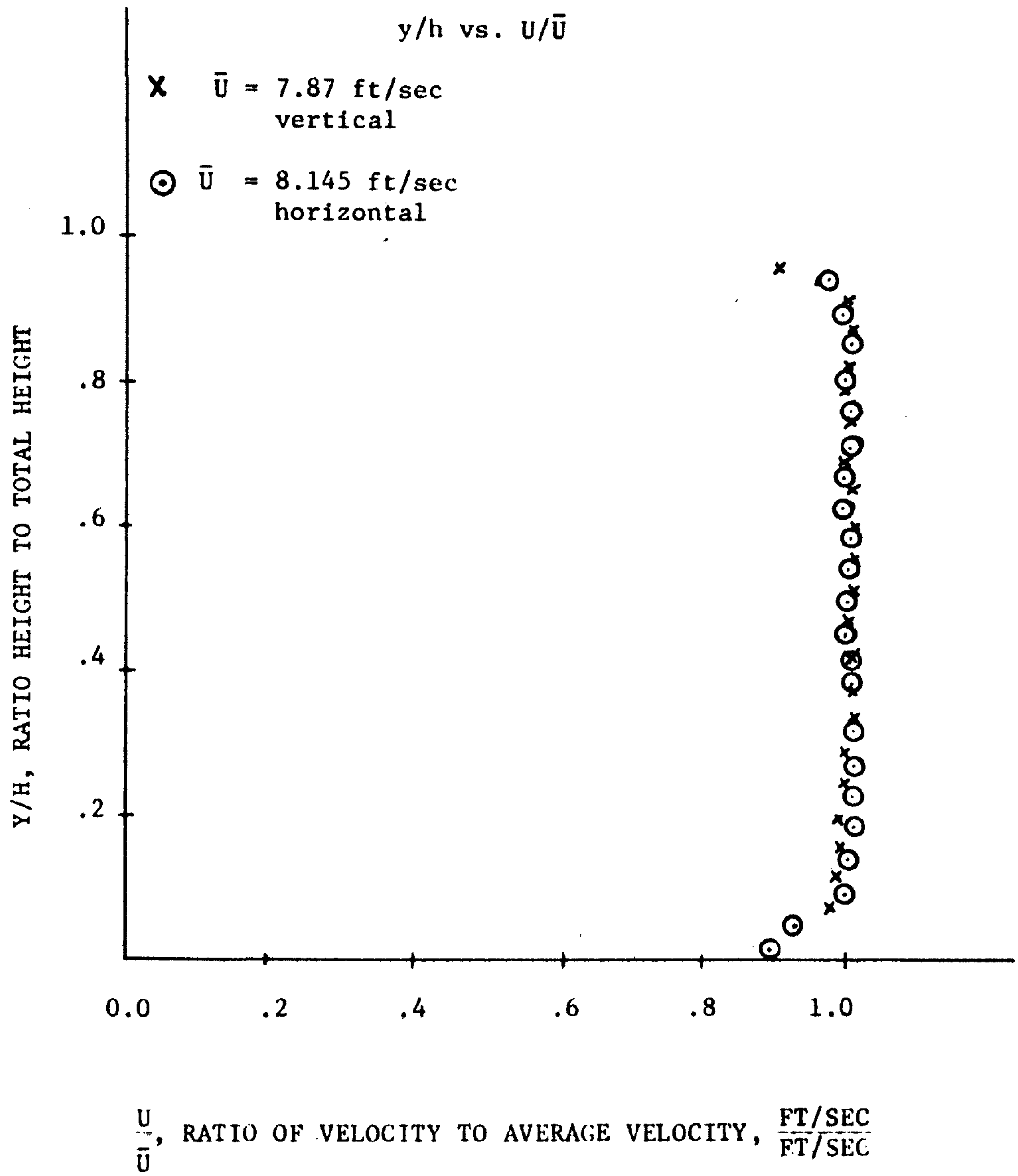


FIGURE 17 - DIMENSIONLESS DISTANCE VERSUS DIMENSIONLESS VELOCITY

allowed to disperse for one hour to one and one-half hours before any data was taken. This time was determined experimentally as the time delay necessary for a consistent count. The procedure for data collection was as follows:

1. Check to insure the following equipment was turned on at least one-half hour before a run.

    a. Oscilloscope
    b. High voltage power supply
    c. Visicorder oscillograph
    d. Laser
    e. Electronic Counter (set at maximum sensitivity)

2. The inner wall of the test section was located. (The location of the wall was determined by the scattering pattern at the interface between the wall and the air.

3. Dial positioner was zeroed. (This dial was used to determine step size of traverses of the scattering volume in the test section)

4. All room lights were turned off.

5. Readings of the count per second were obtained at positions spaced 0.10 inch apart.

6. Visicorder oscillograph and count per second readings were obtained at positions 1, 4 and 7 which correspond to the two wall regions and the center of the test section.

7. Electronic counter sensitivity was varied from a voltage threshold of 55 m.v. to 104 m.v.

8. The concentration level was changed. (For lycopodium spores a wetting agent must be used. For this investigation Industroclean cleanser was added to the system.)

9. Electronic Counter was set back to maximum sensitivity (55 m.v.).

10. Steps 2-19 were repeated.

The data for the point concentration measurements were taken as an arithmetic average of the values taken at the point. Typical distributions for each type of particle run is presented in Figures 18-23.

Coulter Counter Results

Typical results obtained for a few of the runs from the Coulter counter are presented in Figures 24 and 25. The Coulter counter proved to be a poor choice of a check for the results obtained from the scattering system. The primary reason is that the Coulter is extremely sensitive to contaminants in the water used. The Coulter counter would give high counts for clear water and give counts on the same order of magnitude for samples obtained from the particulate system. In fact, in some cases higher counts were obtained for clear water (uncontaminated deionized water). The scattering system did not show this sensitivity to clear water contamination; however, if it had a zero level could have been set and exact counts could have been obtained by substracting this known zero level from obtained values.

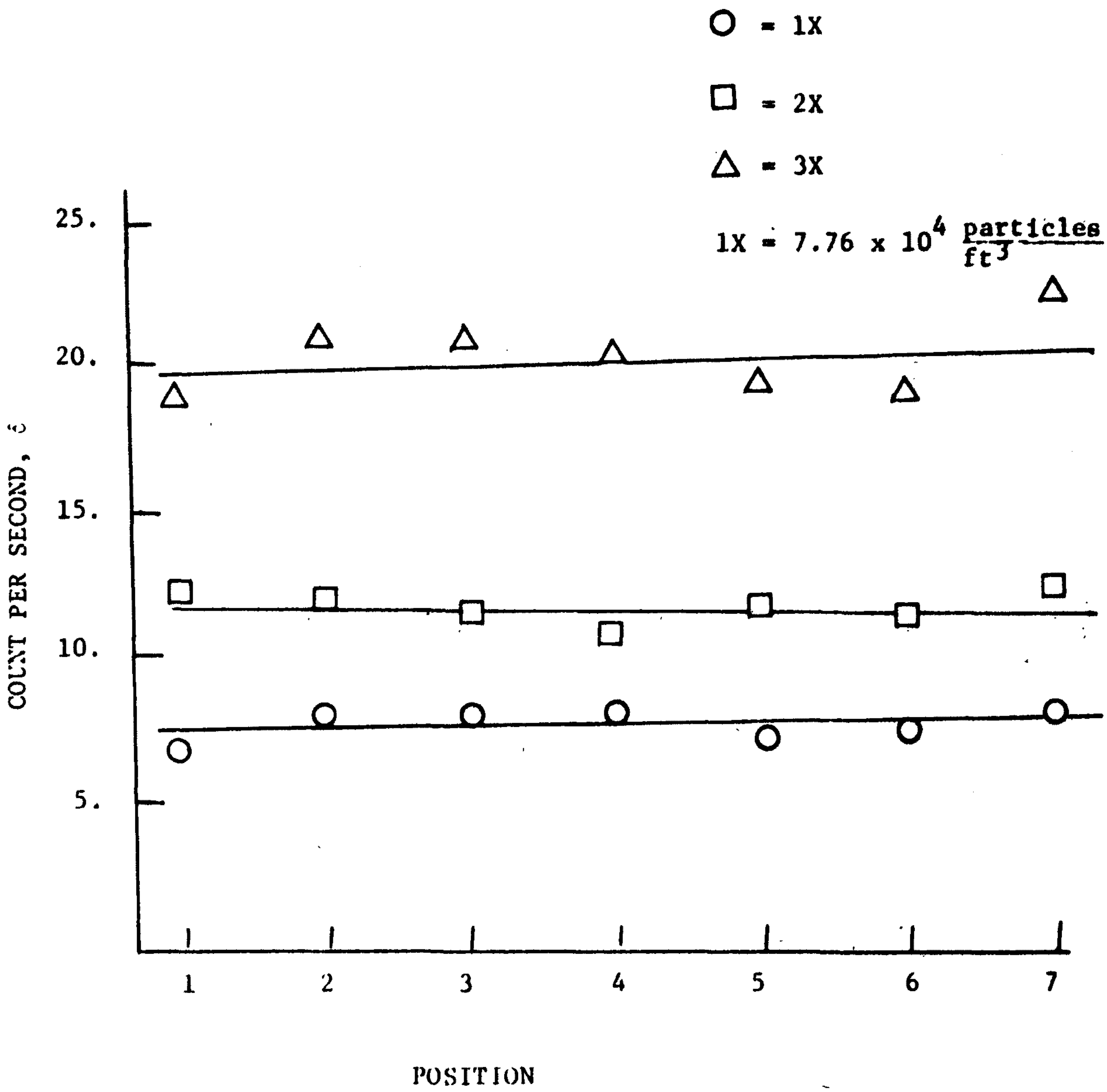


FIGURE 18 - OBSERVED COUNT PER SECOND VERSUS POSITION FOR DOW BEADS

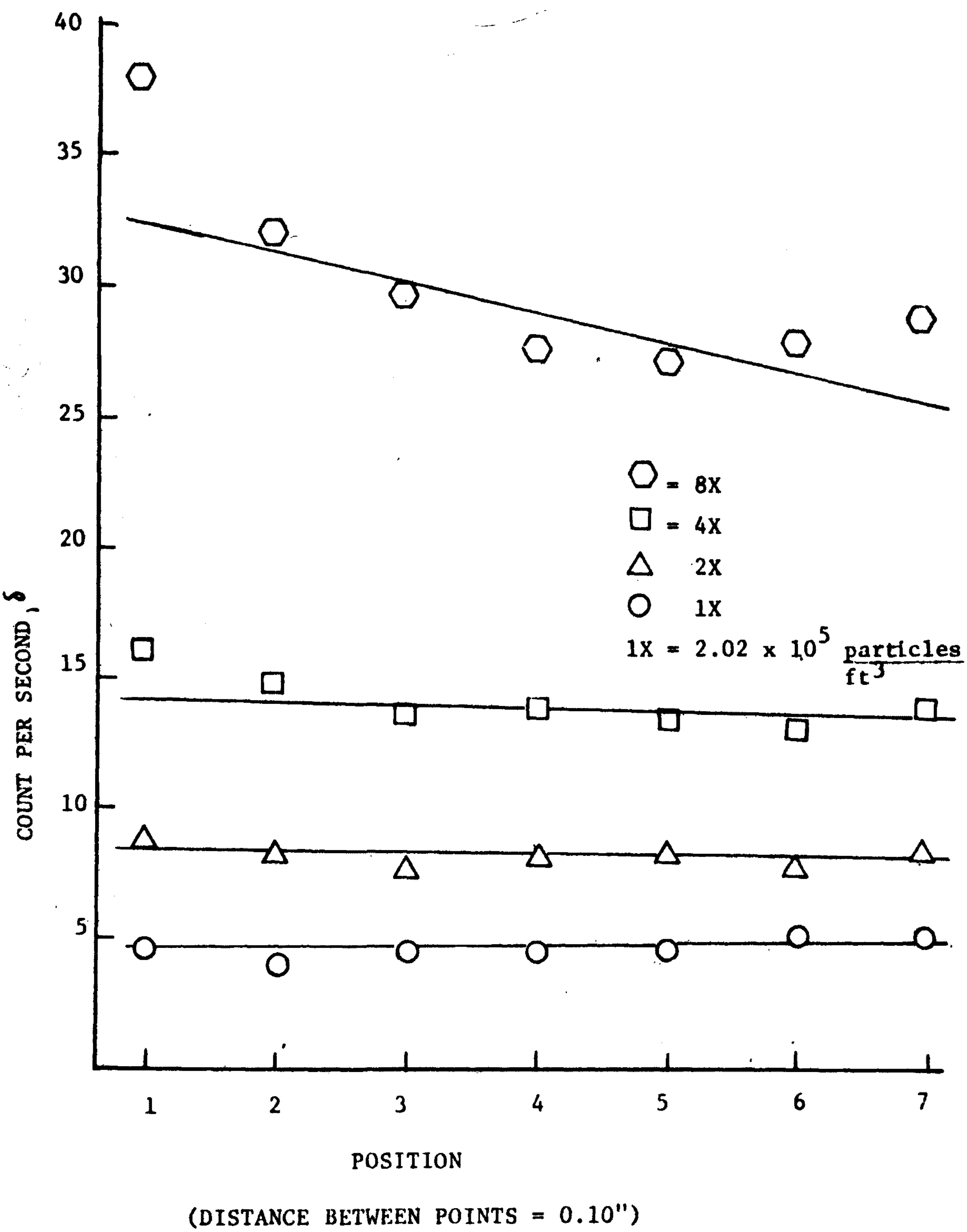


FIGURE 19 - OBSERVED COUNT PER SECOND VERSUS POSITION FOR LYCOPODIUM SPORES

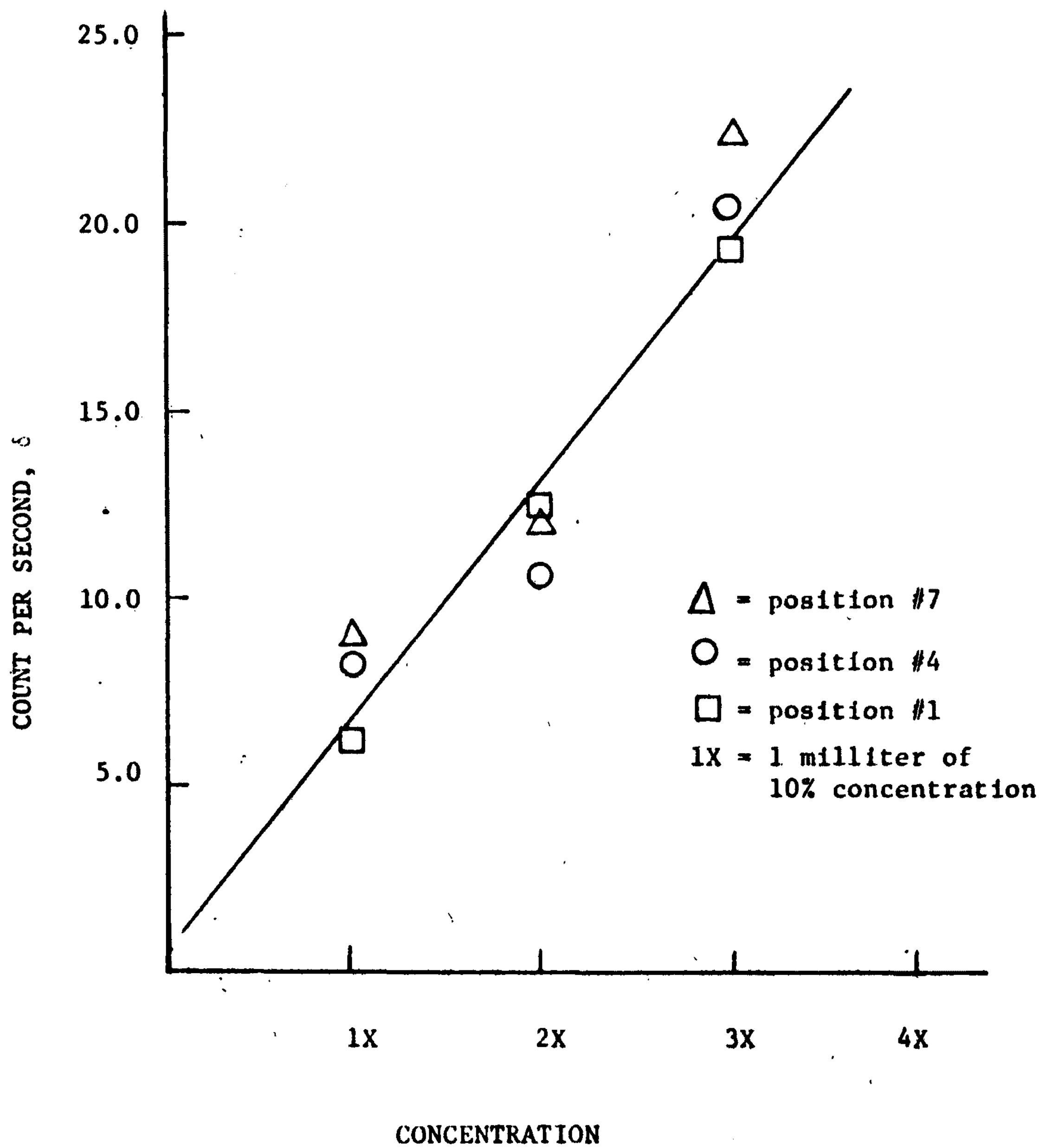


FIGURE 20 - OBSERVED COUNT PER SECOND VERSUS CONCENTRATION FOR DOW BEADS

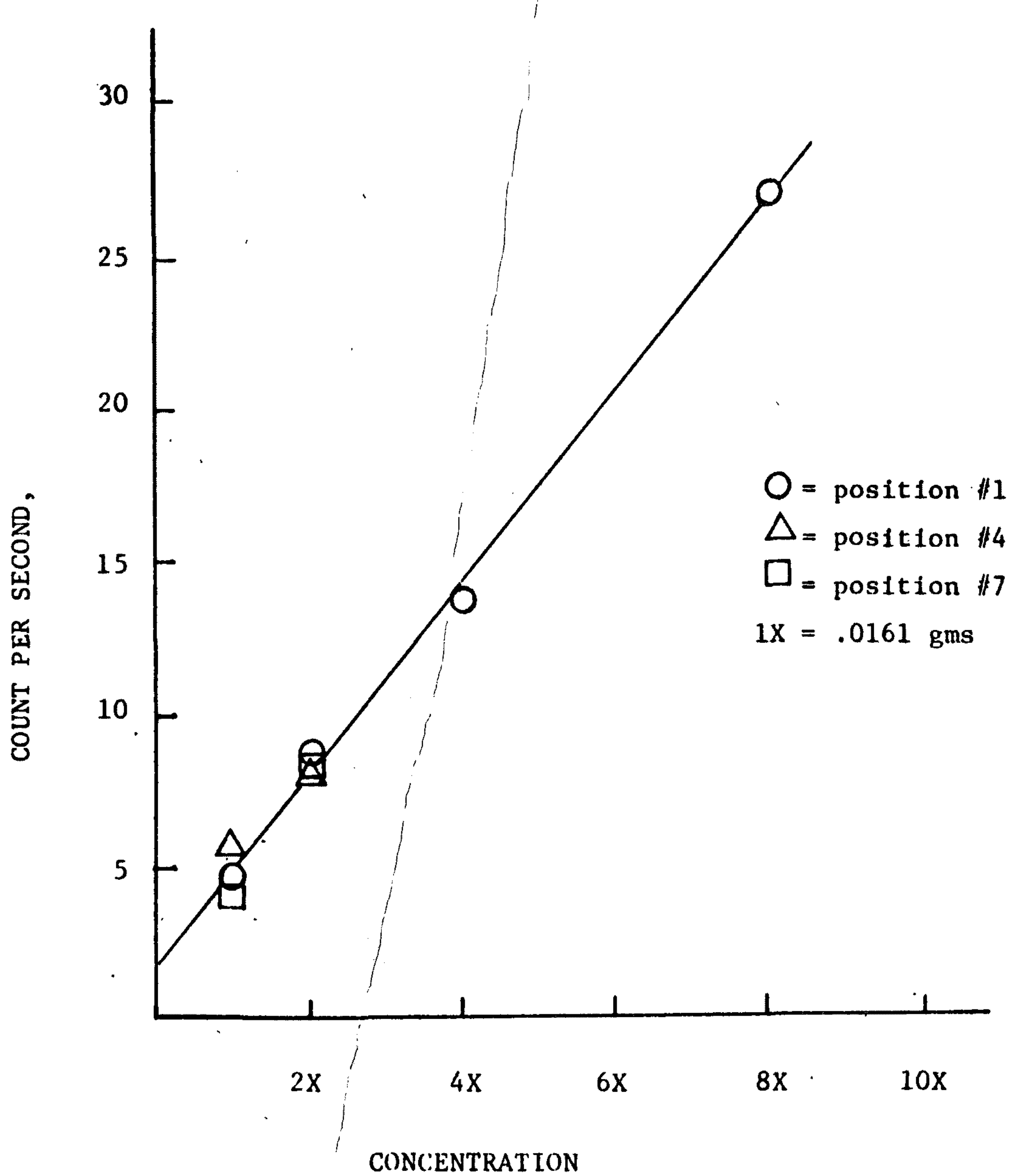


FIGURE 21 – OBSERVED COUNT PER SECOND VERSUS CONCENTRATION FOR LYCOPODIUM SPORES

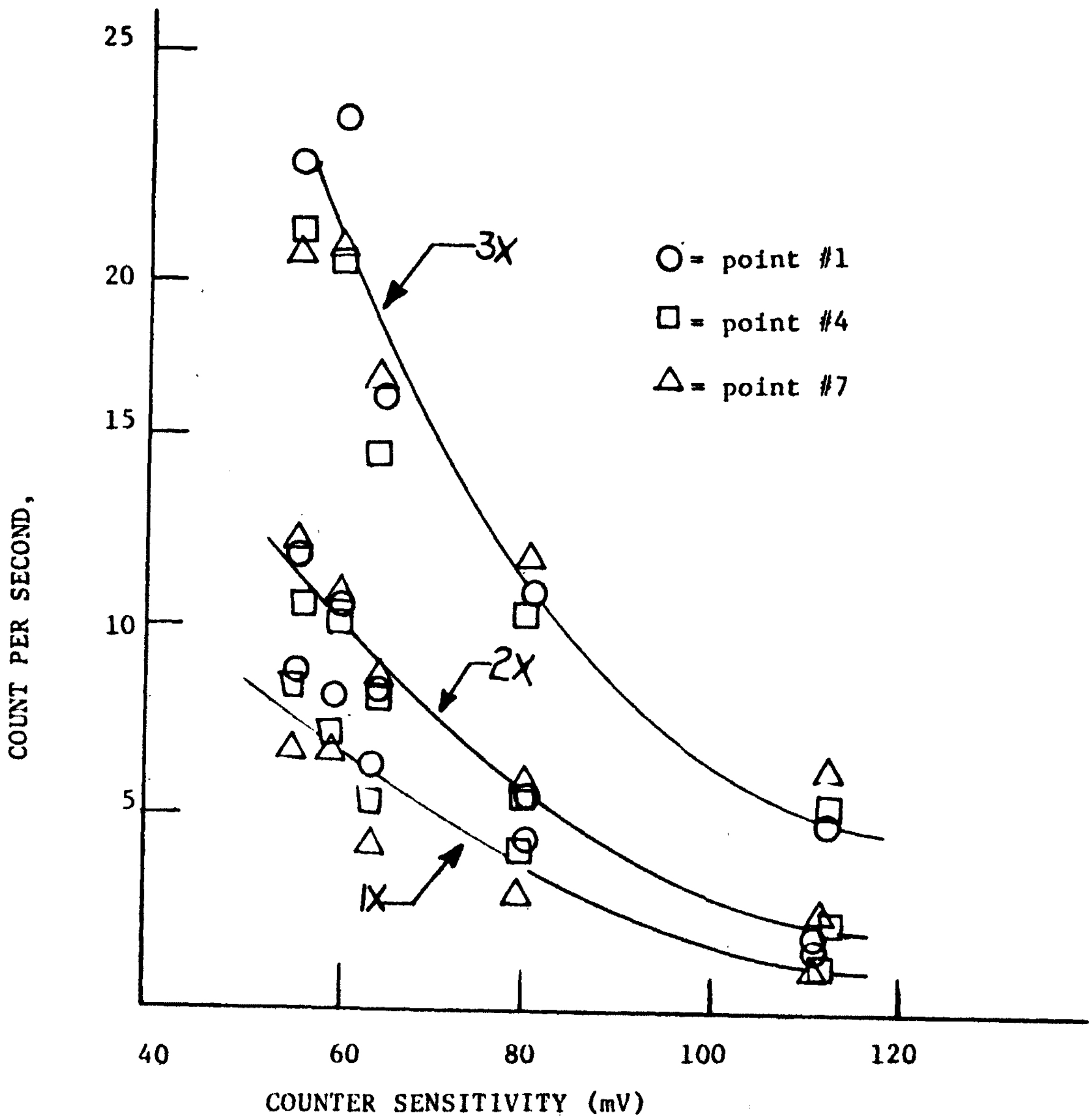


FIGURE 22 - OBSERVED COUNT PER SECOND VERSUS SENSITIVITY FOR DOW BEADS

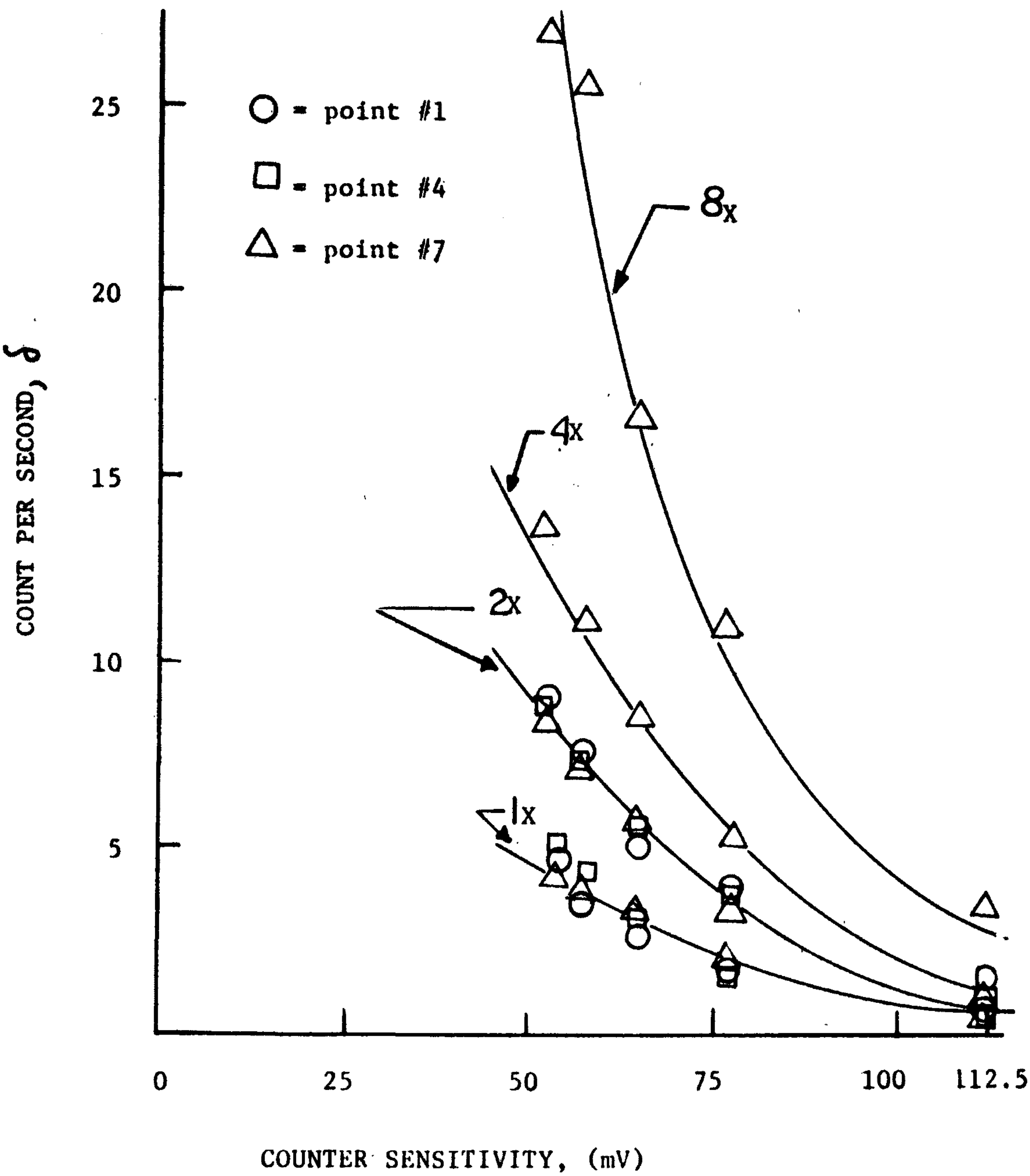


FIGURE 23 - OBSERVED COUNT PER SECOND VERSUS SENSITIVITY FOR LYCOPODIUM SPORES

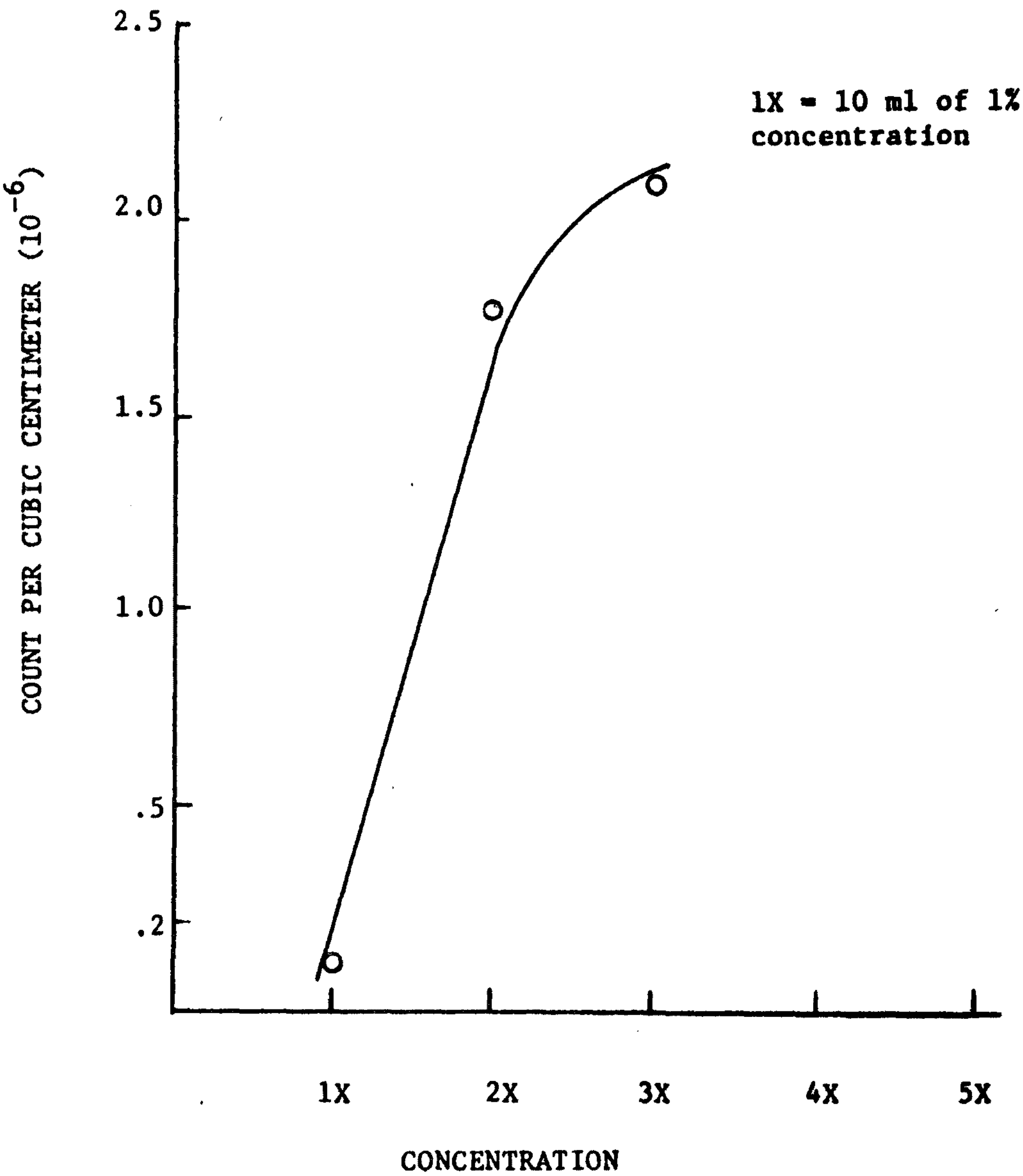


FIGURE 24 - TYPICAL COULTER COUNTER COUNTS VERSUS CONCENTRATION FOR DOW BEADS

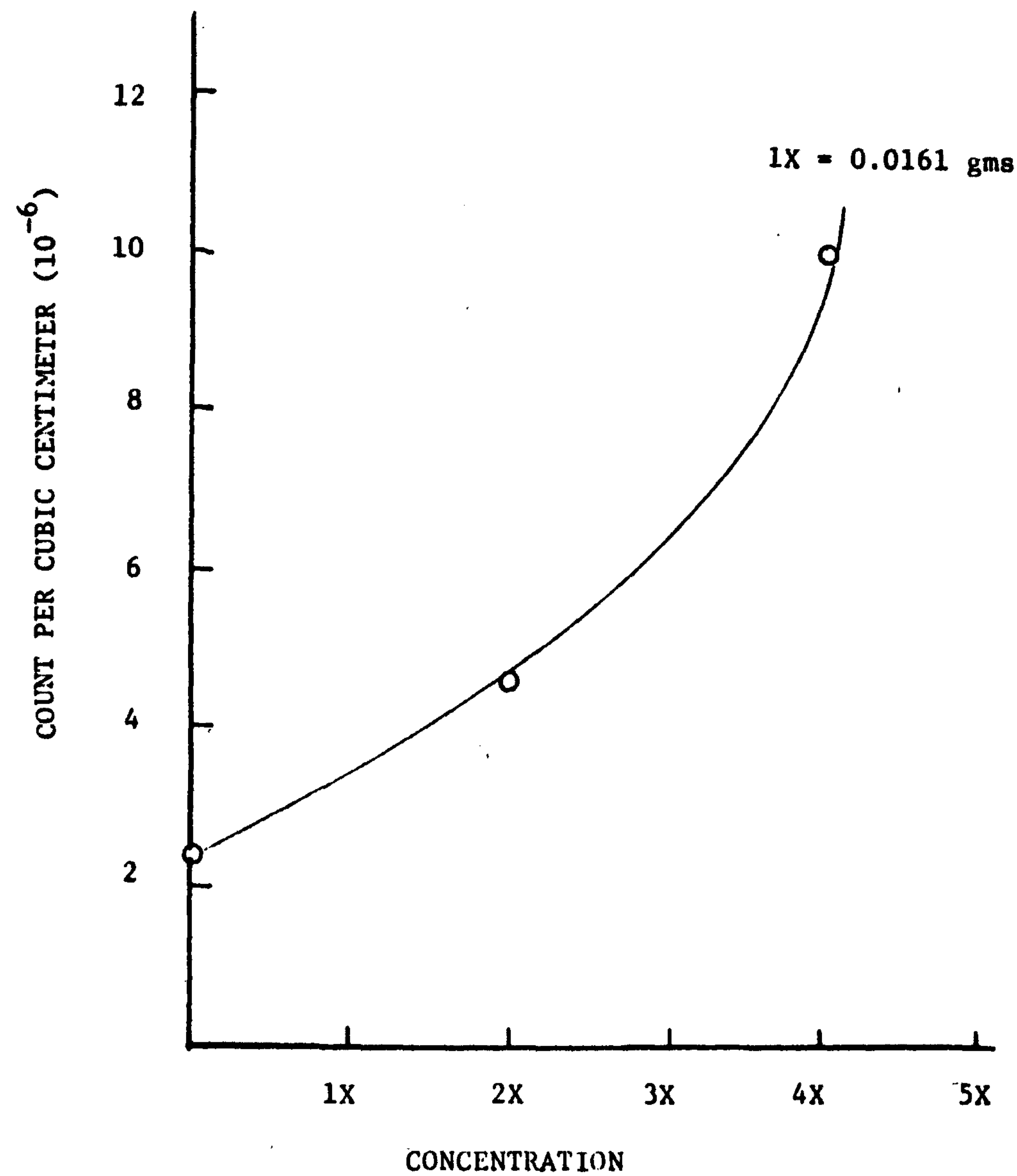


FIGURE 25 - TYPICAL COULTER COUNTER COUNTS VERSUS CONCENTRATION FOR LYCOPODIUM

SECTION VI

DISCUSSION OF RESULTS

The primary results obtained are presented in Figures 18 through 24; they illustrate typical data. Figures 20 and 21 show that a change in concentration results in a corresponding change in counts per second and is expressed by a linear relationship for moderate concentration levels. It can be seen by comparing Figures 18 and 19 (which show the response of Dow beads and lycopodium spores) that similar concentrations levels give similar counts per second. Figures 18 and 19 also show that the concentration profile, like the velocity profile, is flat across the test section for moderate concentrations. At high concentration levels a noticeable assymetry in the profile was observed. The exact explanation for this effect is not known. Figures 22 and 23 show the response of the system to varying degrees of sensitivity. These figures show that a corresponding response to a concentration change was obtained at all levels of sensitivity tested.

Figures 24 and 25 show the response of the Coulter counter to various concentrations. For lycopodium spores the response is almost linear; however, for dow beads the response was nonlinear. It was concluded from these results and attempts at calibration, with this fluid and these concentrations levels, that the Coulter's results were not accurate.

SECTION VII

DISCUSSION OF MEASUREMENT ERRORS

The data presented in the previous chapter illustrate typical experimental results obtained with the system. Due to the nature of the experiment rather large variations were observed in some of the measurements. The source and magnitude of these variations is discussed here.

Effect of Alignment

One of the disadvantages of this system is the sensitivity to alignment. The amount of light received is directly related to the angle between the detector and the incident beam. One assumption that has been made is that the detector and the beam are in the same plane and that the pinholes and the beam are aligned. Deviations from these conditions can greatly effect the results obtained at the counter. An example of this is seen by comparing the results shown in Figures 18 and 26. For the same number concentration different counts per second were obtained. Consequently, the actual value of the count per second is not significant - only the relative effect of changing the number concentration for a particular instrument alignment can be measured.

Concentration Measurement Error

The only error presented here is the error in consistent counts. Figures 27 and 28 show the variation in concentration profile and system response respectively. These figures were obtained by taking the largest deviation from the average. These curves show that the system response was very good because the error in the count shown could be expected just from the nature of turbulent flow.

Particle Suspension Considerations

To avoid the effect of particles separating from the flow and becoming attached to some portion of the system, all runs were made in one continuous sweep. The particles were assumed to remain suspended throughout the run. The effect of particles separating from the system was noted when particles slightly heavier than water were used. For

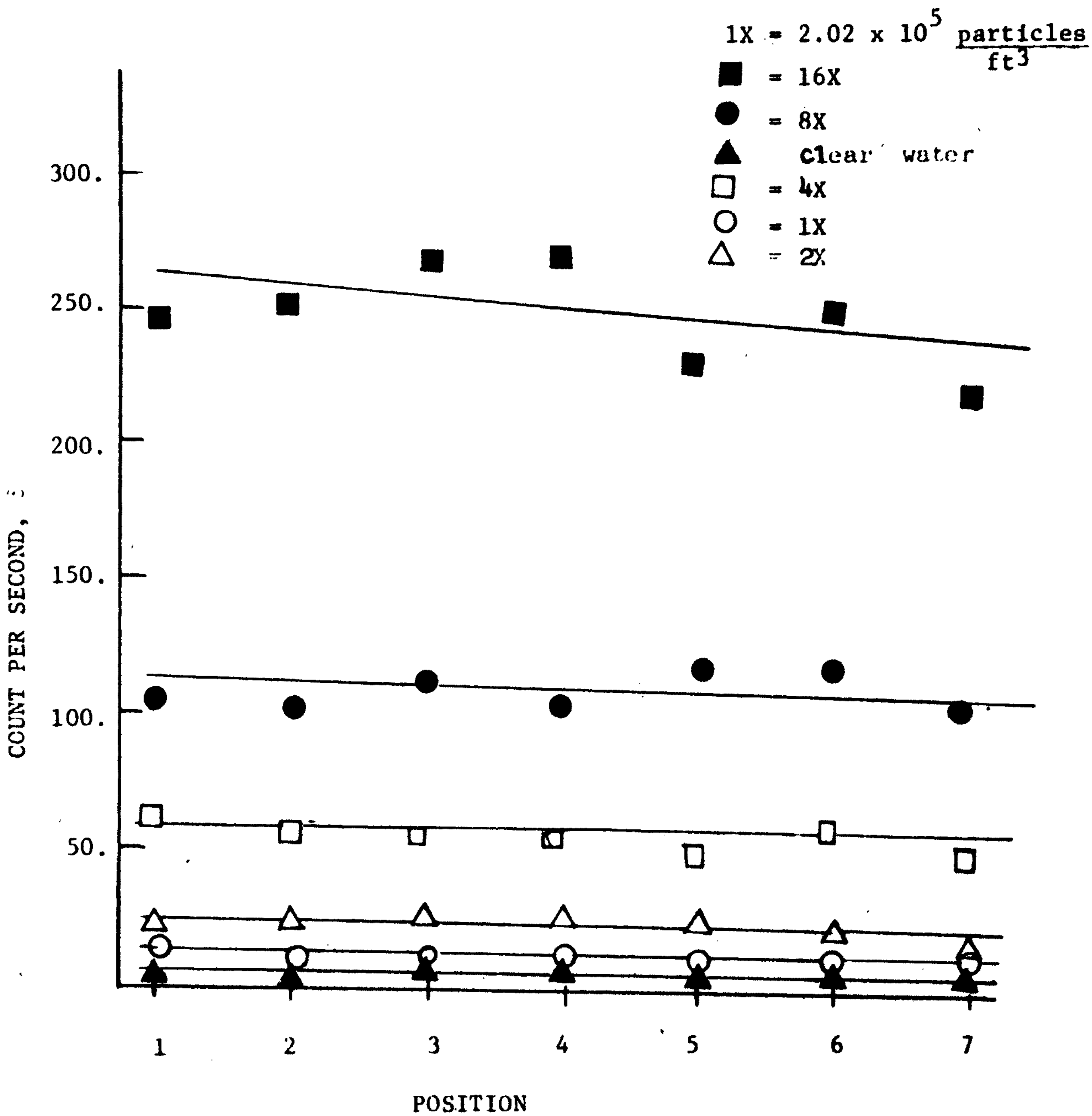


FIGURE 26 - OBSERVED COUNT PER SECOND VERSUS POSITION FOR LYCOPODIUM SPORES (DIFFERENT ALIGNMENT)

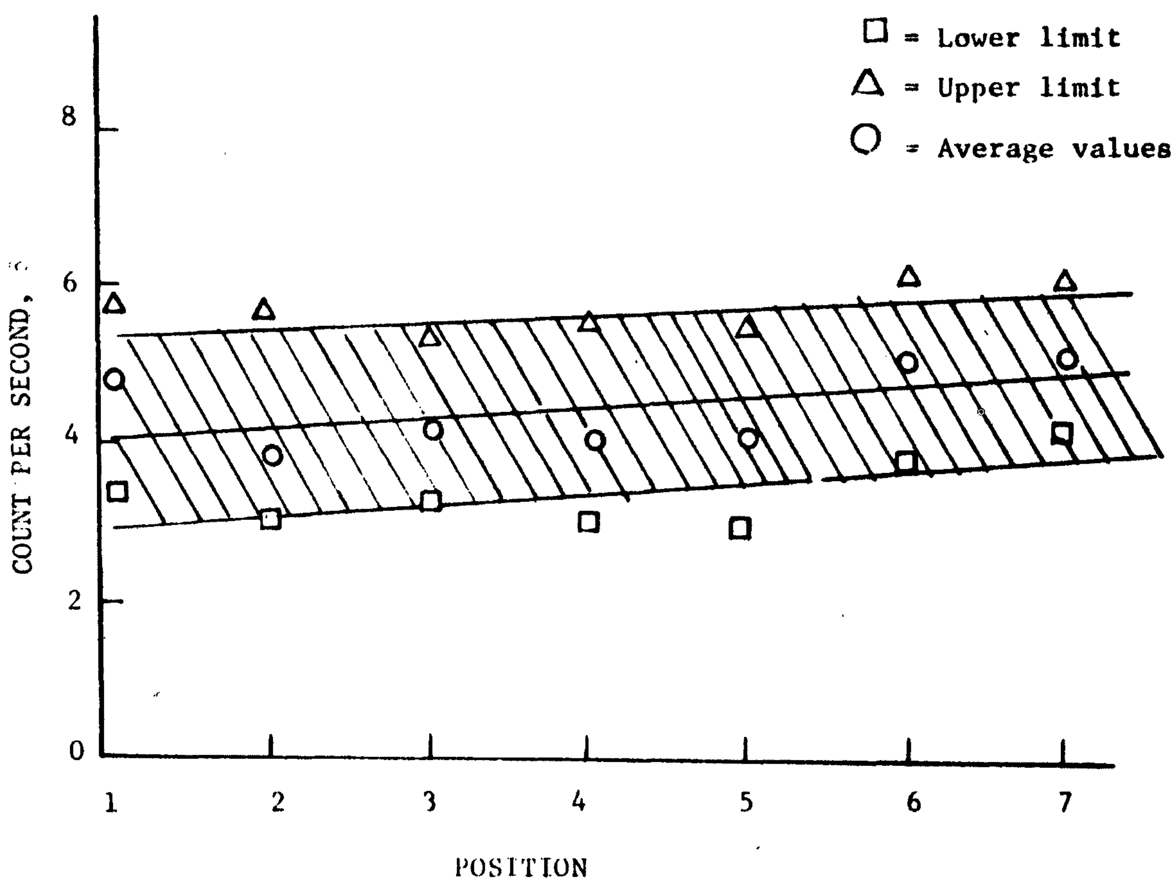


FIGURE 27 - OBSERVED COUNT PER SECOND VERSUS POSITION UPPER AND LOWER LIMITS

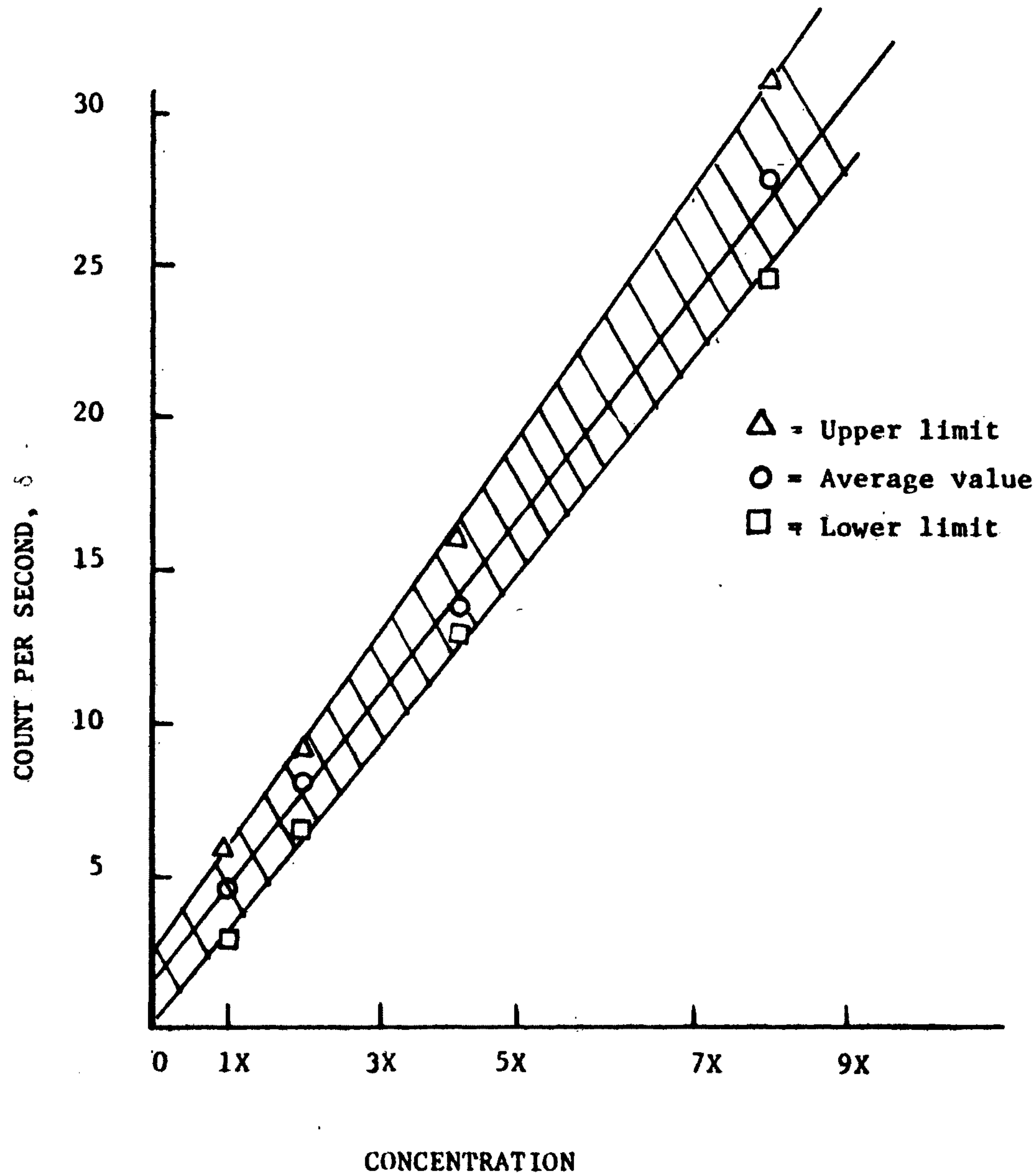


FIGURE 28 - OBSERVED COUNT PER SECOND VERSUS CONCENTRATION UPPER AND LOWER LIMITS

these particles the count first steadied and then rapidly began to decrease. The lighter particles seemed to remain suspended in the fluid rather well. This was determined by allowing the system to run for several hours and then rechecking the count/sec of particles.

SECTION VIII

ACKNOWLEDGEMENTS

The reported work was the result of the Master of Science research of Mr. Charles H. Tinsley, Jr. Professors Victor W. Goldschmidt and Warren Stevenson acted as supervisors of his work.

The support of the project by the Water Quality Office Environmental Protection Agency, and the help provided by Mr. George Ditsworth, Project Representative is acknowledged.

The assistance of the staff of the School of Mechanical Engineering and its Ray W. Herrick Laboratories during the final stages of the work reported is also gratefully acknowledged.

SECTION IX

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SECTION X

GLOSSARY OF SYMBOLS

A_s cross-sectional area of scattering volume defined as L_sD_b

$\bar{D}$ average particle diameter

D_b diameter of beam

f frequency of occurrence for that particle diameter

g 32.2 ft/sec/sec

I scattered light intensity

I_s phototube signal

i $\sqrt{-1}$

k_o $\frac{\alpha'\lambda}{4\pi}$

L_s length of the volume by interception of solid angle α_s

$\bar{L}_s$ stopping distance for impingement separators

L_w free fall travel distance in a cyclone separator

mV millivolts

N total number of particles added to water

N average number of particles in V_s

N_s number of times particle encircles cylindrical portion of cyclone separator

$\underline{N}$ number of particles sampled

n real part of refractive index

n' relative index of refraction

$\bar{n}$ number of scatterers

p parameter determined experimentally used to determine light scattered

q	size parameter $\frac{2\pi r}{\lambda}$
r	radius of particle
S	overall system sensitivity
U	stream velocity
V	total volume of fluid
V_s	scattering volume
V_{ic}	inlet velocity to cyclone separator
V_p	particle velocity
V_t, V_ε	free fall or terminal velocity of one particle
x_j	diameter of a given particle
α'	absorption coefficient
α_s	solid angle viewed by detector
Γ^*	average number of particles per unit scattering volume
Γ	average number of particles per unit volume
$\Lambda L_1 \& \Lambda L_2$	additive terms to L_s for traversing length
δ	count/sec
θ	angle subtended between the beam and the detector
λ	wavelength of the incident beam
ρ_p	density of particle
ρ_f	density of fluid
τ	standard deviation of particle size range

SECTION XI

APPENDIX

In many experimental investigations, it is necessary to have a supply of uniformly sized particles. Particles obtained from various manufacturers, in a range of 10 to 100 microns, do not adequately meet the uniform size specifications. Examples of the types of variance encountered are given in Table 1. The objectives of this appendix are to present a survey of the various techniques suitable for separation of micron range particles by size and to examine the most practical system.

Filtration Separators

Filtration separators are usually made of cloth or of a porous element. This type of separator is commonly used in conjunction with the removal of a particulate from a gas stream. Filter efficiency is dependent on the length of time in operation. Filters start at a low efficiency but increase to values as high as 99.9%. After a short period of operation, the pores become elogged from impingement, adherance of fines or by blockage owing to the larger-sized fractions in the dust being separated. The filter will then build up a "precoat" layer on its upstream surface and thus the precoat actually serves as a high efficiency filter bed.

Sieving is another form of filtration separation. Sieving is a method used to separate the fine particles from the course ones by means of nested screens. The sieving screens are mounted on a metal rim to form cylindrical pans. Such pans, each of different screen size, are nested one atop another with the finest at the bottom and the coarsest at the top. The material is placed on the top and then the screens are shaken. The difference between the pans of the nest represent a certain size range of the material separated.

Impingement Separator

Impingement separators depend on the inertia of the particle. The carrier fluid flows the streamline around an object which the particle cannot immediately follow, due to the particle momentum. The particle is, therefore, decelerated to zero velocity by striking the object. After striking the object, the particles are held into place and collected - usually at shut down. Collection can be made by counter current flow or by centrifugal force imparted on the carrier gas. Zenz (1960) gives a theoretical explanation of this type of separator. The important parameter is the stopping distance (L_s). The stopping distance is a function of the particle velocity, free fall velocity, and both particle and fluid densities. For a spherical particle the stopping distance is given by:

$$\bar{L}_s = \frac{v_p \ \rho_p \ v_\varepsilon}{g(\rho_p - \rho_f)} \qquad \text{(a)}$$

where

v_p = particle velocity

v_t = free fall velocity - v_ε

ρ_p = particle density

ρ_f = fluid density

g = 32.2 ft./sec/sec

Cyclone Separation

The cyclone or centrifugal separator is a device utilizing radial acceleration for separation of particles suspended in a gas stream. It consists of an outer cylindrical-shell and a cone attachment, and is so arranged that the dust-laded gas enters tangentially. This causes a vortex of gas which ascends up the cone and finally ascends to an outlet concentric with the outer cylinder. The particles, however, are impinged against the curved wall and swirl in a downward spiral path due to the effect of an outward centrifugal force imparted by the momentum due to inlet velocity and the force of gravity. The minimum diameter, of the particles separated by this process, is given as a function of fluid dynamic viscosity, free fall velocity, fluid inlet velocity, and the difference in particle and fluid densities.

In order to obtain the function which determines the diameter of the particles to be separated, the distance traveled by the particle laden gas must be determined. This distance is simply $2\pi r_c N_s$ of the cylindrical portion of the cyclone. The time that it takes the gas to travel this distance is $t = 2\pi r_c N_s / V_{ic}$ where V_{ic} is the inlet velocity to the cylindrical portion of the separation. This also is the maximum time allowed for the particles to travel the distance L_w. This is given by:

$$L_w/V_t = 2\pi r_c N_s/V_{ic} \qquad (b)$$

The terminal velocity can be determined from an equation given in a succeeding section if the drag force is computed by Stoke's law for a centrifugal field. The terminal velocity is then given by:

$$V_t = gD_p(\rho_p - \rho_f)/18\ \mu_f \qquad (c)$$

Substituting and solving for D_p, the following is obtained:

$$D_p = 9\ \mu_f L_w/(\pi N_s V_{ic}(\rho_p - \rho_f)) \qquad (d)$$

Gravity Separator

Gravity settling chambers are the simplest type of particle-collection equipment. The principle of operation is that the fluid velocity is reduced below the free falling velocity of the particle. This allows the particles to settle from the carrier fluid by the influence of gravity. The rate at which this occurs is dependent upon both fluid and particle properties. For similar shapes, the settling rate (free fall or terminal velocity) becomes dependent only upon the characteristic length usually the hydraulic diameter. In Wallis (1969) a derivation and also the correlation are given for the terminal velocity.

Any expanded section in line can constitute a gravitational settling chamber, however they are usually a long, empty, horizontal vessel or a long vertical cylinder. For the horizontal vessel, the basic idea is to allow the particle to travel a vertical distance in free fall in less time than it takes the carrier fluid to flow from inlet to outlet of the settling chamber. For the case of equal densities but different sizes the larger particles will fall out first and therefore the length of the chamber determines which diameter particles will settle. The cylinder settling chamber consists of a stagnant or very slow moving fluid in which the particles are dropped. The time at which a certain diameter particle reaches a predetermined depth can be determined thereby allowing a known range to be collected.

Entrainment

Entrainment may be defined as the carry-over of the particle by the fluid, from the particle bed to and through the dispersed phase. The rate of entrainment depends on factors that involve the apparatus, characteristics of the solid and fluid, for all of these. The entrainment process can be described in terms of the free fall or terminal velocity of the particle. When the fluid velocity exceeds the velocity of the free fall of the particle, the particle is carried by the fluid until either the particle is carried completely from the column or the particle forces exceed the momentum of the particle and it returns to the bed. Unfortunately, the entrainment rate cannot be modeled by the terminal velocity alone, other effects such as the throwing up of the particles by the bursting action of the gas at the particle bed and the concentration of the particles are important. Since the entrainment rate is dependent upon free fall velocity it also allows particle separation by size.

Conclusion

The methods surveyed were:

(1) Filters

(2) Sieves

(3) Impingement Separators

(4) Cyclone Separators

(5) Gravity Chambers

(6) Entrainment Columns

Of these methods filters do not prove adequate because of the nature of their operation. Filtration is essentially a catch all operation. Sieving is used by most of the manufacturers and if this method was chosen no finer distribution could be obtained. Impingement separation while theoretically possible is experimentally infeasible because it would require a test program for different types of collector designs.

Gravity separators are useful only when all particles are to be separated or when the densities or size are widely different. Even when the above conditions are satisfied, collection of the particles by the different sizes is difficult. Entrainment was chosen as the more practical because it allows easy collection and because it can be coupled with either cyclone, filter or sedimentation chambers. The cyclone separator is thought to be the best separator to couple with the entrainment bed because it gives a second chance at size separation. Closer examination reveals that for particles with diameters around 100 microns free fall velocity is approximately 0.43 to 1.07 ft/sec. However, to separate particles with 4 μ range results in air velocity control as being less than .01 ft/second. It was concluded that for the particle size separation needed, adequate controls were not available.

SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

1. Report No.	
2.	
3. Accession No.	W
4. Title	TURBULENT DIFFUSION IN LIQUID JETS: PART I
5. Report Date	
6.	
8. Performing Organization Report No.	
7. Author(s)	Charles H. Tinsley, Warren S. Stevenson & Victor W. Goldschmidt
10. Project No.	16070 DEP
9. Organization	Engineering Experiment Station School of Mechanical Engineering Purdue University Lafayette, IN 49707
11. Contract/Grant No.	16070 DEP
13. Type of Report and Period Covered	
12. Sponsoring Organization	

15. Supplementary Notes PART I IS SUBTITLED: Measurement of Particle Concentration by a Light Scattering Probe. Environmental Protection Agency Report number 660/3-74-004a, March 1974

16. Abstract

A technique for measuring particle concentrations in turbulent flows was investigated. This technique is the measurement of the light scattered from an incident beam by the solid contaminants present.

The results show that for moderate concentrations the scattering system gives proportional increases in count to increases in particle concentration. The limitations of this system are the signal to noise ratio and the condition of singular scattering by the particles.

Suggestions on refinements on the correlation technique used are made and observed phenomena which require further investigation are discussed.

17a. Descriptors

Equations, Instrumentation, *Particle Size, Suspension, Turbulent Flow

17b. Identifiers

Lasers, Light Scattering, * Particle Concentration, * Particle Size Measurement

17c. COWRR Field & Group 08 B

18. Availability	19. Security Class. (Report)	21. No. of Pages	Send To:
	20. Security Class. (Page)	22. Price	WATER RESOURCES SCIENTIFIC INFORMATION CENTER U.S. DEPARTMENT OF THE INTERIOR WASHINGTON, D. C. 20240

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WRSIC 102 (REV. JUNE 1971)